Cemented Soil Dams
Some engineering and design advances

Pierre AGRESTI, *ARTELIA*

Cédrine ALLEON, *ISL*

Pierre COCHET, *PCT Consultant*

CONTENT

1. Background
2. CSD stability study
3. Conclusions

1 -Background

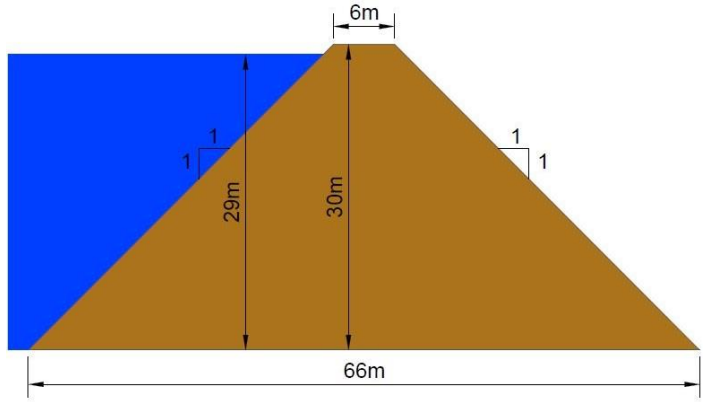
- Part of works carried out by CFBR Working Group (since 2013) for Cemented soil dams (CSD) bulletin (for contribution to ICOLD Committee P on Cemented Material Dams)

- R&D collaborative programme (ISL, ARTELIA, LHOIST, EDF, IRSTEA, Tractebel,…) :
- Data collection on existing construction projects (infrastructures)
- Lab testing programme on a typical lime treated soil
- Numerical soil modelling and stability analysis developed by 2 independent teams and software with PLAXIS (ISL) and FLAC (ARTELIA),

- Several publications (incl. ICOLD Vienna Congress - Q103 : “Treated soil for Small dams and dikes : Materials, Concepts, REX and innovation”; Hydro 2022 CSD Engineering advances)
- special Bulletin to be approved and released by ICOLD Committee P - after n Marseille 2022 ICOLD Congres

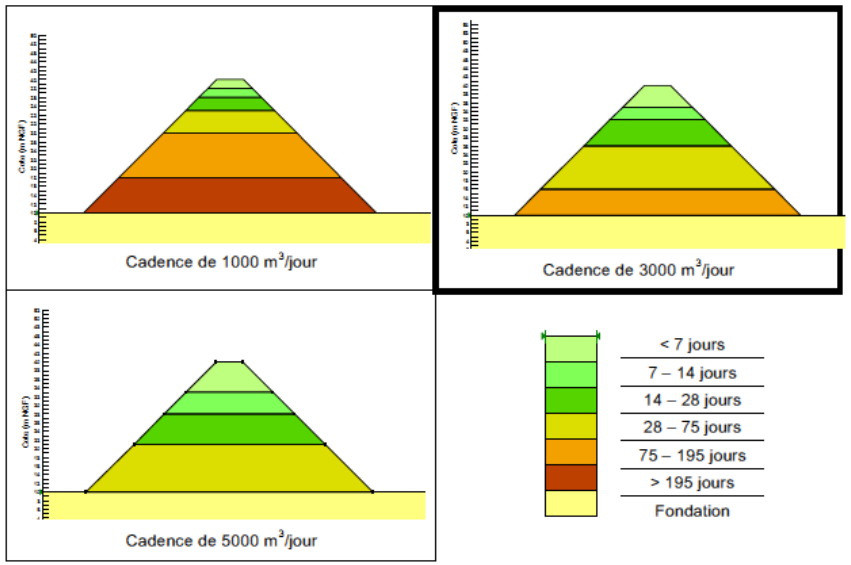
2 - CSD Stability study :

Purpose : investigate stability issues and limits for 30m high typical CSD and define practical design recommendations



Typical profile :

