Studies on CSD and Applications in China

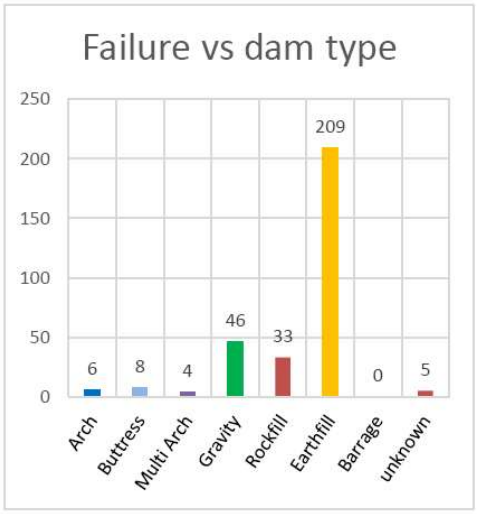
Dr. Jinsheng JIA

Prof., IWHR, China
Chairman, ICOLD TC on Cemented Material Dams
Hon. President, ICOLD

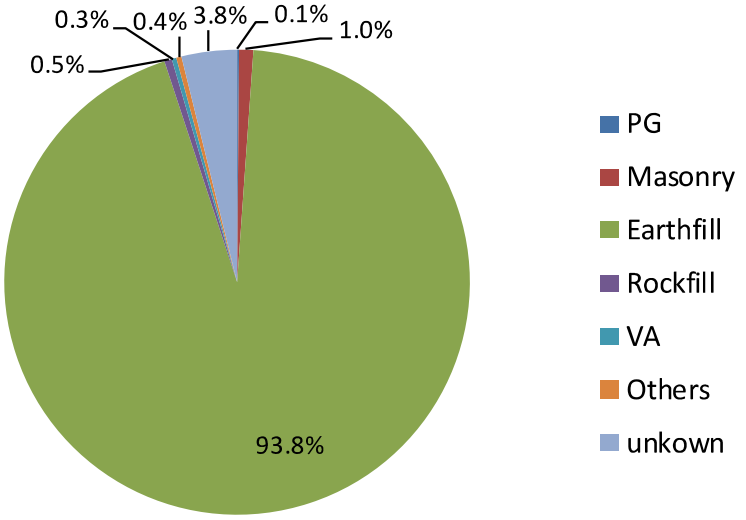
CONTENTS

Challenges to dam safety: Improve safety of Embankment dams

- Dams in China
  - 98566 dams, in which 90538 are embankment dams (92%)
  - 61232 dams lower than 15m
- Lessons learned from dam failures: more than 5000 Dam failure cases in 60 countries, including over 2000 cases in USA, 3000 cases in CHINA.



ICOLD Incident database Bulletin 99 update: Statistical analysis of dam failures



Dam failure cases in China

Dam failure happens almost every year

May 2020, Edenville dam failure, Michigan, USA

- 19 May, 2020， Edenville dam(earth dam, 16.6m high) failed
- Causing overtopping failure of Sanford dam downstream
- Miland city was flooded, more than 10,000 people were evacuated

Failure of Edenville dam

(Height: 16.6m， crest length: 2km)

Overtopping of Sanford dam

(Height: 11m， crest length: 481.3m)

Dam failure happens almost every year

July 2021， Yong'an and Xinfa dam failure, China

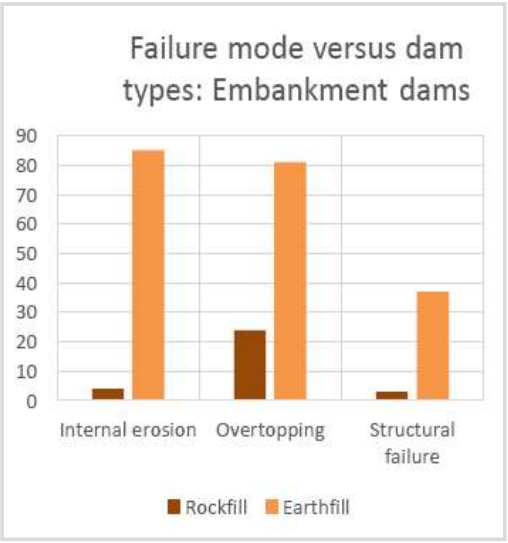
- Yong'an: embankment dam, 14.5m high, water storage capacity of 8hm^3, completed in 1995
- Xinfa: earth dam, 10.6m high, water storage capacity of 38hm^3, first impounding in 1959
- Yong'an failed due to over standard flood, causing failure of Xinfa dam downstream

Guojiazui earthfill dam: 7.5 hours' overtopping in 2021 in Henan Province, China

Although the downstream slope was seriously scoured, the dam did not break due to the asphalt concrete pavement on the dam crest and the concrete steps on the downstream slope

Embankment dam failure mode

Failure mode (embankment dams)	Year of construction						
	<=1900	1901-1925	1926-1950	1951-1975	1976-2000	>2000	Total
Internal Erosion	18	20	11	16	12	3	80
Overtopping -Ext Erosion	22	22	11	30	11	5	101
Structural Failure	8	9	12	12	5		46
Unknown	2			2		1	5
Total	50	51	34	60	28	9	232
		82%	**65%**	**77%**	**82%**	**89%**	**78%**

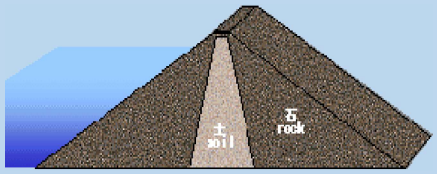


Failure mode for embankment dams: about 80% internal erosion or overtopping

Particles are washed away under the action of infiltration or overtopping flow

How to improve?

