

**CONTRIBUTION FOR THE DISSEMINATION OF ROCKFILL DAM WITH
BITUMINOUS CONCRETE CORE SOLUTION IN PORTUGAL**

**UMA CONTRIBUIÇÃO PARA A DIVULGAÇÃO DAS BARRAGENS DE
ENROCAMENTO COM CORTINA INTERIOR DE BETÃO BETUMINOSO EM
PORTUGAL**

Faustino, Vera, *Aqualogus, Engenharia e Ambiente, Lisboa, Portugal, vlbfaustino@gmail.com*
Caldeira, Laura, *Laboratório Nacional de Engenharia Civil, Lisboa, Portugal, laurac@lnec.pt*
Maranha das Neves, Emanuel, *Instituto Superior Técnico, Lisboa, Portugal, emn@civil.ist.utl.pt*

ABSTRACT

The present work is based on the MSc thesis with the same name, defended in IST in 2009. This work addresses, firstly, a reflection about rockfill dams with bituminous concrete core and aims to contribute to the understanding and divulgation of this type of impervious solution, regarding its application, for the first time, in Portugal. It is initially presented a brief history of this type of dams built to date and about their first appearance. The specificities of bituminous concrete cores are addressed and observation and structural behaviour are also addressed. It is subsequently developed the practical component of the work, the design at preliminary level of the Torno river rockfill dam with bituminous concrete core. From the compiled information and the conducted studies, it may be concluded that the rockfill dams with bituminous concrete core are suitable solutions from the technical point of view, with remarkable results of structural behaviour, which may constitute an alternative dam type solution

RESUMO

O presente trabalho baseia-se na tese de mestrado com o mesmo nome discutida no IST em 2009. Este trabalho constitui uma reflexão sobre as barragens de enrocamento com cortina interior de betão betuminoso e procura contribuir para a compreensão e divulgação deste tipo de solução de estanquidade, com vista a sua utilização, pela primeira vez, em Portugal. Apresenta-se, inicialmente, um breve historial sobre as barragens deste tipo construídas até a data. Em sequência, tratam-se as especificidades das cortinas interiores de betão betuminoso, referindo-se, também, aspectos relacionados com a observação e com o seu desempenho estrutural. Em seguida, desenvolvem-se os estudos de dimensionamento da barragem do rio Torno, a nível de Anteprojecto. Da informação compilada e dos estudos efectuados, pode concluir-se que as soluções de enrocamento com cortina interior de betão betuminoso são soluções adequadas tecnicamente e com excelentes resultados de desempenho estrutural, podendo constituir-se como soluções de barragem alternativas.

1. INITIAL CONSIDERATIONS

The subject of the developed work was the result of the author's interest in dam engineering, in addition to the professional opportunity to take part in the preliminary design studies of the Torno river dam¹.

¹ Work conducted by the AQUALOGUS/CENOR consortium.

The specific conditions associated with the construction site led to the study of an alternative dam type solution with a bituminous concrete core, which would be object of detailed studies at preliminary design level.

The fact that this type of solution had never been constructed, or even studied, in Portugal was a determinant factor in the choice of the subject of the thesis: *A Contribution for the Dissemination of Rockfill Dam with Bituminous Concrete Core Solution in Portugal*.

The thesis comprises two complementary areas, the scientific and the design practice, which goals are hereby presented:

1. a critical bibliographical revision of rockfill dams with bituminous concrete cores (BCC), particularly of their impervious element, which differentiate them from other types of rockfill dams, regarding its application in Portugal, for the first time;
2. practical application of the acquired knowledge in the structural conception of the Torno river rockfill dam with BCC, as well as the development of the main design studies at preliminary design level and the familiarization with specific calculation software.

The main body of the work was organized as follows: *Chapter 1* and *Chapter 5* correspond, respectively, to the initial considerations and to the conclusions and future developments, whereas chapters 2 to 4 aim to accomplish the established goals, as follows: *Chapter 2 – Rockfill dams with Bituminous Concrete Cores*, corresponds to the scientific part of the work; *Chapter 3 – Conception, Characterization and Geological, Geotechnical and Seismological Scenarios of the Torno River Dam* and *Chapter 4 – Design Studies of the Torno River Dam*, refer to the practical component of the work (application of acquired knowledge and design studies).

