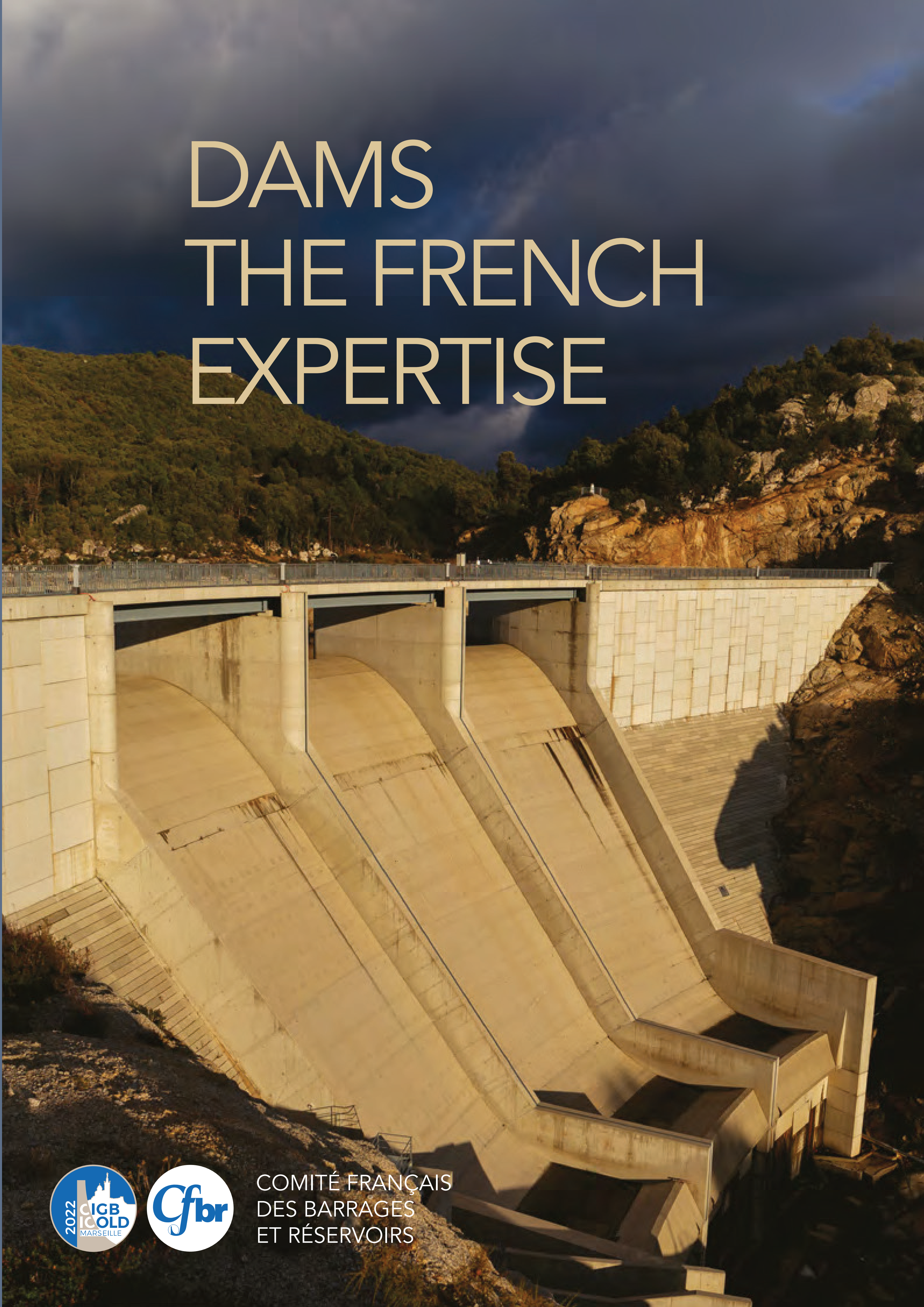
DAMS
THE FRENCH EXPERTISE



CIGB ICOLD 2022 MARSEILLE

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COMITÉ FRANÇAIS
DES BARRAGES
ET RÉSERVOIRS

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DAMS
THE FRENCH
EXPERTISE

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SUMMARY

ACKNOWLEDGMENTS

This book, published on the occasion of the 27th congress and the 90th annual meeting of the International Commission for Large Dams, was prepared by the French Committee on Dams and Reservoirs (CFBR).

Many voluntary members of the French committee participated in its drafting. They were keen to share their know-how, their experiences and their history. The author's index at the end of the book, gives the list of all those who participated in its writing, its reviewing, and its formatting.

A significant part of this work took place in 2020 and 2021, while France and the rest of the world were fighting against the Covid-19 pandemic.

I would like to express my thanks to all the participants for the important work accomplished, despite conditions which may sometimes have been difficult.

Patrick Le Delliou
Former chairman of the French Committee
on Dams and Reservoirs

FOREWORD

The French Committee on Dams and Reservoirs (CFBR) is honored and happy to be hosting the 27th Congress and the 90th Annual Meeting of the International Commission on Large Dams in Marseille in 2022. It is an opportunity to return to the long history, more than three centuries old, of our country's dams and to try to summarize France's contribution to this technology.

Our country has a long history of dams which began with the construction of the Saint-Ferréol dam, 36 m high, between 1667 and 1672, to supply the Canal du Midi connecting the Mediterranean Sea to the Atlantic Ocean. Mining, water supply to waterways and energy production were the main functions of dams built in the 18th and 19th centuries. In the 20th century, it was the development of hydroelectricity that enabled our greatest achievements. Finally, in the past two decades, irrigation, flood protection and the supply of drinking water have allowed the profession to continue operating, in parallel with the upgrading of our facilities.

Between France and ICOLD, there has been a long history of friendship and shared passion for dams, essential tools for developing and satisfying the basic needs of humanity: water, energy, security against floods and droughts. ICOLD was created in Paris in 1928. A founding member alongside the United States, Italy, Romania, Great Britain and Switzerland, France gave ICOLD its first president, Gustave Mercier, elected in London in 1931. Since then, France has given ICOLD two other great presidents: André Coyne (1946–1952) and Pierre Londe (1979–1982).

The CFBR brings together more than 500 actors from the world of dams: government, owners, contractors, engineering companies, teachers, researchers, and individual experts. It is a unique place for meetings and exchanges between all these professionals. With their different positions, each member brings their own vision and expertise to serve a common goal. The richness of the CFBR is to be able to bring all these stakeholders together in its annual technical conference, its working groups and its mirror groups of ICOLD's technical committees. This book aims to share this richness with you.

The CFBR has always wanted to make all its productions available to its members, of course, but more broadly to the barrage community worldwide. The guidelines drawn up by our Committee on various subjects, relating in particular to the justification of the safety of dams, are therefore available on the CFBR website (https://www.barrages-cfbr.eu/). The same goes for the proceedings of our annual conferences which bring together a widespread French audience, as well as a regular European and African participation. Within ICOLD, the French Committee has always campaigned for a widespread and free distribution of the Bulletins of the technical committees.

The CFBR's involvement in the activities of ICOLD has always been strong, through our active participation in most of the technical committees with numerous presidencies or vice-presidencies and the establishment of mirror working groups to offer the French contribution. The production of reports for ICOLD congresses, generally wide-ranging and consistent, is the result of collective work by our members in order to develop and publicize the French vision on the issues debated during the congress. We are proud to have two general rapporteurs for questions at the Marseille Congress.

France's dam facilities supply more than 13% of our electrical energy and a third of our renewable energy; they contribute to the drinking water supply and irrigation and help to protect against floods and droughts. However, the construction of dams is no longer a priority in France. The last few years have even marked a virtual halt in the construction of new dams. Our main current challenge is the intelligent management of this heritage of over 1,000 large dams in order to guarantee their services in a sustainable, economical and safe manner. Our Committee thus largely assisted the government in the development of the new French regulations implemented from 2007 which aim at keeping this exceptional heritage safe.

France played a leading role in the development of dams in the second half of the 20th century. After World War II, Europe had to be rebuilt and, here in France, hydroelectricity was one of the instruments of this renewal. André Coyne played a decisive role in the design and construction of arch dams. Following the failure of Malpasset dam, Pierre Londe was one of the founders of Rock Mechanics and was the inventor of symmetrical hardfill dams. François Lempérière proposed major innovations in spillway design with fuse gates and fuse blocks, and piano key weirs, and continues to offer brilliant and innovative ideas on new dam designs and their new uses in a context marked by climate change and the rapid development of intermittent renewable energies.

I dedicate this book to these three great French engineers who continue to inspire the work of our committee and push us to put innovation at the forefront of our motivations.

French dam engineering was born from the development of hydroelectricity in the second half of the 20th century. In the 21st century, it has managed to survive the end of this great adventure and is now present on five continents. It is ready to tackle a new page in history where dams, in addition to their traditional water storage functions for agriculture, drinking water and irrigation and protection against floods and droughts, will be major tools of the new world energy policy, with their unique capacity to store energy on a large scale. The evolution of the utilization of dams and climate change should soon lead to the planning of new projects and we are preparing for it.

Our construction companies have also largely participated in the adventure of dams, both in France and abroad, particularly in Africa. After two decades of decline, they are back on the international markets where they offer an alternative to international competition.

What does this book contain? It is not a reference book on dams and does not purport to cover all aspects of the design, construction and management of dams. It is rather a series of spotlights on themes where there is a strong French doctrine and where our contribution has been significant.

Chapter 1 tackles the theme of multi-purpose reservoirs which is strongly anchored in the French tradition of waterway development and is the subject of the Symposium organized by the CFBR on the sidelines of the Marseille Congress. Chapters 2 and 3 deal with geology and hydrology and highlight the specificity of the French approach to these two disciplines at the heart of dam design. The following chapters are devoted to the French experience of design, construction and operation of the different types of dams (gravity dams, arches, embankment dams and river barrages) including the river and sea protection levees which recently entered the ICOLD field. Chapter 8 highlights good environmental practices. Finally, three chapters deal with hydromechanical and control system equipment, monitoring, and French practice in terms of hazard studies and risk analysis.

Its drafting is largely based on the contributions of the working groups and the proceedings of our technical conferences, of which it constitutes a summary that we are happy to share with you.

In order to conserve the resources of our planet, the book is available in a free electronic version and in a paid paper version in French or in English.

I hope that reading these few lines will encourage you to go further and appreciate the French approach to dams.

To conclude, I warmly thank Patrick Le Delliou, Honorary President of the CFBR and President of the Editorial Committee, who directed the development of this book. I would also like to thank the various authors who were able to share the best of French expertise in dams in 12 chapters with our colleagues and friends from around the world.

Michel Lino
Chairman of the French Committee on Dams and Reservoirs

CHAPTER 1

MULTIPLE USES OF DAMS

France has a rich heritage of dams and reservoirs, built up gradually over several hundred years (Section 1) with many dams intended for electricity production. A strong trend in recent decades has been the optimization of the use of existing reservoirs, trying to reconcile a wide variety of uses in a changing context: new societal needs, increased consideration of environmental needs, climate change.

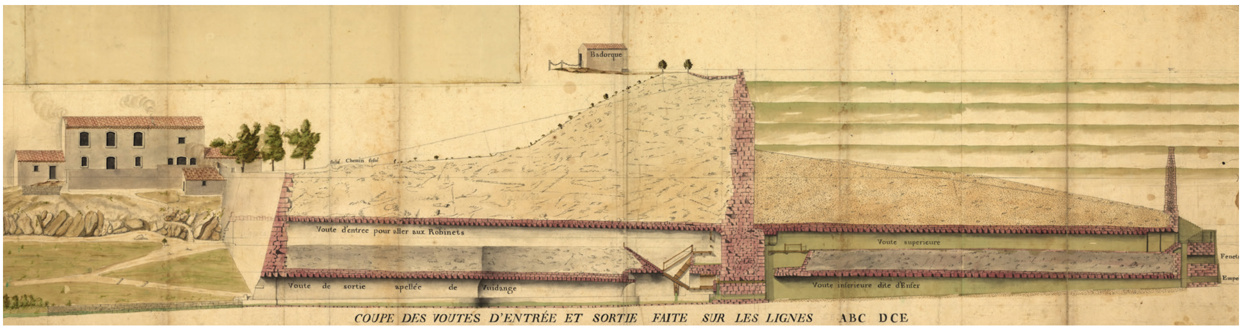
Section 2 presents several examples of French dam facilities where multipurpose is, or has become, the central principle of their operation. It also shows that this question arises automatically for large dam projects in other contexts, with the emblematic case of the Niger Basin. This panorama shows that the question of multipurpose use is posed in a quite different way each time. There is no general rule. Another lesson is that reconciling different uses is a difficult issue.

This has led France to put in place specific tools for successful sharing of uses (see Section 3): governance and financing tools to steer projects, in-depth studies to make the right choices.

In France, as in other countries, the construction of new dams has slowed down considerably. However, the evolution of uses and climate change should lead to the consideration of new projects. Section 4 lists a few avenues explored to achieve this, in a context where French public opinion remains generally opposed to dam projects.

Figure 1.1 – Saint-Ferréol dam / © Voies Navigables de France – Archives des canaux du Midi

Saint-Ferréol dam is the oldest large dam still in operation. Built by the engineer Pierre-Paul Riquet, it was commissioned in 1675 to supply water to the Canal du Midi linking the Mediterranean Sea to the Atlantic Ocean. The lake it forms is now an important place for tourist activities. It is 35 m high and consists of masonry walls and earthfill zones.



1. THE FRENCH DAM PORTFOLIO

France has 722 large dams according to ICOLD's definition. They are located both in mainland France and overseas but the highest of them are in mountain areas (Alps and Pyrenees). The highest is the Tignes arch dam rising 180 m above the foundations.

According to the criteria of French regulations, approximately 2,000 of them are classified as being of public safety interest. Partial censuses estimate the number of small dams (over 2 m high on natural terrain) to be over 100,000. The French portfolio is relatively old; many major dams were built after 1945 (Figure 1.2). Because of French engineering tradition and because they were built earlier, concrete dams are more frequent (52% of the total) than in the rest of the world (19%), see Figure 1.3. In particular, the proportion of arch dams is three times higher in France than in the rest of the world.

Hydropower dams account for nearly 50% of the total number (Figure 1.4). Conversely, the use of dams for irrigation is much less developed than in other countries of the world, although this function has become more frequent in recent years.

The statistics shown in Figure 1.4 concern the main use of dams. However, nearly 35% of the French large dams have multiple uses. The variety of the systems of dams and the variety of their purpose is illustrated with a few examples in the following sections.

Figure 1.2 – Date of construction of large dams in France

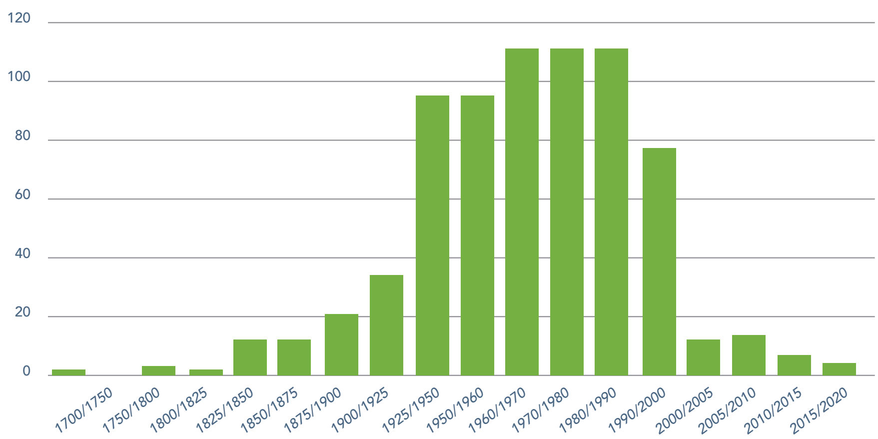


Figure 1.3 – Type of dam (according to ICOLD terminology)

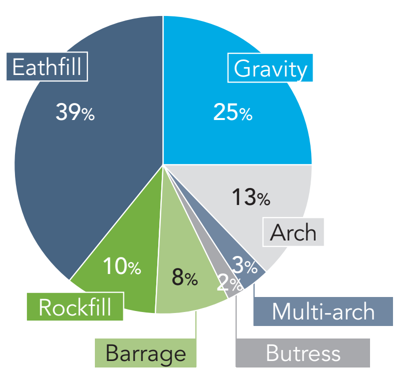
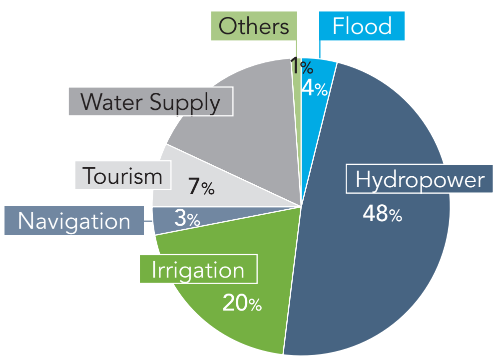


Figure 1.4 – Main use of dam (according to ICOLD terminology)



2. MULTIPLE USES: SOME TYPICAL EXAMPLES

This section describes four systems of reservoirs and shows to what extent the multipurpose component has become established in France, either at the design stage or over time. This is the case of the valley of Saint-Étienne, an industrial region undergoing reconversion where the use of reservoirs has changed considerably over the years; of the Seine Grands Lacs reservoirs that temper the flows of the river Seine in Paris (floods, low water levels) where new uses have been imposed. It is also the case of the Durance-Verdon scheme which has very great economic importance for hydropower, water resources and tourism; and of the lakes on the Gascony hillsides, emblematic of the wealth of ecosystem services provided by the reservoirs.

2.1 The metropolitan area of Saint-Étienne: multiple and evolving uses

Saint-Étienne Métropole has a series of 12 dams whose construction was spread over nearly 200 years, between 1789 and 1972. These structures were created for water storage in response to economic and demographic development and to regulate river flows.

First: the Couzon dam. This dam was set up to supplement the low-water levels of the river Gier to supply a navigation canal initially planned to link the Loire to the Rhône. Due to a lack of financial means and water resources, the canal was finally limited to 15.5 km, with the purpose of transporting coal to the city of Givors. Widely used at the beginning of the 19th century, it was then replaced by a railway, destroyed and filled in during the 20th century, giving way to a freeway linking Givors to Saint-Étienne. The dam was bought by the City of Rive-de-Gier for its drinking water supply at the end of the 19th century, a function that continues today.

The Furan River is historically a river with multiple uses: a driving force for the factories installed on its banks in the 19th century and a source of drinking water for the City of Saint-Étienne. Water quality and quantity of withdrawals have given rise to conflicts of use. Moreover, the flooding of the Furan River endangered the properties and populations settled too close to the banks. As a result, it became necessary to store the river's water and regulate its flow. Gouffre d'Enfer dam (1862–1866) was built to reduce flooding and guarantee the supply of water of a quality that met the specific needs of the manufacturers (arms, steelworks, textiles, etc.) and the population.

From 1870 to 1970, with demographic and industrial development, further reservoirs were needed. For the City of Saint-Étienne, the capacity of Gouffre d'Enfer dam was insufficient and the construction of the Pas-du-Riot dam (1878) was started. Other reservoirs have been built for neighboring communes: La Rive (1870), L'Échapre (1898), Le Cotatay (1905), L'Ondenon (1904), La Chapelette (1907) and Lavalette (1917), Piney (1955), Les Plats (1958), Soulages (1970) and Dorlay (1972).

Today, water requirements, specifically for industry, have declined with the territory's economic transformation and water from dams is only used to produce drinking water. Dams contribute to supplying 98% of the inhabitants with surface water. In addition to this unique vocation as a drinking water resource, secondary uses are being added and developed: communication axes linking the two banks of a valley, particularly sought-after recreational activities. These activities must be reconciled with the necessary protection of the resource and the maintenance of the structures.

Figure 1.5 – Fresco drawn in 2017 on a decommissioned dam: "le naufrage de Bienvenu" by Ella and Pitr / *© Service Communication Saint-Chamond*

With climate change already perceptible on river hydrology, structure functionalities that were almost forgotten of the (support of low water levels and flood control) are once again being discussed. For example, with the encouragement of riverside associations, a flood-control role for dams is under consideration. Or, at the initiative of other groups, a role in supporting low water levels. However, hydrological studies have highlighted the difficulty of fulfilling these three uses with the available reservoirs: storage for drinking water (as high up as possible in the catchments for better water quality, and with sufficient safety reserves for accidental episodes), flood control (further downstream in the valley) or low-water support.

2.2 The reservoirs of the Seine River: floods, low water levels and new uses

The four reservoirs managed by the Seine Grands Lacs (EPTB[1]) are the result of a political will to design and build a series of major hydraulic developments upstream of the Seine watershed to better protect the Paris urban area against floods, while ensuring a certain regulation of flows during low-water periods.

The major floods of January 1910 and 1924, as well as the drought of 1921, indeed highlighted the great vulnerability of the Paris agglomeration to the natural variations in the river's flow. The average discharge of the Seine in Paris does not exceed 300 m^3/s and the natural low-water flow rate can fall below 50 m^3/s, which is too low to meet the needs of an urban agglomeration of more than 10 million inhabitants. Conversely, a situation of severe flooding would result, as in 1910, in the French capital being paralyzed for several months, and to losses estimated at several tens of billions of euros.

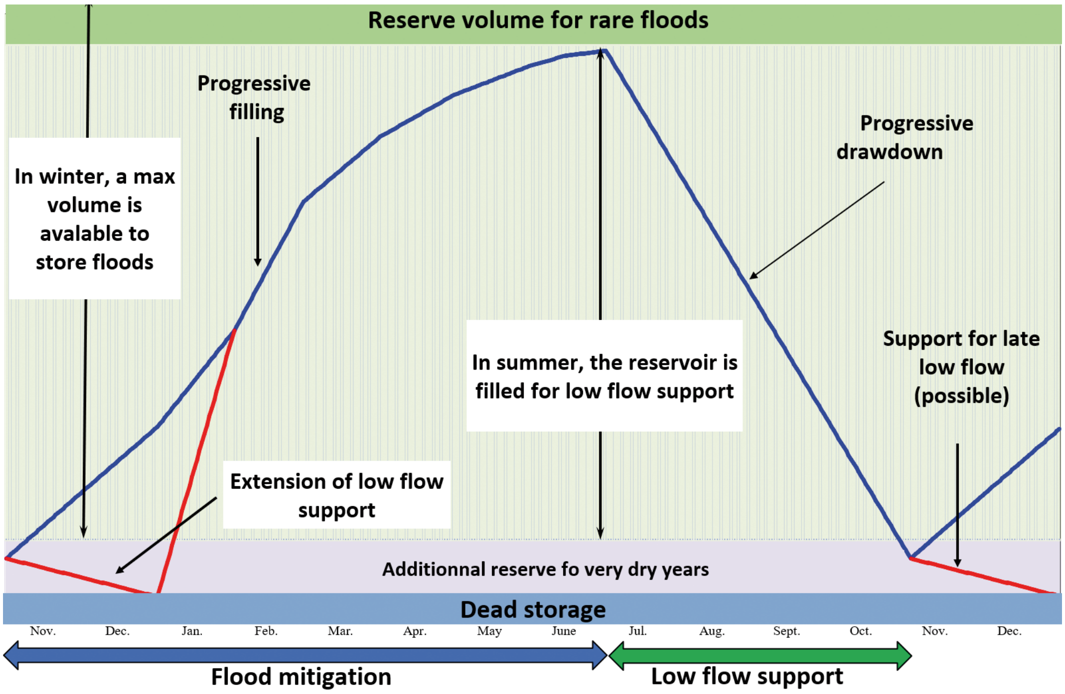
Figure 1.6 – Pannecière dam / © Seine Grands Lacs

Started in the 1930s, the first large hydraulic works involved the Pannecière dam, which was commissioned in 1949. It was followed by the development of three reservoirs diverting the river Seine and its two main tributaries, the rivers Aube and Marne. The latter, also known as Lac du Der, is one of the largest artificial lakes in Europe.
From the outset, these four reservoirs were assigned two distinct objectives, on the one hand flood control and on the other hand low-water support to ensure at all times a sufficient flow downstream to satisfy various

(1) EPTB is the acronym for Établissement Public Territorial de Bassin – that could be translated into Public Territorial Basin Establishment.

uses vital to the local economy, including drinking water supply, irrigation, navigation, cooling of industrial installations or dilution of effluents from wastewater treatment plants in order to restore the rivers' healthy ecological status.
To meet these two objectives, operation rules (Figure 1.7) were drawn up, fixed by prefectural decree and optimized on the basis of a statistical analysis of the hydrological regime of each of the rivers. The principle is that the four structures, which together have a storage capacity of almost 850 million m^3, are filled at the end of June in order to provide sufficient low-water support until the end of October at least, and sometimes until December.

Figure 1.7 – Principle of the operating rules for the reservoirs managed by EPTB Seine Grands Lacs / ©Seine Grands Lacs



The flood-mitigation function of the reservoirs can be mobilized at any time, as the lakes are used to divert and temporarily store upstream flows.
The storage capacity of the lakes, which are in large, natural, impermeable basins surrounded by embankments, also makes it possible to divert fractions of the flood from the main river and release them a bit further downstream. This bypass function, which is used in addition to the storage function, also contributes to flood mitigation by limiting the risk of overflows along the section of river thus short-circuited; this helps to protect some highly exposed local places, in the cities of Troyes and Saint-Dizier.
The flood-control function assigned to the four reservoir lakes in the upper Seine basin is used very regularly, especially during the winter period. Since their commissioning, floods have been systematically capped, with the result that the alluvial valleys downstream have seen a sharp reduction in the frequency and extent of overflows. This has also contributed to certain developments in agricultural practices, with field crops replacing livestock grasslands despite their greater vulnerability in potentially flood-prone areas.
Even for major flood events, such as the one the basin experienced in January 2018, the action of the reservoir lakes is decisive. This last episode was characterized by cumulative rainfall over the entire basin, two to three times higher than normal, during part of December and all of January, with heavy rainfall until April. This resulted in two main flood peaks just 15 days apart.

In one month, the four reservoir lakes stored more than 500 million m^3, with diverted flows that at times reached up to 70% of the natural flows upstream of the intake structures. These structures were used to their full capacity, with intake flows reaching 300 m^3/s for the Marne intake and 160 m^3/s on the Seine inlet canal, a value never reached since the construction of the structure more than 50 years ago.

Figure 1.8 – The Seine inlet canal operating at full capacity in January 2018 / © Seine Grands Lacs

The effect of the structures on the protection of downstream urban agglomerations has been major, resulting in a strong curtailment of flows. In Paris, for example, the water line was lowered by 65 cm thanks to the cumulative action of the lakes. Otherwise, the level would have remained above the critical 6.20 m elevation for about three weeks, making it difficult to protect underground infrastructures such as subways, railways, power stations and many underground basements and underground car parks. According to CCR (major French Reinsurance Fund), the direct damage avoided during this event, due to the action of the reservoir lakes, amounts to nearly 90 million euros, but the costs would actually have been much higher due to impact on networks, which are not included in this estimate.

The effect of the reservoir lakes on low-water support is no less, since the structures can release up to 68 m^3/s throughout the summer and fall, which represents up to 80% of the flows observed in the Seine at Troyes or the Marne at Châlons-en-Champagne. In 2018, as indeed in 2017 and, no doubt, more and more frequently as a result of global warming, this low-water support extended well beyond the period normally expected. Without this action, the flow rate of the Seine would have remained below the crisis threshold at Pont-sur-Seine for more than four consecutive months (until early December), necessarily compromising many activities, including the smooth operation of the Nogent-sur-Seine nuclear power plant.

Beyond these two main functions of flood control and low water support, the four reservoir lakes managed by "Seine Grands Lacs" have established themselves as sites of great ecological richness. Several nature reserves have grown up around the lakes, which over the years have become staging points for wildlife and a temporary refuge for many migratory birds, including the common cranes that congregate there by the thousands every year. Numerous leisure, fishing, hunting and water sports activities have been developed on the 10,000 hectares of the lakes, generating substantial tourism revenues for the local communities.

Simultaneously, Pannecière dam and the Seine lake outlet were equipped with licensed hydroelectric power stations as soon as they were built. Another hydropower production site has since been developed and studies are underway to further develop this renewable energy production potential through new hydropower and photovoltaic schemes. This confirms, if need be, that such structures can perfectly fulfill multiple uses in parallel, beyond their main objectives, and substantially promote both the environmental quality of the environment and local economic development.

2.3 Durance-Verdon scheme: hydropower and water sharing

The Durance is one of the most powerful torrential rivers in France, running from the high mountain ranges of the Alps to the sunny and water-scarce Provence. Nearly 55% of its water comes from melting snow. In the past, Provence used to suffer both devastating floods and seasonal shortages. "The Parliament, the Mistral and the Durance are the scourges of Provence", said the people of Provence! Ironically, despite the presence of two major rivers (the Durance and the Verdon), the region lacks water. Its inhabitants fight over this resource, which is the object of real conflicts, as told by Marcel Pagnol in his novels. From the beginning of the 19th century, development projects in the Verdon and Durance valleys were envisaged. However, the technique of the time did not allow them to be carried out.
It was not until after the Second World War that the project was technically possible. France needed to be rebuilt and had to meet the growing needs for water and energy. This reconstruction required the implementation of numerous hydropower scheme projects. The public utility law of

January 5th, 1955 launched the construction of the Serre-Ponçon dam and the development of the Lower Durance.

In addition to their main purpose (electricity), these schemes had to provide a solution to the problems of water supply in Provence and flood mitigation. In return for a water reserve for agricultural use, the Ministry of Agriculture contributed 12.3% of the capital costs. Serre-Ponçon reservoir was filled in 1960, creating the largest artificial lake in mainland France with a volume of 1.2 billion m^3 of water. The construction of the 250 km long Durance Canal (from Serre-Ponçon to the Étang de Berre) supplies 15 hydropower plants along its course as well as water to Provence via intakes built on the canal. In addition, a reserve of 200 million m^3 has been set up in Serre-Ponçon to remedy the shortcomings of the natural flow of the Durance during periods of intensive irrigation.

Figure 1.9 – Serre-Ponçon dam and reservoir / © EDF – Bertrand Bodin

In 1962, the creation of the Lower Verdon scheme was decided following an agreement between EDF, the Ministry of Industry and the Ministry of Agriculture. The project involved the construction of the Sainte-Croix dam, which provides an additional reservoir of 760 million m^3. This includes water storage of 225 million m^3 for supply water to the departments of Var, Bouches-du-Rhône and Vaucluse.

Figure 1.10 – Sainte-Croix dam and reservoir / © EDF – Gérard Alloin

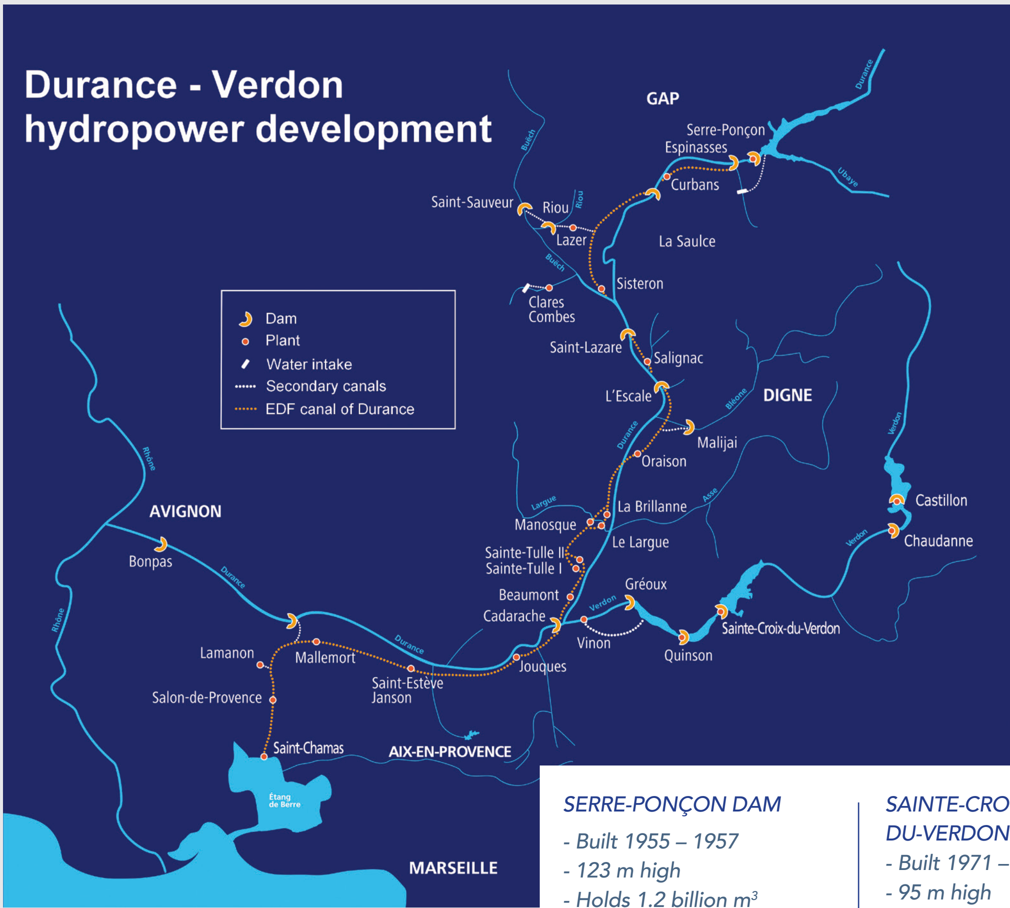
Today, the Durance-Verdon scheme includes 24 power stations, 16 dams, a 250 km canal and installed capacity of 2,000 MW that can be mobilized in less than ten minutes.

In addition to generating an average of 5.5 TWh of renewable electricity per year, this water & energy system is a keystone in the sharing of water in the whole region, allowing:

- supply of drinking water to 3 million people;
- industrial water supply for 440 companies;
- irrigation of 80,000 hectares of farmland;
- mitigation of the effects of floods and droughts;
- development of tourism and economy around the lakes formed by the dams, as in Sainte-Croix-du-Verdon or Serre-Ponçon, major tourist spots in the Provence-Alpes-Côte d'Azur region.

The Durance-Verdon schemes thus play a primordial role in the regional economy, in securing water resources on a historically water-scarce territory and have been sharing water between all uses for 60 years.

Figure 1.11 – Layout of the Durance-Verdon system



SERRE-PONÇON DAM
- *Built 1955 – 1957*
- *123 m high*
- *Holds 1.2 billion m^3 of water*
- *4 Pelton turbines, capacity 365 MW*
- *Max. turbine flow rate: 360 m^3/s*
- *Production: 704 GWh per year*

SAINTE-CROIX-DU-VERDON DAM
- *Built 1971 – 1973*
- *95 m high*
- *2 Francis units, including one capable of pumping 52 m^3/s from the downstream reservoir*
- *Power 145 MW*
- *Max. turbine flow rate: 210 m^3/s*
- *Production: 139 GWh per year*

2.4 Lakes on the hillsides of Gascony (Southwestern France): ecosystem services

Dam reservoirs serve ecosystem uses, most often without this having been part of the uses identified at the time of their design. This is illustrated here with the example of the reservoirs operated by the Compagnie d'Aménagement des Coteaux de Gascogne (CACG).
Ecosystems provide services; an inventory of these services has been drawn up by the Ministry of the Environment, which has identified 43 of such uses and services [CREDOC, 2009]. The territorial approach of CACG makes it possible to respond to some fifteen of these services through both lake development and management.
About twenty mountain and piedmont lakes secure the "Neste" system managed by CACG. These lakes constitute a reserve for the territory: 15 lakes in the foothills and 4 mountain reserves, 118 hm^3 of water that can be mobilized, supporting 1,350 km of watercourses. Among them, the lake of Baïsole (14 hm^3) is a reference in terms of multi-use of water.

Figure 1.12 – Ecosystem services provided by the CACG lakes

15 supply services (production of goods)	15 regulation services (production of services)	13 services of a social character (production of services)
Support for food crops	Flood prevention and flood control	Landscape quality
Support for crops meant for energy production	Mitigation of the effect of droughts	Quality of the olfactory environment
Support for aquaculture	Prevention of geomorphological disorders in watercourses	Quality of the sound environment
Support for Professional fishing	Waste purification and treatment (self-purification)	Intrinsic and heritage value of biodiversity (protected species, etc.)
Production of plants and mushrooms for harvesting	Erosion and mud flow control	Specific human communities
Mineral elements for extraction (aggregates)	Avalanche limitation	Source of artistic inspiration
Support for the production of fibres and other materials	Maintenance of soil quality	Production of animals for hunting
Support for wood production	Recycling of organic matter	Production of animals for fishing
Water supply for domestic use	Regulating the dynamics of pathogens and parasites	Support for nature sports (fresh water, hiking, aerial)
Water supply for industrial use	Regulating the dynamics of harmful and invasive species	Support for tourism and nature recreation
Water supply for power generation	Maintaining pollination	Support for thermalism and thalassotherapy
Water supply for agricultural use	Purification and maintenance of air quality	Support for research work
Bottled water production (mineral and spring water)	Regulation of the local climate	Support for the development of educational knowledge
Reservoir of life	Planetary climate regulation	
Inland waterway maritime transport	Biodiversity and ecosystem functioning	

Contribution financière marginale *
Contribution financiere importante **
Contribution financière majeure ***

Figure 1.13 – Lake of Baïsole / ©CACG – Laurent Pascal

This lake, impounded in 1987, is located on the Baïsole, a tributary of the Baïse River. The services and uses rendered are:

- Raw water – For drinking water.
- Agriculture – The lake contributes to the irrigation of local crops (nearly 10,000 hectares).
- Aquatic Life – An important structure in the Neste System, the lake provides a year-round supply of water to rivers and allows for the maintenance of aquatic life on rivers that would naturally experience significant drawdowns.
- Birds – The site is a privileged passage area for nearly 240 species of birds. Since 2006, an order from the Ministry of Ecology and Sustainable Development has classified the site as a Natura 2000 zone. To favor nesting periods and the need for waders to be close to the shore, CACG operates a fine management of the reservoir shoreline until the end of February (by cushioning natural rainfall variability).
- "Maison de la Nature et de l'Environnement 65" (House of Nature & Environment) – the Department wished to set up an educational place raising awareness of environment issues and interactions between human activities and nature. The department chose to set up this House at Baïsole Lake.

Figure 1.14 – Maison de la Nature et de l'Environnement, associated to the lake of Baïsole / © *Christophe Cuenin*

- Fishing – Recreational fishing also contributes to the attractiveness of these structures. Co-activity is managed through committees of users and consultation.
- Energy – Since 2015, a hydropower plant has been optimizing the use of water: water released into the natural environment (especially the instream flow) is turbined to produce energy (300 kW, 1.1 GWh, or the consumption of about 40 households).
- Navigation – Lake Baïsole also makes it possible, via a partnership agreement with the departments concerned, to maintain a sufficient water level beyond the support flows of the river Baïse to ensure the continued navigability of this river.

Figure 1.15 – Navigation on the Baïse / © *CACG*

CACG thus ensures that water resources are shared and secured between needs related to economic uses and those necessary for the natural environment.

2.5 Niger Basin: promoting multi-purpose use

Since the 1960s, France has provided significant support to several large cross-border river basins, including the Senegal, Niger, Nile, Congo and Mekong basins. Large dams with cross-border impact are the major subject of cooperation between the Member States of the basin organizations. France, for example, played an important role in the creation of OMVS (Organization for the development of the Senegal River) in 1972 and continues to support its actions, which have a positive economic balance sheet for the member countries (hydropower, drinking water, agriculture) through the Manantali, Diama, Félou and Gouina dams, which are jointly owned by the member states.

French development assistance in particular committed at the end of 2007 to "being a driving force in the revival of multi-use dam projects, whose objectives must be correctly dimensioned, alternatives well studied, international compatibilities analyzed, and social, economic and political consequences taken into account and compensated if necessary. The support will only concern works included in an investment program validated by all the riparian countries" (Ministry of Foreign Affairs).

In 2011, the OIEau (acronym standing for International Office for Water), a French public utility association, studied the prioritization of large new dams for CEDEAO (Economic Commission for West African States), then in 2012 for the whole African continent within the framework of PIDA (Program for Infrastructure Development in Africa) developed by the African Union and the African Development Bank.

PIDA's water program aims to develop large multipurpose dams (hydropower and irrigation as a priority) and to strengthen the capacity of basin organizations of African rivers and lakes to plan and develop these infrastructures. Several works have been prioritized in this way in the ten largest basins in Africa.

Regarding the Niger Basin, the International Conference on the Niger River Basin was held in April 2004 in Paris under the auspices of President Jacques Chirac. Bringing together the heads of state of seven Member States of the Niger Basin Authority, it relaunched the "Shared Vision" process and enabled an agreement on the potential development of major upstream structures in Nigeria. France supported a technical component focusing on data collection and decision-making support for the strategic programming of large dams, as well as a component supporting the implementation of ABN (Niger River Basin Authority) reforms.

A model for water resource allocation at the scale of the Niger Basin was developed in 2007 with funding from the French Development Agency (AFD). This model has contributed to the elaboration of the Action Plan for Sustainable Development of the Niger Basin. The ABN Member States have opted for the three multipurpose dams (hydropower, irrigation, low-water support) of Fomi in Guinea (volume of about 5,000 hm^3), Taoussa in Mali (3,200 hm^3) and Kandadji in Niger (1,600 hm^3), the latter of which is now under construction.

The studies relating to the allocation model, the Action Plan, the accompanying Investment Program and the Niger Basin Water Charter validated in 2008 were carried out by French consulting firms, with the support of a French technical assistant working with ABN during the Shared Vision process. The studies for the Kandadji and Fomi dams were also carried out by French engineering companies, which also conducted a study in 2019 on the modeling of the Niger Inner Delta as part of an assessment of the impacts of the Fomi dam.

Figure 1.16 – Map of the Niger River Basin

France is also involved in improving knowledge for the coordinated management of existing and planned dams. This work is based in particular on the use of space altimetry around the SWOT ("Surface Water and Ocean Topography") satellite program planned in 2021 by CNES and NASA(2) that will provide, in addition to the oceans for the first time, space-time variations in the water levels of large rivers, lakes and streams.

3. MULTIPLE USES: THE TOOLS

The previous section shows to what extent dams in France (and worldwide) are increasingly multi-purpose and shows the wide variety of situations. However, managing multiple-use reservoirs is much more complex than managing single-use impoundments, as tools for sharing water and uses must be developed.

- Governance tools are fundamental: they provide the framework for discussing and reconciling the different uses; § 3.1 presents the recent evolution of the governance framework in France.
- Sharing requires a sound basis for estimating resources and needs, and their evolution in the context of climate change: extensive prospective studies, based on accurate data, are necessary, as illustrated by § 3.2.

3.1 Governance: regulatory tools and territorial organization

In France, the construction and operation of existing reservoirs is based on a regulatory framework that has evolved to take better account of the multiple and cross-cutting interests at the regional level. Moreover, public funding is often necessary to enable new projects to be carried out; this funding is conditioned on a certain number of "good practices" which also aim to verify that these multiple and intersecting interests are fully considered.

3.1.1 Water management: considering a territory's various challenges

The bases of the current water law come from three main documents: the law of 1964 on the regime and distribution of water and on the fight against pollution; the law of 1992 on water; the law of 2006 on water and aquatic environments resulting from the transposition into French law of the European Framework Directive of 2000.

The law of 1964 set up the six Water Agencies, whose vocation is pollution control and the management of water resources. The 1992 Water Law states that "water is part of the common heritage of the nation" and sets up tools to reconcile its different uses: in each basin, a Master Plan for Water Development and Management (SDAGE), which defines the strategic orientations for managing the resource; and, for some sub-basins, a Water Development and Management Plan (SAGE) which elaborates at this sub-scale the orientations of the SDAGE. The main purpose of the 2006 law is to achieve good water status, and in some respects modernizes the 1964 and 1992 texts.

The SAGE is drawn up collectively by the water stakeholders of the territory gathered within a deliberative assembly, the Local Water Commission. This commission, chaired by a local elected representative, is made up of three colleges: local authorities, users (farmers, industries, landowners, associations, etc.), the State and its public institutions. The SAGE draws up a Sustainable Development and Management Plan (PAGD), which is enforceable against third parties: any project in the water sector must be compatible with the PAGD. Particular attention is paid to water sharing: Quantitative Water Resources Management Plan, Global Withdrawal Volume Assessment.

Only projects registered in the SAGEs can receive financial assistance from the Water Agencies or the State, and if it is demonstrated that these projects allow the substitution of low-water withdrawals by non-low-water withdrawals.

(2) Centre National d'Études Spatiales (France) and National Aeronautics and Space Administration (USA).

3.1.2 Flood protection: governance in line with water management

On the scale of large basins, a Flood Risk Management Plan (PGRI) is adopted by the State. This PGRI provides a framework for the risk prevention policy and identifies the territories at significant risk (TRI). For each TRI, a Local Flood Risk Management Strategy (SLGRI) document is developed.

The governance of flood protection works, which is part of the PGRI and SLGRI, has recently been reformed. These works now come under the competence of "GEMAPI" (Management of Water and Aquatic Environments, and Flood Prevention), assigned to decentralized, municipal or intermunicipal structures. The GEMAPI competence covers watershed management, river maintenance, flood protection, protection and restoration of ecosystems. This is part of the missions of the water policy defined by the SAGEs.

3.1.3 Authorization procedure: consultation and consideration of all issues

The construction of new schemes or the modification of existing schemes falls within this framework and requires an environmental permit. Since 2017, a single authorization procedure has been in place to ensure that environmental issues are considered globally. The procedure consists of several steps:

- upstream phase (optional): preliminary discussions between the project developer and State services;
- submission of the file;
- file examination phase (4 or 5 months): investigation by the State services, consultation of the authorities and commissions (in particular: CLE commission), opinion of the government environmental authority;
- public inquiry (3 months): gathering opinions and drawing up an inquiry report;
- decision-making phase (3 months): consultation of the Departmental Council for the Environment and Health and Technological Risks or the Departmental Commission for the Nature of Sites and Landscapes; draft decision; authorization order and publicity;
- deadline for appeal (4 months).

This procedure is supposed to consider all the stakes of water uses and all the consequences of the projects. It has become the central component of scheme projects.

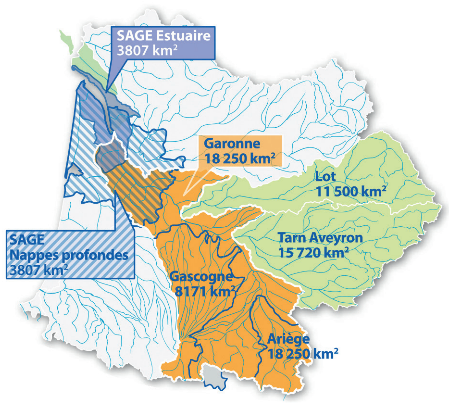
3.2 Policy development: prospective studies of resource sharing

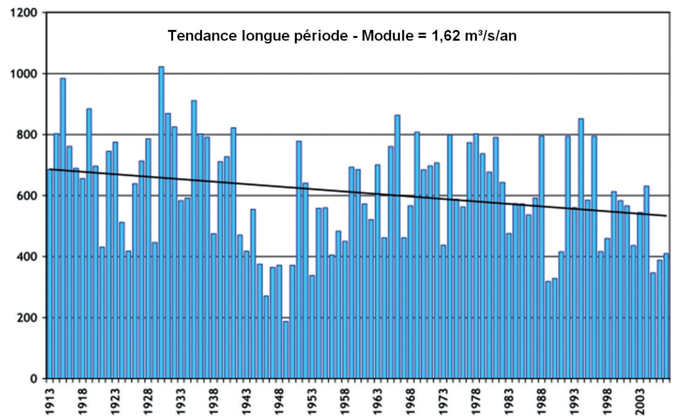
The tools available make it possible to conduct in-depth studies of the resource at the watershed level, and these studies provide useful results for developing a shared management policy.

For example, "Garonne 2050" [Lhuissier & al., 2016] is a prospective approach focusing on water, carried out between 2010 and 2012 at the initiative of the Adour-Garonne Water Agency: it integrates climate change and possible demographic, energy and agricultural changes, as well as their impacts on water resources. It was prepared within the framework of the implementation of the SDAGE 2010–2015. It is conducted in a context where climate change is perceptible in the Garonne basin (28,000 km²), with, for example, a noticeable downward trend in natural flows.

The study develops scenarios, based on the conclusions of participatory workshops, and then quantified them, using a "needs-resources" management model, amongst other elements. The conclusions must be able to help in the decision-making process to anticipate the issues and impacts of global changes on the hydrology of our rivers and water needs. The participatory workshops are designed to integrate a multi-objective approach to water resource management: anthropogenic uses (whether or not withdrawals are made) and environmental services. Storage and flow regulation structures in watercourses are important elements of consideration. In the study, several scenarios are studied by varying a cursor on the use of these hydraulic structures: from single-use (irrigation or hydropower for example) to multi-use (which, in particular, makes it possible to ensure flow support to respect the low water level objectives).

Figure 1.17 – Location of the Adour-Garonne basin and evolution of the average flow of the river





TRANSLATED EXCERPT FROM THE GARONNE 2050 STUDY [LHUISSIER & AL., 2016]

The impact of climate change on the drying up of the rivers in our basin, confirmed by the latest IPCC report, will be major with significant environmental, economic and social impacts. A major adaptation strategy must be devised for the future if we wish to balance water needs and resources in this area. To prepare for this future, certain measures appear today to be "without regret" and urgent to consider, given the time required for implementation. According to the hypotheses adopted, water scarcity will be a recurring and structural problem in 2050 and not the consequence of an exceptional meteorological year. The strategy of "laissez-faire" (minimum compensation) seems risky because it could result in serious health problems, beyond the direct economic and environmental problems, because of the impact on the quality of the resource. Conversely, today's low-flow support target levels seem unattainable in 2050, due to the social, economic and environmental costs that would result from the artificialization of the land.

The level of compensation, in the face of the foreseeable drop in natural flows, i.e. the requirement to artificially support low water levels by maintaining a minimum river flow, is seen above all, for the Garonne territory in 2050, as a social choice (urban water amenities in summer, recreational and landscaping uses, etc.). The more ambitious we are in terms of average demand (integrating both uses and the principle of compensation), and therefore the volumes that must be mobilized to meet it, the greater the risk of default (risk of crisis). In any case, despite the uncertainties about the level and distribution of future rainfall and the uncertainties linked to the modeling assumptions, it is possible to identify robust adaptation options that can be implemented now: working towards water savings and more efficient management, creating new reserves, mobilizing non-conventional resources (groundwater recharge, desalination), increasing or promoting the resilience of aquatic systems, thinking "water and energy" together, managing the resource collectively for the general interest, recovering costs from beneficiaries, anticipating and innovating.

By 2050, even if the uncertainties remain significant for precipitation, the rise in temperature will lead to a sharp increase in evapotranspiration. Natural low-water flows will be halved on average for the Garonne basin, an area which is both very agricultural and attractive from a demographic point of view. The factor that has the greatest impact depends mainly on a societal choice summarized through a double question: what flow do we want in our rivers in summer and what are we able to do? These choices must be made quickly, to implement appropriate responses. In the scenarios studied, the "sobriety of demand" lever is systematically activated but is not sufficient to resolve the imbalance between needs and resources.

4. REFLECTIONS ON THE FUTURE OF DAMS IN FRANCE

Figure 1.2 shows the slowing down and now almost complete halt in the construction of new dams in metropolitan France. This is the result of a gradual change in public perception of dams. The technological risks associated with these structures, the displacement of populations that they caused when certain reservoirs were impounded, the impact of the structures on the river regime and on biodiversity explain the negative evolution of the view taken in France since the last decades of the 20th century with regard to these major hydraulic scheme projects. Even today, the construction of new dams still arouses passions: recent projects for new small agricultural reservoirs, requested by irrigators to compensate for the observed effects of climate change, have led to very lively national debates.

However, new developments may be required to meet current needs (water resources, flood protection) or to respond to climate change issues. It is reasonable to believe that such arrangements are possible and desirable for several reasons.

The benefits brought by existing schemes have been considerable, for society — as illustrated, for example, by the considerable importance of the Serre-Ponçon reservoir in its territory and in the entire Provence-Alpes-Côte d'Azur region — and also for biodiversity — artificial reservoirs that have been classified for their ecological importance, under the Natura 2000 or Ramsar label. It is possible that new reservoirs, designed with this in mind, could also bring social and environmental benefits. This undoubtedly requires long and meticulous preliminary analysis phases to consider the multiple and cross-cutting issues of such schemes. The governance tools put in place provide an appropriate framework for this; it is possible that the success of the first projects of high environmental quality will help to change public perception.

This seems to be a necessity because climate change is imposing its law. On the one hand, the increased penetration of intermittent low-carbon energies (solar, wind) leads to an increase in the need for electricity regulation and storage; hydraulic energy certainly remains a more ecological means of achieving this storage than battery farms. On the other hand, forecasts tend to show that water-saving measures will not be sufficient to compensate for future droughts; more winter storage will be needed.

Thus, the needs are real, and new storage facilities and new sources of hydropower production will have to be built. This requires reconciling the environmental issues of biodiversity and the societal issues specific to each territory. These changing needs and issues call for new ideas. Here are some of the avenues explored.

4.1 Territory projects

Promoted by a recent ministerial direction, territorial projects are developed and implemented under the guidance of a steering committee, with the objective of balanced management of water resources, without deteriorating the chemical and ecological quality of aquatic environments, and with a view to taking into account all the territory's issues. This potentially lengthy process may lead to the emergence of shared solutions.

4.2 Off-river storage

Ecological continuity is one of the key issues of biodiversity. Off-river storage makes it possible to consider new reservoirs that do not create new barriers.
This has been the option used for some decades by the EPTB SGL (see § 2.2), with gravity-fed diversion reservoirs. The EPTB is extending this even further, with the La Bassée project, shown here, whose objective is the temporary storage of peak flood water

Figure 1.18 – La Bassée Project: Flood Storage Reservoir filled by pumping /

© Seine Grands Lacs

It could also thrive outside France: this is the option being considered to create a new storage reservoir in arid south-central Algeria, thus avoiding excessive silting and evaporation.

4.3 Heightening of existing dams

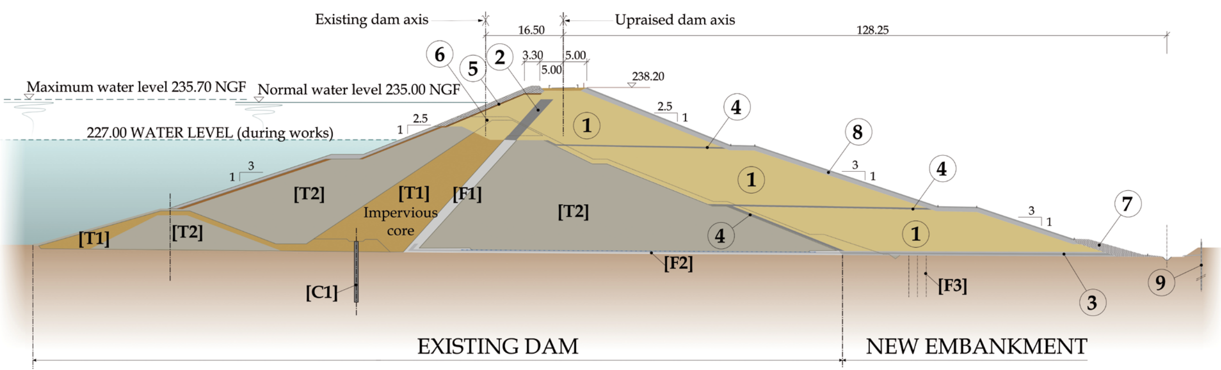
It has become difficult to develop new sites. The optimization of existing sites is often better accepted. This optimization can sometimes take the form of increasing the available resource by raising the operating level of existing reservoirs. On several occasions, a substantial increase in height has been carried out at controlled costs, in conjunction with a dam upgrading operation that was imposed by safety issues (e.g., increase in design flood).

Figure 1.19 – Four recent examples of raising the operating level in France, for dams of different sizes. In three cases, the operation also aimed to improve the flood safety of the dam

Rassisse © ISL Anthony Dols

Les Blanchets © ISL Olivier Lapeyre

Pont-et-Massène © VNF



La Ganguise © BRL Ingénierie

4.4 The hydro-solar combination

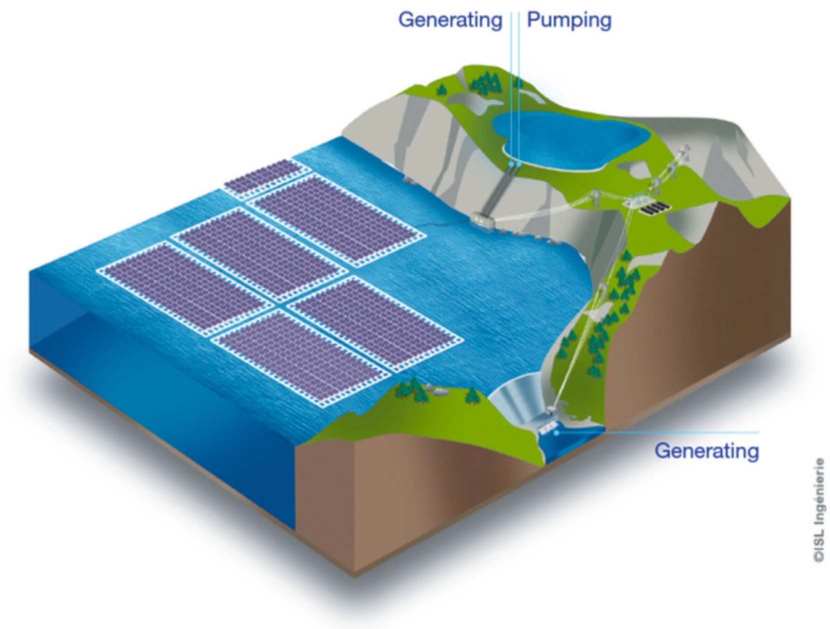
Solar and hydropower can naturally be combined. This is the case, for example, of the So FLEX'hy project to compensate for the intermittency of renewable energies through the flexibility of hydropower: part of the regional "Flexgrid" project, the EDF So FLEX'hy project aims to deploy smart electricity grids on a large scale. Thanks to an industrial-scale demonstrator, the project is testing technical services and solutions designed to optimize the complementarity between renewable production resources (hydraulic, solar, wind). In practical terms, several solar and hydropower plants will be linked together to smooth out the intermittency of solar energy through hydraulic production. Led by an innovative supervisor, this "virtual power plant" will deliver a range of services to grid operators and producers.

In an even more integrated way, the well-calibrated combination of an existing reservoir, floating solar panels and a medium-capacity pumped storage station offers renewable (solar) electricity, guaranteed (thanks to storage) and without water consumption (no impact on the operation of the reservoir).

This provides an opportunity for a new purpose at numerous reservoirs.

This type of combination of hydropower and solar energy can lead to new types of large-capacity power plants, such as the twin dams described by [F. Lempérière, 2018].

Figure 1.20 – Hydro-solar combination / © ISL



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CHAPTER 2

GEOLOGY, FOUNDATIONS, AND FOUNDATION TREATMENT

A geologist's contribution in dam design to assessing the level of safety during operation is essential [Antoine & al., 2018]. The CFBR devoted an entire symposium to the theme of "Dam Foundations" in 2015 [CFBR, 2015]. Only a few elements relating to the history of dam geology, innovative survey techniques and foundation treatment will be discussed in this chapter.

1. GRENOBLE AND THE GEOLOGY OF DAMS

The geology of dams originated in the nineteenth century in the Alpine regions as shown in the following brief history.

In France, as early as 1824, a geology course was created at Grenoble University. IT started very modestly since the staff consisted of just one person: Professor Emile Gueymard, an engineer in the Mine Corps, mineralogist and chemist and holder of the newly created chair of natural history.

At the same time, in 1827, Benoît Fourneyron (Saint-Étienne), inventor of the hydraulic turbine, built a first test turbine with 6 HP of power under a modest fall of 1.40 m. Progress was then rapid: in 1835, a first high fall in the Black Forest was equipped (114 m high – pipe length 500 m). Facilities followed rapidly for the needs of various manufacturers, including: Uriage in 1863 (80 m head) for company Vicat, Domène in 1866–67 for Papeteries des Gorges (30 m head).

