Lessons Learnt - Raising an Earthfill Dam: from the Initial Design to the Dam-Raising Works - Ganguise Dam (France)

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Abstract

Economic reasons or evolving use of water resources may call for an earthfill storage dam to be built in two separate stages. In such cases, the idea is to design the dam structure so that can be raised during a second phase of construction with the least possible impact on its operation.

A look at the Ganguise Dam (a zoned earth fill dam in the South of France) reveals the initial design that paved the way for the two phases of construction, the design of the dam raising works 20 years later, and the unanticipated issues encountered during the implementation phase.

The first phase included certain technical choices to allow the future raising of the dam without emptying the reservoir: appropriate core and drainage device inclines.

After operating the dam for an initial phase of 20 years, the dam-raising design studies were carried out; its height was to be increased by 6 meters to provide 20 Mm3 additional storage. It thus became obvious from the analysis of the initial dam's behaviour that it was necessary to adjust the raising works design. Considering the lessons learnt when the dam was initially built, it was therefore necessary to modify the downstream structures as well as to impose certain limits during the construction works: a maximum speed for building up the earthfill and special monitoring to check dam safety.

Keywords: Upraising, Works, Behaviour, Earth Dam, Monitoring.

1. INTRODUCTION

The Ganguise Dam in the South of France is a regionally important dam for the purposes of storage and providing a steady source of water in the quantities necessary for irrigation, inland navigation on Canal du Midi and protecting natural low flows.

Right from the outset, for economic reasons, it was planned to build the Ganguise dam in two stages. During the first phase, starting in early summer 1977, a 27m dam was built. The works lasted 27 months and it was first filled in November 1979.

When the next stage consisting of raising the dam began, it became obvious that, due to the clayey materials used and the geomechanical and hydraulic behaviour of the downstream shoulder that was intended to support additional earthfill, the construction works would have to address a number of limiting factors.

The design studies, documented by special field investigations to gain insight into the supporting ground for the dam-raising earthfill, led to a series of construction and behavioural monitoring recommendations.

2. DAM DESCRIPTION

2.1. INITIAL DAM CROSS SECTION

The initial dam profile was based on the following standard cross-section (figure 1):

- Upstream shoulder composed of the most permeable materials (sand / sandstone);
- A clayey loam core and a sand filter. It is unusual because of its upstream incline. This choice made it possible to extend it during the fill works carried out from the downstream end;
- Downstream shoulder composed of marl / sandstone materials;
- A three-layered drainage blanket (sand - gravel - sand) connected to the inclined filter. The top layer of sand was entirely or partially replaced by Bidim U64 geotextile.

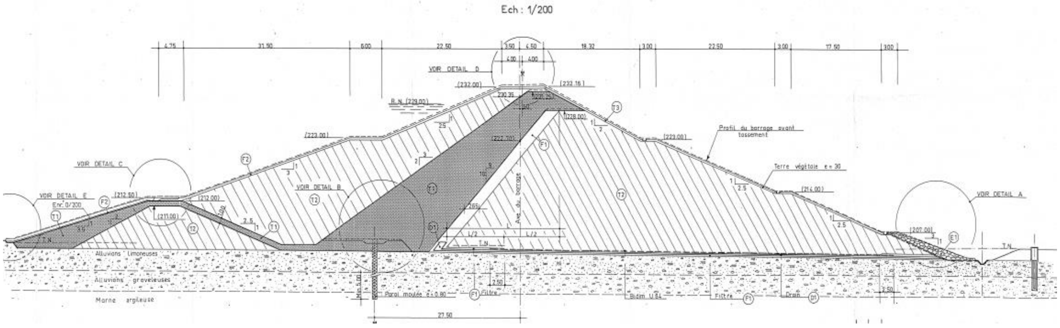


Figure 1: Cross section of initial dam

The aspects of the design selected during the first phase to allow the future raising of the dam, were paramount, especially as they allowed the works to take place without interrupting dam operation. The main aspects were:

- Inclination of the core and its filter in a downstream direction so that the shoulder could be raised without emptying the reservoir, therefore with uninterrupted dam operation;
- Integration of the additional load due to the raising of the shoulder in the overall structural design calculations.

