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Pisão dam. Multi-purpose hydraulic scheme of Crato - Portugal. Issues involving the natural materials availability

Barrage de Pisão. Schéma hydraulique polyvalent de Crato - Portugal. Questions liées à la disponibilité des matériaux naturels

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ABSTRACT: This article addresses the issues related to the geotechnical design of a zoned embankment dam, about 50 m high, located in the centre-south of Portugal. It addresses, more specifically, the issues related to the research and characterization of borrow areas for the various natural construction materials and the geometric optimization of the dam to maximize the exploitation of the various materials within the future submerged area of the reservoir, thus minimizing the environmental impacts caused by open pit exploitation outside this area, or by transport from commercial exploitations located at great distances.

RÉSUMÉ: Cet article aborde les enjeux liées à la conception géotechnique d'un barrage en remblai zoné, d'environ 50 m de hauteur, situé dans le centre-sud du Portugal. Il aborde plus spécifiquement les défis liées à la recherche et à la reconnaissance de zones d'emprunt pour les divers matériaux naturels de construction et à l'optimisation géométrique du barrage, afin de maximiser l'utilisations des différents matériaux au sein de la future zone immergée du réservoir, réduisant ainsi les impacts environnementaux résultants de l'exploitation à ciel ouvert en dehors de cette zone, ou du transport depuis des exploitations commerciales situées à de grandes distances.

Keywords: Dam; construction materials; environment.

1 INTRODUCTION

The Pisão Dam is the main asset of the Crato Multi-Purpose Hydraulic Project, whose primary objective is the establishment, in the northeast region of Alentejo, of a new strategic water reserve. Having multiple purposes, this Project will allow the supply of water for human consumption, will enable the irrigation of around 5400 ha of agricultural fields and will have an estimated installed capacity for the production of electrical energy of about 150 MW in full operation. The energy will be produced through a set of photovoltaic plants, installed on land and over the stored water.

The first studies for the dam date back to the 60s and 70s of the last century. Since then, several geological and geotechnical studies have been carried out in different phases, with emphasis not only on the site of the dam and hydraulic structures, but also on the construction materials research.

Given the geometry of the valley at the dam site, characterized by a large amplitude, the option for an embankment dam was always the only one that seemed feasible, with the solution for the dam's typical cross section being entirely conditioned by the construction materials available at the site.

2 GEOLOGICAL AND GEOTECHNICAL FRAMEWORK

The dam will be located approximately 20 km west of Vila do Crato, implanted in Ribeira de Seda. At the dam's site, the river runs on the contact between geological formations of different strengths, which results in a quite asymmetrical valley. In fact, granite formations occur on the left bank, which, due to their great strength, gives rise to more vigorous reliefs with steep slopes, whilst, on the right bank, softer schist formations occur, resulting in a relatively wavy and soft relief. About 85% of the works are located in the right bank, involving the schist rock mass.

In the right bank, dominated by schist formations, the rock mass is covered by residual soils presenting reduced thickness. The rock mass is often observed at the surface being these soils inexistent.

Below the residual soils, grey schists predominate. Although rarely, greywacke levels have also been detected. The rock mass presents a weathering profile corresponding to a thin horizon of weathered and disaggregated rock, quickly passing to a horizon of moderately to slightly weathered and fractured rock.

In the left bank, where granite formations occur, the residual soils are more abundant, and the weathering profile is more irregular.

3 GENERAL CHARACTERISTICS OF THE DAM

The Pisão Dam, with a volume of about 2 700 000 m^3 and a crest length of 1382 m, will have a zoned embankment solution (Figure 1), with a low permeability core made of fine clayey soils (1). The upstream and downstream shells (3) will be made of soil-rockfill mixture, with a coarse sand with fines prism (2) in the transition zone between the upstream shell and the core (1). Such prism will allow the gradual reduction of permeabilities from upstream to downstream, as well as a transition in terms of stiffness.

In geometric terms, the embankment dam cross section has a maximum height of around 54 m above the foundation and a crest width of 10 m. The upstream and downstream slopes will have an inclination of 1V:2.5H and 1V:2H, respectively. The downstream slope will include three berms, 3.0 m wide, located at elevations 208.8 m, 221.8 m and 236.8 m (Figure 1).