In 1868, Aristide Bergès, an engineer who would rapidly become a celebrity, came to settle in the Dauphiné region. He was a Pyrenean manufacturer of mechanical shredders for pulp who was looking for sources of hydropower. In January 1869, he started to build a 200 m fall on the Combe de Lancey stream at Domène, near Grenoble that was successfully pressurized in September 1869. Other achievements rapidly followed such as the Saint-Mury fall (1891) in the same sector. The profitability of these developments was, however, strongly influenced by the flow fluctuations between winter and summer in the Alpine streams. To make the best use of the morphology of the Combe de Lancey valley (and using a solution that was emerging at the time), he came up with the idea of using Crozet lake (1974 m altitude) as a flow regulator. In 1897, he dug the lake out 25 m below its normal level, increasing its usable volume to nearly 1,300,000 m^3. A similar result could of course be obtained by creating a lake with a dam in an altitude valley. The era of big dams was coming.

However, the users of electric power (various industries) had to be close to the actual hydropower plant. The energy produced was not transportable. Long-distance transport using conductive cables was first thought of by Marcel Desprez who successfully carried out various experiments in Paris in 1881, first over a short distance (1,800 m) then in Munich in 1882 over a distance of 57 km! In 1883, at the request of the municipality of Grenoble, he carried out a famous experiment in the transport of electrical energy between Vizille and the Halle aux Grains in the city center of Grenoble.

The coincidence of dates between the beginnings of hydropower and the creation of a geology laboratory (still very modest) at Grenoble University is remarkable. Emile Gueymard's three successors: Professors Charles Lory, Wilfrid Kilian, and Maurice Gignoux established its renown for a century, between 1849 and 1955. They were the fathers of alpine geology in France and then of dam geology.

Hydraulic engineers at the time quickly realized that the increasing size of the structures posed problems of support stability and sealing. A good knowledge of the terrain was therefore essential. Cooperation between the geological and hydraulic sciences became inevitable. But where could competent professionals be found? Geology for construction purposes was completely overlooked by the public and misunderstood at the university. No training of professional geologists existed at the time. Only university professors were likely to be consulted. In these conditions, Wilfrid Kilian was the expert during the initial studies for the Génissiat and Serre-Ponçon projects, where surveys were carried out in 1898–99 (preliminary design of 1901). He shared this experience (which was totally unheard of for a geologist) in two public lectures given in Grenoble in 1921, entitled "Geology and hydroelectric development of waterfalls" [Kilian, 1921]. He cited schemes that were being built at the time, such as Viclaire in the Tarentaise, Saulce-Ventavon on the Durance river and mentioned the construction of Avignonet dam on the Drac (which filled rapidly with alluvium from the Drac and is now buried under Monteynard reservoir). Wilfrid Kilian took part in studies for Génissiat dam.

The growing importance of reservoir dams obviously played a vital role in the Alpine massifs, which morphologically offered numerous possibilities for reservoirs and high falls. Switzerland, the Alpine country par excellence, developed its numerous hydropower resources very rapidly. However, little was yet known of the geology of the Alps at the end of the 19th century, although it progressed rapidly thanks to Swiss geologists. As early as 1893, Hans Schardt took up the geological concept of Marcel Bertrand's thrust sheet, which was exploited very successfully in 1895 by Maurice Lugeon, professor of geology at Lausanne, to explain the complex structures of the French Alps. The Grenoble geologists were in turn inspired very fruitfully in the French Alps and links were created between Mr. Lugeon and Mr. Gignoux.

Citing Maurice Lugeon offers a very direct link between alpine geology and that of dams. A real "king" among the alpine geologists, his very practical mind rapidly made him an indisputable specialist of dam geology in Europe and worldwide. His name is still familiar to dam engineers all over the world, who are generally unaware that he was a very great geologist. He came up with the eponymous classic water test for the design of the sealing screens for large dams [Lugeon, 1932].

With dam techniques developing very rapidly, the need to train various specialists was soon necessary. In Grenoble therefore (not surprisingly), specific training for electrical engineers started in 1900 with the creation of the Grenoble Electrotechnical Institute (IEG), followed in 1929 by that of the Hydraulic Engineering School. These two schools supplied many engineers who largely contributed to the vast program of hydroelectric equipment of France after the second world war.

Grenoble's geology teachers understood that there were certain opportunities there for future students. They encountered a major obstacle however: the complicated French administration system and the reluctance of academia relative to vocational training. Further education diplomas were created around 1880 to obtain a degree in natural or physical sciences), but there was no question of applying these sciences. However, on October 20th, 1901, the Ministry of Public Instruction authorized the Grenoble Faculty of Sciences to issue a diploma of Applied Geology and Mineralogy. An important step had been taken by using this title, but the qualification remained very fundamental.

Those in higher education were not unaware of the new hydraulic science, since, as mentioned above, it was materialized by the creation of a School of Hydraulic Engineers which obviously taught courses in the subjects needed for the practical application of hydraulics in the fields of industry and planning. Geology was then considered as one of these and Maurice Gignoux was chosen to teach dam geology. Both he, and Maurice Lugeon, with whom he collaborated, participated in the study of several Alpine sites.

In 1948, Reynold Barbier was appointed assistant geologist at the Grenoble University after teaching at the Petroleum Institute in Strasbourg and Toulouse. He became Professor in 1953, holding a new chair in Applied Geology. Gignoux and Barbier together published the internationally renowned work "Geology of Dams and Hydraulic Facilities" [Gignoux & al., 1955]. As Maurice Gignoux died a few months later, it was left to Reynold Barbier in 1955 to develop teaching about dam geology in Grenoble.

Figure 2.1 – Extract from "Géologie des Barrages et des aménagements hydrauliques"

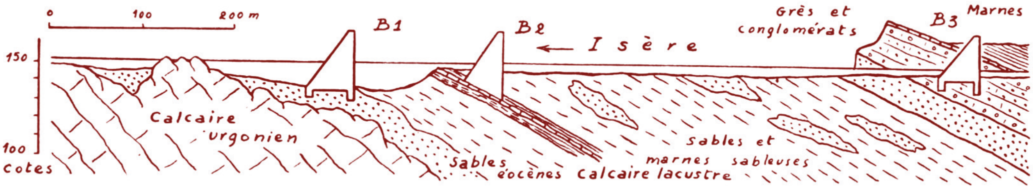


FIG. 98. – PROJET DE BARRAGE DE VALENSOLE SUR LA BASSE ISERE

Coupe géologique suivant le cours de l'Isère à la suite de la campagne de sondages (d'après «Solétanche») ; hauteurs doublées
Un emplacement aval sur les calcaires urgoniens a été tout de suite abandonné, car ceux-ci sont très corrodés et renferment des poches de sables éocènes. L'emplacement B_1 profiterait d'un niveau où ces sables sont localement plus cohérents. En B_2, on a cherché à utiliser la présence d'un banc calcaire. Enfin en B_3, on a étudié la possibilité de fonder l'ouvrage sur une barre de grès et conglomérats.

Fig. 98. – VALENSOLE DAM PROJECT ON THE LOWER ISÈRE

Geological profile following the course of Isère river following the drilling campaign (after «Solétanche»); doubled heights.
A downstream site on the Urgonian limestones was immediately abandoned because they are highly corroded and contain pockets of Eocene sands. Location B1 would benefit from a level where these sands are locally more coherent. In B2, the presence of a limestone bank was sought. Finally, in B3, the possibility of basing the structure on a bar of sandstones and conglomerates was studied.

The creation in 1961 of a third cycle comprising two options, Mountain Range Geology and Applied Geology, formalized the teaching of dam geology at the University. This opened up opportunities for teaching and research that the Geology laboratory had never known. The creation of the third cycle involved a year of specialized teaching, the DEA, preparation for a doctorate. A geology option in Civil Engineering allowed geology students to train in non-geological disciplines, such as soil, rock and hydraulic mechanics, or engineers who wanted to become familiar with geology. The essential point was that this course of study led to a high level of scientific training (state doctorate, DSc) or a professional level (PhD) in the field of applications of geology in civil engineering [Cheylan, 1966] [Schneider, 1967] [Marinos, 1969] [Thérond, 1972] [Giraud, 1986] [Couturier, 1987].

This course was immediately a great success with students and potential employers. In fact, it benefited from a very favorable context in Grenoble. From 1945, with the creation of Électricité de France (EDF), France started a vast program of hydraulic installations. One result was the parallel development of industries such as civil engineering (construction of dams and tunnels), the metallurgical industry (turbines, penstocks, valves…) and the electrical industry (alternators, transformers, cables of all types…). Since the beginning of the century, Grenoble had been home to companies specializing in most of these techniques, notably in hydraulics (Neyret Bellier – Picard Pictet – Neyrpic, Bouchayer and Viallet for hydraulic lines), and in electrical equipment (Merlin and Gerin). A major engineering office specializing in hydraulic applications developed within the Neyrpic industrial group, becoming the Société Grenobloise d'Études et d'Applications Hydrauliques (SOGREAH) in 1955. The latter specialized, among other things, in the study of dam projects, mainly abroad, where it acquired a worldwide reputation. Close relations were established with Reynold Barbier, who headed the Geology laboratory for years.

At the university level, other research laboratories (and related courses) were also created in Soil Mechanics (with Jean Biarez) and Rocks (with Jean Kravchenko). Grenoble University became a major pole for the teaching and research of applied sciences relating to soils and rocks. An initiative of Jean Biarez and Reynold Barbier led to the creation of an interdisciplinary Institute of Geology and Mechanics (IRIGM became LIRIGM), which only ceased to exist a few years ago. This Institute, however, was at the origin of the creation of a Geotechnical Engineers School (ISTG) within Grenoble University, that civil engineering geologists such as Pierre Antoine, Denis Fabre, A. Giraud, then Bernard Couturier and Pierre Desvarreux, a converted Centralian to geology, participated actively in.

This school maintains the long-standing tradition of collaboration between geologists and mechanics within a much larger network of schools, Grenoble Polytech.

This association of geology with dam projects materialized outside the university, with the creation of a Permanent Technical Committee of Dams and Hydraulic Works within the French government, in 1966, following the Malpasset disaster (1959). This Committee advises on all new dam projects and substantial alterations or rehabilitation of old structures that exceed 20 m above foundation sites. It consists of twelve members and includes a geologist. Since its creation, three Grenoble university students have succeeded each other (Reynold Barbier, Pierre Antoine and now Bernard Couturier).

Figure 2.2 –

From left to right: André Giraud (IRIGM), Bernard Couturier (CTPBOH), Denis Fabre (IRIGM), Reynold Barbier (ex-CTPBOH), Pierre Antoine (ex-CTPBOH), Jean Letourneur (IRIGM)

2. CONTRIBUTION OF DIGITAL TECHNOLOGIES IN ESTABLISHING GEOLOGICAL MODELS OF ROCKY MASSIFS

The use of digital technologies complements "traditional" geological survey techniques, in a broad sense, by facilitating the 3D representation of the rock mass in which a dam, gallery or an outdoor or underground hydropower plant is located. These new technologies, however, cannot replace geological field surveys which remain the fundamental work for a new project or the maintenance of an existing structure [Antoine & al., 2018].

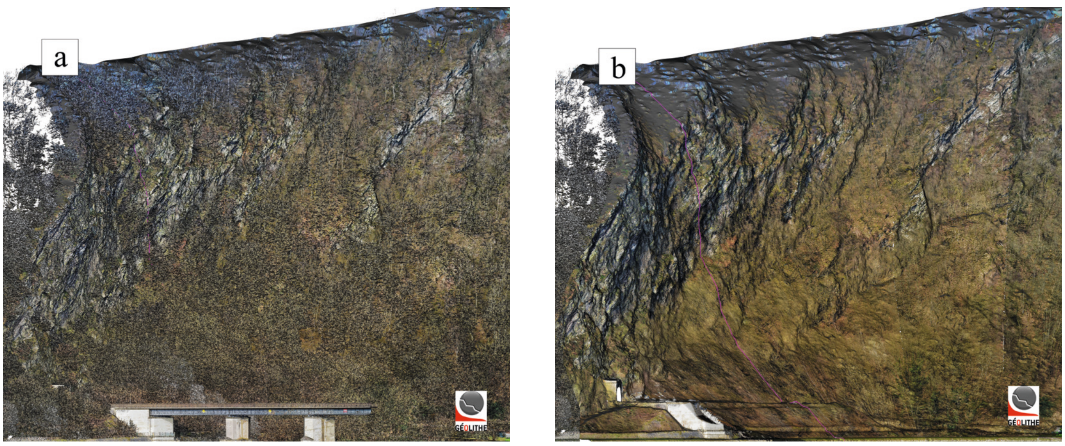
2.1 Use of drones and Lidars

Modeling the topography of sites studied by the combined use of drones and Lidars makes it possible to obtain precise topographic surveys of dam sites without requiring significant means of topographical investigations on the ground.

This modeling then makes it possible to propose a 3D model in which all the observations and recognitions can be integrated.

Figure 2.3 – Lidar Survey from a Drone / © Géolithe

Figure 2.4 – Laifour site (08) Digital model obtained by Lidar multi-echo survey: (a) before vegetation treatment; (b) after removal of the vegetation the bund wall of a bridge at the foot of slope can be seen / © Géolithe



At EDF, LIDAR technology was used to map the catchment area supplying the Mont-Cenis dam reservoir more effectively, including the Lamé and Laro landslides as well as the Lamé sinkholes.

Drones make it possible to image the inaccessible areas of the reception pits downstream of dams; this allows a better understanding of the structural conditions conditioning the rock's erodibility in these pits. In areas that are difficult to access, this technique also makes it possible to observe cliffs. The photos taken by the drones are processed by 3D software and restored in the form of raised images, which facilitates stability studies.

2.2 Digital structural analysis of the rock mass

These new technologies improve the structural analysis of the rock mass, previously performed using a direct mapping of the rock outcrops and classical geological surveys.

Figure 2.5 – Survey and digital structural analysis on the Jouques site of an outcrop of lumpy Berriasian clay limestone, made from the digital model. (a) geo-referenced and colored point cloud; (b) colored point cloud according to the normal of each point; (c) Directional family classification for faults and joints – Poles and Plans, Schmidt, and Wulf patterns / © Géolithe

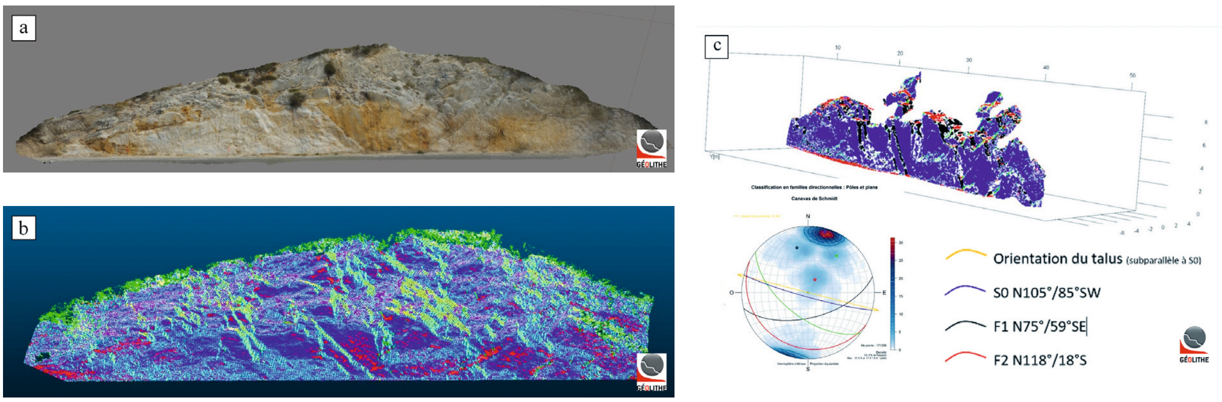


Figure 2.6 – Numerical structural analysis of detail Pombourg site made using the digital model in an Oxfordian nodular limestone massif, each discontinuity family is represented by a color / © Géolithe

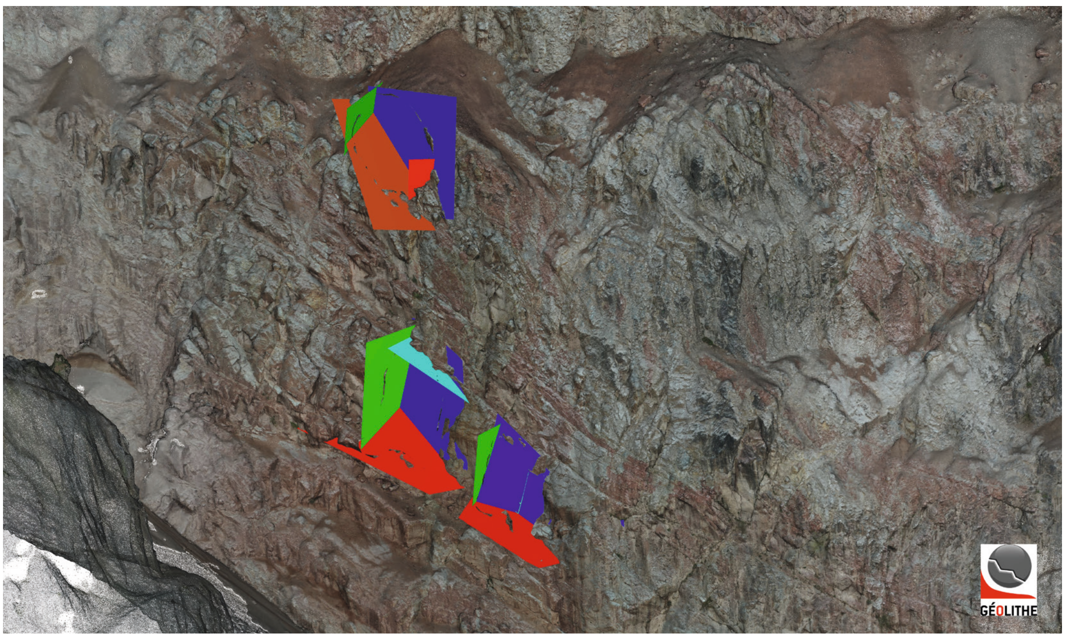
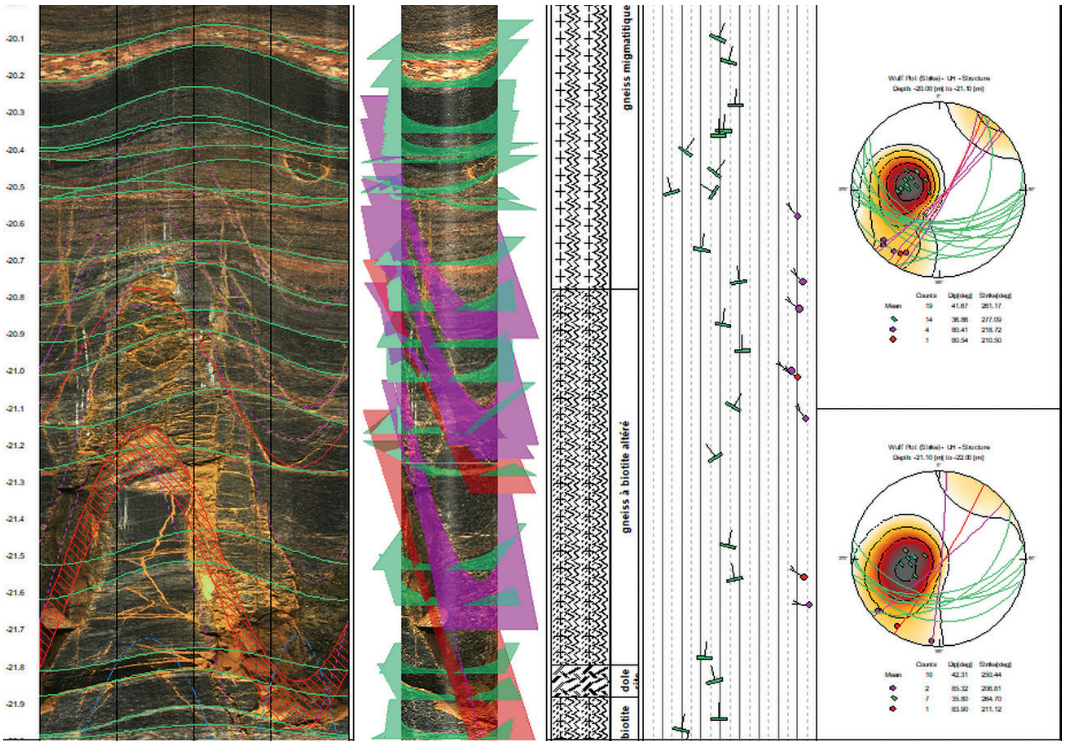


Figure 2.7 – Volobe hydropower scheme (Madagascar), Logging with digital imager and structural analysis showing Dolerite veins within Biotite Gneiss / ©Géolithe



For stability calculations for concrete gravity dams, the imaging of the cylinder wall of drill holes makes it possible to see if the concrete-rock contact is tight and if it can be given a tensile strength and therefore a cohesion.

2.3 Assembly of digital models

The integration of all these digital elements in the geological software programs, which are complementary to the traditional elements that also include, according to need, the geotechnical parameters of compressibility and / or permeability, allows better specification of the geological model of the site through a clearer visualization of fault zones and concentrations of joints. This is extremely useful for a gallery, cliff stability, or the positioning of the axis of a future dam.

Figure 2.8 is an example of the integration of digital elements for the abutment of an arch dam:

Figure 2.8 – SHEM dam of Marèges Full digital model with integration of all stratigraphic readings / ©Géolithe

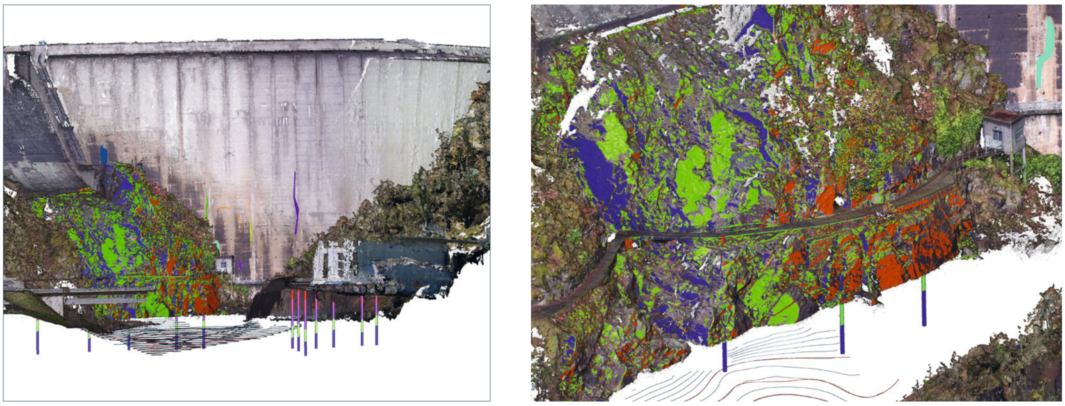
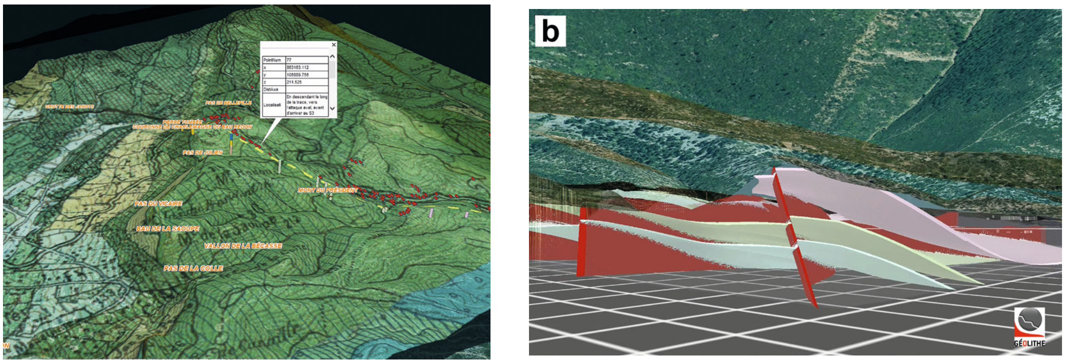


Figure 2.9 shows the integration of numerical elements for the hydraulic gallery of Les Janots in the Crown of Charlemagne sedimentary massif in the Turonian (pyritic blue marls and nodular marly limestones, rudist limestones, Sandstone) and Cenomanian formations (rudist limestones, ferruginous sandstones, sandy marls).

Figure 2.9 – (a) Digital Terrain Model (DTM) overlay / Geological map / soundings / field surveys; (b) in-depth view of the different geological formations and faults obtained by 3D geological modeling using the Geomodeleur3D software / © Géolithe



These pictures, combined with all the available data, are very useful for making a comprehensive 3D geological and geotechnical model showing the location of the possible karstic anomalies inside the rock mass in order to limit the risks of cave water outflow, a lack of rock support or rock face instability when excavating the tunnel.

2.4 Research & Development in applied geophysics

An oil-based geophysics survey (very high-resolution seismic reflection) was used to get a picture of the concrete-bedrock contact of gravity dams.
The regulatory changes (earthquakes and floods) lead owners to question existing margins for justifying the stability of gravity dams. The objective is to improve the characterization of the concrete-bedrock contact and any asperities and rock teeth that significantly increase the shear strength.
The method currently being explored by EDF-DI-TEGG, for dams with poorly documented excavation lines is to make an analogy between a dam wall and the axis of a directional drilling to use the oil seismic method, known as the Vertical Seismic Profile (VSP), see Figure 2.10, using both the P and S waves.

Figure 2.10 – Principle of VSP

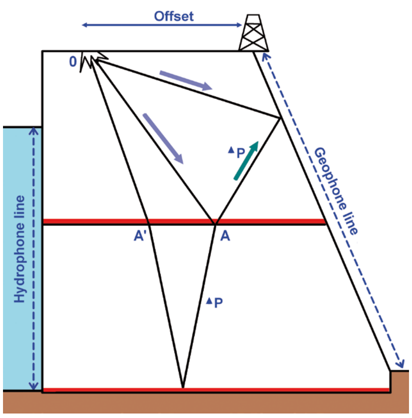


Figure 2.11 – Pseudo VSP image of a dam

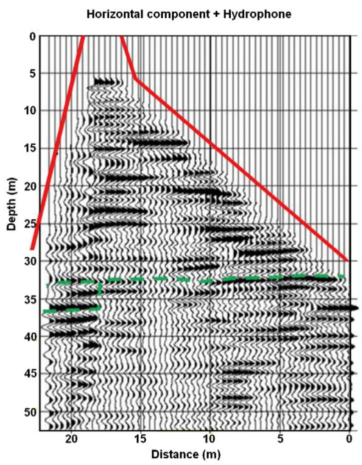
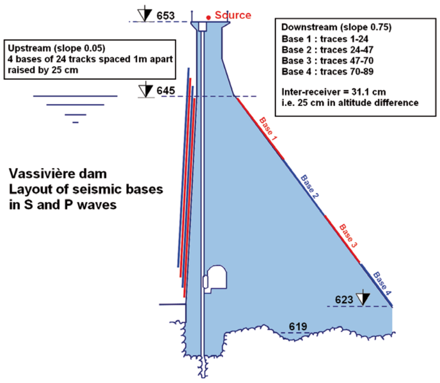


Figure 2.12 – Application to Vassivières dam



This method was used for Vassivières dam. Digital simulations (synthetic signals), made from the first field tests (see Figures 2.11 and 2.12), are ongoing to assess the sensitivity of the method to get a picture of the asperities and rock teeth (shape and dimension) of the concrete-bedrock contact according to the wave velocity contrast between the concrete and the rock mass.

2.5 Conclusion

The digital technologies for the geological survey of a hydro site (as with all sites) are in addition to the geological mapping and the traditional geological surveys and offer a more accurate view of the rock mass near a dam site.

These technological evolutions do not cancel the need to carry out successive geological and geotechnical surveys with intermediate syntheses when defining the geological site model and during the project works. The end goal is to optimize the structure's integration in the natural environment.

The use of these digital applications is evolving and growing. Coupled with the development and the rationalization of projects through B.I.M. (Building Information Modeling) and the use of Artificial Intelligence (A.I.), it will be possible to increase the reliability of the site history and the integration of the structure in the natural environment.

All the data received during the design, works, monitoring and maintenance of the dam will be available on site thanks to evolving "increased reality devices" that can be consulted on a tablet. These various digital tools and the geophysical research in very high-resolution seismic reflection will help to reassess dam safety within each context of the structure.

Nevertheless, the geological mapping of the site and the observations during the works will always be a preliminary necessity for all site surveys.

PIERRE LONDE (1922–1999)

After graduating from the École nationale des Ponts et Chaussées, Pierre Londe started his career at the Coyne & Bellier consulting and engineering office.
In 1953, together with George Post, he published "Rolled-earth dams", a book with a preface written by André Coyne, used as a reference in France for many years. We can therefore say that he contributed to the development of soil mechanics in this country.
In 1959, following the failure of Malpasset arch dam, Pierre Londe was deeply involved in the scientific studies to explain why a part of the rock mass was ejected from the left bank. He defined the Londe wedge stability method that studies potentially unstable rock masses. This kind of dangerous geological configuration is systematically looked for on all arch dam abutments worldwide. In this way, he also contributed to the development of rock mechanics.
He was a member of numerous academic societies and scientific councils: CFMR (Rock Mechanics French Comity), CADAS (Science Academy), etc.
In 1979, he was elected president of the International Commission of Large Dams.
He was a famous engineer who spent most of his working life at Coyne & Bellier; for over 50 years he devoted his activities to studying and designing dams in France and abroad.

3. FOUNDATION TREATMENTS

This paragraph shows the need to reconcile resin grouting and the environmental constraints in dam facility maintenance operations.

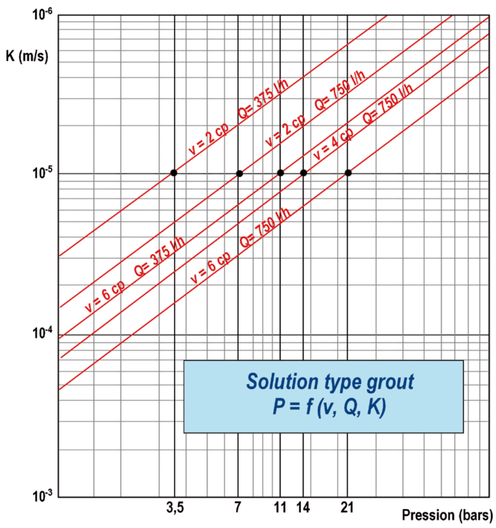
Standard grouting with bentonite and cement cannot penetrate the low granular permeabilities ($K < 5 \times 10^{-5}$ m/s) and cannot be used for the very high permeabilities ($K > 10^{-3}$ m/s) due to turbulent flows in very cold water from the bottom of dam reservoirs (temperatures < 10 °C or even 4 °C). For these extreme permeabilities, resins and non-granular liquors are still required, despite their complex chemistry and their possible toxicity.

3.1 Low permeability field

For the low permeabilities, granular impregnation grouting using micro-cements can grout the upper part of the low permeability range ($K \# 10^{-5}$ m/s), but not below this permeability due to their granularity. The nano-silicas are still in the trial stages. The silica liquors and the resins are still indispensable because of their absence of granularity and their low viscosity ($\nu \leq 5$ mPa.s). Therefore, the sand lenses inside the sandstones of the Germanic Trias of the Vieux-Pré dam in the Vosges mountains were grouted with a hard silica gel. The 600 C hardener of the silica gel is toxic, but its dosage is very low; it has since evolved towards the 600 E hardener which is much less toxic for the environment.

During the reservoir impounding, an underpinning impregnation grouting had to be carried out from the grouting tunnel of the sand included in the crevices at the core contact. To avoid the hydro-jacking of the contact between the core clay and the bedrock sandstone, the grouting pressure had to be as low as possible, so the viscosity also had to be as low as possible. Siprogel ($\nu \approx 2$ to 3 mPa.s), which is a mix of toxic acrylic monomers and sodium silicate gel, was used to impregnate the sand with a low pressure.

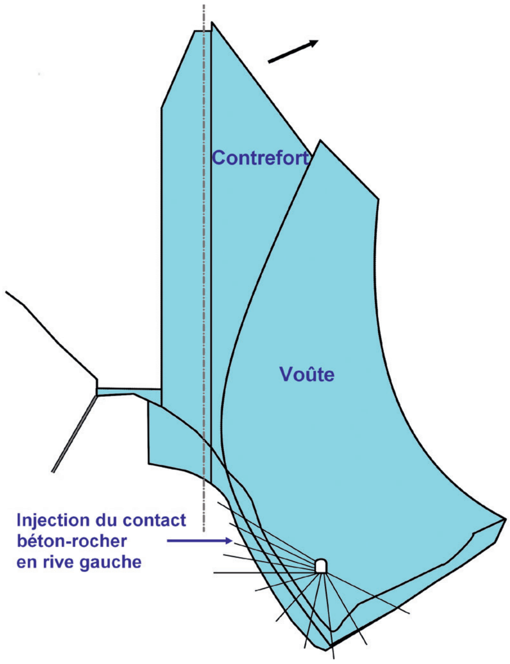
Figure 2.13 – Relationship between grouting pressure P in bars (1 b = 0.1 Pa) permeability K in m/s – viscosity ν in centipoises (1 cp = 1 mPa.s) and grouting flow Q



A low-viscosity resin ($\nu = 2$ cp), with a low flow (Q = 375 l/h), can inject low pore permeability (sand) $K = 10^{-5}$ m/s low pressure P = 3,5 bars.

The properties of Siprogel were also used for sealing the concrete-bedrock contact of the arch dam at Roselend dam (H = 150 m) and the concrete-concrete contact between the arch dam part and the buttress dam part that apply pressure on the foundation in different ways. The very low opening of the contact cannot give a significant leakage flow but can propagate a high pressure downstream. The very thin contact and its opening variations according to the reservoir level have required the use of Siprogel since 1963 for its low viscosity and its elastic properties. Elasticity is not a long-lasting property (lifetime 10 to 15 years) and the Siprogel has to be replaced regularly.

Figure 2.14 – Roselend dam – Concrete-bedrock contact grouting



Because of its toxicity, the production of Siprogel was stopped 15 years ago. For the last reinjection in 2010, a new resin had to be found, with as low a toxicity as possible. This new resin is based on ethyl methacrylate and amines and its properties (viscosity and elasticity) are quite similar to those of Siprogel.

Experience has shown that companies need to improve their skills to master the complex chemistry of the resin in contact with very cold water and that grouting pumps must be adapted to the aggressiveness of resin components.

3.2 High permeability field with turbulent flow

To stop turbulent flows, bentonite-cement grouts are easily diluted, even when stiffened by the addition of about 10% of sodium silicate. In 1993, to stop a quicksand condition in the Rhône river alluvium, downstream from Herbens weir (Jonage canal near Lyon) the use of a polyurethane resin was not very well mastered by the grouting company. It was only after a number of disappointing tests that this polyurethane resin grouting was finally successful.

In 1996–1997, to stop leakage through the bituminous concrete core of Lastioulles Sud dam in the Massif Central, polyurethane resins had to be used again. Previously, several bentonite-cement grouting campaigns had failed. It must be mentioned that the water velocity at the core was very high, estimated at 1 m/s.

Figure 2.15 – Lastioulles dam – bi-component polyurethane resin grouting

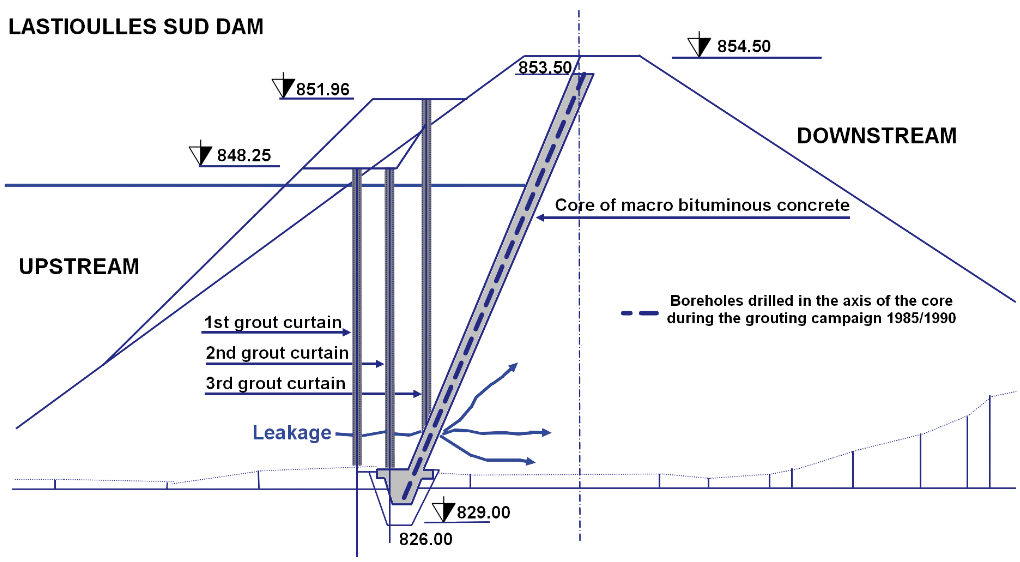


Figure 2.16 – Resin tests at EDF-TEGG laboratory in 1999: turbulent flow through pebbles with water cooled first to 10 °C then to 2 °C through a 10 m long transparent PVC hose / © EDF

Due to this situation and the complexity of the polyurethane resins, from 1997 the EDF-TEGG laboratory in Aix-en-Provence carried out several series of tests on the existing mono- and bi-component polyurethane resins.

Only two bi-component polyurethane resins were selected. One mono-component resin caused the hose to explode because of the production of a high volume of carbonic gas.

One of the selected bi-component resins was used to stop the leakage of the core of Lastioulles Sud dam and also for the grouting campaigns at Lastioulles Nord dam.

As regards the possible environmental impact, each component of the bi-component polyurethane resin (di-isocyanate et polyol) is individually toxic, but the reaction product is inert. Subject to controlling the polymerization reaction, particularly checking that the reaction is complete, there is no environmental impact. The fishing company downstream from the Lastioulles Sud dam has not undergone any damage.

3.3 Conclusion

Resins are necessary for dam maintenance. Some of them have had to be replaced to meet the requirements of the changing environmental regulations. This is not so easy because of the increasing complexity of the resins' chemistry and their complicated implementation. Their use requires an increased level of skill for the grouting company and the adaptation of their grouting equipment to the aggressiveness of the resin components.

4. LANDSLIDES IN DAM RESERVOIRS

Operating a large dam portfolio (68 dams subject to special intervention plans and 255 potential and active slide movements in dam reservoirs), including some sensitive sites, EDF has a long experience in predicting and managing slope movements, both during the initial impoundment and during operation. This has been shown in numerous publications, including at conferences of ICOLD.

Figure 2.17 – La Berche landslide on July 21st, 2015 © EDF-DI-TEGG

This experience was applied in 2015 to assess the possible impact of the Berche landslide in the Chambon dam reservoir. It was possible to evaluate the height of the induced wave from the landslide type. This study was published at the Vienna congress ICOLD 2018 Q102.

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CHAPTER 3

HYDROLOGY AND SPILLWAYS

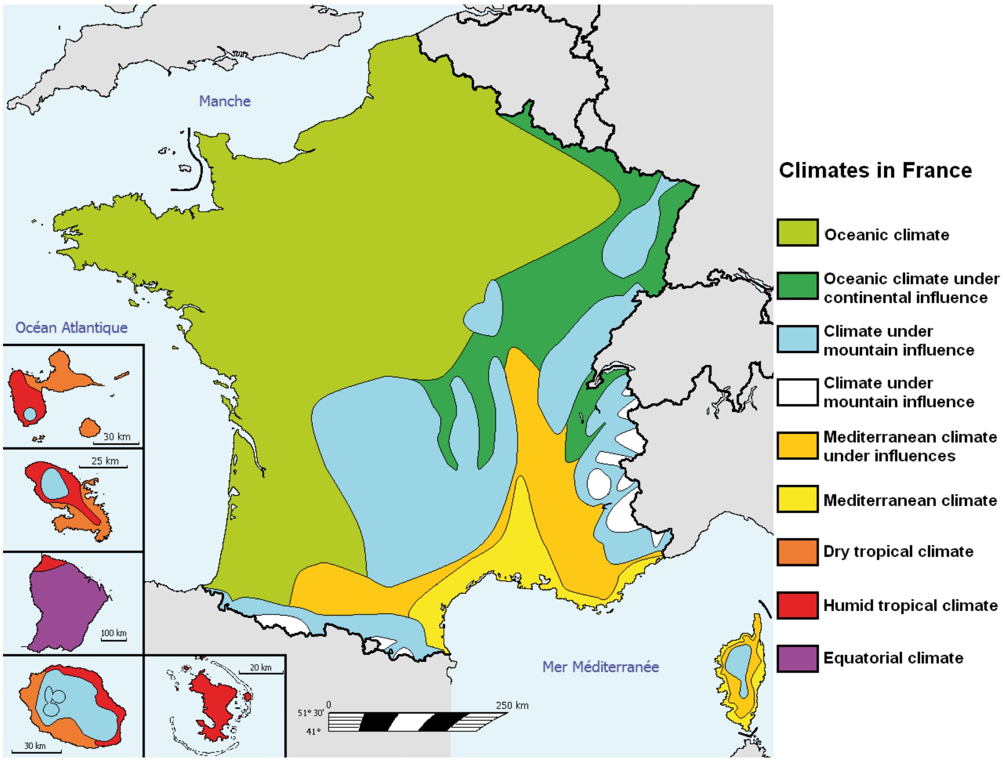
1. HYDROLOGY

1.1 Hydrology and the geography of France

Mainland France (551,000 km²) lies around the 45th parallel north and has a temperate climate. Within this temperate climate, however, there are significant variations depending on latitude, altitude and proximity to or distance from a coastline.

The Figure 3.1 presents the main types of sub-climate that can be found in mainland France as well as in its overseas departments and territories.

Figure 3.1 – Climates in France and its overseas departments / © www.librecours.eu – J. Daget



As shown on the two maps in Figures 3.2 and 3.3, average rainfall and rainfall intensity vary significantly from one region to another.

Figure 3.2 – Average annual rainfall (mm) /
© Météo France

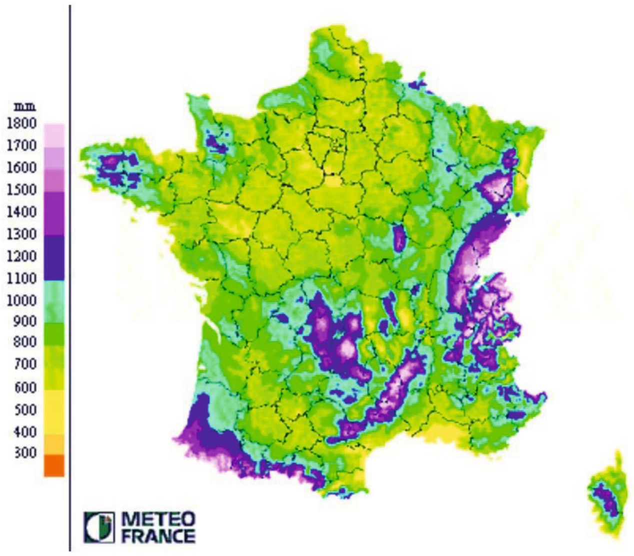
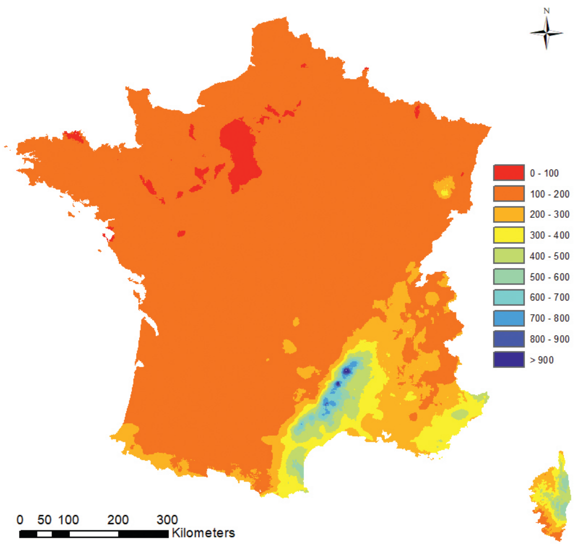


Figure 3.3 – Rainfall lasting 24h and with a 1000-year return period (in mm) – SHYREG / © INRAE – P. Arnaud



Climate variability is even more marked in the overseas departments and territories.
French dams are a good illustration of these very different hydrological conditions, as shown by the following illustration resulting from a synthesis of the most recent hydrological studies (PoNSOH – INRAE synthesis). The map in Figure 3.4 divides mainland France into hydrological zones. For each zone, the authors sought to establish a correlation between the 1000-year peak discharge (QP1000 in m³/s) and the catchment area surface (SBV in km²) and to connect the two through a $QP1000 = A.\ SBV^a$ relation. Parameter A varies considerably depending on the region (from 3 to more than 20 in mainland France and up to more than 50 in overseas). Depending on the region, the flow QP1000, calculated by the regional formula for a catchment area of 100 km², is in a very wide range of 100 m³/s to 3,200 m³/s.

Figure 3.4 – Hydrological regions of France (PoNSOH – INRAE summary)

This variability in the climates of mainland and overseas France and then in the hydrology has enabled French engineering firms to develop robust hydrological methodologies and tools.

1.2 French methodologies for estimating extreme floods

The French methods for estimating structures' design floods fall within the scope of probabilistic methods: they estimate the distributions of pertinent variables (such as peak discharge or flood volume) for up to long return periods (10,000 years). This is a particularity on the international stage, which tends to be dominated by so-called "deterministic" methods of the Maximum Possible Rainfall-Maximum Probable Flood type.
Complementing "conventional" methods drawing on observed rainfall and discharge statistics (GRADEX and similar methods, AGREGEE and SPEED), the 2000s saw the emergence of some more sophisticated methods based on stochastic rainfall generation and rainfall-runoff simulation (SCHADEX and SHYPRE-SHYREG).

1.2.1 GRADEX method

The GRADEX method was introduced in the late 60s by EDF [Guillot and Duband, 1967]. It is a probabilistic method that extrapolates the discharge frequency distribution on the basis of the rainfall frequency distribution within a basin. It hence provides estimates of the upper quantiles of average discharge and peak discharge. It can be applied to catchment areas measuring between a few and ten thousand square kilometers. The GRADEX method is presented in detail in a CFGB bulletin [CFGB, 1994].

The method is based on three main assumptions:

1. at the time step for the study (i.e. over a period suited to the river basin flood dynamics), extreme precipitation follows an exponential decay distribution. The scale parameter of this distribution is the "gradex"; it is specific to a given site and a given season;
2. the runoff deficit, i.e. the difference between the rainfall water volume and the runoff water volume at the river basin outlet at the time step for the study, ceases to increase in terms of average value beyond a certain rainfall value. In other words, once the soil of the catchment reaches a certain degree of saturation, the runoff deficit distribution ceases to depend on the rainfall or discharge value. This concept translates graphically into a parallelism between the precipitation distribution function and the runoff distribution function at an equivalent time step. The starting point of this extrapolation, referred to as the "pivot point", is set at a return period of between 10 and 50 years depending on the catchment area considered;
3. the peak discharge for any return period can be calculated on the basis of the runoff volume (at the time step for the study) by using an average multiplicative factor that is characteristic of the catchment. This factor, called the "form factor", can be estimated using the flood hydrographs recorded on the catchment area.

Its overall formulation has remained more or less unchanged; however, the way it is applied has evolved as computation resources have progressed, and this includes a shift from processing maximum precipitation by season or by month to doing so for all of the rainfall observed.
Between the late 1960s and the 2000s, the GRADEX method was used extensively in French-speaking engineering circles (EDF and consulting firms) to perform the dimensional designs of several hundred dams in France and in North Africa. Its simplicity of form and its intellectual elegance contributed greatly to its reputation within the hydrological community. In the 1990s, however, the scientific community and some users of the method began pointing out a number of limitations, such as the fact that it underestimates the probability of extreme rainfall with regard to certain observations, the sudden transition at the "pivot point" between the distribution of observed discharges and that of rainfall in the basin, and the unrefined nature of the rainfall-runoff transition. These reservations led hydrologists to re-examine the issue in depth and work on methods based on stochastic rainfall generation and rainfall-runoff simulation: SCHADEX and SHYPRE-SHYREG.

1.2.2 SPEED: probabilistic system

The SPEED method (the French acronym for Probabilistic System for Discrete Event-based Studies), developed by Sogreah [Cayla, 1993], is based firstly on a specific regional analysis of rainfall and secondly on the relationship discovered by Sogreah between rainfall and flood discharge.

This method is based on the same principle as the GRADEX method but uses a different rainfall-runoff transformation formula. It enables a rainfall-runoff relation on a basin to be defined and, hence, extrapolated at rare frequencies.
The method can be applied to catchment areas of a size no larger than the usual coverage of a rain shower, that is up to 2,000 km² (or 10,000 km² in the case of cyclonic rainfall: over a long period and an extensive area but with a low intensity).
The method can be applied not just to annual rainfall and stream flows but also to rare types of rainfall and to flood discharges [Cayla, 2012] [Carré, 2013].

1.2.3 SCHADEX

The SCHADEX method (the French acronym for Climato-Hydrological Simulation for the Assessment of Extreme Discharges), developed at EDF-DTG, has been the benchmark method for dimensional designs of spillways on EDF-Hydro dams since 2007. It is particularly well suited to mountainous areas, as it includes an explicit representation of niveoglacial processes.

It draws on two main components:
- a probabilistic model of extreme rainfall, MEWP (Multi-Exponential Weather Pattern), which combines exponential distributions adjusted on observed rainfall samples grouped together by type of weather [Garavaglia & al., 2010];
- a stochastic rainfall-runoff simulation process, based on the MORDOR hydrological model [Garavaglia & al., 2017], which is used for simulating rainfall events of any intensity on the complete range of possible basin hydric conditions (saturated soils, snow stock etc.), thus generating several hundreds of thousands of floods [Paquet & al, 2013].

It estimates the complete distribution of flows (for return periods of up to 10,000 years) for basins measuring between ten and several tens of thousands of square kilometers, and for any type of climate. Summary hydrographs adapted to all the floods simulated can be generated using the SHYDONHY method [Paquet, 2019], to be injected as input into hydraulic models of schemes or valleys in order to calculate the distributions of water levels reached in reservoirs or rivers [Lassus & al., 2017].

1.2.4 SHYPRE-SHYREG

The SHYPRE method (the French acronym for Simulation of Hydrographs for the PREdetermination of floods) and its regionalized version SHYREG (SHYpre REGional) have been developed by Irstea since the 2000s with support from the French Ministry of Ecology. The method aims to create multiple flood hydrographs in various shapes statistically equivalent to the hydrographs observed. It draws on an hourly rainfall generator and simple hydrological modeling, to produce several tens of thousands of such hydrographs [Arnaud & al., 2002]. These are then used to simulate the functioning of hydraulic structures subject to extreme floods and to propose a complete frequency distribution of their responses. The regionalized version (SHYREG) estimates extreme floods at non-gauged sites. It is based on a simplified version of the SHYPRE method and a mapping of the parameters required to implement the method. This regionalized approach has been applied all over France (mainland and overseas), and the results have been compiled in a database that has been made available online [Arnaud & al., 2014].

1.2.5 Summary of French methods for estimating extreme floods

The EXTRAFLO research project, performed between 2008 and 2013, aimed to compare all the methods for predetermining extreme rainfall and floods that were commonly used in France, drawing in particular on catchment areas for which information dating back for long periods was available [Lang & al., 2014].
For estimating extreme floods on a gauged catchment area, the project concluded that it is important to use additional information (on rainfall in particular) to consolidate the extrapolation of flood distribution, and recommends the use of simulation methods based on rainfall information (SCHADEX, SHYPRE).
For non-gauged catchment areas, it is preferable to use the SHYREG-discharge simulation model. However, the approach has not been validated outside the usual range of surface areas of gauged basins [10 to 2,000 km²] and additional study and expertise would be required for it to be applied to basins functioning in a specific manner (under influence of snow, karst, dams, urban areas).

2. SPILLWAYS

2.1 French methodologies and contributions in the field of spillway hydraulics

2.1.1 Laboratories at the leading edge of physical modeling

As early as the beginning of the 20th century, French research organizations and engineering firms understood the benefits of physical modeling on a reduced scale in the field of hydraulic development schemes.

The laboratory of Artelia (formerly Sogreah) was created in 1917 with the initial aim of testing turbines and hydraulic developments on the Drac and Romanche rivers. Boosted by its initial successes, the laboratory significantly developed its study activities using scale models, and gradually expanded its work to include all components of dams and power plants and, subsequently, to maritime defenses, industrial facilities and urban developments.

The hydraulics laboratory of EDF (Laboratoire National d'Hydraulique et d'Environnement or LNHE) was created in 1947 to support the construction of the company's power plants (initially hydro, but also thermal and nuclear). The LNHE is dedicated to studying how water and the environment interact with EDF's generating facilities. The laboratory's activities encompass its historical work using physical scale models alongside the development of numerical modeling tools. It is still at the leading edge today, developing the modeling tools of the future such as 3D models (VOF, Lagrangien) and implementing experimental physical models such as the "Saut de l'Ange" (characterization of the hydraulic capacity of plunging jets for studies of downstream erosion issues).

Created in 1936, the Compagnie Nationale du Rhône hydraulics laboratory (CNR), holder of the concession to develop the river Rhône, performed all of the studies related to the designs of its facilities. The laboratory's tasks have expanded over time to ensure the dependability of the facilities along the Rhône. Today it is involved in managing hydraulic risks and optimizing the operation of facilities.

Although the principles of physical modeling are relatively long-established, they are still pertinent and even indispensable in the absence of an alternative, especially for studying complex phenomena such as those combining water-air or water-sediment interactions.

A large number of hydraulic structures around the world have hence benefited from the experience acquired by these laboratories. Figures 3.5 and 3.6 give a few examples.

Figure 3.5 – Water intakes at the Venda Nova pumped-storage plant)

Physical model / © Artelia – Derrien

Prototype / © Artelia – Derrien

Figure 3.6 – Spillway at the Causse Corrézien dam

Physical model / © Artelia – Loisel

Prototype / © Artelia – Loisel

2.1.2 Numerical expertise

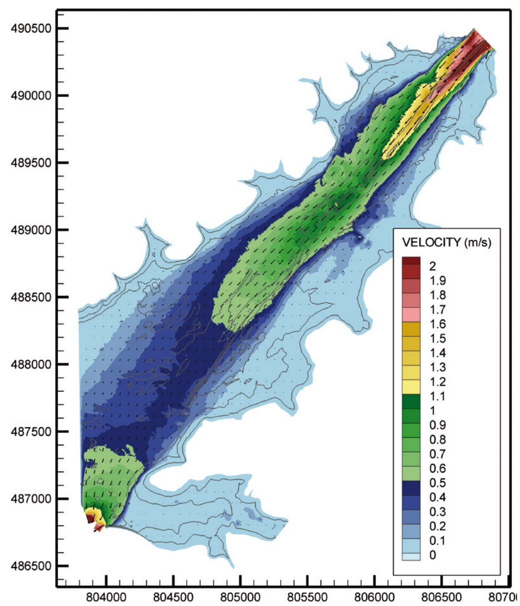
In parallel with physical modeling, French engineering firms have also pioneered many computation codes for performing numerical modeling studies of unconfined or pressurized flows.

TELEMAC-MASCARET

One of the most recent and most widely used systems worldwide is the TELEMAC-MASCARET system, owned by EDF and developed jointly by an international consortium composed of Artelia (France), BAW (Germany), CEREMA (France), Daresbury Laboratory (United Kingdom) and HR Wallingford (United Kingdom).

The TELEMAC-MASCARET system proposes a suite of 1D, 2D and 3D software applications for calculating movements of water, dissolved substances and sediment in natural aquatic environments: rivers, lakes, estuaries, coasts and continental margins. It has now been made available in an open source form and is supported by a large international community of scientists who contribute constantly to its development.

Figure 3.7 – Velocity field in the reservoir of Nachtigal dam (Cameroon) / © Artelia – Gonzales, Delinares



CFD modeling

French engineering firms have also been involved for many years in developing CFD (Computational Fluid Dynamics) software systems through R&D projects financed by their own or shared funds, but also through studies performed internally or on behalf of clients.

For example, Artelia frequently uses OpenFOAM® (Open Field Operation and Manipulation) CFD Toolbox, while EDF and other French engineering firms use FLOW 3D®.

2.2 Spillways on French dams

Most of the hydraulic structures in France were built in the 1950s and 60s. Their average service life is 70 years. French dams are equipped with spillways adapted to the techniques and design rules of the time: profiled free-flow spillways, fixed roller gates for the largest gates, tilting gates, and radial gates [Cottin, 2009 and Royet, 2009]. The primary purpose of a large percentage of French dams is hydropower generation, so they are often equipped with several large gates in order to optimize production management and maximize reservoir volume.

The discharge capacities of a significant proportion of French dams have been increased since the 1990s as a result of re-evaluations of past hydrological studies and changes in regulatory requirements. Rehabilitating and modernizing an existing structure is often more difficult than building a new one, because the constraints are often more substantial: factors to be considered include the structure's history, the state of the civil works (the oldest structures are built of masonry or cyclopean concrete, while some concrete structures are affected by swelling), the available footprint, safety management, and operating constraints (optimizing hydropower production, irrigation or drinking water requirements, leisure activities, etc.). Over the past twelve years or so, more than 60 rehabilitation projects of this type have been implemented in France [CFBR, 2019].

Figure 3.8 – (a) Record dam on the river Agout (2015) – Four radial gates were replaced with four piano key weirs (PKW) following the installation of a temporary protective cofferdam enabling the dam to be kept in operation, (b) PKW being fitted on Étroit dam (2009) / © EDF – F. Laugier

In parallel, more comprehensive safety assessments introduced in the early 2000s began factoring the reliability and robustness of flood spillway structures into risk assessments. These approaches provided an objective basis for assessing the technical and economic benefits of incorporating self-contained free-flow spillways and fostered the emergence of some significant innovations in the spillways field.

One of these is the fusegate — a French design patented by Hydroplus — which is widely used throughout the world having been fitted on more than 70 structures. Lussas dam in the Ardèche region of France was the first dam in the world to be fitted with gates of this type, in 1991. They provide a means of increasing discharge capacities or optimizing power plant production capacities by raising the reservoir's full supply level. They range in height between 1 m and more than 10 m. They can be made of concrete, steel, or a combination of both and in some cases allow overtopping before they tip over. They can be installed rapidly since many of their components can potentially be prefabricated, reducing dam downtime during the works phase.

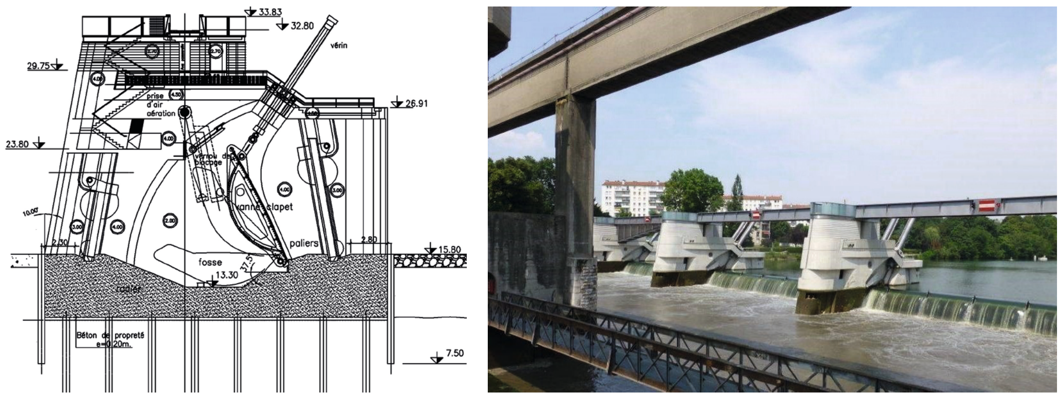
Figure 3.9 – Concrete fusegates on Tréauray dam in France (2014) and Terminus dam in the USA (2004) / © Hydroplus

A second major innovation, the Piano Key Weir (PKW), offers a means of harnessing the simplicity and robustness of free-flow spillways while maintaining a discharge capacity comparable with that of gated structures (they increase the discharge of a profiled free-flow spillway as much as four-fold). The PKW was developed by the French association HydroCoop on the basis of developments pursued in several hydraulics laboratories including the university of Biskra in Algeria and the LNHE [Lempérière 2003]. The world's first PKW was installed on Goulours dam in France in 2006 [Laugier, 2006]. Today some fifteen PKWs have been fitted in France and about thirty on all five continents [PKW register and Erpicum, 2017].

