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Behaviour of Portuguese rockfill dams with upstream impervious membranes

Comportement de barrages en enrochement avec membrane imperméable en aval au Portugal

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ABSTRACT
There are 7 rockfill dams with upstream impervious membrane in Portugal, 4 of them built in the last 12 years. In the paper, some aspects of the experience acquired by the National Laboratory of Civil Engineering (LNEC) in this kind of structures are presented, including a brief description of the dams and some of the most significant monitoring results, particularly those related to movements.

RÉSUMÉ
Il y en a 7 barrages en enrochement avec membrane imperméable en aval au Portugal, 4 parmi elles ont été construites dans les dernières 12 années. Dans cet article, on présent quelques aspects de l'expérience acquise par le Laboratório Nacional de Engenharia Civil dans ce type de structures, incluant une brève description des barrages et quelques résultats de la monitorisation entendus comme les plus significatifs, en particulier on ce qui concerne les déplacements.

1 INTRODUCTION

Till the decade of the 1960's, embankments of rockfill dams with upstream impervious membranes were normally built by dumping and sluicing the rock in high lifts. The slopes of these dams were quite steep, in the order of 1.3(V):1(H), close to the natural slope angle of the materials. Paradela Dam, with 108 m of height, was constructed in 1958 in northern Portugal, being the highest in the world at the time. Until then, lower dams, built with the same method, had showed satisfactory structural behaviours. However, Paradela Dam soon exhibited high deformations that led to the appearance of fissures, loss of water tightness in the concrete membrane joints and high infiltration flows. This kind of behaviour, unexpected at that time, was later on observed in other dams of similar dimensions.

Deformations in rockfill materials are caused by breakage of rock particles at contact points, with a consequent readjustment of the particulate medium after every fracture. The level of breakage depends on several factors, of which the stress state is the most important. High dams, with materials subjected to significant levels of stress, exhibit higher deformations than lower dams. Other factors that diminish breakage are low void ratios, well graded grain size distributions and high strength of rock fragments. Normally, a decrease of the strain rate takes place in the long term with the readjustment of the particles.

Since the 60's, taking advantage of a deeper knowledge on rockfill materials rheology, as well as technological advances in earthwork construction equipment, rockfills started to be built in thin lifts, compacted with vibrating rollers of, at least, 100 kN of static weight, and with addition, normally, of abundant amount of water. These embankments have exhibited a quite satisfactory structural behaviour. In fact, in statistical analyses on accidents of rockfill dams with upstream membranes, only failures due to overtopping are generally encountered.

In 1990, the Portuguese Dam Safety Code (RSB) took effect, leading to more strict proceedings in performing structural behaviour and safety analyses of these structures. Particularly, specific monitoring plans, containing behaviour models and explicit predicted values for the different magnitudes to be measured, became compulsory for every dam. In the case of rockfill dams with upstream membranes, special attention is given to the structure movements and infiltration flows. Since the publication of the RSB, the Laboratório Nacional de Engenharia Civil (LNEC) has been responsible for performing structural behaviour analysis of almost all rockfill dams recently built in Portugal, and has also supervised safety evaluation studies for older dams. A brief description of the Portuguese rockfill dams with upstream membranes is presented next, including some of the most relevant monitoring results with regard to their deformational behaviour.

2 DAMS ANALYSED

Compatibility of the embankment movements with those admissible by the upstream impervious membrane is essential for this kind of dams. Upstream membranes are normally made of reinforced or asphaltic concrete, and sometimes of steel. Accurate monitoring of the movements that take place at different parts of the structure is of uppermost importance in order to analyse its structural behaviour and to develop models to be used in future projects. In Table 1 the main characteristics of the Portuguese rockfill dams with upstream impervious membranes are shown. Some cross-sections are also shown in Figure 1.

The 56 m high Pego do Altar Dam, constructed in 1948, was provided with an impervious membrane of welded steel plate (1/4 to 5/16 inches thick) built on top of a thin levelling concrete layer and a 0.8 m thick masonry layer. The main part of the dam is composed of quarried rock dumped in thick lifts. Semicircular plates, 0.4 m in diameter, were used for vertical expansion joints in the membrane, spaced out 15 m. The monitoring devices are, basically, surface marks and flow gauges.