Local material (particles)



Embankment dam

Cement + Local material

Cemented Material Dam

Cement + aggregate (fully cemented)

Concrete Dam

Cemented soil

The Great Wall built 2200 years ago:
Cement the soil with glutinous rice paste for foundation reinforcement

Using cemented soil to build a dam

- **Cementitious material**
  - **Cement, lime**
  - **Flyash ?**
- **Mix proportion**
- **Properties of CS** (test methods of concrete and soil are both adopted)
  - **Strength: ≥4MPa (No guideline of CSD)**
  - **Impermeability**
  - **Durability**
- **Dam design criteria**
- **Quality control**
- **Construction equipments: Mixer**
- …

Experiments on properties of cemented soil

- **Cement, fly ash and lime (mass ratio, 2:1:1) are chosen as the cementitious materials**

■ Specimen preparation of cemented soils

- ✓ Specification for Soil Test SL237-1999
- ✓ Specification for Mix Proportion Design of Cement Soil JGJ/T233-2011

Mixing

Casting

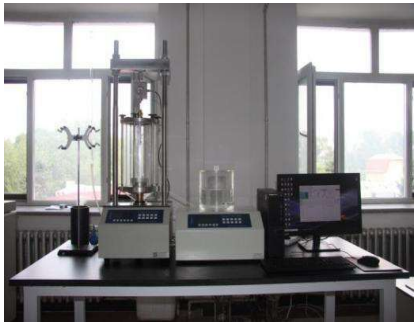
Curing

■ Performance test

Compaction

Unconfined compressive test

Direct shearing



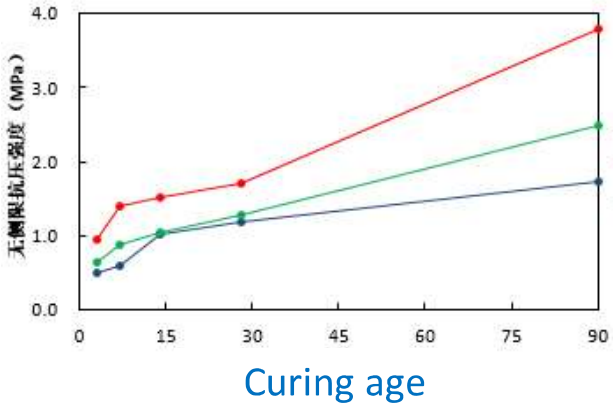
Tri-axial tests

Permeability test

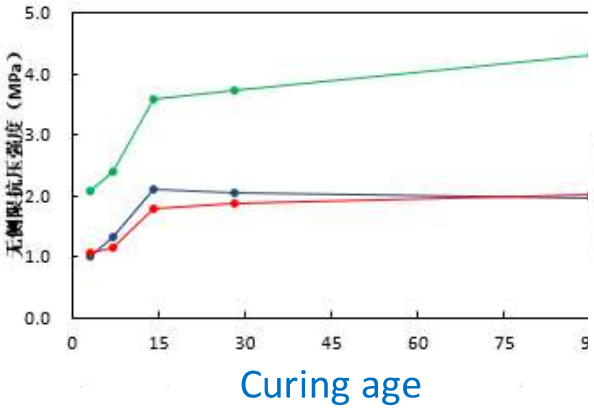
Unconfined compressive test

Unconfined compressive strengths (UCS) at different ages with cementitious materials content (4%~10%)

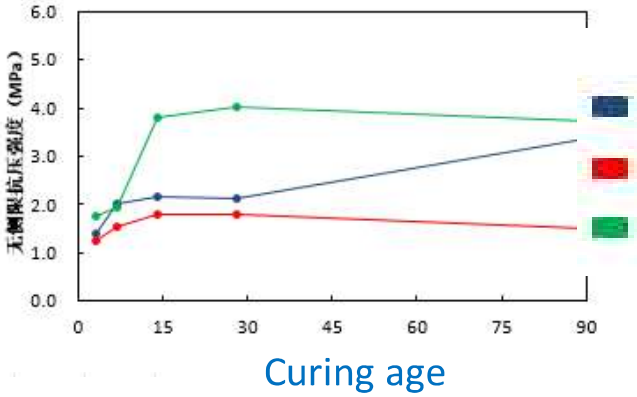
Cementitious materials content 4%



Cementitious materials content 6%



Cementitious materials content 10%

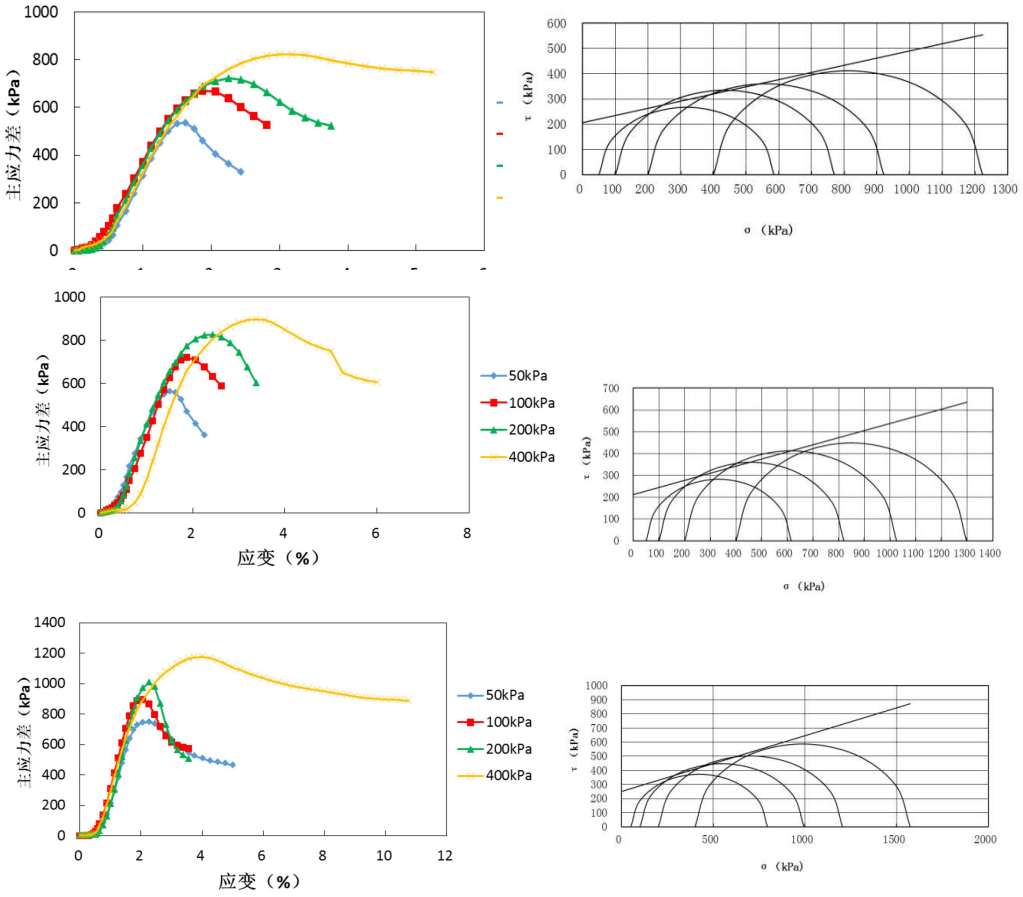


C:L:F=1:1:2
C:L:F=1:2:1
C:L:F=2:1:1

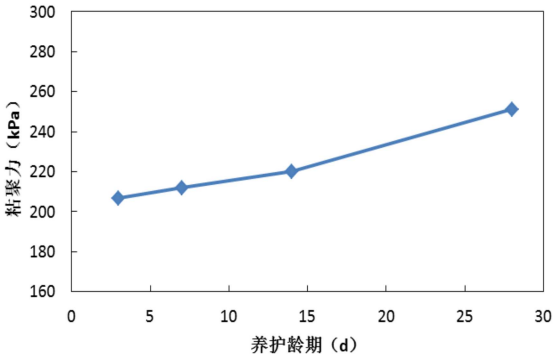
C-cement
L-lime
F-fly ash

- For the cementitious materials content of 10%, UCS at 14d could be **higher than 4 MPa**
- The compressive strength increases when the total amount of cementitious materials is increased
- Cement contributes most to the early age strength