2.2. INITIAL DAM BEHAVIOUR

After observing its behaviour by means of dam monitoring, which revealed the presence of residual pore pressure and movement in the downstream earthfill, it became clear that there was a need for more insight into the nature of the materials in the downstream shoulder. A special series of investigations was therefore carried out on the initial dam structure.

2.2.1. SCHEDULE OF INVESTIGATIONS

The whole programme [figure 2] scheduled in several interventions included:

- 10 core drillings to extract 33 undisturbed samples;
- 13 *piezocone* test (CPTU) (a cone penetration test (CPT) with additional measurement of the porewater pressure) stopping just above the drainage blanket, grid 25 x 50m;
- Controlled pumping tests in each of the existing piezometers in the earthfill;
- Laboratory tests: Identification testing, Oedometer test, Drained and undrained triaxial tests, Testing $\overline{B}$ in a triaxial load cell.

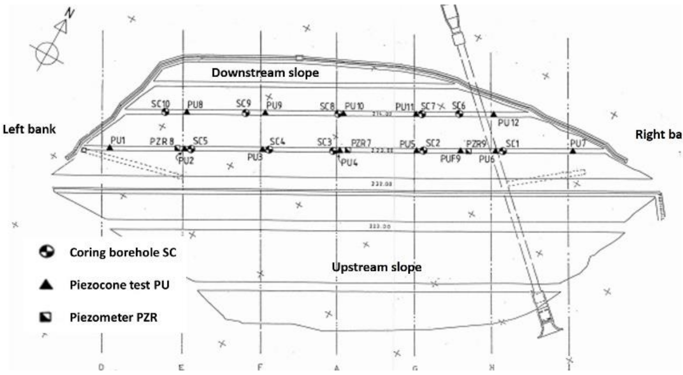


Figure 2: Location of the investigations on the downstream shoulder

2.2.2. TYPE OF MATERIALS

The features of the dam to be raised are:

- The downstream shoulder earthfill materials tend to be "marl" rather than "sandstone" (mainly clayey and gravel-type "marls"), therefore not very permeable;

- The downstream shoulder materials are moderately compressible, slightly overconsolidated, and some parts were found to be insufficiently compacted;
- Insufficient thermal and hydromechanical protection of the downstream earthfill, hence the possibility of infiltration of meteoric water through desiccation cracks;
- Decompression of the upper part of the “marly” earthfill since runoff and infiltration naturally decompress such insufficiently protected materials;
- Heterogeneous but high degrees of saturation in the downstream shoulder [figure 3].

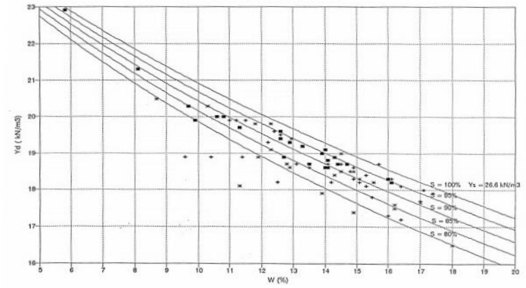


Figure 3: Degree of saturation in samples taken from the existing dam

2.2.3. MAIN OBSERVATIONS FROM SPECIFIC INVESTIGATIONS

The main results from the Piezocone tests are as follows:

- Medium to poor compactness at shallow depths,
- Rapid variation in peak strength, probably due to the great heterogeneity of the materials,
- Mostly negative pore pressure due to the “dilation” of the earthfill.
- Relaxation test results indicating:
- Presence of decompressed materials down to a depth of 3 to 5m in the downstream slope,
- Localised pore pressure the same as hydrostatic pressure indicating local saturation due to infiltration from the surface, facilitated by the presence of shrinkage cracks or construction defects: compacting defects, works performed during wet periods.

