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Assessment of displacements and deformation mechanisms in a rockfill dam: case study of Cerro da Mina reservoir

Évaluation des déplacements et des mécanismes de déformation dans un barrage en enrochement: étude de cas du réservoir Cerro da Mina

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ABSTRACT: Reservatório Cerro da Mina is an industrial water reservoir, consisting of rockfill lined by an impervious HDPE membrane. Monitoring showed that the rockfill experienced a few moments of sudden deformation in the first years of operation. The assessment of the environmental conditions in the periods of interest revealed that these more abrupt displacements coincided with periods of intense rainfall, rise in the water level in the reservoir and low evaporation. Both vertical and horizontal deformations of the rockfill showed a tendency of sudden increase when a new maximum in the precipitation record occurred and the precipitation values exceeded the potential evaporation, indicating that the increase in humidity in the rockfill voids led to a significant decrease in the rock pore suction, causing wet-induced collapses in the rockfill. Additionally, except potentially for the first load due to filling, the influence of the oscillation of the water level in the reservoir was not considerable for the vertical displacements, but significant in the horizontal direction.

RÉSUMÉ: Le Reservatório Cerro da Mina est un réservoir d'eau industrielle, constitué d’un remblai en enrochements recouverts d'une membrane imperméable en PEHD. L’auscultation a montré que l'enrochement a connu quelques instants de déformation brusque au cours des premières années d'exploitation. L'évaluation des conditions environnementales au cours des périodes d'intérêt a révélé que ces déplacements plus brusques coïncidaient avec des périodes de précipitations intenses, d'élévation du niveau de l'eau dans le réservoir et de faible évaporation. Les déformations verticales et horizontales de l'enrochement ont montré une tendance à une augmentation soudaine lorsqu'un nouveau maximum dans l'enregistrement des précipitations se produisait et que les valeurs des précipitations dépassaient l'évaporation potentielle, ce qui indique que l'augmentation de l'humidité dans les vides de l'enrochement a conduit à une diminution significative de la succion des pores des blocs rocheux, provoquant des effondrements due au mouillage de l'enrochement. De plus, hormis potentiellement la première charge due au remplissage, l'influence de l'oscillation du niveau d'eau dans le réservoir n'était pas considérable pour les déplacements verticaux, mais significative dans les horizontales.

Keywords: Wet-induced collapse; impervious rockfill dam; rockfill deformations.

1 INTRODUCTION

Reservatório Cerro da Mina (RCM) experienced a few moments of relatively small, yet sudden settlements on the rockfill embankment during the first years of operation. Under constant load, the largest post-constructive settlements are normally anticipated at the beginning of the operation of the dam, and the rates in which strains occur are expected to reduce over time (Oldecop and Alonso, 2007, Kermani et al., 2017). In this case, however, superficial settlement markers, vertical extensometers and inclinometers installed in the rockfill recorded peaks of movements some years after the end of construction and first load due to filling. The moments of increase in the settlement rates coincided with periods of large pluviosity, when the water level in the reservoir and the moisture in the rockfill tend to rise.

The relation between shift in environmental conditions and change in deformation rates are quite known in geotechnical monitoring, and assessing the mechanisms involved can enhance the understanding of the structure’s behaviour and provide a better prediction of future movements. This study aims to present monitoring data of the rockfill, correlate with the conditions existent in the moments of sudden deformation and, based on that assessment, explain the mechanisms involved.

2 ROCKFILL CHARACTERISTICS

RCM is a 1,45 hm^3 industrial water reservoir located in Castro Verde, Portugal. The embankment consists, on the west side, of a main embankment with a maximum height of approximately 30 m, and on the north side, of a saddle embankment of 11 m on its highest section. Due to chemical activity of the industrial water stored, the reservoir is operated considering zero discharge to the environment. A double lining system was installed, consisting of a 2,5 mm HDPE membrane, lying on a geocomposite clay liner. The embankment was constructed with sound or moderately weathered greywackes excavated from the pond area, according to the zoning in Figure 1:

- Type A: support material for the lining system. Only sound greywacke rock used. Less than 5% of fines, 40 mm ≤ D100 ≤ 60 mm; 3,3 mm ≤ D50 ≤ 12 mm.
- Type B: filter for materials type A and C. Only sound greywacke rock used.
- Type C: good quality material, well compacted rockfill with high deformability modulus. Only sound greywacke rock used. Less than 5% of fines, 300 mm ≤ D100 ≤ 600 mm; 20 mm ≤ D50 ≤ 150 mm.
- Type D: random finer rockfill. Use of moderate weathered greywacke rock allowed. Less than 5% of fines, 60 mm ≤ D100 ≤ 280 mm; 7 mm ≤ D50 ≤ 55 mm.
- Type E: protection layer. Blocks between 50 mm and 800 mm.

The geomechanical characterization of the rockfill was executed in two phases. For the design, samples from not so fresh greywacke were tested. In the beginning of construction, fresh greywacke from the experimental fills was tested to validate the design assumptions. The main results are shown in Table 1.

3 DISPLACEMENT MONITORING

The monitoring plan of RCM was conceived according to the Portuguese dam safety regulation and specificities of the reservoir. Regarding the assessment of displacements on the rockfill, there are 25 superficial survey beacons installed on the crest, 17 of which located on the main embankment and 8 on the saddle embankment. There are 3 inclinometer casing tubes, each one associated to vertical extensometers (consisting of magnetic rings) in different elevations of the rockfill. Additionally, the water level on the reservoir is recorded daily and a meteorological station measures precipitation and evaporation potential.

Table 1. Index-properties of greywacke rockfill (mean ± standard deviation [number of samples]).

Parameter	Design phase	Construction
Apparent density (kgm^{-3})	2581 ± 17 [10 samples]	2588 ± 33 [6 samples]
Porosity	4.81 ± 0.83 [10 samples]	4.25 ± 0.71 [6 samples]
Uniaxial compr. (MPa)	40.0 ± 4.4 [10 samples]	-
Crushing – Pa$_{50}$ air dried (kgf)	1219 ± 378 [4 samples]	1033 [1 sample]
Crushing – Pa$_{50}$ saturated (kgf)	690 ± 218 [4 samples]	506 [1 sample]
Los Angeles abrasion test	39.0 ± 5.7 [2 samples]	27 [1 sample]
Slake durability – 7th cycle, dry	2.5 ± 0.3 [4 samples]	-
Slake durability – 7th cycle, wet	7.2 ± 2.7 [4 samples]	-
Maximum water content (%)	1.86 ± 0.35 [10 samples]	1.65 ± 0.27 [6 samples]

This study will present the analysis of the inclinometer and extensometers installed in the centre of tallest section of the rockfill, IB3. Table 2 presents the initial elevation of the extensometers.

Table 2. Initial elevation of extensometers in section IB3.

Extensometer	Initial elevation (m)
IB 3 – Ring 9	238.215
IB 3 – Ring 8	235.079
IB 3 – Ring 7	232.088
IB 3 – Ring 6	228.959
IB 3 – Ring 5	225.859
IB 3 – Ring 4	222.731
IB 3 – Ring 3	219.654
IB 3 – Ring 2	216.541
IB 3 – Ring 1	213.465
Datum	211.920

Figure 2 presents the total vertical displacements measured and Figure 3 the post-construction vertical displacements measured in the extensometers IB3. As expected, the readings suggest that the largest deformations occurred during the construction and initial months after its completion. The form of the vertical displacement curves in the first year (between the end of 2013 and November of 2014) was similar to the expectations, with the general shape resembling a logarithmic relation in time, steeper in the beginning,