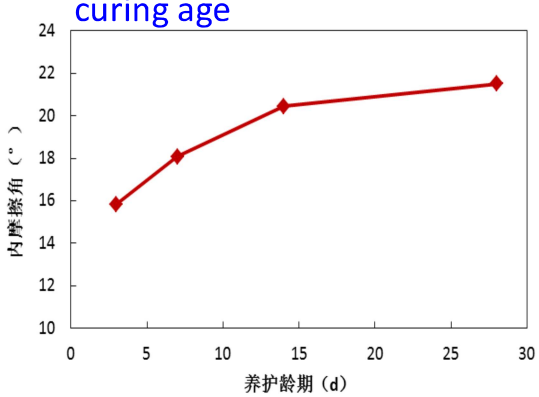
Triaxial tests and shearing strength



Cohesion force with curing age



Internal friction angle with curing age



- Residual strength increases when the confining stress is increased
- Cohesion force and friction angle increase when the curing age is increased
- The cohesion force at 28d increases by 22% compared with the cohesion force at 3d, while the internal friction angle increases by 36%

Durability test

Dry-wet cycle

- Immersed for 5h at 20.0±2℃
- Drying for 42h at 71±3℃

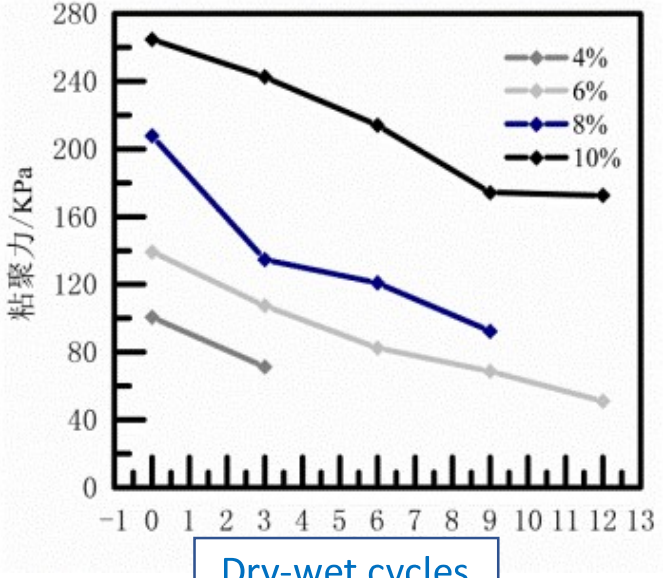
Freeze-thaw cycle

- Freeze temperature: -23℃, for 24h
- Thaw temperature: ~21.0±1.7℃, for 23h

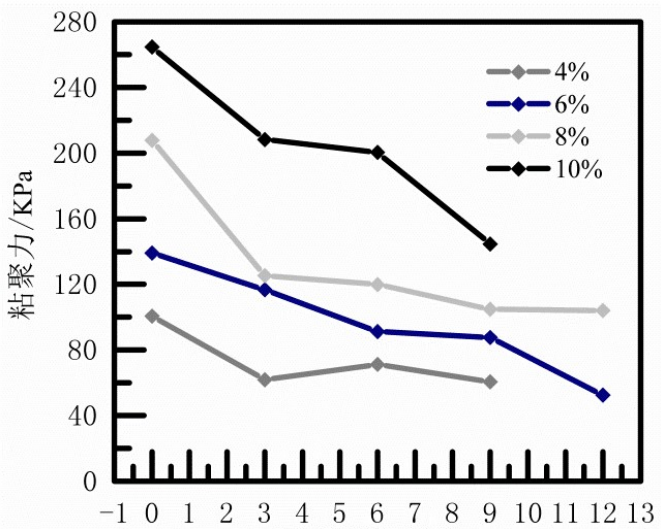
Immersion test

- Temperature: 20.0±2℃

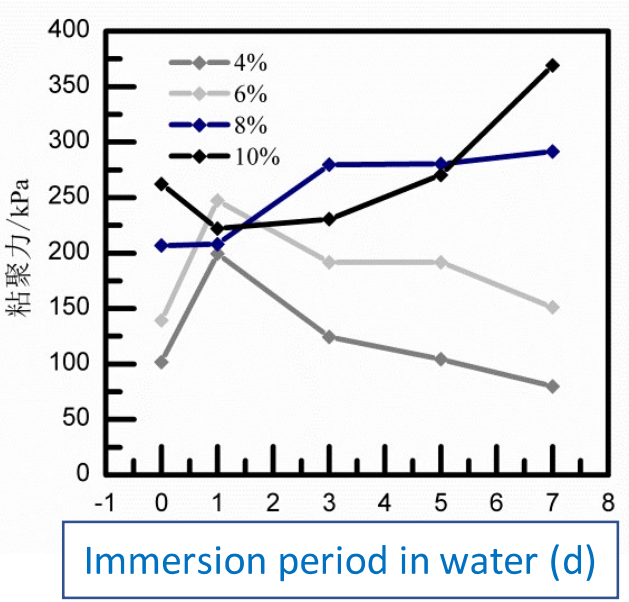
Variation of cohesion of cemented soils under different environmental conditions