Paradela Dam (Fig. 1) is a dumped rockfill structure with an upstream reinforced concrete slab, provided with vertical and horizontal joints. Junction between the slab and the grout curtain is made by means of a cut-off concrete wall provided with a drainage gallery. Since the first filling, the membrane suffered excessive movements, cracking and leakage, forcing to early and periodical repair works to reduce infiltration flows. In 1980 a flexible synthetic membrane, impregnated with an impervious resin, was used to cover the slab. The monitoring system is composed of surface marks, fissuremeters in the gallery, flow gauges at different point of the galleries and downstream area, and piezometers.

Table 1: Characteristics of the dams analysed

Dam	Rockfill type	Max. height (m)	Reservoir volume (hm^3)	Membrane type	Slopes (*)	Fill volume (hm^3)	Crest length (m)	End of construction
Pego do altar	Porphyry (dumped)	56	94	Steel	1,25H:1V (u) 1,4H:1V (d)	0.37	192	1948
Paradela	Granite (dumped)	108	164.5	Reinforced concrete	1,3H:1V (u) 1,3H:1V (d)	2.70	540	1958
Vilar	Granite (dumped)	58	100	Reinforced concrete	1,1H:1V (u) 1,3H:1V (d)	0.30	240	1965
Lagoacho	Granite (compacted)	38	4.9	Reinforced concrete	1,3H:1V (u) 1,3H:1V (d)	0.25	240	July 1992
Apartadura	Limestone-dolomite (compacted)	46	7.5	Asphaltic concrete	1,6H:1V (u) 1,45H:1V (d)	0.45	284	July 1992
Odeleite	Metagreywacke (compacted)	65	130	Reinforced concrete	1,3H:1V (u) 1,4H:1V (d)	1.00	350	May 1996
Arcossó	Granite (compacted)	40	4.9	Reinforced concrete	1,7H:1V (u) 1,5H:1V (d)	0.39	315	August 1999

(*) u: upstream; d: downstream

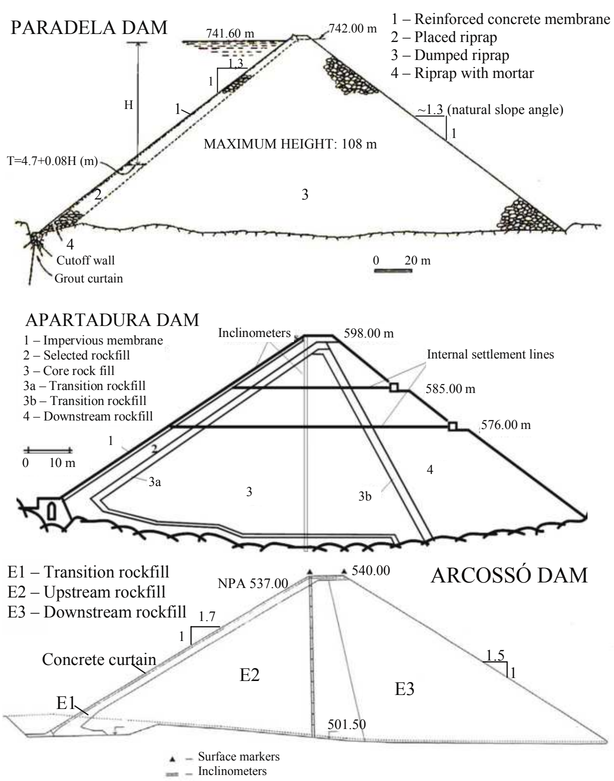

Figure 1. Cross-sections of some of the dams

Vilar Dam is similar to Paradela Dam in structure and behaviour, but lower in height. The monitoring system includes surface marks at crest and upstream facing, piezometers and fissuremeters at the drainage gallery, and infiltration flow gages.

