Analysing the elastic behaviour of an arch-gravity dam

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The analysis of the behaviour of an arch-gravity dam in Spain, described here, was carried out by seven independent engineering teams. The case under consideration corresponds to 'Theme A' at the Ninth International Benchmark Workshop on Numerical Analysis of Dams, which took place in Saint Petersburg in June 2007, organized by the ICOLD Committee on Computational Aspects of Analysis and Design of Dams. Among many lessons learned, those relating to the capabilities of the various models implemented, the differences observed in the numerical results, and the analysis of all sources of uncertainty are the main focus of this article.

As is currently widely accepted in dam engineering, the proper assessment of the behaviour and safety of these critical infrastructures requires the provision of an appropriate instrumentation system and a sound procedure for interpreting data, a realistic data management programme, and the implementation of numerical models Besides these very important tasks which have to be undertaken carefully in view of all the uncertainties involved, the behaviour of the dam itself is a source (sometimes the main one) of uncertainty The role of benchmarks, allowing for comparisons of results to be made using different constitutive models, computer codes, and so on, can be very relevant to an improved understanding and assessment of the uncertainties involved in cases like the one here presented. This case was formulated by the authors of the article, and corresponds to material designated as 'Theme A' at the Ninth International Benchmark Workshop on Numerical Analysis of Dams, in Saint Petersburg in June 2007, organized by the ICOLD Committee on Computational Aspects of Analysis and Design of Dams

The seven participants (P) in 'Theme A' contributed significantly to a better understanding of the capabilities of different codes and modelling strategies, as well as to an improvement in our understanding of the degree to which different ways of considering certain load hypotheses may affect the final results Also, as a result of their contributions, some key conclusions can be established regarding future modelling and site investigation needs, and also regarding the balanced programme of work required in both modelling and site investigation to minimize uncertainties and maximize the efficiency of investments The participants and their papers are given in Table 1, together with the reference (P1 to P7) assigned to each in this article

The formulators (the authors of this article) work at the Universidad Politecnica de Valencia and at the Canal de Isabel II (the water supply company of Madrid which owns the dam) They worked together on the document, 'First review and general analysis of the safety of the dam', with OFITECO (a Spanish engineering consulting firm specializing in dam engineering), the company responsible for that contract

1. Scope of the work

The structure studied, La Aceña arch-gravity dam, is operated by the 'Canal de Isabel II', the company in charge of Madrid's water supply system It is a symmetrical arch-gravity dam defined by a circular arch with a radius of 150 m for the upstream face and an aperture equal to 90 sexagesimal degrees. The crest

Table 1: Participants at the Workshop and their papers

Ref.	Title of contribution	Authors	[1]Company/Institute
P1	Analysis of the elastic behaviour of an arch gravity dam	Eduardo Echeverria[1] and Ignacio Escuder[2]	Univ. Politecnica de Valencia and OFITECO [2]Univ Politecnica de Valencia, Spain
P2	FEM analyses for the interpretation of the structural behaviour of La Aceña dam	Massimo Meghella and Piero Masarati	CESI Ricerca SPa Italy
P3	Analysis of the elastic behaviour of an arch gravity dam	T Bourgoin and C. Noret-Duchêne	Coyne et Bellier France
P4	Analysis of the elastic behaviour of La Aceña arch gravity dam	Gjorgi Kokalanov Ljubomir Tancev and Stevcho Mitovski	Civil Engineering Faculty Skopje, F.Y Rep of Macedonia
P5	Elastic analysis of an arch gravity dam behaviour using Merlin	Yoshinori Yagome[1] Yoshihisa Uchita[1] Victor Sauoma[2]	[1]Tokyo Electric Power Service Co Inc; Japan Univ of Colorado, USA
P6	Elastic analysis of an arch gravity dam using Diana	Gerd-Jan Schreppers and Giovanna Lilliu	TNO Diana BV, The Netherlands
P7	Numerical simulation of an arch gravity dam behaviour during operation	Adrian Popvici Radu Sarghiuta	Technical University of Civil Engineering of Bucharest, Romania

arch (without right and left abutments) is 235.6 m long and has a maximum height of 66 m The upstream face is defined by a cylindrical surface, and the cantilevers have a variable thickness with altitude The thickness of the crown cantilever ranges from 4 m on top to 28.8 m at the bottom. The dam (arch and abutments) is divided into 19 cantilevers, separated by joints.

The photograph below shows the structure from downstream.