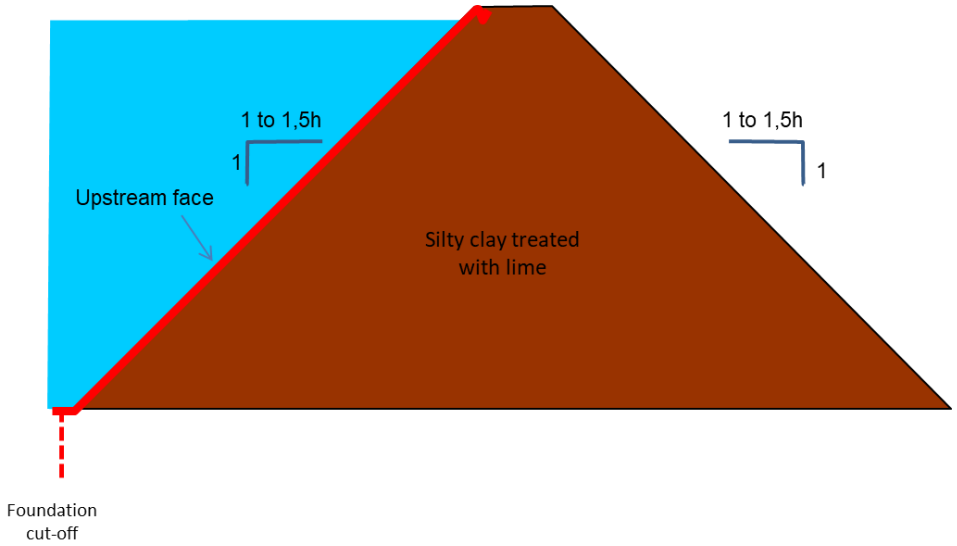
- Slope 1,25h to 1,1h /1v
- B crest = 6m
- L= 300 m
- Rigid foundation
- Watertight upstream facing
- Construction progress = 1 000 to 5 000 m³/day



Purpose : investigate stability for construction and operation conditions for typical faced CSD

Main assumptions:

- H= 30m maximum
- B crest = 6m
- Rigid foundation
- Impervious upstream facing
- Symmetrical profile
- Slope : 1h to 1,5h / 1v
- Various placement rates



Questions :

Influence of time dependent characteristics ?

Stability during construction :

- Size limit ?
- Design slope criteria ?
- Pore pressure development ?

Others related questions : foundation suitable conditions, early age cracking effect,…

Soil characteristics

Natural soil : Silty clay (Loess from Belgium) used for a trial embankment in Rouen

- Fine content (<80 µm) = 99,5%; Clay content (<2µm)= 12% (A2)
- PI : 7 – 8 %
- Wnat = 17,9 %
- Cohesion= **0kPa**
- φ= 35°

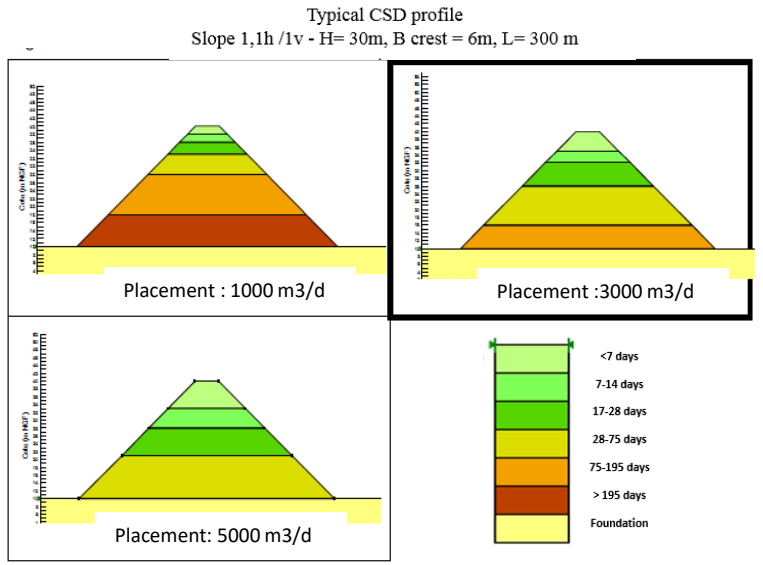
CSD trial embankment (Rouen)