The conclusion was that the presence of saturated or near-saturated zones would be conducive to the development of pore pressure with the additional load of the dam-raising earthfill. To assess the parameters characterizing the development of pore pressure under the effect of the additional load, triaxial cell tests $\overline{B}$ were carried out.

3. UPRAISING DAM

3.1. UPRAISING PROJECT DESIGN

The general design of the dam-raising project is based on putting in place the additional earthfill from the downstream side until it raises and crowns the embankment at a height of 238 NGF, in other words making the dam 6m higher. At the same time, along the banks, special watertightness mechanisms are introduced; at the downstream toe, the drainage network is consolidated, and the upstream facing protection is completed.

Materials of the same kind as those already in place are used to raise the dam by building on top of the initial structure after capping off the crown, stripping off the top layer and preparing the subformation level in the valley, along the banks and on the downstream facing.

The technical characteristics of the new dam and its reservoir are shown in [Figure 4]:

	Initial dam	**Upraised dam**
Dam	Zoned earthfill dam	
Height above ground level	27 m	33 m
Crest length	410 m	614 m
Crest width	7 m	10 m
Maximal lenght upstream/downstream	180 m	235 m
upstream slope	3,5/1 – 3/1 – 2,5/1	3,5/1 – 3/1 – 2,5/1
Downstream slope	2,5/1 – 2/1	3,5/1 – 3/1 – 2,5/1
Volume of embankment	690 000 m3	1 270 000 m3
Reservoir capacity	21 Mm3	42 Mm3
Uprasing works	27 months	24 months
Filling of reservoir	2 years	6 years

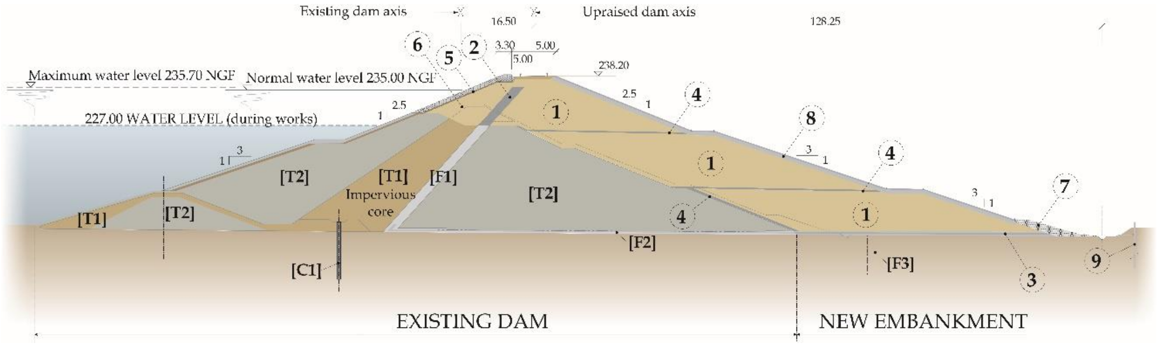


Figure 4: Upraising dam cross section

[T1]: silt / [T2]: / [T4]: impervious core / [F1]: chimney drain / [F2]: drainage blanket / [C1]: diaphragm wall / [F3]: relief wells /
1 : Fill (mixture of clay and sil) / 2 : Inclined chimney drain (sand) / 3: drainage blanket (gravel and sand layers) / 4: sand blanket / 5: geotextile filter / 6: riprap / 7: Toe protection (small riprap) / 8: slope revetment (mixture of sand and gravel) / 9: relief wells