2. ROCKFILL DAMS WITH BITUMINOUS CONCRETE CORES

2.1. Initial Considerations

Bituminous mixes have been used as impervious internal elements in earth and rockfill dams since 1949 (ICOLD, 1982).

The Portuguese dam of Vale do Gaio is referred by the International Committee of Large Dams (ICOLD) as the first of its kind. The used bituminous mix is, however, different from the bituminous concrete studied in the present work.

In fact, since their initial application, various bituminous mixes were experimented, and the construction techniques of bituminous concrete cores were improved. ICOLD (1982) differentiates several types of impervious solutions: bituminous mastic (solution selected for the Vale do Gaio dam), cyclopean mortar, cyclopean bituminous concrete, fluid bituminous concrete and dense bituminous concrete.

The dense bituminous concrete solution (hereon designated by bituminous concrete) – which was the work's main object of study – is, presently, the most commonly adopted solution and was initiated, in 1962, at Kleine Dhuenn dam, in Germany.

In November 2008, 86 dams with this kind of impervious solution were constructed, 18 were under construction and 3 were in design phase (Kolo Veidekke, 2008). The maximum heights of these dams vary between 11 and 170 m, with a mean value of 48.6 m (most of the dams are between 30 and 60 m high). 37 of these dams are located in China, 23 in Germany and 12 in Norway.

Approximately 80% of these dams have rockfill at the upstream and downstream shells.

2.2. Bituminous Concrete Composition and Characteristics

Regarding its composition, bituminous concrete can be defined as a poly-phasic media, composed by solid particles (aggregates and filler), and by bitumen and air filling the voids in the solid matrix. The main function of the bitumen is to act as an adhesive to the aggregate particles and filler.

Bitumen is a chemically complex material, being the result of the mixture of mostly open chain hydrocarbons, with some minority cyclic hydrocarbon molecules and functional groups containing sulfur, nitrogen and oxygen.

Bitumen proprieties can be plotted in a temperature/viscosity/penetration graph, which allows selecting the construction temperatures in light of the optimum viscosity intervals, in order to obtain good workability.

The behavior of a bituminous mix is deeply influenced by the voids filled with air, namely relatively to the permeability. Mixes with air void content inferior to 3% are virtually impervious, presenting permeability coefficients inferior to 10^{-10} to 10^{-11} m/s.

The aggregates used in bituminous concrete mixes are defined by the Füller curve specifications $(P = (\frac{d}{D})^n \times 100)^2$ and the maximum diameters vary between 16 (Strabag, 1990) and 19 mm (Falcão, 2007).

The filler percentage present in the aggregate may vary between 8 and 12%, and the material may have various origins (for instance, fly ash, cement, hydrated lime or limestone).

Bituminous concrete is a ductile visco-elasto-plastic material, which has the ability of auto-repair in case of fissuring or cracking. Its rheological behavior may be simulated by elastoplastic models, with Mohr-Coulomb failure criteria, hyperbolic models or more complex models derived from non-linear visco-elastic models of bitumen, like the Maxwell-Norton model (Razavi, 1989), and aggregate representative models (like Hujeux, 1979).

Falcão (2007) conducted a series of laboratorial tests for hydraulic and mechanic characterization of bituminous concrete with three different types of aggregates (granite, mica-schist and limestone) with different bitumen contents. A summary of some of these results for a bitumen content of 5.5% is presented in Table 1.

Table 1 – Bituminous Concrete Mixes With 5.5% Bitumen Content. Hydraulic and Mechanic Characteristics (Falcão, 2009).