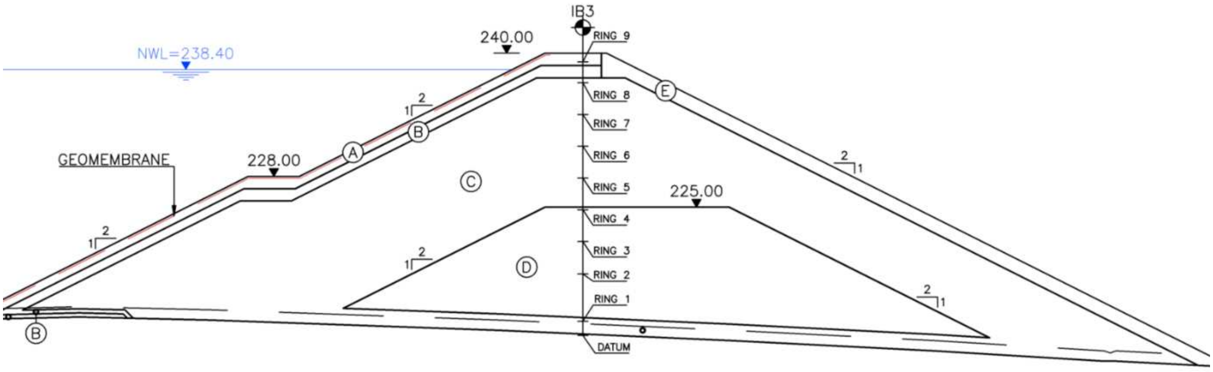

Figure 1. Typical cross section of RCM (adapted from Cenor, 2010).

reducing inclination after the first few months and showing a tendency to future stabilization. In addition to these predictable significant movements recorded in 2014, it is possible to notice though three moments of abrupt settlement: in the last months of 2014 and the first months of 2017 and 2018.

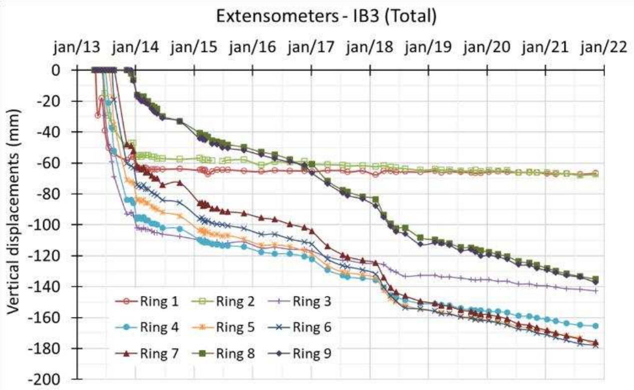

Figure 2. Total vertical displacements at IB3.

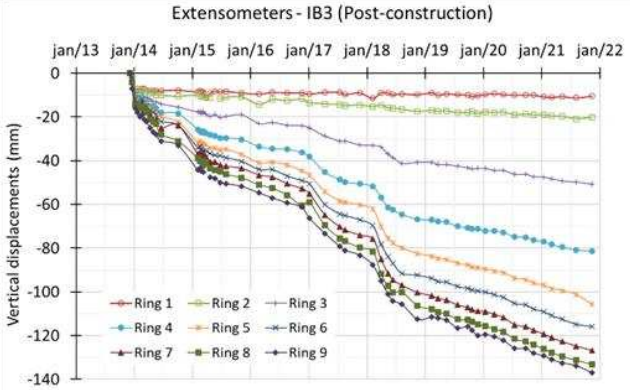

Figure 3. Post-construction vertical displacements at IB3.

Figure 4 presents the horizontal displacements in the main axis of inclinometer IB3. To associate the displacements in the vertical and horizontal directions of the rockfill, Figure 5 depicts the evolution of horizontal movements in the points of the inclinometer at the closest elevations of the magnetic rings. These readings suggest a significant increase in the horizontal displacement at the three moments previously identified in the vertical direction. Additionally, these instruments also show the tendency of a periodic horizontal movement of the embankment, superposed with those discussed moments of abrupt displacement and with long-term deformations. These fluctuating movements are significant smaller than the recorded in the moments of abrupt vertical deformation, but still evident.