3.2. THE MAIN RESULTS OF THE TECHNICAL STUDIES ON THE RAISING OF THE DAM

3.2.1. INFLUENCE OF THE RU COEFFICIENT – RU = $\Delta u/\Delta\sigma$

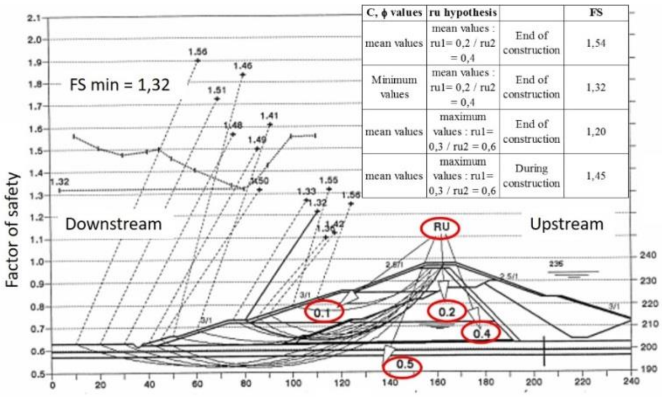
For a dam made of uniform clayey materials with conventionally designed slopes, there is a risk of failure as soon as the coefficient *ru* exceeds 0.4; pore pressure is therefore a primary concern in its design. Generally speaking, the factor of safety is 1 for *ru* values between 0.4 and 0.7. But it is important to remember that it can be very ambiguous to apply the same *ru* coefficient to an entire earthfill component [2]. In this case, the *ru* values used are by zone.
The ratio u/□ also undergoes a rapid increase from degree of saturation Sr = 96% upwards [2].

3.2.2. CALCULATION OF STABILITY AFTER COMPLETION

The investigations carried out on the downstream shoulder (Piezocone tests and undisturbed core samples) during the dam-raising studies, the results of the geotechnical tests and those of the dam monitoring piezometer measurements imply that locally, certain parts of the downstream shoulder can be subject to pore pressure due in particular to the presence of non-dissipated meteoric water.

This is why cautious values for the *ru* coefficients were used in the stability calculations for the downstream slope taking mean ranges of *ru* and looking for a 1.3 factor of safety, and a “maximum” range of *ru* to make sure that the stability was always verified (FS > 1).

The stability calculations [figure 5] on the central section P10 located in the bottom of the valley were carried out. For the various assumptions of mechanical characteristics and *ru* values, the overall stability coefficients range from 1.54 to 1.20.



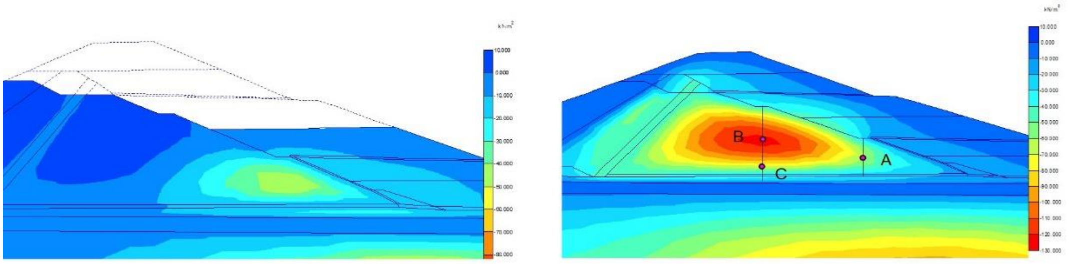
C, ϕ values	ru hypothesis		FS
mean values	mean values : ru1= 0,2 / ru2 = 0,4	End of construction	1,54
Minimum values	mean values : ru1= 0,2 / ru2 = 0,4	End of construction	1,32
mean values	maximum values : ru1= 0,3 / ru2 = 0,6	End of construction	1,20
mean values	maximum values : ru1= 0,3 / ru2 = 0,6	During construction	1,45

Figure 5: Results of downstream slope stability computing based on minimum mechanical characteristics and mean *ru* values

It can be seen that the most critical case is at the end of the construction works. The construction of the end part of the earthfill zone, a predominant threat to stability, can be steered according to the results of the pore pressure monitoring.

3.2.3. ASSESSMENT OF PORE PRESSURE DEVELOPMENT

To assess settlement, a finite element approach (Plaxis) was used to understand the earthfill construction phases divided into undrained loading stages and a consolidation phase. For each stage of construction [figure 6], the zones in which pore pressure had developed were identified and the magnitude of the parameter $\frac{\Delta u}{\Delta \sigma_1}$ was assessed.