Aggregate	Permeability coefficient k (m/s)	Effective cohesion c' (kPa)	Internal effective friction angle ϕ' (°)	Deformability modulus, $E_{(1\%)}$ (MPa)
Granite	10^{-11}	376	27	55 ⁽¹⁾
				75 ⁽²⁾
				123 ⁽³⁾
Mica-schist	4×10^{-11}	397	28	140 ⁽¹⁾
				270 ⁽²⁾
				300 ^{(3)(*)}
Limestone	9×10^{-12}	242	15	20 ⁽¹⁾
				20 ⁽²⁾
				22 ⁽³⁾

- (1) Preconsolidation stress = 249 kPa
- (2) Preconsolidation stress = 491 kPa
- (3) Preconsolidation stress = 981 kPa
- (*) Axial strain = 0.8%

2.3. Structural Conception

ICOLD (1992) recommends the construction of central vertical cores with constant thickness for dams with maximum height up to 60 m. For higher dams, the core can tilt in the upper third of the dam, thus

² Where P is the percentage of material passed in a specific sieve, d is that sieve's, D is the maximum aggregate diameter and n is a power variable between 0.41 and 0.50 for bituminous concrete mixes.

minimizing the possibility of a separation between the core and the upstream shoulder material. The construction of tilted cores along the height of the dam is more expensive and does not introduce any visible technical advantage (ICOLD, 1992).

The thicknesses of the core and transition zones (which are constructed simultaneously), are function of the height of the dam and the design actions, as well as the standard construction equipment dimensions. Usually, the core thickness varies between 0.5 and 1.2 m, and the transition zones vary between 1 and 2 m.

The exterior geometry is defined like all other earth or rockfill solution, by the freeboard, crest width and embankment slopes (and benches), which definition is conditioned by the local settings, construction materials, foundation characteristics and hydraulic structures operation definitions.

Relatively to the construction materials, according to the consulted bibliography, the maximum dimension of the aggregate (D_{max}) relates to the D_{10} of the transition materials ($D_{100 (mix\ aggregate)} \geq D_{10 (transition\ zone)}$). It should be also guaranteed the following grading relation between the transition materials and the shoulder materials (ICOLD, 1992): $D_{100 (mix\ aggregate)} \geq \frac{1}{4} \cdot D_{100 (shoulder\ embankment)}$.

2.4. Construction and Control

The construction of bituminous concrete is currently materialized by a paving machine, denominated Paver. The Paver incorporates storage devices for bituminous concrete and transition materials, which are alternately applied. It also incorporates compaction and leveling, as well as warming and drying devices, guaranteeing a first compaction of the core and transition zones (prior to the compaction with vibrating rollers).

The initial layers of bituminous concrete and transition materials are executed manually, until a leveled and long surface is obtained (about 30 m), so the Paver can be operated. The interface between the bituminous concrete and the foundation plinth is covered with a 10 to 20 mm thick bituminous mastic. Figure 1 illustrates some constructive details of bituminous concrete cores.



Figure 1 – Illustration of Some Constructive Details: (a) Application Of The Bituminous Mastic Layer; (b) Manual Placing Of Bituminous Concrete; (c) Working Paver; (d) Final Compaction Of Core And Transition Zones (adapted from Kolo Veiddekke, 2008).

The layers of bituminous concrete core and transition zones are executed with approximately 0.20 to 0.30 m (0.20 m being the usual value), and compacted with 3 to 6 passages of a vibrating roller with 0.5 to 2.5 ton. The placing temperature depends on the bitumen class that is used. B60 and B65 bitumens are compacted at temperatures of 160 to 180° C, whereas B180 bitumens are compacted at temperatures between 140 to 155 °C (Höeg, 1993).

Tests conducted on mixes after manufacturing and before placing comprise, generally, the analysis of the composition of the mix, temperature control, Marshall Tests (unit weight and strength vs. bitumen content) and permeability tests. Tests conducted on mixes that are being placed consist of spreading tests and temperature control. Finally, tests conducted on compacted mixes comprise composition of the mix, unit weight and also compaction and porosity, permeability, shear resistance and deformability tests.

2.5. Performance

The structural performance of BCC rockfill dams is considered by ICOLD (1992) excellent, both in static and seismic conditions.