Treated soil

- Quick lime treatment : 2,5%
- Moisture Content : 18.2 % (OMC+1)
- Compaction target: ≥ 95 % ρd OMC
- Dry density = 17,2 kN/m^3
- Density (wet) = 20,4 kN/m^3
- Cohesion peak = var. 20 kPa (@t=0) to 100 kPa (t=195 days)
- Cohesion peak (residual) = **var. 20 kPa (5 kPa) [@t=0**] to - **100 kPa(60kPa) [@t=195 days]**
- φ= var. 35° (@0d) to 39° (@75d)

Standard Limit Equilibrium analysis

- Mohr-Coulomb constitutive law
- Layered model (C & φ varying with time)
- Sensitivity analysis for each construction stage (peak or residual Shear Strength, pore pressure, placement rate,…)
- Circle and block failure results :
  - Construction cases => SF >= 1,30
  - Normal operation cases => SF >= 1,50

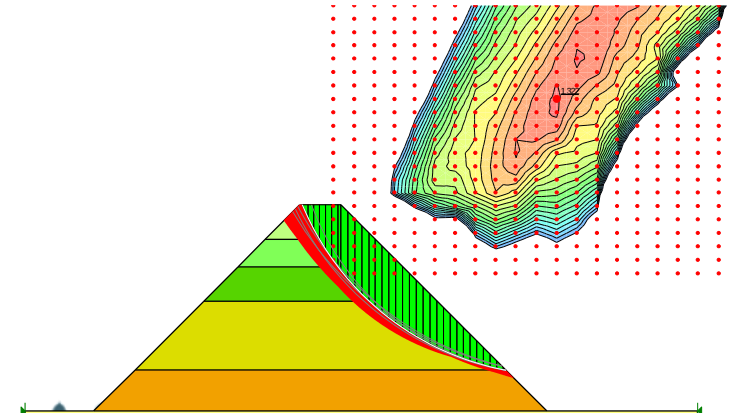


Conclusion : stable but uncertainties and sensitivity to :

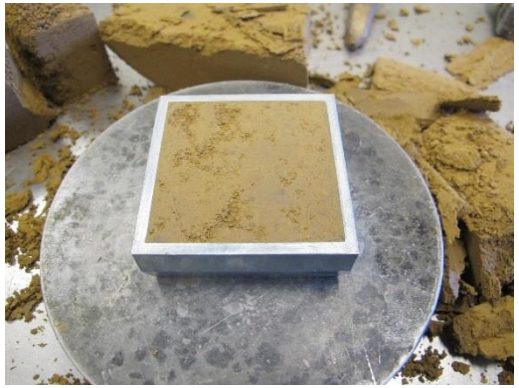
- pore pressure (if r_u > 0,2)
- high placement rate and time of first filling

⇒ pore pressure development investigation by lab testing

⇒ enhanced stability and settlement analysis with enhanced elasto-plastic models



Laboratory testing program & results

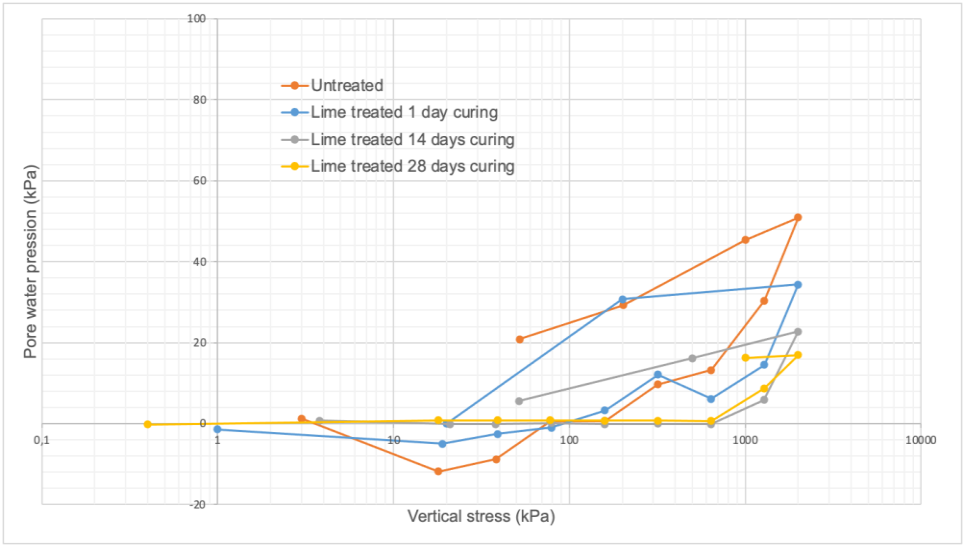


- Complementary lab test for consolidation behaviour on :
  - Pore pressure
  - Cohesion development at early age
  - PCC limits