Earthfill height 218m

Earthfill built up to final height

Figure 6: Example of estimated pore pressure during the construction phase

3.3. SPECIFIC DESIGN FOR NEW EMBANKMENT

- Specific design features drawn from 20 years of operating and monitoring feedback on the initial dam:
  - The working constraints for building the new earthfill:
    - Use of materials for the new downstream shoulder with a water content between Wopt - 1% and Wopt + 2%;
    - Real-time checking of pore pressure in the existing embankment thanks to a network of 9 vibrating wire load cells;
    - Limiting the earthfill construction speed as follows:

per day	per week	per month
2 layers	3.00 m	8 m

- Technical choices:
  - Use of layers of sand in contact with the two shoulders to dissipate pore pressure due to the clayey nature of the initial downstream shoulder;
  - Use of a shrink-prevention layer on the downstream slope to prevent cracking in the clayey materials subject to seasonal wetting and drying cycles;
  - Diaphragm walls instead of grout curtains for watertightness on the banks (figure 4) after proof of the limits of the grout curtain in the foundation layers with alternating little-permeable marly layers and permeable sandstone layers. In places, sandstone facies imposed additional injections;
  - Building an absorbing well and a riprap drainage blanket covering the slopes on the right bank to attenuate internal erosion risk in a sandstone facies.
  - Regarding filling, the CTPB-OH (French Technical Committee for Dams) requested gradual filling over a 3-year period.

3.4. MONITORING AND BEHAVIOUR

3.4.1. MONITORING SYSTEM

The different behavioural analyses of the dam during the raising works revealed strong presumptions of pore pressure forming within the basic structure due to the clayey nature of the materials and their water content, and thus threatening its stability, especially towards the end of the dam-raising works.
This is why a pore pressure sensor network was installed beforehand figures 7 & 8).

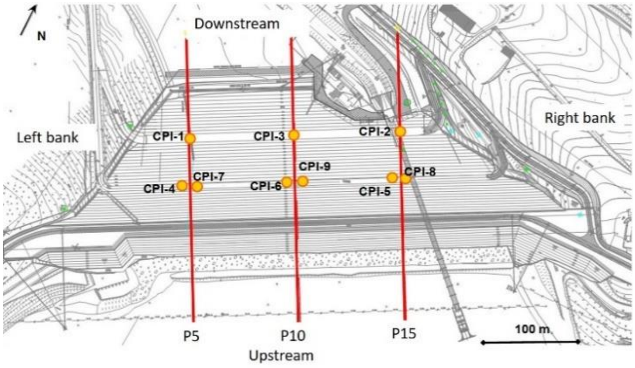


Figure 7: Location map of monitoring points

To maintain a fast response time, the sensors were installed in chambers 0.50m high with a 3m swelling clay plug and the wells filled with grout.

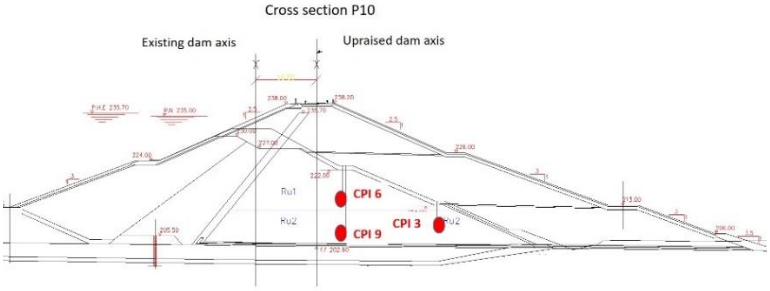


Figure 8: Location cross section of monitoring points

3.4.2. DAM BEHAVIOUR

Most of the sensors showed that pressure developed very quickly if the sensors were in the area affected by the loading.

Monitoring included:

- the evolution of pore pressure values and the rise in the earthfill;
- the estimation of the respective *ru* coefficients and comparison with those used in the calculation assumptions

Here is the first $u = f(t)$ graph for the height of the added earthfill, where u is the pressure recording [figure 9].