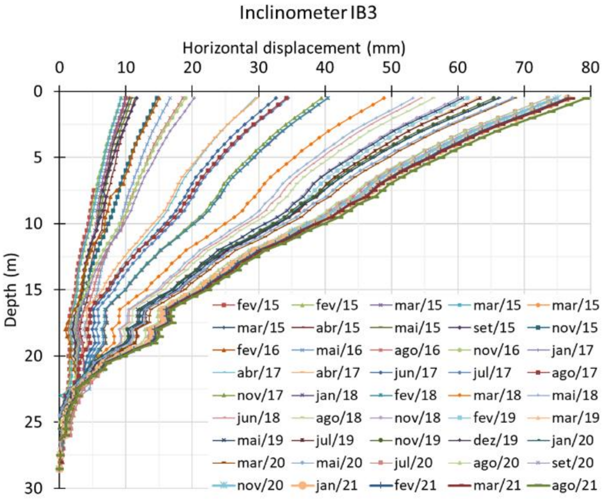

Figure 4. Horizontal displacements at inclinometer IB3.

Figure 6 presents the relations between post-constructive vertical and horizontal displacements for the extensometers on IB3. In terms of this relation, an interesting aspect is that the ratio in which the displacement of the rings occurred did not show any tendency of shift caused by the collapses. Except for the extensometers located at the lowest elevation (Rings 1 and 2), which did not exhibit clear tendencies in any direction, the trends of the ratio of vertical and horizontal displacements remained virtually unchanged after the collapses, suggesting that these events affected the movements in both directions in a similar manner. It is also noticeable that the ratio between vertical and horizontal displacement tends to increase with depth.

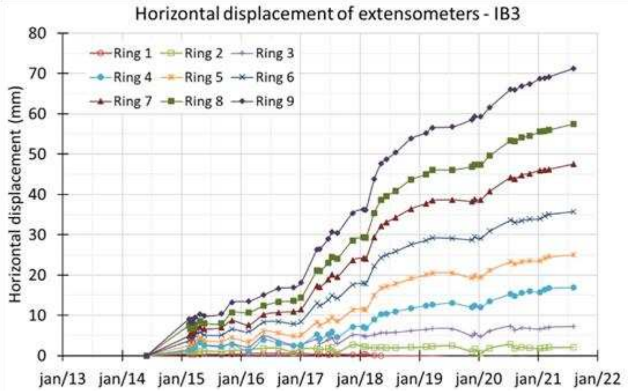

Figure 5. Horizontal displacements elevations equivalents to the vertical extensometers at IB3.

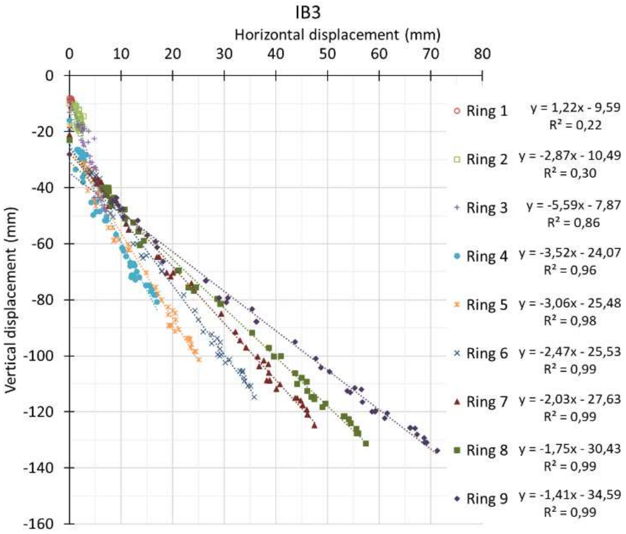

Figure 6. Relation between vertical and horizontal post-constructive displacements on IB3 section.

4 ENVIRONMENTAL CONDITIONS AND DEFORMATION MECHANISMS

Figure 7 presents the monthly measurements of precipitation and potential evaporation. The moments of abrupt movements recorded in the displacements monitoring devices coincide with intense pluviosity and low potential evaporation. The sudden deformation due to intense wetting of a rockfill mass can be often linked to the well-known phenomenon of wet-induced collapse, which is associated to the increase of humidity in the rockfill voids, causing a reduction of suction in the pores of the rock particles (Alonso and Cardoso, 2010, Alonso and Tapias, 2019). This loss of suction permits the fractures of the rock elements to suddenly propagate at a much higher velocity, causing rapid particle breakage, leading to rearrangement of these fractured elements and consequent reduction of the rockfill voids. This phenomenon is expected to occur every time a new lowest value of suction is reached in the rock pores, until zero suction is reached for the first time (Alonso et al., 2005).