Lagoacho Dam, built in 1992 of granitic rock, was the first rockfill dam constructed in Portugal in thin compacted layers. Reinforced concrete was used as the water barrier on the upstream slope. The 0.4 m thick concrete slab is divided only by vertical joints spaced 15 m apart. The slab rests at the bottom, along a perimeter joint, on a concrete toe wall fixed to the rock foundation by tie-rods. The monitoring system allows the measurement of surface movements, as well as internal horizontal and vertical movements (the latter, by means of inclinometer tubes functioning as vertical extensometers with the aid of special devices). Relative movements of the upstream slab joints and infiltrated flows at the downstream area also measured.

Apartadura Dam (Figure 1), located in central Portugal, is the only one in the country with an upstream asphaltic concrete membrane. The dam was built of limestone-dolomite quarried rock compacted in thin layers, and is provided with a drainage gallery at the bottom of the upstream slope. Instrumentation installed during construction is concentrated in three central cross-sections of the embankment. In each of these sections, two horizontal extensometers are located at two different levels to measure internal movements in the upstream-downstream direction. Internal settlements are also determined along the same horizontal alignments by electrical cells that measure hydraulic levels. Vertical inclinometer tubes, located approximately at the section axis, allow the measurement of horizontal and vertical internal movements in the embankment. Inclined inclinometer tubes were installed, as well, along the upstream membrane to determine its deformation. The monitoring system also includes surface marks, flow gages and piezometers in the foundation.

Odeleite Dam, another rockfill dam compacted in thin layers, is located in southern Portugal, serves for water supply and supports a main roadway at the crest. The monitoring system is composed of surface marks, inclinometer tubes provided with special devices to measure horizontal and vertical internal movements, and horizontal alignments to measure internal movements as well. Because of the 10 m thick alluvial layer underneath the downstream slope toe, no infiltration flow gauge was installed at the downstream area.

Arcossó Dam (Figure 1), located in northern Potugal, was first designed to carry an upstream asphaltic concrete membrane, which was later substituted by a reinforced concrete slab, 0.25 m thick, with vertical joints spaced out 12 m. A grout curtain was constructed from the concrete toe wall, which is fixed to the foundation granitic rock by tie-rods. The monitoring system of the dam includes, basically, three vertical inclinometer tubes, located in central cross-sections and installed during the construction of the embankment, which allow measuring horizontal and vertical internal displacements, surface marks, located at the crest of the dam, and infiltration flow gages.

3 STRUCTURAL BEHAVIOUR

In the decade of the 80's, on the occasion of Odeleite Dam construction, several studies were carried out in the country to define the most appropriate design solutions and construction practices for rockfill dams with upstream impervious membranes. These studies, which took into account statistical analyses of accidents in this kind of dams, concluded that the construction of embankments of low deformability, compatible with a satisfactory performance of the upstream membrane, is favoured by present construction techniques, which imply compacting thin rockfill lifts, with heavy rollers and abundant addition of water, and using reinforced concrete slabs (presently the most used type of membrane) with vertical joins (constructed with no gap), without horizontal joints (except for the toe perimeter joint which requires special care) and provided with a concrete toe wall, normally without drainage gallery which is considered dispensable (Veiga Pinto, 1984).

3.1 *Embankment construction*

The theoretical curve for the settlement profile measured along a vertical axis of the cross-section of a rockfill dam during construction is given by a parabola with the maximum settlement at mid-height of the embankment, assuming one-dimensional case, homogeneous fill and non-deformable foundation. Considering two-dimensional conditions, the elevation of the maximum settlement at end of construction is affected by the value of the Poisson's ratio and the effect of the lateral slopes, and can occur at mid-height or higher. Material heterogeneities also determine the position of the maximum settlement (Pagano et al., 1998).

No information about internal displacements during construction is available for the Portuguese rockfill dams constructed by dumping. For Pego do Altar Dam, surface settlements of marks located on the upstream and downstream slopes at different elevations are known. Maximum construction settlements of 76 cm and 25 cm were measured at the upstream and the downstream slopes, respectively, at about 60% of the fill height. Construction of this dam progressed rather slowly, between 1943 and 1948, and the greatest increments of settlements happened in the rainy seasons, even if the placement of the rockfill was interrupted.

