Computational identification of real displacements of an arch dam using nonlinear material with geochemical damping

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Abstract

The Belesar dam is an impressive arch dam existing in Spain which has experienced an unusual displacements field due to geochemical reactions between alkaline components of the cement and concrete aggregates. A preliminary study was carried out over past decade intended to computationally model dam structural behaviour. Recently, a new study containing improvements with regards to the previous one has been completed. The research worked out defines a sophisticated constitutive law for the concrete including orthotropic geochemical damping. The numerical results show a good adequacy with respect to the measured displacements of the dam.

1 Introduction

The Belesar Dam is an arch dam located in North West Spain. It has a height of 130 m and its maximum length at the top is about 275 m.

The dam has been monitored since construction works finished in 1963. The structure behaved as predicted at the beginning of the service life but soon afterwards the dam showed unexpected upstream displacements. This structural response was a consequence of an expansive process in the dam concrete due to chemical interaction between alkaline components of the cement and concrete aggregates. According to data from the monitoring system of the dam this phenomenon was first located in the left side of the dam, and has spread out to most of the dam mass since 1979.
2 Monitoring system of the Belesar dam

The dam possesses a quite complete system to obtain loading values, temperature data and structural responses. A brief description follows:

— Dam displacements are measured at six locations, distributed along the dam volume at different heights. Altitude values are indicated in Table 1, and locations are presented in Figure 2.

Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>R0</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude (m)</td>
<td>330</td>
<td>312</td>
<td>292</td>
<td>272</td>
<td>252</td>
<td>232</td>
</tr>
</tbody>
</table>

— Concrete and water data temperatures are obtained by thermometers located at the exterior and inside the dam. The number of thermometer locations is higher than 300 and provides a complete set of data temperatures along dam thickness.

— A number of 249 extensometers are located in the dam to control material strain. They are distributed in the upstream and downstream sides and at half thickness of the dam.

Figure 1: Picture of Belesar dam.

Figure 2: Location of displacement devices.
Data provided by the aforementioned devices are stored in computers, allowing several kinds of printed output of the collected information.

3 Time history of dam displacements

Usual values of dam displacements are related to reservoir level and material temperatures. Yearly variations present upstream displacement in summer, due to higher temperatures and the lower amount of impounded water, and downstream values in winter due to the opposite situation.

Displacement data from the Belesar dam presented at the beginning this type of yearly variation, but with an average value moving continuously upstream. The process was quite slow from 1963 to 1979 but it has increased in intensity since that year. Historical evolution at position R0 (330 m) of locations 1 is showed in Figure 3.

Year numbers are on the horizontal coordinates and displacements (mm) are on the vertical axis, with positive values corresponding to downstream values.

![Figure 3: Historical evolution of dam displacements at R0 in location 1.](image)

As has already been mentioned, the increase in upstream displacements was caused by volume expansion of dam concrete due to a geochemical phenomenon which produced higher values of stresses and therefore diminished dam safety.

4 Preliminary study in 1994

Because of that a study finished in 1994 aimed to set up a finite element model of the dam capable of emulating past behaviour of the dam and consequently providing a tool to predict future evolution of dam displacements and safety.

The structural model used in the analysis of Belesar dam appears in Figure 4. The model is composed of dam and surrounding rock foundation, which turn out to be formed by three materials of two different mechanical properties.
The structural model contained 5075 isoparametric finite elements of 20 nodes. After imposing boundary conditions the total number of degrees of freedom was 75873. All the materials were considered lineal and isotropic.

![Figure 4: Finite element model of Belesar dam.](image)

The numerical results provided by this study were quite appropriate [1] but the authors considered that the methodology could be improved in a few ways:
— A more detailed information of the database of geochemical expansions.
— A better definition of the finite element model of the dam.
— A more precise identification of the elasticity modulus of the concrete.
— More complex constitutive law for the concrete.

By combining these four lines a closer identification of the real displacements of the structure could be obtained and the next paragraphs explain the study carried out considering them.