In the reviewed bibliography there is no record of anomalies that have required rehabilitation intervention, regarding the structural performance of this kind of dam solution. There are, however, for some dams, records of significant seepage flows through the dam body and foundation (approximately between 10 and 20 l/s) that were reduced over time without any kind of intervention. There is only the case of the Norwegian Riskallvatn dam (Höeg, 1993) where the seepage flows were extremely high (100 l/s after first impoundment). This flow (mainly through the foundation) was also reduced over time without any action to, approximately, 20 l/s. The referred flow reduction was attributed to the natural sealing of fractures in the rock foundation.

3. CONCEPTUAL DESIGN AND CHARACTERIZATION OF THE TORNO RIVER DAM

3.1. Generalities

Torno river dam is located on Torno River, in Vila Real district, in a granite environment and at elevated heights, in the proximity of Alvão Mountain. The construction site is a moderate slope valley, with a chord-height ratio of 10, affected by hydrothermal alteration and with several geological accidents.

No fine-grained materials were found, either inside the reservoir or in the vicinities of the construction site, for the construction of an earthfill dam or a traditional core for a rockfill dam. It was therefore analyzed the alternative rockfill solution with a bituminous concrete core.

3.2. Structural Conceptual Design

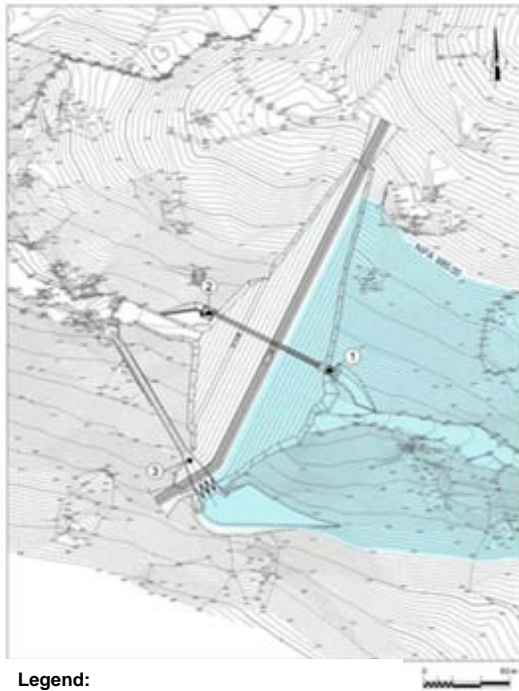
Torno river dam³ has a maximum height of 32 m, and a mostly straight crest, with a length of 262.5 m.

Figure 2 and Figure 3 illustrate the plan and cross-section of the dam (AQUALOGUS/CENOR, 2009).

The exterior geometry is characterized by the crest width (7 m), the crest height (887.5) – fixed according to the normal and minimum freeboard values –, the embankment slopes (1:1.4; V:H) and the definition of berms (one, downstream, 3 m wide, at level 872.5 m).

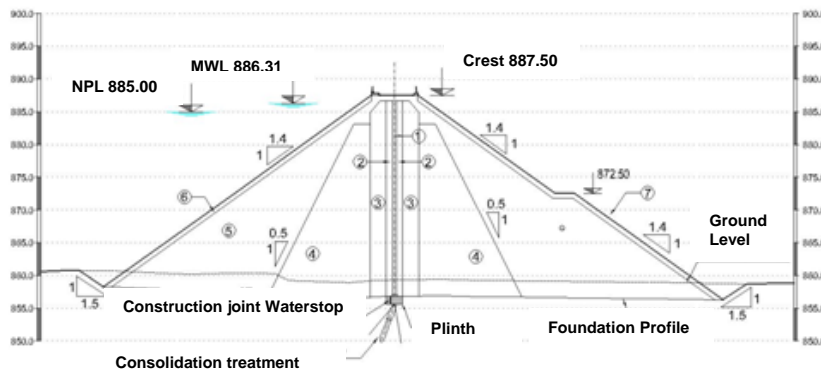
³ The presented solution corresponds to one of the two alternatives (Alternative II) of the dam (both with bituminous concrete core) developed in the preliminary studies.