As for rockfill dams constructed by compaction in thin lifts, Figure 2 shows the settlement profiles at the end of construction for three of the dams, determined along vertical alignments of central cross-sections. Design calculations for Apartadura Dam by the finite elements method, assuming linear elastic properties (Young's modulus of 80 MPa and Poisson's modulus of 0.3) for the rockfill material, gave a maximum displacement of 8 cm at the end of construction at the center of the embankment. Maximum settlements measured at the end of construction in the 3 central vertical inclinometer tubes were of the order of 5 cm. A simplified back-analysis gave values between 70 and 360 MPa for the modulus of deformation, E_s (vertical geostatic load divided by the vertical strain measured in the tubes), the smallest values corresponding to the lower zone of the embankment.

Maximum settlements measured during construction of Lagoacho Dam were of the order of 7 cm at mid-height of the dam, similar to the values obtained in the design calculations.

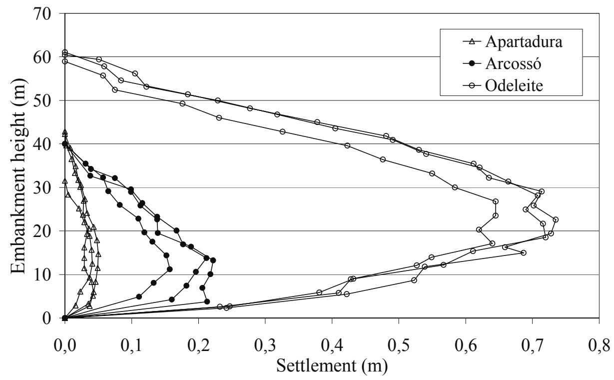

Figure 2. Internal settlements measured in vertical inclinometers tubes during embankment construction

Settlements measured during construction of Odeleite Dam (Figure 2) were considerably greater than the values predicted in the design. Maximum deformation at mid-height of the embankment was 2.4%. From the settlements measured at the end of construction, a modulus of deformation of 35 MPa was obtained by back-analysis for the lower 15 m of the fill, being of 50 MPa for the upper 50 m. These values were lower than the one considered in the design (90 MPa), probably because of the use of a metagreywacke with a higher degree of weathering and more sensitive to water than foreseen.

The design of Arcossó Dam predicted a maximum construction settlement of 20 cm at mid-height of the embankment, considering a constrained modulus (D) of 55 MPa, value deduced from the results of the geomechanic characterisation of the rockfill materials to be used, and applying the empirical method derived from the Classification of Marsal and Resendiz (Marsal et al., 1975) and the simplified equation: $\Delta h_{max\text{-}c} = 0.30(\gamma H^2/D)$. Internal settlements measured at the end of construction in the 3 inclinometer tubes varied between 15 and 22 cm. Maximum settlements were observed at about one third of the embankment height (Figure 2), probably because of a non-negligible deformability of the foundation and a certain heterogeneity with regard to the deformability of the fill material. Actually, from the results of the settlement measurements, three zones could be distinguished vertically with regard to the modulus of deformation: the first 13 m of fill, with a value of the modulus of about 65 MPa, an intermediate zone, with a modulus of 125 MPa, and the upper 13 m of fill, with a modulus of about 65 MPa.

3.2 *First filling of the reservoir*

During the first filling of the Pego do Altar Dam reservoir (1949-1950), significant leakage flows were measured at the downstream area, caused by cracking at the expansion joints of the upstream membrane, as well as between the membrane and the cut-off wall, which forced to repair works. There is some information about the crest displacements measured since the end of construction till July of 1954. A maximum crest settlement of the order of 30 cm and a maximum downstream horizontal movement of 20 cm were registered in that period.

For the other dumped rockfill dams, Paradela and Vilar, no information has been found about movements during first filling.