The juxtaposition of these innovative spillways alongside existing traditional structures offers the ideal compromise in terms of safety and functionality: high discharge capacities, sediment flushing to limit reservoir siltation (gated bottom or mid-level outlets), robustness, reliability, and removal of floating debris (surface spillways). This combination now underpins the philosophy used for sizing many new structures or rehabilitating old ones designed or built by French consultancies and firms [Chapuis, 2018].

In the case of river barrages, a recent trend is to replace old gates with large tilting gates (up to 8 m high) or, on smaller facilities, to install inflatable dams (a principle conceived in 1947 and patented by a French engineer called Mesnager). Tilting gates offer an optimal technical and economic trade-off for these river barrages with a limited risk of floating debris becoming trapped, no re-loading of the gates, and a limited risk of them failing to open. Inflatable dams are widely used on structures where the reservoir supply level must be constantly fine-tuned. Many projects have recently been completed or are currently in progress on French waterways (notably the VNF Aisne-Meuse project [VNF, 2012] and [Carlier, 2017]).

Figure 3.10 – Chatou dam on the river Seine / © Boidy, 2013



2.3 Dependability of French spillways

In addition to structural and hydraulic aspects, the dependability of gated spillways is a constant concern for French operators, and they have developed practices that set the standard in the profession [Reverchon, 2015]. The dependability of flood spillway structures is based on the following principles:

- reliability of operation, whether manual or automatic, is ensured by implementing redundancies and systematically eliminating common modes;
- inherent safety is ensured by the operator and during downgraded situations operations are carried out without the help of an automated system;
- facilities are kept in operational condition through periodic monitoring, inspection and testing.

Designing, operating and maintaining spillways involves examining the various risks inherent to hydraulic safety:

- operation-related risks: the kinetics and scale of uncontrolled or inadvertent gate opening can have an impact on people or property downstream of the structure;
- flood risk: uncontrolled gate operation or a failure to open can pose a risk for the structures or aggravate the consequences for local residents upstream or downstream of the structures;
- structure failure risk: an unavailable or inoperative spillway can undermine the stability of the other structures as a result of uncontrolled bed aggradation in the reservoir.

Precise instructions are hence needed in order to prepare for all possible situations. The rules for operating such structures are governed by the need to maintain first the safety of third parties and then that of the structures. The operations that take priority are those related to flood relief. Automatic operation offers significant benefits for the spillways of low-head dams; for high-head dams with large storage capacities, on the other hand, the benefits of this type of operation must undergo a thorough risk assessment.

FRANÇOIS LEMPÉRIÈRE

50 years of innovation and audacity dedicated to hydraulics and dams

François Lempérière was born in 1926 and graduated from the École Polytechnique and École Nationale des Ponts et Chaussées. He worked for construction firm GTM (now Vinci Construction) for more than 40 years. He contributed to the construction of large dams on rivers in France and other countries (the Rhône, Rhine, Nile and Zambezi), including the Cahora Bassa dam as well as some major maritime structures (Le Havre Antifer breakwater, cruise ship dry dock in Saint-Nazaire, Port of Jeddah). He was also involved in the construction of motorways, canals and nuclear power plants.

He was a particularly active member of ICOLD and the French Committee on Dams and Reservoirs (CFBR). At ICOLD, he sat on five technical committees, and was vice chairman of the Construction Technology Committee and chairman of the Dam Costs Committee. He contributed to eight ICOLD bulletins on dam construction methods, costs and economics.

From 1950 to 2012.

Between 1991 and 1995 he was chairman of the CFBR. In 1997, along with Pierre Londe, he co-founded HydroCoop, a non-profit association to promote assistance for developing countries and international technical cooperation on dam engineering, with a special focus on flood control, spillways and sedimentation issues. Constantly on the lookout for innovative, economical and safe solutions, François Lempérière was the brainchild behind several major developments in the field of dams and spillways. For instance, he invented the principle of fusegates (of which 70 have been built around the world) and labyrinth spillways, also called piano key weirs. The PKW, a concept developed with collaborators including Professor Ouamane and Michel Ho Ta Khan, has now been used on 30 dams around the world [Lempérière, 2003]. He has also published many articles introducing innovative concepts for hydropower generation or storage in rivers or at sea, including "Twin Dams", "Emerald Lakes" and "Tidal Gardens". He recently proposed an alternative pumping station concept to protect Paris against flooding.

In 1996 he received an award from the French Académie des Sciences for his fusegate concept. In 2018 he was honored with the ICOLD Lifetime Achievement Award.

Top photo: F. Lempérière
Bottom photo: EDF – F. Laugier

CASE STUDY
Sainte-Cécile-d'Andorge Dam (France)

A. Presentation of the dam

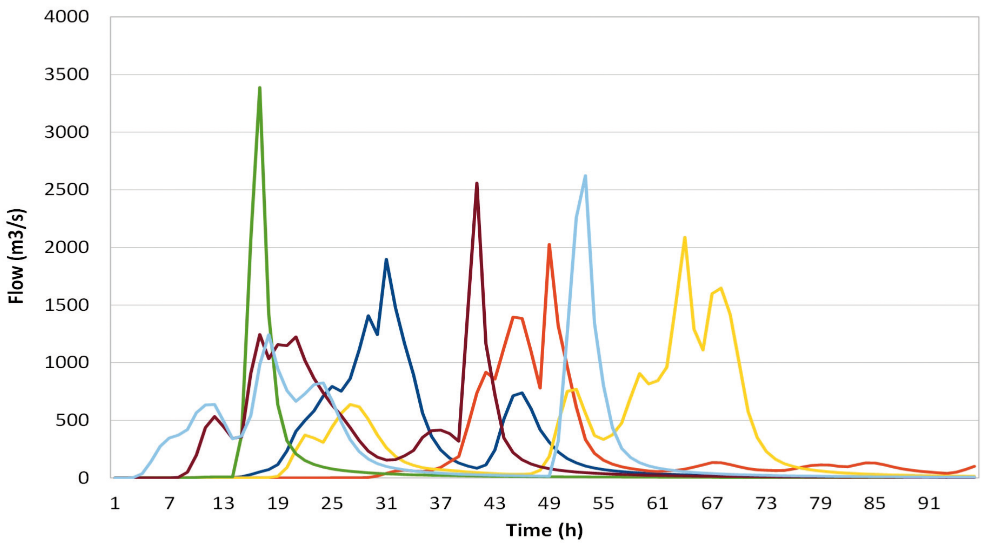
Built in 1967 to damp floods and maintain summertime low flow levels in the river Gardon d'Alès, Sainte-Cécile-d'Andorge dam is a rockfill dam with an upstream facing. The height above its lowest foundation is 45 m. The spillway is composed of two mid-level outlets and a bellmouth tower connected to a concrete double hydraulic gallery passing under the rockfill to the downstream side.

At the elevation of the outlet sills, the quasi-permanent reservoir has a volume of 0.88 Mm^3. The water storage intended for flood mitigation, situated between the elevations of the outlets and the bellmouth sill, has a volume of 14.8 Mm^3.

B. Revision of hydrological data

Following the hydrological events of the early 2000s that affected several neighboring dams, the hydrological study was updated in 2008 and then again in 2012 using the SHYPRE method. The design hydrological hazard was determined for a return period of 10,000 years in accordance with the French recommendations for large fill dams. The SHYPRE method was used to generate a large number of flood hydrographs (Figure 3.11), the passage of which through the reservoir and the spillway was then simulated. A probability distribution for the maximum reservoir level could then be established. It transpired that the return period for dam overtopping is approximately 1,800 years and that the 10,000-year reservoir level is estimated to be 3 m higher than the fill crest elevation. The flood spillway therefore had to be upgraded.

Figure 3.11 – Example of SHYREG hydrographs giving a 10,000-year reservoir level at the dam (Y-axis: discharge in m^3/s; X-axis: time in hours) / ©HYDRIS – Fine



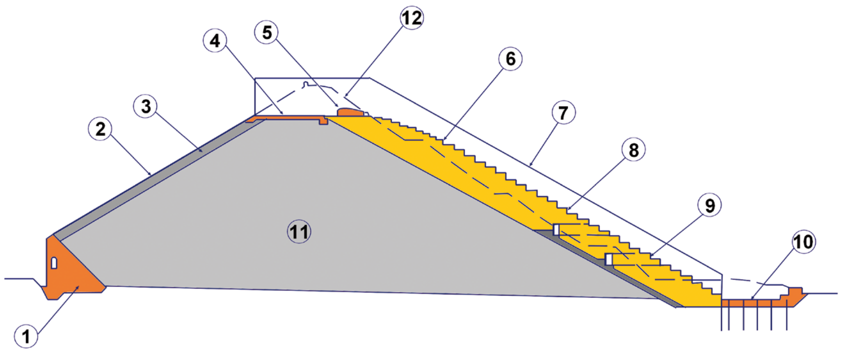
C. Solution for upgrading the flood spillway

The following criteria were adopted for the consolidation project (the last two being in keeping with the recommendations of CFBR [CFBR, 2013]):
- maintain an optimum "flood damping" function up to T = 100 years;
- design flood with return period T = 10,000 years, transiting with a freeboard relative to the crest;
- probability of the flood-danger elevation being reached lower than 10^{-5}/year.

The consolidation project being studied by ISL consists of building an additional free-flow spillway integrated into a solid RCC shoulder laid on the downstream side of the fill (Figure 3.12). The weir, 45 m in length, is set at the level reached for a 100-year return period (optimal flood damping function). Energy is dissipated by the steps of the downstream facing and by a stilling basin excavated and developed at the toe (reinforced concrete invert anchored to the rock and side protection blocks).

The dam crest elevation will be raised by 0.4 to 0.7 m above the current crest and a new 1.1 m-high parapet will be developed on the upstream edge of the crest.

Figure 3.12 – Typical cross-section of the additional spillway on an RCC shoulder /
© ISL – A. Salmi



1. Concrete cofferdam and upstream gallery
2. Transition material
3. Upstream watertightness
4. Reinforced concrete slab
5. Weir
6. RCC shoulder
7. Guide wall
8. Drainage gallery
9. Drain
10. Stilling basin
11. Rockfill
12. Existing downstream slope

CASE STUDY

New Fulaij Dam (Sultanate of Oman)

A. Hydrological analysis

The climate in the Sultanate of Oman is arid to semi-arid and characterized by low rainfall averaging approximately 100 mm/year. However, its coastal location and the presence of mountain ranges give rise to frequent flash floods that can inundate vast plains and affect many inhabited areas.

In recent years, the country has suffered the devastating effects of cyclones Gonu (2007) and Phet (2010), which brought record-breaking rainfall of 440 mm in 24 hours and 300 mm in 24 hours respectively. The estimated return period of the cumulated rainfall from cyclone Gonu is around 500 years.

This hydrological information led the Ministry for Water Resources to instigate a program of flood protection measures. For more than a decade, Artelia assisted the Omani authorities in designing and supervising the construction of many flood-control dams, including New Fulaij dam, which is presented below.

B. Presentation of the dam

Located just upstream of the city of Sur, a major regional capital, the purpose of New Fulaij dam is to damp floods on Wadi Rafsah by creating a storage volume of 20 hm^3 and thus protect palm groves, business and residential areas against future flooding.

It is a rockfill dam with an asphaltic concrete core (H = 26.50 m; L = 1,100 m) fitted with a concrete spillway (H = 30 m; L = 140 m) and a flushing structure consisting of four fixed roller gates (4.6 m x 3.6 m) and a water intake.

Wadi bed channelization works (excavation, protection, embankments) over 9 km (that is 3×10^6 m^3 of earthworks) rounded off the project.

C. Design and construction of the spillway

A physical model was built at the laboratory of Artelia in order to:
- check the hydraulic conditions and performance of the spillway;
- study the discharge capacity of the bottom gates and the energy dissipation structures;
- test erosion downstream of the structures;
- optimize the spillway stilling basin dimensions (to limit costs).

Figure 3.13 – Modèle physique de l'évacuateur du barrage de New Fulaij /
© Artelia – Loisel

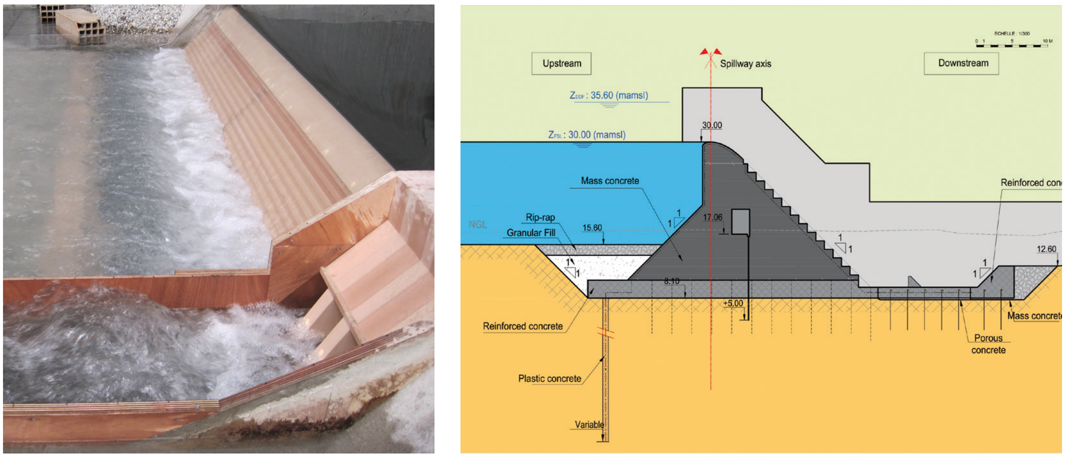


Figure 3.14 – Flood spillway under construction and following completion / © STRABAG

The dam construction and downstream recalibration works were completed in 2017. The dam withstood overtopping for the first time during a tropical storm in May 2019.

CASE STUDY
Malarce Dam (France)

A. Presentation of the dam

Malarce dam [Pinchard, 2013] was built in 1969 on the river Chassezac. It is a concrete gravity dam with a height above its lowest foundation of 31.4 m, fitted at the outset with three radial gates equipped with upper tilting gates closing outlets measuring 14 m wide by 11.5 m high.

Figure 3.15 – Photographs of Malarce dam viewed from downstream on the right bank before construction of the new PKW flood spillway and from upstream during works / © EDF – T. Pinchard

B. Hydrological context – Insufficient discharge capacity and record flood gradients

The theoretical discharge capacity of the dam (4,000 m^3/s at the maximum water level, situated 1 m above the full supply level) was validated on a scale model at EDF's hydraulics laboratory in Chatou. Following a re-evaluation of the hydrological studies in 2008, a peak design flood (1,000-year return period) of 4,600 m^3/s was adopted, resulting in a capacity shortfall of approximately 600 m^3/s. The largest known flood is approximately 2,700 m^3/s.

Moreover, the river Chassezac is subject to "Cévenol"-type flash floods during which discharges can increase rapidly, up to 1,300 $m^3/s/h$ in the case of the 1,000-year flood.

C. Decision to design a new PKW spillway

Given the very steep discharge increase gradient, the decision was taken to build a new spillway that would be self-contained and require neither energy nor a human presence in order to operate. A free-flow spillway therefore seemed to be the most appropriate solution.

Because of the narrow configuration of the dam and valley, a Piano Key Weir was the only type of spillway capable of guaranteeing the requisite hydraulic efficiency in consideration of the available hydraulic heads.

The safety improvements achieved on Malarce dam by building a PKW were hence not limited to merely increasing flood discharge capacity at the maximum water level by 15%. Increasing discharge capacity for extreme downgraded scenarios (operator absent, or a main and backup power supply failure) accounted for a significant proportion of the safety improvements made.
In addition, the PKW enhances operating flexibility since it will come into operation first, under a 50 cm head, before the tilting gates begin performing their regulating function.

The total footprint of the PKW on the right-bank block of the dam is 42.5 m wide and the weir operates under a nominal head of 1.5 m. The weir has an overhang of more than 6.5 m on the upstream side and 2 m on the downstream side. It is composed of 12 inlet keys and 12 outlet keys. On the downstream side, a reinforced concrete apron protects the rock against erosion, and structures at the toe of the chute (flip bucket and deflector walls) dissipate energy and prevent risks of dam toe erosion.

D. Construction and implementation of the PKW

Construction began in November 2011 and ended in November 2012. More than half of the works phase was devoted to preparing the site (access, demolition and earthworks). At the location now occupied by the PKW, more than 800 m^3 of high-quality concrete had to be demolished.

The site workforce amounted to approximately 30 people, up to a maximum of 60 during peak periods, for a cost of approximately 4.5 million euros.

The Malarce PKW was overtopped twice in May 2013, a few months after the works were completed. The first event reached a discharge of approximately 50 m^3/s and the second one 200 m^3/s, that is a nappe of 18 and 50 cm respectively. The PKW operated as expected and no damage was observed. Since then, the PKW has been overtopped by significant floods on about ten occasions.

Figure 3.16 – Malarce dam / © EDF – T. Pinchard

a) Physical model

b) Construction

Figure 3.17 – Malarce dam – Downstream view of the new PKW / © EDF – T. Pinchard

Figure 3.18 – PKW of Malarce dam / © EDF – T. Pinchard

a) PKW of Malarce dam Completed PKW

(b) During overtopping

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CHAPTER 4

RESERVOIRS AND ENVIRONMENT

1. INTRODUCTION

Large dams are infrastructures that have a major impact in shaping the surrounding area. Most of the dams in France were built in the mid-twentieth century, which means that we have a great deal of information on the various environmental and societal aspects of their construction and subsequent use. For many years, following the initial social disruption caused by their construction (displacing villages, etc.), they have mainly been appreciated for the diverse benefits they bring, depending on their function(s): drinking water supplies, flood control, hydropower generation, etc. It is only relatively recently (since 2000), that awareness of their impact on the environment has grown, sometimes leading to dramatic local conflict over engineering projects (e.g., Sivens agricultural dam), or to recurrent opposition to the development of small hydroelectric plants, for example.

In line with France's commitments relative to climate change and biodiversity in general, changes to the regulations that came about as a result of France's "Grenelle" Environment Forum in 2007 have been stepped up over the last 15 years. In particular, we have seen the principle of the mitigation hierarchy (Prevent-Reduce-Compensate) applied to all development projects and programs that have a major impact on the environment and which was adopted in the French law on August 8th, 2016 on reclaiming biodiversity, nature and landscapes.

This growing awareness had been anticipated, by Électricité de France (EDF) amongst others, which developed a Research and Development (R&D) partnership with CEMAGREF (the research institute now known as INRAE), from the 1990s, which has included work on instream flows and lockage water. Since the early 2000s, all the major hydropower plant management companies have invested in R&D, forming partnerships reaching out to other institutions (CNRS, AFB [the French Biodiversity Agency], universities, etc.) and looking at all aspects of the environment (ecological continuity, water quality, biodiversity, etc.). This investment in furthering our understanding of ecological processes and the impacts of dams in contexts subject to multiple sources of stress caused by human activities has led to the development of advanced expertise in assessing situations and implementing solutions to mitigate such impacts.

In this chapter, we present some examples of good practices that factor in the environmental issues most closely related to dams and water impoundment structures: sediment management, restoring biodiversity and protecting water resources. Given the future role of hydropower in driving energy transition, questions relative to the carbon footprint of such engineering structures and, more generally, the need to take Environmental and Social (E&S) aspects into account as criteria in the design of new engineering works, are also discussed below.

2. GOOD SEDIMENT MANAGEMENT

The accumulation of sediment upstream of a dam is a subject of concern for facility operators since it restricts use by reducing the useful volume(river navigation, drinking water, irrigation, hydropower, flood storage, etc.) or reducing the water quality (eutrophication that can affect leisure use, for example). For the watercourse and its users downstream, sediment deficit, especially a deficit in terms of the rock fraction, may also, in the longer term, cause ecological malfunctions or damage engineering structures (bridges, etc.). While structures that have wide gates (such as barrages and river dams) ensure a certain level of sediment continuity provided that specific precautions are taken (see chapter 8), other types of structure often require particular and costly management measures (extraction, land management, etc.).

2.1 Promoting fine sediment transport

On the Upper Rhône River Basin, fine sediment fluxes are managed according to a special protocol that was developed in the early 1980s. The Swiss operators organize flushing to prevent extra-flooding caused by sedimentation in the Verbois dam reservoir. The flow of fine sediment released downstream of the dam is rigorously controlled by the Compagnie Nationale du Rhône (CNR) at the Génissiat dam reservoir, to maintain a mean rate of Suspended Solids (SS) below 5 g/l in the French part of the Rhône.

Figure 4.1 – Controlled lowering of the water level in the Génissiat reservoir during Swiss flushing operations in the Upper Rhône in 2012 / © CNR – Camille Bezzina

This requirement for managing the dam is extremely strict, but is nonetheless justified by the nature and diversity of the river-related challenges and uses: high environmental value of the "Old Rhône" sections, drinking water supply for Lyon, water intake for the cooling systems at EDF's nuclear power plants, CNR dam safety, river navigation safety, etc. The requirement is met thanks to meticulous real-time management of the reservoir water level and of the solid fluxes released out of the three water outlets judiciously located at different levels of the dam: a bottom gate, a mid-level gate and a surface spillway [Peteuil, 2013]. To this end, in situ measurements are taken and transmitted in real time to the dam command center to decide on the most appropriate operations to be performed at any given time. In addition to SS concentration, these measurements also monitor many other elements: physical and chemical, toxicological and bacteriological content, drinking water catchments, protected species, the "Old Rhône" sections and fish protection zones, bathymetry, etc.

Following a joint study carried out by the French and Swiss operators and authorities after the flushing operations performed in 2012, this effective management solution has, since 2016, been extended to the Swiss part of the Rhône to ensure sustainable sediment management that is consistent on both sides of the border [COTECH, 2014]. A multi-year management plan designed to meet all the cross-border objectives has been defined (2016–2026). It combines three types of management, involving the different hydropower plant management companies:
- supporting sediment transport during Arve River floods;
- three-yearly partial lowering of the water level in the Verbois reservoir, with supporting operations at Chancy-Pougny dam and special management measures at CNR facilities in line with those implemented since the 1980s;
- additional dredging to remove specific targeted deposits (using a suction dredger and discharging sediment into the main riverbed of the Rhône).

Figure 4.2 – Dredging robot / © EDF

Dredging operations may be subject to significant technical and environmental constraints; EDF, in partnership with Watertracks, is currently developing a dredging robot called NESSIE®, an ROV designed to minimize pollution which is used on the Chambon reservoir, with pumped storage of the sediment-filled water and discharge into the Romanche (see Figure 4.2).

In both examples, R&D is carried out by the hydropower plant management companies (CNR on the Rhône, and EDF on the Romanche) and the HEPIA laboratory (Geneva School of Engineering, Architecture and Landscape) aiming at a better understanding of the incidence of different concentrations of suspended solids on fish, depending on length of exposure, species and stage of life; research is ongoing to fine-tune the criteria currently used (Newcombe & Jensen index, 1996) in view of future operations

2.2 Finding uses for the sediment

Hydropower plant management companies that have to scour their installations need to find ways to use the sediment removed; so-called "mineral" industries (ceramics, cement, concrete, road-building, etc.) are widely known and may be a good way of using the sediment removed from navigation channels as part of a recycling and circular economy approach (e.g., sediment from the locks on the Rhine). However, these industries are rarely used for hydropower plants as they are generally located too far away from recycling facilities for this to be an economically viable solution. For this reason, research has focused on using the sediment in land reconstruction to restore environments degraded by human activities (industrial wastelands), or for re-use in local farming sectors. Following experiments conducted by the French Chambers of Agriculture using materials recovered from dredging marine sediment or sediment from rivers used for shipping [Balloy & al., 2018] and after demonstrating both the possible benefits and the conditions for this solution, a number of pilot sites were launched by VNF to optimize the technical procedures (e.g., sediment from the Baulieu canal) and by EDF (e.g., sediment from the Escaumels impoundment or from Mont-Cenis dam), and to demonstrate the benefits for different types of crop (beetroot, corn, pasture/prairies, etc.)(1).

2.3 Promote coarse sediment transport

Coarse sediment that accumulates upstream of a dam is made up of solids that are then "missing" from the river downstream in terms of ensuring proper river function. Sluicing during flooding remobilizes a great proportion of these solids and transports them downstream. However, operating procedures employed at hydropower plants do not always prevent build-up of the coarsest sediment forming a delta where the river enters the reservoir, which can cause problems for river users. On the Roya river, for example, the build-up of solids on the Breil reservoir used to be very unsightly: when renewing the hydropower plant operating license, extensive renovations were carried out on the plant, including a review of water flow and the conditions for sluicing, which served to improve sediment transport. At Saint-Sauveur, on the Büech river, even though the dam is regularly sluiced, the increased flood risk on the banks of the reservoir led to scouring the coarse substances and feeding them into the river downstream, as well as a review of the flood control rules (lowering the flow rate threshold for sluicing operations). 44,000 m^3 of solids were recovered and used to raise the channel bottom, thereby re-establishing proper sediment function [Brousse & al., 2018].

(1) See Assises nationales de la valorisation des sédiments, Conference held in Paris, Oct. 1st, 2019 – http://www.cd2e.com/?q=assises-nationales-sediments-paris-2019

3. PREVENTING THE EROSION OF BIODIVERSITY

3.1 *On the Rhône*

The program for the hydraulic and ecological restoration of the river Rhône came about as a result of a desire shared by local councils, river management companies (CNR, EDF & VNF) and the French government to re-establish the natural swift flow of the river. Launched in 1998, the program includes four key types of operation:

- increasing instream flows in sections bypassed by hydropower plants;
- restoring oxbows, which are branches of the river that have become disconnected from the mainstream, most of which were partly dried out, and which have now been filled with water and reconnected to the mainstream;
- restoring fish migration routes, mainly by building fish passes alongside dams and at points where tributaries meet the mainstream.

Figure 4.3 – Restoration scheme and RhôneEco / © GRAIE 2016 – G. Chagny dans RhonEco

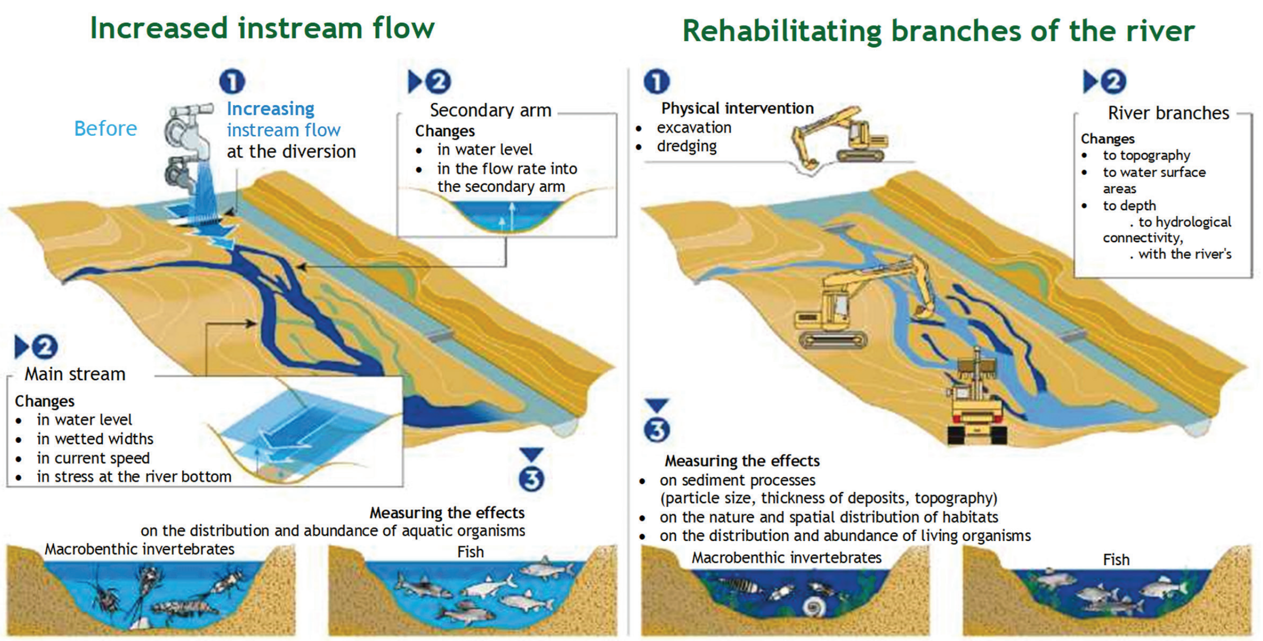


Figure 4.4 – Small hydropower plant and fish pass at Rochemaure /
© CNR – Camille Moirenc

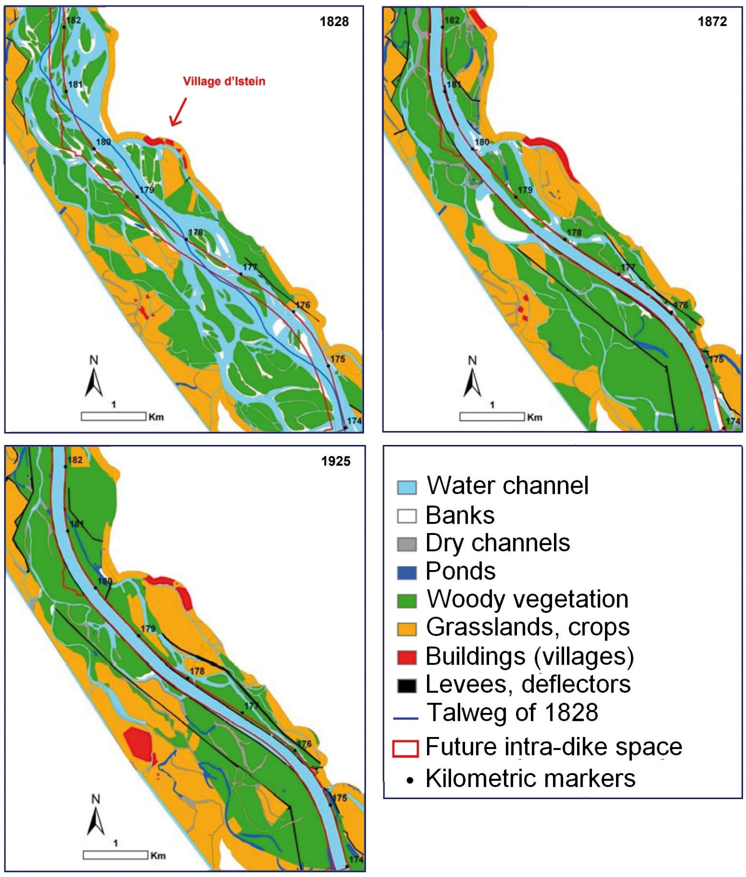
In line with the actions mentioned above and to offset the significantly increased instream flow causing production loss at the main power plant, small hydropower plants were built aside mobile dams, with output of 4 to 8 MW, and turbine flow of 50 to 85 m^3/s. At the same time, fish passes were built (pool pass for upstream migration, collection gallery and pipe system for downstream migration).

From 2000 to 2015, work was carried out on nearly a quarter of the length of the river (120 km), including the restoration of 38 blind channels and the construction and commissioning of 4 small hydropower plants, two of which have fish passes. Carried out on an exceptional scale on at international level, the program has, since the outset, included a scientific support program called RhôneEco. Coordinated by multidisciplinary research teams, RhôneEco has served to develop an exceptional understanding of the river's ecological condition and its evolution following the restoration work. The fact that different restoration operations were carried out has significantly increased the diversity of environmental conditions in the landscape (Figure 4.5). This has in turn enhanced biodiversity in the flora and fauna communities.

Figure 4.5 – Restoration of the Dames blind channel (Bourg-Saint-Andéol) a) before b) after / © CNR – C. Mora

3.2 On the Rhine

Figure 4.6. – Evolution of the bed of the Rhine / © Arnaud 2012



The industrial and navigational challenges presented by development on the Rhine combine with the need to factor in new environmental and societal ambitions aimed at re-establishing ecological conditions that have been altered by intense river development. Up until 1840, between Basel and Lauterbourg, the Rhine was still wild and undeveloped, a river consisting of multiple channels, gravelly banks, plant-covered islands and shallows that hindered navigation (Figure 4.6). Work to create impoundments and rectify the river bed between Basel and Neuf-Brisach, carried out in the 19th and early 20th centuries, resulted in fixing and downcutting the river bed by several meters; sediment transport was also significantly reduced, mainly due to hydropower plants upstream of Basel.

Kembs dam was built in 1932, diverting the main part of the water flow (Kembs plant design flow of 1,400 m^3/s) into the Grand Canal of Alsace, thereby bypassing the river, which then became known as the "Old Rhine" (Figure 4.7). The Old Rhine is fed by the instream flow and discharges from the dam during flooding. Since the impoundments and channeling, the riverbed can be seen to be paved and incised, altering the ecological conditions.

Figure 4.7 – Kembs dam /
© EDF – Airdiasol – R. Rothan

As in the case of the Rhône, a series of hydraulic and environmental measures aiming to restore the Old Rhine's hydromorphological and ecological conditions downstream of Kembs dam have been implemented [Garnier & al., 2014]:

- increased instream flow (from 52 m^3/s in winter to 150 m^3/s in summer), pumped by a new 8.4 MW hydropower plant, generating 28 million kWh, and creating attraction flow for the new adjoining fish pass;
- pass systems built to allow the movement of fish and beavers, including a bypass channel for fish between the Petite Camargue Alsacienne (national nature reserve) and the Grand Canal of Alsace.

Figure 4.8 : Little Rhine /
© EDF – Airdiasol – R. Rothan

- Restoration of a river branch on the Ile-du-Rhin (over 7 kilometers), named the Petit Rhin (Little Rhine), re-establishing a series of natural wet and dry ecosystems, encouraging biodiversity in a 100-hectare plot formerly used for farming [Pascal, 2018]; for example, the number of bird species has increased threefold, and a whole gamut of different vertebrate and invertebrate species soon colonized the site, making it a major reservoir of biodiversity for the Alsace Plain.

Figure 4.9 : Old Rhine /
© EDF – A. Barillier

- An innovative program to re-introduce solids to the bed of the Old Rhine, aimed at restoring and improving natural aquatic and river habitat conditions: two methods were used to inject gravel from former deposits from the Rhine into the main channel and the erosion of riverbanks due to flooding after dikes were removed in the 19th century. Since 2013, over 50,000 m^3 of solids have been re-injected into the Old Rhine, and 1,000 m of riverbank have been weakened to promote erosion, thus diversifying aquatic habitats, and encouraging more diverse fauna [Barillier & al., 2018].

4. SAVING WATER RESOURCES

In addition to generating electricity, hydraulic infrastructures, in France as in many other countries, have sometimes been designed for a number of purposes and to support many different services, including river navigation, drinking water supply, drought mitigation (offsetting low water), irrigation, etc. Such multi-use management also contributes to a region's economic development but does require appropriate governance across the entire catchment basin.

A good example of this is the Durance-Verdon system, where the planned and coordinated management of the 30 hydropower installations in the two valleys supplies 2,00 MW to the electric grid and also supplies water to the population and to industry for the entire region, as well as being used to irrigate farmland, control flooding, manage droughts, ensure the banks of large reservoirs can be used by tourists and meet the criteria for silt and freshwater discharge to enhance quality in the Étang de Berre (see Chapter 1).

This balanced approach to sharing water resources and reconciling different uses is also part of the business model defined by the founders of CNR back in 1933. This model, cited as an example in the French law on energy transition passed in 2015, considers that income from operating hydropower plants on the Rhône river, a national public asset, should also benefit the regions in which such income is generated to finance the development of the waterway, irrigate the valley and deploy projects in the general interest, for example in relation to energy transition, the development of tourism, and sustainable farming.

Growing awareness of the scarcity of water resources due to climate change (e.g., the Garonne 2050 prospective study), can be seen in water policy, in encouraging water-saving usage and

Could floating solar panels be an effective means of saving water?

Much of mainland France is suitable for the development of solar power plants for energy. They still have the disadvantage of requiring a great deal of space which, potentially, may have an impact on use (farming), the landscape and biodiversity. The development of floating solar power plants, covering much of the water surface of impoundments, would help prevent the water from overheating and evaporating in the summer, whilst generating electricity during a period of maximum water stress. A project has recently been commissioned by CNR on La Madone irrigation lake in Mornant (Rhone), in which 630 floating solar panels now combine the generation of photovoltaic solar electricity (227 kWc) and the development of aquatic biodiversity thanks to the installation of artificial habitat modules underneath the floats, enabling fauna and flora in the lake to develop.
Another pilot site is being developed on the Lazer hydropower reservoir in southern France, with 15 MWc installed capacity for an area covering 24 hectares (80% of the reservoir's surface area) [Grenier & al., 2019]. Outside France, studies led by TRACTEBEL are underway to integrate a floating solar power plant at the Kossou impoundment in Côte d'Ivoire.

Figure 4.10 – Lazer hydropower reservoir / © EDF

better front-end resource management. For example, the Adour-Garonne Basin Committee (AEAG), the French government and the Nouvelle-Aquitaine and Occitanie regional councils recently set five priorities for adapting to future water shortages estimated at 1.2 billion m^3 by 2050 for the whole river basin [AEAG, 2018]: in addition to planned water savings by the different users, this includes the development of nature-based measures (restoring wetlands, etc.), countering soil erosion, supporting new and more water-efficient sectors, with a focus on storage and optimizing existing resources, in particular hydropower plant reservoirs, and new dam development. Social acceptance of new dam development is not a given: Sivens dam will not now be built in light of intense opposition to the plans, while Caussade dam (Lot-et-Garonne) was built in spite of the fact that it was not granted a license due to an inadequate assessment of its impact on biodiversity and water resources.

In fact, it is often the failure to factor in the impact on biodiversity on land (eliminating wetlands, etc.), or on the aquatic environment (degraded water quality, risk of unwanted species taking over, etc.) or on the landscape, which causes such conflict. The difficulties involved in designing new water storage systems inevitably increases pressure on existing hydropower reservoirs, which were not originally designed for multiple uses. That implies a need to find a new business and governance model for the facilities in question

5. SUPPORTING ENERGY TRANSITION

Energy transition entails increasing the share of variable energy sources in the electric power system, for which electricity storage solutions need to be developed. Hydropower currently accounts for 99% of storage capacity in France, and, given its flexibility, its role is set to grow in the future. However, it remains to be demonstrated that this solution is not a significant source of greenhouse gas emissions, at a time when large dams are under scrutiny due to CO_2 or CH_4 emissions, including those in temperate zones [see Baulieu & al., 2017 for the USA; DelSontro & al., 2010 for Switzerland, for example]. Nonetheless, recent scientific publications show that these emissions vary a great deal depending on geographic region and, in the case of alpine and peri-alpine reservoirs in Switzerland, are lower by several orders of magnitude than total emissions measured at reservoirs in tropical regions.

Since 2011 in France, all private-sector companies and associations with over 500 employees, as well as all municipalities with over 50,000 inhabitants, have been required to publish their greenhouse gas balance every four years. Électricité de France publishes a greenhouse gas balance every year on its internet portal, that takes account of emissions related to filling reservoirs. Emissions are calculated using the IPCC method based on reservoir surface areas of over 1 hectare and average total emissions per climate zone.

At the same time, EDF has developed expertise in measuring and evaluating emissions in situ, at tropical reservoirs [Guérin & al., 2016; Deshmukh & al., 2018], and in mainland France [Descloux & al., 2017], and has been involved in developing the International Hydropower Association's (IHA) G-Res Tool, used to estimate net greenhouse gas emissions due solely to the presence of the dam [Prairie & al., 2018]. In 2017, researchers at the IHA studied 498 reservoirs worldwide using the G-Res tool and showed that global median intensity of greenhouse gas emissions from hydropower reservoirs included in the study was 18.5 gCO_2-eq/kWh.

Outside France, TRACTEBEL and AERA Group, on behalf of their client, CI-Energies, have obtained carbon certification for the largest hydropower dam in Côte d'Ivoire. The Executive Council of the United Nations Framework Convention on Climate Change (UNFCCC) officially registered the Soubré hydropower dam under the Clean Development Mechanism (CDM) in 2017[(2)]. With the potential to have the highest number of carbon credits in Côte d'Ivoire, this power plant will stop the emission of over 600,000 tons of CO_2 a year by Côte d'Ivoire's national grid. The Soubré hydropower scheme, located upstream of the Nawa natural falls on the Sassandra River, is a key project of Côte d'Ivoire's national energy strategy. With installed capacity of 275 MW and output of 1,170 GWh, it is the largest dam in the country.

(2) https://cdm.unfccc.int/Projects/DB/RWTUV1476171677.04/view

6. INTEGRATING ENVIRONMENTAL AND SOCIAL FACTORS IN DESIGN CRITERIA

It is interesting to remember that all the examples given in this short chapter barely entered into the minds of the early developers and that they only account for a small part of initial development investment; the costs may nonetheless seem "inaccessible" or "untimely" to some existing dam operators, when it proves necessary to correct the impact after the fact. In today's social and environmental context, where project owners and funding organizations must relay society's expectations, integrating solutions, from the design stage, that reduce a project's total environmental footprint, complying with the Prevent-Reduce-Compensate principle, is therefore not only essential if the project is to be accepted, but is also almost certain to reduce costs in the medium and long term.

Studies on the environmental and social impact of large dams must now systematically meet these demands and seek, above all, to integrate the facility in its specific context, ensuring they are included in design criteria (e.g., see EDF's experience presented in [Nathan 2016], [Beche & al, 2017], [Beche & Nathan, 2019] and that of TRACTEBEL in [Tomczak, 2018]). This is how recent projects have been able to go ahead abroad, bearing in mind the fact that it is not necessarily a question of building the largest dam, but the most appropriate.

In Guinea, alternatives to the project were analyzed, and showed that three times fewer people would be displaced if the sides of the reservoir were 20 m lower, while still meeting optimal output for the Kaléta-Souapiti complex. That is how the decision to build the Souapiti dam was made. It will soon be completed [Tomczak, 2018] and [Tomczak, 2018b].

Furthermore, we must be careful not to underestimate the social and economic benefits for underdeveloped regions. When building a large dam, the original objective of social and economic development for the region is now clearly stated and project owners are keen to maximize the benefits: roads and bridges will improve access to the region, as well as providing access to electricity in the area near the dam. Add new public infrastructures to the mix and local social and economic development related to building the dam is all for the good. Integrating environmental and social (E&S) factors in design studies is also key.

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CHAPTER 5

GRAVITY DAMS

In France, large gravity dams are both a tradition dating back to the 18th century and a field that is always rich in new approaches.

The traditional aspect is that of the construction of several hundred dams, representing 25% of the large dams of France. The new approaches cover both the maintenance of these facilities (safety assessment, upgrading), and new design & construction by French engineers and contractors, mainly outside France. This feeds an active research and development activity.

This chapter begins with two specific insights into the history of gravity dams in France (section 1): the history of masonry dam design and the contribution to RCC technology. Section 2 is devoted to the maintenance of existing dams, which has given rise to several advances over the past 20 years: the development of a standardized body of justifications by calculation; the improvement of physical tools for assessing old structures; the implementation of various upgrading procedures for dams with uncertain stability. Finally, section 3 illustrates some themes for which research remains active in France.

1. SOME ELEMENTS OF HISTORY

1.1 Old masonry dams

Historically, gravity dams were first built in masonry. This type of dam represents most of the dams built in France during the 19th and early 20th centuries. [Royet, 2003 and 2013] provides an overview of the 70 French masonry dams built before 1950.

1.1.1 17th to 19th century: rationalization and optimization of dam geometry

The oldest masonry dams consist of a relatively thin masonry wall supported by a large downstream backfill and sometimes also an upstream backfill (to ensure stability when emptying), like Saint-Ferréol dam (H = 35 m, completed in 1675), which is France's oldest large dam still in service. At the same time, masonry dams without backfill also emerged, generally quite massive and with buttresses (Figure 5.1, type 1), especially when they were not arched, like Paty dam (H = 16.5 m in 1766, raised to 20 m in 1870). A third geometry of old masonry dams is characterized by stability that is essentially ensured by the arching effect. This is the case at Zola dam (H = 36 m, 1854) which, at the time, was the world's highest masonry arch dam.

Around 1850, the research of Sazilly and Delocre led to proposing more slender gravity profiles, using better distributed material. This is the profile of "equal resistance" published in 1853 in the "Annales des Ponts et Chaussées": the masonry's "fatigue rate" is equal at the upstream face with the reservoir empty and at the downstream face with the reservoir full. The upstream and downstream faces, inclined and concave, result in a typical 'hollowed-out' cross section (Figure 5.1, type 2). Compressive stresses are very low at 600 to 800 kPa. The first example of this type is Gouffre d'Enfer dam (also called Furens dam) (H = 55 m, 1866), a world record at the time.
At this time, some dams were being built with a vertical upstream face and substantially straight downstream face, and a total batter slope of approximately 0.6 to 0.7, reduced to 0.58 at Bouzey dam (H = 24 m, 1881).

1.1.2 1884 and 1895: the two Bouzey accidents

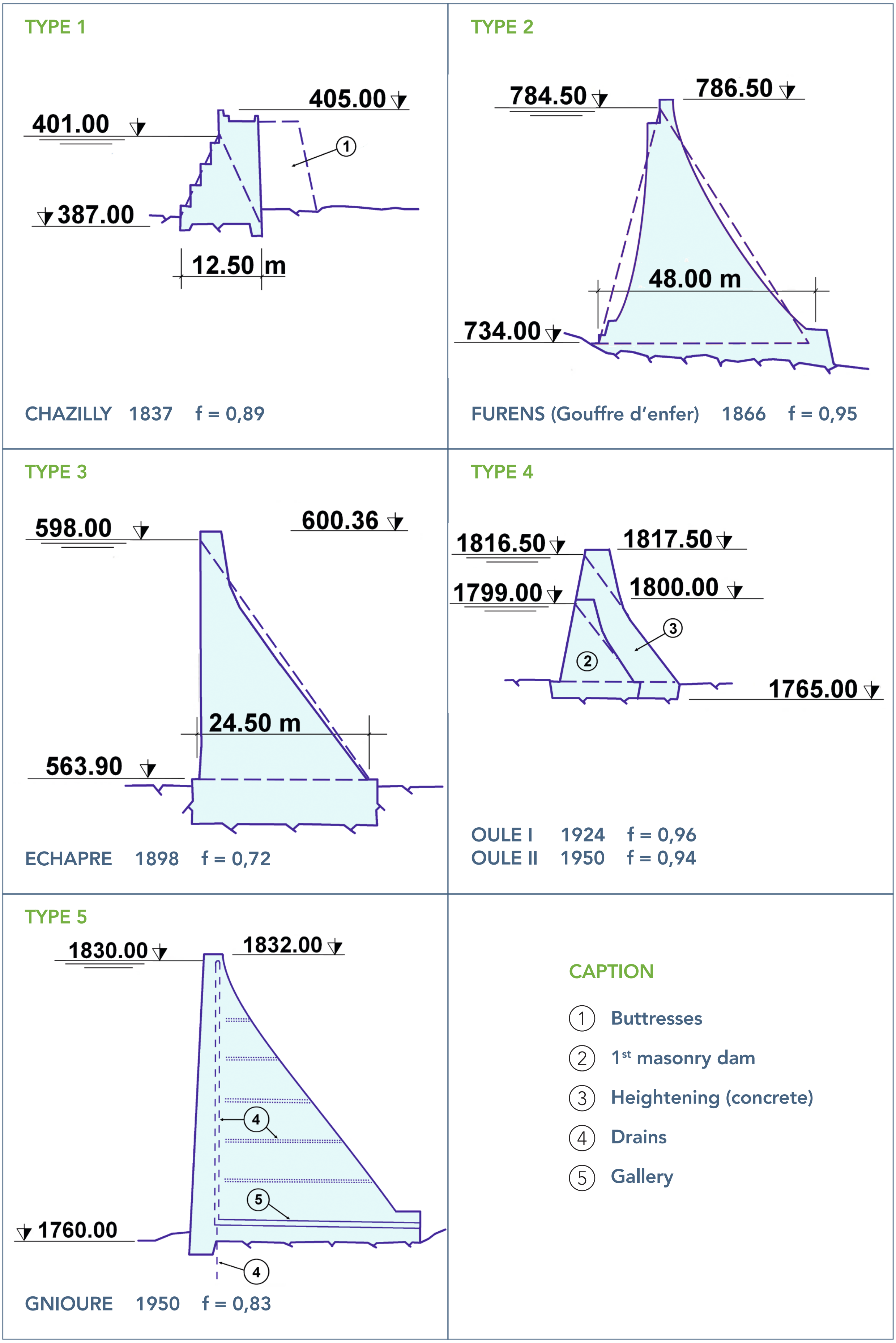
A general sliding movement on the foundation was observed on March 14th, 1884, during the initial filling of Bouzey reservoir, leading to the adjunction of a masonry abutment at the downstream foot. On April 27th, 1895, the catastrophic failure occurred when the central part of the masonry, above the downstream abutment, slid and overturned. Following this failure, Maurice Lévy drew attention to the effect of pore pressures resulting from the penetration of water into the dam body.

The largest dams were then recalculated. Some were decommissioned, others stabilized by a downstream embankment or protected by upstream facings (this latter method being known as "Lévy facing") to reduce pore pressures throughout the body of the dam to zero. At Chartrain dam (H = 55 m, 1892) the condition of no traction at the upstream toe was considered for the first time. The allowable compressive stress was increased up to 1.1 MPa.

1.1.3 20th century: modern design dams, then transition to concrete dams

Dams built after 1900 have benefited from calculation methods that consider the criterion of no-traction at the upstream facing and the pore pressures. This has resulted in triangular profiles with generally rectilinear faces, often inclined upstream and with a minimum of 0.8 upstream + downstream slope (Figure 5.1, type 4). The latest generation of French masonry dams is characterized by active drainage, within the dam body and the foundation (Figur 5.1, type 5), as in the case of Gnioure dam (H = 70 m, 1950).

Figure 5.1 – Evolution of typical profiles of French masonry dams



At that time, however, concrete had already taken over, with Éguzon (1926), Grande Rhue (1927), Sautet and Chambon (1934) dams. This generation of conventional vibrated concrete (CVC) dams is characterized by the great care taken in the foundation treatment, including grouting and drainage. Dam body drainage and a gallery at the upstream toe was provided for large dams. Widely used until the 1990s, CVC eventually gave way to roller-compacted concrete (RCC).

1.2 The French contribution to RCC technology

Olivettes dam was the first large French dam made of Roller-Compacted Concrete (RCC), in 1988. The RCC production design is based on an alternative proposed by the contractor to an AFRD (Asphalt Face Rockfill Dam) which was quite popular at the time in France.

Following this achievement, the RCC technique aroused great interest in France. It could, indeed, lead to time savings and a significant reduction in costs.

Figure 5.2 – Riou dam / © BETCGB – Stéphan Aigouy

In 1989, France decided on an R&D program bringing together the main stakeholders in the field of dams: the BaCaRa project.

Among the topics discussed was the issue of the upstream facing. Various solutions have been implemented, tailored to each site. Riou dam provided the opportunity to implement a Sibelon stretched PVC geomembrane developed by the Italian companies Carpi and Italform and used for the first time on a new project. Olivettes, Choldocogagna and Touche Poupard dams include a conventional concrete upstream facing built in layers at the same time as the RCC.

Sep dam was equipped with a conventional reinforced concrete upstream wall, built ahead of the RCC, fixed on a plinth and designed to withstand seismic forces and transmit them to the foundation. Petit-Saut RCC is protected from the acidic waters of the reservoir by a vibrated concrete upstream wall built ahead of the RCC.

Table 5.1 lists the dams built in France during the BaCaRa project.

BaCaRa (1989–1996): collaborative research project on RCC dams

- *30 organizations: project owners, designers, contractors, Government, Federation of Public Works.*
- *5 million € of studies and tests.*
- *Related to: RCC material, stepped spillways, dam design (watertightness, stability).*

Regarding RCC material, BaCaRa focuses on:

- *low exothermic and slow-setting binders made from products of the steel industry, possibly supplemented with fly ash;*
- *relaxation of specifications on aggregates;*
- *conditions for hot-joints;*
- *use of moderate intensity rollers.*

Tableau 5.1 – *List of RCC dams built during the BaCaRa project period*

Dams (BCR)	Dam: lenght (m); *height (m);* *RCC volume (m^3)*	Reservoir: *area (ha);* *volume (hm^3)*
Olivettes, 1988	255 ; 36 ; 80 000	40 ; 4,4
Riou, 1991	322 ; 26 ; 41 000	15 ; 0,8
Choldocogagna, 1992	100 ; 36 ; 19 000	11 ; 0,85
Sep, 1994	145 ; 46 ; 49 000	33 ; 4,7
Touche-Poupard, 1994	200 ; 36 ; 34 000	143 ; 15
Petit-Saut, 1994	740 ; 51 ; 250 000	31 000 ; 3 500

Numerous techniques were developed and used to carry out these works. For Riou dam: downstream facing with extruded concrete, including at the spillway; upstream facing using the supports of the future geomembrane as formwork for the RCC; galleries excavated with shovels, or with a tunnel-heading machine on RCC more than one month old; low-grade RCC made from aggregates without grading; construction during cold periods; partitioning of the working surface, allowing three layers to be made per day. Choldocogagna dam led to interesting results on the minimum dimensions of a structure compatible with an economically competitive RCC.

These experiences have shown that cooperation between project owners, designers and contractors constitutes a method that usefully shares responsibility, leads to good work quality and guarantees cost-efficiency.

Abroad, French engineers and companies have contributed to the evolution of the RCC technique (grout-enriched RCC, zoned dams, upstream/downstream facing design, spillway face design, inclined layers, etc.) on several iconic dams around the world (Figure 5.3).

Figure 5.3 – Some RCC dams designed by French engineering companies

Aoulouz (Morocco) – 1991
H = 75 m – V = 0,9 hm³
© TRACTEBEL

Tha Dan (Thaïland) – 2004
H = 93 m – V = 5 hm³
© TRACTEBEL

O. Mellegue (Algeria) – 2019
H = 51 m – pkweir + marches
© ISL – Luc Deroo

Tabellout (Algeria) – 2015
H = 121 m – V = 1 hm³
© TRACTEBEL

GIBE III (Ethiopia) – 2016
H = 246 m – V = 6 hm³
© TRACTEBEL

Souapiti (Guinea) –2020
H = 110 m – V = 4 hm³
© TRACTEBEL

2. JUSTIFICATION AND MAINTENANCE OF EXISTING DAMS

2.1 A Standard Set of Justifications: the CFBR Guidelines

The justification of gravity dams on the basis of the double observation that French practices in terms of justification of these dams were heterogeneous and that the professional references available also presented noticeable differences between them. The final version of the guidelines was published in 2012 and translated into English: http://www.barrages-cfbr.eu/IMG/pdf/recommandations_cfbr_2012_poids.pdf.

These guidelines adopt the format of semi-probabilistic methods with limit states, like the Eurocodes, which constitute a standard well adapted for harmonizing practices. These guidelines form part of a coherent set of professional guidelines concerning dams and dikes, relating to the justification of the stability, the seismic risk, and the design of spillways.
These guidelines successively examine design situations, actions and combinations of actions, material strength properties, limit states and limit state conditions.
Design situations are classified into several categories differentiated by the time interval during which the distributions of all the data (actions, resistances) are considered constant:

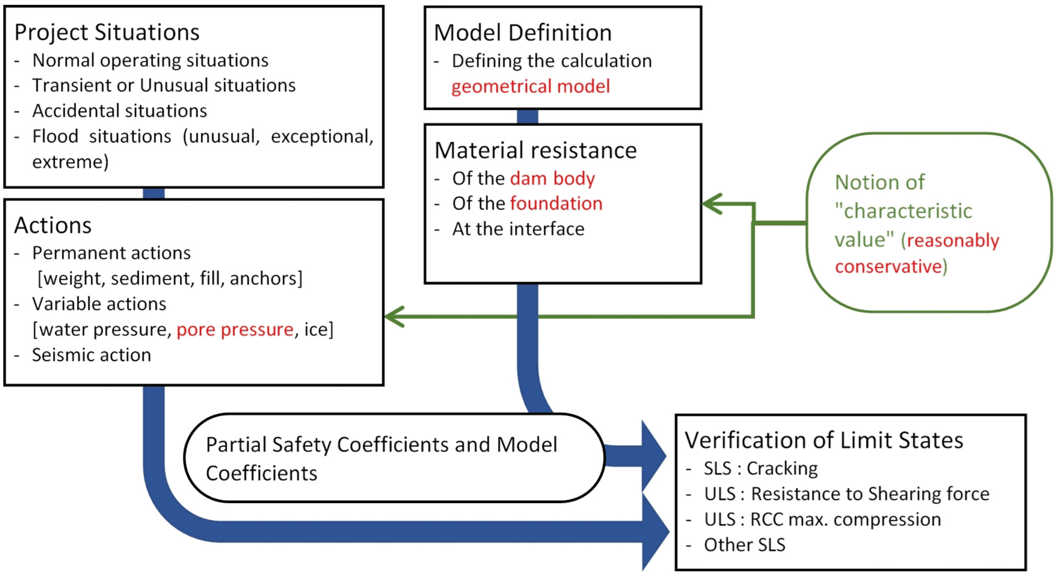
- normal operating situations;
- transient or unusual situations: temporary operating conditions or fairly high probability of occurrence;
- accidental situations;
- flood situations, where it appeared necessary to introduce specifically:
  - unusual flood situations (for flood control dams);
  - exceptional flood situations (corresponding to reaching the highest water level – HWL);
  - extreme flood situations (beyond which the integrity of the structure would no longer be guaranteed).

The materials' strength properties as well as the permanent actions are considered in the calculations using their characteristic values, that is to say a conservative estimate of the strength value or the intensity of the action. The conservative estimate therefore calls on the expert's judgment, based on available test results and / or based on guideline values from the literature.
The variable actions of water and the accidental seismic action relate to the design floods and earthquakes, by methods described in other volumes of the CFBR Guidelines.
The stability of gravity dams is justified for different limit states, differentiating the following SLS (Serviceability Limit States) and ULS (Ultimate Limit States):

- lack of resistance to shearing force;
- stress at the upstream foot and extension of the cracks from the upstream face;
- lack of compressive strength.

For each limit state, we write a limit state condition, which involves actions, strength properties (weighted by a partial factor – noted γ_m – taking into account the uncertainty on the knowledge of the property) and a model factor (γ_d). The model factor considers all the other uncertainties, in particular the uncertainties relating to the hydraulic model and to the limit state model.

Figure 5.4 – Method for gravity dam stability assessment (with main issues listed in red characters)



For example, the limit state condition for the lack of resistance to shearing force on a dam section is as follows, for each design situation:

$$[C\kappa / \gamma_{mC} . L' + N'.(\tan\varphi)\kappa / \gamma_{mtan\varphi}] > \gamma_{d1} . T \quad (1)$$

with:

- $C\kappa$ and $(\tan\varphi)\kappa$ characteristic values of cohesion and tangent of sliding angle;
- L', non-cracked length on the considered section;
- N and T, the normal and tangent components of actions on the considered section;
- N' = N-U, with U the resultant of pore pressures on the considered section;
- γ_{mC} et $\gamma_{mtan\varphi}$ partial factors affecting strength characteristic values;
- γ_{d1} the model factor related to lack of resistance to shearing force limit state.

The values to be adopted for the partial factors affecting strength characteristics and for the model factors are as in the following table.

Table 5.2 – Partial factors

Combinations	Persistent & transient	Unusual	Accidental / Extreme
γ_{mC}	3	2	1
$\gamma_{mtan\varphi}$	1,5	1,2	1
γ_{d1}	1	1	1

2.2 Assessment of old dams

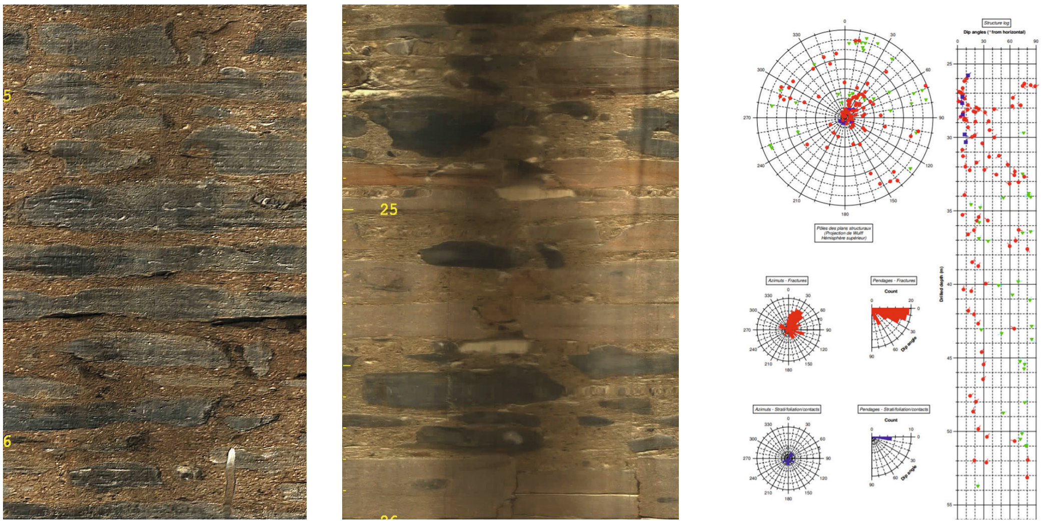
Many French gravity dams are remarkable for their age. Together, they offer a unique perspective on the issue of aging and the life span of these structures with some 50 masonry dams over 150 years old, and several concrete dams over 70 years old.
Questions have been raised about the aging of these structures and their ability to withstand extreme stresses, such as earthquakes. These are not simple questions, due to the variability of the materials and the construction methods used, illustrated, for example, by Figure 5.5 at Rochebut dam (1909) and Chazilly dam (1837).