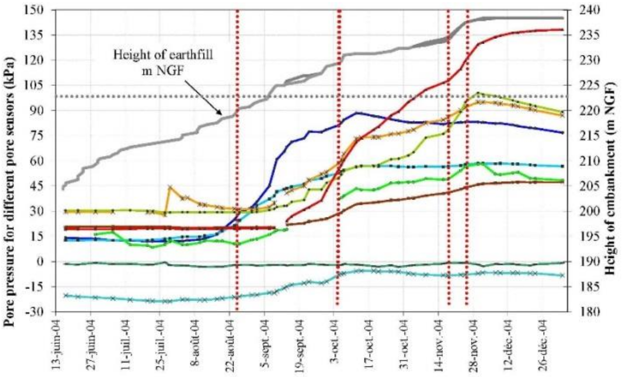


Figure 9: Evolution of pore pressure over time - Indication of the height reached during construction of the downstream shoulder

It shows a more or less pronounced rising trend in pore pressure as the height of the earthfill increases. At some of the sensors, this evolution is due to increased sensitivity to the speed at which the fill embankment rises resulting in a drop or an evening off in the pressure when the fill works are interrupted.

Pore pressure development depends on the degree of saturation, Sr, and the position in the zone under strain considering the elements that facilitate dissipation: the sandy interface layer. [2] indicates that the initial water content plays a decisive part in the development of pore pressure. Above Sr = 96%, there is a rapid increase in pore pressure.

In order to analyse the development of pore pressure and to monitor dam safety, the graph *ru* = f(t) was plotted, where *ru* = Δu / γ.h [figure 10] where Δu is the pressure variation since the beginning of the fill works, γ.h is the overloading due to the raised earthfill, where γ = 21.5 kN/m^3 (value obtained when testing the dam-raising earthfill materials).

Considering the ru values used for the stability calculations (case of the average values: ru inf = 0.4 and ru sup = 0.2), the observed values are below the mean values used in the assumptions for the stability calculations. Nevertheless, due to the sensitivity of the response to strain, the building speed for the earthfill specified in the contract was made more stringent in order to anticipate potential problems.

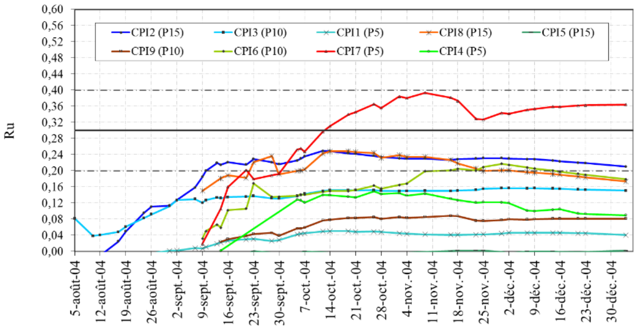


Figure 10: Evolution of the ru coefficient over time

If we refer to literature-based analyses [figure 12] regarding the influence of the initial degree of saturation on the evolution of pore pressure under loading, the unusual variations in the measurements at CPI7 (red line) can be explained by the initially high level of saturation (figure 11). This confirms the importance of respecting the speed at which the dam-raising earthfill is put in place, specified at the design stage.

