1. Introduction

La Aceña dam is a large arch gravity dam, around 66 m high above the foundation, belonging to the Madrid water supply system. The main aim of this analysis is to gain data for the deformation-stress state of the dam, following the history of the behaviour of the structure (related to water level and temperature time histories), by means of numerical experiments. These data would serve for comparison with the measured results that will be followed by interpretation of the obtained data and in the end conclusions concerning the obtained results and the behaviour of the dam.

2. Description of the three dimensional numerical model of analysis

2.1 General part

The used computer software SOFiSTiK for stress-strain analyses, produced in Munich (Germany), is based on the finite element method. It has a wide range of possibilities for simulation of dam behaviour and inclusion in the analyses of all necessary phenomena, important for real simulation of the dam behaviour, such as: automatic discretization of the dam body taking into account the irregularities in the geometry of the dam base, application of different constitutive models for materials, simulation of the dam body construction and reservoir filling in increments, and so on. The program has rich possibilities for presentation of the output results. In our work, mainly plane graphical presentation was used, showing the output results in the main cross sections, as well as in longitudinal section.

2.2 Discretization of the dam body

Using the given data 3-dimensional (3D) mathematical model of the dam was build. The given data didn’t suit the SOFiSTiK format, and Visual Basic computer program was written. The program transformed the receiving data in appropriate format. In other to simulate the construction stages, the body of the dam was built in 23 increments. Every layer was approximately 3m high. Fig. 1 shows the general view of the dam body together with the surrounding rock foundation.
The finite element mesh was generated using SOFiSTiK automatic mesh generator. Three types of element were used to model the dam’s body: BRIC, QUAD and SPRING elements. The solid element of SOFiSTiK is the BRIC element (Fig. 2), a general six-sided element with eight nodes.

![Figure 2. BRIC element](image1)

The plane element QUAD (Fig. 3) is a general quadrilateral element with four nodes. In order to simulate the behaviour of the interfaces of the dam (joints between concrete blocks, dam-foundation interaction), spring elements are introduced.

![Figure 3. QUAD element](image2)

The surfaces of the BRIC element can be described by special QUAD-elements, which can also be employed for the display of stresses in BRIC-elements. The QUAD-elements are introduced in order to simplify the process of generation the water pressure loads and coupling springs between blocks.

![Figure 4. SPRING element](image3)

Springs can be defined as support conditions or as coupling springs between two nodes. The spring is defined by means of a principal direction and two spring constants. The spring constants CP and CT are assigned to the principal and the lateral direction, respectively. If a
friction coefficient and/or cohesion are input, the lateral spring can not sustain forces greater than:

\[ \text{Friction\_coeff.} \times \text{Compressive\_force} + \text{Cohesion} \]

The element’s geometry is checked by the program for node numbering order, re-entrant corners and side ratios smaller than 1:5. This complex modelling of the dam resulted in finite element mesh with 10.383 finite elements and 56.638 nodes. This talks enough of the complexity of the numerical solution and the possible difficulties that can appear during the execution.

### 2.3 Constitutive relationship and parameters of the materials

The choice of the parameters for the materials is one of the most important questions in the numerical analyses of dams. In this analysis linear-elastic constitutive stress-strain relationship was applied for all materials used in the model. The properties of the materials used in the analyses are given in Table 1 (according to the appendix for material data).

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>FOUNDATION</th>
<th>DAM BODY</th>
</tr>
</thead>
<tbody>
<tr>
<td>specific weight</td>
<td>22 kN/m³</td>
<td>23.6 kN/m³</td>
</tr>
<tr>
<td>E (Young modulus)</td>
<td>10000 Mpa</td>
<td>20000 Mpa</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Coef. of thermal exp. A</td>
<td>0</td>
<td>(10^{-5} , ^\circ\text{C}^{-1})</td>
</tr>
</tbody>
</table>

In the second stage of the analyses some calibration of the material properties was done. The material properties were changed so the displacements in the appropriate node match the values given with the benchmark.