Dry-wet cycles



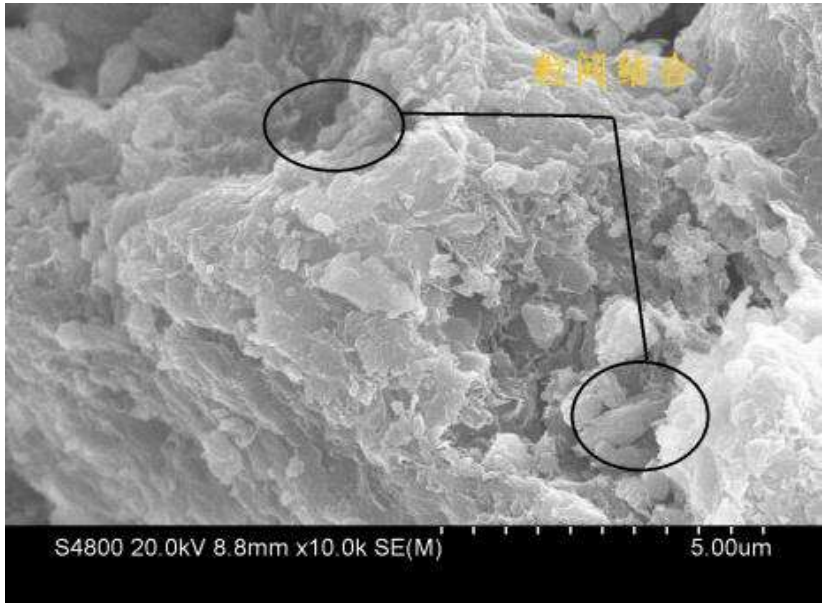
Freeze-thaw cycles

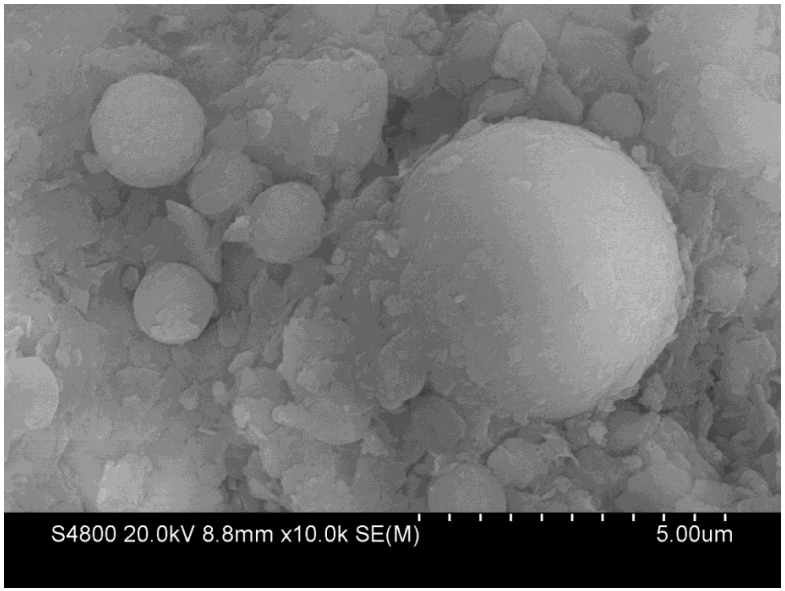


Immersion period in water (d)

- Resistance to severe environmental is influenced by cementitious materials content
- The more the cementitious materials, the greater the durability of cemented soils

Microstructural analysis

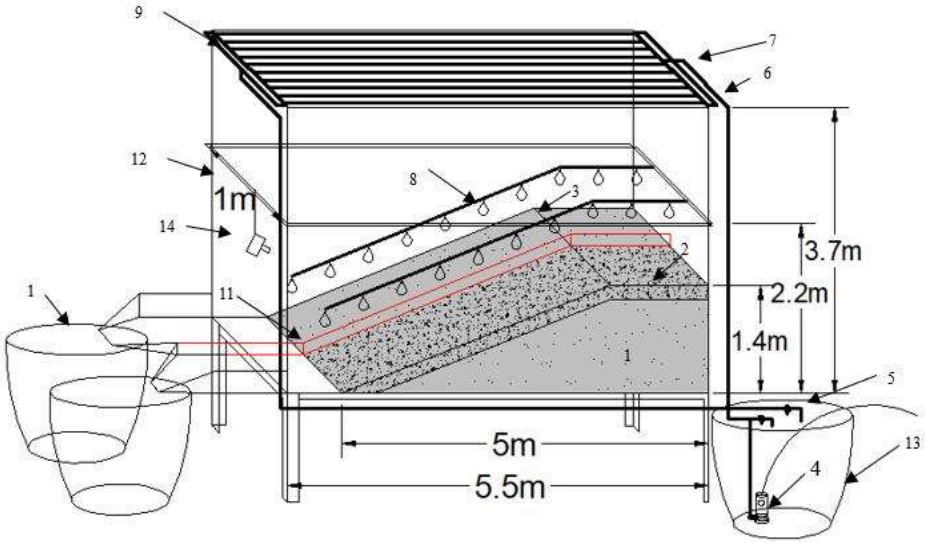


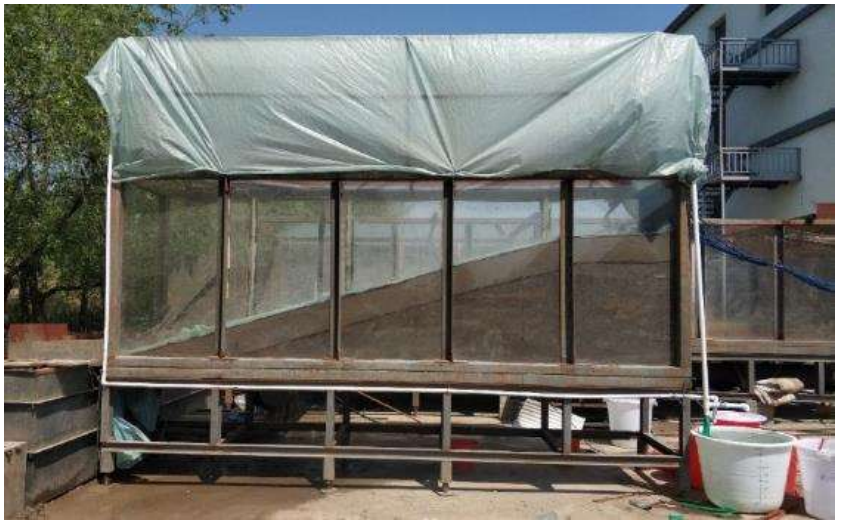


Hydration products from cement and fly ash which bond the soil particles and densify the soils, lead to the increase of the strength

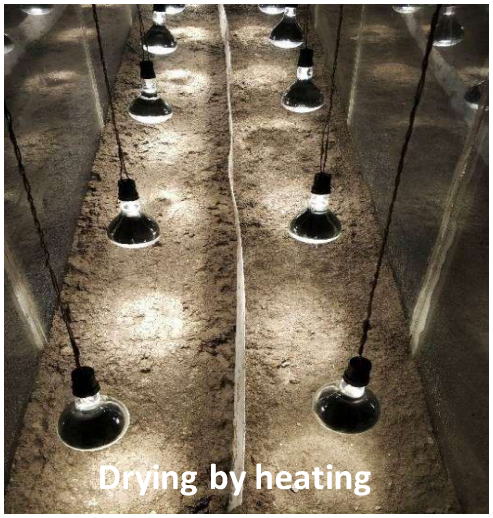
Rainfall erosion model test

- **Clayey soil vs cemented soil (Cementitious materials： 1% lime + 1%cement + 4% FA)**
- **Rainfall intensity 3.5mm/min, Rainfall 70mm**
- **Dry-wet cycles: 25**