All 3 moments of abrupt increase in displacement rates correspond to the highest record of accumulated precipitation until that moment. In addition, no historical maximum occurred without an abrupt settlement, causing this interesting one-to-one relation. Furthermore, in every moment of abrupt settlement, the amount of precipitation surpassed the potential evaporation, which occurred only a few times (17 of 108 months) in the period of monitoring. It should be acknowledged, though, that the excess precipitation for the second collapse does not correspond to a new maximum. It is consistent, however, to the largest period recorded in which the balance of rainfall is positive: 3 consecutive months. These observations indicate that wet-induced collapse is probably the mechanism responsible for the abrupt settlements recorded in the rockfill.

Figure 8 presents the variation of water level in the reservoir. Despite acknowledging pluviosity as the main cause for the deformations, it is possible that the variations of the water level in the reservoir have also affected the deformations of the rockfill, and therefore their influence should be assessed as well. Since RCM has an impervious HPDE membrane internally, the influence of the water level is restricted to the load on the embankments, without any percolation on the rockfill or foundation directly associated to the pond. Table 3 presents the variation in the cartesian stresses calculated by a stress-strain model of the section of inclinometer IB3, estimated in points halfway between the rings, comparing before and after the filing of the reservoir. The results show that the variation in the vertical stress due to filling is practically negligible in the vertical direction, but significant on the horizontal direction.

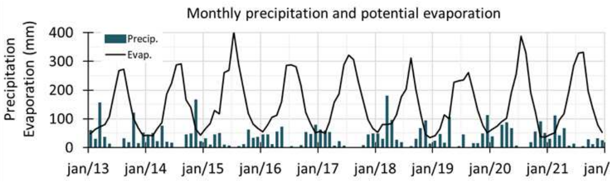

Figure 7. Monthly precipitation and potential evaporation.

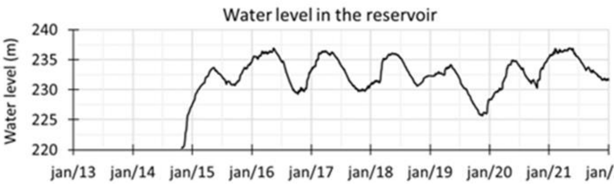

Figure 8. Water level in the reservoir.

Table 3. Variation of vertical and horizontal stresses with filing of the reservoir.

Elevation	Variation on effective stress	
	Vertical	Horizontal
Datum - Ring 1	+2,7%	+1,9%
Ring 1 - Ring 2	+2,5%	+5,2%
Ring 2 - Ring 3	+2,2%	+10,0%
Ring 3 - Ring 4	+2,0%	+17,4%
Ring 4 - Ring 5	+1,7%	+25,4%
Ring 5 - Ring 6	+1,1%	+31,7%
Ring 6 - Ring 7	+0,8%	+36,1%
Ring 7 - Ring 8	+0,4%	+28,0%
Ring 8 - Ring 9	+0,3%	+9,2%

Another relevant aspect regarding the variation of the reservoir level is that none of the 3 moments of collapse corresponded the maximum level recorded in the reservoir. In that matter, in the first semesters of 2016 and 2021 water levels were higher than in any of the moments of abrupt deformation, and on these occasions the movement rates did not show significant increase.

Besides the small effect on the vertical stress underneath the centre of the crest and the fact that the moments with the highest water level do not correspond to the highest settlement rates, two other relevant aspects support the conclusion that variation of water load does not play a key role in the abrupt vertical displacements. First, the extensometers and superficial settlement beacons did not exhibit any clear tendency of swell associated to the partial drawdowns of the reservoir. If those increases in vertical stress were the main cause for additional compression of the rockfill, decreases should produce some level of extension – or at least significant reduction in the settlement rate –, which did not happen. The second point relates to the fact that after the maximum load was reached for the first time, the rockfill would be subject to unload-reload cycles, in which the stiffness of the material would be substantially higher. Therefore, the deformations associated to the fluctuation in the reservoir level following that moment should be much smaller than the associated to the first filling, differently from what really occurred.