### 2.4 Loading of the dam

According to the given data, appropriate water presser and temperature loads were created. SOFiSTiK has very efficient tools for load generation. With the VOLU-statement, a loading on volumes, group of BRIC-elements or all QUAD-elements within the volume is enabled. The changes of the pressure load along tree edges are specified. All referenced elements of the group or the volume will be loaded. The selection of elements is only by a sheared cube (Fig.5), defined by three selectable directions \(p_1-p\), \(p_3-p_2\), \(p_5-p_4\), which must not be collinear.

For transfer of the water pressure loads, some QUAD elements faces the upstream of the dam’s body was created (Fig.6). This elements has only geometrical values, they have no contribution on the total structure stiffness. Referencing these QUAD elements in the VALU statement cause simple transfer of the water pressure in appropriate node loads.
The water load is applied as hydrostatic pressure in increments combined with the temperature load. Figure 7 shows the applied water load on the dam.

Previous investigations made on similar objects showed that the temperature distribution is not uniform inside the dam’s body. In the core of the dam the temperature is almost uniform. Near to the faces it is dramatically changed (Fig. 8a.). SOFiSTiK supported only uniform temperature in the BRIC elements. Having in mind the temperature distribution and SOFiSTiK possibility of temperature presentation, we decided to create three different zones for temperature distribution. One at the upstream side, the other at the core, and the third at the downstream side of the dam body (Fig. 8b).
The temperature load is applied in accordance with the data from the appendix for temperature and the height of the thermometers installed in the dam body. In the intermediate part of the dam (in the BRIC elements), in dependence from the location of the thermometers, there is a steady distribution of the temperature in longitudinal direction, while in the ends of the dam upstream and downstream, there is a difference in the temperature values compared with the intermediate part because of the influence of the water and the environment. The distribution of the temperature in one cross section is shown on Fig. 9, while Figure 10 shows the temperature distribution on the 3-D model of the dam.

Figure 9. Temperature distribution in cross-section of the dam body

Figure 10. Temperature distribution on the 3-D model of the dam-foundation system
2.5 Analyses

The dam was analyzed on statically action of water pressure loads and temperature. The results from the analyses showed that the chosen mathematical model is too stiff. The deformations in the considering nodes were much lower than the measured ones. In our opinion the reason for this inconvenience was that the body of the dam was modelled as continuous one. In reality the dam was constructed in blocks with working joints between them. There is some sliding between blocks at the contact that make the structure more flexible. So, we decided to redesign the previous mathematical model and to create model that would have a real behaviour on the contact of the blocks. In the new mathematical model the dam’s body was constructed of several blocks. Each block was built in 23 increments. The blocks were made of BRIC elements, Fig. 11. On the contact faces between blocks, distributed coupling spring elements were introduced. These springs have one longitudinal and two transversal stiffness. SOFiSTiK has very nice tool for generation of this type of springs. Two structural areas that face the block body should be generated. Simply referencing these areas and introducing the spring’s properties would generate appropriate springs in the nodal points of the area.

![Figure 11. Distribution of the coupling springs](image)

Similar coupling springs at the contact of the dam with terrain should be created. With introduction of the coupling springs two contact phenomenon are taken under consideration: sliding between blocks and sliding between dam and terrain. In this study case the properties of the springs were estimated by calibrations. We change the transversal stiffness of the spring until the maximum displacement in the joint match the recorded data. The longitudinal stiffness should be a large number. This large stiffness should ensure the contact of the faces of blocks. In the reality the stiffness of the springs should be taken form experimental data.
3. Results obtained from the analyses

- Using the above described methodology and parameters, the following results of the displacements were obtained:

- Due to the death load (self weight of the dam), maximum vertical settlement appears at the dam crest in the main dam cross section with the value of 7.46 mm (Fig. 12), while the maximum displacement is located in the same level, with value of 3.78 mm (Fig 13).