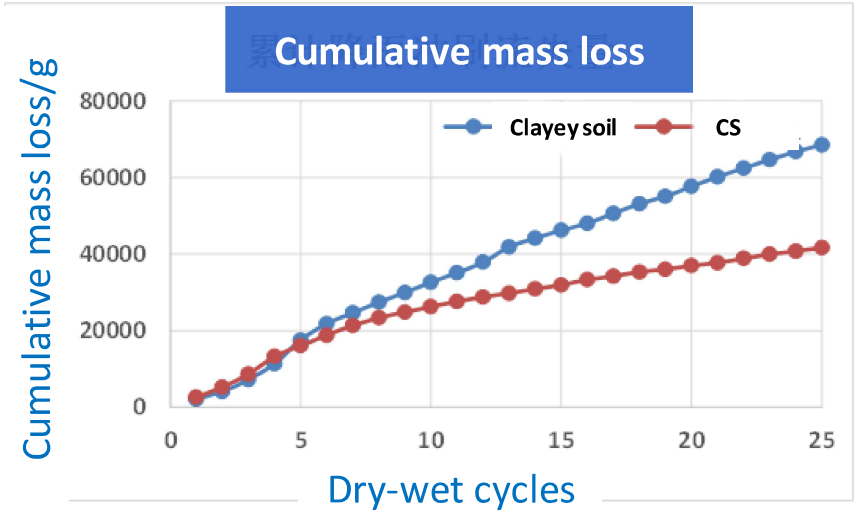
Clayey soil | Cemented soil



Clayey soil | Cemented soil

Mass loss of clayey soil is much greater than that of cemented soil

- **Mass loss of clayey soil after 25 dry-wet cycles: 4%**
- **Mass loss of cemented soils: 2.3%**



Overtopping model test of CSD

- **Dimension of the chute: length-10m, width-1m, height- 2.2m**
- **Soil: dry density 1.59 ~ 1.63g/cm^3, Moisture content: 20% ~ 22%**
- **Cementitious materials: 10%**
- **Curing: 28d, UCS: >4MPa**

Mixing of cemented soil

Compaction of cemented soil dam

- overtopping flow: from 0.05m^3/s to 0.26 m^3/s in the first 16hrs and kept the flow for the rest 28hrs
- width of overflow edge: narrowed to 60cm and 30cm respectively when the test lasted for 28hrs and 36hrs
- the maximum overtopping height: 55 cm

Flow (m^3/s)	Overtopping height (cm)	Overtopping time (h)	Hole width on the crest (cm)
0.05	5	8	0
0.13	10	8	0
0.26	16	12	0
0.26	30	8	60
0.26	55	8	30

Overtopping height 5cm

Overtopping height 10cm

Overtopping height 16cm

Width of overflow edge 60 cm

Width of overflow edge 30 cm

overtopping 4h

overtopping 8h

overtopping 16h

overtopping 24h

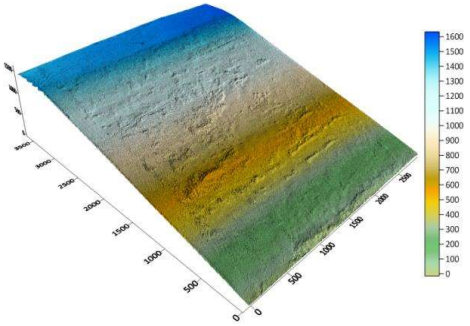
overtopping 32h

overtopping 44h

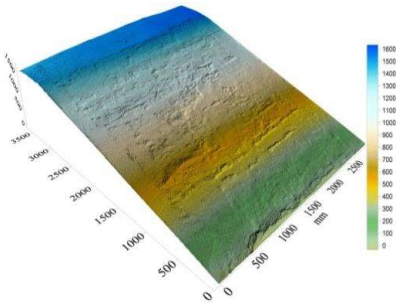
■ Erosion was monitored through 3D laser scanning technology