- Testing program :
  - Shear boxes, oedometric tests; triaxial tests (CUU; CIU);
  - Natural and 2,5% lime treated soil
  - Ages : 0, 1, 7, 14, 28 days

Main outcomes

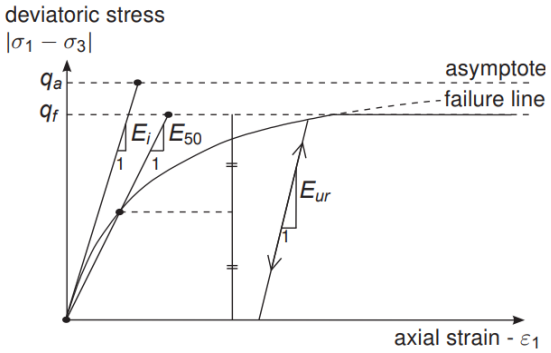
- Quick cohesion improvement confirmed
- **No pore-pressure development (r_u< 0,05)**
- **Improvement of Over Consolidation Pressure (OCP)**
- No evidence of brittle failure : Hardening/softening plastic failure

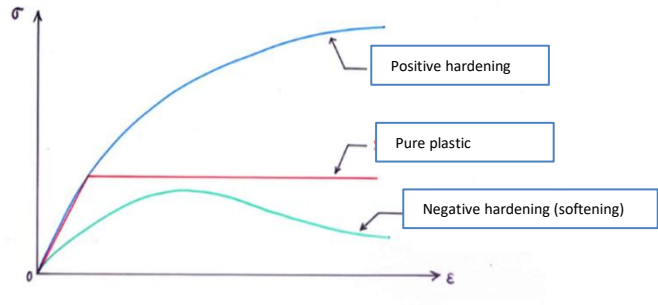


Oedemetric tests untreated vs. treated (@different curing time)

Numerical model analysis

- **2 softwares :**
  - Plaxis
  - Flac 2D
- **3 time dependant constitutive laws :**
  - Mohr Coulomb (MC)
  - Plastic Hardening Model (PHM or HSM) Over Consolidate Pressure *(time dependent or not)*
  - Modified Cam-Clay (MCC)
- **Pore pressure :**
  - r_u= 0,1 (0-0,2 for sensitivity)
  - *Simplified saturated approach with Skempton coefficient*
- **Stability computation stage for each fill layer (40cm)**





Plastic Hardening Model (PHM or HSM)

Constitutive law parameters

FLAC : Plastic Hardening Model (PHM)

Parameters	Symbol	Value	Unit
Wet Density	γ	20,4	kN/m³
Poisson Coef.	ν	0.2	-
Friction angle	ϕ'	35.7 @ 0 days 36.0 @ 7 days 36.4 @ 14 days 37.1 @ 30 days 39.2 @ 75 days and after	°
Cohesion	c'	20 @ 0 days 25 @ 7 days 30 @ 14 days 42 @ 30 days 75 @ 75 days 100 @ 195 days 110 @ 390 days and after	kPa
Tensile strength	f_t	$c'/\tan(\phi')$	kPa
Ref. pressure	p_{ref}	100	kPa
Failure ratio	R_f	0.9	-
Elastic modulus power	m	1	-
Elastic modulus @ 50% of Ref. Pressure	E_{50}^{ref}	3 @ 0 days 6 @ 7 days 9 @ 14 days 15 @ 30 days 30 @ 75 days and after	MPa
Œdométric ref. modulus	E_{oed}^{ref}	same E_{50}^{ref}	MPa
Loading/unloading ref. modulus	E_{ur}^{ref}	$3 * E_{50}^{ref}$	MPa