During first filling of the rockfill dams constructed in thin compacted layers, the measured values of the movements were close to the predicted values. Maximum crest settlements of 1 cm, 2.8 cm, 5.6 cm and 5 cm were registered in Lagoacho, Apartadura, Odeleite and Arcossó dams, respectively. Figure 3 shows the crest settlements and the downstream horizontal crest deflections measured during the first filling of Arcossó Dam. The longitudinal crest movements did not exceed 2 cm towards the center of the valley. The maximum movements measured in the inclinometers were of the same order as those measured at the crest. A filling stage at 2/3 of the maximum water level was held for three months during the first filling of the reservoir.

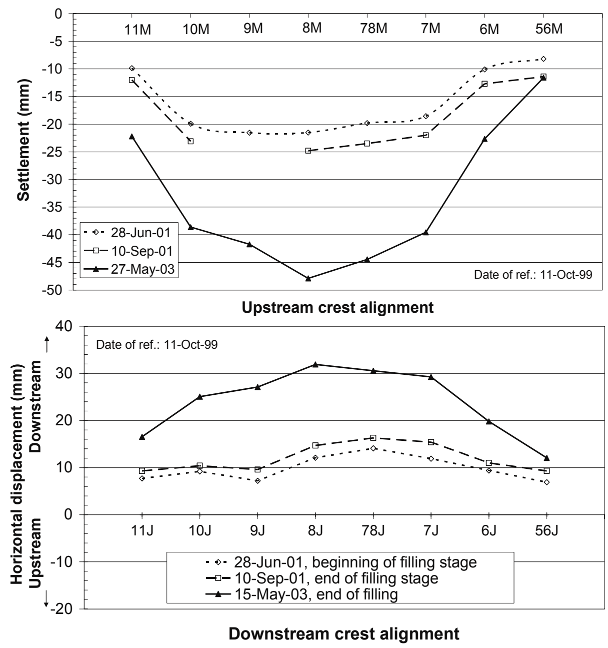

Figure 3. Arcossó Dam. Crest settlement and crest upstream-downstream horizontal displacement during first filling of the reservoir

3.3 *Reservoir operation*

A significant annual rate of displacements is presently registered in Vilar and Paradela dumped rockfill dams, despite their age. In both dams, no clear tendency for a decrease in these rates is yet observed, at least in the last 20 years, approximately, for which lectures are available. Infiltration flows through the upstream membrane are relatively high, especially in Paradela (300 to 700 l/s in 2002), and repair works for the membranes have been necessary several times throughout the life of these structures. Figure 4 shows the settlements measured along the crest of Paradela Dam in the last ten years. The shape of the curves reveals the existence of a secondary valley close to the right abutment. Crest settlements are presently measured at the central section of the embankment at a rate of, approximately, 0.6 cm/year. In Figure 5, settlements measured at three of these crest marks are plotted versus time. As seen in this figure, the greatest increments of settlement occur in the winter, the rainiest season. With regard to the horizontal movements in the upstream-downstream direction, an annual average increase of 0.3 cm towards downstream has been registered in the last years. In the longitudinal direction, the movements, oriented toward the deeper part of the valley, have been less significant.

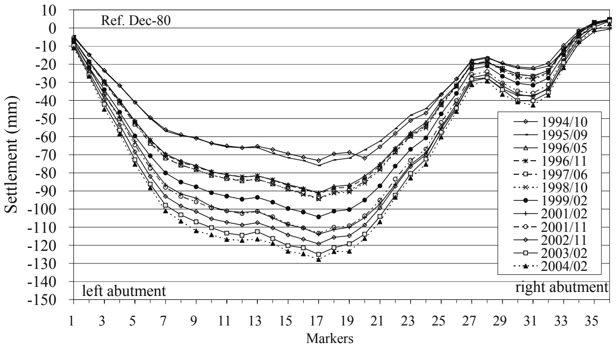

Figure 4. Paradela Dam. Settlements along the crest in last 10 year, referred to December 1980