- Average erosion depth: 0.65cm
- Maximum erosion depth: 10cm

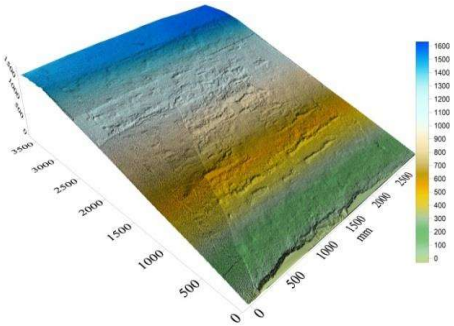
3D laser scanner



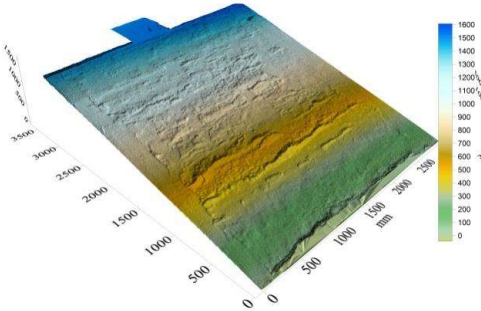
overtopping 30min



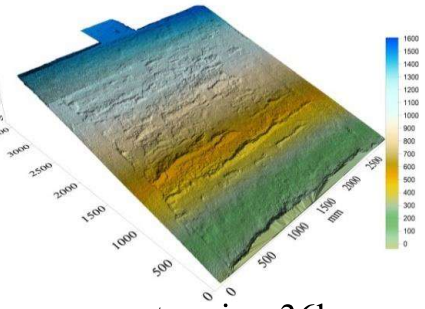
overtopping 6h



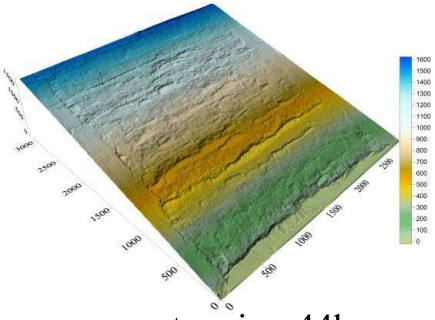
overtopping 18h



overtopping 30h



overtopping 36h



overtopping 44h

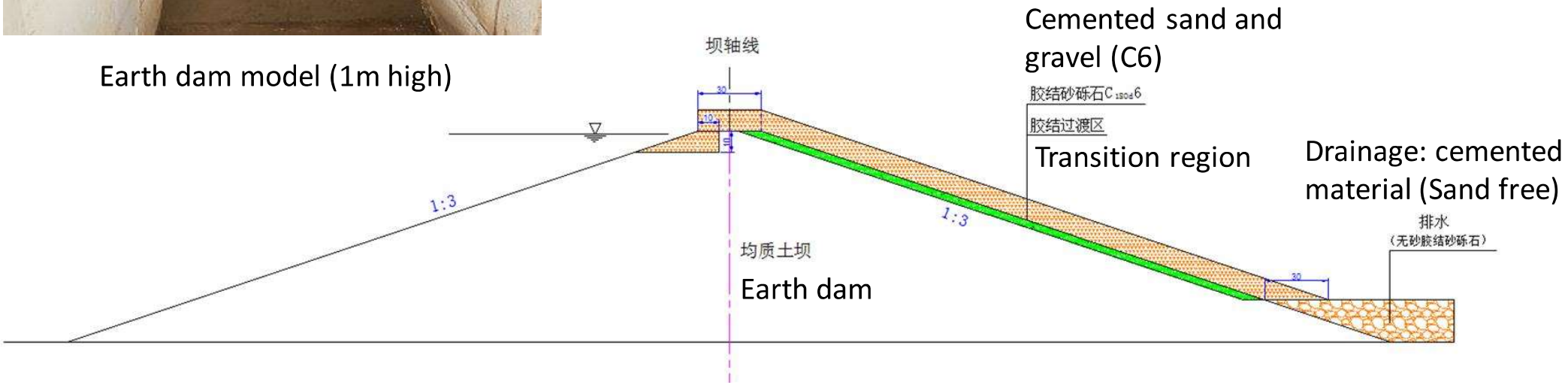
Overtopping model test of embankment dam with cemented material cover

Earth dam model (1m high)

The downstream slope of the dam model is covered with cemented material by 20cm

Mix ratio of cemented sand and gravel

Sand rate	Water binder ratio	Water (kg)	Cement (kg)	Fly ash (kg)	Sand (kg)	Gravel (Max. 40mm) (kg)
31%	1	120	60	60	670	1490



Cemented sand and gravel (C6)

Transition region

Drainage: cemented material (Sand free)

Earth dam

Solution to improve the capacity of embankment dams to resist overtopping failure

Overtopping for 50h
Max. flow velocity 4.7m/s

Application of Cemented Soil in Longxikou Levee

Minjiang River,
A big branch of the upper Yangtze River

Qianwei Levee

- **2.775 km long**
- **max. height: 14.1m**
- **CSGR levee on gravel foundation**
- **completed in 2020**

Longxikou Levee

- **23 km long**
- **to be built on a soil subject to liquefaction in case of earthquake**
- **the thickness of this weak silty soil is between 3 to 8m**
- **cemented soil foundation: increase bearing capacity, decrease settlement**

the foundation treated soil by a mix of cement and fly-ash

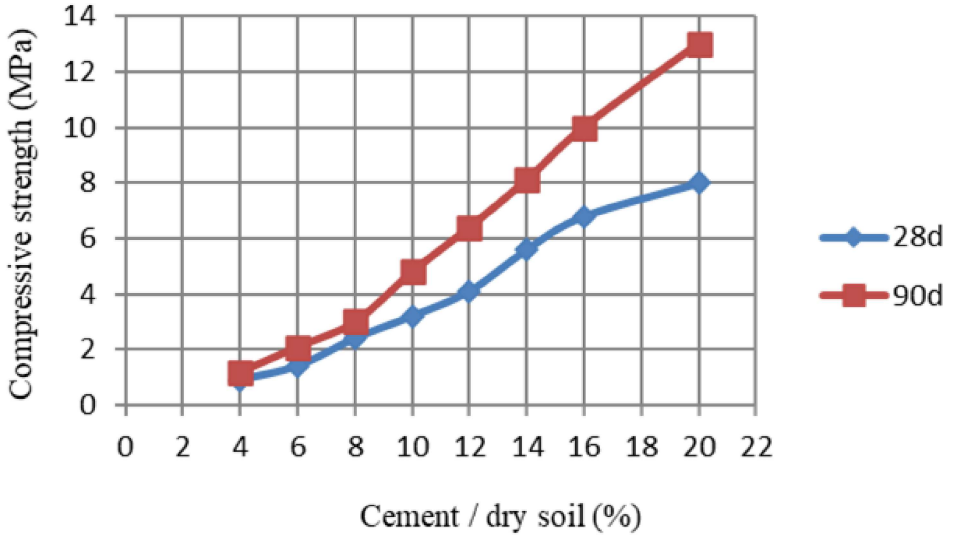
- **Sandy clay of low liquid limit (CLS)**

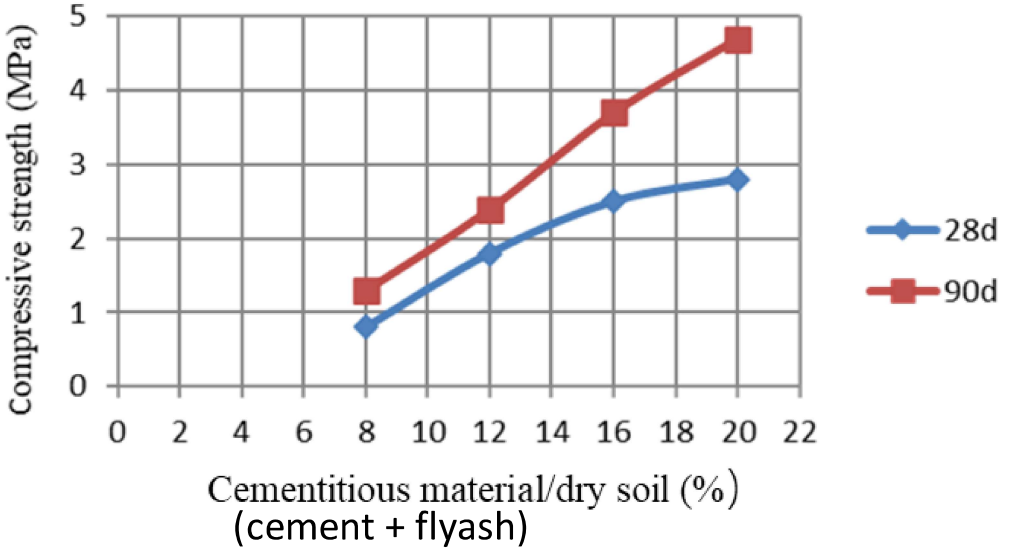
  liquid limit is 28.0%, the plastic limit is 17.2%, the plasticity index is 10.8

  sand content (0.075~2mm) is 28.6%, powder content (0.005~0.075) is 60.5%, clay content(~0.002) is 10.8%
- **Cementitious materials**

  cement or cement + fly ash (1:1)