The crest width was estimated according to empirical formulas, that take into account the height of the dam, and the crest height was established based on the normal reservoir level (885) and the maximum reservoir level (MRL =886.31), which were combined with the action of the wind on the reservoir and its effects (wind setup and wave run-up on the upstream slope), as well as the settlements of the dam.



Legend:
 1. Bottom outlet intake tower
 2. Bottom outlet dissipation basin
 3. Spillway

Figure 2 – Torno River Dam Plan (AQUALOGUS/CENOR, 2009)



Legend:
 1. Bituminous Concrete Core (bitumen content 6%)
 2. Selected Granular Material (0.2 to 60 mm)
 3. Selected Transition Rockfill (1.5 to 180 mm)
 4. Well Graded Rockfill ($D_{max}=400$ mm, fine% <8%)
 5. Selected Rockfill ($D_{max}=600$ mm, fine% <5%)
 6. Upstream Rip-Rap ($D_{max}=600$ mm)
 7. Downstream Rip-Rap ($D_{max}=600$ mm)

Figure 3 – Torno River Dam Cross Section (AQUALOGUS/CENOR, 2009)

The embankment slopes depend on the shear strength of the various dam body and foundation materials, and were validated by global stability analysis, in static and seismic conditions, of the critical stages of the dam life – after construction and with the full reservoir level – as stipulated by the Portuguese design guidelines for dams (SRB, 1993). The downstream berm has purely functions of accessibility for inspection and monitoring of the embankment dam.

Relatively to the internal zoning of the cross section, the bituminous concrete core is designed along a single vertical plane, in alignment with the axis of the dam. The core is 0.50 m wide, and the transition zones (upstream and downstream) are 1.2 m wide.

The proposed bituminous mix is manufactured from B65 bitumen, granite aggregate (explored in the reservoir area) and hydrated lime, with an average bitumen content of 6% and an air void content below 3%.

The aggregate is composed by sand (fine, medium and coarse), as well as fine and medium grain gravel. The mean gradation curve for the aggregate is the Füller curve for $n=0.48$ and $D_{max}=17$ mm. The transition materials immediately upstream and downstream from the core (material 2) are constituted by cobble, and a well graded mixture of cobble and sand, without fine materials. The D_{10} varies between 0.70 and 3.20 mm and the D_{max} between 40 and 60 mm.

Upstream and downstream from the transition zones, two vertical zones, 2.5 m wide, are adopted, which make the final transition between the core and the upstream and downstream shells. These are composed by two materials: one, in the interior part of the shoulders, constituted by a mixture of blocks, cobble and sand, with D_{max} between 140 and 400 mm, and a fine fraction lesser than 8%, and another, in the exterior part of the shoulder, with D_{max} between 300 and 600 mm and a fine fraction inferior to 5%.

Figure 4 illustrates the gradation ranges for the dam materials.