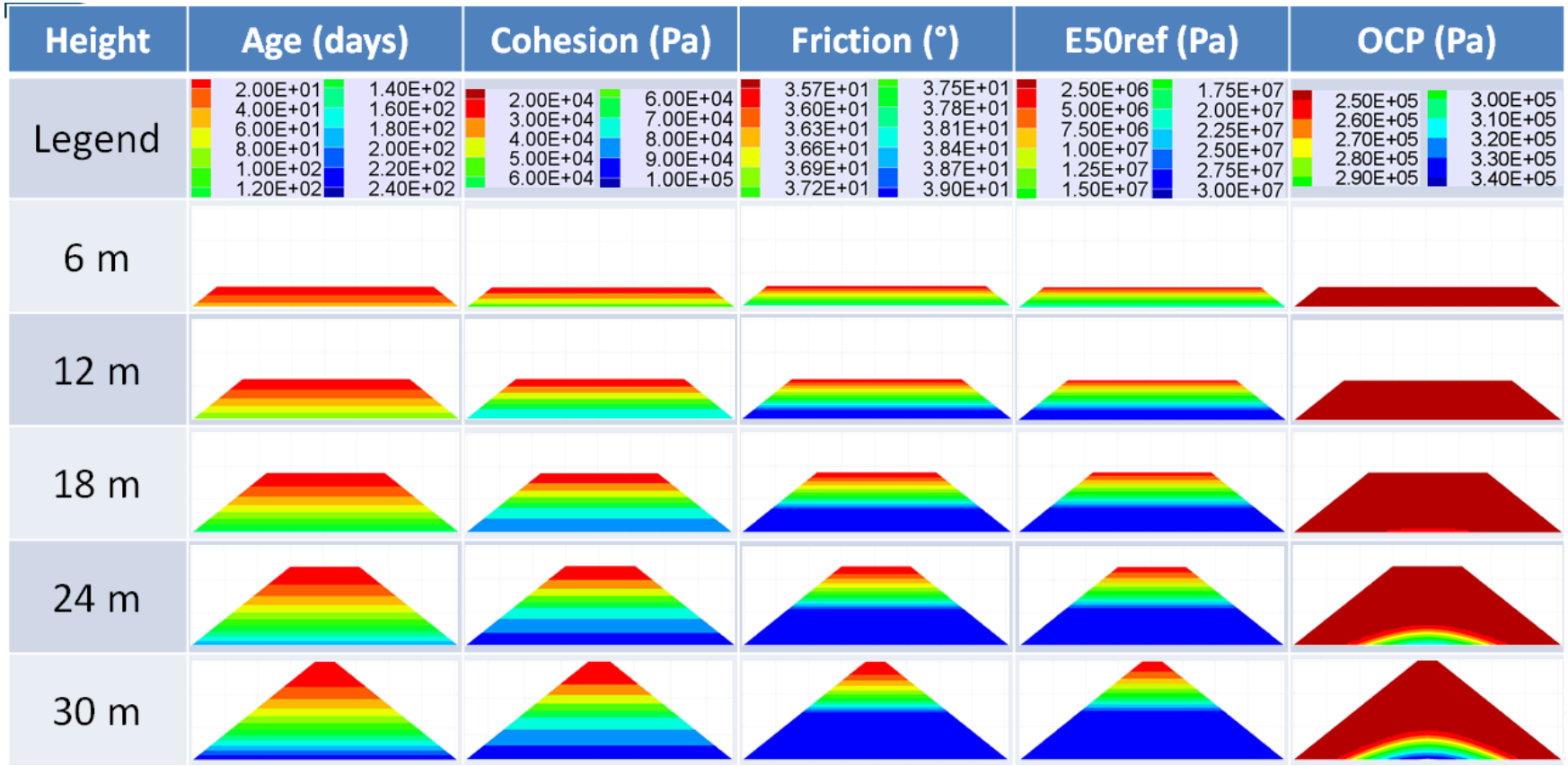
PLAXIS : Hardening Soil Model (HSM)