- Treat the soil with a mix of 6% cement and 6% fly-ash : 1.8 MPa after 28 days and 2.4 MPa after 90 days





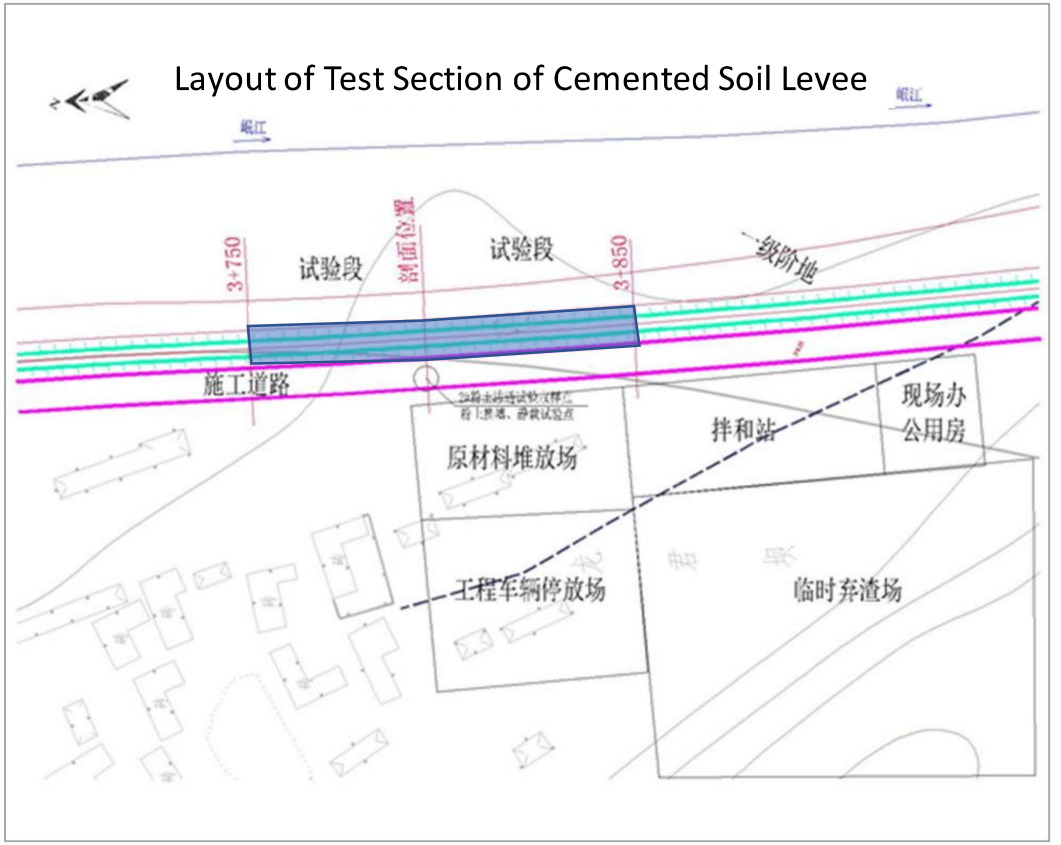
■ **Comparison tests of soil before and after treated: Cemented soil has higher mechanical strength and higher anti-permeability**

	Soil: Sandy clay	Cemented soil	
Compressive strength	356kPa	≥2MPa	180d
Permeability	10^{-3}~10^{-4}cm/s	10^{-7}~10^{-8}cm/s	90d
Elastic modulus	3 MPa	2.5 GPa	
Friction	/	0.79	
Cohesion/MPa	0	0.69	
Disintegration in water	Yes	No	28d

Soaking disintegration test

■ the mass loss rate is less than 2% after being soaked for 180 days after 28d age

- **A large number of test results have raised the confidence of the owner**
- **A test section of cemented soil levee of about 100m long has been planned and will be constructed soon**



Application of Cemented Soil in Pangtoupao Levee

- **Pangtoupao levee suffers from erosion and damage because of the long-term operation in the cold area**

- height: 5m
- crest width: 6m
- Upstream slope ratio 1:2.5
- Downstream slope ratio 1:3

- Average lowest daily temperature in winter: -24℃
- Average highest daily temperature in summer: 30 ℃
- Average yearly rainfall: 600mm