Figure 5.5 – Heterogeneity of block size and mortar filling, Rochebut & Chazilly /
© ISL Olivier Lapeyre

Recent progress in investigation methods improves the quantification of the characteristics of ancient masonry.

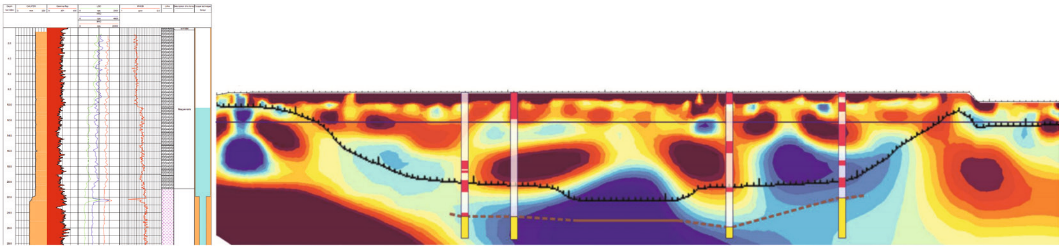
Large-diameter drillings are usefully complemented by imaging providing: automatic logging of discontinuities and the quality of the bonding between the dam body and the foundation (Figure 5.6).

Figure 5.6 – Imaging in drill holes, Pont-et-Massène dam / © Lim Logging



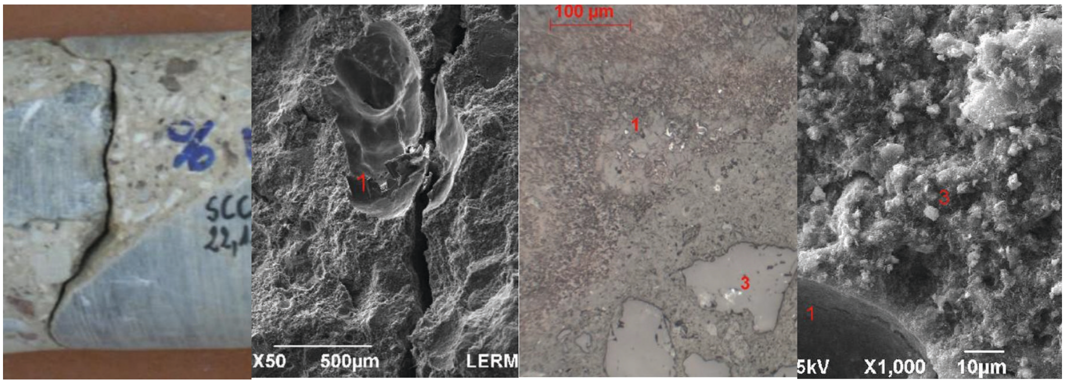
Geophysical methods are becoming more accurate. Seismic or electrical tomography (Figure 5.7) provides a qualitative image of the entire dam body. Gamma probes are sometimes successful in providing density profiles.

Figure 5.7 – Gamma density profile and tomography, Pont-et-Massène dam /
© Lim Logging et Soldata



Masonry dams are suspected of deteriorating with age due to the dissolution of the lime contained in the binding mortar, with several consequences: loss of density, increased leakage, loss of mechanical resistance.
Many French dams have been examined in order to detect possible aging: observation of cores, measurement of the density of the masonry or mortar, mineralogical analysis, scanning electron microscope to observe the microstructure of the mortar (Figure 5.8). The evaluation of aging by combining these different approaches, remains in the field of expertise, to separate the initial heterogeneity of the material and the possible evolution by aging.

Figure 5.8 – Aging: multiscale examination / © LERM



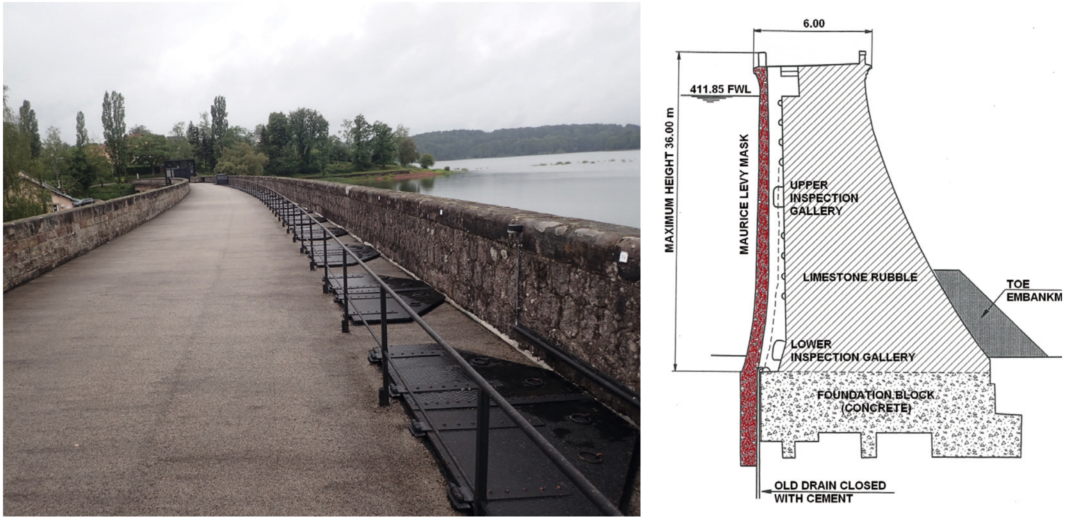
2.3 Rehabilitation and reinforcement projects

Several French gravity dams have been the subject of rehabilitation and upgrading operations. The motivations for these operations were varied; only those intended to improve stability conditions (excluding flooding) are described here.
At the beginning of the 20th century, several dams were upgraded following the Bouzey and Grosbois failures through instability on the foundation or in the body, the primary cause of which was the development of interstitial pressures. The upgrading option consisted of creating a watertight upstream facing (“Lévy facing”) or mechanically reinforcing the dam: buttresses, downstream embankment.
Over the past twenty years, several necessary upgrading operations have been implemented thanks to the French guidelines, which have enabled the most sensitive dams to be better identified.

2.3.1 Sealing of the upstream facing: from the Levy facing to the geomembranes

Several masonry dams that were too slender were reinforced at the beginning of the 20th century using a non-reinforced concrete mask (Figure 5.9). This solution is very modern in its design: it allows the masonry to be taken out of water and a gallery to be set up at the upstream toe of the section; all the dams equipped in this way have performed well up to now. Unfortunately, it is a little costly.

Figure 5.9 – Ban de Champagney dam – the Levy facing: a century-old sealing solution / © ISL



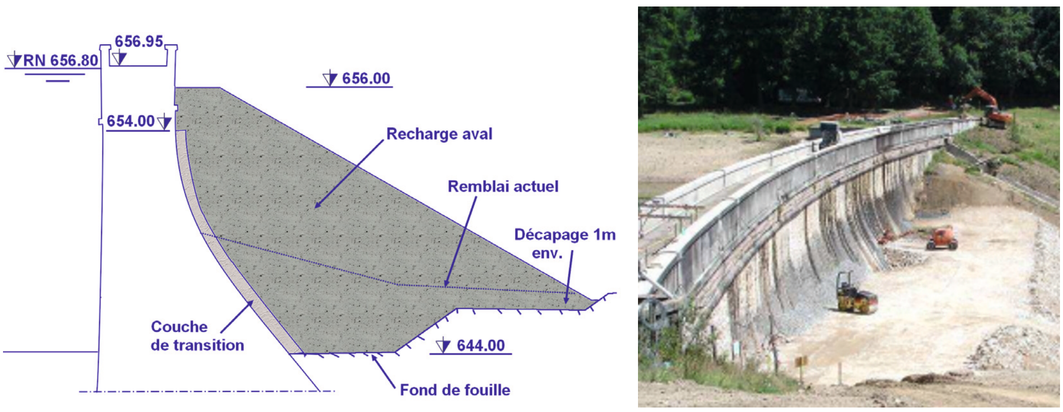
In France, as elsewhere, the development of geomembranes has brought back to the forefront the possibility of protecting masonry against seepage.

For smaller dams, the traditional techniques retain their interest: repair of masonry joints at the upstream facing, completed by skin low-pressure grouting, produces good results, provided it is carried out by qualified workers.

2.3.2 Downstream abutment: buttresses, embankments

When dams are not too high, the addition of a downstream embankment provides stabilizing thrust. Alternatively, the addition of a concrete backfill against the dam reduces stresses in the dam body and in the foundation.

Figure 5.10 – Gimond dam – Typical profile and view during construction work / © TRACTEBEL



Stabilization by a downstream rockfill has been carried out on six dams over the past 35 years. For downstream backfilling, experience leads to recommending the use of a 0–400 mm rockfill. This typical gradation optimizes the slope of the embankment in comparison to earth material and provides a greater stabilizing force compared to larger rocks.
Buttress or concrete gravity structure reinforcements have regularly been considered, always with the aim of ensuring a "monolithic" resulting structure through a good and lasting bonding between the old and new concrete.

Figure 5.11 – Rassisse dam, stabilization by concrete backfill (left: before; right: after) / © ISL – Anthony Dols

2.3.3 Prestressing

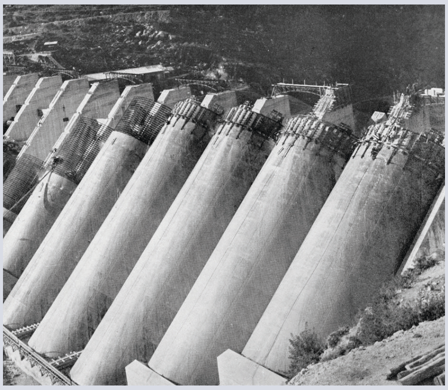
France has been a pioneer in the use of prestressing, thanks in particular to the contributions of Eugène Freyssinet and André Coyne.

The use of prestressing is still active today for new or ageing hydraulic structures. Significant progress and innovations have been made in the field of cables and bars, corrosion protection, post-tensioning, and instrumentation. Pathologies identified and analyzed have led to process improvements.

Post-tensioned geotechnical anchors can provide a suitable solution for stabilizing, reinforcing, rehabilitating or raising dams while minimizing the impacts on hydro operation and environment, particularly those related to reservoir emptying, and optimizing costs.

EUGÈNE FREYSSINET (1879–1962)

Eugène Freyssinet
© Association Eugène Freyssinet



Beni Bahdel dam
© Association Eugène Freyssinet

On October 2nd, 1928, Eugène Freyssinet, after promoting mechanical vibration of concrete and concrete curing, filed a patent along with his colleague Jean Seaille for a "process for manufacturing reinforced concrete parts". This patent describes a pre-tensioning system by means of adherent wires, using hard steels with a high yield strength, suitable for the construction of concrete beams, pipes, and frames.

Between 1925 and 1930, the construction by the "Société Limousin et Compagnie – Procédés Freyssinet" of the Albert-Louppe Bridge crossing the river Élorn at Plougastel, with three concrete arches with a span of around 136 m (a world record at that time), confirmed Eugène Freyssinet's experimental results relative to delayed deformations of concrete.

Between 1937 and 1941, Eugène Freyssinet developed the flat jack and used it in Algeria, in partnership with the Campenon Bernard Company, to impose compression on the slab of the Iron Gates dam and to apply a stabilizing force at the base of Beni Bahdel dam, through the buttresses. Eugène Freyssinet would use this technology on many other structures around the world.

On August 26th, 1939, Eugène Freyssinet filed a patent for "tensioned cable systems for the construction of prestressed concrete structures". This process uses reinforcements made of parallel tendons, tensioned by special cylinders, and then blocked by anchoring cones.

Several operations to stabilize gravity dams (Lampy, Pontabouland, La Roche, Chardes, Jouseau, Malarce, Sainte-Marguerite…), or the gravity abutments of arch dams (Rassisse, Pont-du-Roi, Bazergues, Bimont, Maury…) or the dam abutments (Laouzas) have been carried out in France in recent years [Veylon, 2018]. The use of prestressing for these structures with a long service life has required and appropriate design, including, in particular: the choice of steel grades, proper consideration of the relaxation effects, control of the local stresses on the concrete, protection against corrosion for service lives exceeding 100 years, instrumentation to allow monitoring and the possibility of re-tensioning if necessary.

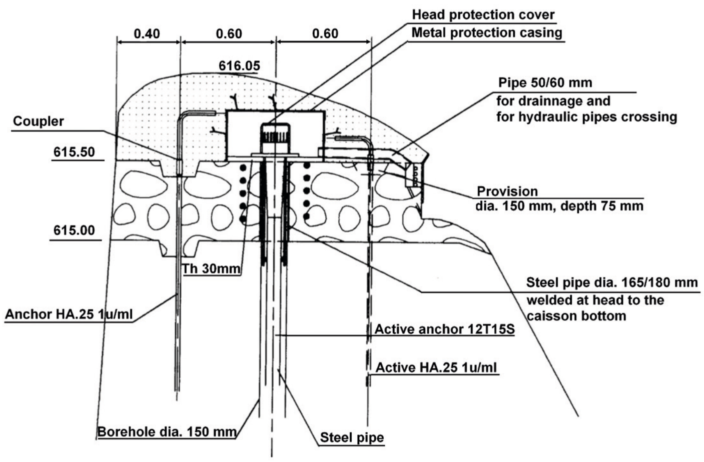
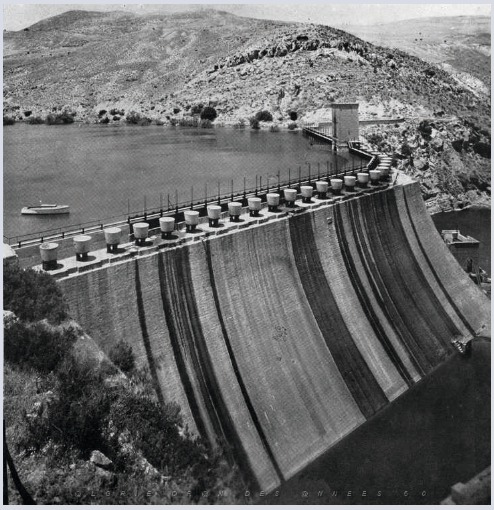


Figure 5.12 – Pontabouland dam – typical cross-section of the crest / © EDF

ANDRÉ COYNE (1891–1960) AND PRESTRESSING

© Jean Coyne



Cheurfas dam
© www.tenes.info

For nearly thirty years, André Coyne was a major figure in the field of design and construction of large dams, i.e. about 100 dams including 55 arches. His profound conviction that each structure must be designed to fit closely with the site while minimizing its cost and preserving its architectural beauty gave an exceptional impetus to the field of dams.

André Coyne met Eugène Freyssinet on the Albert-Louppe Bridge construction site. From their exchanges, the idea of using prestressing in hydraulic structures was born.
On July 1st, 1929, André Coyne filed a patent synthesizing several new ideas relating to the use of prestressed cables of high service tension, anchored in the foundation and designed to stabilize dams.

In 1931, he implemented this idea for the first time on the Cheurfas dam site in Algeria, where 37 tie rods consisting of cables stretched with a force of 1000 tons were installed as part of the operation to raise the structure.

Between 1930 and 1935, the construction of the Marèges dam in the Upper Dordogne, France and the first double-curvature arch dam in Europe, gave André Coyne the opportunity once again to use post-tensioned cables with a tensile strength of up to 500 tons. These anchors provide a stabilizing force to the left bank abutment that houses the spillway. In France, this type of anchoring would be used by André Coyne on the multiple arches of Saint-Michel dam, the abutments of the Maury dam, or to reinforce the rock abutments of Castillon and Chaudanne dams. Other works designed by André Coyne in France also use prestressing for various reasons, including the dams of Bort-les-Orgues, l'Aigle, Chastang, Grangent and Yaté.
André Coyne was President of ICOLD (1946–1952).

2.3.4 An exceptional operation: the reinforcement of Chambon dam

[Chulliat, 2013] presents the case of Chambon dam, a 90 m high gravity dam, subject to a major alkali-reaction phenomenon, likely to affect its integrity under earthquake conditions.
A first rehabilitation operation was carried out in the 90s: grouting of cracks, concrete backfilling of the surface gated spillway (replaced by an underground spillway), a waterproofing membrane and sawing of the concrete.
The assessment of the structure, carried out between 2007 and 2010 on the basis of specific investigations and a finite element calculation based on the monitoring results, highlighted in particular: continued swelling, that was not slowing down; the development of a state of internal stresses with potential harmful consequences; evolutionary cracking.
This led to a second reinforcement operation, recently completed, with:

- the installation of 415 horizontal prestressed tie rods crossing the structure from upstream to downstream, including a tension adjustment device;
- supplemented by a carbon fiber net on the upstream face, the function of which is to retain the small blocks not pinned by the tie rods and to distribute the pullout force of the tie rods;
- 7 new diamond wire saw lines 16 mm in diameter;
- replacement of the 1990 waterproofing membrane, which had to be removed to allow the work to be carried out; an operation accompanied by a thorough assessment of the durability of the 1990 membrane.

Figure 5.13 – Chambon dam, works in 2014 /
© EDF – François Taule

3. A FIELD WITH ACTIVE RESEARCH

3.1 Current topics

As far as gravity dams are concerned, there are many current research topics in France. For example:

- at the border between gravity dams and embankment dams: hardfill dams and cemented soils (see § 3.2);
- assessment of earthquake resistance (see § 3.3);
- assessment of concrete dams under extreme flood conditions, including overtopping;
- numerical simulation including couplings (hydro-mechanical, thermo-mechanical);
- AAR and internal sulfate attack: understanding mechanisms, modeling;
- improved understanding and assessment of mechanical parameters at the dam-foundation interface;
- evaluation of the contributions of probabilistic calculations and approaches considering uncertainties;
- understanding of the behavior of coupled dam-anchors and assessment of the gains provided by passive anchors;
- investigation methods (see in particular § 2.2).

A focus is made below on two topics that have been active for many years and always bring new developments: hard embankment and the numerical modeling of gravity dams.

3.2 Hardfill Dams and Cemented Soils

Figure 5.14 – Some Hardfill Dams using French Technology

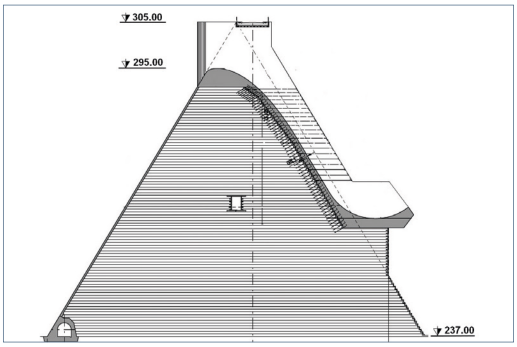
Marathia (Greece) – 1993:
1st dam hard embankment; H = 31 m
© M. Dunstan

Koudiat Acerdoune (Algeria) – 2009
H = 121 m
© TRACTEBEL

Saf–Saf (Algeria) – 2010
H = 36 m
© ISL Thibault Guillemot

Rizzanese (France) – 2012
H = 41 m
© EDF

Wadi Umti (Oman) – 2014
H = 23 m
© Artelia

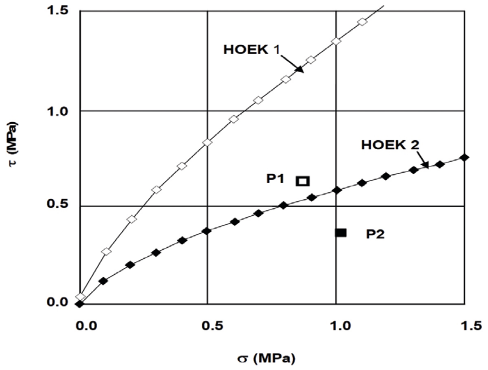


Mellegue (Tunisia) under construction
H = 70 m
© ISL

In 1992, in the continuity of tests and reflections initiated within the BaCaRa research program, Pierre Londe and Michel Lino proposed a design for hardfill dams (Faced Symmetrical Hardfill Dam). By 2016, more than 50 such dams had been built worldwide, some of which are illustrated in Figure 5.14.

The success of this French innovation stems from advantages identified as early as 1992:

Figure 5.15 – Stability of gravity dams on poor foundations (h = 100 m)



Advantage 1: FSHD can be built on poor foundations.
The diagram in Figure 5.15 shows typical curves for a good quality rock (Hoek 1) and a poor quality rock (Hoek 2). It also shows the stresses imposed by a conventional gravity dam (P1) and a FSHD (P2).

The load diagram of a FSHD upon the foundation is much more homogeneous than that of a conventional gravity dam and there is also relatively little difference between an empty and a full dam.

This theoretical result is confirmed in practice. FSHDs were built on foundations of soft marl, loosely cemented sandstone, weathered granite, siltstone and argillites.

Advantage 2: FSHD uses site materials and little cement.
The compressive strength required for hardfill is low, a few MPa, and the shear stresses are also low. This makes it possible to envisage aggregates of lower quality than those specified for a classical RCC: alluvium with a significant content of fines; weathered rocks, soft rocks. The cement content can also be reduced. This principle of economic design was adopted as early as 1995 for Rizzanese dam in Corsica, which was not finally built until 2012, but in compliance with the original project.

Advantage 3: FSHD is adapted to extreme loads.
Resistance to earthquakes and exceptional water levels is good: the trapezoidal profile avoids excessive shear stresses under extreme loads. During construction, a possible flood submerging the dam can be tolerated.

The success of the FSHD has led to new ideas, regarding other possible new dam materials, in particular the reuse of fine materials (silt, clay) enriched with lime or cement to form a resistant material.

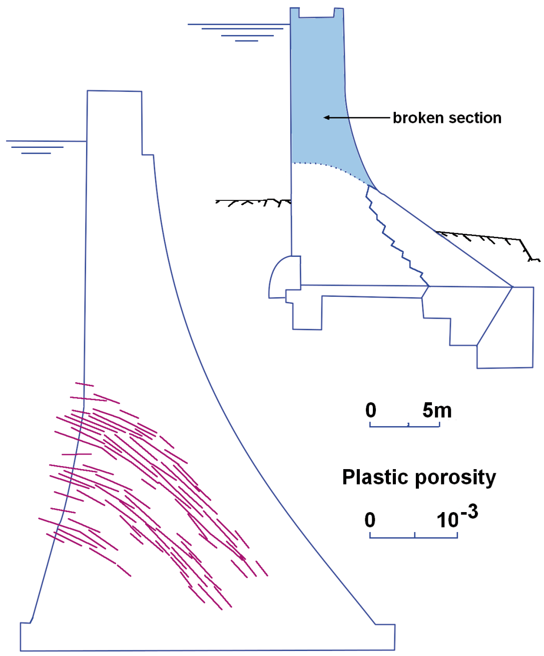
This observation led to a collaborative R&D project: "DigueElite". The project brings together a variety of stakeholders: research institutes, project owners, engineers, and the material

Figure 5.16 – DigueElite; full scale test / © INRAE

processing industry. Each of the stakeholders contributes to the research through financial or in-kind contributions. The French government and local authorities support the research effort by making substantial financial contributions. This work was rewarded with an innovation prize during the ICOLD congress in Vienna in 2018. Regarding the DigueELITE project, we can also refer to chapter 7 § 2.9 and chapter 9 § 4.5.4.
Research into the possible formulations, laboratory tests and a full-scale test have demonstrated the benefits: the treatment provides cohesion and compressive strength and provides resistance to internal and external erosion. Research and development continue in France (construction of a research platform) and within the ICOLD community (Technical Committee P "Cemented Embankment Dams") with a highly active contribution from the French participants.

3.3 Numerical Modeling

Figure 5.17 – Comparison between cracking estimated by a poroplastic model and the failure surface observed at Bouzey dam



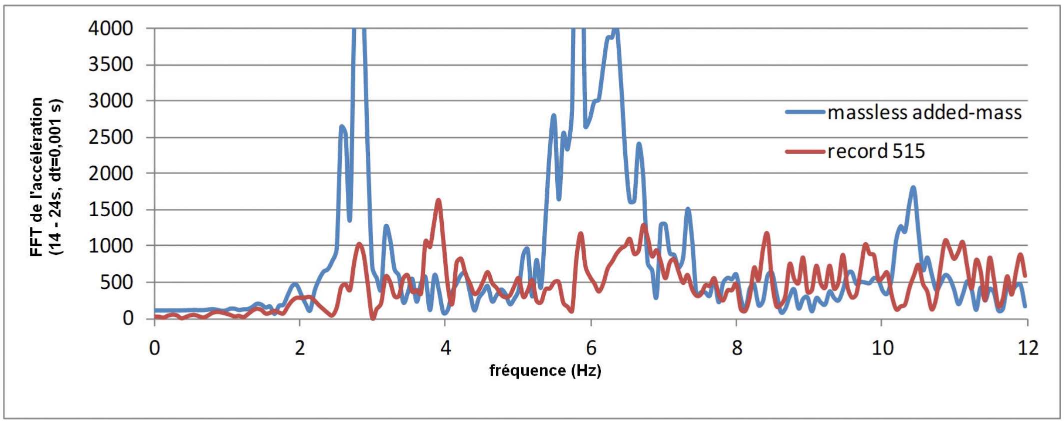
To avoid the a priori choice of a failure surface and to include the full physics of a failure, the development of poroplastic-type models [CFBR 1994] was initiated in the 1990s. It aimed, for instance, at representing the failure of Bouzey dam in 1895 [Carrère, 1990]. This type of model is based on a continuous representation of a saturated porous medium, with potentially cracked concrete.

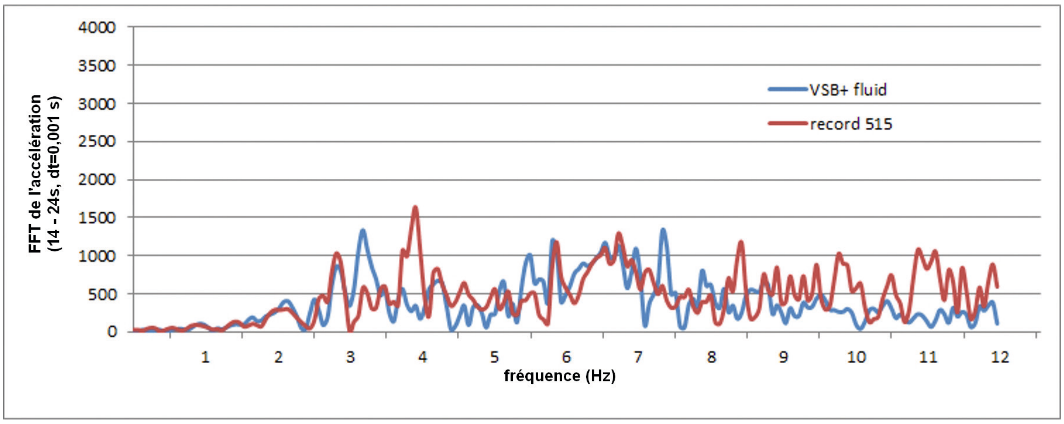
For concrete cracking, a criterion of plasticity is retained, expressed as a function of the main stresses and the pore pressure. The permeability varies anisotropically according to the tensor of the plastic deformations.

In the field of earthquake calculations for concrete dams, a major development effort has been made by French engineering firms. Initially in the 1990s, with the development of simplified methods for the pre-dimensioning of gravity dams [Tardieu, 1993], then 20 years later within the framework of the French-Japanese cooperation [Fry, 2018] on the seismic behavior of dams and their equipment. The latter was published in a book [ICOLD, 2017] synthesizing the contributions and knowledge shared during this collaboration.

In the specific field of numerical modeling of concrete dams, it demonstrated the relevance of using advanced numerical methods taking into account water compressibility, foundation inertia and absorbing boundary conditions in order to correctly represent the seismic behavior of Japan's Tagokura dam, recorded by accelerometers. These models provide results that are much closer to the records than conventional models (i.e. with massless foundation and Westergaard's added mass), see Figure 5.18.

Figure 5.18 – Comparison of horizontal accelerations, measured (red) and calculated (blue) for two calculations: on the left, the classical calculation (massless foundation; reservoir modeled by added masses), on the right a modern calculation including: water compressibility, inertia of the foundation and absorbing boundary conditions





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CHAPTER 6

ARCH DAMS

The dam portfolio of France is richly endowed with arch dams, with some hundred structures, mainly built between 1935 and 1980.

1. THE DEVELOPMENT OF ARCH DAMS IN FRANCE

1.1 Forerunners

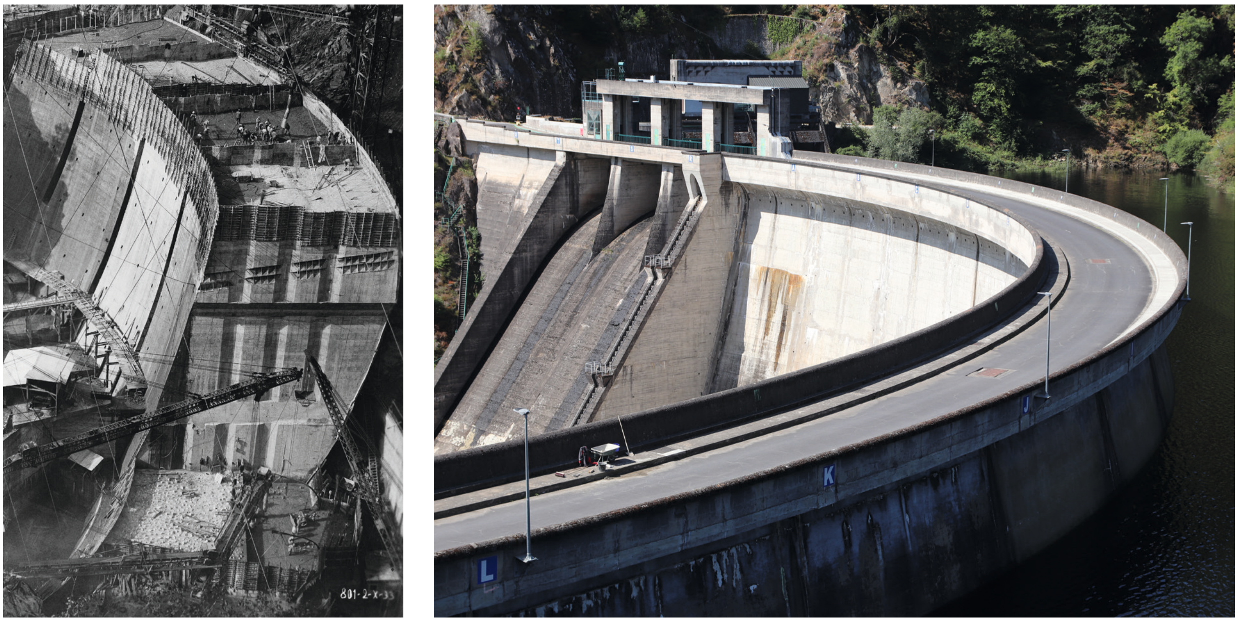
Traces of the first arch dam can be found in Martinique: 8 meters high and about 40 meters wide, Latouche dam (now completely out of water) has a marked curvature downstream and is supposed to have been built in 1716. Zola dam, located near Aix-en-Provence and still in operation, is the dam that marks the arrival of this type of structure in metropolitan France. 43 m high, it is built of masonry and was impounded in 1852. Although the tube formula was already established at that time (experimentally by Mariotte in 1673, demonstrated by Navier in 1826), it seems that the dam was designed in consideration of the rocking stability of its cantilevers, with only empirical consideration of the arch effects.

Actually, the introduction of arch dams in France came with the small Savenay dam, between Nantes and Saint-Nazaire, built in 1917 by the US army which had just entered the First World War, to provide their military hospital with water. This modest structure of an unprecedented shape in France, built of concrete, still a new material, would in the following years, excite government's civil engineers who were in charge of developing hydroelectricity in France. Among these, André Coyne, in charge of monitoring the dam, took inspiration from it when he came to design Pont-Rolland dam in Brittany, a very thin arch whose aim was to "test high rates of fatigue".

With the fitting out of the river Truyère in the Massif Central, Bromme dam (H = 42 m) commissioned in 1932, really marked the beginning of the construction phase of hydroelectric arch dams. Marèges dam (H = 90 m, 1935), which closely followed, would become the reference for all those that came afterwards. On this double-curvature structure, André Coyne developed the calculation method by plunging arches. The dam is characterized by several innovations: a typical double-curvature shape (with a system of supports to stabilize cantilevers in empty reservoir conditions), a ski jump spillway and an abutment block stabilized by active anchors…

After starting before the Second World War and continuing as best it could during the occupation, the French hydroelectric development program resumed in 1946 with the creation of "Électricité de France" (EDF). Many sites were in the mountains, in relatively narrow valleys where both topographical and geotechnical conditions are favorable to concrete structures, especially arch dams. The experience gained at Marèges was used for the design and construction of many hydropower plants. This development was mainly carried out through the cooperation between the EDF departments and the consulting engineering firm Coyne et Bellier, created in 1947 by André Coyne precisely for this purpose.

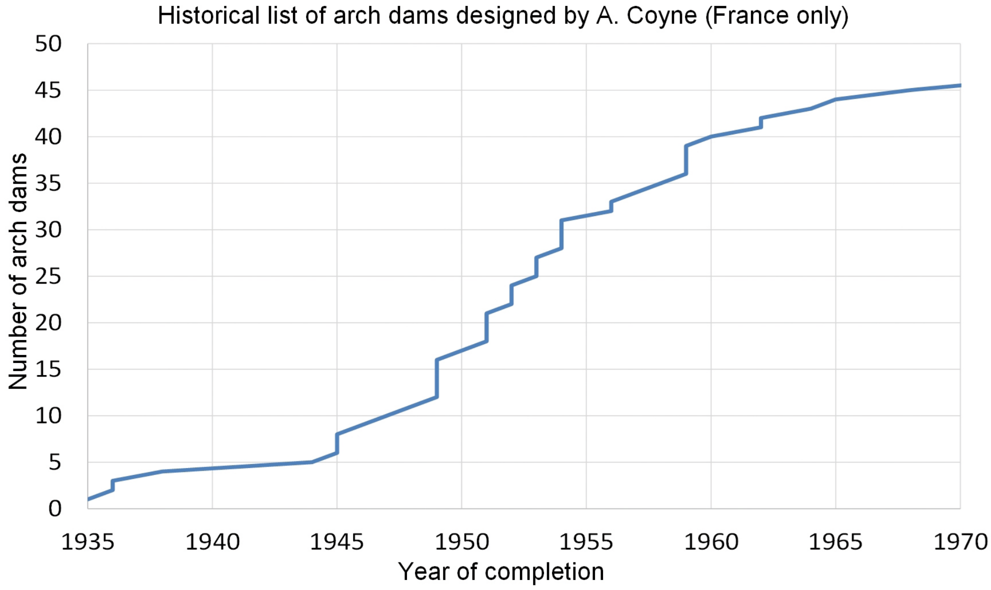
Figure 6.1 – Marèges dam / © SHEM & SHEM-Sophie Le Scaon



1.2 Arch dams in the French electrification program

Figure 6.2 shows the increase in the number of arch dams commissioned, designed under the direction of this engineer, mostly between 1935 and 1973; some of these works are aimed at supplying water to cities, however most of them are part of hydroelectric schemes; to be complete, the arch dams designed by other engineers would have to be added; the implementation rate appears to have reached almost 3 schemes per year between 1950 and 1960.

Figure 6.2 – History of commissioning arch dams designed under the direction of André Coyne



ANDRÉ COYNE (1891–1960)

André Coyne was born in Paris in 1891. Just after graduating from the École Polytechnique and École Nationale des Ponts et Chaussées, he participated in the 1914–18 war. His professional career began in Brest, in the State civil services in charge of maritime works. Appointed a member of the Large Dams Commission for the General Council of Bridges and Roads in around 1925, he was put in charge of monitoring the small Savenay arch dam, built in 1917 by the U.S. Army, near Donge. It was an opportunity for him to discover the technology of arch dams, already well developed in the United States, which he saw as a very promising solution. From then on, his career would be to develop France's energy development policy, aiming to gradually replace coal with hydroelectric power ("houille blanche" = "white coal"), through to the 1970s. Appointed as head of the development planning department for the Upper Dordogne in 1928, he designed Marèges dam, which at that time was the largest arch dam in Europe. The great merit of André Coyne is to have brought order and simplicity to its construction by affirming principles which he kept to until the end of his career: prudent innovations based on the observation and evaluation of precedents, optimization of the dam with its associated structures, a search for simplicity of form that would facilitate construction and reduce delays and costs.

In addition to his direct role in the development of the Dordogne schemes, M. Coyne took over the management of the Large Dam Technical Department, a new department tasked with "building and maintaining technical documentation on the distribution of electrical energy, the development of rivers and in particular large dams…".
André Coyne was also a professor at the École Nationale des Ponts et Chaussées. When the Second World War was declared, he recruited his students as trainees at Aigle arch dam construction site in the Massif Central to prevent them from being deported to Germany. This project progressed at such a slow pace that it was not completed until the end of the war.
After the war, the country's hydroelectric equipment resumed with the creation of EDF. André Coyne left the senior position he held in the French administration to embark at the age of 56 on a new adventure, founding the engineering firm ACJB in 1947, surrounded by a very young team, some of whom were his students from the École Nationale des Ponts et Chaussées. His first projects were dedicated to EDF's hydroelectric developments, beginning with the ones started during the war in the Massif Central. Most were arch dams, designed, calculated, and built at a rate of 2 to 3 per year. In addition, there were projects for multiple-arch dams, then embankment dams, again benefiting from American experience. André Coyne's field of activity then expanded, first to works for other purposes than hydropower in France, then abroad (Portugal, Maghreb, South Africa, China…). He soon became known outside France, thanks in particular to his involvement in creating (in 1928) the International Commission of Large Dams, for which he was president from 1946 to 1952.

© Jean Coyne

As a virtuoso amateur violinist, André Coyne was inspired by this art when he invented vibrating wire sensors and created the Telemac company to manufacture them.
A few months before his death, André Coyne learned of the Malpasset dam disaster at the end of 1959, but he would never know the precise reasons. His final recommendations to his collaborators would be to do everything possible to elucidate what he saw as a mystery, which they did indeed do in the following years.

In this series, the highest dam is Tignes dam in the Alps (H = 180 m, 1952).

Figure 6.3 – Tignes dam with night lighting: the highest French arch dam (180 m) /
© Alain Pellorce

From 1970, the rate slowed considerably, as the number of favorable sites decreased. The last arch dams built were Vouglans in the Jura (H = 130 m, 1968), Laparan in the Pyrenees (H = 106 m, 1985) and Puylaurent in the Massif Central (H = 73 m, 1996), whose hydroelectric function is only marginal.

Figure 6.4 – Puylaurent, the last arch dam built in France in 1996 / © EDF – Claude Fougeirol

1.3 The architecture of French arch dams

A dam is never invisible: it is a strong sign that must be as beautiful as its natural surroundings. The search for pure forms is not contradictory, quite the opposite, with structural efficiency. Some achievements are emblematic in this respect, one example being Roselend dam (H = 150 m, 1962), an unlikely combination of an arch / buttress dam, considered by many to be the most beautiful dam in the world.

Figure 6.5 – Roselend Dam: a fine example of integration into its natural environment / © Cervos/Urope

On a different level, efforts were made to combine the different components of a scheme, like at Aigle dam, where the narrowness of the site meant combining the hydropower plant, placed at the arch toe, and the spillway, with its ski jump chute and flip bucket just on top of the plant: these constraints resulted in an unmistakable aesthetic success.

Figure 6.6 – Aigle dam: an example of the integration of works / © BETCGB

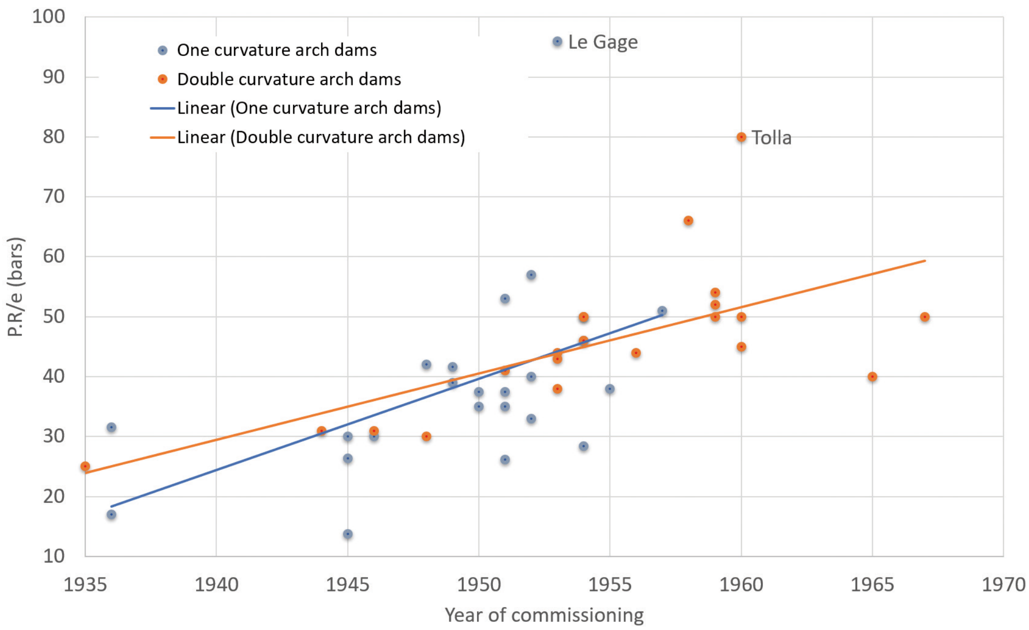
2. DIMENSIONING METHODS

2.1 Evolution of analytical methods

The first methods for analyzing and designing arch dams used two-dimensional modeling of horizontal arches. They come from bridge engineering, as André Coyne pointed out in his course at the École Nationale des Ponts et Chaussées: "An arch dam transfers most of the water's thrust onto the abutments by arcing effects. It's like a one-arch bridge that has been turned 90° upstream."

The formula of the so-called "P.R/e" tube (demonstrated by Navier in 1826) is the simplest, but the most widely used in pre-dimensioning because it has the quality of providing the average arc stresses. Figure 6.7 represents the values of the P.R/e for arch dams built to Coyne and Bellier designs from 1935 to 1967: there was an increase in reference values between the beginning of the period in the 1930s and the mid-1950s, when the value of 50 bars (5 MPa) was reached. Some excursions at higher levels correspond to experimental works (Le Gage, Tolla) or of particular design (Moulin Ribou).

Figure 6.7 – Average arch stresses (PxR/e) for French arch dams from 1935 to 1970



As soon as the relative thickness of an arch becomes important, moments of bending under the hydrostatic load result in tensile stresses downstream at the crown as well as upstream near the arch abutments. Hence the next step, which consists of virtually eliminating tensile areas that are not supposed to transfer any stress, by opening joints or cracks (Figure 6.8). This is the notion, which also comes from bridge engineering, of an active arch inscribed in the geometry of the real arch. The determination of tensile areas and the resulting extreme stresses is based on the studies by Résal and Pigeaud [Annales des Ponts et Chaussées, 1898] and is obtained, in practice, by a graphic method using the "Géhin protractor" (valid for a symmetrical arch on rigid supports, Figure 6.9). The maximum compressive stress is usually close to double the average stress in the original geometric arch. This dimensioning method, known as 'active arches', was used for the sizing of most arch dams in the 1950s.

Figure 6.8 – Thin elastic arc and active arch inscribed in a thick arc

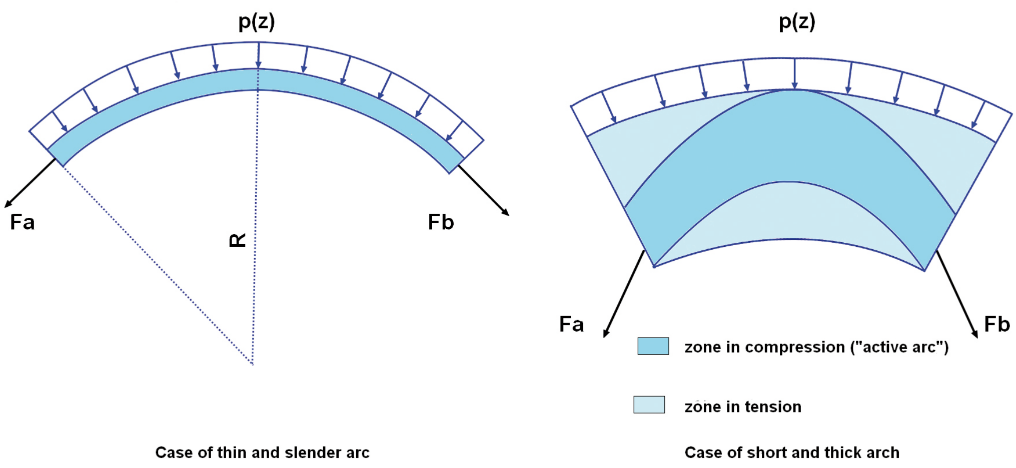
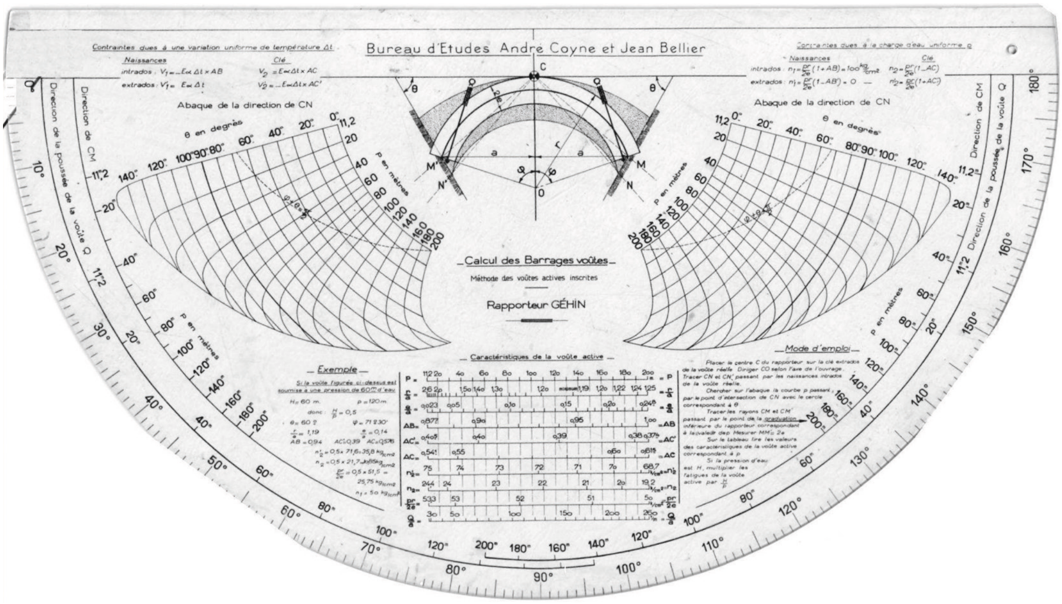


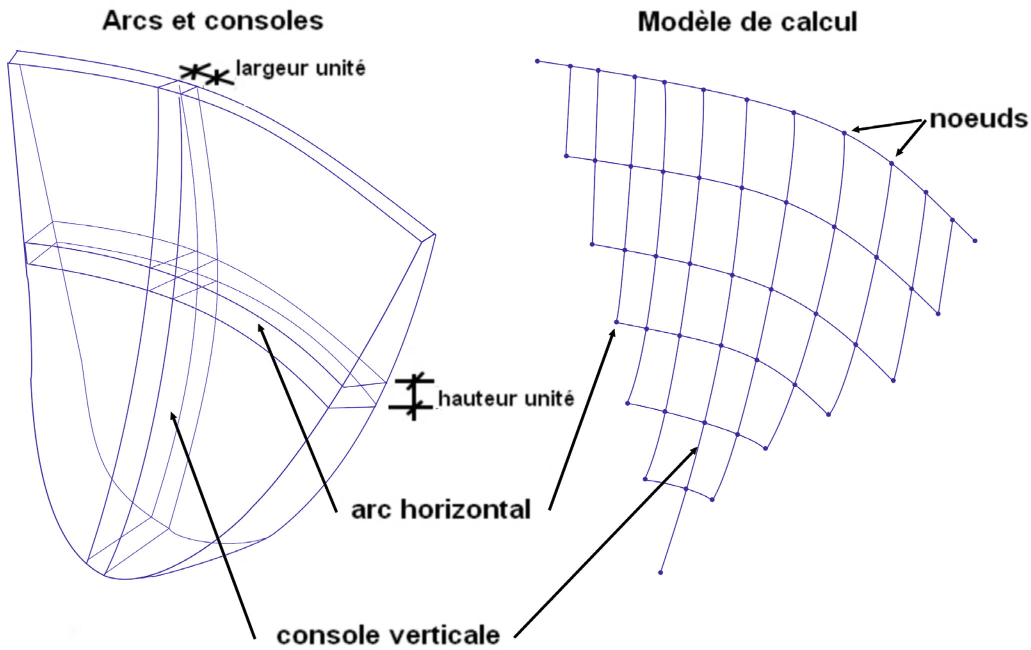
Figure 6.9 – The "Géhin protractor" used for pre-dimensioning in the 1950s



To complete this section on two-dimensional models, we must mention the notion of plunging arches: used for the design of the Marèges project (1935), it results from observing the stress distribution as it appeared on the downstream face of physical plaster models, widely used at that time, and as it would appear later with 3D digital models. This methodology was also used for the design of Roselend dam, in addition to physical models made of plaster and rubber.

Subsequently, dimensioning methods used in France were inspired by the first calculations with adjustment between the arches and the key cantilever, carried out in the USA by Visher and Wagoner in 1889, followed by Ritter in 1913. The principle is to distribute the hydraulic load between the horizontal arches and the cantilever crown, which is supposed to represent all the vertical links. The generalization to a collection of several vertical cantilevers led to the USBR's Trial Load (1938, Figure 6.10), which was completed by Mr. Leroy by adjusting the 6 degrees of freedom, which was made possible by computer calculation. The first application of this was Vouglans dam (H = 130 m, 1968).

Figure 6.10 – Principle and mesh for the Trial Load Method



From the 1970s on, the finite element method appeared, introduced in the field of civil engineering by O.C. Zienkiewicz. The new method rapidly fascinated many engineers and took over from everything that was done before. This method was used first for the design of the last French arch dams (Laparan, Puylaurent) and then, above all, to support the many French engineering projects carried out abroad. These include Sir, Turkey (H = 120 m, 1991); Gomal Zam, Pakistan (H = 133 m, 1993); Tekeze, Ethiopia (H = 180 m, 1998); Katse, Lesotho (H = 185 m, 1999); Xiaowan, China (H = 292 m, 2001); Berke, Turkey (H = 201 m, 2007)…

2.2 Experimental methods

In addition to improving numerical methods and gradually optimizing dam shapes through feedback, raising the theoretical average stress from 25 kg/cm^2 (Marèges) to more than 45 kg/cm^2 (La Palisse), two experimental structures were designed and built: Gage dam (H = 47 m, commissioned in 1954) and Tolla dam (H = 90 m, commissioned in 1961, Figure 6.11). These exceptionally thin structures were designed in such a way that the theoretical average stress was about twice that of other dams designed at that time: about 10 MPa for Gage and 8 MPa for Tolla.
Gage dam was operated for about ten years while being intensely monitored: the detection in November 1963 of a singular crack suggesting the existence of a shear mechanism led to the construction of a second dam, positioned few meters upstream (Gage II, Figure 6.12).
Tolla dam, as originally designed, experienced significant cracking from its first impounding, which was attributed to the high foundation rigidity and to underestimated thermal effects. Massive reinforcement using comforting rings, founded remotely to the dam's downstream toe in order to maintain a low-side operation of the structure during the works, was quickly put in place (Figure 6.12).

Figure 6.11 – Tolla dam – Initial design

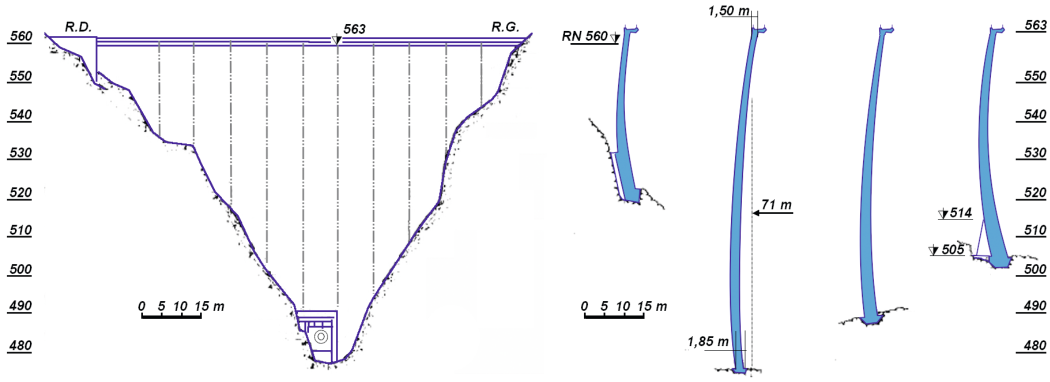
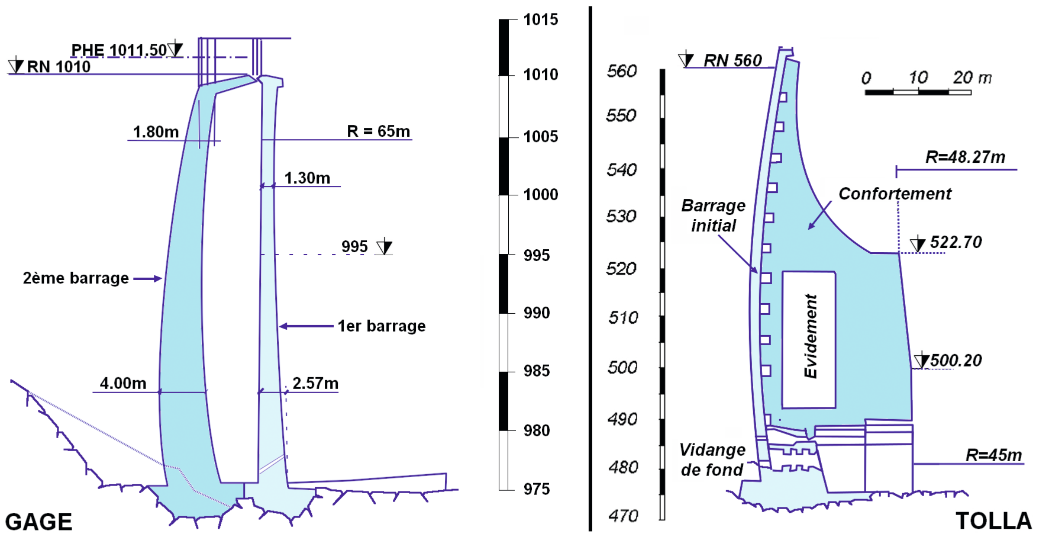


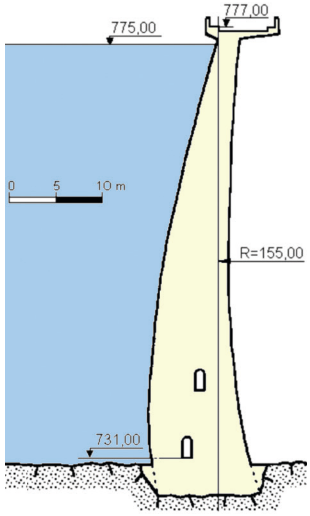
Figure 6.12 – Le Gage, double arch – Tolla dam after reinforcement



2.3 Arch dams in wide valleys

Perhaps more than anywhere else in the world, French engineers have worked hard to build arch dams in sites where the width made the design of structures complicated. The period of construction of a large part of the French dams just after the 2nd World War, with limited access to resources, probably contributed to the choice of these structures requiring less concrete.
The problem of these arch dams in wide sites is the tendency to develop tensile stresses and cracking in the upstream toe; this has added to the expertise of French engineers in this field, whether in analyzing behavior, monitoring, assessing the geological role or the design of remedial works.

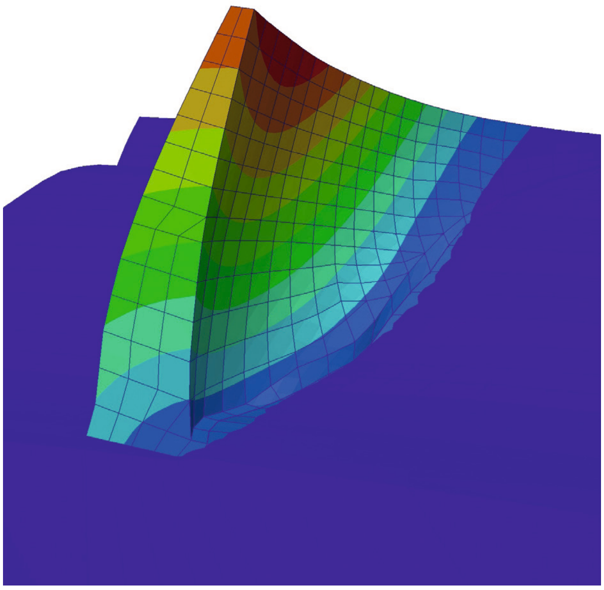
Figure 6.13 – Downstream view of Laouzas dam and vertical section of the key cantilever / © BETCGB



Among the works concerned by this problem, some of which have already been written about [ICOLD 2003], we can mention Laouzas dam (Figure 6.13), a 52 meter-high structure completed in 1965. Despite the presence of a horizontal joint located in front of the drainage gallery in the central blocks, the concrete-rock contact gradually opened from upstream to downstream due to thermal, hydrostatic effects combined with major concrete creep, resulting in the development of uplift pressure at the base of these central cantilevers.

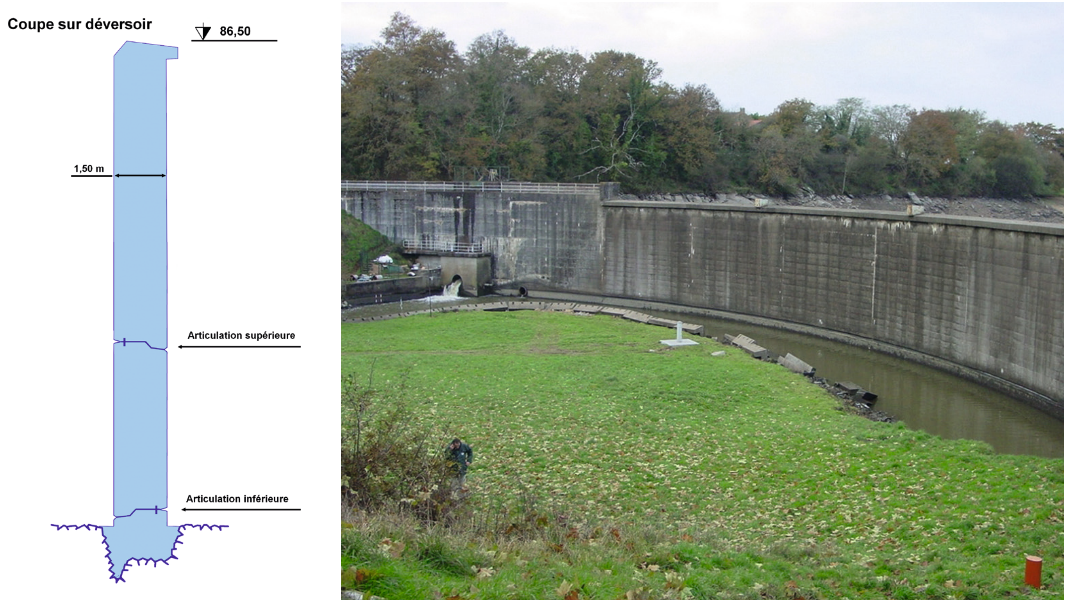
The reinforcement of the monitoring system, with in particular the implementation of numerous piezometers below the central blocks as well as at the downstream toe and many finite element analyses with non-linear constitutive laws and hydro-mechanical coupling at the concrete-rock contact, have made it possible to understand the mechanical operation of this structure better. These elements led to the reinforcement of the rock abutment at the downstream toe of the dam with a reinforced concrete beam cleverly housing drainage, pre-stress and monitoring devices (Figure 6.14).