Concluding that collapse due to wetting is the main mechanism responsible for the abrupt settlements recorded in RCM suggests that Rings 1 and 2 of all extensometers, which did not show clear pattern shift for their deformation trends through time, probably have reached very low values of suction (perhaps even zero) at least once, probably during construction were seepage may have happened before the lining installation. There are no measurements to confirm that proposition, but these are the rings located at the lowest elevation in the rockfill, placing them closer to the bedrock seepage and further from the atmosphere, thus less subject to evaporation in dry periods than the more superficial rings.

Regarding the association with environmental conditions and measurements of the inclinometers, substantial increases in the horizontal displacements were recorded concomitantly to the abrupt settlements. In the moments of wet-induced collapse, the horizontal movements essentially follow the same behaviour registered for the vertical displacements. Therefore, all considerations made regarding the association of settlements and pluviosity is valid for the horizontal movements as well. The moments of the 2nd and 3rd collapses are quite evident, and although before the 1st collapse there was only the initial measurement 8 months earlier, the horizontal displacements registered next are substantial, suggesting that a collapse could have happened.

On the other hand, the important influence of the water level in the reservoir on the horizontal stress acting on the rockfill is fairly noticeable on the displacements recorded in the inclinometers, contrasting with the reduced impact seen in the vertical direction. Occurring simultaneously with long-term deformations, the oscillation of horizontal movements related to the fluctuation on the water level is very clear. The superposition of these two phenomena produces a curve that resembles a periodic relation (due to the variation in the water level) around an inclined axis (due to the time dependent deformations). Rises on the reservoir levels tend to produce larger horizontal movements, while partial drawdowns generates slowing or even recuperation of those displacements. Nevertheless, the influence of wet-induced collapses still is much more prominent in terms of total displacements, with a substantial portion of all horizontal measurements being caused by them.

5 CONCLUSIONS

The analysis of the instruments monitoring movements of the embankment in association with the environmental conditions allowed to conclude that the mechanism responsible for the unexpected abrupt settlement registered in the embankment was wet-induced collapse, a very well-known post-construction deformation mechanism for rockfill. The main arguments to support this proposition are based on the fact that all collapses recorded were associated to a new maximum in the precipitation historical series, and every time a new maximum was registered, a collapse occurred. Also, every collapse occurred in months in which precipitation exceeded potential evaporation, suggesting that an increase in humidity in the rockfill was probable. The analysis of the fluctuations of the water level in the reservoir permitted to conclude that these oscillations represented a small change in the vertical stress underneath the centre of the crest, making improbable the association of these events to the rapid settlements. Moreover, no abrupt deformation was recorded when the water level reached its maximum, and the extensometers and superficial beacons never registered swell associated to the reduction of load due to partial drawdowns of the reservoir.

All these evidences support the conclusion that the influence of the variations of the water level in the reservoir is probably very reduced and, if existent, restricted to the first filling. In addition to that, the general behaviour registered by the extensometers and superficial settlement beacons in RCM were very similar to typical deformation curves of rockfill upon wetting (Justo, 1990, Alonso et al., 2005, Alonso and Cardoso, 2010, Oldecop and Alonso, 2007).

The inclinometers demonstrated substantial increases in the horizontal movements in the same moments that abrupt settlements were recorded in the extensometers, suggesting that wet-induced collapse causes deformation in both directions. However, differently from what happened with vertical displacements, measurements in the inclinometers showed that fluctuations in the water level have impact in the horizontal movements of the rockfill. Rises in the reservoir are coincident with increases in the horizontal displacements rates, as well partial drawdowns are followed by reduction in the movements rates, eventually even indicating some recuperation in the displacements. Nevertheless, this influence is only perceptible in the periods when no collapses occur, since when the mechanisms overlap the displacements due to plastic strains are considerably larger.

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