The internal drainage system consists of a sub vertical filter, 3.0 m wide, which extends downstream at the base, through a drainage blanket. At the bottom of the valley, the 1.5 m thick drainage blancket, extends to the downstream slope face, guaranteeing the exit of the seepage. This drainage blancket is extended laterally to the abutments, and includes outlets distributed along the right bank, due to the crossing of several secondary water lines.

At the downstream shell, a rockfill toe (E2) was defined which, in addition to improving the slope stability conditions, will protect the embankment from water flooding during spillway discharges. In addition, the upstream slope face will be protected from wave-induced erosion by a protective rockfill layer (E1), beneath which a filter layer (F1) will be placed.

4 BORROW AREAS AND MATERIAL CHARACTERIZATION

4.1 General Considerations

In the initial studies (late 60s / early 70s of the 20th century), the solution considered for the dam involved a homogeneous cross section, built with residual soils from granite rock mass. Later, at the beginning of the 21st century, a review of the type of dam was carried out, in light of technological advances in dam construction, resulting in adopting a zoned cross section, with a clayey core and soil-rockfill mixture for the shells.

Since then, construction materials studies have focused, above all, on researching clayey materials for the construction of the core. To this end, the research began by essentially being confined to the future reservoir area, as required by good practices. However, given the scarcity of soils in the region with suitable characteristics for use in the dam core, namely fines content and plasticity requirements, the research was extended to areas located outside the reservoir, being the main concern the quantity assessment of the available materials.

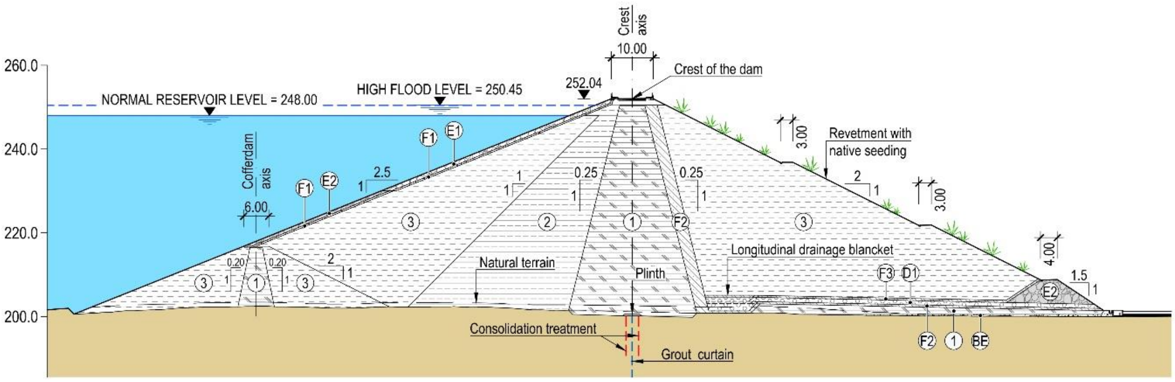

Figure 1. Typical cross-section of the da.m for the highest section (Aqualogus / TPF, 2023a).

4.2 Borrow areas

When defining the borrow areas, the main objective was to maximize the exploitation of the various materials within the future submerged area of the reservoir. Therefore, it was considered that the soil-rockfill mixtures for the shells would come from the excavations to be carried out on the right bank, whether resulting from the implementation of the bottom outlet or the creation of borrow areas inside the future reservoir, involving the highly weathered and highly fractured upper part of the rock mass as well as the residual soils cover. The coarse sand with fines prism would be made up of granitic residual soil from either the excavations for the spillway or the creation of borrow areas inside the reservoir area, on the left bank. The biggest challenge was then the identification of soils with suitable characteristics for placement in the core, and specially in sufficient quantity. With that in mind, geotechnical investigations surveys were carried out involving seismic refraction and excavation pits with sample collection. Along the different phases of the dam studies, since the late 60s / early 70s of the 20th century until 2021, a total of 57 seismic refraction tests, 48 excavation pits were executed and 90 samples were collected and submitted to laboratory testing.

Table 1 shows the distribution of the collected samples by borrow area.

Table 1. Samples submitted to laboratory testing (Aqualogus / TPF, 2023b).

Borrow area	Geological formation	Location referring to reservoir	Samples
E1	Schist	Inside	19
E2	Schist	Inside	32
E3	Ultrametamorphic rocks	Outside	17
E4	Granite	Inside	10
E3a	Schist	Outside	4
E3b	Schist	Outside	1
E3c	Schist	Outside	0
E3d	Schist	Partially inside	3
E3e	Ultrametamorphic rocks	Partially inside	4

4.3 Material characterization

Grain size distribution curves, Atterberg limits and specific gravity were determined, as well as the compaction and permeability characteristics. Table 2 presents the average values obtained in the laboratory tests.