Figure 6.14 — Laouzas dam: opening of the concrete-rock contact and reinforcement of the rock abutment at the dam's downstream toe / © EDF



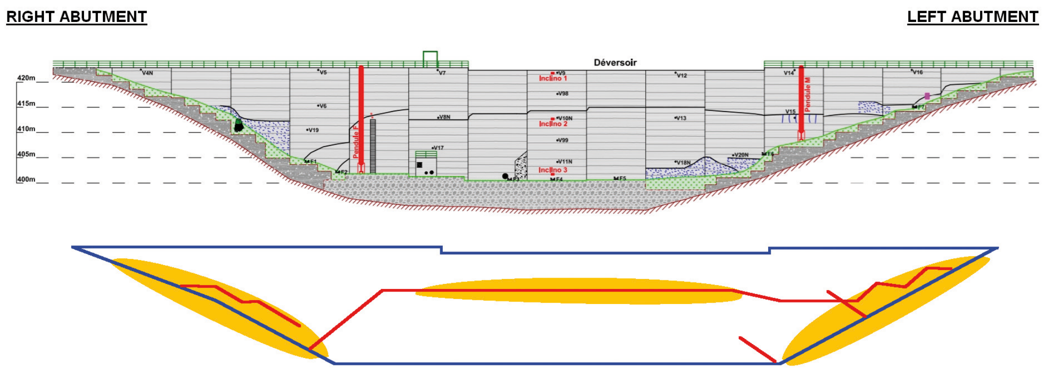
At least one French dam has been the subject of a particular design, aimed at giving it a pure arch operation: it is the small dam of Moulin Ribou near Cholet (H = 21 m, 1955), located in a very wide site. In this design the vertical transfer of stress by cantilever effect was completely neutralized by the creation of a double horizontal articulation (Figure 6.15).

Figure 6.15 – Moulin Ribou dam on the Moine river / *© Coyne et Bellier – Alain Carrère*



This relatively complex and expensive device worked perfectly in preventing the creation of cracks in the structure. But the same engineer, working on another very similar dam a few years later, chose to let nature create the free joints necessary for the proper functioning of the structure: this is Pont-du-Roi dam (King's Bridge, H = 27 m, 1959), in which a horizontal crack actually developed from the initial impounding (Figure 6.16), without any negative consequences…

Figure 6.16 – The Pont-du-Roi arch dam – Main cracks



2.4 Guidelines for justifying the behavior of existing arch dams [4]

2.4.1 But et composition du groupe de travail du CFBR

In line with the technical guidelines setting out the best practices for sizing and verifying gravity and fill dams, the CFBR has set up a working group to establish guidelines for existing arch dams.

This working group involved some fifteen people, including contractors, design engineers, experts, and government representatives. Among these members are several international experts who have been involved in the design of arch dams in France and around the world; their valuable contributions to this document are necessary to pass on to the current and future generations the fundamental principles of verification and monitoring of such structures.

The main objective of the projected guidelines is to provide a synthesis of best practices in arch dam verification, with a strong didactic purpose, and to propose methodological approaches and principles for performance evaluation for evaluating the safety of these works. The focus is put on existing dams and is a guide to assess, not to dam design.

The guidelines were developed on the basis of accidentology, international incidentology and observed behaviors, to infer the failure mechanisms specific to these dams. They also rely on certain problems that have particularly mobilized the French engineering forces in recent years, such as: stability at the toe of arch dams located in wide valleys, stability of unblocked abutment blocks under the effect of thermal and / or concrete swelling stresses, arch / foundation interactions, concrete creep and swelling, seismic resistance, etc. These studies have led to methodological developments in terms of non-linear modeling, hydraulic / mechanical coupling in cracks, considering thermal effects… The guidelines can be downloaded from the CFBR website at the following URL: https://barrages-cfbr.eu/IMG/pdf/recommandations_cfbr_2018_voutes.pdf (in French and English).

2.4.2 Summary of the Report

Only the most salient points of the guidelines document are included here.

General concepts

The chapter "General Concepts" is based in particular on the history of calculation methods and on accidentology. The analysis shows that only two arch dams have failed completely in the world: Malpasset in France and Meihua in China. Nevertheless, there have also been several incidents / accidents that have not necessarily led to total failures, but to releases of part of the reservoir, or to unwanted/deviant behavior.

The concept of "adaptation" was introduced to characterize the behavior of these highly hyperstatic works, in three levels:
- those that correspond to "normal" behavior of the structure, acceptable for sustainable situations;
- the states of adaptation leading to a gradual increase in local disturbances that do not call the overall stability of the structure into question;
- beyond that, the appearance of disorders that can lead to failure.

The difficulty in assessing the safety of the arches is in correctly estimating the limits of acceptability of these adaptations. The expertise of the geologist, the geotechnician, the civil engineer and the modeler proves decisive in answering this problem. The report is therefore above all a medium that helps to guide the experts in their reflection.

Foundations

The foundations are an arch dam's key safety element. Their main role is to take over the loads transmitted by the arch. It is necessary to emphasize the importance of:
- a geological and hydrogeological model of high quality;
- the detection of realistic exit kinetics, especially for rock wedges;
- a distinction between the different scales that describe the rock structure.

This can only be done by a geologist who is a specialist and competent in the field of dams.

From a geomechanical point of view, the report:

- takes the different types of modules into consideration (1st load, reversible, dynamic, irreversible), the determination of which depends on the evaluation method;
- emphasizes the need for a dialogue between the geomechanical engineer and the numerical analyst to carefully select the characteristic parameters: for example, the choice between peak or residual resistance;
- does not give guide values of shear parameter, but rather the right way to get them.

Concrete in arch dams

This chapter particularly deals with:

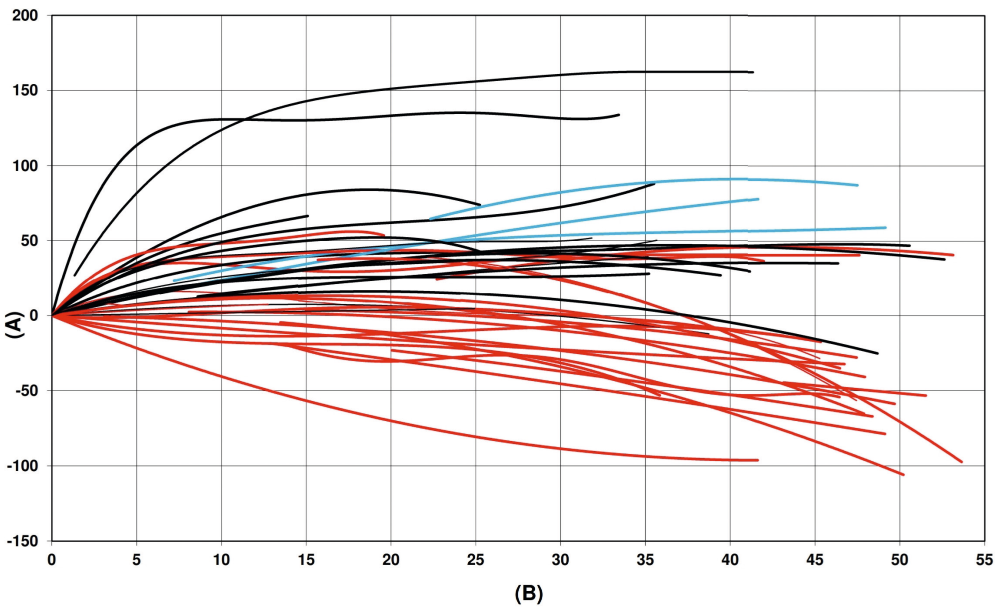
- the different tests and investigation methods available to determine materials characteristics;
- concrete behavior as well as irrecoverable phenomena (swelling, shrinkage, creep);
- concrete mechanical properties (thermal parameters, elasticity moduli, dynamic properties…). Some reference values are given.

Surveillance and monitoring

Reversible behavior of structures is of course mentioned; however, the focus is particularly directed towards irreversible behaviors (shrinkage, swelling, creep, abutment movements, change of thermal or operating conditions. Broad feedback on the known behavior of arch dams through monitoring is proposed, especially based on engineering works [CFBR 2018].

Figure 6.17 shows an analysis carried out on arch dams of EDF in 2003 [Fabre, Bourdarot, 2003]. Based on this feedback, the report provides guidelines on possible monitoring and testing devices corresponding to the mechanisms identified. The report also presents the statistical and more specific methods (developed in recent years) used in France.

Figure 6.17 – Deformations of the crest (positive value: downstream displacements) Vertical axis (A): Deformations of the crest arc (shortening in μm/m) – Horizontal axis (B): years after the end of impounding – Black: double-curvature arches; Red: single-curvature arches; Blue: Arches with high overhang / © EDF



Actions and action combinations

Among the loads to be considered, focus is put on considering the thermal effects, which is a specificity of arch dams. It was chosen to make a distinction between arches that are deemed vulnerable to thermal effects (for example, dams in wide valleys, those relying on abutment blocks or fine structures). For these, additional situations are to be checked.

If several load cases are proposed for consideration (see table 6.1), the guide stresses the need to consider realistic scenarios for the arch dam under consideration.

Table 6.1 – Load cases

Situation name	Description of external actions	Description of thermal conditions
	Normal operating situations	
10-year seasonal operating situations	Most frequently associated reservoir level* Most frequently associated reservoir level*	10 years winter 10 years summer
	Rare or transient situations	
Rare seasonal situation*	U/S reservoir NL and corresponding D/S level(s) U/S reservoir NL and corresponding D/S level(s)	Winter Summer
Rare flood situations combining significant seasonal thermal loads	Rare flood without marked seasonality of the flood regime	Winter and Summer
	Rare flood with marked seasonality of the flood regime: Associated seasonal flood Strongest seasonal flood	Most prejudicial winter and/or summer thermal loading Associated thermal loading
	Extreme or accidental situations	
Extreme situation of a flood combined with a thermal load	Flood to be defined	Thermal loading to be defined
Extreme situation of an earthquake combined with a thermal load	Earthquake to be defined	Thermal loading to be defined

** If the operating water level is different from NWL for seasonal operating situations.*

Failure mechanisms, criteria and safety assessment

Based on accident and incident analysis, 6 main mechanisms have been identified:

- The question of rock wedges (feedback: Malpasset, but also Frayle, Idbar, El Atazar, Montsalvens). On the basis of the geological and hydrogeological model, the probable kinematics of the mechanism must be identified. The most widely used method is the one proposed by Londe. There are, however, other more recent methods such as discrete element modeling. The main message is to perform sensitivity analyses (on uplift pressures and/or friction angles), rather than introducing safety coefficients. The reinforcement solution lies mainly in draining the abutments.
- Sliding along the foundation surface (feedback: Meihua dam). The analysis is based on normal and tangential forces and stresses on the concrete/rock contact. A graduated approach is proposed. A point of vigilance is made on the abutment blocks:
  - the first approach is a linear approach. This is accepted/valid if a majority of the concrete rock contact remains in the elastic area. This would be the case for narrow valley vaults;
  - the second approach is non-linear. This is to ensure that the stress shift to adjacent consoles allows for a new balance. In this approach, millimeter movements would be acceptable in normal and rare situations. Up to centimeter in extreme. Safety margins are sought by reducing shear strength;
  - for thrust blocks, the same approach is possible. But if they play a significant role for the stability of the dam, they must be sized as a gravity dam.
- The opening / loosening of the concrete/rock contact. The loosening of the upstream contact area is visible on several arch dams in wide valleys (see § 2.3). Aspects to be checked are especially water pressure conditions: cracks opening, spreading of uplift pressure, increased hydraulic gradients. It is important to ensure that changes in stresses do not cause other fracture mechanisms.
- Overcoming permissible stresses in the concrete material. The working group is not aware of any cases of compression arch failure. The development of cracking (traction) is not a rupture mechanism. It is the non-cracked area that will undergo greater compression and the efforts transmitted are accentuated. Criteria have been proposed. The guide also recommends checking the absence of significant shear surface in concrete (Mohr-Coulomb criterion).
- Erosion by overflow (feedback: Sweetwater Dam). Three types of possible erosion mechanisms have been identified: abutment erosion in the vicinity of the arch ends (bypasses); erosion of abutment rock masses by destabilizing rock scales under the effect of dynamic pressures; erosion of rock masses at the valley bottom, caused by the impact of the waterfall. The hydraulic and geology engineers determine the scouring, then the structure's stability after the loss of rock volumes downstream has to be assessed.
- Internal erosion in special geological situations (feedback: Lake Lanier Dam). Internal erosion of the foundation is the last mechanism identified and may be the least likely, although there is one known case: Lake Lanier Dam failure due to internal erosion of its foundation. Arch dams are by nature not sensitive to this phenomenon, because the foundation rock is supposed to be of good quality, but special geological conditions are possible (regressive erosion in faults with mylonite, extrusion / ejection of sandy and clay fillings…). It is difficult to define a boundary gradient beyond which erosion or blowouts start, depending on the nature and compactness of the eroded materials. This risk assessment remains in the expert hands of the geologist.

Models

This chapter discusses possible modeling in different parts of the structure.

- Modeling and analysis of the dam body:
  - modeling with a linear elastic constitutive law;
  - modeling with a non-linear constitutive law (with joint elements, damage approach type (cracking / degradation is memorized).

- Modeling and analysis of the foundation:
  - elastic linear modeling (isotropic / anisotropic);
  - discontinuous approaches (Londe's wedges, discrete elements).
- Modeling and analysis of the dam/foundation interface:
  - linear approach;
  - non-linear approach (joint elements with different options for their constitutive law).

The method of progressively reducing shear strength, previously cited, is also detailed. In addition, irreversible effect modeling and earthquake modeling are specified.

2.5 The role of French engineering on arch dams abroad and in France

French engineering, after initially relying on experience abroad, mainly in America, developed its own methodologies, thanks to the large number of projects launched over a few decades, from 1935 to 1975. The construction of these structures was carried out by civil engineering companies who, for their part, have developed many specific methods, in fields as diverse as forms, in situ cooling of concretes, injections, etc. And operators, because of the large number of structures, have developed methods and rules for managing, monitoring and maintaining their structures. All these achievements have therefore formed the basis of French expertise in the field of arch dams.

This experience has been widely exported all over the world, including:

- Portuguese arch dams (in close cooperation with the University of Coimbra): Santa Luzia (H = 76 m, 1944); Castelo Do Bode (H = 115 m, 1950); Venda Nova (H = 97 m, 1951); Salamonde (H = 75 m, 1953);
- schemes in Africa, from Morocco (Bin-el-Ouidane, H = 135 m, 1953) to Lesotho (Katse, H = 185 m, 1999) via Kariba on the Zambezi (Zimbabwe-Zambia, H = 128 m, 1959);
- the contribution of French engineering teams to several Chinese hydropower projects: Kukuan (Taiwan, H = 86 m, 1962); Lijiaxia on the Yellow River (H = 150 m, 1988); Xiaowan on the Mekong River (H = 292 m, 1997);
- many others worldwide: Sir and Berke in Turkey; Rapel in Chile (H = 110 m, 1967); Gomal Zam in Pakistan (H = 133 m, 1993); Tekeze in Ethiopia (H = 180 m, 1998), Budhi Gandaki in Nepal (H = 262 m, underway).

Moreover, the accumulation over time of experience in monitoring acquired by French dam operators (the oldest arch dams are 100 years old) has revealed specific behaviors, with certain pathologies that have had to be analyzed, understood, evaluated and corrected. These field-acquired skills are available to dam owners around the world to help them solve their monitoring, maintenance and rehabilitation problems.

Here are some examples:

- Kariba on the Zambezi river (Zimbabwe-Zambia): concrete AAR swelling, downstream erosion, gate engineering.
- Katse (Lesotho): assistance with maintenance of water intake works.
- Cahora Bassa (Mozambique): 5-year inspection, safety reassessment.
- Dumbea (New Caledonia): reinforcement studies.
- Belesar (Spain): diagnostic mission (swelling of concrete).
- Sir (Turkey): 10-year safety review.
- Bimont and other French arch dams affected by concrete swelling pathologies (alkali-aggregate and / or internal sulfate reaction).
- Laouzas, Vouglans, Pont-du-Roi: for arch dams in wide valleys as exposed in § 2.3.

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CHAPTER 7

EMBANKMENT DAMS

1. THE CONTRIBUTION OF CFBR IN THE FIELD OF EMBANKMENT DAMS

The Comité Français des Barrages et Réservoirs has gone through three periods of innovation. The period of the "30 glorious years" from 1950 to 1980, the end of the 20th century during the 80's and 90's and the beginning of the 21st century.

The construction of a large number of dams, justified by the country's development, was completed in the 1980s with the impoundment of dams for pumped storage power plants (Grand'Maison and Le Verney) and support for the water resources of nuclear power plants (Vieux-Pré, Mirgenbach and Naussac) or for drinking water plants (La Verne). The development of dams continued all over the world, particularly in the many countries that were equipping themselves at that time. These developments in countries with very different geographic and climatic condition from France offered an opportunity to explore new types of projects and new technologies. Throughout this period, the Coyne et Bellier engineering company launched or supported several innovations: reinforced embankment dams (Vallon des Bîmes and Conqueyrac), mixed embankment-BCR dams (Mae Suai and R'mil), cores made of coarse materials (Serre-Ponçon, Mont-Cenis, Grand'Maison), shoulders in friable rock (Vieux-Pré), spillways on embankment (Lebna, Vallon des Bîmes) and diaphragm walls connected to the upstream facing (Le Verney and Pla de Soulcem). At the same time, the Compagnie d'Aménagement des Coteaux de Gascogne, in charge of building numerous water reserves for irrigation with clay dams, developed an innovative spillway concept on the downstream face of these dams.

In the 1980s and 1990s, the focus was on the rationale for dam safety. The mastering of numerical modeling was affirmed with the Aubry-Hujeux constitutive law and the Gefdyn software, which contributed exclusively to the seismic analyses of dams under extreme earthquakes. It was at that time that the first evaluations of the risk of internal erosion appeared.

In the 2000s, emphasis was put on the environmental aspect, water resource management (the Comité Français des Grands Barrages became the Comité Français des Barrages et des Réservoirs), the strengthening of safety characterized by the regulatory generalization of risk analysis and, recently, the development of new materials for embankments: lime-treated clays and calcified granular materials.

The following paragraphs provide a brief overview of the contribution of these innovations to the design, construction and operation of embankment dams.

2. NEW CONSTRUCTION AND REINFORCEMENT TECHNIQUES

2.1 Embankment dams in reinforced soils

Reinforced embankment dams consist of reinforcing the embankment with steel to create a downstream retaining wall with a modular concrete facing. This principle, developed by André Coyne at the Col de Saint-Cassien dike, was applied to Vallon des Bîmes dam (see § 2.6.2), using the"Terre Armée" process to make the floods spill over the dam crest. The reinforcements are made of flat galvanized steel strips. This solution is reserved for small reservoirs and small catchment areas with potentially violent floods. The dam's service life depends on the state of corrosion of the steel strips.

Conqueyrac flood-control dam on the Vidourle river is made up of a sub-vertical upstream facing and downstream modular concrete scales connected to the upstream face by passive reinforcements. These passive reinforcements are embedded in precast, prestressed concrete beams on a bench, to ensure the durability of the reinforcement, and therefore of the dam, in accordance with the usual long-life expectancy of dams. The end connections are also encased in concrete. This technology was chosen because the foundation is highly karstic: depending on the location of rainfall on the catchment area, the limestone caves produce water or suck water unpredictably into the dam's foundation and its immediate vicinity. The reservoir is constantly empty but suddenly fills up during floods combined with resurgences under the dam body. This highly draining reinforced rock mass accommodates these resurgences. Extreme floods can spill over the crest of the dam

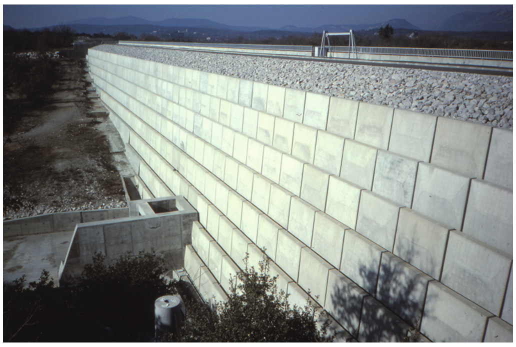
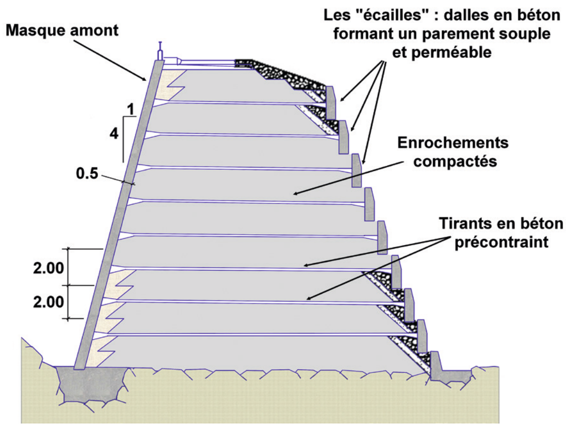


Figure 7.1 – Conqueyrac Dam (France)
– Top left: downstream facing
– Top right: Bottom drain
– Bottom left: Dam section

© Coyne et Bellier



2.2 Hybrid embankment-RCC dams

A hybrid dam consists of an upstream embankment and a downstream zone in RCC. It has been used for the cofferdams of the Sir and Berke arch dams in Turkey, Katse dam in Lesotho, Mae Suai dam in Thailand, R'mil dam in Tunisia and Wadi Wala dam in Jordan.

The upstream clay fill and the downstream RCC fill rise simultaneously. The embankment serves as a seal, an access track to the RCC placement level and the upstream formwork for the RCC. The RCC placed downstream allows the structure to spill over a long length, which is particularly useful when extreme floods are difficult to assess. In the case of the Mae Suai Dam, the RCC section closes laterally downstream to protect the banks.

Figure 7.2 – Mae Suai dam (Thailand) under construction /
© Coyne et Bellier

The criteria imposed on the RCC are very flexible according to whether the site can provide even poor aggregates. The embankment is made of granular materials containing more than 14% fines to ensure watertightness. This type of dam can be built very quickly between two floods and spills perfectly during the construction and final phases.

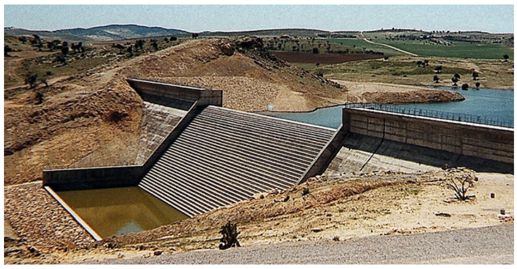
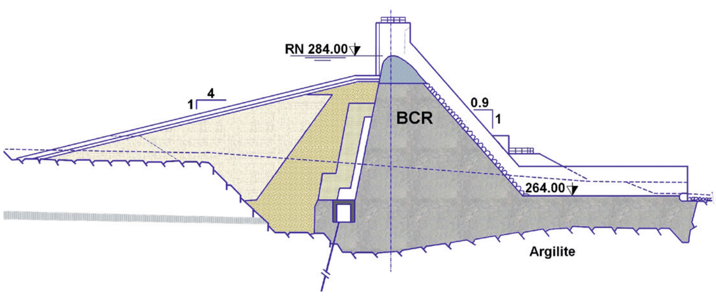


Figure 7.3 –
R'Mil dam (Tunisia) –
End of construction
– Top left: upstream view
– Top right: downstream view
– Bottom: section with spillway
© Coyne et Bellier



2.3 Shells in friable rockfill

The core of rockfill dams can be made of coarse material if the fine content (% < 0.1 mm) contains more than 15% of reasonably plastic fines (VBS > 0.4). The core of Grand'Maison dam consists of 0.5 m-thick layers of very coarse morainic material. Its watertightness is ensured by the fines content (% < 0.1 mm greater than 17%, and average equal to 26%). The advantage of this solution is that it costs very little, there is no need for selection other than to eliminate large blocks and, above all, the materials located in the immediate vicinity of the site can be used directly. The deformation modulus of this core is close to that of the shells, which eliminates the problems associated with differential settlements between core and shells. For large dams, this considerably reduces the risk of arching effects, relieving the vertical stress in the core and allowing its hydraulic fracturing.

2.4 Shells in friable rockfill

Vieux-Pré dam is a zoned dam, with shoulders made of sandy sandstone from the Vosges. Provided that the banks downstream of the core are protected by a filter to prevent the risk of internal erosion in the event of water resurgence, the material performs perfectly. The deformation modulus and angle of friction of this compacted sandstone are high, allowing an economic profile for the dam. This solution meant that full use could be made of the site's materials and reduced the cost and environmental impact of the dam in the Vosges mountains.

2.5 Diaphragm wall in plastic concrete

Two embankment dams with bituminous facing, Le Verney and Pla de Soulcem, are based on a thick alluvial foundation. A plastic concrete diaphragm wall ensures the watertightness of the dam-foundation system. In both cases, the anisotropy of the alluvium and moraine makes it possible to ensure watertightness by means of a partial cut in the alluvial foundation while maintaining a satisfactory underground flow. The permeability anisotropy ratio of kh/kv of materials deposited in the valleys by rivers and glaciers is frequently very high: values of 100 or 200 have been measured. In this case, partial cuts are frequently sufficient to ensure the proper functioning of the reservoir by taking advantage of the low vertical permeability of the foundation. They are much simpler and less expensive to achieve than total cuts, which are difficult to perfect.

The connection between the top of the diaphragm wall and the upstream dam facing uses innovative devices, very different from the complex system of copper slabs and joints commonly used in South America (e.g., at Olmos Dam in Peru). The solution adopted at Verney dam consists in making an upstream toe, also in plastic concrete, at the head of the diaphragm wall, measuring approximately 5 m by 5 m, through which the diaphragm wall passes, and in which the reinforced concrete plinth is anchored, providing the connection between the upstream facing in reinforced concrete or bituminous concrete and the diaphragm wall. The plinth and its anchor are continuously reinforced without joints. The diaphragm wall is placed at the foot of the embankment to benefit from part of the vertical compression forces during construction of the embankment.

2.6 Spillways on embankments

2.6.1 Free overflow spillway on embankment dams made by CACG (France)

The Compagnie d'Aménagement des Coteaux de Gascogne, CACG, created in 1959, contributes to the economic development of agricultural areas. To compensate for the significant deficit in water resources observed in these areas, it has taken on the responsibility of creating numerous reservoirs and hillside dams made of homogeneous clay fill.

To reduce the land footprint of the facilities whilst optimizing their cost, CACG designed and built spillways on embankments [Martin 1999]. The first project dates back to 1962 in Boulogne-Sur-Gesse and involves an 8 m high embankment and a design flow of less than 30 m^3/s. This structure was undamaged by the 1977 flood, the return period of which is estimated at 500 years. Between 1967 and 1994, CACG built 85 spillways based on a standard model, comprising a concrete chute opening into a stilling basin made of concrete, riprap or cement-bound riprap. Settlement is accommodated by transverse joints sealed by waterstops, the underside of the invert being entirely drained by longitudinal drains. In the 1980s, four structures, with a central weir length exceeding 12 m spilling a modest load, were built with their chutes and stilling basins made of rockfill bound by concrete grouting resting on a 20 cm concrete mat. Starting in 1995, the upstream wall of the stilling basin was replaced by slopes with concrete-bonded riprap facings; the chute now consists of successive shotcrete blocks made like "piano keys" in a trench excavated in the backfill, the walls of which have been previously gunited. The advantage of this solution is that it halves the construction time and limits erosion phenomena at the contact between the wall and the fill.

In conclusion, the solution of spillways on clay embankments, applied since 1967 to some 100 dams, appears to be an economically satisfactory solution for low to medium height structures (8 to 22 m high) located on small watersheds (design flood peak discharge flow of less than 300 m³/s).

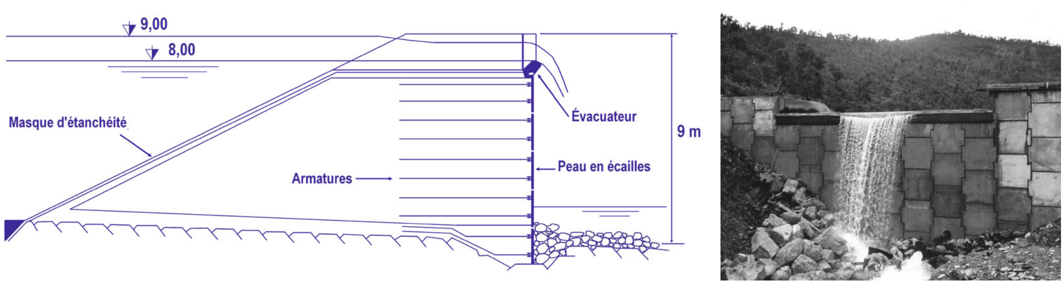
2.6.2 Vallon des Bîmes dam (France)

Error: Remplace "Vallon des Bîmes spillway dam in 1979" by "Vallon des Bîmes spillway dam designed by Alain Cassard et al. in 1972"

The technique of "Terre Armée" was developed as a retaining wall technique for roads. The first application to dams was Vallon des Bîmes spillway dam in 1979. Being a prototype, the structure has a height limited to 9 m. The upstream slope of the embankment is inclined and covered with a membrane that ensures the structure's watertightness. The downstream face of the embankment, made of precast concrete modular slabs, is vertical; it must be founded on a foundation with good characteristics and deep enough to prevent it from scour in the stilling basin (Figure 7.4).

Figure 7.4 – Vallon des Bîmes dam: section and downstream face / @ Coyne et Bellier

Error :Remplacer "@ Coyne et Bellier" by @ Alain Cassard"



Since then, this design has been taken up outside France, for example in the construction of the Taylor Draw dam in the United States (height: 22.5 m).

2.6.3 Lebna dam (Tunisia)

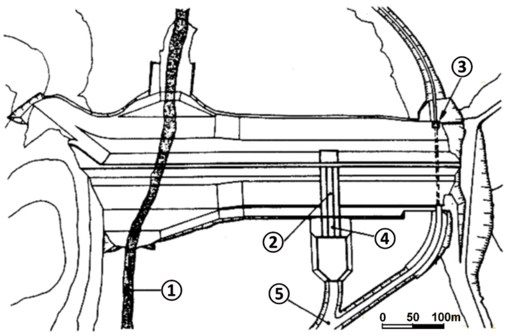
Lebna dam was commissioned in 1986. It is quite low (20 m), and its special feature is its very large spillway anchored to the surface of the embankment (design flow 300 m³/s). This arrangement was dictated by a particularly unfavorable geological and topographical context for positioning the spillway on the bank (whether on the surface or in a gallery); moreover, the loose and compressible foundation of the dam prevented the construction of a combined embankment-concrete structure, as well as the arrangement of a spillway tower connected to a spillway gallery under the embankment adapted to the flows to be released.

At the time of design, the perception of the risks associated with the installation of a spillway on an embankment meant that this solution was only envisaged for small dams with limited head and flood flows. These risks are mainly related to the deformability of the embankment, its erodibility, the infiltration that occurs in any dam (mainly near the downstream foot) and the release of water near the dam toe.

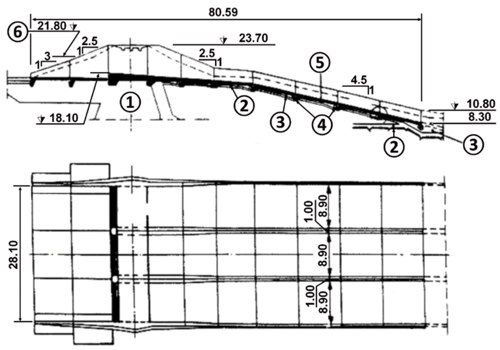
The width of Lebna spillway, about 30 m, is small compared to the dam's 600 m crest length. It was therefore positioned where the dam foundation is the most homogeneous. Differential settlement, which is more harmful than absolute settlement, must be avoided. To limit the latter, the spillway was notched into the previously completed embankment up to the crest, to pre-consolidate its foundation.

Special precautions were taken to ensure proper operation of the spillway (Figure 7.5). From a structural point of view, the spillway is made up of three independent blocks, like "piano keys", and studs hinged in "tiles" in the upstream-downstream direction; each block rests upstream on small concrete cut-offs ensuring good anchorage in the embankment, the movements of the blocks being homogenized by longitudinal steel bars passing through the joints.

Figure 7.5 – Lebna dam: general layout of the works, section and plane view



1. Oued Lebna
2. Spillway on embankment
3. Inlet tower and bottom outlet
4. Stilling basin
5. Tailrace canal



1. Core of dam
2. Filter
3. Drain
4. 300mm drain pipe
5. Geotextile
6. Maximum water level

To limit concentrated leaks and risks of erosion, a good connection is first ensured between the inlet block and the dam core. Secondly, a particularly efficient downstream drainage system must be designed. To do this, each block is drained independently; the leakage flow from each block is captured by a system of nozzles, placed in the anchorage trench of the lower block, and then sent to lateral collectors. In the event of relative movement of the blocks and pipes, this independent function is maintained by means of Waterstops and Sika seals. Flow is restituted in adjacent concrete plunge basins downstream from the three blocks.

This facility has been in operation for over 30 years. In 1996, it experienced a spill that lasted about ten days; 30 million m^3 passed through the spillway, the equivalent of the reservoir. The maximum inflow into the reservoir, estimated at 470 m^3/s, for a released flow of 100 m^3/s, corresponds to a 100-year flood. The spillway functioned perfectly; only a few Sika seals had to be reworked. To date, the spillway's behavior has been completely satisfactory.

Figure 7.6 – Lebna dam: downstream face and its spillway / @ Coyne et Bellier

2.7 Geotextile filters in embankment dams

Geotextiles include woven and nonwoven geotextiles. In almost all cases, geotextile filters used in dams are nonwoven geotextiles. They are usually made of polypropylene or polyester.

The first use of a geotextile in a dam [Giroud & al. 1977] was in 1970 as a filter for gravel drains in the downstream part of Valcros dam, a 17 m high embankment dam made of silty soil with a very broad particle size distribution. A traditional sand filter was planned, but, at the last minute, the specified sand being unavailable, a quick decision was required. A new material, not yet known as geotextile, had been tested for a road application. It was a nonwoven fabric used to separate a layer of aggregates from a clayey soil. The success of these tests, i.e. the fact that the fine soil particles did not pass through the fabric despite the stresses exerted by the trucks driving over the aggregate layer, suggested that the fabric could be used as a filter between gravel drain and silty soil. Necessity justified the audacity and the decision was made to use this nonwoven fabric as a filter in Valcros dam. On two occasions, years after completion of the dam, samples of geotextile taken from the dam underwent laboratory tests which showed the geotextile's durability and the negligible changes in its permeability, indicating that no significant clogging had occurred. At the drain outlet at the downstream toe of the dam, a constant trickle of clear water has been flowing since the dam was impounded in 1970.

There was an element of luck in the success of the Valcros dam filter, which created an obligation to carry out research that led to criteria for the dimensioning of geotextile filters. After improvements and intermediate publications, these filter criteria were the subject of a final publication [Giroud 2010]. It is interesting to note that this research on geotextile filters has had the positive side effects of improving the granular filter criteria, which shows that the use of geosynthetics fits perfectly into the more general framework of geotechnics.

The example set by Valcros dam has been followed by the designers of many dams where a nonwoven geotextile filter is used, including several dams in France, such as: La Valière dam (1976) with a drainage blanket; Chateauvieux dam (1983) with an inclined internal drain; Dzoumogné dam (2000) with an inclined internal drain and a drainage blanket. Dams built in Africa using geotextile filters include: Sidi M'hamed Ben Taiba dam (2003) in Algeria, with horizontal gravel drains wrapped in a nonwoven geotextile filter to ensure the stability of the upstream part in case of rapid drawdown of the reservoir; and Samira dam (2001) in Niger, with a vertical drain and a drainage blanket, both of which are made of gravel with a nonwoven geotextile filter [Degoutte & Fry 2002].

The proper use of geotextile filters requires careful attention to design, specifications and installation: (a) The geotextile filter should be selected based on soil characteristics using filter criteria. (b) The chemical composition of the water can influence the geotextile's durability. Thus, in the case of alkaline water, a polyester geotextile should not be used. (c) Water should not be allowed to bypass the geotextile filter: to avoid this problem, precise specifications are needed. (d) Like a sand filter, a geotextile filter cannot work if the soil upstream of the filter is highly permeable with a gap-graded particle size distribution such that fine soil particles carried by the water accumulate on or in the filter. This case requires special provisions. (e) A geotextile filter becomes clogged if it is not in intimate contact with the soil. Intimate contact is only possible if the grading of the drain gravel is such that the stresses exerted by the gravel on the geotextile are as uniform as possible. The dam designer must therefore specify the grading of the gravel not only to ensure the permeability of the drain but also to ensure that the geotextile is in intimate contact with the soil. It must also be specified that the ground surface is not too uneven to ensure that the geotextile can be installed in intimate contact with the ground. (f) Geotextiles, being made of fine filaments, have a large specific surface area and are therefore sensitive to UV radiation. They should therefore be installed as soon as possible after removal of their protective wrapping and covered promptly.

Geotextile filters used in dams have many advantages over traditional granular filters: as industrial products, they are always available and, subject to quality controls, their characteristics are uniform, constant and reliable; they are light (less than 500 g/m^2), therefore easy to transport to dam sites that are difficult to access; they are easy to install regardless of the configuration of the drainage systems. These advantages are important, especially for smaller dams where the cost of filters is relatively high.

The durability of geotextile filters located inside an embankment dam (at a sufficient depth to be out of reach of rodents and roots) is more than 50 years, as indicated by the performance of Valcros dam, and more than 45 years according to the feedback provided by a considerable number of geotextile filters installed after the construction of Valcros dam in all types of structures around the world. However, the durability is lower than the above values for geotextile filters that are insufficiently protected against exposure to UV radiation or rodent attacks.

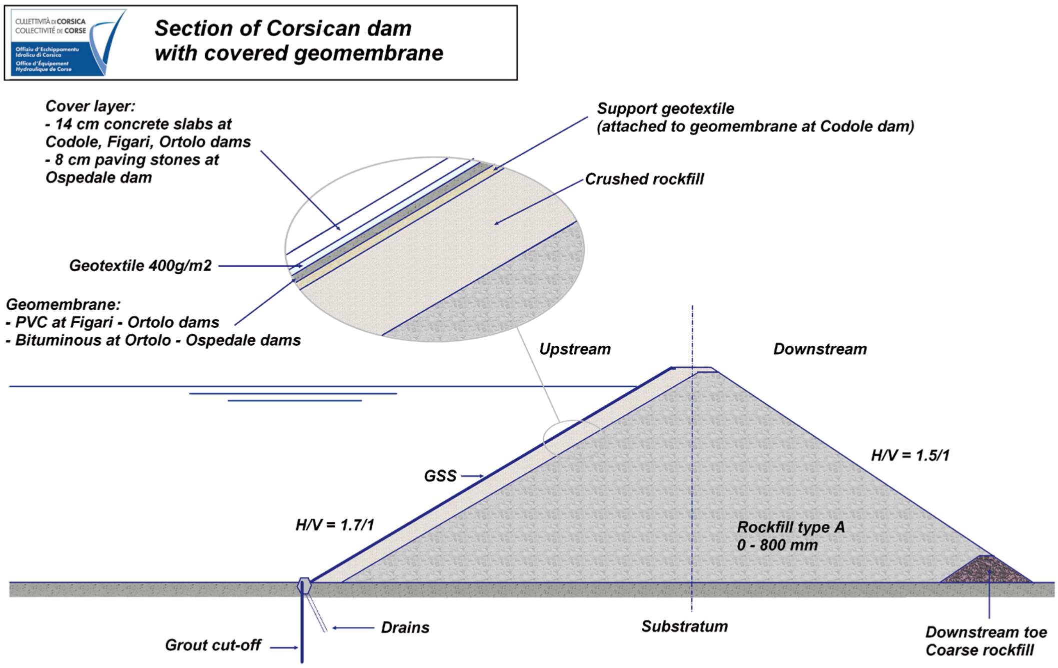
2.8 Dams with Geomembrane Waterproofing System in Corsica

The Office d'Équipement Hydraulique de la Corse (OEHC) manages Corsica's water resources. Due to the scarcity of land and under the impetus of Claude Tisserand, a generation of Corsican dams using the Geomembrane Waterproofing System (GWS) concept was developed and improved [Royet & al. 2002].

2.8.1 Ospédale dam (1979)

In 1971, the OEHC had only worked on the Alésani dam, a rockfill dam with an upstream asphalt lining. It is a beautiful, laborious and costly project, whose watertightness is fully satisfactory. Five years later, the solution of the upstream asphalt lining was chosen for Ospédale dam project, based on the principle of "why change things that work?". But what was already complex and costly on a large dam like Alésani almost bankrupts a small dam like Ospédale, because it requires the same fixed costs, investments in specialized equipment, transport costs (an important item in Corsica), testing and development procedures. Moreover, the geographical location of Ospédale at an altitude of 950 m, seriously complicates the work (with over 50 cm of snow during the harsh winters of the construction period and roads in poor condition).

Figure 7.7 – Section of dams covered with geomembranes in Corsica / © OEHC



Following the call for tenders, Colas (and its local agency Corsovia) was awarded the contract with a bituminous geomembrane solution called Coletanche (5 mm thick), which it had developed a few years earlier and applied to a few small structures. This solution is easy to implement with a light and easy-to-manufacture material (crowning winches, slope spreader, etc.). The rest of the structure is directly inspired by the Alésani dam (gradient of the slopes, grading and, above all, the support layer in draining bituminous concrete), an invariable design for all the following structures, still following the principle of "why change things that work" (Figure 7.7).

However, there was still an important problem to be solved: the protective cover layer. A concrete slab was considered, but its implementation posed more or less the same problems as that of an asphalt lining. This is why the solution of interlocking paving stones (SABLA paving stones), which are easy to lay, without any special equipment (just let them slide on the facing until the laying team picks them up and places them correctly) was adopted. Started in 1976, the dam was completed in 1979 without any major problems. However, in operation, the paving stones did not seem to be properly blocked. A paving stone sliding on its support has no relation to a paving stone laid flat on a layer of sand. As a result of the support's unevenness and imperfections in the installation, the paving stones were not tightly clamped to the upper part of the facing. Following heavy storms, different-sized slabs of the paving stones were washed away and found at the toe of the dam. They could only be put back in place in dry years, when drawdown was possible. They were tightened and rejoined with mortar (Figure 7.8) and have not been removed since.

This rehabilitation in November 2007 offered the opportunity to take, three series of geomembrane samples for a detailed study of the evolution of its properties [Touze-Foltz N. & al. 2011]; the results show a significant loss of flexibility in the order of 75% (which is not an unacceptable disadvantage for a flat and static membrane), a slight loss of breaking strength of 18% and a complete waterproofing: leaks not measurable during the tests). Contrary to these excellent results observed on the geomembrane, the general condition of the interlocking paving stones, although of good quality, remains a cause for concern. Their surface is attacked by aggressive water (water in granitic soil); this phenomenon, already noticeable after about ten years, is still being monitored.

Figure 7.8 – Bulging (left) – Exposed aggregates and mortar leaching (right) /
@ C. Tisserand

2.8.2 Codole dam (1985

This dam was built according to the same cross-section design as Ospédale dam, and is about the same height (28 m vs 25 m), but it is longer and, above all, has a different GWS, selected following calls for tenders. Watertightness is ensured by a 2 mm thick PVC membrane, combined with the supporting geotextile. The cover layer avoided the problems encountered with the "self-locking" paving stones (not to say automotive paving stones!) by pouring a 14 cm thick layer of reinforced concrete in 5 m x 5 m slabs with welded mesh, resting on a 400 g/m^2 geotextile. The anchoring of the crest differs from that of Ospédale by applying a bolted plate on a concrete beam, which is much more satisfactory geometrically than the trench anchoring of Ospédale dam. 4 or 5 easily removable precast, pointed reentrants were placed in this layer of protective concrete to allow for possible inspection and/or sampling of the sealing layer (an operation that has not been carried out to date). This design and these works, although on a considerable scale, did not pose any problems during construction or operation. The leakage rate, studied from 1984 to 2000, is between 0.6 and 1.2 l/h/m^2 of dammed section, which is 2 to 4 times lower than at Ospédale.

2.8.3 Figari dam (1990)

This 35 m high rockfill dam, built according to the same design as its predecessors, differs from them only by the GWS. It is a pity that the 2 mm PVC waterproofing is not attached to the geotextile, due to a supplier problem. On the other hand, the double machine welding with central channel allows an excellent compressed air control on all the joints. The protective cover layer is made of concrete reinforced by polyester fiber "reinforcement".

This realization did not pose any major problems, either in construction or in operation, except when a storm washed away a large part of the still unprotected geomembrane during construction. The lack of problems shows that the technique had been well developed in its third generation. The leakage rate is 0.5 to 1 liter/s, about the same as Codole dam.

2.8.4 Ortolo dam (1996)

Its height of 37 m and its design are close to those of Figari dam. However, in the call for tenders, a GWS made of bituminous geomembrane won the contract. The fourth realization could have been just "routine"… but this was not the case! During construction, the dam was subjected to an extreme flood just before the installation of the membrane. The diversion conduit, calculated for the ten-year flood, was rapidly saturated and clogged by tree trunks. The impounding of the reservoir was almost completed (see photos in Figure 7.9) and drawdown was impossible!

The danger for the embankment became imminent… It was not possible to send a diver who could be sucked out if the log jam broke! There was only one solution left: to blow up the log jam with explosives… This was done, fortunately with total success! In the future, other arrangements will have to be made, because not all countries have experience with Corsican fireworks. At the end of these events, the GWS was set up without difficulties. Although this submersion resulted in the erosion of rockfill fines, the settlement was acceptable.

In 2018, the average settlement reached 26 mm since the beginning, with a maximum of 60 mm on a downstream benchmark, with a tendency to stabilize and even a slight rise during the last measurements. As for leakage flows, they remain very moderate, below 4 l/s, i.e. 2.6 l/h/m^2 of dammed section (flows comparable to those of Ospédale dam).

Figure 7.9 – Ortolo dam: extreme flood during construction. Upstream face (top) and downstream (bottom) / @ A. Sanguinetti

2.9 Lime-treated soils

Treating soil with lime is an old technique which has been developed spectacularly for over half a century. There are many reasons for this development: recovery of silty-clay and/or wet soils, optimized management of natural material resources, reduction of the disturbances and costs generated by the transport of borrowed materials, reduction of execution times and the overall cost of the work. It was the field of transport infrastructures, within the framework of the policies for deployment and modernization of the networks (motorways, airport platforms, lines for high-speed trains) that was the first to take advantage of the progress made in the technologies of execution and the control of the performances of the treated materials.

In the field of hydraulic works, the applications correspond to curative and sometimes preventive treatments, following damage or concerns resulting from the behavior of components of the works: unstable, erodible or dispersive soils. In this way, in the early 1980s, Michelbach reservoir (7.8 hm^3 of water for domestic use in Eastern France) was sealed by applying a 30 cm layer of soil treated with 2% lime and 5% cement at the bottom of the reservoir. Other realizations exist on all continents (Figures 7.10 to 7.13).

Figure 7.10 – Friant Kern Canal (USA, 2012) – Typical failure of the concrete protection slab of the embankment due to the presence of expansive soils / @ Lhoist

Figure 7.11 – Friant Kern Canal (USA, 2012) – Section of embankment rehabilitated in 1973 by lime treatment of swollen soils, without a concrete protection slab / @ Lhoist

Figure 7.12 – Hvezda dike (Czech Republic, 2003) – Following floods, treatment of wet sediment with lime for dike reconstruction / @ Lhoist

Figure 7.13 – Hvezda dike (Czech Republic, 2003) – General look of the dike after reconstruction / @ Lhoist

In recent years, significant laboratory and in-situ research has been undertaken to quantify the performance of lime-treated soil in terms of stability, impermeability and resistance to internal erosion. In France, the resistance to surface erosion has been successfully tested at full scale by overflow tests on a demonstrator structure, within the framework of the "DigueELITE" research project. (Figure 7.14). All the results were presented at the ICOLD Congress in Vienna in 2014 and the project received the Innovation Award [Nerincx & al., 2018]. These results have been incorporated by ICOLD's Technical Committee P on Cemented Material Dams (CMD) into the technical bulletin on the use of treated soils in dams (CSD: Cemented Soil Dams).

Based on the functions identified by DigueELITE (table 1), it is possible to highlight the interest of the soil-lime component for hydraulic structures and to constitute the first elements of a useful database for designers.

*Figure 7.14 – Evaluation of in situ resistance to overflow:
a) Demonstrator test of the DigueElite Project (Vidourle, 2016),
b) Platform test (Rhône River, 2018) /* (a) © INRAE – S. Bonelli (b) © Symadrem

Table 7.1 – Functions of the soil-lime component in a hydraulic structure

Desired function	Workability of the material	Stability	Permeability	Resistance to internal erosion	Surface protection	Evacuation
Properties of the composant	Ease of implementation (in the case of wet soils)	Stability under dead weight and possibly seismic loading	Watertightness	Resistance to internal erosion	Resistance to external erosion	Resistance to high-speed flows (evacuation channel, etc.)
Verified properties for the soil-lime component	Current and codified application (standards local guides)	Current and codified application (standards, local guides)	Demonstrated in laboratory and field (demonstrator)	Demonstrated in laboratory and field (demonstrator)	Demonstrated full-scale (overflow on demonstrator)	Under study

Soil treatment with lime, which has already been tested and widely applied in other fields, therefore opens up new possibilities in the field of hydraulic engineering, in particular:

- recovery of poor quality silty-clayey materials;
- stiffening of structures' slopes through improved mechanical stability;
- simplification of the filtration and drainage system thanks to the resistance to internal erosion;
- design of structures (sections of dikes or small dams) resistant to overflow.

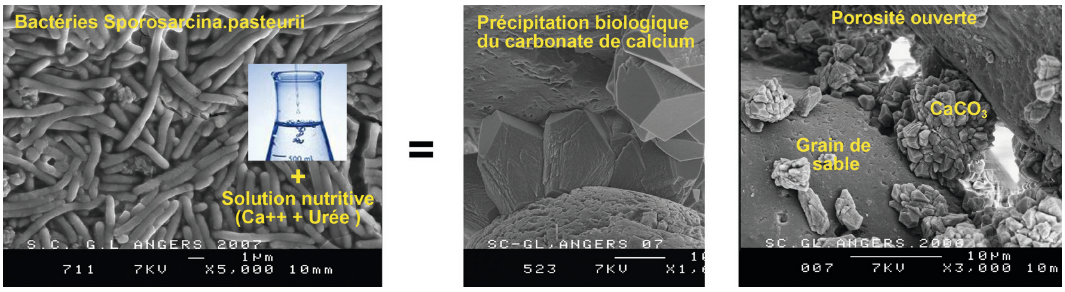
2.10 Calcified granular materials through biogrouting

Biogrouting is an innovative eco-technology of biological soil consolidation that mimics natural calcification processes to cement soils in place. The porosity and therefore the permeability of the soil are not significantly altered after treatment. Its application is considered for the reinforcement of hydraulic structures under hydraulic load (dams, levees, dikes, hydroelectric canals, and irrigation canals) relative to the risk of internal erosion and the risk of liquefaction.

It is applied by injection from small diameter boreholes distributed over the area to be treated at the required depth. Biological cementing is obtained through an enzymatic reaction leading to the formation of calcite in situ. This reaction is catalyzed by a bacterium naturally present in the soil — Sporosarcina pasteurii — in the presence of a calcifying solution composed of urea and calcium chloride (Figure 7.15).

Calcite corresponds to a very stable mineral form of calcium carbonate $CaCO_3$ whose crystals will physically bind the soil grains together. Cohesion and mechanical resistance are considerably increased: depending on the treatment parameters, several hundred kPa can be obtained in a few days.

Figure 7.15 – Principle of the biocalcification reaction by the ureolytic pathway /
© Soletanche Bachy



The Biocalcis© process, developed and patented by Soletanche Bachy, is intended for applications in unsaturated zones or under static groundwater, which leaves the possibility of "resting" phases after each application of the calcifying solution. The results of the BOREAL project make it possible to define the criteria for the biocalcification treatment to levees in the presence of groundwater flows. The development of an injection procedure compatible with an implementation under high hydraulic gradient and high flow velocities was carried out on the basis of typical real levee configurations.

Research on both the formulation of the biocalcifying agents (bacteria-calcifying solutions) and on the implementation methods was necessary, with tests ranging from small laboratory scale to semi-industrial scale in physical models. To guarantee the long-term safety of the structures after treatment, the chemical and mechanical durability of the calcified material was studied in parallel, with tests on the resistance of the material to internal erosion (JET, CET, HET) and cyclic triaxial liquefaction tests. These tests allowed data to be acquired that could be used on the scale of the site and to carry out numerical modeling to complete the injection process, in areas sensitive to liquefaction, which could justify the performance of the levee and its foundation.

Finally, a study was performed to ensure the environmental acceptability of the process and to verify the safety of the treatment from a biological and chemical point of view. A study protocol is proposed, covering both the biological aspects (fate of the bacteria used, influence on the ecosystem) and the chemical aspects (influence of the calcifying solutions before and after reaction on the surrounding environment), with reference to the legislation in force and in comparison with the usual reinforcement techniques based on hydraulic or chemical binders. All the results of the BOREAL project demonstrate that the biocalcification process is effective in reinforcing hydraulic structures against internal erosion and liquefaction phenomena. Several validation steps have been carried out in terms of durability, dimensioning, implementation protocols and control methodology, under physical model conditions representative of real cases of application [Esnault Filet A. & al. 2018].

Figure 7.16 – BOREAL injection tests in physical model at CACOH laboratory /
© CNR Soletanche Bachy

The realization of in situ demonstrators should validate the BOREAL process as a new reinforcement process for existing embankment structures.

3. NEW NUMERICAL METHODS OF DAM ANALYSIS

3.1 Effective stress analyses with hydro-mechanical coupling

The unquestionable contribution of numerical models based on the finite elements method (FEM, written in Euler or Lagrange coordinates references) is to carry out any type of transient calculation of dams under effective constraints and to quantify the major effects of drainage by coupling the mechanical equations to those of water transfers. The use of behavioral laws has become widespread, from the elastic-plastic Mohr-Coulomb law (1960s), to the hyperbolic Duncan-Chang law (1970s), to the elasto-plastic laws with strain-hardening or softening at several load surfaces (Cam-Clay, Prevost, Aubry and Hujeux in the 1980s). Since the 1990s, micromechanical models integrated using the discrete element method (DEM) have been progressing, but their applications are still the domain of researchers. Whilst Duncan's law is suitable for the construction of large zoned dams, it is unable to reproduce softening and progressive rupture and thus seismic behavior. It is to fill this gap that the Aubry-Hujeux law [Hujeux, 1979] was initiated and integrated by Aubry into the Gefdyn software [Aubry & al. 1982 and 1990]. By including four load surfaces with volumetric and kinematic strain-hardening, this law generalizes the Mohr-Coulomb and Cam-Clay models and can thus model any type of soil. Its ability to simulate the behavior of dams under extreme earthquakes (Infernillo 1989 and San Fernando 1994 modeling) or during draining [An Chau Ngoc 1999] is such that it is still used today.

Finite element models can be used to accurately describe the response of soils under complex loads, provided that many parameters are identified and a minimum of computational resources are used. Fortunately, shortcuts simplify the use of some models by introducing explicit laws of evolution in a simplified formulation. Thus, a model integrates in FLAC2D the two main phenomena of liquefaction: (1) the relation linking the deviator initiating the liquefaction to the number of cycles via Byrne's law, and (2) the relation taking into account the residual resistance after liquefaction. Once these two mechanisms have been calibrated, the model correctly predicts the failure of the lower San Fernando dam, the absence of failure of the upper dam during the 1971 earthquake and the absence of damage during the 1912 earthquake [Le 2006].

The seismic recordings collected by the Japanese Committee JCOLD on dams point out the physical phenomena necessary for an accurate prediction of the seismic behavior of embankment dams [Fry and Matsumoto 2018] which are (1) the consideration of the dam's 3D characteristics in the vibratory movement; (2) the elastic parameters to be determined on site; (3) the stiffness and damping evolving with the seismic loading; (4) the increase in pore pressure taking into account the non-saturation; (5) the decrease in strength towards its residual value as the acceleration time history progresses; (6) the settlement calculated as the sum of compressibility and shear. To integrate all these phenomena, a new simplified approach has been developed, the Fr-Jp approach [Fry and Matsumoto 2018]. The results of validation tests of the method based on records of acceleration at dam base match the acceleration time histories recorded on crest of a lot of Japanese dams. An analysis of the robustness of this method justifies its ability to reproduce well-documented failures during extreme earthquakes (Fujinuma and San Fernando dams).

The USACE study generalizing Sarma's approach evaluates the response of a dam on a tabular loose foundation. This widely-used approach considers a damping of 15% to 20% and elastic modulus. An update of this study [Durand 2018] leads to a simplified seismic analysis of the dikes, based on 512 simulations of dikes with more realistic hypotheses (earthquakes adapted to European seismic context and non-linear behavior of materials). The results are available in the form of abacuses and Excel spreadsheets from neural networks.

Recently, the granular approach [Chang and Hicher 2015] appears to be the most relevant approach to simulate the flow of a liquefied soil layer and its consequences in a finite element model. As for the discrete element method (MED), which also models the static and seismic behavior of a dam [Vincens & al. 2016], it requires the development of user-friendly pre-processors and post-processors.

3.2 Assessment of the internal erosion risk

The basis for assessing the risk of internal erosion dates back to the Aussois workshop in 2005. This workshop was organized by EDF, under the lead of Professor Fell, with the support of the CFBR. The event brought together some thirty international experts, who were called upon to share their experience. At the end of this consultation, a consensus was reached on risk assessment [Fell and Fry, 2007]. The internal erosion process is broken down into four phases: (1) the initiation of erosion; (2) the continuation of erosion (or lack of total retention); (3) the progression of a conduit, or instability (unraveling); and (4) initiation of the breach or failure. Initiation involves four mechanisms: (1) concentrated leak (or crack) erosion; (2) backward erosion; (3) contact erosion; and (4) suffusion. These mechanisms and their evaluations are then adopted in ICOLD Bulletin 164. The internal erosion risk assessment methodology examines all the processes that can develop, from the application of loading to failure, in eight steps: (1) definition of the loading situations; (2) location of the different initiations of erosion initiation; (3) assessment of the likelihood of initiation; (4) analysis of the conditions of continuation (or on the contrary of filtration); (5) examination of the conditions of progression; (6) assessment of the failure of detection; (7) assessment of the conditions of a failed intervention; (8) verification of the conditions for protecting the populations in case of failure. This approach favors a probabilistic risk assessment, but the type of assessment is left to the initiative of the engineer, based on his experience: it can be based on judgment, qualitative quantification or the purely probabilistic approach.

To deepen this risk assessment, the CFBR was involved in the ERINOH project (ERosion INterne des Ouvrages Hydrauliques – Internal Erosion of Hydraulic Structures) from 2006 to 2013. This project develops tools for characterizing the resistance and detection of internal erosion. The contribution of the ERINOH project takes the form of three guides. In the first guide [Francois 2016], the emphasis is first placed on knowledge of the site (the structure, its foundation, the phenomena to be understood and the defects to be detected). Then, an overview of the available detection methods is given. "Where does the water pass through? and What is the flow rate?" are the two fundamental questions to which the detection methods answer. Temperature measurements, self-potential measurements and tracing methods are among the most frequent to obtain good results.

The second guide reviews the laboratory tests available to quantify erosion resistance [Chevalier and Bonelli, 2017]. The Hole Erosion Test (HET) is used to establish the identity of the clay or silt making up the fill body or core, by quantifying two basic parameters: the critical stress or erosion threshold, and the erosion coefficient or erosion kinetics. These parameters allow an initial safety barrier to be quantified: a pipe's resistance to concentrated leak erosion. Pipe erosion develops in the openings of a coherent soil (burrowing hole, crack, or void in contact with a pipe…).