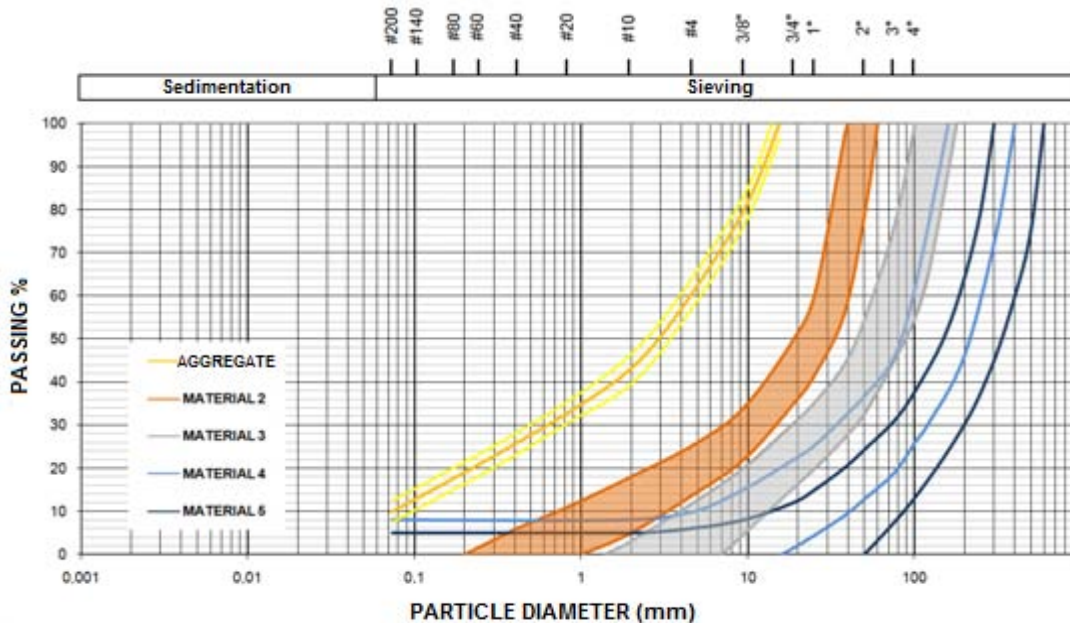


Figure 4 – Gradation Ranges For the Dam Materials.

3.3. Monitoring Scheme

As a result of the performed studies, a monitoring system is proposed as follows.

Taking into account the singularities of the dam and the recommendations of the Portuguese Inspection and Monitoring guidelines for dams (SRB, 1993a), a global risk index of 19.6 was calculated, resulting in the following physical quantities to be measured and related devices: **1.** superficial vertical and horizontal displacements of the embankment – superficial land marks; **2.** internal vertical and horizontal displacements of the embankment – inclinometers and linear extensometers; **3.** internal horizontal bituminous core displacements – extensometers (in the downstream half of the core); **4.** total stresses – total pressure cells; **5.** partial flows – weirs; **6.** pore

pressures – hydraulic piezometers; **7.** reservoir levels – limnometric scale; **8.** precipitation, wind, evaporation and temperature – meteorological devices; **9.** seismic accelerations – accelerographs.

4. DESIGN STUDIES OF THE TORNO RIVER DAM

The dam cross section was studied in light of the ultimate limit states and serviceability limit states, critical to its design.

Relatively to the ultimate limit states, the collapse safety against external erosion was verified through the definition of the freeboard, and the global stability was verified in static and seismic conditions (pseudo-static and pseudo-dynamic analysis). The safety against piping was not verified on account that this is not a critical situation for this kind of dams.

The static and pseudo-static analyses were performed according to the Simplified Bishop method, automatically with SLOPE/W software (Geoslope, 2004). Global factors of safety greater than those prescribed in the Portuguese guidelines (SRB, 1993) were obtained for the relevant design situations of the dam ($CS_{min}=1.4$, for the construction phase, and $CS_{min}=1.5$, for the normal water level of the service phase).

For the pseudo-dynamic analysis, a non linear elastic equivalent model was adopted for the dam body. Thus it was possible to estimate the amplification of the seismic action, from the foundation of the dam until the crest, and to evaluate the displacements associated with critical slip surfaces (these are function of the ratio between the amplified acceleration and the acceleration which leads to a unitary pseudo-static factor of safety, according to the Newmark method, 1965). The analysis was performed according the methodology proposed by Makdisi and Seed (1977).

The maximum accelerations in the foundation (defined from seismological studies) were, for the operating basis earthquake (T=1000 years), equal to 1.50 m/s^2 and 0.90 m/s^2 , respectively, for type 1 and type 2 actions (according to the RSAEEP⁴ definition), and, for the maximum credible earthquake (T=10000 years), equal to 3.0 m/s^2 and 1.80 m/s^2 , for type 1 and type 2 actions. During the calculations, the RSAEEP normalized power spectral density functions were used, and the actions were multiplied by 1.5. Between the base and the crest of the dam, the maximum acceleration amplification was 3.2 to 3.9 and the maximum calculated displacements about 0.22 m and 0.08 m, respectively for the two types of actions considered.