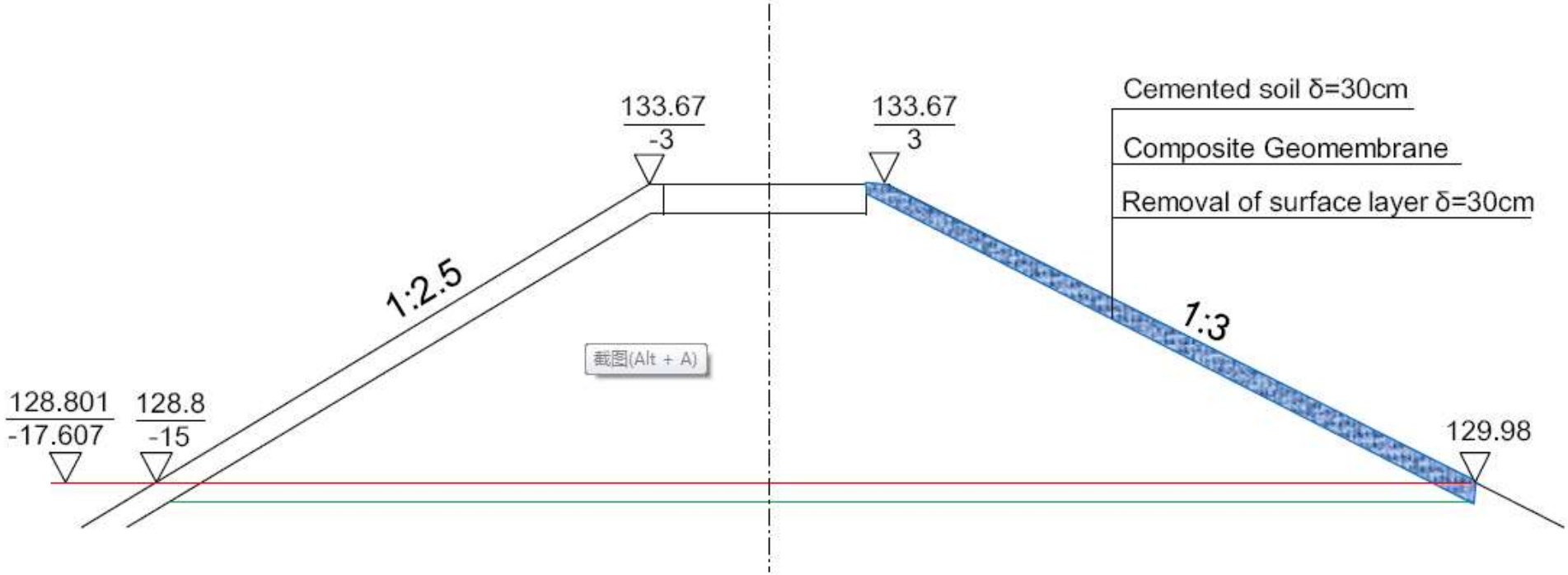
Scour marks at downstream slope

Scour marks at upstream slope

Uneven settlement

Bank caving

■ **Cemented soil is used to repair the downstream slope with a treatment depth of 30 cm**



Construction

Mix

Transport

Spread

Watering

Compaction

Leveling

Curing

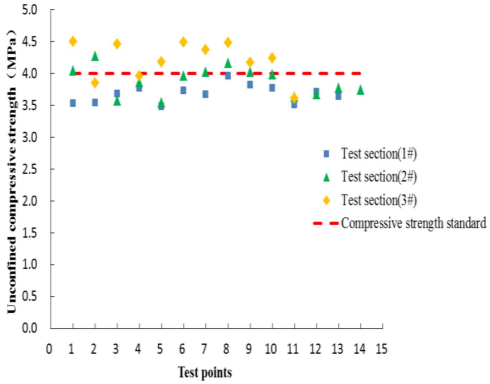
Completion

- 5000 m^3 Cemented soil in total
- During 2-year service, it suffered several rainstorms. There is no severe crack at the surface
- Through in situ test, UCS of Cemented Soil was about 4MPa.

CMD after construction

CMD after nearly tow-year service

In situ test



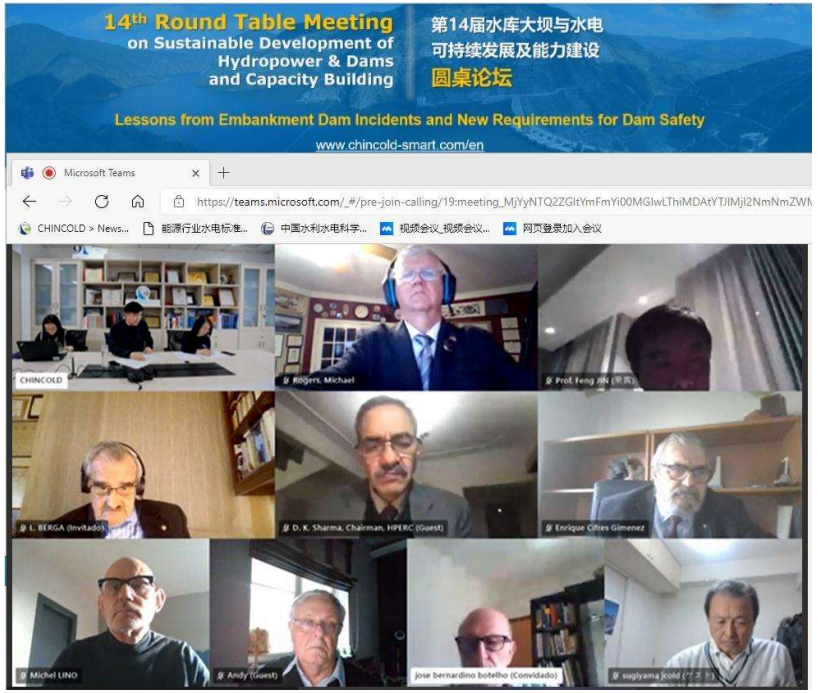
Test results

What's going on…

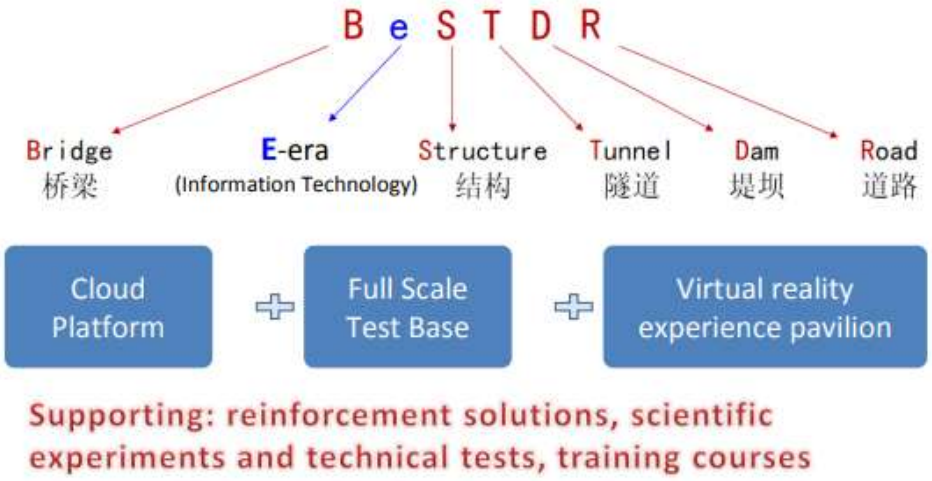
Solutions to improve the capacity of embankment dams to resist overtopping failure

- Last year, China experienced several heavy storms. The Ministry of Water Resources , P. R. of China attached great importance to safety of embankment dams, considering overtopping in case of over- standard flood.
- A special study is being carried out on how to improve the flood control capacity of reservoirs in China. CMD and dam downstream face protection measures could be options.

- Dec., 2021, Forum on "Lessons from Embankment Dam Incidents and New Requirements for Dam Safety"



- **Full-scale test site to be built**
  - **BeSTDR Infrastructure Hospital – Full Scale Test Base in Pingyu County, Henan province**
  - **10-meter-high, 5-meter-width dam model**
  - **Solutions to improve the capacity of existed embankment dams to resist overtopping failure**
    - ✓ interaction mechanism of the cemented material
    - ✓ mode of resisting failure
  - **Measures for embankment dam reinforcement**



Thank You for your kind attention!

Jinsheng JIA
Prof., IWHR; S.G., CHINCOLD; Hon. President, ICOLD
Email: jiajsh115@vip.126.com; jiajsh@iwhr.com