It is rigorously modeled by Bonelli [Bonelli & al. 2013]. The resolution allows an estimation of the erosion kinetics, maximum discharge flow and the breaching time of homogeneous dams with the results of the HET tests as input data. For granular soils, the approach is completely different, i.e. the extreme segregation conditions that may exist are identified to determine the consequences in terms of permeability, velocity and fine particle entrainment capacity. The conditions of the initial state for the assessment must be as close as possible to those of the soil (intact sampling) and to the most credible adverse situations. Therefore, the second guide details the use of 17 devices developed during ERINOH, characterizing the following 7 phenomena: (1) dispersivity; (2) filtration; (3) suffusion; (4) contact erosion; (5) regressive erosion; (6) conduit erosion; and (7) surface erosion. For each device, the apparatus, the soil class concerned, the key figures, the state of the art and the test conditions are described.

The latest guide is dedicated to engineering methods [Deroo and Fry, 2020]. It has five main chapters. After the introduction, chapter 2 proposes real cases of internal erosion. The idea is to provide a diagnostic aid through a concise presentation of the most frequent physical mechanisms, which could occur in other dam sites. Once the pathological situations have been clarified, it is important to name and classify them. The glossary in chapter 3 should help to understand the concepts and phenomena. Chapters 4 and 5 then bring together the available elements of the diagnosis: analytical formulae (chapter 4) and risk situations (chapter 5). Finally, chapter 6 proposes three levels of diagnosis of the risk of internal erosion. The proposed approaches aim at an ambitious level of quantification and are, in this respect, innovative and without an equivalent in other countries. They can be very effective but still require a validation period and

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CHAPTER 8

BARRAGES IN CANALS AND RIVER DAMS

1. INTRODUCTION

The first barrages on rivers were built in the 16th century to help commercial trading and this led to the emergence of a new technology for controlling bodies of water by building dams across water courses and canals. Barrages were needed to artificially raise the water level upstream of the structure in order to maintain sufficient draught for boats. Moreover, the need for boats to get through the obstacle, either from the upstream reach to the downstream reach, or vice versa, led Leonardo da Vinci to propose the concept of the chamber lock, and the need to release floods was what led to the whole concept of gated dams or barrages, which can offer minimum resistance to flood flow as soon as flood waters arrive.

Previously, the creation of an artificial drop in water level on a river had allowed hydraulic force to be used by means of a wheel and then a turbine. For this reason, from the end of antiquity, mills accelerated the development of dams that could create this type of waterfall.

As rivers get closer to the sea and further away from their sources, valleys widen and both flood flows and human occupation increase. Barrages built in these locations are generally designed to be almost entirely transparent allowing flows of water (liquid and solid) to travel freely in the water courses. They necessarily include significant hydromechanical equipment to adjust the degree to which the water course is blocked; this type of dam is called a barrage in river or gate-structure dam. Generally modest in height, these so-called "low-head" structures serve a number of important functions in today's often highly urbanized environment: water level management (during high and low water events), drinking water supply, irrigation, recreation, navigation, hydropower production, etc. In the latter two cases, the barrage includes a lock and a power plant, which are located either by the dam, or on a canal into which part of the flow is diverted.

In France, the barrages are relatively old. Some of the structures still in operation today are over 100 years old. Aging structures, changes and improvements to river navigation (a very advantageous alternative to other modes of transport), developments in the energy market, regulatory and environmental changes (continuity of fish stocks and sediments) and also societal changes are all factors behind the deep metamorphoses of these key hydraulic structures in land-use planning in France. Finally, the multiple uses of water have always been, perhaps even more today than before, an essential factor in the design and operation of these structures.

This chapter presents some iconic schemes or recently refurbished schemes in France, with the focus on the implementation of new and ambitious solutions in an increasingly complex context. The projects presented concern the rivers Seine, Aisne, Meuse, Romanche, Isère, Rhône, Rhine, Durance and Couesnon and also the Seine-Nord Europe Canal. The rivers and canals where these projects are located are identified on the map below.

Figure 8.1 – Location of rivers with dams described below

La Seine
Source: plateau de Langres
Exutoire: M anche
Longueur :776km.
Module à l'embouchure : 563 m3/s

Le Rhône
Source: glacier du Rhône, en Suisse
Exutoire: Camargue, mer Méditerranée
Longueur : 812 km
Module à l'embouchure : 170 m3/s

L'Isère
Soute: Alpes parc national de la Vanoise
Exutoire fleuve Rhône
Longueur : 226km
Module à l'embouchure :333 m3/s

La Romanche
Source: Alpes parc national des Ecrins
Exutoire : rivière Drac
Longueur : 78km
Module à l'embouchure : 100 m3/s

L'Aisne
Source: Argonne, Nord de la France
Exutoire: rivière de l'Oise
Longueur :356km
Module à l'embouchure : 65 m3/s

Meuse
Source: Pouilly-en-Bassigny, Nord France
Exutoire: mer du Nord
Longueur :950km
Module à l'embouchure : 357 m3/s

Couesnon
Source: St Pierre-des-Landes
Exutoire: Mont St Michel, Manche
Longueur : 100km
Module: 7 m3/s

Le Rhin
Source: lac de Toma, Alpes Suisse
Exutoire : mer du Nord
Longueur : 1233 km
Module: 2300 m3/s

La Durance
Source: Montgenèvre, Alpes
Exutoire: Rhône
Longueur :324km
Module: 120 m3/s

2. MAINTENANCE AND MODERNIZATION OF EXISTING STRUCTURES

2.1 *Gate replacement*

Program for replacing gates on the lower Isère river. 15 gates in total on the 3 hydroelectric barrages on the lower Isère (Pizançon, La Vanelle and Beaumont-Monteux) are to be replaced. The oldest were brought into service in 1921 (Beaumont-Monteux). The works started in July 2012 and will continue for over a decade. The gates are 15 and 18 m wide and 10 to 14 m high, weighing between 110 and 150 t each. It takes 8 to 14 months to change just one of them. The works also include changing the operating elements (motors, chains, reduction gears) and modernizing the control system equipment together with the lifting equipment on the dams (overhead cranes, stoplog gantries). The original gates on these dams were painted with coatings containing asbestos which are being completely retreated by specialized contractors. As the works require stoplogging of openings for long periods, flow transit of and energy dissipation over a small number of openings requires increased monitoring for scour phenomena downstream, through regular bathymetric measurements and laser scans.

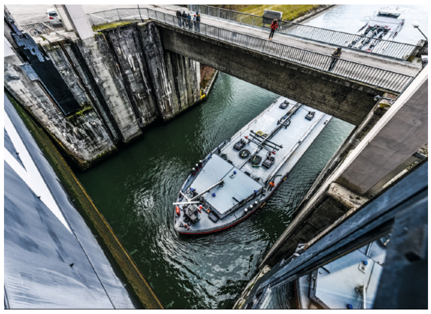
Figure 8.2 – Barrages at La Vanelle / © EDF-Philippe GROLLIER/PWP and Pizançon / © EDF-Franck ODDOUX/PWP

Programs for the maintenance and replacement of lock gates on the Rhine. Navigation on the Rhine river started in the 18th century and now holds an important place in European transport priorities. As Europe's leading commercial river today, the Rhine is a major regional economic stake for Alsace and for the countries flows through (France, Germany, Switzerland). Every year, 30 million tons of goods transit on the Alsace section of the river (with Strasbourg and Mulhouse being second and third internal ports of France).

Over and above energy production, the schemes on the Rhine are there to ensure open and free navigation of boats on the Rhine, round the clock and throughout the year. Eight locks between Kembs and Strasbourg thus allow 15,000 boats per year to pass.

A modernization program for the locks on the Rhine, extending over several years, should ensure the survival of this alternative and ecological mode of transport. Starting a few years back, major maintenance and modernization operations have focused on the locks at Strasbourg, Fessenheim and Kembs dams. In 2016, the Kembs lock gate, dating from 1932, was replaced by a new one 26 m wide and 18 m high, weighing 600 t. The gate was designed in accordance with fatigue design rules in order to withstand the large load fluctuations and the high number of operating cycles (40 to 50 lock cycles per day for 70 years). Maintaining river traffic during the works is one of the major challenges facing the program.

Figure 8.3 – Navigation on the Rhine – Kembs lock
© EDF-Agence Rea/X. Popy & EDF-Lortscher



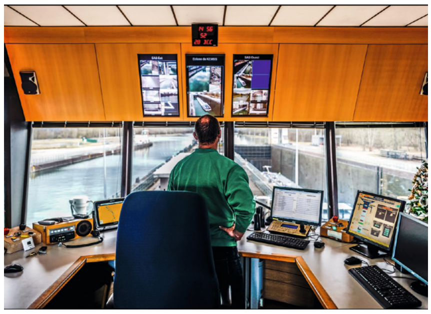
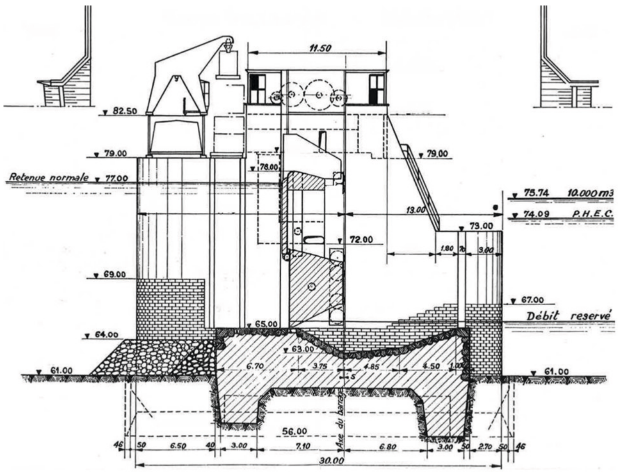


Figure 8.4 – Replacement of gates downstream of the lock chambers / *© EDF-AIRDIASOL/Rothan & EDF*

2.2 Civil structures and the problem of downstream scour

The first barrages built on the Rhône were the ones at Donzère and Rochemaure, both with their foundations on marl and, in the case of Donzère, also on limestone. Their hydraulic design, fine-tuned on physical models in the test laboratory, resulted in locating the hydraulic jump and the associated energy dissipation in a "bucket" type stilling basin. Initially, no specific protection downstream from this basin was planned.

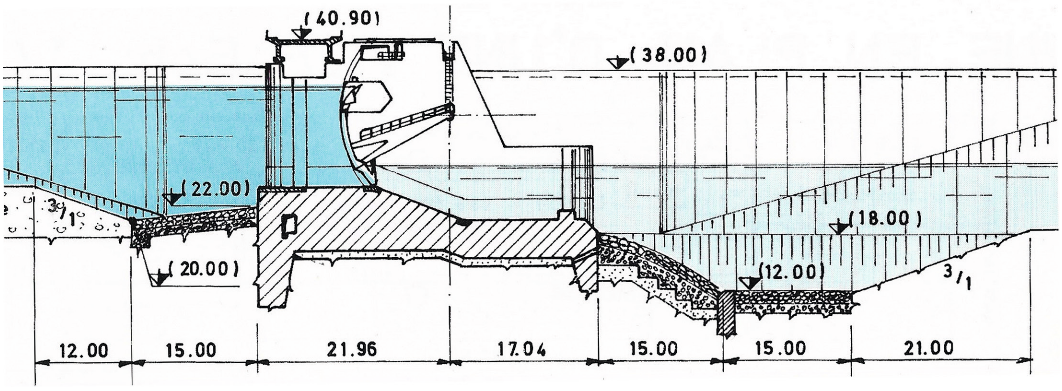
Figure 8.5 – Rochemaure barrage (Montélimar barrage – commissioned in 1957) / *© CNR*



The initial feedback quickly revealed a pronounced scour phenomenon immediately downstream of the basin, leading to fears of imminent undermining. Reinforcement measures were put in place, consisting of the excavation — controlled excavation in this case — of plunge-pools several meters deep and 10 to 20 m wide immediately downstream of the basin, which were then filled with riprap, with large rock sizes.

These protective measures downstream were then systematically studied on a physical model, resulting in a "Chatou" type design which proved satisfactory until the end of the sixties. A turning point came with the Roche-de-Glun barrage which, after being brought into service in 1968 with this type of protection, rapidly had to be reinforced. Also, after some new research and intermediate steps (Caderousse barrage brought into service in 1975), the design homed in on a new type of basin / downstream protection, called the "Gerland".

Figure 8.6 – Caderousse barrage (commissioned in 1975) / © CNR



For the studies of the Péage-de-Roussillon development, the hydraulic design of the Saint-Pierre-de-Bœuf barrage (1977) was the subject of a major innovation. Rather than attempting to stabilize the hydraulic jump and dissipate the associated energy in the pronounced bucket of the basin (involving a fairly large specific volume of the basin and fairly deep excavations for the foundation), it was proposed to "shift" it to break a few tens of meters downstream of the basin. In this zone, the creation of pools corresponding to the residual energy to be dissipated did not pose any structural problem to the barrage itself. The technical solution here consisted of making the basin substantially thinner, though still having a slight bucket, and of adding dissipation baffle blocks on its downstream section. The latter were used in conjunction with a sub-horizontal protective carpet, to shift the jump to break sufficiently far downstream of the structure. Since then, all the structures on the Rhône have been designed in this way which has proved to be entirely satisfactory in use.

Figure 8.7 – Pierre-Bénite dam / © CNR

The change in the design of barrage basins on the Rhône clearly illustrates the crucial aspect of the design of their downstream protection and the progress made over the years in terms of design. Monitoring scour downstream can reveal changes which, in some cases, call for a substantial re-design. The use of 3D numerical models helps optimize the design cost and associated timelines without, however, completely replacing the physical modeling and the analysis of feedback of experience. Very recently, the combination of physical and numerical modeling helped optimize the protection works downstream of the stilling basin of the Seyssel barrage (1951) subject to slow scour leading to fears of an undermining of the dam basin and the separating wall between the plant and the gate-structure. The approximately 17,000 m^3 of riprap required for these works were put in place in 2015, supplied by a 1.8 km navigable channel created for this purpose.

Figure 8.8 – Seyssel barrage – Aerial view and riprap works / © CNR

The Beaumont-Monteux works on the Isère river experienced scour phenomena downstream from the time it was brought into service (1921), due to the fact that its flat apron had no energy dissipation device. Successive reinforcement works carried out to stop this scouring did not provide any long-term protection. Molasse blocks, for example, were torn away downstream of the dam in the recent floods of 2008 and 2010. A 3D numerical model was used to simulate flows and to analyze them in terms of currentology, in order to define the operating scenarios relevant to the dam's design. The complexity of the phenomena required the studies to be continued on a physical model. All these studies led, in 2015, to the recommendation of an optimum solution preventing any scouring and undermining:

- a change to the dam management procedures to ensure symmetrical gate opening and the distribution of the flow released through all the openings;
- the creation of a stilling basin on the apron, comprising baffle blocks downstream of the gates and a lifting end sill;
- the stabilization of scoured areas by a carpet of riprap.

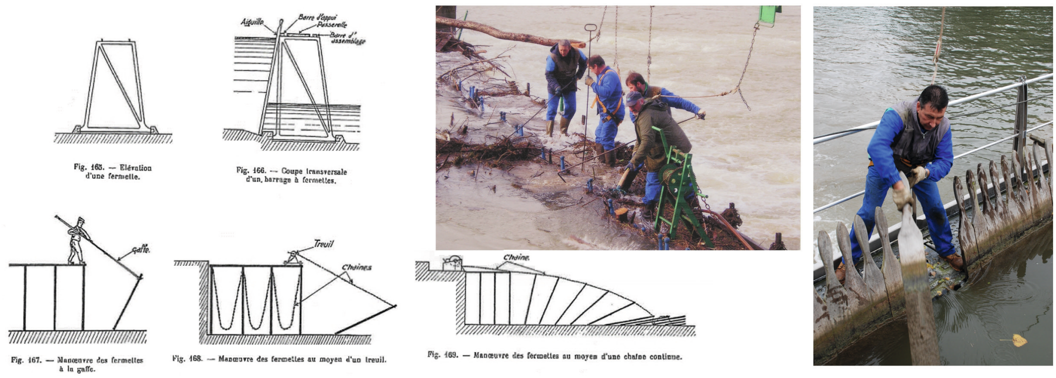
Figure 8.9 – Beaumont-Monteux barrage / © EDF-Philippe GROLLIER/PWP
and view of the physical model / © Artelia

2.3 Complete modernization of barrages

Voies Navigables de France (VNF) manages dams and barrages which are designed to maintain the water line in periods of low water, for navigation and other uses (canoeing and kayaking, fishing, withdrawals, leisure activities, hydropower production).

Some one hundred of these structures date back to the 19th century and no longer meet current operating needs. These manual dams (Poirée system, Aubert elevation devices, etc.) do not allow for accurate water level regulation and disrupt the circulation of fish species and sediments. Their operation also presents constraints in terms of the human resources needed, the risk exposure and the physical strain on dam operators.

Figure 8.10 – Illustrations of Poirée type barrage operation / © VNF



In the context of the modernization of French river infrastructures, VNF thus embarked, in 2004, on a program over several years, to replace these barrages, for the following purposes:

- to regulate the water level more reliably (response to navigation needs and to withdrawals and discharges of water);
- to provide a faster and safer response to the water level control of barrages during floods (reaching full opening in a short time);
- to reduce the risks to operators working on the structures;
- to restore old dams due to their poor general condition;
- to create fishways where there are none or where they do not work properly, in order to improve ecological continuity along the water course.

These modernization projects may cover an entire dam or a cascade, as in the case of the Vives-Eaux barrage and the Aisne and Meuse barrages respectively, described below.
The Vives-Eaux barrage. The Haute Seine route, on which the Vives-Eaux barrage is located, comprises 8 barrages and 15 locks.

Figure 8.11 – Old barrage in operation since 1928, fitted with Aubert flashboards / © Artelia

Figure 8.12 – Barrage brought into service October 23th 2019 / © Artelia – Hervé Abbadie

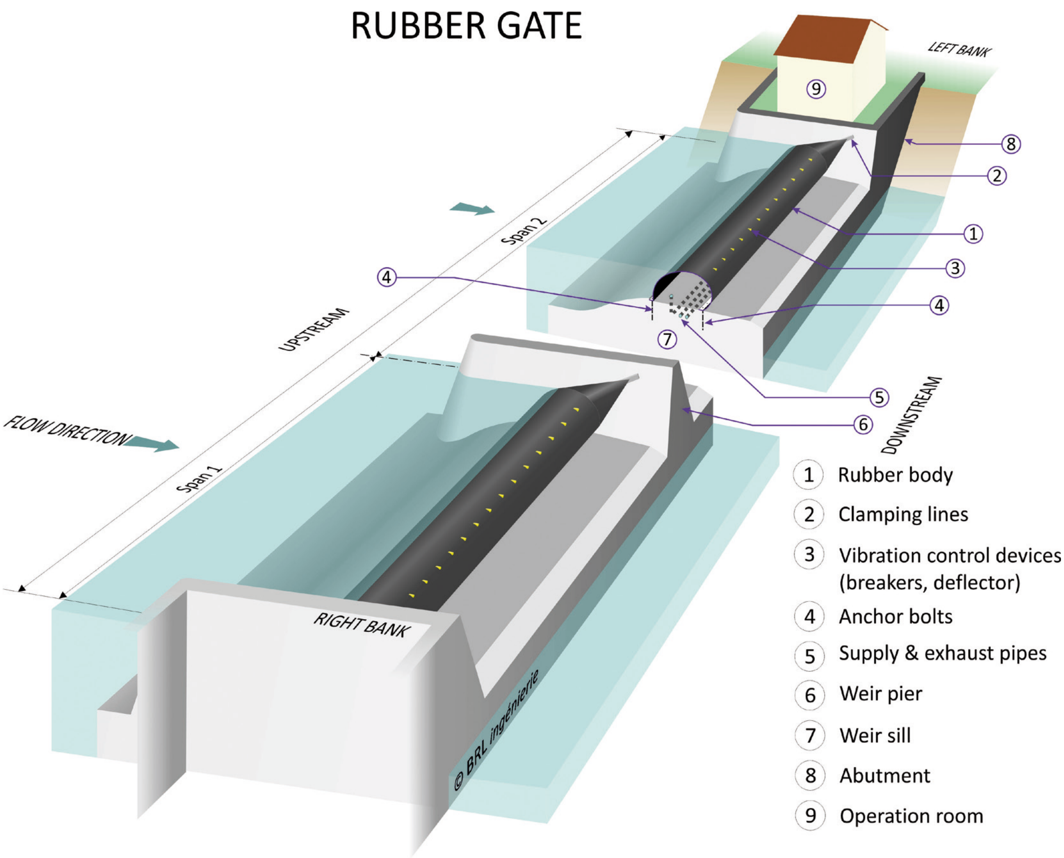
The renovation of all the barrages upstream of Paris involved implementing flap gates controlled automatically by a centralized system allowing their coordinated operation. The complete hydraulic modeling of the upstream part of the valley allowed the flow of flood waters through to Paris to be simulated, and, depending on the level of these flood waters, the degree and the timing of flap gate operation to be defined, along with the navigation conditions during these floods, in particular to identify the levels triggering navigation bans.
The rehabilitation of the Vives-Eaux barrage, built in 1928, and already refurbished with Aubert flashboards in the 1970's, for its part, consisted of the complete dry construction of a new barrage upstream of the existing one, while maintaining navigation conditions.

The Aisne and Meuse barrages. The Aisne and Meuse rivers comprise respectively 6 and 23 barrages to be refurbished. To address the challenges of consolidation, standardization and optimization of the management of these two catchment areas, in 2013 VNF signed a Public-Private Partnership with a view to replace, in the context of a single project, the 29 barrages by March 2020 at the latest and to operate a fleet of 31 barrages by 2043.

The rehabilitated structures will also be fitted with water-inflatable closure devices, over a total length of 2 km — a world record. The commissioning of four run-of-river hydroelectric power plants is also part of this project.

The technology of water-inflatable closure devices is based on the principle of communicating vessels: a number of pits (water columns) housed in a plant room on the bank are used to collect water from the river, raise the water level by pumping and bring it into contact with the membrane by means of a supply pipe to fill it, and drain the membrane by means of a valve or pump, depending on whether there is a head difference between the upstream and downstream reaches of the barrage.

Figure 8.13 – Diagram of water-inflatable barrage operation / © BRLi



Water-inflatable closure devices have many advantages:
- ease of operation;
- rapid deployment: 4 years to install 75 water-inflatable closure devices;
- adapted to the dimensions of movable passes with standardization possible (width classes from 16.80 m to 34.80 m and height classes from 1.75 to 2.86 m);
- integration in the landscape (no need of footbridge or external operating element);
- 30-year service life of membranes (resistance to abrasion, ice jams, UV, etc.);
- cost of works and operating costs often lower than for flap gates.

Figure 8.14 – Fépin barrage brought into service on February 2017 / © BRLi

3. ADAPTATION OF EXISTING DEVELOPMENTS TO NEW ENVIRONMENTAL AND SOCIETAL STAKES

3.1 Multiple uses of water and electricity

Multiple uses of water and adaptation to new energy challenges: Durance-Verdon case. The Durance-Verdon cascade of dams and barrages is run by EDF. It comprises two head reservoirs (dams of Serre-Ponçon and Sainte-Croix). It is described in detail in Chapter 1 "Multiple uses of dams".

The Provence-Alpes-Côte d'Azur region is also France's top solar region. This is why experiments bringing together gravity hydraulic and photovoltaic means of production have been carried out on the Durance basin. These experiments allowed intermittent variable production to be smoothened out and grid control services to be tested.

To address the significant challenges of sediment continuity on the Durance, a vast program was constructed within which numerous studies and diagnostics were carried out to build an overall management strategy (see next section).

3.2 Sediment continuity

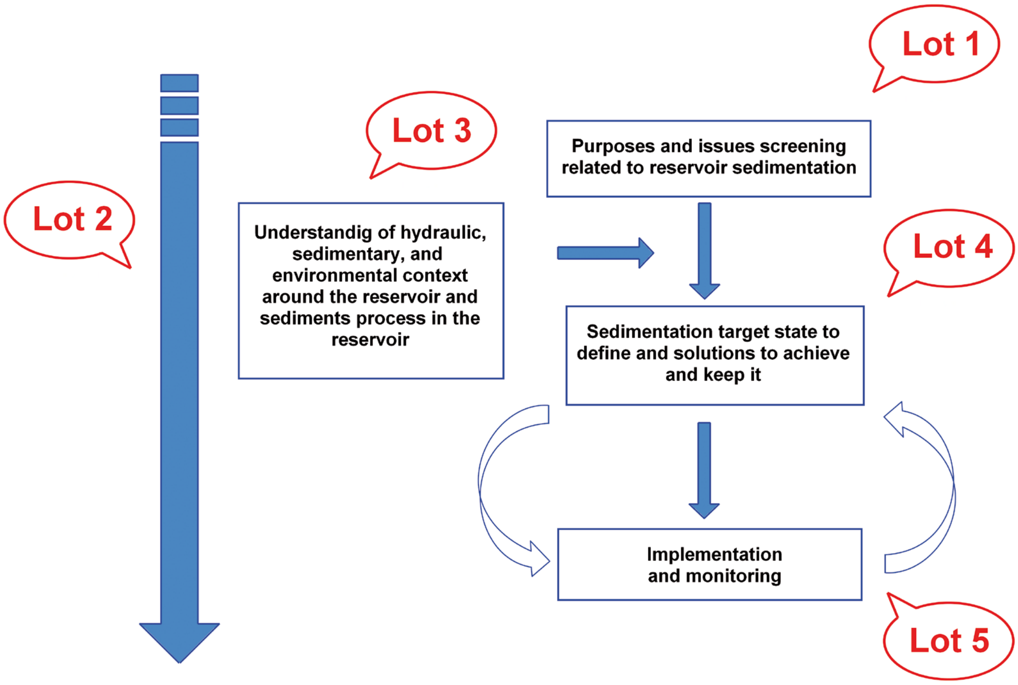
To cope with the multiple challenges associated with sediments on the barrages damming the rivers (power production, safety, environment in and downstream of the reservoir, multiple uses of water, etc.), on the Rhône river continuous surveys were done to map the river bed with a hydrographic boat, and also the accurate follow-up during the passage of floods was monitored by a dedicated team of hydraulic engineers. Furthermore, other solutions such as the target sediment state approach were deployed, the concept of which consists of defining the state of the bed of the reservoir compatible with the project's functions. Solutions (operation mode of structures, works) were then sought and enforced to move towards this target state and maintain it over time. The production of a summary document including all the stakes associated with sediments means that the operator can have consistent management over time. This document is, moreover, a tool for communication between all stakeholders. A broad monitoring program by recordings was implemented to understand the processes and evaluate the effectiveness of the solutions. A feedback loop was set up in order to adapt the solutions and the target beds if necessary.

As an example, on the Durance cascade, the coordinated management between Saint-Lazare and Mallemort schemes was put in place for the operation of the structures, while guaranteeing sedimentary transit transparency, the supply of a sedimentary support for the biology and non-aggravation of flood risks.

On other structures, reinjection actions were also carried out to compensate for the sediment deficit (see the example of the Rhine in Chapter 4 "Reservoirs and Environment").
On the river Isère, the operation of the Saint-Égrève barrage has been changed over the years thanks to improved knowledge about sedimentary transit functioning. Thus, management by hydraulic flushing was supplemented by a number of means to keep the beds of the reservoir within target levels, zone by zone (maintaining hydraulic flushing, dredging of particular zones, optimized operation of gates during floods, lowering of the upstream water level and constant efforts to maintain these measures to produce regular assessments).

On the Arc barrages, the sediment management means are designed to ensure the dispersal of tributary cones and thus to prevent flooding (see the example of Arc in Chapter 4 "Reservoirs and Environment").

Figure 8.15 – Illustration of the Target State approach / © EDF



3.3 Fish continuity

Fish migration transparency is part of any new dam and barrage project but can also constitute a complete program in itself where an existing structure is not equipped for this.
The "Rhône Mediterranean Migrator" plan launched more than 15 years ago has seen the construction of numerous fishways at the barrages on the Rhône.

Another illustration of fish migration transparency on barrage's concerns the site of Notre-Dame-de-la-Garenne on the Seine, which in 2011 had a new fish pass built on the island separating the gate structure from the locks.

This pass comprises an artificial river, 170 m long, allowing various species to get over the 4 m head. It comprises a channel with a shallow gradient, aiming to come close to flow conditions encountered in the natural environment. This was the first man-made river "with macro-roughness" of this size in France.

The principle of this river with macro-roughness is to spread the total vertical barrage head evenly over the entire surface area of the structure. The role of the chute blocks (macro-roughness elements) is to act as a hydraulic speed reducer and refuge for fishes (low-speed zone) immediately downstream. The roughness of the bed is a further place where fishes can rest and get their bearings.

The particular feature of the structure is that it comprises an unconcreted apron with macro-roughness composed of sheet piling segments driven into the ground, so as to reduce the speed of the flows and also ensure the stability of the base of the structure. For a more "natural" appearance, the structure was designed such that the sheet piles are always covered with a thin film of water, reproducing the effect of a riverbed.

Figure 8.16 – Dam, fish pass and locks of Notre-Dame-de-la-Garenne / © VNF

Figure 8.17 – Photograph of macro-roughness out of water and in water / © BRLi

This man-made river has, downstream, a control flapgate to maintain a head of around twenty centimeters guaranteeing the attractiveness of the structure. In addition to this flapgate, there is a specific ramp for small eels (elvers) to facilitate their passage.

4. INNOVATIVE NEW PROJECTS

4.1 The Seine Nord-Europe Canal project

The Seine-Nord Europe canal is the central link in the European priority Seine-Escaut project. This European project consists of the creation of a wide-gauge river link between France, Belgium and the Netherlands within the European multimodal North Sea – Mediterranean Sea corridor, in a multimodal logic, to more effectively connect other modes of transport, sea ports and inland ports in the North of France and Europe.

The Seine-Nord Europe canal project thus aims to remove the bottleneck between the Oise valley and the Dunkerque Canal at Valenciennes, for which the Canal du Nord is currently used; however, the latter's gauge being restricted to 700 tons, the presence of an underground gallery section limiting safe transit and the number of locks are brakes on the development of river transport and the creation of a multimodal inland port network. The project will improve the circulation of goods by water between France and neighboring countries, with a view to developing sustainable transport with greater concern for environmental constraints. This will help create and consolidate multimodal platforms and container terminals at regional, national and European level, gradually and in the long term.

The construction of this important project, 107 km in length, minimum 54 m wide to roof and 4.5 m deep, will comprise six very deep locks and one junction lock with the existing Canal du Nord, and a 1.3 km canal bridge crossing the Somme river. It will need 61 road and rail restorations and will comprise 4 business platforms with transshipment quays plus 3 further transshipment quays, 2 industrial quays serving local industry and 2 recreational boating facilities.

A dam which can store 14 million m^3 of water will supply the canal's highest reach. The entire project will call for major earthworks (around 60 million m^3 of earthmoving) and will comprise embankments over 20 m high over significant lengths of its route. Studies have been under way since 2005 and works are scheduled for 2020–2026.

4.2 Complete reconfiguration of a series of developments

Close to the Oisans mountains, the largest hydroelectric site under construction in France has been in progress since 2011. More powerful, better integrated into the landscape and more environmentally friendly, this new underground complex replaces the current 6 surface power stations and 5 barrages in the Romanche valley. This project optimizes the operation of the river.

The new water intake diverts water into a new 9.3 km entirely underground waterway replacing several kilometers of canals and penstocks which crisscross the valley today. The power station, comprising 2 caverns, is equipped with 2 Francis turbines for maximum 92 MW power and a mean annual output of 560 GWh, or 155 GWh more than the current 6 power stations combined. This 30% increase corresponds to the electricity supply for a town with a population of 60,000. The layout was put into service in October 2020.

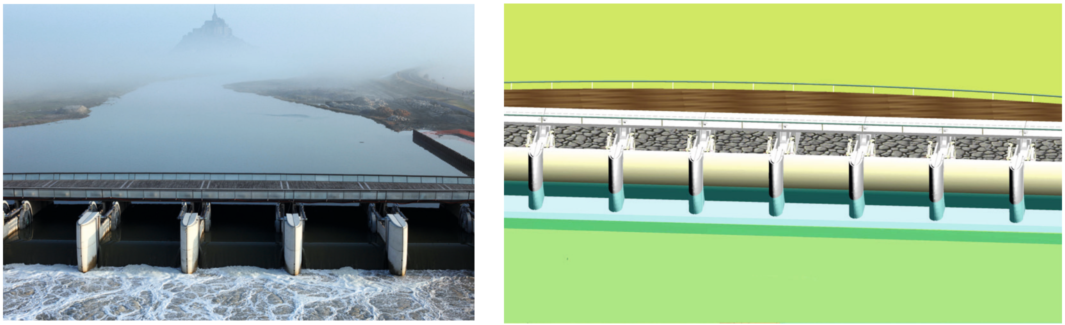
Figure 8.18 – The Livet barrage and water intake / © EDF-Christophe Huret

4.3 Restoration of the maritime character of Mont-Saint-Michel

The new Caserne barrage on the Couesnon river testifies to a "process of sustainable development of the territory preserving the identity and quality of the site". Silting at the foot of Mont-Saint-Michel has speeded up due to polderization, channeling of the Couesnon, construction of the dike road leading to the abbey and a flood control dam interrupting the river's natural flow. Rather than proceeding with mechanical dredging of sediments, the new dam uses the natural phenomenon of tides to remove, day by day, the sand gathered in the bay at the mouth of the river. The technical solution proposed — particularly smart for this unique structure — consists of creating a gate structure, with 8 hydraulic openings, 9 meters wide, equipped with radial gates. The barrage is open to the public. The gangway over the piers, the actuators and the large gates are exposed so everyone can see the way it operates, technical sophistication of the barrage and the French engineering expertise.

The barrage: the civil structures of the barrage are designed to prevent any differential settlement of the structure given the poor geomechanical characteristics of the soils on which it stands

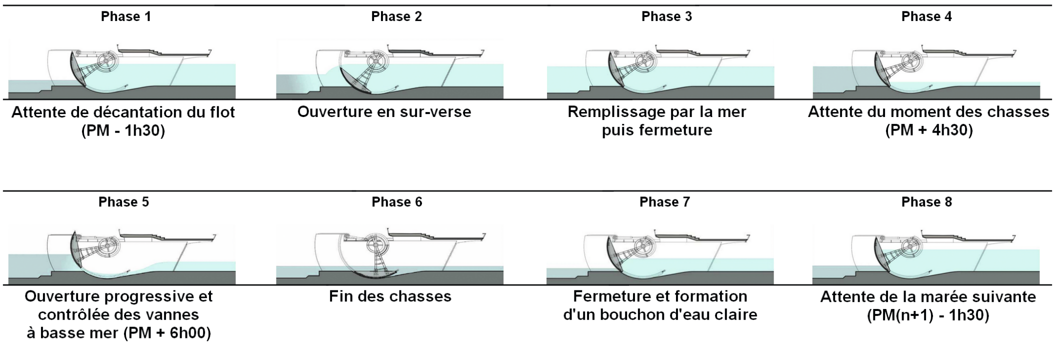
Figures 8.19 – Barrage commissioned mid-2009 / © Thomas Jouanneau et Modèle 3D (2005) / © BRLi



The equipment. The barrage's eight radial gates are designed in "line" and control close to 80 meters of water line during the operations of filling by the sea and of flushing with water. They are anchored to piers (maximum 8 m high, minimum 1.8 m thick), using prestressed bars. The main special feature was to position the gates in the opposite direction to the usual layout. This wise choice allowed a very compact barrage design with optimum hydraulic operation; the sluices disappear into the apron, their movement being secured by the removal of sediments carried by the tide, thereby keeping the structure unobtrusive when seen from Mont-Saint-Michel. Finally, the permanent movement of the sluices due to the cycle of tides makes it an unusual hydraulic structure.

Figure 8.20 – Actuators, arms and sluice actuators, at high tide / © BRli

Figure 8.21 – Operation of sluices during a tidal cycle / © BRLi



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CHAPTER

9

FLOOD PROTECTION LEVEES

1. INTRODUCTION

Levees (also called dikes) are raised structures, mainly embankments, built near coasts, rivers and artificial navigation routes, which are not regularly reshaped by the action of waves and current, and whose primary objective is to provide protection against flooding and / or to channel flows. This chapter mainly deals with the following types of levees:
- ***flood protection levees (fluvial, maritime, torrential, etc.) which often also have a function of erosion control;***
- ***embankments along canalized rivers (examples: Rhine, Rhône), which often have both the functions of canalization and flood protection; these dikes have a permanent, although variable, load.***

2. HISTORY OF LEVEES IN FRANCE

As in most developed countries, flood protection levees in France have been built, repaired, raised during successive flood events, and very often forgotten between two rare events distant in time. Recent national and international history reminds us of the interest of these works, of their being well designed and constructed and above all of continuing to maintain them so that they can ensure their function when a rare hydrometeorological event requires it.

2.1 "Old" history

In France, existing flood protection levees are the result of a long and complex history, where the function of flood protection was not always the only one, or even the main one, and have evolved over the development of the valley. This frequently explains the lack of knowledge about their internal composition and, therefore, the difficulties linked to assessing and diagnosing them.

River dikes have often originated from more modest structures, not necessarily watertight nor part of closed systems, the original purpose of which was to facilitate agriculture by reducing water speeds in the flood plain. These structures have been progressively raised over the centuries, generally after each major flood. During the 19th century the development of navigation on important rivers and during the 20th century the development of urbanization led to modifications linked to the functions of the works and of the systems that they compose. The levees then also serve as traffic lanes and are often also referred to as "causeways" ("chaussées" in French), which historically designates both the traffic function and that of the hydraulic barrier.

Coastal levees have also evolved over the course of history, from structures with different functions or from natural configurations: reclamation levees (reclaiming of land from the sea), levees for protection against flooding, separation of fresh and salt waters or defense against marine erosion, harbor works, or dunes. They originate from the increasing use of coastal land for the benefit of human activities, first for harbor development or for the reclamation of agricultural land on coastal marshy lands, before tourist attraction favored anthropization and the reinforcement of the seaside near the seaside towns. From modest earthworks allowing land reclamation and cultivation outside the periods of high tides, the structure of coastal works becomes more complex to fight against the often combined effects of agitation and erosion and to establish a multifunctional role in regional planning. They have thus gradually developed across all seaside environments (marshes, dunes, beaches, etc.) to promote the development and protection of human activities (industry, agriculture, tourism) against marine weather phenomena and the dynamic evolution of coastlines.

In mountain environments, on torrents and torrential rivers, levee systems are subjected to violent natural hazards, characterized by an intense sediment transport (bedload transport, even debris flow). These torrential phenomena are likely to cause significant morphological changes in the bed during floods and on its banks in the event of overflows. They are related to streambed displacements, bed aggradation, erosions, or even woody debris (log jams) that strongly modify flow conditions. Like river levees, the main function of torrent levees is to prevent overflows of torrential flows into protected areas, at least up to the level of protection. In doing so, they limit, sometimes strongly, streambed displacements of the watercourse and must resist the various deterioration and damage mechanisms to which they are subject (impacts, external erosion, generalized incision of the bed, localized scouring, localized impacts and shocks, overflow, etc.). They are thus exposed to violent actions resulting in particular from the intense sediment transport which characterizes torrential flows, but also potentially to other specific phenomena of the mountain environment (avalanches, landslides). For some torrential levees, defense against erosion and bank setback may even be the main function.

2.2 Recent history (since 1993)

2.2.1 The Camargue floods (1993-94) and their consequences in terms of organization and regulations

During the floods of the lower Rhône in October 1993 and in January 1994, multiple breaches and other damage occurred on the levees in the area. The breaches notably caused the flooding of Camargue Island (12,500 hectares and 450 houses flooded), causing heavy losses including the death of numerous bulls and horses. It was the starting point of a national awareness of the need to manage levees effectively and to work on the specific subject of levees at the level of engineering best practices, as well as in research and development and in the organization of state and local managers.

2.2.2 Other major events since these dates

Among major events, we can note:
- the 1999 flood of the Aude river: breaches in the town of Cuxac. A housing estate flooded under 2 m of water, several hundred houses flooded, 5 casualties (a total of 25 casualties in the department and 35 in the region, not all linked to levee failures);
- floods on the Agly river in 1999, 2013 and 2014: considerable damage, overflow areas and several breaches identified on the levees; the resulting floods caused significant property damage;
- floods of the Gard and Rhône rivers in 2002: breaches in Aramon and Comps in the Gard Department resulted in the flooding of inhabited areas and caused numerous victims (including 5 in Aramon) and considerable damage (1 billion euros);
- 2003 flood of the Rhône river: breaches caused the left bank (north of the city of Arles) and right bank (from the south of the city of Fourques down to the sea) of the Rhône to be flooded, causing a billion euros in damage in the area of the large Rhône delta and the flooding of 12,000 people;
- 2010 Xynthia storm on the Atlantic coast: the conjunction of strong winds and strong tides gave rise to a storm surge causing major flooding in coastal areas (mainly in the Charente-Maritime and Vendée departments); the consequences were very serious: 49 dead, 2.5 billion euros in direct damage and 200 km of levees needing to be rebuilt;

- torrential floods in June 2013 in the Hautes-Pyrénées and Haute-Garonne departments: this is the most recent torrential flood that caused damage across two departments, with several dozen buildings destroyed; several erosion breaches occurred on torrent levees and have led to rambling flows and changes of riverbeds; the economic damage was major (almost 80 million euros for roads and infrastructure alone).

2.3 Levees portfolio in France

The portfolio of flood protection levees was estimated at around 8,600 km in 2005 and, since then, extrapolated figures of 9,000 km of river levees and 1,000 km of coastal levees have been regularly repeated. This is an order of magnitude from a census and not a total from the regulatory classification of levees or systems.

3. EXAMPLES OF PROTECTION SYSTEMS

Flood protection levees work within systems that protect an area against floods up to a certain level. These systems can include levees, other works whose main function is or is not flood protection, as well as natural elements. We present below several examples of protection systems that illustrate the diversity of issues and systems.

3.1 The lower Rhône river

The levees of the Rhône delta (about 250 km) were significantly raised after the great floods of 1840 and 1856 in place of older works, some of which dated back to the 12th century. Qualified as "not submersible" (see 4.4) at the time, these works, which protect more than 100,000 people and three times more during the summer season, showed their limits during the floods of 1993, 1994, 2002 and 2003. During these events, 17 partial breaches and 12 breaches, mainly caused by internal erosion, were identified. In the aftermath of the 2003 centennial flood, the State and regional authorities implemented a vast flood prevention plan on the scale of the catchment, called Plan Rhône, which notably provides for the complete renovation of the Rhône Delta levees over 20 years.

Rather than raising the levees, the option to accept flooding during rare floods (return period 100 years upstream of Arles and 50 years downstream) while considering the breaches as unacceptable until exceptional floods (return period 1,000 years) was decided. This choice involves in particular the creation of segments of levees resistant to overflow, which consists of reinforcing the embankment slope on the protected side with concrete riprap in order to withstand high velocity in the event of overflowing. Upstream and downstream of these segments, the crest of the levees is set 50 cm above the millennial flood to avoid any risk of overflowing.

In addition to safety and protection objectives, environmental objectives have been defined and integrated into the levee system design. The structures built along the river are taken down and rebuilt 50 to 100 meters from the river in areas without environmental issues, thus avoiding the destruction of riparian environment. In the space given back to the river, wetlands are restored or created and allow riparian forest to expand, thereby creating an ecological "wall" against the risk of scouring of the banks.

The structures have been designed to guarantee their safety and durability for the next 100 years. The project optimized the recycling and transportation of materials and thereby reduced the site's carbon footprint. Out of the 400 million euros of investment planned, 50% has already been realized.

Figure 9.1 – Strategic setback south of Arles (left) and construction of an overflow resistant levee (right) / © Symadrem

Figure 9.2 – Construction of an overflow resistant levee with all the components needed for its safety and durability (watertightness, filtration, drainage, spilling) / © Symadrem

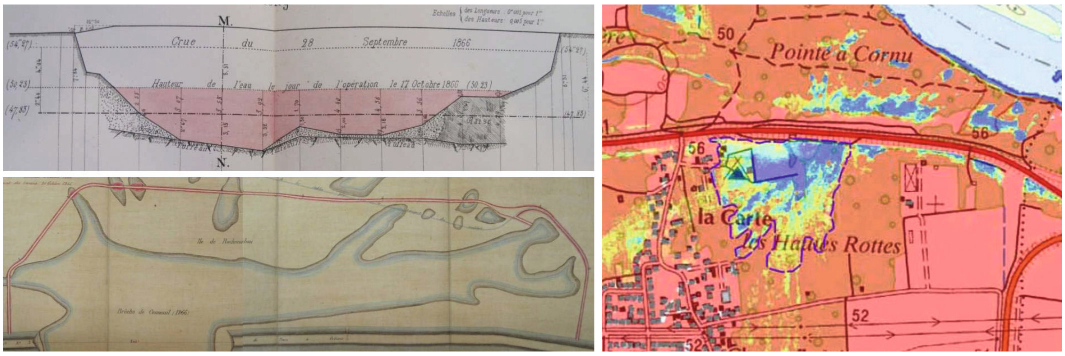
3.2 Loire moyenne

The Loire is the longest river entirely in France, with a length of 1,012 km. The middle course of the Loire River (Loire Moyenne in French) indicates the stretch of river from its confluence with the Allier to that in the Maine, between the cities of Nevers and Angers. It is characterized by a minor bed that is part of a wide valley almost completely protected by levees, also locally called "levées" in French. They form a quasi-continuous embankment along each bank, totaling a line of levees of more than 500 km (main defense line). These structures delimit around forty protected areas, sheltering nearly 300,000 people, with major agglomerations such as Nevers, Orléans, Blois and Angers.

These levees have a history that goes back to the Middle Ages: the oldest historical reference is an ordinance of Charlemagne from 779 AD regarding the Loire Angevine (around Angers). The first writings corroborating the role of levees for protection against floods date from the 12th century, after a significant flood in 1150. Until the 19th century, many floods led to repairing, reinforcing and raising the levees until the design of the current protection systems was reached. The database on the Loire levee breaches and damage is certainly the richest in France, with, in particular, the identification of nearly 390 "breaches"(1) from three major floods in the second half of the 19th century. The history of the Loire levees has shown that inflation of the construction of protection structures did not make it possible to protect populations and property from the devastating effects of major floods and may even have amplified their consequences.

So, from the second half of the 19th century, reflections on the "share of water", that is to say the need to allow the expansion of floods in certain parts of the protected area by means of spillways or lower levees, were generalized and accompanied by the implementation of a program of reliability of the embankments discussed with the residents.

Figure 9.3 – 1866 breach (250 m) in the levee from Tours to Conneuil: longitudinal profile, principle of emergency repairs and modern digital elevation model of the erosion pit / *© Archives départementales et DREAL Centre-Val de Loire*



An example: the Orléans levee

The Orléans levee designates a protection system composed of 43 km of first-row levees (main defense line), 5 to 7 m high, and a weir in the upstream part of the system, in the town of Jargeau, created after the great floods of the end of the 19th century.

The "Val d'Orléans" protected area, located on the left bank of the Loire and at the confluence with the Loiret, covers an area of 16,700 ha with 61,800 inhabitants and nearly 21,000 jobs spread over the territory of 16 municipalities. Fourteen breaches were described during the three major floods of the 19th century), most of which were caused by overflowing. The width of the breaches varied from 50 m to 800 m in length, and from 5 m to 19 m in depth from the top of the levee.

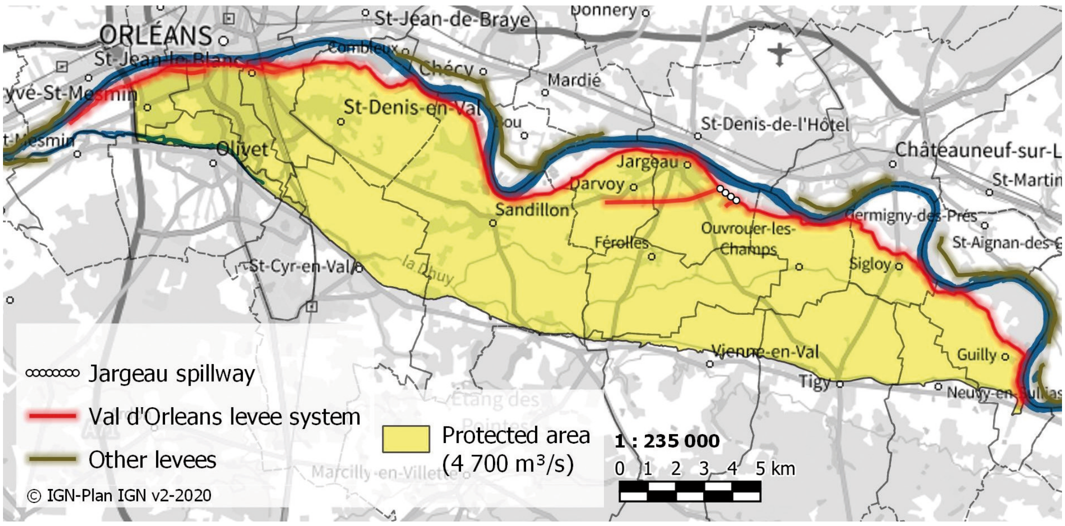
(1) The quotation marks come from the fact that the now clearly established and shared definition of breach (complete opening of the embankment from one side to the other) may in the past have designated major damage not going up to the breach.

Figure 9.4 – Spillway of Jargeau (Val d'Orléans 45): from left to right unprotected area, fuse, non-erodible downstream slope, dissipation zone and protected valley /
© Rémy Tourment

The 2012 hazard study (see 5.1) of the Val d'Orléans and the additions made in the context of the 2019 administrative authorization of the levee system (see section 5) made it possible to define or specify the following characteristics of the protection provided by the system against flooding of the Loire River:

- in appearance, and considering only the crest level of the levees, the valley would be protected, except in the case of failure before overflow, against the Loire floods up to an annual probability of 0.005 (return period of 200 years) and it is open downstream at the confluence with the Loiret, which excludes this part of the valley from the protected area;
- the safety level of the levees (probability of failure becoming significant) is estimated to correspond to an annual probability of the river flood of 0.014 (return period of 70 years);
- the spillway, located upstream from the town of Jargeau, was built at the end of the 19th century in order to make the system resilient to overflowing; nevertheless, the evolutions of the river bed since that time mean that overflows occur in several places of the system at the same time as the overflow on the weir (return period of 200 years);
- considering the safety level of the levees, the guaranteed protection level of the area is 4.7 m at the reference scale, that is a flow rate of 4,700 m³/s in the Loire (return period of 70 years).

Figure 9.5 – Levee system of the "Val d'Orléans" and associated protected area /
© DREAL Centre-Val de Loire



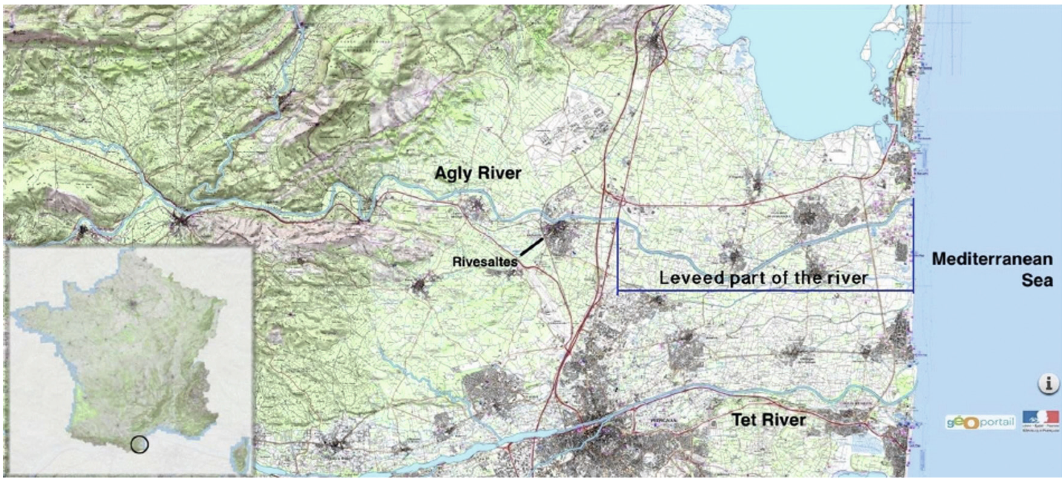
The hazard study also made it possible to define a certain number of risk reduction measures, including the reinforcement of levees in order to prevent their failure before the flood level reaches the crest level (apparent level of protection).

Figure 9.6 – Reinforcement works on the Loire side slope (left) and waterproof "deep soil mixing" screen in the levee of Orléans (right) / © DREAL Centre-Val de Loire

3.3 The river Agly

The last downstream 13 kilometers of the Mediterranean coastal river Agly are bordered by levees. The catchment of the river upstream from the leveed corridor has an area of 1,044 km². Between 1969 and 1974, the riverbed was recalibrated by increasing its width from 30 m to 65 m and a continuous embankment of about 3 m in height was erected at the top of each reprofiled bank. These structures currently protect around 30,000 people.

Figure 9.7 – Situation of the downstream part of the river Agly / © IGN Géoportail



According to the design studies (1967), this development was supposed to be able to contain a 25-year return flood, whose flow was estimated at 1,250 m³/s, with a freeboard of 0.5 m under the levee crest. The initial project had planned two 600 m safety spillways (one on each bank) to limit the flow. These spillways at the upstream end of the leveed corridor were never built.

Figure 9.8 – Breach on the Agly levees in 1999 / © DREAL Occitanie

The levees have suffered from many floods (7 times in 18 years) that have caused damage. Following the 1999 flood (highest flood undergone by the levees, with overflowing resulting in a major breach of 70 m and ten partial breaches), local crest raising of about 0.5 m high was carried out, on the land side. These raisings, for a total length of about 1 km, are made up of concreted riprap.

The floods of 2005 and 2006 caused more damage, but without overflowing. These floods led the manager to initiate an in-depth diagnosis aimed at deciding on the levels of protection and security offered. This diagnosis highlighted:

- a relatively low capacity of the leveed corridor, in the order of 800 m³/s (almost two times less than the value predicted by the design studies) corresponding to a flood with a return period of between 5 to 10 years;
- structural fragility of the structures and their foundations, the compositions of which are heterogeneous with the presence of permeable gravelly materials ($k \sim 10^{-3}$ m/s) and uniform fine sands that are particularly sensitive to internal erosion.

The conclusions led to estimate that a failure was almost certain for a 10-year flood. This point was later verified with:

- March 2013 flood, which generated overflows over several kilometers, two breaches, one of which of was over 80 m in length, and much damage caused by internal erosion of the levees and their foundations (including hundreds of sand boils, some having generated slope instabilities);
- March 2014 flood, which led to slight overflows and new damage due to internal erosion;
- January 2020 flood, which once again led to overflows over the levees and new damage (erosions and sand boils).

For these last three floods, people living in a strip of 300 m along the levees were evacuated as a preventive measure due to the risk of breaches.

A reinforcement program was proposed in 2014 with one or more safety spillways and without changing the level of protection. Despite the criticality of the system, the probability of failure and the severity of the consequences of failure all being high, this project is not currently carried out due to:

- the difficult social acceptance of safety spillways;
- the difficulty in obtaining the land necessary for the works and limiting their environmental impacts;
- the high investment cost (estimated at around 45 million euros) with regard to the level of protection obtained (return period 5 to 10 years).

3.4 Saint-Malo

The center of the historic town of Saint-Malo in north-eastern Brittany, is surrounded by medieval ramparts rebuilt after the Second World War. It is implanted on rocky islets which are connected to the east with the cliffs of Paramé by a dune ridge and used to be separated towards the south from the islet of the town of Aleth and from Saint-Servan by a marshy zone. The dune ridge therefore protected an inland bay and a retro-littoral maritime marsh on the right bank of the estuary of the Rance river. The drying up of this depression from the 14th century and the progressive embankments since the 18th century allowed the extension of the harbor and the town districts, especially around the train station. The coast, which remained natural until the 16th century, was gradually transformed by the extension of harbor activities and by major works in the 19th and 20th centuries leading to coastline fixation, land reclamation, harbor facilities and the development of seaside urbanization.

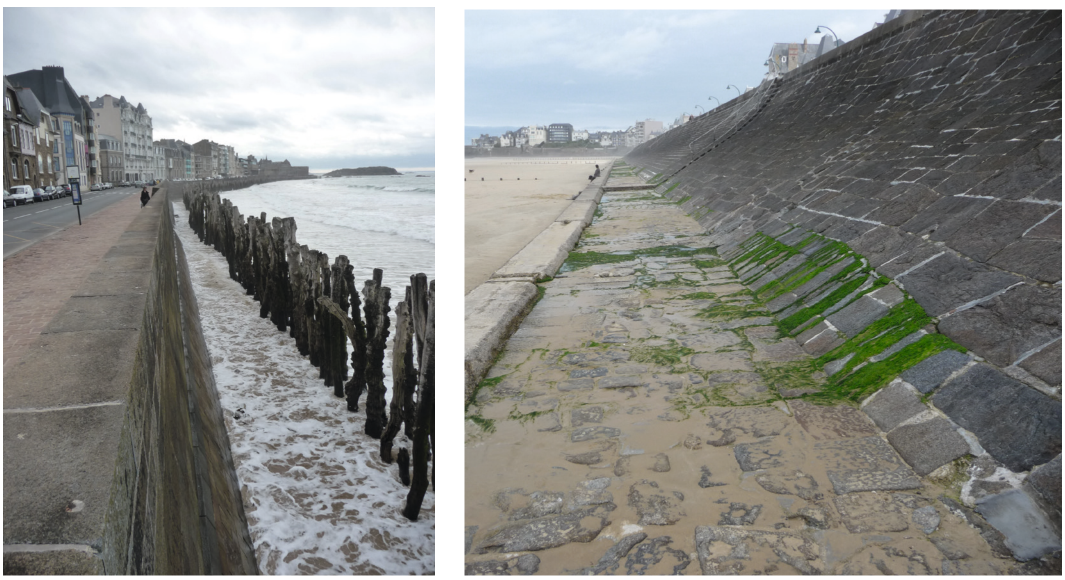
The Saint-Malo levee system is therefore made up of a complex succession of coastal structures including:

- a dune ridge that is now totally artificially reinforced by dikes over a length of 3 km (Palmié, Paramé and Sillon dikes);
- the ramparts which surround the old town for almost 1 km;
- harbor facilities inserted into the urban fabric and characterized by the presence of 4 tidal basins surrounded by quays;
- all this is supplemented with ancillary works, such as spikes or stakes, aimed at fighting erosion phenomena or reducing agitation.

The historical study of marine weather and hydrodynamic events reveals that the main phenomena affecting Saint-Malo's levee system are, in order of importance:

- overtopping all along the entire length of the Sillon and Paramé levees;
- deterioration of structures and erosion: also concerns the Sillon and Paramé dikes, but may also affect to a lesser extent some parts of the ramparts;
- overflowing: mainly concerns the harbor facilities (Saint-Malo and Bas Sablon) up to the cove of Solidor, due to their low altitude essential for their maritime uses.

Figure 9.9 – Sillon and Paramé levees / © Cerema



4. TECHNICAL CORPUS

Flood protection levees, like those of canals, are hydraulic structures comparable to dams, but which differ in their specific features. The basic disciplines, geotechnics, civil engineering, hydrology, hydraulics… are the same but are used differently. Thus, the abundant literature devoted to dams can possibly be used for levees, but not always directly or without adaptation or transposition. CFBR in 2012 and more recently ICOLD [Tourment, 2018] officially integrated levees alongside dams in their scope, which will ultimately make it possible to have recommendations applicable to levees specifically, or common to dams but explicitly. One of the productions expected from the new ICOLD technical committee LE on levees is a dams-levees inter-comparison report which will clarify the similarities and differences between dams and levees and allow future work benefiting the whole community of hydraulic structures.

4.1 CFBR guidelines

CFBR guidelines for the justification of embankment dams and levees [CFBR, 2015] propose the harmonizing of engineering practices relating to the stability of hydraulic embankment structures in France. The format of the justifications is consistent with that of the French guidelines on gravity dams, ultimately leading to a coherent set of professional guidelines. These guidelines adopt the format of semi-probabilistic limit state methods, like the Eurocodes, which constitute a standard framework, well suited for harmonizing practices. The structures falling within the scope of the CFBR document explicitly include flood protection river levees and permanently loaded levees (canals, canalized rivers). The limit states considered in the current version of the document are global stability (sliding), hydraulic uplift at the downstream foot and the lack of bearing capacity of the foundation / settlements.

These guidelines applicable to embankment dams and levees will be extended to the damage and failure mechanisms of internal erosion and external erosion.