Parameters	Symbol	Value	Unit
Dry Density	γ	17.3	kN/m³
Poisson Coef.	ν	0.2	-
Friction angle	ϕ'	35.7 @ 0 days 36.0 @ 7 days 36.4 @ 14 days 37.1 @ 30 days 39.2 @ 75 days and after	°
Cohesion	c'	20 @ 0 days 25 @ 7 days 30 @ 14 days 42 @ 30 days 75 @ 75 days 100 @ 195 days 110 @ 390 days and after	kPa
Failure ratio	R_f	0.9	-
Elastic modulus power	m	1	-
Elastic modulus @ 50% of Ref. Pressure (100 kPa)	E_{50}^{ref}	5 @ 0 days 7 @ 7 days 9 @ 14 days 13 @ 30 days 26 @ 75 days and after	MPa
Compressibility index	Cc	0,18 @ 0 days 0,15 @ 7 days 0,13 @ 14 days 0,09 @ 30 days 0,05 @ 75 days and after	-
Swelling index	Cs	0,033 @ 0 days 0,016 @ 7 days 0,011 @ 14 days 0,006 @ 30 days 0,003 @ 75 days and after	-

$E_{50\ ref}(t)$, $C(t)$, $\phi'(t)$, $Cs(t)$, $Cc(t)$

Time dependent parameters

Construction sequence and time dependent characteristics

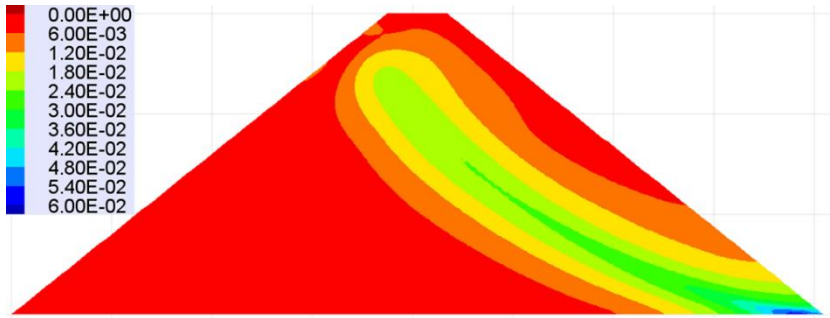


Model : PHM - Layer thickness = 0,4m (FLAC) or 1m (PLAXIS)

Results (FLAC) - First filling

- Factor of Safety (HSM – r_u= 0,1)

	FoS
End of Construction (dry)	1,9
Instantaneous filling at EoC	1,9
Filling @30 days after EoC	2,1
Filling @90 days after EoC	2,3

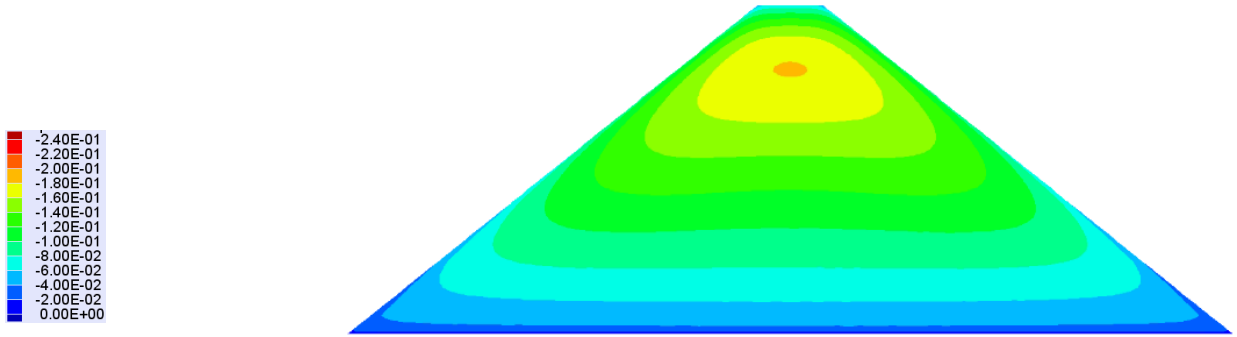


Failure shear strain ratio (FoS)

Results (FLAC) – First filling

- Settlement (HSM – r_u= 0,1)