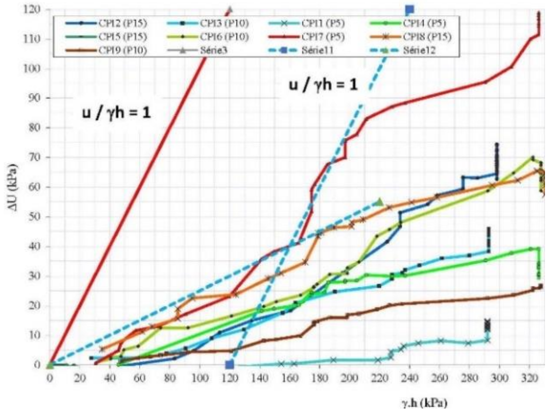


Figure 11: Evolution of pore pressure according to overloading

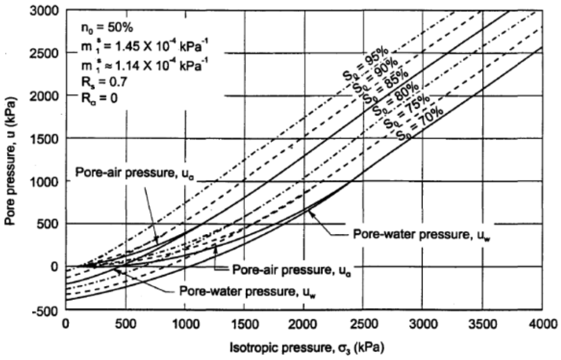


Figure 12: Variation in pore pressure for different initial degrees of saturation, So, using the Hilf method [3]

4. POST-CONSTRUCTION BEHAVIOUR

After a period during which there was an increase in pressure due to the overloading caused by the earthfill put in place, all the pressure cells recorded a slow decline resulting from gradual and continuous dissipation of the pressure inside the earthfill zone. So far, none of the measurements indicate that the upstream water level has had any effect on pore pressure.

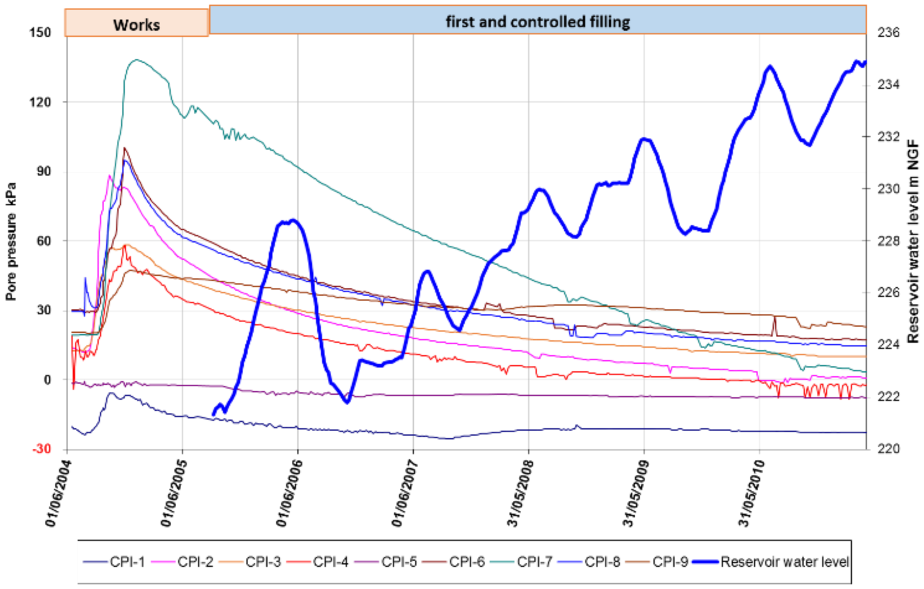


Figure 13: Pore pressure after works and during first and controlled filling

5. CONCLUSIONS

This project is a reminder of the undeniable benefit of knowing the behaviour of the existing earth dam structure that was to become the foundations of dam-raising works. It is important to know not only the type of materials used but also the parameters interacting with the development of pore pressure: the compactness of the earthfill, the water content influencing its response to strain and the estimation of specific parameters such as $\overline{B}$.

In the case of the Ganguise Dam, the studies heightened our awareness of the safety issues that arise when pore pressure develops, thanks to insight from laboratory tests and finite element modelling. It was thus possible to determine limitations to be observed during construction and a monitoring system allowing the works to be performed while the dam was still in operation.

Although the monitoring carried out during the construction works showed that the safety and stability of the dam were not affected, the choices made definitely proved to be appropriate. Caution in the design approach is a must, especially when confronted with heterogeneous materials and high initial degrees of saturation.

6. REFERENCES:

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