The CFBR working group on levee refurbishment techniques publishes the results of its work in 2021. Based on around forty fact sheets, each describing a repair or reinforcement technique applied to levees, the guidelines are organized into chapters, each devoted to a function or a problem: sealing, drainage and filtration, stability, including crest raising, external protection, included and crossing structures, transitions, vegetation and burrowing animals.

4.2 International Levee Handbook (ILH)

The International Levee Handbook [CIRIA, 2013] is the international reference on flood protection levees. Published in 2013, it has been the subject of five years of work by more than 130 main contributors. It includes ten chapters with 1,350 pages in total. France was one of the most active countries in its drafting, alongside Great Britain and the USA, without forgetting important contributions from the Netherlands, Germany and experts from several other nations. Beyond its participation in the steering committee, the technical editorial team and in leading three of the ten chapters, France organized the final workshop that ended with an inauguration ceremony in the town hall of Arles. The French translation was released in early 2020.

4.3 Other initiatives

In response to the need for common terminology and approaches in the profession, the Ministry in charge of the Environment has commissioned a working group to publish a “Levees Referential”, the aim of which is to be a common technical base allowing a mutual understanding between the actors of the field (levee managers, State services, engineering consultants, other flood risk or territorial managers) during their exchanges. It is not a prescriptive or regulatory document. The concepts and principles presented are for the purpose of clarification and sharing of vocabulary and even of certain methods.

In a recent history, the first guides published in France specifically on flood protection levees came out from 2000 and were based on works carried out since the first floods of the 1990s: [Mériaux, 2007] [Fauchard, 2007]. In addition to these works, the profession as a whole contributes to the dissemination of knowledge during scientific and technical conferences, regularly organized by CFBR in connection with themes similar to dams, by SHF (https://www.shf-hydro.org/) on themes related to hydraulics and hydrology, or during three conferences specifically related to levees (2004 Orléans, 2013 and 2019 Aix-en-Provence).

4.4 *Risk analysis and hazard study*

The risk analysis of flood protection systems has been the subject of a recent methodological development [Tourment 2019]. The proposed methodology makes it possible to assess natural hazards, the performance of the protection system and the consequences of floods in the protected area. It is one of the most complete studies of a system, taking stock of knowledge and making it possible to guide decisions relating to the management or modifications of the system. A risk analysis is based, among other things, on a diagnosis of the works making up the system, including hydraulic and structural diagnosis. This diagnosis should make it possible to determine:

- the system's protection level (water level in the natural environment up to which no water enters the protected area) to be declared by the owner and for which he must, in France, comply with regulations ensuring a probability of failure of less than 5%;
- the system's safety level (water level up to which the works have quantifiable safety margins with a negligible probability of failure in regard to all failure modes);
- the danger level (level beyond which the structure no longer has quantifiable safety margins; there may be hidden margins that the engineer cannot quantify; the probability of failure becomes significant (around 1/10 or more, depending on authors);
- the level of security of the local populations (level up to which the populations in the protected area are not in danger).

In terms of decision support, a risk analysis can usefully be supplemented by a cost-benefit analysis and a multi-criteria analysis, as described for example in [Cheetham, 2016].

4.5 *Safety spillways and hydraulic design of levee systems*

Levees, and more specifically, levee systems, protect against flooding up to a certain level. Beyond this level, whether by overflow, bypass or structural failure, the protected territory will be flooded.

The question of the residual risk of flooding in areas protected by levees is crucial in terms of understanding and managing the flood risk in these territories.

In order to avoid breaches when the level of protection of a levee system is exceeded, the system should have a certain resilience to overflow and, in the case of river levees, this involves defining low points (without levee) or safety spillways, allowing "controlled" flooding of the protected area and therefore minimizing the consequences of this flooding. A handbook [Degoutte, 2012] presents the different types of structures on river levee systems, it addresses their functional aspects, hydraulics, river morphology, civil engineering and the management of flood situations. Its translation into English is published in 2021.

Engineers have been trying in past centuries to design "non-submersible levees". This was the case on the Loire and on the Rhône. This concept of "non-submersible levees" has to be banished from our vocabulary because:

- it is ambiguous (never submerged, or not resistant to submersion?);
- apart from colossal works it is not possible that a complete system of dikes will never be exceeded; moreover, on a river, any increase in the level of protection of a system leads to a rise in the level of floods and therefore the risk of overflow on other systems;
- it can give a false impression of unlimited protection to the population in the protected areas.

Spillways, while being necessary for the population safety, are hard for people to accept, who sometimes prefer to be satisfied with the existence of the risk of devastating floods by breach in a random manner rather than a controlled flood on sectors dedicated for this purpose. Discussion and education during public meetings are essential. On the downstream Rhône, where 10 km of overflow-resistant dikes were built between Beaucaire and Arles, more than twenty meetings were necessary over 5 years. The semantics have evolved during meetings with the population. We have thus progressively gone from the administrative term of "safety spillway" to "overflow levee" to finally retain "levee resistant to overflow".

The design of levee systems can be done in a similar way to dams by choosing a crest level for the spillway corresponding to the protection level and by setting the crest level of sections not resistant to overflow at the level of exceptional floods (variable depending on the protected assets) plus a freeboard. The length of overflow-resistant sections is often conditioned by the impact on the water levels upstream, downstream or on the opposite bank of the river. The non-aggravation of water levels, which is one of the founding principles of French regulations on water structures, often requires the creation of long overtopping segments.

For small protected areas, so as not to set the crest level of levees that do not resist overflow to exceptional occurrences of floods, some damage on these sections can be accepted, provided that the protected area has been pre-filled before overflow, so a sufficient mattress of water at the foot of the structure at the time of the spill on the unreinforced sections can prevent their breaching.

The hydraulic design is done for the whole system: watercourse, levee system, including spillway(s) and levees not resistant to overflow, protected area. In some cases, it is necessary to design complex systems with several rows of levees and to consider nearby systems (upstream, downstream, opposite bank) [Cheetham, 2015]. The design uses modeling, generally two-dimensional, the uncertainties of which must be clearly displayed and taken into account in the general calibration and design: uncertainties specific to the model, future morphodynamic changes and development of the vegetation (the impacts of which can be considerable, as shown by studies carried out on the Agly river).

As far as possible, these uncertainties can be assessed and should be reduced. They must be monitored with a strong commitment from the contracting authorities in terms of hydrometry (measurement scales, flood gauges, post-event flood leash survey) and by monitoring vegetation and bathymetry. As such, recent developments in camera gauging constitute a particularly interesting innovation.

4.6 *Focus on some innovative techniques*

4.6.1 Use of drones for levee surveillance

Inspection and monitoring of levees and more particularly of flood protection levees, pose specific difficulties due to the length of the structures, their heterogeneity and the absence of permanent load. Levee surveillance therefore remains largely based at the moment on visual inspection. The use of airborne means for the collection of topographic data (LiDAR DEM) and images or even high-resolution videos, tested in 2006 on several levee systems, allows a complement to this traditional method of inspection.

The DIDRO project [Boggio, 2019] aims to provide ready-to-use solutions for levee surveillance, both during normal periods and during hydrometeorological events (river floods, sea surges or storms), or even crisis (flooding of the protected area resulting from a breach and / or an overflow) by combining several sensors (HR photos, LiDAR, photogrammetry, thermal infrared, near infrared, etc.) on-board drones; DIDRO goes as far as assistance with the visualization of this data to help assessment experts and project managers in their decision support roles.

4.6.2 Fiber optics

Fiber optics are increasingly used for early detection of water seepage. Various experiments have been carried out or are in progress. On the Rhône river, 23 km of optical fiber have been integrated into the drains of newly reconstructed levees. This equipment, conducted on an experimental basis, should make it possible to distinguish regular seepage from progressive leaks indicating an ongoing internal erosion process in the embankment.

4.6.3 A GIS for levee managers' data management

The management of levees and associated engineering tasks (assessments, risk analysis, reinforcement design) relies on a great deal of data and in return also produces a large amount of data. This mass of data has a production (or reconstitution) cost, we rightly speak of "data patrimony". In order to improve the management of this wealth of information about their levees, several managers have joined forces, on the basis of an initial design by Cemagref, to develop and deploy SIRS Digues in 2004. The computer tool, which combines the functions of a GIS with those of a database, makes it possible to manage information on the various components of the "leveed" system: structure and geometry of the levees and the river bed, hydraulic structures, transportation infrastructure, communication and energy networks, incidents and damage, flood history, land use, works and studies, organizations and stakeholders. It therefore facilitates all the tasks of the manager and the engineers who act on his behalf.

The national association of dike managers, France Digues, is now the contracting authority for SIRS Digues; it proceeded with the development of V2 and is in charge of its subsequent maintenance, in connection with a growing base of user managers.

The new modular architecture of V2 makes it possible to envisage the development of new modules: vegetation (description and management), assessment assistance, etc.

4.6.4 Lime reinforced embankments

Lime treatment is commonly used to improve and stabilize loamy and clayey soils, as part of infrastructure construction. The interest of this technique for embankment hydraulic structures is growing. Indeed, it has been shown during research programs that the soil-lime material can effectively fulfill a series of functions for hydraulic structures: stability, low level of permeability, resistance to internal and surface erosion. Laboratory-scale experiments and full-scale works, as well as feedback from experience in France and around the world, have supported these findings.

In France, the cofferdam installed upstream from Pannecière dam (17 m) during reinforcement works (2011-2013) was built in granite arenas treated with hydraulic road binder. When re-filling the dam, this cofferdam was not removed but supported overflow without apparent damage.

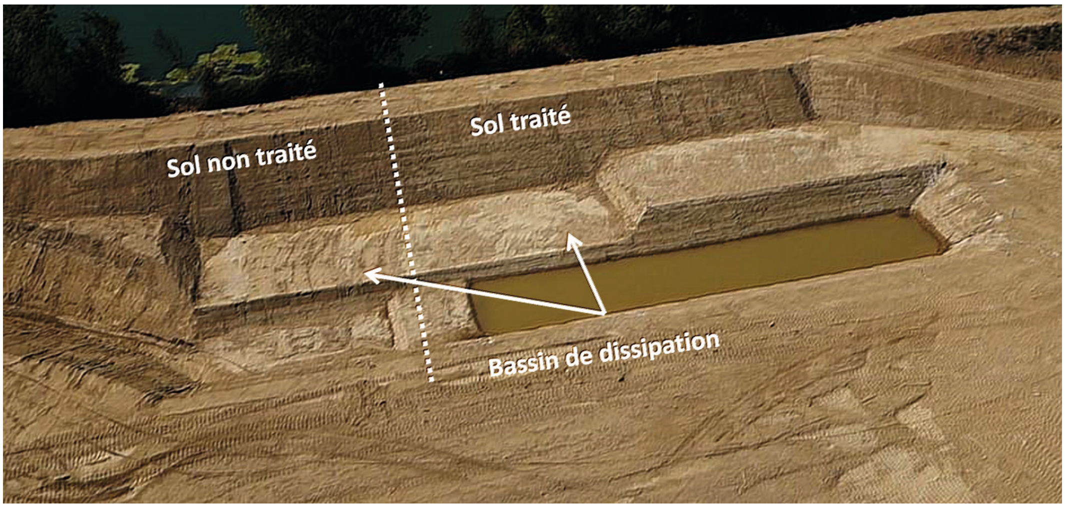
Figure 9.10 – Pannecière cofferdam being built et being overflowed / © BETCGB/ISL

Other significant older works have also used lime-treated soil to improve workability and stability. We can mention Fond Pignon dam (37.5 m – 1987-1990) made from lime-treated chalk, or Michelbach dam (22 m – 1982) whose upstream blanket has been treated with lime.

In order to improve knowledge of lime-reinforced embankment hydraulic structures and to explore innovative designs for such structures, innovation projects have been launched.

Between 2013 and 2018, the DigueELITE R&D project focused on the resistance to overflowing of a levee in lime-treated soil along the Vidourle river (Gard, France). This resistance could be quantified using an innovative in situ overflow test device, resulting from the project. This project, and in particular the resulting concept of levees and small dams resistant to overflow, was awarded the ICOLD Innovation Award at the Vienna Congress (2018). Regarding this project, we can also refer to chapter 5 § 3.2 and chapter 7 § 2.9.

Figure 9.11 – Aerial view of the construction site for DigueELITE / © INRAE



Since 2018, the DIGUE 2020[2] project aims to build and monitor an experimental structure in lime-treated soil in a fluvial-marine environment with a high-yield method (in situ treatment). It will make it possible to assess the impact of salinity and to study resistance to wave action, the objective being to control the construction and maintenance costs of coastal levees. The levee is currently under construction (April 2020).

Finally, as part of the Seine-Nord Europe Canal project, a new wide-gauge navigation canal 107 km long, an investment of more than 3 billion euros, experimental sections in treated soils (lime, bentonite and cement) are planned to study the feasibility of an economical alternative for sealing and protecting against erosion dikes of nearly 10 m in height.

5. REGULATION AND ITS DEVELOPMENTS

Prior to any regulation on flood protection levees, the French government acknowledged the need to have a better understanding of the national levees' portfolio and the associated stakes (protected assets, risks). Since 1999, a census has been undertaken for this purpose. In view of the importance of this portfolio, regulations have gradually been put in place: first a circular requesting the classification of dikes "of interest to public safety" (2003), then more complete regulations (Decree and its orders of application) on the Safety of Hydraulic Structures in 2007, which defined four classes of dams and levees, each with their own obligations, adapted in 2015 following the implementation of the GEMAPI competence (management of aquatic environments and flood prevention). For levees, the 2015 regulations specified the management scale: levee systems.

(2) Co-financed by the European Regional Development Fund, State Fund, PACA Region and Departemental Council 13.

5.1 Technical regulations

In essence, the technical aspects of the regulation aim to clarify the obligations of those responsible for structures (levee system managers with regard to levees) in order to ensure the safety of populations. These elements also allow good asset management due to:
- knowledge and surveillance of the structures (structure file, register, organization document, inspection and monitoring reports);
- detailed visual inspections;
- hazard studies including full technical examination (previously also safety assessment);
- declaration to the authorities of events or developments involving, or likely to jeopardize, the safety of people or property.

The structures file, the register and the organization documents must be kept up to date continuously; inspections, examinations, assessments and risk analyses must be carried out at a frequency depending on the class of the levee system.

A regulatory hazard study for a levee system must be based on an analysis of the risk of flooding its protected area (see 4.4), taking into account the existence of the system, its performance (and therefore, on the contrary its possibility of failure). It must justify the level of protection guaranteed by the system(3).

In addition, consultants working on behalf of managers must be approved for carrying out safety assessments and risk analyses or projects for creating or modifying structures; in the case of works, the project manager must ensure the entire mission (design + implementation).

5.2 Governance

One of the main difficulties with regard to the appropriate management of flood protection structures was a lack of local managers:
- at the level of hydraulically coherent protection systems;
- with sufficient technical, human and financial resources.

The implementation of the GEMAPI competence responds to this organizational difficulty. In addition, the levee system manager is now also the manager of the aquatic environment, which responds to a social demand for consistency in actions.

The France Digues association, created in 2013, regroups levee managers and has the mission, by networking them, of:
- disseminating and sharing knowledge and experiences;
- strengthening the skills of managers;
- representing the profession of levee managers;
- providing managers with assistance.

Today, it brings together about fifty managers and the number is steadily increasing.
In addition to the central role played by managers, the State has a dual role: at the central level, the Ministry in charge of the Environment is in charge of defining regulations and at the local level, the control services for the safety of hydraulic structures are in charge, in conjunction with the managers, of verifying its application.

(3) The expression "Hazard study" is the translation of the French term "Étude de dangers" of the regulations and it is generally used for levee systems, in particular by ILH. However, CFBR has chosen a different translation for the dams: "Safety Review Risk Assessment", or "SaRRA" (see chapter 12).

6. CONCLUSIONS AND PERSPECTIVES

Levees, which are actually old or very old structures, have only very recently been the subject of organized attention from actors in the community of hydraulic structures (managers, public authorities, engineers, scientists), less than thirty years in France and a similar period in the other countries known within the international community that is currently being put in place. Nevertheless, while admitting that a great deal of knowledge still needs to be acquired or deepened, enormous progress has been made since the 1990s in our country:

- evolution of management structures, organization of an association;
- inventory of levees and associated protected areas;
- implementation of specific regulations;
- appropriation of a "risk" approach (hazard studies, risk analysis);
- publication of technical guides;
- many research works;
- integration of the topic of levees in the CFBR scope.

Other communities, more specialized in terms of disciplines (SHF for hydrology and hydraulics, CFMS for geomechanics and geotechnics…) are also taking an increasing interest in levee-related issues.

The efficiency of the structures and the safety of populations is henceforth reinforced, although many efforts are to be made over the long term, particularly for the sustainability of management and maintenance, a sine qua non condition for the reliability of protection systems when an event occurs after a long period of time without being solicited.

7. REFERENCES

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CHAPTER 10

ELECTROMECHANICAL EQUIPMENT AND CONTROL SYSTEMS

1. INTRODUCTION

The oldest structures in France's hydropower production portfolio are 80 years old. Most of them are operated automatically, and their instrumentation and control (I&C) systems and the electromechanical equipment they comprise need to be renovated regularly. The renovation work needs to include management of the associated risks, to guarantee hydraulic safety, as well as the safety of people and property, while maintaining production continuity as far as possible.

This chapter sets out to share examples of CNR's and EDF's renovation organization and practices in the areas of I&C systems and electromechanical components:
• for CNR: the renovation of an I&C system for six developments along the Rhône;
• for EDF: the design of dam I&C systems.

2. RENOVATION OF THE I&C SYSTEM FOR A SET OF SIX RUN-OF-RIVER DEVELOPMENTS (CNR)

The Compagnie Nationale du Rhône, part of the Engie group, operates 18 hydropower developments along the Rhône (6 on the Upper Rhône between Switzerland and Lyon) and 12 on the Bas-Rhône (between Lyon and the Mediterranean)). The renovation project covering the I&C system of the 6 developments on the Upper Rhône arose in the context of major changes for CNR as it became an "independent electricity producer". The company had just put in place the centralized remote control of the French section of the Rhône between 2000 and 2001. From 1990 to 2004, via the R2000 project carried out with EDF and the Geneva Industrial Services project, CNR maintained and confirmed its experience in the renovation of I&C systems and the automatic operation of dams and plants.

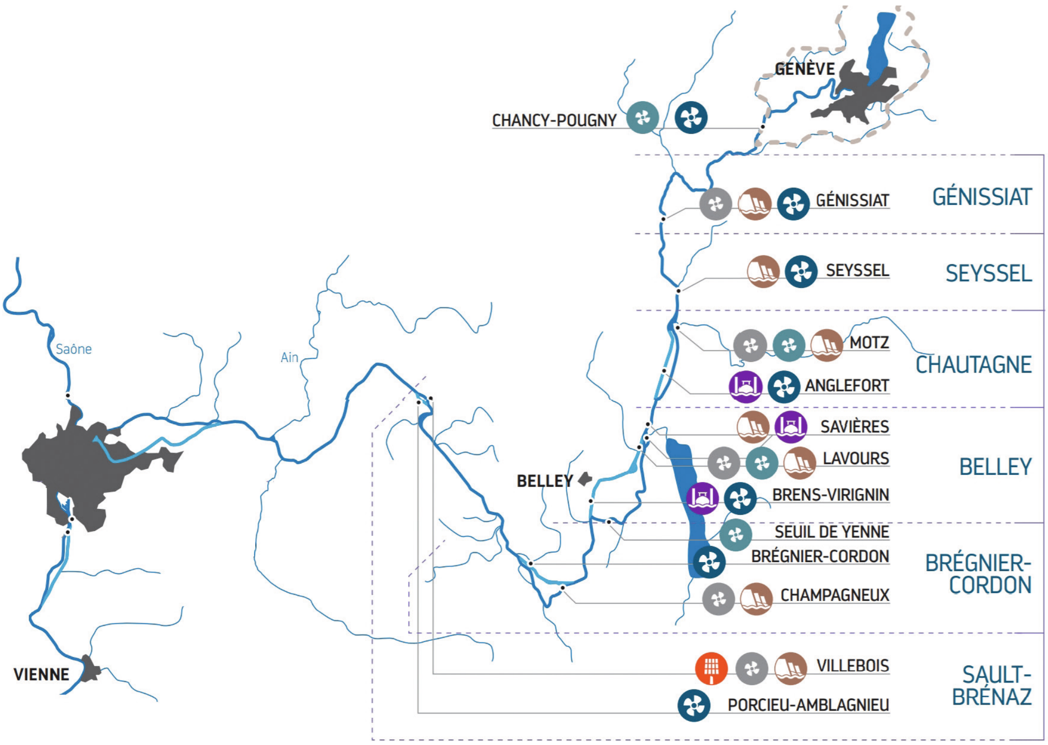
The newest I&C system architectures on the Upper-Rhône dated from the 1980s, and CNR's access to the skills and equipment needed for their maintenance was gradually diminishing. The functional development of existing architectures and their permanent integration in the remote control of the Rhône was viewed as extremely risky or even not achievable without the renovation of equipment and software.

In 2004, CNR decided to embark on a project to renew the I&C systems of the 6 developments on the Upper Rhône.

2.1 The geographical context

The project team started with the oldest development on the Rhône, Génissiat dam, which is the head development and so controls the flows in the valley. The team then carried out the renovation at Seyssel, followed by Sault-Brénaz, Chautagne, Belley, and finally Brégnier-Cordon.

Figure 10.1 – Upper Rhône Development Scheme / © CNR



2.2 The main project objectives

A group, comprising people who worked on the automation of the Upper Rhône in the 1980s, on the Rhône 2000 project, the SIG project and the remote control of the Rhône, came together to define the main technical choices and the organization needed for feedback in order to achieve two main objectives:
1. to ensure hydraulic safety and the safety of property and people;
2. to manage the project risks.

To achieve the first objective, the decision was made to:
- capitalize on the experience gained from operation and maintenance over the previous 20 years and from the implementation of structuring projects carried out by CNR, by:
  - defining a target I&C system architecture for a development on the Rhône;
  - involving the "people with knowledge" of the old architecture (operators, maintenance personnel, electrical inspectors, engineers, etc.) from within the company at all phases of design, testing and validation.

- Ensure reliability of the software to be developed, by:
  - using test platforms;
  - the production and application of test specifications in consultation with the "people with knowledge" in the company.
- Limit disruption due to the renovation by:
  - defining a phasing of the renovation tranches in consultation with all the stakeholders concerned;
  - installing the new architecture in parallel to the existing architecture and providing the means to switch easily from one to the other;
  - informing and training all the user stakeholders throughout the project;
  - tasking the maintenance of the new architecture to the project team for a trial phase of around one year;
  - removing the old architecture after the trial operating phase and getting the people authorized by the company to validate functionality.
- Implementing more precise automatic and sequenced impoundment control that would meet the challenges of hydraulic safety and production improving the schemes' display, control and command interfaces.

To achieve the second objective, the decision was made to:
- define and observe a scope of renovation in terms of equipment and software;
- produce a risk analysis and take action to limit these risks;
- produce and observe a coordinated plan for all the work sections;
- form a project team bringing together people with experience in I&C system renovation;
- choose robust and tried-and-tested equipment;
- define and implement a modular scalable architecture, consistent with all the I&C system architectures of the developments on the Rhône.

2.2.1 The functional principles

The project team proceeded with a detailed reverse engineering to identify the existing functionalities precisely, transfer them to the future operating architecture and thus pool the knowledge gained from over 20 years of operation.

Changes were made to the condition log report to reduce its complexity. The existing condition log was characterized by a set of configuration files found on different equipment, which was a source of error and maintenance difficulties. In addition, a homogenization of the designation of alarm levels between the upper and lower Rhône was implemented to optimize the remote control system and reduce risks of error.

To reduce the risk condition log's heterogeneity, its configuration was centralized in the scheme control computer. To date data at source and to improve the log's precision, CNR, in partnership with Schneider, developed a communication card called W315S in IEC104 protocol implemented in each programmable logic controller (PLC) of the architecture used. The data is thus configured at a single point and then distributed automatically to the communication cards with synchronized dating for each PLC.

Changes were made to the man-machine interfaces on the standard control computer in order to facilitate the control and command of the main functions with the creation of the following views:
- condition log (ability to change the degrees and wording from the scheme operation post, to sort etc.);
- development configuration;
- hydraulic condition of the impoundment;
- choice of instruction drawing based on temporary instructions in force;
- …

As far as possible, the project team developed standard software modules with the aim of simplifying future maintenance and adding improvements and changes to all the renovated schemes over the course of the project. This principle was applied both for the software and for all the maintenance and operating documentation for the new architecture.

Based on our experience from the renovation of the lower Rhône, we built the new architecture in parallel with the old so as not to disrupt the automatic control of the scheme, or its operation. We therefore kept the possibility of switching back to the old architecture depending on operating needs (for example, a new hydraulic situation before nightfall or before a weekend). This principle considerably reduced outages.

For the first two schemes, at Génissiat and Seyssel, CNR decided not to renew the 1st-level relay unit. In the next four schemes, the already automated 1st-level units were renovated.

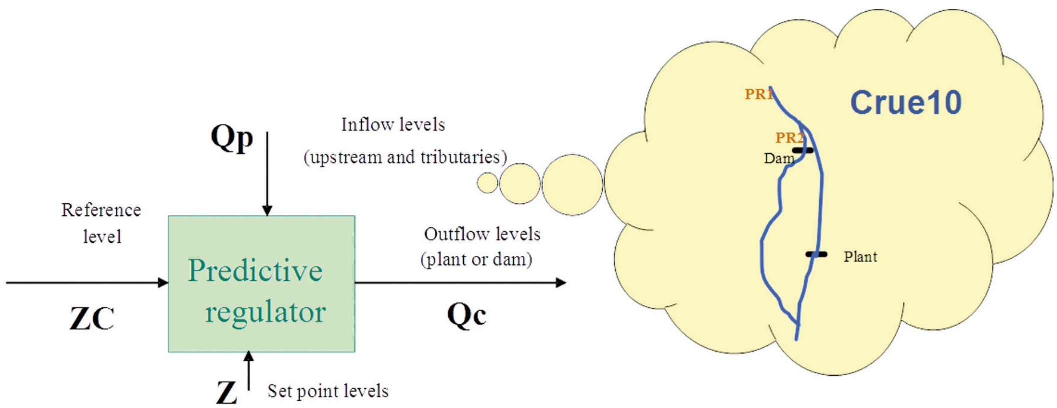
Upstream of the project, the dam gate controls had been renovated, as had the manual emergency controls on the dams. In parallel with the project, safety PLC's were installed in each scheme, with the particular feature at Belley and Brégnier-Cordon that the original failsafe functionalities were retained and integrated.

To regulate the water levels in the impoundments, predictive-type regulation systems were chosen, like for the lower Rhône, the principle of which had been developed in the context of a thesis and with the aid of the research company ADERSA. CNR opted to re-work the sequenced regulation principle of the Upper Rhône and to put in place appropriate simulation tools.

2.2.2 General principle of predictive regulation

- Regulation allowing the value of the regulated magnitude (level) to be "predicted" within a given period.
- Need to know in advance how the water level will react => integration of a mathematical model (CNR's open-channel flow calculation software: "CRUE 10").

Figure 10.2 – Functional principles of predictive regulation / © CNR



2.3 The organizational principles

The project team was formed from a core of people with experience in previous renovation projects so as to be able to improve functionalities and optimize timing. Throughout the project, this team controlled and managed turnovers over time by:
- organizing the cover phases between people;
- stabilizing the team by selecting internal personnel to manage the works sections of each of the disciplines concerned (electricity, automation, industrial and scientific IT).

With regard to the functional, organizational and phasing principles, the operators were involved from the design stage and then throughout the project:
- reverse engineering and specification phase;
- the validation stages and participation in tests;
- the supplementation of test specifications and documentation;
- training for operators in the new architecture as the project progressed, before and after commissioning.
- …

There were several levels of decision-making authority:
- at the operational level: validation and site progress meetings;
- in the project management company: operational committees;
- with the departments concerned by the project: project steering committees.

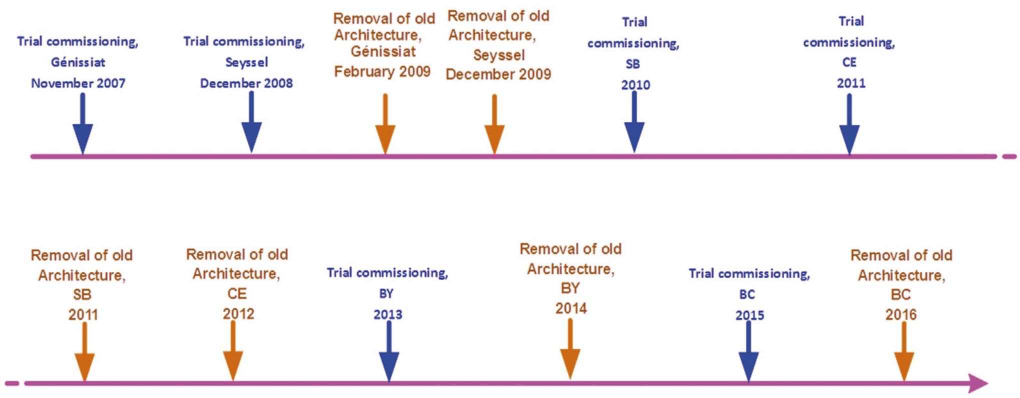
To manage the risk associated with software development, validation platforms were produced and rolled out, integrating the control computer, all the PLC's, the impoundment simulators and operating devices. Therefore, on the platform, in-depth testing of the complete architecture was carried out in accordance with the test specifications for each software. The platform tests were conducted over periods of about a year depending on the complexity of the functionalities of the development concerned. This approach provided gains in terms of reliability and on-site commissioning time (time divided by 5 relative to the experience gained).

The hydraulic risk was reduced by the development of a predictive platform for sequenced water levels. This concerned better management of the impact of actions upstream on downstream sections, and more particularly the complex management of flood plains. To improve software reliability, the team used, on the platform, actual data from the past, recorded in different hydraulic situations and in particular in flood situations. Furthermore, following commissioning, the project team was tasked with maintenance for a test phase, the length of which was set by the operator. Throughout the test phase, the development was controlled with the new architecture, with the possibility of switching back to the old architecture at any time. During this phase, the project team was available at all times to support the operator in managing the tools and with any need for corrections or developments. The latter proved to be minor.

2.4 Chronology of rollout of the target architecture

Initial discussions were held in early 2005. The project team was put together in late 2005. Génissiat was brought into service in late 2007. Between Génissiat and Chautagne, 4 years elapsed and 4 schemes were brought into service: Génissiat, Seyssel (2008), Sault-Brénaz (2010) and Chautagne (2011). Regarding the two remaining schemes, the decision was made to work on renovating one unit per year. This reduced production outages, gave operators the time to monitor other construction sites and gave the project team time to develop the sequencing simulation tools for water level regulation.

Figure 10.3 – Deployment timeline / © CNR



2.5 A new architecture

The old architecture was an architecture in which the intelligence was concentrated in the computers. The technological and financial context provided the opportunity to distribute the functions over a range of equipment. CNR thus achieved a modularity which simplifies maintenance and understanding of the architecture, and which provides the option, over time, of developing the architecture with managed impact. To limit the risks of losing the remote control of schemes, CNR elected to duplicate the computers and to have hot redundancy of computers. The general principles of the target architecture with distributed functions are represented in figure 10.4.

Figure 10.4 – General principles of the control-command architecture / © CNR

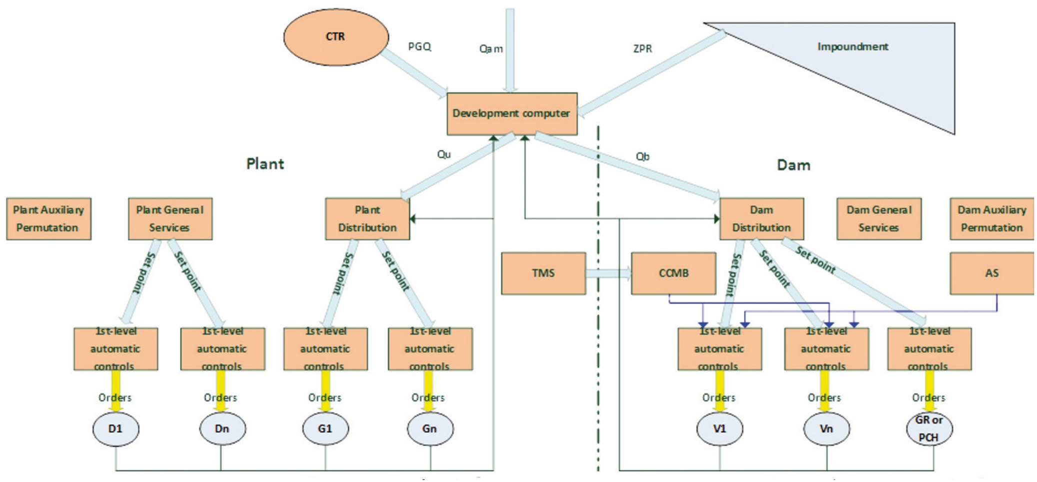
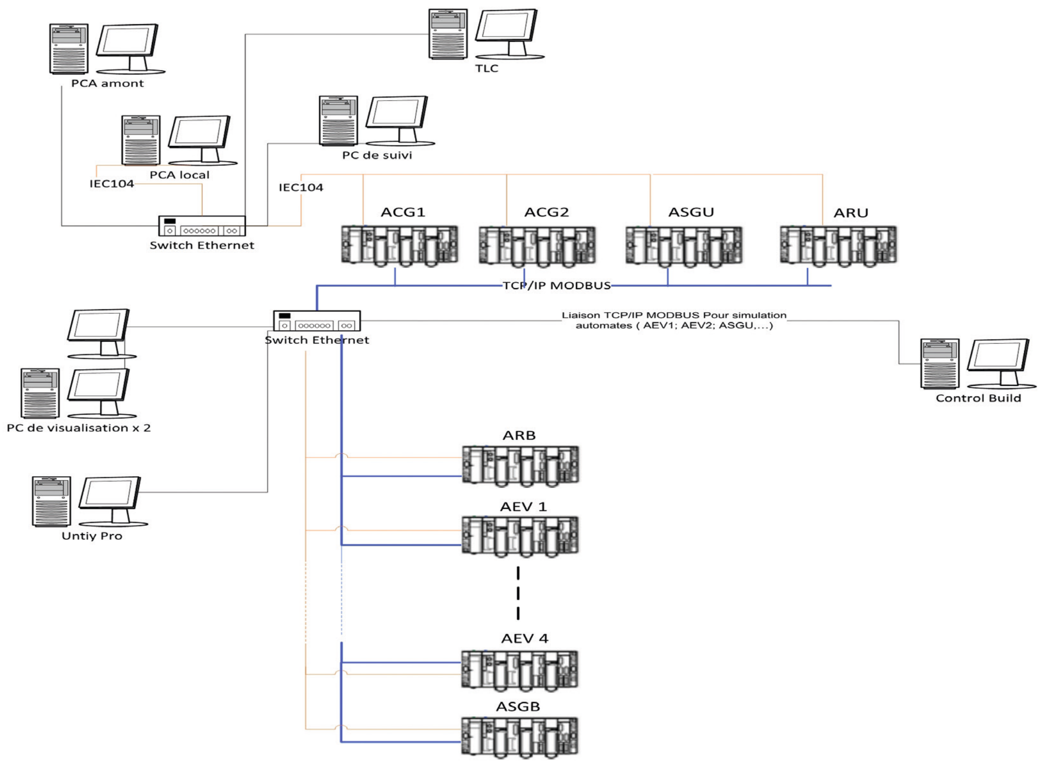


Figure 10.5 shows the Brégnier-Cordon validation platform.

Figure 10.5 – Brégnier-Cordon validation platform / © CNR



2.6 A reference architecture

The taking into account of the feedback and the sound knowledge of weaknesses in the architecture to be renovated contributed to the achievement of objectives. The renovation strategy was produced with a view to managing the software and hydraulic risks, as well as the risks associated with planning and budget. The use of functional modularity (one piece of equipment / one function) facilitated the integration of future changes, such as subsequently in 2015 the renovation of the 1st-level units in the Seyssel power station. Subsequently, the functional validation of the sequenced control of the 6 high-flow schemes was completed successfully during the flood in early May 2015. These good results confirmed the wisdom of a long period of work on a complete simulation platform. The management and knowledge of this target architecture makes it a reference architecture within CNR. The methodology used was then rolled out by the company's renovation project teams when carrying out I&C system renovation projects.

3. DESIGN OF DAM I&C SYSTEMS (EDF)

Électricité de France (EDF) has been designing and building hydropower facilities for over 70 years and operates more than 600 dams (including 220 major dams). Flood spillways are often fitted with gates (approx. 1,400), of all designs and types: wagon, segment, Stoney, flap….

3.1 Design rules for a dam I&C system

To control these units safely, EDF has in its library of safety documentation, a document containing design rules, called X-EL 01-20 "Controlling flood spillways – Prescriptions for the operational safety of dams – Design rules for their instrumentation and control systems".

These rules were produced following an incident in June 1984, on La Croux dam on the Tarn. The two main gates opened gradually during the night, causing an artificial flood with a gradient estimated at 400 $m^3/s/h$. This incident, which did not claim any victims, stemmed from a malfunction of the dam's flood PLC which had just been replaced without fully testing the program. To address any failures of the I&C system, design requirements are based on the following principles:

- following a risk analysis, making control, be it manual or automatic, more reliable, using redundancies and the systematic elimination of common modes;
- fail-safety is ensured by the operator and, in a degraded situation, without the aid of an automated system;
- the installations are kept in operational condition by surveillance and regular inspections and tests.

The priority operating maneuvers are in particular those related to the transit of floods. To this end, the following are required:

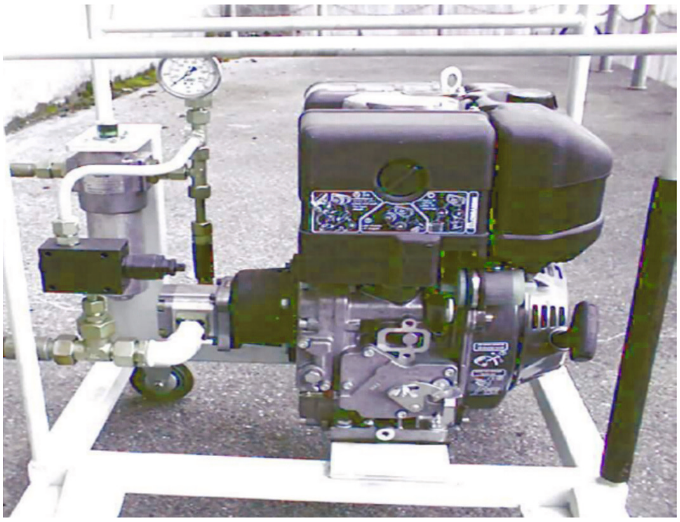
- adaption of the operating rules depending on the type of structure and the environment in which it is located;
- compliance with operating rules by integrating possible equipment failures;
- adaption of the safety requirement to the potential consequences of failures (downstream situation…).

Regarding the basic requirements applicable to the installations:

- the main alternative source must have an emergency power supply from a dedicated generator set for the dam (which only powers the units on the flood spillway, and the equipment essential for the dam's operational safety). Its design is secure for this specific situation;
- the distribution of the alternative energy must be handled with care. In particular, all the common points between the normal source and the emergency source must be avoided as, in the event of a fire, for example, the emergency source would risk depriving the spillway of its switching energy. The power cable ducting must be protected from any external stresses;

- every flood unit is fitted with a dedicated, stand-alone PLC, for its operation and inherent protection, dependent only on the energy sources necessary for its maneuvering. This PLC must include an incremental control device (also called "tiered" or "stepped");
- the dam is controlled at least from these individual gate enclosures. A manual control can be put in place from a centralized control station in a building at the dam. One or more gates can also, if necessary, be controlled by an automatic control system which must be situated at the dam;
- in some cases, where the operator cannot be on site in time, a safety PLC, totally independent of all other equipment, must always be used. It intervenes whenever the reference measurements deviate significantly from normal operating ranges. It is part of the structure's "failsafe" devices;
- a final emergency device common to all the gates allows, as a last resort, a flood outflow device to be operated in the event of a failure of the power supply or motorization, the I&C system or even in the event of a generalized fire. The open time must be compatible with the flow gradient concerned. This is the final barrier to any malfunction.

Figure 10.6 – Example of a final emergency pump unit / © EDF



Note: the operation of a dam generally makes use of level, flow or position measurements and in any event needs alarms to be routed to the operators. To control the structure in a normal and degraded situation, the operator must in any event have: the height of the water level, the position of the device and adequate lighting. The reliability and safety of detection and transmission means are therefore essential. The information that is essential to ensure the operation of the dam in any situation (surveillance of the structure, automatic or manual control of the dam and the control devices) must in particular meet the following requirements: use of very robust equipment, tried and tested in use, duplication of totally independent measurement points, display on stand-alone devices independent of the dam PLC, monitoring of measurement availability and consistency…

The result of all this is that, besides the small number of deviations recorded during operation in the case of structures complying fully with these rules, safety reports[1] carried out confirmed the excellent robustness of the system, since they only rarely concerned the critical path of "feared central events". Indeed, in this case, only the automatic controls — fairly rare in our structures — can be concerned.

This internal rule document is updated on a regular basis, either due to feedback or to technical advances. It has therefore gone through several stages:

- originally, it was designed to represent a body of rules with associated solutions, in a two-column document for producing a survey of the existing situation compared to clearly defined rules;
- the document was updated for the first time in 2009, at which time a certain number of points were specified based on feedback, while reinforcing the "downstream risks" aspect. The double column was removed, as conformity analysis practice no longer required this initial provision;
- the document was updated once again in 2019 with an in-depth modification. On this occasion, as Engineering had its own complete reference work since 2018, this document became a document of requirements only. It looks in particular at the upstream phases, the expression of needs and functional and safety analysis phases for several trades.

(1) These reports are formally defined as "Safety Review Risk Assessment" – see Chapter 12.

3.2 Engineering design reference work for the I&C system of dams and first applications on various sites

Given the need to renovate a large number of dams in the forthcoming years, in 2018, EDF's hydraulic engineering department produced a new complete reference work for dam I&C system installations (around 90 documents not including documents in common with the plant) including:

- a summary note with an engineering process and a few guides;
- technical guides: architecture, 1st-level flood spillway, AC and DC low-voltage auxiliaries, GE (Generator set), backup device, PCC (common control station), dam MMI, 2nd-level automatic controls;
- standard layouts: 1st-level flood spillway, low-voltage auxiliaries, backup, PCC, SAG (general auxiliary services);
- standard structures and standard modules for the different PLC's;
- contract documents for contractors (STG — general technical specifications and STM — technical equipment specifications).

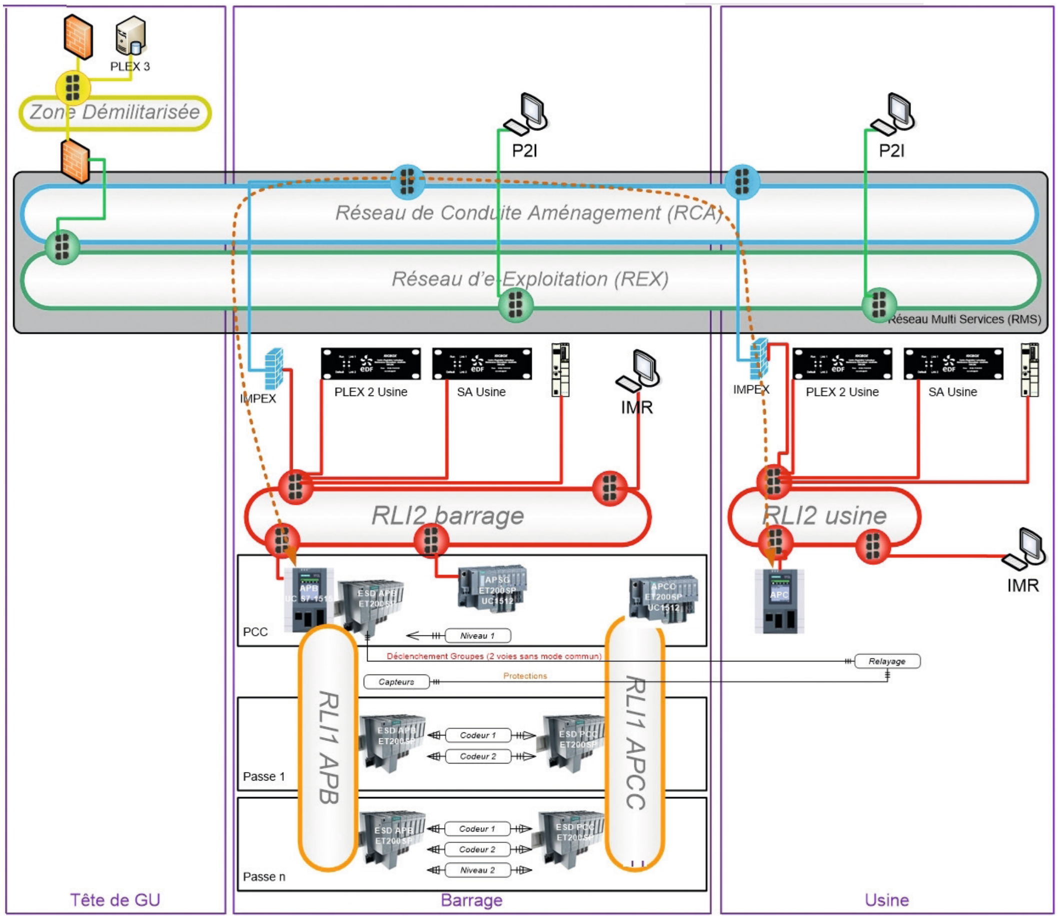
In addition to the standard solutions and standard PLC programs and modules, it was necessary to incorporate the introduction of information acquisition functions by the latter by means of networks, without impacting the safety and fundamentals described above: a certain number of new rules were therefore issued:

- separation of safety functions by making the dam PLC independent of the general services PLC which receives all the auxiliary functions;
- limitation of network use for "convenience" control functions, while providing the possibility of manual control in all situations (even if PLCs should break down);
- strict use of new protections…

It should be noted that the entire process and technical principles were validated in EDF Engineering's "technical committee for I&C system safety" which is an "expert" safety authority. This committee was created to comment on and validate any safety component project with regard to both conformity and certain proposed solutions which differ from or are in addition to the reference work., By acting in advance in this way, in a joint reference work, there is no need to repeat construction details since they are provided in a complete and express reference work. Instead, the grounds for the renovation can be verified, namely the input data which are often the source of the deviations observed. Thus, a review of these projects can cover the validation of input data rather than the form of implementation.

These standard layouts are used in all the current configurations which are to be used on several dams on the Rhine (4 sites), the lower valley of the Ain (3 sites), Montrigon dam in the Alps and other future projects.

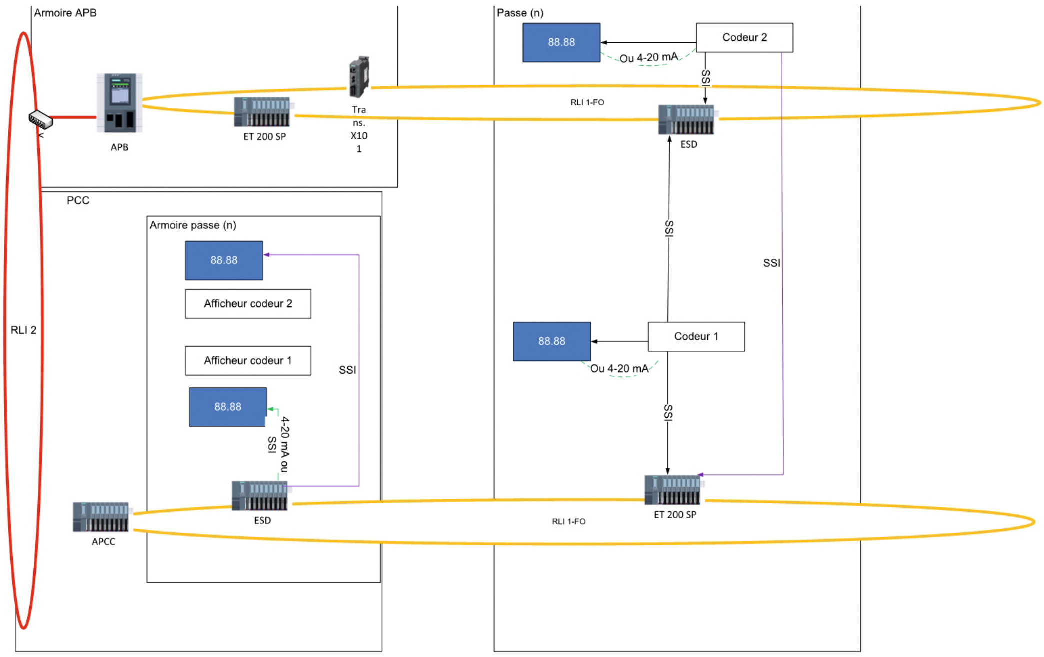
Figure 10.7 – Example of architecture (Marckolsheim dam / © EDF



Zone démilitarisée	*Demilitarized zone*
Réseau de conduite aménagement (RCA)	*Development control network (RCA)*
Réseau d'e-Exploitation (REX)	*E-operation network (REX)*
Réseau multi services (RMS)	*Multi-services network (RMS)*
Déclenchement groupe (2 voies sans mode commun)	*Unit trigger (2 channels without common mode)*
Protection	*Protection*
Capteur	*Sensor*
Codeur	*Encoder*
Relayage	*Relay*
Tête de GU	*Head of GU (Head of Plant Group)*
Barrage	*Dam*
Usine	*Plant*

For this dam, the gate positions are managed as shown in Figure 10.8.

Figure 10.8 – Example of acquisition of position of elements / © EDF



Armoire APB	*APB cabinet (dam PLC cabinet)*
Armoire passe (n)	*Pass cabinet (n)*
Afficheur codeur	*Encoder display*

It should be noted that, as the structures on the Rhine are extensive and complex, this type of layout can be simplified to tailor it to the complexity and challenges of sites.

3.3 The complete reference works

The intangible principles and the "closely monitored" rules have been confirmed over time and have proven to be reliable in the risk analyses of the safety reports. Every structure undergoes a detailed and specific risk analysis of the flood spillway function of the dam concerned and the risks downstream, the latter being validated in EDF's technical committee for I&C system safety. The new complete reference work created in 2018, including layouts and software, will help achieve greater conformity with these rules.

4. CONCLUSION

For all these practices, we can highlight the will to manage risks, take experience into account, and monitor interventions on structures in operation. With integrated engineering, EDF and CNR have been able to produce and enrich doctrines and methodologies which, by having a systemic approach and then applying a standard, are best suited to the challenges faced..

5. REFERENCE

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CHAPTER 11

CONTROL AND MONITORING

Like many other countries, France is no exception to the general observation that it is society's expectations and the search for ever greater protection against industrial risks that mean that most of our dams are now inspected and monitored.

However, in France, monitoring is an old practice which met the initial need of dam designers and builders to validate the technical progress made through observation. This approach, which is characteristic of any scientific approach, has led engineers to measure, observe and analyze the response of structures to different types of stress.

To do this, it was very often necessary to adapt or devise specific instrumentation and data processing methods. As a result, apart from a few techniques already well mastered elsewhere (such as topography), new technical solutions have frequently been proposed and implemented by engineers in the profession. And what our predecessors have been doing in this area for decades has often proved to be relevant and sustainable.

Building on these solid foundations, the profession has always been open to new technologies: it has integrated advances in electronics and computing since the 1960s and has continued to develop new means and methods of surveillance. These have significantly changed the way we inspect and monitor our works, and this trend is set to continue in the future. In this changing technical environment, operators have also seen their activities evolve; they have adapted and retain an essential role in the monitoring process.

It is this past history, its current events and the beginnings of its future that we propose to introduce you to in this chapter.

1. THE BEGINNINGS OF DAM CONTROL AND MONITORING IN FRANCE

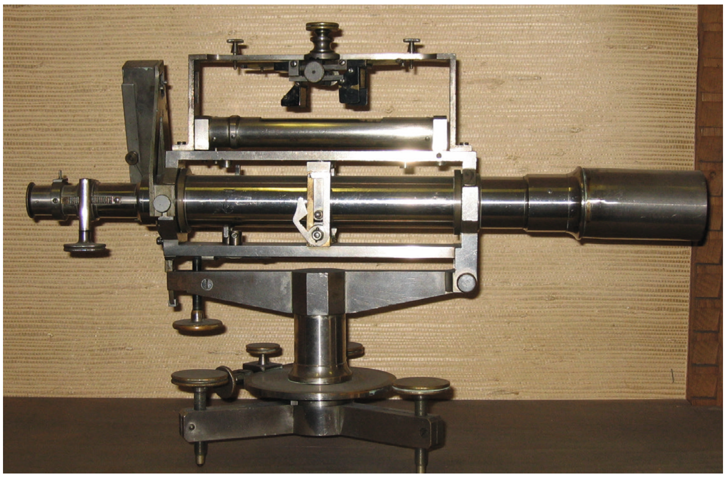
In the early days, the design and construction of dams were experimental in approach, as modeling tools were not available, and observing dam behavior reassured the engineer. The monitoring of dams to ensure a sufficient level of safety was therefore based either on visual examination or on control by measurement.

1.1 The first measurements on dams in France

The oldest measurements were leakage measurements to assess the watertightness of the structure, and topometric measurements (leveling, alignment, etc.) to assess the movements and therefore indirectly the stability of the dam.

Figure 11.1 – Level A. Berthélémy 1883-1886 /

Source: Bibliothèque patrimoniale numérique de l'École nationale supérieure des mines de Paris.



Built between 1830 and 1838, the masonry dam at Grosbois in France presented many problems since its first filling and was reinforced several times. In order to assess its effectiveness, topographical surveys were carried out as early as 1852, using the unique sighting scope available at the French Public Works Research Laboratory (Laboratoire Central des Ponts et Chaussées).

1.2 The development of specific control instruments

The development of innovative constructive solutions for dams has led to an increasing number of questions from designers and builders alike in order to understand the behavior of structures and ensure their safety. In response, innovation has focused on the development of sensors, instruments and measurement methods.

It was especially in the inter-war period and after the Second World War, in a strong period of construction associated with the realization of works of different types and materials with ever greater heights and more complex geologies, that the daring engineer expressed his needs for control measures. In order to validate its calculations, observations on the behavior were certainly essential, but quantification by measurement had become indispensable, either because of the orders of magnitude involved, or because the data was located in the structure's core and could only be accessed by an instrument placed inside the dam.

For example, André Coyne, a designer of arch dams, came up with the deformation measuring device he needed but which was not available on the market at the time. Based on vibrating wire technology, he developed the vibrating wire extensometric sensor in 1931, also known as an **"acoustic indicator"**, which was to equip the Bromme arch dam (1930-1932) and, above all, the double-curvature arch dam at Marèges (1932-1935).

Robust, accurate and with good durability, the vibrating wire sensor has also been used in the design of pore pressure measuring instruments replacing hydraulic back pressure cells. The first large French dams to be equipped with them were the Serre-Ponçon dam (1958) and the Mont-Cenis dam (1965).

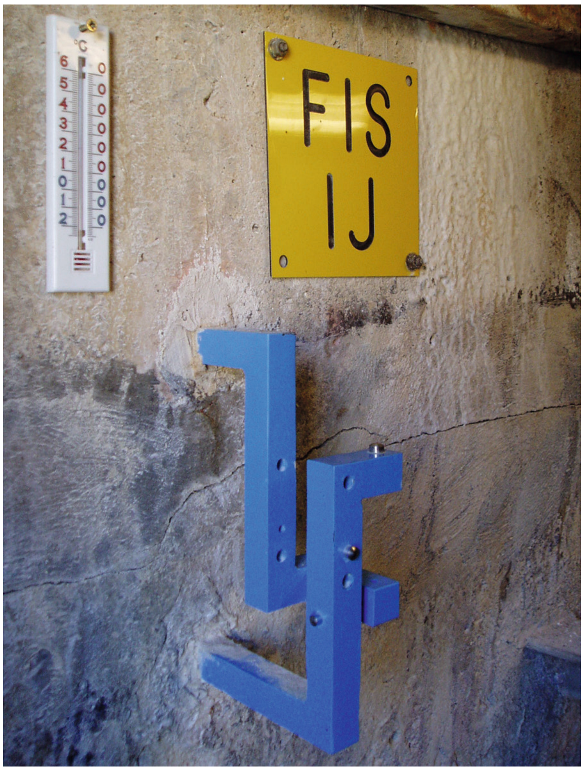


Figure 11.2 – Vinchon au droit d'une fissure / © EDF

Because of the complexity of topographic measurements and their reduced acquisition frequency, engineers sought to develop instruments to track movements. Starting in the 1950s, the direct pendulum, a "simple" plumb line, was used to measure a differential displacement between a measuring table and an anchorage point on the structure. We had to wait until the 1960s to come up with **the inverted pendulum**, and the measurement of absolute displacement in the foundation. In 1973, EDF/FTM patented the device for carrying out vertical boring with a reduced diameter.

The determination of engineers to acquire measurements for monitoring structures has led to apparently simple but ingenious instruments.

The **Vinchon**, named after its inventor, is a good example of this. This instrument allows a precise follow-up of the movements in the 3 dimensions of the joints or cracks of work.

1.3 Two regulatory milestones in dam surveillance regulations

The strengthening of regulations dictated by the tragic accident of Malpasset dam (1959), then by low dike breaches (early 2000s), resulted in an increasing requirement for the monitoring and inspection of dams. Texts issued by the government (circular of 1927 and circular 70-15 of 1970) first codified the practices and organization of monitoring in France, with particular attention paid to "large dams". The 2006 Water Law and subsequent decrees consider the potential dangerousness of both large and small dams. It gives dam owners greater responsibility and reinforces the State Services' control mission, with increased possibilities of recourse in the event of failure.

These regulatory developments are a reminder of the need and importance of surveillance processes, monitoring systems and regular analysis of the data acquired.

2. DAM SURVEILLANCE IN FRANCE TODAY

2.1 The objectives of surveillance

Surveillance includes the measurements of the structure's monitoring devices and the visual observations made during technical visits.
The exploitation of this data has different purposes linked to different time periods:

1/ A first **short-term challenge:** this is a matter of alerting in the event of significant and rapidly changing anomalies in relation to historical behavior that could jeopardize safety. Immediate action may be required to return to an acceptable level of safety.

2/ A second **medium-term issue:** the monitoring data is used by an approved engineering and design department which identifies slow behavior drifts or the evolution of degradation in the medium/long term. The analysis focuses on understanding the phenomena and their potential consequences (loss of technical performance, etc.). This analysis may lead to adjustments in monitoring, the initiation of work or further analysis.

3/ A third long-term issue: slight drifts or slow and/or complex pathologies that require further analysis through modeling and stability verification calculations. The aim is to anticipate the long-term consequences of the developments observed.

2.2 Defining surveillance operations

Surveillance contributes directly to structure safety by enabling a permanent verification of the balance between the stresses applied and the structure's strength through variations in hydraulic and mechanical parameters and the resulting displacements.

The monitoring system and the control points for inspections are defined with the following two objectives in mind:

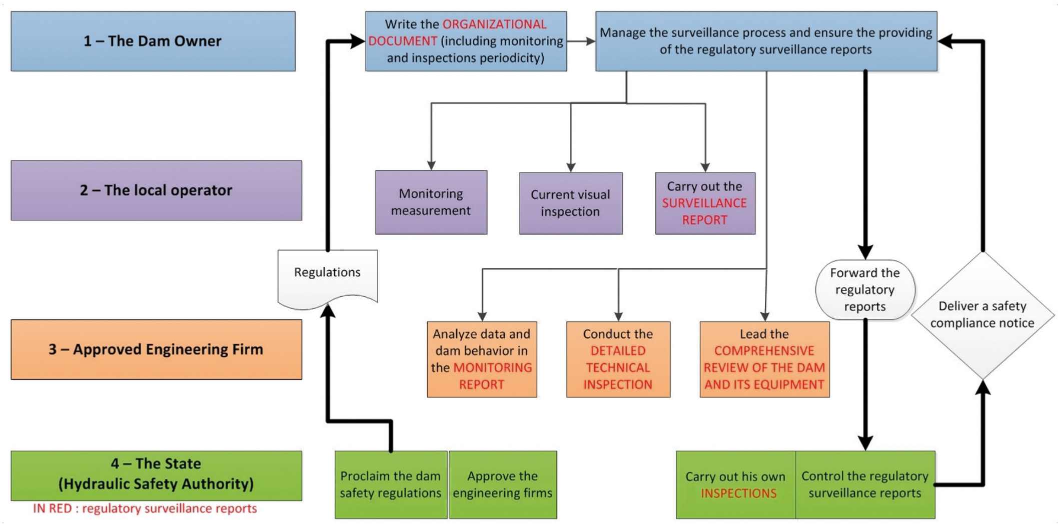
- to check that the structure's behavior is in accordance with the design assumptions in terms of the stresses applied to it (water load, uplift, etc.) and its reaction (movements, displacements, settlements, etc.);
- to detect signs of ageing, whether they are dysfunctions and minor deterioration or symptoms of pathologies (swelling reactions in concrete, internal erosion, etc.).