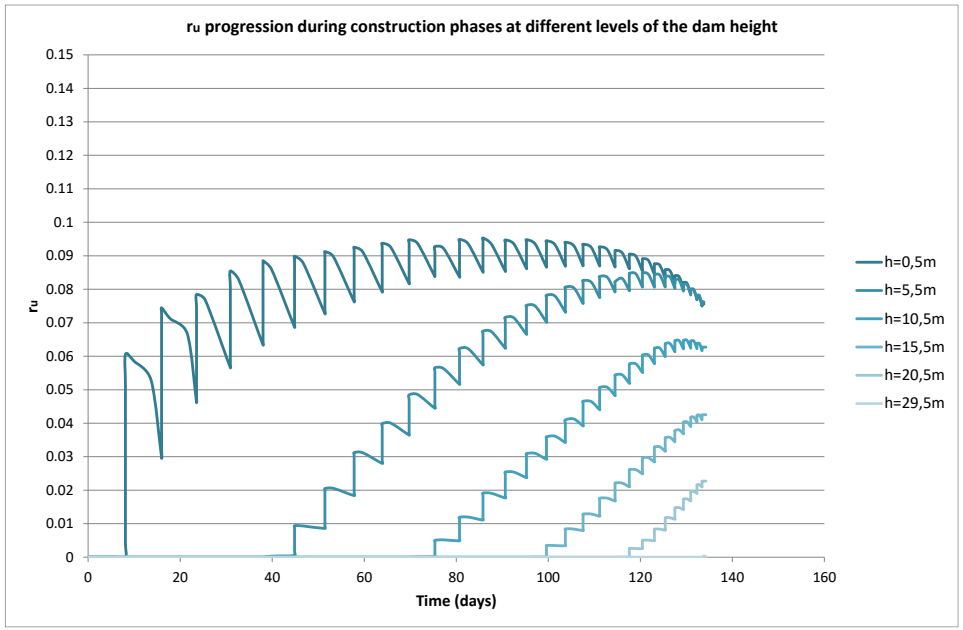
	Maximum settlement (cm)	Horizontal downstream max . Displ. (cm)	Max reloading Elastic modulus (Mpa)
End of Construction (dry)	18.	11,9	130
Instantaneous filling at EoC	18.4	13.1	140



EoC Settlement (m)