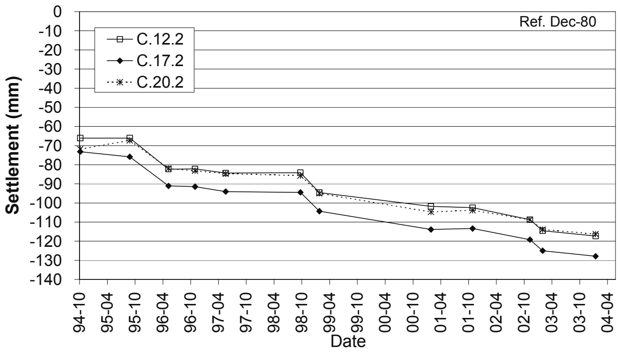

Figure 5. Paradela dam. Crest settlements versus time, at central marks

Settlement rates are considerably lower for the dams constructed in thin compacted layers. In the design calculations, empirical equations were normally used to predict the expected crest settlements of the dam after the first filling of the reservoir. In the case of Arcossó Dam, the following creep equation: $\Delta h_f = \alpha\ H \log(t_2/t_1)$ was used to determine the increment of crest settlement (Δh_f) between times t_1 and t_2 after first filling, being H the embankment height, and α an nondimensional parameter whose value was taken equal to 0.6%. Using this equation, an expected settlement of 41 cm was predicted for the first 50 years of the exploration of the reservoir.

Figure 6 shows the maximum crest settlements measured in Lagoacho Dam since the end of the first filling of the reservoir. Maximum settlements did not exceed 1.4 cm in a period of about 10.5 years, and, in the last 4 to 5 years, the increases of settlement have been rather small. As seen in Figure 6, settlements measured along both the upstream and the downstream crest alignments are very similar, though there is a little seasonal oscillation in the values registered in the upstream alignment, influenced possibly by changes in temperature. As to the infiltration flows, the total values measured downstream in the last years never surpassed 5 l/s.

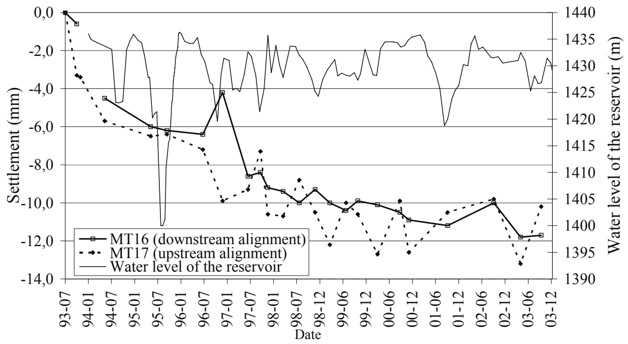

Figure 6. Lagoacho Dam. Crest settlements measured at the upstream and the downstream alignments since the end of the first fillling

Maximum crest settlements measured in Apartadura Dam, referred to the end of first filling, have reached 0.8 cm in 8 years, therefore indicating a very satisfactory structural performance of the fill. In the case of Odeleite Dam, crest settlements measured 5 years after the end of the first filling were of 5 cm.

4 CONCLUSIONS

A brief description of the Portuguese rockfill dams with upstream impervious membrane was presented, including some of the most significant monitoring results, particularly those related to movements during construction, first filling of the reservoir and reservoir operation. Reference was made to the differences of structural behaviour between the older dams, built of dumped rockfill, and the most recent ones, built in thin layers compacted with vibratory rollers. With regard to the structural safety, it is important to note that the behaviour of all these dams (either those composed of dumped rockfill or those constructed of rolled layers) has been satisfactory. However, the order of magnitude of the displacements has been significantly higher for the dumped rockfill dams, leading to damages in the upstream impervious membranes, and, therefore, to higher infiltration water flows. Emphasis has to be laid on the importance of implementing adequate monitoring plans for these structures, taking into account the magnitudes to be measured and the values they can reach. A proper monitoring plan requires a timely installation of the instrumentation, as well as appropriate and rigorous measurement frequencies for the different devices. Good geotechnical judgement is, anyhow, essential for a correct analysis of the results, taking into consideration the accuracy of the readings, the results of visual inspections and knowledge of all eventual incidents and accidents occurred to the dams.

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