Once defined according to this logic, the surveillance operations specific to the work are recorded in an organizational document. This document describes in detail the surveillance, in terms of the periodicity of measurement of the monitoring devices and the periodicity of visual inspections of the structure, for normal situations and during special events (floods, earthquakes, periods of extreme cold, etc.). This is the main surveillance organization document, the content and relevance of which are analyzed throughout the structure's service life in order to adapt the monitoring arrangements over time.

2.3 The stakeholders of surveillance, their roles and responsibilities

The flowchart below presents the four main stakeholders in dam surveillance and their respective responsibilities in the steps of the process:

Figure 11.3 – Organization chart of dam surveillance in France



The dam owner is responsible for the safety of the dam, whether it is a concession or a property. The dam owner relies on 2 separate entities to provide surveillance:

- **local operator,** who carries out the highly recurrent surveillance missions and the maintenance of the monitoring equipment;
- **approved engineering firm** specializing in hydraulic structures, whose role is to analyze the phenomena observed or measured with a high level of expertise on the one hand and to lead the monitoring missions of low recurrence (e.g., examinations specific to the comprehensive review of the dam, commonly carried out by the engineering firm because of the skills required, even if it is not a regulatory requirement) on the other. The particularity of these approved engineering firms is that they are independent and approved by the State, based on their skills and experience, to be authorized to carry out these missions.

The State exercises its supervisory role and power to guarantee public security. It is represented by an inspector who ensures that the dam owner complies with the regulations and the obligations arising therefrom regarding the safety and security of the works. The inspector is the privileged interlocutor of the dam owner and as such:

- is the recipient of all regulatory documents that the owner is required to draw up;
- carries out regulatory inspections of the dam owner.

The state representative has police powers and may, as a last resort, request that structure operation be stopped.

2.4 Surveillance operations and associated documents

In the regulations, the State has set the periodicity of surveillance operations for each category of structure according to the volume of the water reservoir and the height of the structure.

Table 11.1 – Documents relating to surveillance and safety required by French regulations

DELIVERABLE REQUIRED BY REGULATION	Periodicity according to dam category		
	Class A (large dams)	Classe B (medium dams)	Classe C (small dams)
CURRENT SURVEILLANCE REPORT: relates the events that took place during the period (flood, works, etc.) and presents the data from the monitoring and periodic visits, as well as the results of the tests (valves, alarms, etc.) that took place during the period.	1 year	3 years	5 years
Carrying out a **DETAILED TECHNICAL INSPECTION:** identifying any damage that could affect safety, checking the state of the safety devices and the monitoring system.	1 year*	3 years*	5 years*
MONITORING REPORT: analyses the monitoring data over the period and gives an opinion on the structure behavior.	2 years	5 years	5 years
COMPREHENSIVE REVIEW OF THE DAM: examines all submerged or hard-to-reach parts of the work (civil works and electromechanical devices).	10 years	15 years	/

** Minimum frequency supplemented by inspections on any significant event or development.*

3. AN OVERVIEW OF NEW DAM MONITORING AND DIAGNOSIS TECHNIQUES

Standard monitoring is based on the measurement of instruments chosen and positioned in order to report on structure behavior and its evolution. The monitoring device is designed according to the type, dimensions and technical features of the dam in question. As such, the monitoring devices and methods installed on dams in France comply with the current practices of the profession and are consistent with the guidelines of the ICOLD bulletins.

Due to their robustness and durability, conventional devices have the advantage of guaranteeing very good monitoring continuity and are designed to last. But new techniques can usefully complement the standard monitoring, offering the following specificities:
• wider spatial coverage than with point sensors;
• a higher resolution and density in the areas being examined.

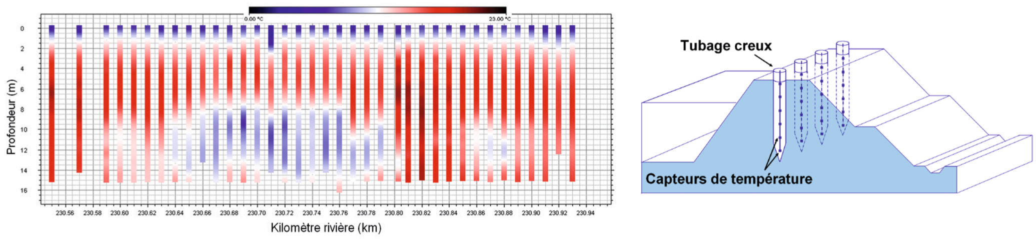
These 2 specificities allow slow pathologies such as erosion phenomena or swelling of concrete to be identified and characterized from the first symptoms when these are still very localized and of low amplitude. Among the techniques recently developed, several have now reached a stage of operational maturity: thermometric measurement in fill, geophysical methods and new means of topographical measurements (terrestrial, airborne and satellite).

In some cases, the acquisition device may be permanently installed and allow continuous monitoring of the dam.

3.1 Temperature monitoring in embankments

The detection of anomalies in the temperature distribution field within an embankment can be carried out using a chain of temperature gauges installed in vertical pipes laid in a longitudinal profile perpendicular to the internal flows. This makes it possible to locate the leakage area but also to quantify the flows.

Figure 11.4 – Longitudinal thermometric profile - Principle of sensor arrangement and monitoring data of detecting a leakage area / © CNR

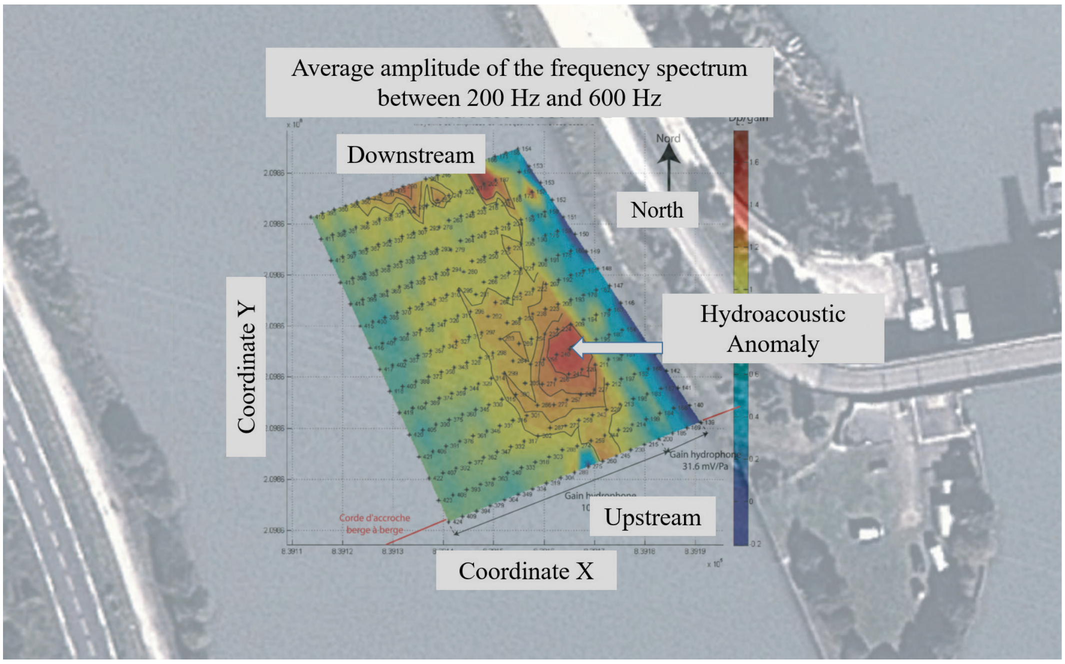


Distributed temperature measurement by fiber optics, processed with software for the spatial and temporal analysis of its variations, also makes it possible to detect and locate areas of preferential hydraulic circulation in embankments. With this system, the monitoring of large structures is greatly improved and many new or upgraded structures are now equipped with it. Developments are under way to broaden the scope of application of this technology, to determine deformations in embankments and to quantify flow velocities (a parameter allowing a more accurate assessment of the risk of internal erosion).

3.2 Geophysical monitoring

Geophysical methods consist of measuring one or more physical and/or electrical properties in an environment in a non-intrusive manner. Thereby, they give access to intrinsic characteristics of the work, but without altering it. This feature is very useful for “taking the structure’s pulse” or “following the evolution of some parameters at the structure’s core” during low recurrence examinations (5, 10 or 15 years, for example). For example, acoustic measurement methods (Figure 11.5) or electrical tomography methods have been adapted to monitor internal flows in earthen structures. Other geophysical methods have been developed to characterize the density of materials and to identify its long-term evolution in case of pathology.

Figure 11.5 – Illustration of a hydroacoustic method application: location of a seepage zone / © CNR



3.3 Automated topometry

Three-dimensional dam monitoring can be automated using robotic stations that take measurements according to a programmed cycle. The advantage is that the frequency of the measurements can be increased (daily or even hourly), e.g., during rehabilitation work (grouting, laying of anchors). Monitoring the stability of abutments or slopes may also require the installation of such devices.

The evolution of equipment and treatment methods now allows surveying by robotic station without referenced targets on site, which can be useful in meeting certain monitoring needs in emergency situations with difficulties of access to the surveyed area.

3.4 Lasergrammetry (LIDAR or 3D Scanning)

This technique allows the determination of point clouds in 3 dimensions, with a parameterizable density that can be very high. It therefore allows superficial rather than point control of the areas to be monitored. The survey can be carried out using fixed or airborne ground lasers (helicopter or now UAVs). As this method does not require the installation of a target, it is suitable for non-monolithic, deformable structures, for which a topographic survey with point targets does not meet the need to detect local disorders (sinkhole, settlement, deformation of masonry facing, etc.).

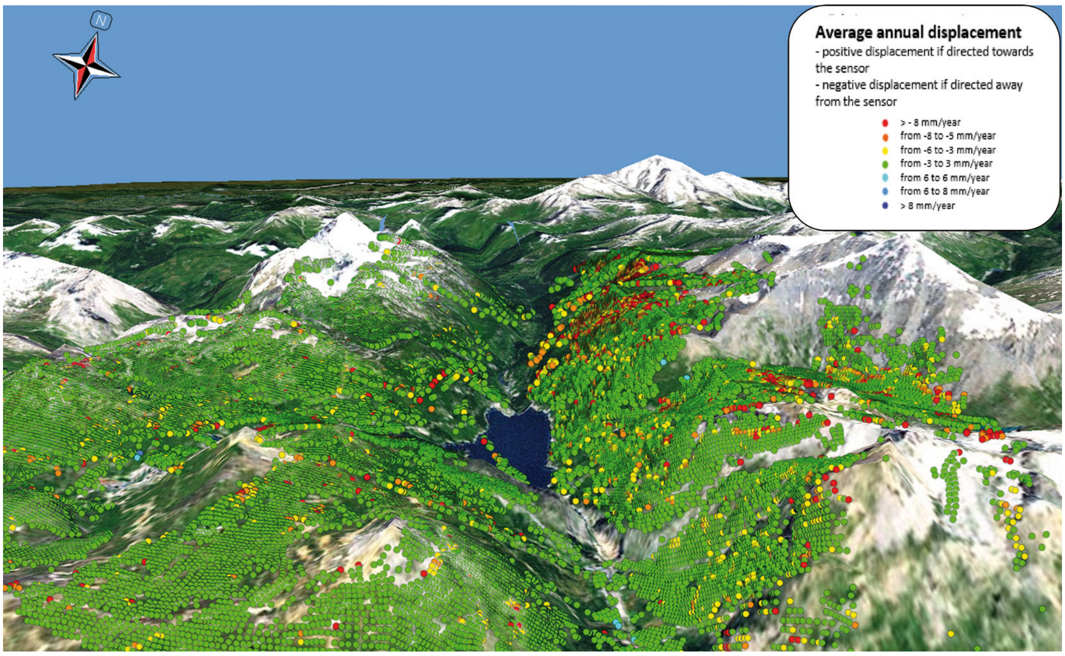
3.5 Radar satellite interferometry (InSAR)

Radar image processing allows the acquisition of information on the movements of an area by comparing radar measurements taken at different dates from a satellite in orbit around the earth. The monitored parameter is the variation in distance between the satellite and a reflection zone on the soil searched for in the different images by processing algorithms. A major interest is that in the areas covered by such satellites, old images archived by space agencies can be used.

Nevertheless, this technique has limitations. The accuracy of the distance measurement is dependent on the type of radar band used, the number of images available, and the reflection quality of the transmitted signal (it can be very good on flat concrete surfaces, but poor on a slope covered with vegetation or snow). It is therefore advisable to check before setting up long-term monitoring that the desired accuracy can be achieved with the available data and possible treatments.

The launch of new satellites and the development of new monitoring services make it a future technique adapted to the monitoring of large areas: large linear fills, slopes…

Figure 11.6 – Identification of landslide areas on the slopes of the Tignes dam reservoir [Boudon, 2012] / © EDF



In conclusion, without replacing conventional approaches, these modern methods provide a complementary and useful vision.

4. ACQUISITION, PROCESSING AND ANALYSIS OF MEASUREMENTS AND MONITORING DATA

Although some tasks have been largely automated and computerized, the basic process of data collection and processing remains unchanged: acquisition of measurements on the structures, transformation into values that characterize the physical phenomena from metrological characteristics and first measurements taken during installation, then validation and integration into databases. In fact, the main challenge for dam owners is to maintain in the long term:
- a level of requirement and rigor guaranteeing the proper performance of these activities;
- a level of monitoring that is always adapted to the issues at stake and to knowledge of the dam's behavior;
- the control of the quality of measurements by relying on a robust and durable device design and regular maintenance;
- data storage.

Data acquisition and transmission, and computer processing technologies have provided structuring tools for monitoring. They facilitate and secure the operation and storage of data. But they have also brought new possibilities for visualization and analysis, considerably enhancing the relevance of behavioral diagnosis.

From now on, all the major French dam owners and engineering firms have hardware and software solutions that meet the traditional needs of monitoring, to which are added more sophisticated processing tools in order to always "interpret measurements in the best way".

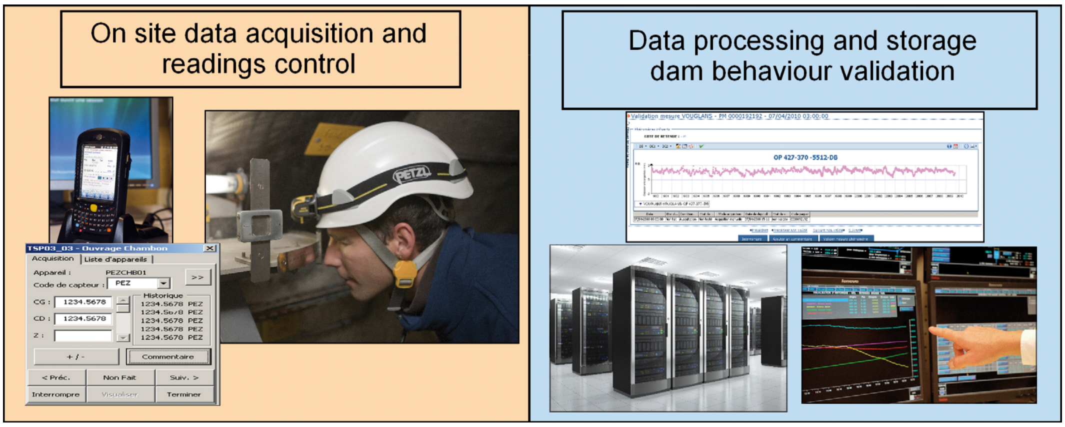
4.1 Acquisition and basic processing of measurements

Expectations and good practices regarding data acquisition and processing are well known and shared by the profession and will therefore not be detailed. Recent developments have mainly been aimed at making the work of operators easier and the acquisition and processing chain more robust.

The use of smartphones and tablets for recording and transmitting readings is becoming increasingly common. It allows on-site monitoring of the correct execution of measurements and early identification of any deviations.

Monitoring software integrates the traceability of operations and saves all useful information: time series of readings and measurement results, characteristics of monitoring devices and gauges, results of visual and metrological examinations, etc. The databases and the visualization and analysis functions of this software are accessible to many players via intranet or internet.

Figure 11.7 – Illustration of the control process (data collection / processing) / © EDF

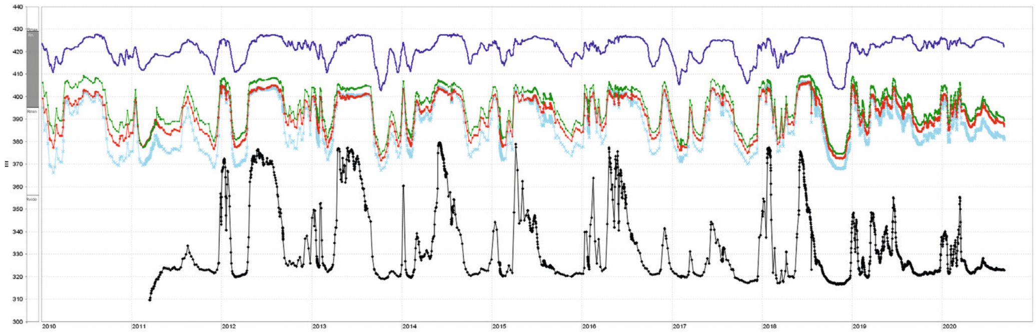


However, all this automation should not make us forget the importance of carrying out measurements and visual examinations in situ, as well as the continuous training of the personnel in charge of the tours. The days of people being permanently installed on dams are long gone but maintaining a close relationship between the dam and the operators remains a key element of monitoring.

4.2 Commonly used visualization functions and statistical processing

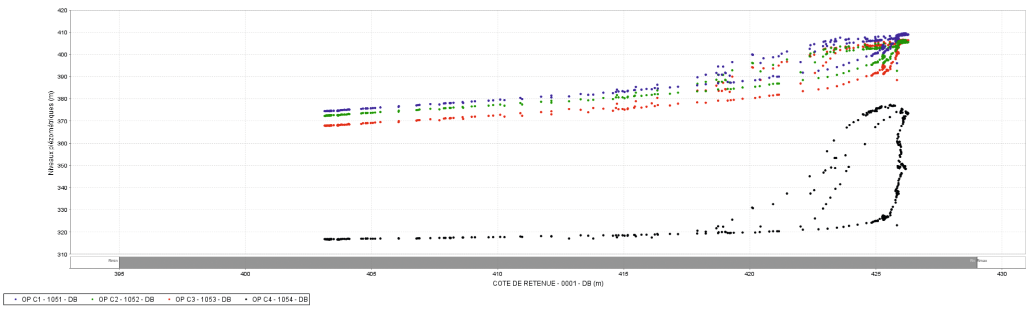
The first level of analysis of the control data is based on **graphical representations.** The most common of these are:
- the presentation of the evolution of the physical phenomena monitored over time. In the figure below, the pressure peaks of the most downstream piezometer (OP C4, black curve) highlight the phenomenon of the opening of the concrete-rock contact of a high arch dam in winter;

Figure 11.8 – Measurements of the reservoir level and 4 piezometers installed under the central block of an arch dam (from OP C1 in green upstream to OP C4 in black downstream) / © EDF



- the presentation of the variation of physical phenomena as a function of the main stresses (hydrostatic, thermal and temporal). The first example (Figure 11.8) shows the evolution of the pressures of the 3 most upstream piezometers (OP C1 to OP C3) of Figure 11.8 as a function of the reservoir level. The variability of the uplifts above reservoir level 418 reflects the impact of seasonal thermal conditions at the time of measurement.

Figure 11.9 – Correlation of the 4 piezometers in Figure 11.8 with the reservoir level in 2018 / © EDF

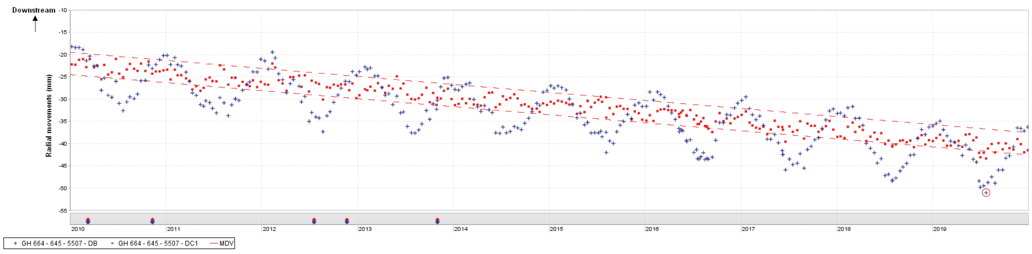


In the second example (Figure 11.10), the graphical representation of the radial displacement of a dam provides a clear visualization of the thermal influence of the season and the temporal evolution related to the aging of the concrete.

Figure 11.10 – Representation of the radial displacement of the central block of an arch dam affected by an alkali-response pathology: as a function of time (top graph) and over annual periods (bottom graph) / © EDF

These relations between the measured physical phenomena and the main stresses find a simple mathematical expression through the **HST model** (for Hydrostatic, Seasonal and Temporal) developed in the 1960s by EDF [Willm, 1967] and widely used by approved engineering offices. From the date of the measurement and the level of the associated reservoir, this model determines the parameters of the response functions of the phenomenon to seasonal and reservoir variations and its law of evolution over time. It is then used to calculate and construct time series of values of the phenomenon corrected for the reversible influences of the coast and the season. This type of modeling is particularly useful for the early detection of behavior abnormalities and the identification of irreversible long-term changes. This model has been integrated into many control software systems.

Figure 11.11 – Evolution of radial displacement of Figure 11.10 as a function of time – Raw values (blue) and values corrected for water level and seasonal variations (red) / © EDF



The initial formulation of the **HST model** was subsequently adopted in different forms to consider other influencing variables (e.g., air or concrete temperature), or by formulating the response functions of the phenomenon to stresses differently. Among these new models, the most interesting are those integrating the delayed effects of hydrostatic head variations on flows in fill dams [Simon, 2016] or the delayed thermal effects on displacements and deformations in concrete dams [Penot, 2005].

4.3 New analytical methods

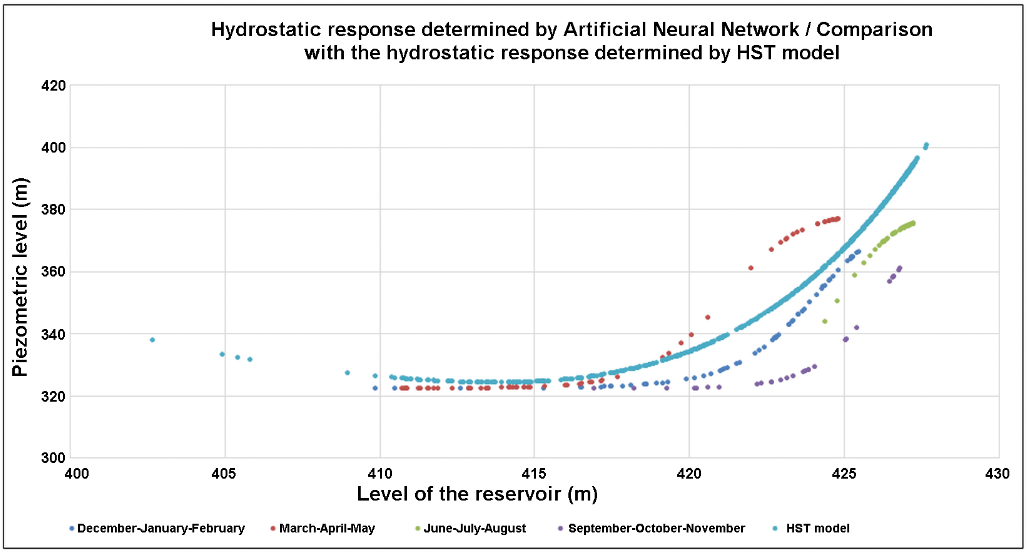
The various **statistical models** mentioned above have a reduced number of parameters to be determined (about ten) and have a physical formulation that makes them easily interpretable. Their main limitation, however, is the assumption of independence and additivity of the different solicitations, which is not always the case. A classic bias is the coupling of hydrostatic and thermal effects: the upstream displacement of an arch dam, in hot periods, is more marked at low elevation than at high elevation.

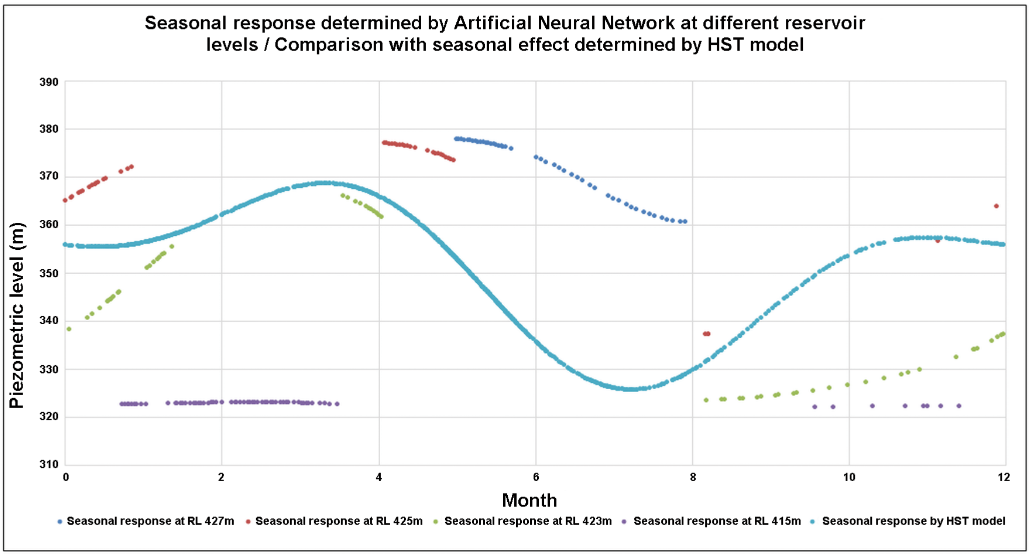
This explains the interest and recent use, in France, of **artificial intelligence methods and algorithms** developed in other sectors of activity. The most common methods, and the best mastered, are neural networks [Simon, 2018], but other developments and research are being conducted with techniques called SVM (Support Vector Machines), BRT (Boosted Regression Trees), RF (Random Forest), GA (Genetic Algorithms)… These are purely statistical methods, offering great flexibility of calibration, and freedom from the limitations of conventional models. However, their implementation and interpretation are complex, with a very large number of parameters to be calculated (usually around 50) and do not allow extrapolation of variations in the physical phenomenon studied outside the field of available measurements.

The example below illustrates the interest of neural network modeling to interpret the variation in water pressure measured at the concrete-rock contact of an arch dam. The neural network was used to highlight the variations in the OP C4 piezometer in Figure 11.8, which are known to be dependent on the coupling of hydrostatic and seasonal stresses. The top graph shows the variation in pressures for the same water level at different times of the year: pressures are higher in cold periods (red curve) when the contact is open. The lower graph shows the variation of pressures according to the season for different reservoir levels: at low level (purple curve), the contact is closed, and the piezometer does not react to reservoir variations.

The hydrostatic and seasonal influences calculated by the HST model are represented by the quasi-continuous blue curves. We thus perceive the limits of this type of model, which determines an "average influence" that is not representative of the dam's actual behavior. Conversely, the neural network can determine a hydrostatic effect that varies according to the season or a seasonal effect that varies according to the reservoir level.

Figure 11.12 – Analysis by artificial neural network of the variations of the OP C4 piezometer in Figure 11.8 / © EDF





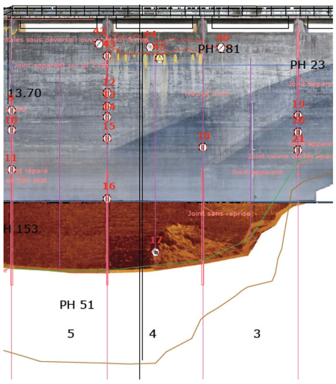
4.4 Processing of information from monitoring and comprehensive review

Comprehensive reviews of class A and B dams and their equipment, carried out during risk analysis studies[1], are carried out in often difficult and potentially dangerous access and environmental conditions, with sometimes high costs in relation to the perimeter to be inspected and the expected level of quality. To meet the needs and challenges of project owners, new technical resources and service offers have appeared over the last ten years.

(1) These studies are formally defined as "Safety Review Risk Assessment" – see Chapter 12.

Thus, the use of UAVs for aerial inspections and 3D mapping of structures is now commonplace. The speed of inspection and the automation of image processing are major advantages. The numerous possibilities for graphical reproduction and visualization offered by image processing software facilitate the reading, analysis and presentation of the examination results.

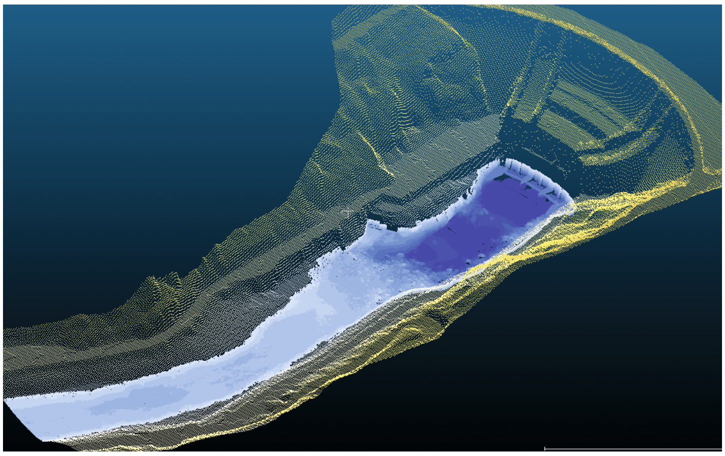
Figures 11.13 et 11.14 – Exploitation of UAV shots: on the left 3D model and on the right plotting of inspection results on 2D orthophotos / © EDF

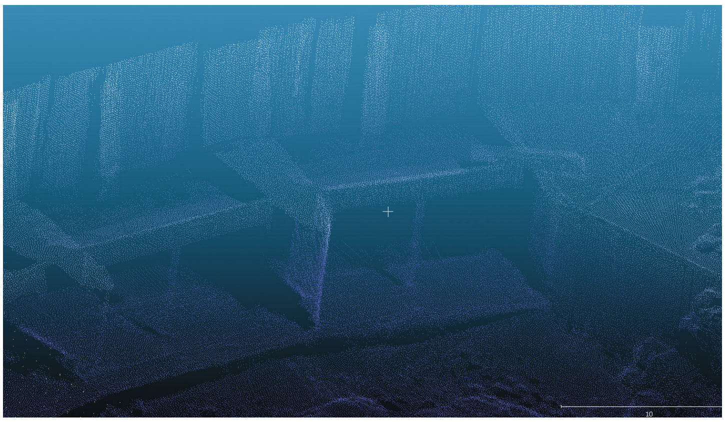


The use of underwater robots equipped with different types of sensors for the inspection of structures and hydro-mechanical components is becoming systematic for examinations without dewatering the reservoir. These inspections are generally supplemented by a bathymetric survey of the reservoir in order to monitor the evolution of its mud silting state.

The 3D aerial and underwater surveys can easily be merged to provide complete modeling and mapping of the dam and its reservoir.

Figures 11.15 and 11.16 – Illustration of the combination of a 3D aerial (top) and a bathymetric bottom) surveys, for downstream erosion monitoring / © EDF





5. CONCLUSION AND OUTLOOK ON DAMS SURVEILLANCE

Dam monitoring and inspection is now a matter of course in France. This result is the culmination of a technical history rich in developments and innovations, but also in incidents and accidents. Dam safety regulations have always been able to incorporate these changes and events. Our dams are now more and better monitored than they were in the past, with monitoring adapted to the different issues, and with databases and knowledge bases that are increasingly complete.

The approved engineering and design departments have seen their action strengthened in the diagnosis and control of the safety of structures in service. However, the operator retains a key role in the early detection of behavior anomalies and the possible implementation of actions to make the dam safe.

As we have seen throughout this chapter, many changes and developments have accompanied our surveillance practices over time. They have provided useful additions to conventional means of control for monitoring and diagnosis. Their use should be encouraged when it is useful: to this end, the CFBR plays a leading role in promoting the sharing of new developments and experimental results.

Finally, and to encourage the ever-present dynamic of progress, a few lines on the prospects for developments that can be foreseen or imagined for the future:
- the generalization of the use of augmented (or virtual) reality tools for on-site monitoring;
- real-time monitoring with remotely connected sensors;
- the use of ever more efficient data processing and analysis algorithms, facilitating the understanding and interpretation of monitoring data;
- assimilation in global models (concept of "numerical twin") of all the information useful for a continuous and predictive evaluation of safety criteria: control measurements, monitoring data, operating and environmental data, etc.

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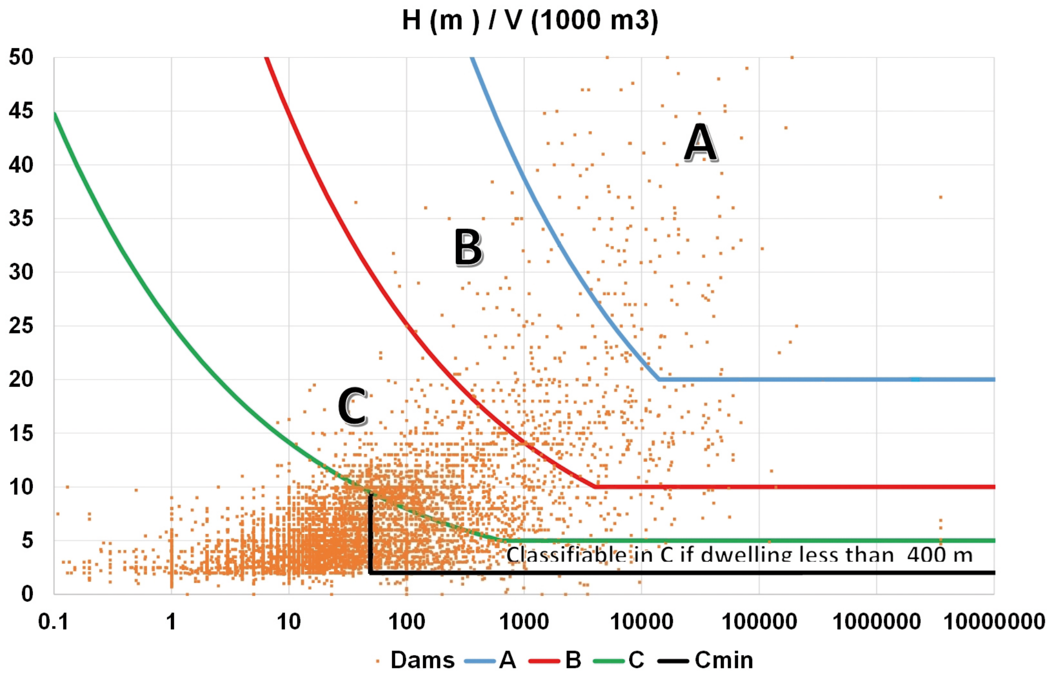
CHAPTER 12

DAM SAFETY AND RISK ASSESSMENT

1. INTRODUCTION

France has 722 large dams according to the criteria of the ICOLD World Register of Dams. Under French regulations, French dams are divided into three classes (A, B and C), according to the $H^2V^{0.5}$ coefficient taking into account the height of the dam above its foundations (H in m) and its reservoir volume (V in million m^3). Classes A and B are for the largest dams (Class A: H ≥ 20 m and $H^2V^{0.5}$ ≥ 1500; Class B: H ≥ 10 m and $H^2V^{0.5}$ ≥ 200) and include 631 dams. Class C includes 1,466 dams of smaller size (H ≥ 5 m and $H^2V^{0.5}$ ≥ 20 or H > 2 m and V > 0.05 hm^3 if there is a dwelling downstream). The graph below displays this information.

Figure 12.1 – Distribution of dam classes in France



The owner (or licensee) maintains and supervises his dam. By law, he is responsible for his dam. The Government, through its regional dam safety control services, must ensure that the dams it authorizes comply with the regulations so as not to threaten public safety. The authority therefore monitors the action of the owner or licensee, verifying that he fulfills his obligations and ensuring that the safety level of the dam is adequate.

The owner must define his dam safety policy and his safety management system. The environmental code sets the regulatory requirements for dam safety, which is based on four principles: safe design, safe monitoring and operation, prevention of the risk of failure through Emergency Action Plans (French acronym: "PPI") for certain dams, and periodical dam safety reviews and risk assessment reports. These reports are called "Études de Dangers" (acronym: EDD) in French. In order to better represent the content of these reports, the English translation adopted is "Safety Review Risk Assessment", or "SaRRA".

1.1 Safe Design

Until recently, dam design and the review of existing dams were based solely on professional best practices. In this regard, the guidelines of the French Committee on Dams and Reservoirs are an essential source.

In 2018, a specific regulation setting essential requirements for dam safety (decree of August 6th, 2018) introduced regulatory requirements for the design criteria. This regulation introduces three essential safety requirements for dams, relating to normal operating conditions, in the event of a natural hazard, or in the event of an incident on the dam or its equipment (failure of a gate for example). They are based on two technical annexes specifying, in particular, input design flood (IDF) and design earthquake required by regulation. The specificity of the French regulations in terms of essential safety requirements is to distinguish existing dams from new dams, with fewer requirements for the former than for the latter. The regulations also set deadlines for the French dam portfolio to comply with these requirements (before 2035 for all dams).

Other parameters required for dam design, including resistance properties, partial coefficients and limit state status, fall within professional guidelines, including those of the French Committee on Dams and Reservoirs.

Finally, the Government delivers formal accreditations to consultancy firms on the basis of a report demonstrating their skills. Depending on the capabilities of the candidate firms, an accreditation, according to dam size, is given for the various engineering services (dam surveillance and monitoring, design studies, and works supervision).

1.2 Safe operation and surveillance

French regulations require that these activities be described in several documents, with periodicities depending on the type of activity and class of the dam:

- the dam register and the organizational document: a register must be kept on each dam and the operator must report all the actions carried out and all the events that have occurred on the dam and its appurtenant structures. The organizational document includes the operator's procedures for monitoring and testing the dam equipment, as well as those relating to the operator's action during exceptional or accidental events (e.g., flood controls);
- the periodic "operation and surveillance" report and the in-depth technical inspections: the person in charge of the dam describes the dam's operation during the period (special events, floods, incident management, etc.) and reports on the condition of the dam and its equipment (visible parts) through routine visual inspections and in-depth technical visits covering the dam's structure, the hydromechanical equipment and the control system equipment;
- the monitoring report: based on the analysis of the readings of monitoring sensors installed in the dam, the owner must present a report describing the mechanical (movement, displacements, deformation) and hydraulic (leakage and piezometry) behavior of the dam and its foundation.

In addition to these documents, owners must report incidents and accidents that may have occurred on their dams and equipment to the control Authority.

1.3 Preventing the risk of dam failure through emergency plans

In France and for all class A dams of a height of over 20 m and with a volume of over 15 million m^3, an Emergency Action plan (or PPI) is developed. A risk assessment of the failure scenario must be carried out by the dam owner including determination of the break wave characteristics and of the inundated areas. In an area downstream close to the dam he must also install and manage warning devices (sirens). The local Government services in charge of emergency situations are responsible for the development of the overall Emergency Action plan and the dissemination of information to the population (via the local communities)..

1.4 Dam Safety Review Risk Assessment (SaRRA)

All aspects of dam safety detailed above are included in a SaRRA report. French regulations give a central role to this report, the purpose of which is the regular safety review and risk assessment of the dam (every 10 years and 15 years respectively for Class A and B dams). The main principles of SaRRAs are detailed below.

2. RISK ANALYSES FOR DAM RISK MANAGEMENT

In 2007, French regulations introduced the requirement to carry out risk assessments for large dams (classes A and B). At the core of the risk prevention system, the SaRRA is the essential basis for developing prevention strategies. It is managed under the responsibility of the dam owner or licensee and focuses on identifying risks, quantifying their occurrence and consequences and demonstrating how the risks of major accidents to the dam and / or its appurtenant structures are managed. SaRRAs are performed by project managers — either from consultancy firms or the dam owner's technical departments — accredited by the Government on the basis of their demonstrated skills. They are reviewed by the Government's supervisory authority.

The SARRA reports required by French regulations explicitly refer to the risk assessment methodologies and operational safety methods. The methods of analysis, including a safety and issues evaluation, are left to the choice of the project manager, depending on the characteristics of the dam to be analyzed. The steps of a SaRRA are detailed below.

2.1 Input data for a SaRRA

Obtaining risk assessment requires the best possible knowledge of the dam, its environment and its behavior, as well as the operation processes and the level of performance of its equipment and safety systems. Therefore, the development of a SaRRA includes a search for input data in the preliminary process, most of which is synthesized in the tables below:

Table 12.1 – Input data for a SaRRA

Data collected at the beginning of the risk assessment	Description
Reference data describing the dam and equipment	Characteristics of the reservoir and geology. Design justification for civil works and mechanical equipment (gates,…) / Drawings. Sketches and/or instructions for equipment and control system operation. Final acceptance protocol and test report; first filling report. Records of studies and work associated with major changes.
Operating, monitoring and maintenance data	Operating reports including exceptional events (floods, earthquakes, drawdown, etc.). Incident sheets. Periodic inspection results and reports. Monitoring results and reports. Results of periodic tests.
Organizational documents and operating procedures	Safety Management System organization document. Procedures and operating instructions (particularly for dam management during flood events and dam monitoring).

The collection of input data is complemented by a critical analysis of the existing data on natural hazards that may have an impact on the safety of the dam. If necessary, studies are resumed or undertaken if there are none.

Tableau 12.2 – List of natural hazards taken into account

Identification and characterization of natural hazards (possibly updated for risk analysis purposes)	Hydrological and seismic hazards. Risks of landslides and avalanches. Risks related to wind, lightning, forest fires, frost, snow, siltation, erosion and changes in the riverbed.

To complement this collected data, a comprehensive review of the dam system and all its equipment is carried out. It aims to provide the most complete and accurate picture possible of their condition and their operation. This is carried out by specialists (civil engineering, mechanics, control-system), with means adapted to the operating context (with emptying, full restraint or with partial lowering of the reservoir which constitutes the most frequent case). The photos below illustrate the diversity of investigations conducted during this diagnostic phase.

Figure 12.2 – Checking the location of a limit water level sensor in a well / © EDF

Figure 12.3 – Camera inspection of a drain / © EDF

Figure 12.4 – Examination of the condition of a butterfly valve lens in a bottom outlet / © EDF

Figure 12.5 – Review of the condition of a Galle chain actuating a flood gate / © EDF

2.1 Functional analysis

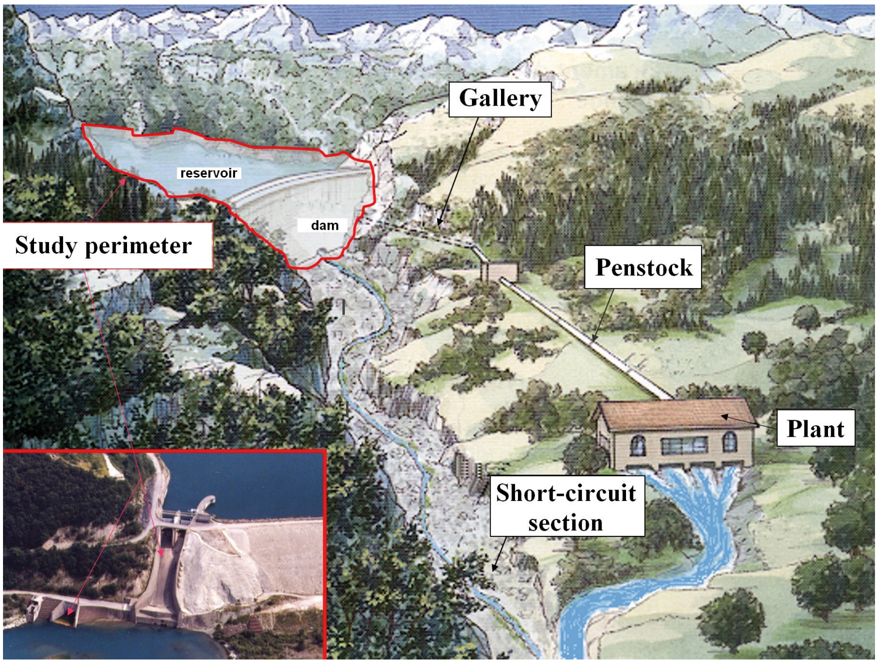
SaRRAs include a functional analysis. This allows the dam's functions to be identified and characterized, in order to provide the information necessary to search for the failure modes. It describes the dam's uses: water storage, hydropower generation, flood mitigation, low water support, and defines the functions of the various components as well as the interactions between the dam and its environment.

The functional analysis defines the "study perimeter" that includes the dam and all associated structures and equipment that contribute directly to safety functions (Figure 12.6).

It identifies the functions performed by the dam's components: the main functions that represent the function the component was designed for and the technological functions that the component must perform to maintain its integrity and ensure its performance.

The functional analysis describes the interactions between the upstream and downstream environment and the dam itself. This makes it possible to identify the external factors of threat, the natural hazards, and the potential safety issues.

Figure 12.6 – Illustration of the study perimeter



2.2 Failure mode analysis

Based on the functional analysis, SaRRAs implement an analysis of dam failure modes, which aim to determine the initiating, intermediate and feared events of failure scenarios. The two main methods used in France are the Preliminary Risk Analysis (PRA) and the Failure Modes and Effects Analysis (FMEA).

The PRA method, used in 77% of risk analyses, is a simplified risk analysis based on expert judgment: hazard identification is carried out using the experience and knowledge of the expert panel set up for the risk analysis. The method is relevant to dams, as expert judgment remains essential for determining some of the deterioration processes and failure modes. It should be noted that in the absence of standardization of the method, there is great variability in the PRAs produced. Thus, some PRAs appear very complete in the analysis of failure modes and are ultimately more akin to FMEAs.

Table 12.3 – Example of the application of the PRA for an arch dam

Dam element	Operating condition	Failure mode	Impacted function	Consequences	Post-accident kinetic	Severity	Type d'événement	Remarks
Dam	All conditions	Failure global instability, gravity abutment instability, loss of stability of abutments	Water retention	Inundation wave. Rapid drawdown of the reservoir	Rapid	Severe	Feared event	Earthquake not taken into account: dam in low seismicity area and experience feedback generally very favorable on the dynamic behavior of arch dams during an earthquake.

The FMEA method, used in 23% of the analyses, allows for a detailed analysis of the dam's failure modes. In a standardized framework, its advantage is the accuracy and quality of the analysis. The FMEA method is therefore a comprehensive analysis of the failure modes of the dam components, after a good functional analysis. It is therefore well-suited to a complete or even quantitative risk analysis.

Table 12.4 – Example of application of FMEA for the upstream shoulder of a rockfill dam

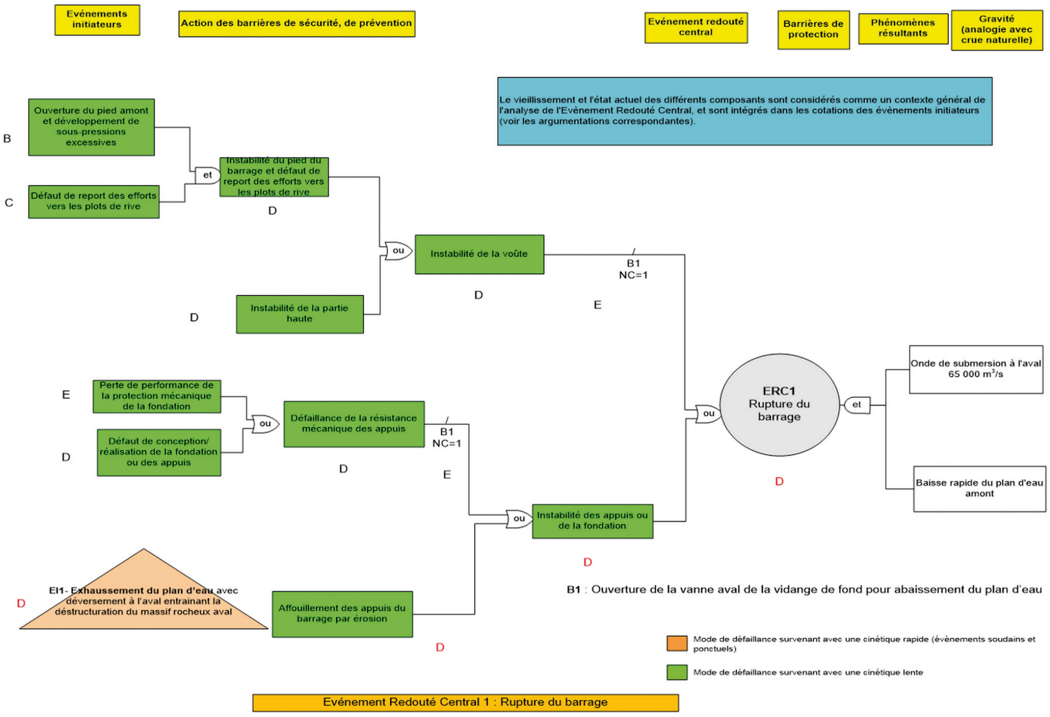
	Functional analysis (level 1)			*FMEA (level 1)*		
N°	**Component level 1**	**Main functions**	**Technical functions**	**Failure modes**	**Causes**	**Effects**
1	Upstream shoulder.	Ensure upstream shell and core stability. Resistance to mechanical stresses. Internal slope stability.	Resistance to hydrodynamic impacts (waves).	Slide of upstream shoulder – global failure.	Excessive seismic foundation and / or interface displacements.	Slide of the upstream slope and the core.
				Erosion of the upstream slope.	Excessive wave action excessive degradation of rockfill, loss of materials.	Erosion in the water fluctuation zone

2.3 Representation of scenarios using tree diagrams

Based on knowledge of failure modes, a SaRRA produces a representation of failure scenarios as a tree diagram. This diagram is based on a graphic visualization of the accidental sequences that may occur on the dam. The methods used in the SaRRA are either:

- the Event Tree Method: this describes failure scenarios from an initiating event, leading to the failure of a component or part of the system to determine the resulting events. The sequence of failure modes until the occurrence of a potential accident is determined by an inductive approach;
- the Failure Tree Method: this describes the possible combinations of events that allow the realization of a previously defined feared event. The starting point of building a failure tree is the feared event itself and the principle is to define successive levels of events such that each is a consequence of one or more events of the previous level, through a deductive approach;
- the Bow Tie Method: this combines a failure tree and an event tree around the same Feared Central Event (FCE, French acronym is ERC). FCEs are dangerous situations leading mainly to the partial or total loss of integrity of the dam or any of its elements (bottom outlet or spillway gate, etc.). The bow tie provides a global view of the different accident scenarios and their impact on their environment. The bow tie method is used prominently in SaRRA reports (90%).

Figure 12.7 – Example of a bow tie analysis relating to the failure of an arch dam by exceeding its failure water level



2.4 Safety assessment

The principle is to individually assess the probability of failure of the elementary events of a scenario and then aggregate them by mathematical rules adapted to the chosen method, ultimately achieving the scenario's overall probability.

In SaRRA reports the most common practice in assessing probabilities for failures is a semi-quantitative approach in which probability classifications are obtained using analysis grids that match expert judgments with probability ranges.

Table 12.5 – Example of a semi-quantitative table for assessing events

Probability class	E	D	C	B	A
Qualitative (The definitions are valid only if the number of installations and the feedback are sufficient)	"Possible event but extremely unlikely" not impossible according to current knowledge but not encountered on a world scale on an important number of structures	"Event very unlikely" already occurred in the business sector but risk mitigation measures made its probability drop significantly	"Unlikely event" already occurred in the business sector. The risk mitigation measures did not make its probability drop significantly	"Probable Event" occurred or can occur during the installation's lifetime	"Usual event" already occurred on the analyzed site and can occur several times during the installation's lifetime in spite of corrective measures
Semi-quantitative	This scale is intermediate between the qualitative and quantitative scales and provides the accountancy of the risk control measures already implemented, in compliance with article 4 of the order.				
Quantitative (per unit and per year)	10^{-5}	10^{-4}	10^{-3}	10^{-2}	

Another less common practice is a probabilistic quantitative approach to safety assessment, in which assessments are made using probabilistic models, statistical analyses, or, failing that, expert judgment.

Regardless of the approach chosen, the safety assessment is produced by a working group of experts and operators. This panel monitors and validates scenario modeling, assesses the probability of failures as a single probability interval or unique probability and validates the probability assessment of the scenario as a whole; that also includes the inter-comparison of the probability of all analyzed scenarios and their prioritization.

SaRRAs identify safety barriers into the scenarios. These barriers are technical or organizational elements that provide a safety function. Risk analyses essentially consider prevention barriers, which are measures to reduce the likelihood of an adverse event. A barrier must be independent of the feared event, reliable, have a response time in line with the kinetics of the feared event and must be able to be tested.

2.5 Assessing the severity of scenarios

In SaRRAs the result of an overall assessment of dam safety, for each failure scenario, is expressed in terms of consequences on human, material, organizational and environmental issues upstream and downstream of the dam and its reservoir. The consequences of each potential accident are characterized by the flows and volumes released from the reservoir, the intensity, the kinetics and the duration of these effects. This makes it possible to assess the seriousness of the consequences for the affected area, particularly in the vicinity of important stakes.
The investigations carried out are adapted to the importance of the stakes for the safety of people and property and allow:
- hydraulic modeling of the break wave for identified accidents;
- hydraulic numerical simulation phenomena (inundated areas on an adapted scale (1/25,000) mentioning the main characteristics of the break wave;
- an assessment of the population impacted with a precision relevant for civil protection needs (populations per hectare of residential, commercial, industrial zones, etc.).

Using a severity grid (table 12.6), a severity classification is then assigned to each scenario, depending on the most penalizing impact on the area downstream of the dam

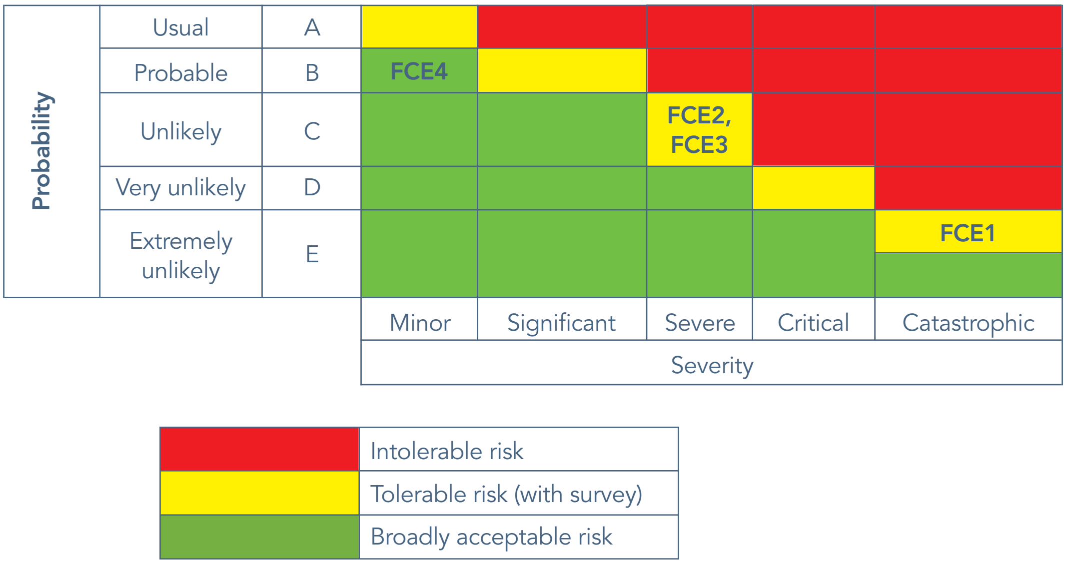
Table 12.6 – Example of severity classification allocation grid

CONSEQUENCE SEVERITY CLASSIFICATION (in descending order)		NUMBER OF PEOPLE exposed in **fast** kinetic zone	NUMBER OF PEOPLE exposed in **slow** kinetic zone
5	Disastrous	Over 1 000	Over 10 000
4	Catastrophic	100 to 999	1 000 to 9 999
3	Important	10 to 99	100 to 999
2	Serious	1 to 9	10 to 99
1	Moderate		1 to 9

2.6 Scenario criticality assessment

Once the severity of the consequences and the occurrence of the scenarios have been determined, the SaRRA cross-references these two pieces of information to determine a scenario's criticality. To do this, French practice has relied heavily on criticality matrices, consisting of the display and prioritization of the different scenarios in a synthetic table. The two entries "severity" and "occurrence" for potential scenarios can be found, as shown in Figure 12.8.

Figure 12.8 – Example of criticality grid with display of tolerability limits



Ultimately, this assessment should enable the project manager to propose measures to control or reduce the risks as low as reasonably possible (ALARP principle). The objectives achieved are represented in a residual risk criticality matrix that takes into account the contribution of the various reduction measures.

3. THE CONTRIBUTIONS OF SaRRA REPORTS FOR DAMS IN FRANCE

3.1 Contributions of SaRRAs

The risk assessments in SaRRA reports carried out in France systematically on the 631 or so large dams in the country's portfolio have, in the opinion of all stakeholders, had major positive impacts for dam safety. These contributions include:

- dam safety has long been viewed primarily from a "civil engineering" aspect. However, SaRRAs have enabled a new functional multi-skill approach, as opposed to the compartmentalization that could exist between each professional sector;
- a significant improvement in knowledge about the dam and its appurtenant structures. The SaRRA final report is an excellent document for a descriptive synthesis of what is known about the dam. The available data has been formally criticized and validated;
- identification and inter-ranking of major failure scenarios and major safety risks. Potential failures that were not necessarily well recognized may sometimes be brought to light by examining complex scenarios combining failures of hydromechanical equipment or the control-system with hydrological scenarios that can lead to accidents ranking from the failure of the dam to less severe events (failure or unwanted opening of a gate). SaRRAs have provided a comprehensive view of the risks posed to dams together with a proposal for prioritized actions, thus constituting a valuable decision-making tool for the measures to be implemented by the owner.

3.2 Communication around SaRRA reports

SaRRAs significantly complement knowledge of major risks and other risks associated with dam development. Prior to the implementation of risk analyses, the only known elements of dam risks came from the emergency plans which were only available for larger dams. They are therefore a new approach for the public and for local authorities.

For professionals working on dams, risk analyses give a sense to some maintenance or monitoring activities and may lead to a review of certain practices so as to take risks into account better. Risk analyses frequently offer a better understanding and therefore acceptance of the constraints of availability of safety equipment, for example. Risk analyses then allow a new reference framework for the operation of the dam system for all those involved in their operation and maintenance.

3.3 Moving towards a second generation of risk analyses

Risk analyses are now essential documents in France, through which the person in charge of a dam system demonstrates its safety in all operational conditions. It is a useful document for all the stakeholders, including the supervisory authority, which makes it possible to identify critical points for the dam safety.
With the evolution of the regulations in 2015, the French government wanted to reaffirm and strengthen the role of risk analyses. A new decree consolidates the required content of risk analyses through:

- improvement of input data: a comprehensive review of the dam and its equipment, an assessment of its condition, behavior and design is now explicitly required before starting the risk assessment;
- more precise elements on the dam safety management system: management of subcontracting, definition of responsibilities;
- improved risk assessment, including a systematic supply of dam break flood wave maps in 1/25,000 scale, the analysis of scenarios other than dam failure but which could lead to serious consequences, etc.

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The French Committee on Dams and Reservoirs was created in 1926 and was one of the founding members of the International Commission of Large Dams (ICOLD) in which it has been and is still very engaged and active. With more than 500 members, the Committee has a long tradition of sharing, exchanging with its members and, more broadly, with all stakeholders in the field of dams and, more recently, of levees.

«Dams, the French expertise», published on the occasion of the 27th congress of ICOLD is in line with this tradition of exchanges and communications. Through 12 chapters covering many fields of activity, it presents the history, know-how, experiences, innovations, and research areas that the French Committee of Dams and Reservoirs choses to share, especially among the participants in the 27th congress of ICOLD.

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