5 Description of the new study

5.1 Detailed consideration of the geochemical expansions

The company owning the dam provided a more precise database of numerical values of the expansions which was divided into three historical divisions. Also information about the values of the deformation was given not only at downstream and upstream sides of the dam but also at some locations in the interior of the dam volume, precisely at the middle thickness of it. The temporal sequence of data was:
— Year 1963 to 1970.
— Year 1971 to 1976.
— Year 1977 to 1997.
The locations where the expansion values were given are presented in figure 5 for years 1963 to 1970. Information for the following years was described similarly.

![Figure 5: Values of expansion from 1963 to 1970 (x105).](image)

To define the expansions since 1998 the yearly rate of expansions between 1977-1997 was chosen extending the temporal interval considered up to 2001.

The discrete distribution of expansions was transformed into a continuous field by using a thermal analogy. By doing that cumulative values of expansion at each point of the dam can be obtained. Figure 6 presents the expansion values in the dam in year 2001.

### 5.2 Finite element structural model

The existing mesh of finite elements was improved in order to introduce more elements in the dam, creating two layers of isoparametric hexahedral elements along the thickness. Also more volume of surrounding rock was included up to a length of 85 m upstream and 100 m downstream. The number of elements defined at each part of the model was:
a) Downstream.

b) Upstream view.

Figure 6: Expansion fields at year 2001.

— Arch dam: 1952.
— Abutments: 255.
— Foundation rock: 1343.

The new model described more accurately the set of structural components without increasing the number of degrees of freedom with respect to the previous structural model. Figure 7 shows the new finite element mesh.

Figure 7: Finite element model used in the study.
The structural model was subjected to two load combination representing the worst scenario for the dam.

Combination A: Selfweight + Water pressure (330 m) + $T_{\text{min}}$ + Expansion field.
Combination B: Self weight + Water pressure (285 m) + $T_{\text{max}}$ + Expansion field.

Structural analysis was carried out with the commercial code COSMOS/M [2-3].

5.3 Constitutive law for concrete considering orthotropic geochemical damping

The current level of knowledge of the expansion process inducted in concrete by alkali-aggregate chemical reaction is partially unclear. One of the most updated approaches in modelling such behaviour links the expansion evolution to the compressive stress field in the material [4] and a few dams have been studied with this procedure [5-6]. This formulation defines a set of parameters of geochemical damping in the concrete. Clark, Hobbes and Charlwood [7-10] stated that such chemical phenomenon attenuates because the compressive stress of the material and it almost stops when an upper value of stress is reached.

Nominating $\varepsilon_u$ as the ratio of free expansion in the concrete, $\sigma_L$ as the lower stress level for free expansion and $\sigma_U$ as the stress level which stops the phenomenon, the expansion $\varepsilon$ for a stress $\sigma$ can be written as

$$
\varepsilon = \varepsilon_u \quad \text{if} \quad \sigma \leq \sigma_L
$$

$$
\varepsilon = \varepsilon_u \frac{\log \frac{\sigma_U}{\sigma}}{\log \frac{\sigma_U}{\sigma_L}} \quad \text{if} \quad \sigma_L \leq \sigma \leq \sigma_U
$$

$$
\varepsilon = 0 \quad \text{if} \quad \sigma_U \leq \sigma
$$

Recommended values for $\sigma_L$ and $\sigma_U$ are

$$
\sigma_L \approx 0.3 \text{ MPa} \quad \sigma_U \approx 5 - 8 \text{ MPa}
$$

Arch dams have different stress level at each direction, therefore in this piece of research it seemed logical to consider different levels of attenuation at each coordinate axis and therefore three damping parameters $\alpha_x$, $\alpha_y$, $\alpha_z$ were defined

$$
\alpha_x = \alpha \zeta_x \quad \alpha_y = \alpha \zeta_y \quad \alpha_z = \alpha \zeta_z
$$

being $\alpha = 10^{-5}$ m/m and $\zetax$, $\zetay$, $\zetaz$ geochemical damping coefficients, which could be obtained by the following criteria, fixing the value $\sigma_U = 6$ MPa.