Referring to serviceability limit states, stress-strain studies were conducted, using the PLAXIS finite element software (Plaxis BV, 2009). Calculations were made in a plane deformation state and in effective stresses to the highest dam cross section. Construction and first impoundment stages were simulated.

The maximum obtained settlement, in construction stage, was approximately 0.11 m, at about mid height of the cross section. The maximum obtained horizontal displacement, after the first impoundment, was 0.032 m, on the upstream face of the core.

Based on empirical formulas, the long term settlements of the dam were estimated in approximately 0.13 m, after the life span of the dam (t=100 years).

The seepage flows through the body and foundation of the dam were estimated using the SEEP/W finite element software (Geoslope, 2007). The obtained seepage flows were very low (lower than 1 l/s), seeping mainly through the foundation.

⁴ Regulamento de Segurança e Acções para Estruturas de Edifícios e Pontes (CIRRT, 1986)

In the performed calculations regarding the bituminous concrete core, the shear strength, deformability and permeability parameters used were the ones characterized by Falcão (2007), through triaxial and permeability tests on bituminous concrete with granite aggregate, namely: $c'=380$ kPa; $\phi'=27^\circ$; $E(\delta=1\%)=70$ MPa and $k=10^{-11}$ m/s. For the rockfill shells, the shear strength and deformability parameters were deducted based on index proprieties of the prospected rock in the reservoir, as well as correlations present in the bibliography. For the foundation, the strength and deformability parameters were indirectly estimated, and the hydraulic characteristics were estimated taking into account the results of the performed Lugeon tests.

5. CONCLUSIONS AND FINAL CONSIDERATIONS

From the compiled information on rockfill dams with bituminous concrete core and the performed studies, it can be concluded that this rockfill dam solution is adequate from the technical point of view and with remarkable structural performance results, thus constituting a valid alternative dam solution. In spite of the few economical data, this type of solution seems competitive, especially for locations where fine materials for the construction of a traditional core are scarce.

Due to the mechanical and hydraulic characteristics, durability and auto-repair capacity, ICOLD (1982) considers this type of solution capable of guaranteeing all safety and functionality requirements.

Some of the advantages associated with rockfill dams with bituminous concrete cores are the following: **1.** bituminous concrete is a ductile visco-elasto-plastic material, which has the capability of auto-repair in case of fissuring or cracking; **2.** the construction procedures allow the execution of the core with no joints, and its compaction minimizes the volumetric expansion (which could increase the permeability of the mix and the cracking susceptibility); **3.** the small core exposure area during construction and the bituminous concrete thermal capacity grant it adequate characteristics against adverse weather conditions; **4.** the central position of the core protects it against external actions; **5.** the core construction occurs simultaneously with the construction of the transition zones, which allows that the dam itself fulfil cofferdam functions; **6.** this type of impervious solution (with some alterations to the traditional composition of the bituminous mixes) can be used in softer foundations, such as alluvial deposits (Höeg, 1993).

The main disadvantages relate to the repairing difficulties of this type of dam, to the fact that there are very few companies in the world specialized in executing bituminous concrete and, finally, to the lack of published information on rockfill dams with bituminous concrete cores.

Rockfill dam with bituminous concrete core constitutes a never before built solution in Portugal, and its development, in the country, should involve the construction of the first solution of this kind. The construction of the Torno river dam may potentially point out several lines of future studies related to the bituminous concrete core, namely:

1. on the level of the rheological behaviour of bituminous concrete mixes, through the testing of the components of the mixes, and the mixes themselves, varying the type of bitumen, aggregate and their grading;
2. on the modelling level, using rheological models with parameters derived from the carried out tests, and finite elements analysis in either plane state of deformations or tridimensional state;
3. on the constructive and quality control specification level, and also the construction technologies;
4. on the monitoring and observation level, by installing specific monitoring devices for bituminous concrete cores, and their performance evaluation.

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