- The influence of the temperature changes was analysed using the data given at the beginning of the formulation of the problem. In our report only the radial displacements from temperature load for one increment, for the period 07.02.1990-24.04.1990, are given (for the longitudinal dam section), Figure 14. The maximum calculated value for this increment is 2.06 mm and is located at the dam crest. Later on, much more date concerning temperature changes and measured displacements were supplied by the Formulator, but due to limited time and complexity of the problem, it was impossible to perform completely new analyses. Namely, to satisfy all requirements and to get real results, it is necessary to simulate the construction of the dam in more increments (blocks), to apply spring elements in all joints, and, which is very important, to introduce the non-linear behaviour of the interfaces, based on the experimental data.

- The influence of the water load was analysed for the period of 72 days, in which water height in the reservoir aroused approximately from 16 to 52 m above the dam foundation. Under these conditions, the radial displacements in the dam body reached the value of 16 mm, Fig. 15 and 16. In the same time, the maximum value of the vertical displacement is slightly above 3 mm and is located at the middle of the highest dam cross section, Fig. 17. The Radial displacements for this load case are also shown on the longitudinal dam section, with the maximum value of 16.3 mm, Figure 18. This value, together with the appropriate incremental value obtained by temperature load, gives the total maximum radial displacement of approximately 18 mm, given by the Formulator of the problem. To obtain this value, we have changed previously formulated model, introducing spring elements in the middle blocks of the dam (Figure 11), with appropriate stiffness parameters, and calibrating the elasticity modulus for the concrete (it was increased by 60%).

4. Conclusions

From the performed and above described analyses, following main conclusions could be drawn out:

4.1 SOFiSTiK software is a powerful tool for complex three-dimensional stress-strain analyses of dams. It has rich possibilities for modelling of the system dam body – foundation, for application of different constitutive laws, as well as for complex load influences.

4.2 Calibrating the previously done model, using some of the advanced features of SOFiSTiK software, it was possible to explain some of the results obtained by the measurements performed in the service period of 66 m high arch-gravity La Aceña Dam, in Spain. But, to explain the complete behaviour, and to answer all questions, it is necessary to do very complex model, with simulation of the real construction procedure, introduction of all joints between concrete blocks with non-linear constitutive law, application of all loads with the real loading history, and, in the same time, calibrating the model using the measured data. In our opinion, it is possible to fulfil these requirements, but this job requires much effort, and it is time consuming.

4.3 Despite the rapid progress of the computer techniques, to perform a three-dimensional stress-strain analysis of such a complex structure, as a dam is, it is not yet an easy task.
Figure 12. Vertical displacements in the main dam cross section caused by the dead load of the dam [mm], $Y = (0.0 \div 7.46)$ mm

Figure 13. Radial displacements in the main dam cross section caused by the dead load of the dam [mm], $R = (0.0 \div 3.78)$ mm
Figure 14. Incremental radial displacements from temperature load in the longitudinal dam section (for one increment, for the period 07.02.1990-24.04.1990) [mm], R= (0.0 ÷ 2.06) mm

Figure 15. Values of the radial displacements in the central dam cross section depending on the reservoir water height during the period of reservoir filling. The water heights are given in meters above the foundation, the displacement in mm.
Figure 16. Values of the radial displacements in the central dam cross section depending on the reservoir water height during the period of reservoir filling in 73 days. The water height and the displacements shared the vertical axes – respectively in m and mm.

Figure 17. Values of the vertical displacements in the longitudinal dam section, caused by the water pressure during the period of reservoir filling (see Fig. 4 and 5). The values are given in mm. – means displacement downward, + upward.
Figure 18. Values of the radial displacements in the longitudinal dam section, caused by the water pressure during the period of reservoir filling (see Fig. 4 and 5). The values are given in mm. + means displacement to downstream direction.