$$
\frac{\sigma_{x_{\text{max}}} + \sigma_{y_{\text{max}}} + \sigma_{z_{\text{max}}}}{3} = 6 \text{ MPa}
$$

and
\[ \sigma_{x_{\text{max}}} \leq \sigma_U \quad \zeta_x = 1 \quad \text{and if} \quad \sigma_{x_{\text{max}}} \geq \sigma_U \quad \zeta_x = \frac{\sigma_U}{\sigma_{x_{\text{max}}}} \quad (4.a) \]

\[ \sigma_{y_{\text{max}}} \leq \sigma_U \quad \zeta_y = 1 \quad \text{and if} \quad \sigma_{y_{\text{max}}} \geq \sigma_U \quad \zeta_y = \frac{\sigma_U}{\sigma_{y_{\text{max}}}} \quad (4.b) \]

\[ \sigma_{z_{\text{max}}} \leq \sigma_U \quad \zeta_z = 1 \quad \text{and if} \quad \sigma_{z_{\text{max}}} \geq \sigma_U \quad \zeta_z = \frac{\sigma_U}{\sigma_{z_{\text{max}}}} \quad (4.c) \]

Condition (3) assures that the criteria are not biased in any direction and \( \zeta_x, \zeta_y, \zeta_z \) are obtained by an iterative process resulting from applying expression (3) and (4).

The complete definition of materials required the value of elasticity modulus. An extensive test carried out for specimens of the Belesar dam allowed one to identify a value of \( E \) for long duration loads.

The set of mechanical data were

Concrete: \[ E = 17.000 \text{ MPa} \quad \nu = 0.25 \]
Foundation rock type 1: \[ E = 37.000 \text{ MPa} \quad \nu = 0.25 \]
Foundation rock type 2: \[ E = 12.500 \text{ MPa} \quad \nu = 0.25 \]

According to the definition of the geometrical damping each load combination produces different values of the set \( \alpha_x, \alpha_y, \alpha_z \). For the load combinations considered in the study the results turn out

Combination A:
\[ \alpha_x = 0.8 \cdot 10^{-5} \text{ m/mº C} \quad \alpha_y = 10^{-5} \text{ m/mº C} \quad \alpha_z = 10^{-5} \text{ m/mº C} \]

Combination B:
\[ \alpha_x = 0.6 \cdot 10^{-5} \text{ m/mº C} \quad \alpha_y = 10^{-5} \text{ m/mº C} \quad \alpha_z = 10^{-5} \text{ m/mº C} \]

6 Comparison between computational results and real displacements

Structural analysis of the finite element model was carried out considering load combinations A and B with the expansion field in years 1963, 1970, 1976, 2001. The numerical values of the displacements were compared with those provided by the monitoring system of the dam located as indicated in Figure 2. The next figures represent together the actual displacement from 1963 to 2001 and the lines corresponding to the results of the numerical model. The line defined by points 1, 3, 5, 7 corresponds to combination A while the line between points 2, 4, 6, 8 is the output produced by combination B.

Comparison between computational values and actual displacements was made at the following points.

Location 1: Level R₀, R₁, R₂
Location 2: Level R₀, R₁, R₂, R₃
Location 3: Level R₀, R₁, R₂, R₃
Location 4: Level R₀, R₁, R₂
Some of the graphs are included in Figure 8.

(a) Location 1; level $R_0$.

(b) Location 4; level $R_1$.

Figure 8: Comparison between computational results and actual displacement.

7 Conclusions

Some conclusions can be extracted from the research work carried out.

— Displacement fields produced by the numerical model indicate that the material behaves as isotropic until 1978 and then the orthotropic law is activates.
Numerical results obtained from the structural analysis contain very adequately actual displacements at locations 1, 2, 3. When the orthotropic law is included the accuracy of the numerical results improves.

Comparison between computational results and real values at location 4 are close enough until 1983, then accuracy is lost. By looking at the displacement field of the dam it seems that between 1983 and 1984 there is a sudden increment of the deformation of the dam, probably related with sliding between concrete joints. This phenomenon is not included in the structural model and it deserves to be studied in future research.

References