Table 2. Average values of the index properties (Aqualogus / TPF, 2023b).

	< #200 (%)	PI (%)	w_{opt} (%)	$\gamma_{d,max}$ ($kN{\cdot}m^{-3}$)	G_s (.)	k ($m{\cdot}s^{-1}$)
1	33	10	13	18.9	2.68	10^{-9}
2	10	-	10	19.9	2.74	10^{-7}
3	12	-	9	20.0	2.67	10^{-7}

1 – Clayey soils; 2 – Sandy soils; 3 – Soil-rockfill mixtures

Regarding the mechanical properties of strength and stiffness, the materials were characterized through undrained consolidated triaxial tests (CU), with measurement of pore pressures. For soil-type materials, to be applied in the core (fine soils) and in the transition zone (coarse sand with fines prism), the specimens were tested in normal triaxial chambers (4''). In the case of soil-rockfill mixtures, it was necessary to use 230 mm chambers, to guarantee representation in relation to the maximum particle size of the mixture.

The specimens were remoulded complying with the optimal characteristics of the compaction test and were then consolidated to a pre-established stress. Finally, they were subjected to triaxial shear by increasing the deviatoric stress, q, until an axial deformation of 20% was reached.

The soils' strength (c' and ϕ') and stiffness design values were determined from the undrained triaxial tests' responses. Compatible secant drained Young modulus, E', was inferred for different levels of axial strain, namely for the axial strain associated with $q/p'max$, for 0.10% and 1% strain. The Poisson coefficient values were adopted after the literature values. Table 3 presents the considered design values.

Table 3. Design values for strength and stiffness properties (Aqualogus / TPF, 2023b).

	φ' (°)	c' (kPa)	E' (Mpa)	ν' (.)
1	32	0	40	0.35
2	37	0	50	0.30
3	40	0	70	0.30

1 – Clayey soils; 2 – Sandy soils; 3 – Soil-rockfill mixtures

5 MATERIAL AVAILABILITY AND DESIGN OPTIMIZATION

In any embankemnt dam, the most important element corresponds to the waterproofing element, which will ensure that there will be no relevant seepage through the body of the dam. In the case of the Pisão Dam, this element is materialized by the core, made up of clayey soils. Finding soil with the appropriate characteristics and in sufficient quantity for the construction of the dam core therefore became the main constraint of the material research studies.

Although initially, the site seemed very promising in terms of the presence of this type of soil since it is usually expected that schist rock masses give rise to clayey residual soils, what was found was a reduced quantity of these soils given the weathering profile of the rock mass. In fact, the schist rock mass presented a thin horizon of residual soil of about 1.0 m thickness on average (typical values between 0.5 and 1.6 m), or often inexistent. This profile was considered to lead to insufficient available volumes and important difficulties in the "clean" exploration of too thin layers of material, due to possible contamination either with top soil or with coarse material. Consequently, it was decided to search for borrow areas with better exploitation potential outside the future reservoir area, while at the same time to reduce to a minimum the need for clayey materials.

Fine materials were identified in greater abundance outside the area of the future reservoir in a radius of 1 to 3 km of the dam, corresponding to residual soil from ultrametamorphic rocks, specifically migmatite gneisses. This rock mass presented a more regular weathering profile and an average thickness of residual soils of about 1,3 m (typical values between 0.9 and 2.1 m).

Simultaneously, the core geometry was optimized, resulting in a thinner core of fine material with a minimum width of 6.0 m and 4V:1H slopes. The geometry optimization allowed the reduction in the need for fine soils from about 529 800 m^3 to 401 500 m^3.

6 CONCLUSIONS

The Crato Multi-Purpose Hydraulic Project, which includes the Pisão Dam, was considered an anchor of development by all the 15 municipalities of Alto Alentejo, by the population and by the Government, being an historical aspiration and demand dating back more than half a century.

Given this strategic importance, it became necessary to make decisions in the design stage that, although not the most desirable, would make the dam's construction viable, such as the exploitation of materials outside the future reservoir area.

However, given the thickness of exploitable material, it was considered that the implementation of current environmental recovery measures would straightforwardly reverse the impacts of this exploitation, returning the area in question to its usual use.

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