Results (Plaxis

Pore pressure (r_u) at end of construction – HSM model



Pore pressure development

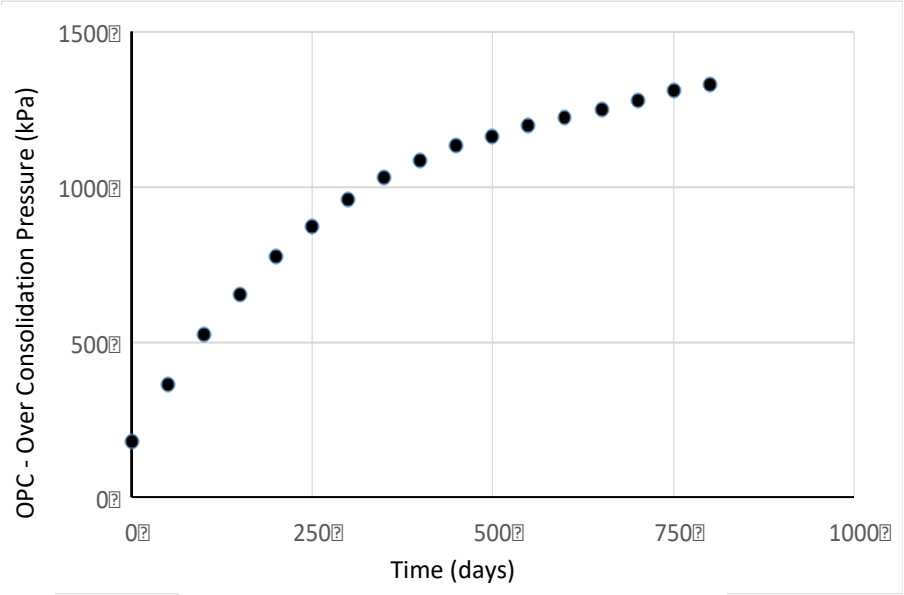
r_u = 5% at initial state of material

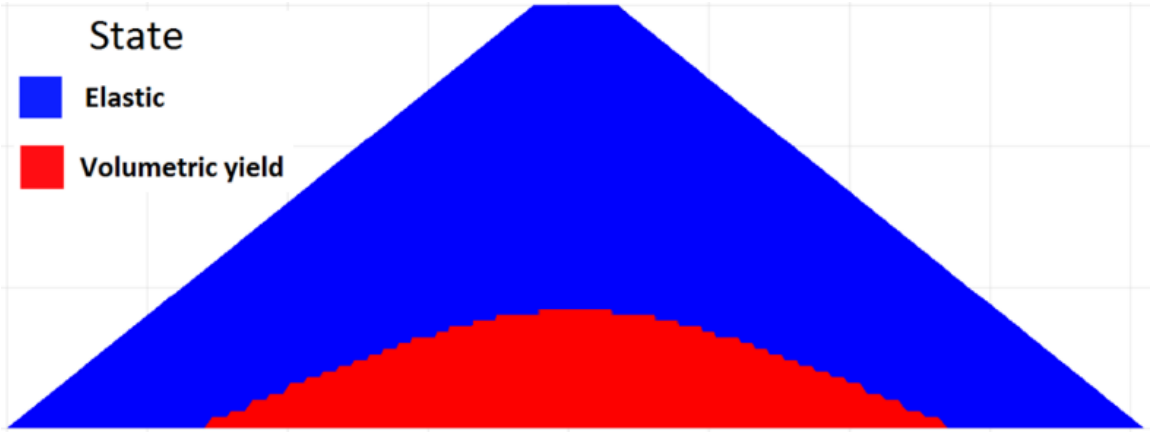
r_u build up during construction phases but remains under 10%

Effect of stress exceeding OCP

Safe assumption shall be made on OCP to stay away from Normally Consolidate behaviour at dam base
With slope 1h/1v geometry

FoS slightly higher than 1.3 but significant plasticity at dam base
ok for smaller dam height but not recommended for h≥30m

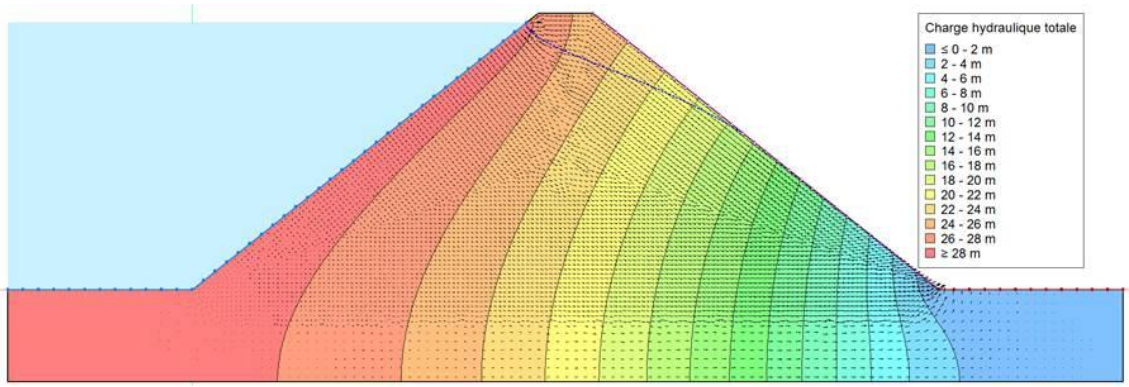




Results (FLAC) – Accidental case

- Facing failure
- Full developpement of pore pressure

	FoS
Facing failure (No watertighness system)	1,10 to 1,20



Not allowable for usual/unusual conditions but safe for accidental conditions, if drawdown and repair works are possible.

4 - Conclusions

- Progressive increase of shear with curing time is the key parameter for CSD stability
- Stability during construction may be critical depending on slope and placement conditions
- No excessive pore pressure failure risk (for usual placement rates < 2-5 m/day)
- No significant selfweight settlement (< 1% H at EoC) - foundation settlement compatibility to be carefully considered (see following example)
- **Recommended design slopes :**
  - for smaller dike or CSD (H< 10m) : 1h/1v possible
  - for medium heigh dam (H= 20-30m) : 1.25H/1V recommended
- **Steeper slope or higher height might be envisaged but :**
  - significant plasticity may occur at the bottom level,
  - stability may be at risk in case of facing failure.
- **Comprehensive lab testing program compulsory** (various dosages, curing times, constitutive law calibration)
- Strain-hardening time-dependent constitutive models are recommended for stability analysis and design optimization
- Early age cracking may be considered in case of permanent water exposure : facing recommended.