Climate Effects on the Behaviour of Earth-Rockfill Dams

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ABSTRACT

The aim of this work is to study the climate effects on the behaviour of an earth-rockfill dam during the construction and the consequences of the changes of the mechanical characteristics of the materials due to climate in settlements measured during the first impoundment. An earth-rockfill dam with a cross-section similar to the one of Odelouca dam in Algarve, Portugal is studied. This dam was chosen because it is a zoned earthdam with a central clay core and rockfill shoulders and because its construction was stopped for more than 3 years during which the cofferdam was exposed to climate actions. When compared to other granular materials, rockfill-type materials exhibit a different behaviour because they show significant settlements induced by creeping due to fracture propagation and particle rearrangement. This behaviour is deeply linked to the water content of the rockfill and therefore climate must be considered in the behavioural analysis. A numerical model was developed using program CODE_BRIGHT, which solves coupled thermo-hydro-mechanical problems. Two constitutive models for unsaturated soils were adopted for the clay core and the rockfill of the shoulders which allow to calculate volumetric deformations due to suction and stress changes. The model for the rockfill material also accounts with creeping. An initial study was performed where climate was not considered. The results from this study were compared with those from the studies where climate actions were included. The results show the existence of displacements induced by weather action during the construction phase with small effects on the impoundment phase.

KeyWords: Climate, Earthdam, Rockfill, Suction, Volumetric deformation, Water Content

1. INTRODUCTION

This paper presents the study of the effects of weather interaction on the mechanical proprieties of an earthdam. The dam studied has geometry similar to the one of Odelouca dam located in the Algarve, with 76 feet high and a cofferdam incorporated in the upstream shoulder. Large zoned earth and rockfill dams usually have a cofferdam included in its geometry to prevent water access during the construction period. This element is built with the same materials as the dam and is included in its body. Considerable construction periods result in exposure to atmospheric cycles and important settlements may occur.

Despite the fact that the settlements of the cofferdam do not affect the final geometry of the dam because they occur during the construction, fracture phenomena of rockfill material and rearrangement of fragments controlled by the presence of water are responsible for changing
the mechanical properties of this material. Thus, the rockfill material resulting from this process will be denser than the material placed in construction and therefore will have different hydro-mechanical behaviour. This breakage phenomenon is more important the longer the exposure time of the cofferdam to atmospheric actions confirming the relevant role assumed by wetting in the behaviour of these materials.

In this work, some cases are studied in order to understand if the referred changes of the properties of rockfill mainly of the cofferdam due to weather exposure may affect the behaviour of the dam, especially during the first impoundment. They correspond to two different situations. The first situation, Study 0, is the reference case where climate is not included. The second situation is the case where climate actions are considered but two other simulations were performed considering different histories of the dam construction. In all cases, the construction process was simulated considering the construction followed by the first impoundment. Additional studies are held to help understand the contribution of the consideration of percolation on the foundation soils during construction and impoundment phases and also the influence of the consideration of anisotropy of permeability in the compacted plots but they will not be presented in the paper.

Constitutive models for unsaturated materials were adopted which allow to estimate volumetric strains due to suction and stress changes. The unsaturated soil constitutive model named Barcelona Basic Model, BBM, was adopted for the clay material (Alonso et al., 1990). For the rockfill material it was adopted the constitutive model proposed by Oldecop & Alonso (2001), which includes creep phenomena related with fracture propagation. The numerical model was developed using CODE_BRIGHT (Olivella, 1996), which solves coupled thermo-hydro-mechanical problems.

2. PRESENTATION OF THE CASE-STUDY

The geometry of the model performed was inspired in the Odelouca dam, a 76 m high earth and rockfill dam with a cofferdam included, located in the Algarve, Portugal. It has a typical design: a central core of low-plasticity clay is stabilised by two rockfill shells. For the simulation of the construction of the referred dam, a numerical model was developed using CODE_BRIGHT software based on finite element method. Construction was simulated by adding layers with 7,3 m to the foundation soil. The geometry used for the numerical calculation considers four materials: Rockfill, Clay, Foundation Soil 1 and 2 and it is shown in Figure 1.

Figure 1 – Geometry of dam used in CODE_BRIGHT program
It is necessary to use adequate constitutive models for the materials that account with their unsaturated state. Barcelona Basic Model (Alonso et al., 1990) was adopted for the clay of the core. The model proposed by Oldecop & Alonso (2001) was adopted for the rockfill material. This model takes into account the volumetric strains caused by particle rearrangement resulting from breakage phenomena, which is controlled by relative humidity. The parameters adopted for all the models are explained in Dias (2010).

Climate data considered is from Vidigal meteorological station due to its proximity to Odelouca. All the data shown in Figure 3 was published online by the Portuguese National Hydric Resources Information System (http://snirh.pt/, 2009) and was considered in the numerical model during the construction phase.

The impoundment phase was simulated imposing a water pressure in the boundary located between the water and the foundation material named as foundation 1. The pressure is calculated by $P_w = \gamma_w \times H$ where $H$ is the water elevation in the reservoir.

Four studies were conducted using this model and are explained below.

**Study 0 - Validation of the numerical model**
Climate is not included in the model, only self weight. This study was necessary for comparison purposes with those where climate was included.
Study 1 – Analysis of the influence of the construction sequence considering the climate effects
The results of this study and their comparison with those from the previous one are the main purpose of this work, which is the analysis of the behaviour of the dam considering the changing in the mechanical proprieties of the rockfill materials due to climate actions. Two scenarios were studied where climate was considered. In the first case, Case A, the construction sequence of Odelouca dam was reproduced. The most relevant event in this case is that after the construction was suspended for four years after the cofferdam being built. In Case B, the construction was simulated without interruptions. The following time-lines explains the chronological events considered in Case A and B.

![Time-line for Case A and B](a) - Events considered in case A

![Time-line for Case A and B](b) - Events considered in case B

Figure 4 – Chronological lines of cases A and B

Study 2 – Evaluation of the contribution of water percolation in the foundation soils
A second study was made where the importance of considering the characteristics of hydraulic permeability of the foundation soil was evaluated. For this analysis, the results of study 1 – Case B were compared with those from an identical model with a waterproofing foundation soil.

Study 3 - Influence of anisotropy of permeability in the compacted soil
Due to the compaction process of the soil layers, horizontal stratification is expected with consequences on the permeability of the compacted soils. This study analyses the influence in the design of the consideration of the anisotropy of permeability through the comparison of the results found in study 1 – Case B with those from an identical model in which isotropic permeability was considered for all materials.

3. RESULTS
The study of suction evolution during construction and pore pressures during the impoundment are controlled in the points illustrated in Figure 5 (a). The vertical and
horizontal displacements obtained in the calculation process were measured in the four vertical sections identified in Figure 5 (b).

![Figure 5 – Position of vertical section and control points.](image)

**Effects of Climate in global Behaviour (Study 1) – Dam Construction Stage**

Suction evolution is important to understand the transition from unsaturated to saturated soil since this transition affects the behaviour of the materials. Figure 6 shows its evolution during the construction phase in cases A and B.

![Figure 6 – Suction Evolution in Cases A and B](image)

The evolution of the vertical displacements of section I is shown in Figure 7 (a). The lines that have the same symbol are related to the settlements induced by the construction of the same layer in cases A and B. Maximum vertical displacement is similar for cases A and B. However, due to atmospheric exposure, case A shows fewer displacements during the construction of the main dam than in case B, suggesting stiffness increment of the cofferdam due to fragments breakage caused by wetting. Figure 7 (b) illustrates the settlements of a superficial point located at the top of section I. Time between cofferdam and main dam construction resulted in a vertical displacement of 3.5 cm in this point. Despite showing larger displacements at the end of the dam construction, case A exhibits less settlement during this step. Study 0 reveal 2.8 cm difference between case B.
The vertical displacements calculated in section II at the end of construction for cases A and B are plotted in Figure 8 (a). The top point of this section was analysed in terms of settlements in Figure 8 (b). Case A shows larger displacements motivated by the suction history. During the exposure time, the zones where clastic tension was not exceeded did not have their behaviour condition by breakage phenomenon. The only change was the relative humidity increase between the rock blocks. The construction of main dam increased the stress levels and clastic tension was reached. The compressibility of the rockfill showed was controlled by the presence of water. Case A shows lower suction during this stage resulting in larger volumetric deformations, due to its higher compressibility. Suction-mean stress diagram in a point that affects section II is plotted in Figure 9 (a). In case A, LC curve (Alonso et al., 1990) is crossed to a lower mean stress value resulting in larger volumetric variation (Figure 9 (b)).

The vertical displacements calculated in sections III and IV at the end of the construction are plotted in Figure 10. Similar results between cases A and B were found.
(a) Vertical Displacements in Section II

(b) Vertical Displacements in a the top of section I

Figure 8 – Vertical Displacements in Section II

Figure 9 – Evolution of suction with mean stress and volume with mean stress

Figure 10 – Vertical Displacements calculated in sections III and IV
The deformed shape of the dam at the end of the construction is in Figure 11. Displacements are magnified (25x).

![Figure 11 – Shape of deformed geometry at the end of construction phase](image)

**First Impoundment Stage**

The vertical displacements calculated at the end of the first impoundment are plotted in Figure 12.

![Figure 12 – Vertical Displacements calculated in Cases A and B](image)
As easily understood by observing the deformed shown in Figure 13, the displacements calculated in section I have positive sign which is explained by the weight of the rest of the dam acting on the cofferdam. Comparatively, cases A and B show minor differences but larger deformations are found in Case A. In section II, the differences in estimated settlements between the two cases are approximately zero. Section III, located in the core presents identical settlements in both cases leading to the conclusion that during impoundment phases, the settlements of this section are not affected by climate exposure time during construction.

The shape of the deformed geometry at the end of the construction phase is represented in Figure 13. Displacements are magnified (35x).

![Shape of deformed geometry at the end of first impoundment phase](image)

**4. CONCLUSIONS**

The main study (study 1) pretended to analyze the consequences on the behaviour of an earthdam of the construction sequence. The study allowed the following conclusions:

The vertical displacements during construction were within the expectable values for earth-rockfill dams and the highest values were measured at about half the height of the structure;

Suction evolution during cofferdam construction and its exposure time indicate the existence of wetting and drying cycles coincident with summer and winter seasons;

The global decrease of suction has resulted in an increased compressibility of the cofferdam which is manifested mainly during the construction of the main dam. The largest settlements are explained by the fact that the rockfill particles break more because of higher relative humidity (low suction);

Some differences were observed between case A (construction interrupted) and B (no interruption) in which Case A shows larger displacements. Upstream area of the main dam exhibited the larger disparities with the section II showing 17,1% more displacements comparing to case B, at the end of construction.

However, the settlement evolution showed that the cofferdam accidental impoundment and the exposure time included in case A resulted in smaller deformations during the construction of the main dam, suggesting an increasing in the stiffness of the material;

Vertical displacements measured at the end of the first impoundment were larger in case A, indicating that the material exhibit a different behaviour, result of the changes induced by different constructive process.
Concerning the other two studies performed, wetting due to climate is more intense when the foundation is impervious. As expected, wetting due to the impoundment is faster with a pervious foundation, resulting the percolation in this boundary. The consideration of the anisotropy in the permeability had small effects in the analysis.

5. REFERENCES