The joints of the dam were sealed in February of 1989. A year later, during first impounding (February 1990 to May 1991), the instrumentation and monitoring system measured stresses and displacements in the dam body, the performance of the joints, and seepage. The analysis of data recorded during that period resulted in the following conclusions:

- The maximum displacement towards the abutments (tangential) was 3 75 mm, reached when the reservoir was at its maximum normal operating level
- Radial displacements (upstream-downstream) were in the range of 12 3 to 18 mm, with slight differences between the blocks. The maximum recorded relative movement in any of the joints was 1 88 mm
- The maximum seepage flow (40 l/min) also occurred at the maximum normal operating level The maximum measured through a single block was 1.7 l/min

Movements recorded after first impounding by four plumblines have consistently shown a range of radial displacement of approximately 40 mm That exercise was aimed at analysing the stress-strain behaviour of the dam, and interpreting the recorded displacement from 1999 to 2001 (the pattern of behaviour has remained constant since then), as related to water level and temperature time histories.

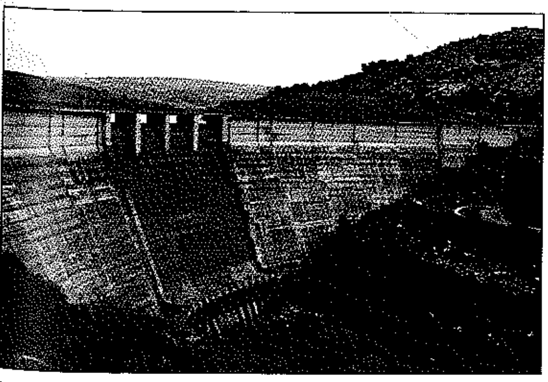
The seven participants were asked to justify their numerical tool (finite difference, finite element or any other type), their geometric model (cell sizes and location) and all constitutive models, before proceeding with the two parts of the problem:

(1) calculating displacements for a series of particular dates according to the given data in the block where the plumbline 3 is installed; and,
(2) varying any of the characteristics of the analysis to obtain values for displacements as similar as possible to those recorded by plumbline 3 (see location in Fig 1), followed by an engineering interpretation of the meaning of such changes in the calculation model

2. Summary of given data

The data provided to all participants in various electronic formats (dwg, excel, and so on) were related to the geometry of the dam, the geology of the foundation, the mechanical characteristics of the concrete and rock, temperature, and detailed records of movements relating to water levels from January 1999 to November 2001. Some examples of the data given are shown in the following Figures and Tables.

Fig. 2 shows the cross section of the dam at block No. 3, where pendulum 3 is located Fig 3 represents the geology of the foundation, and Fig 4 represents



View of the dam from downstream.

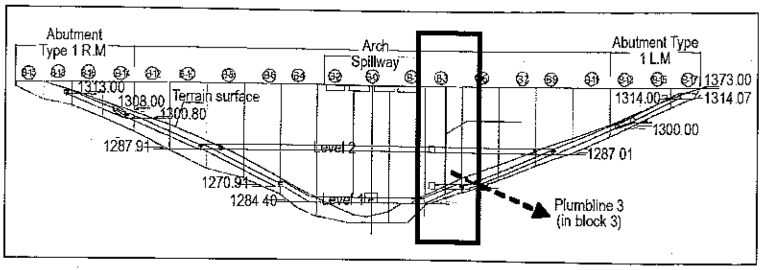


Fig 1. The location of plumbline 3

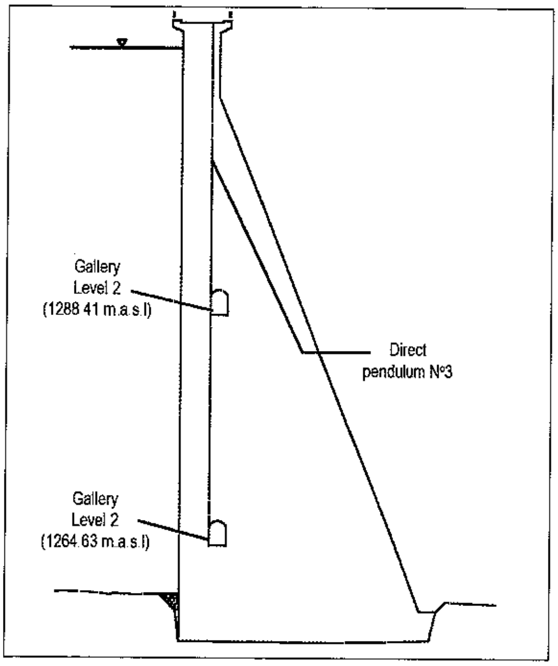


Fig. 2 Cross-section of the dam

Table 2: Static properties of the materials

Property	Foundation	Dam body
Specify weight	22 kN/m^3	23.6 kN/m^3
E (Young's Modulus)	10 000 MPa	20 000 MPa
Poisson's ratio	0.2	0.2
Coefficient of thermal expansion	0	10^{-5}°C^{-1}

Table 3: Historical monthly average temperatures near the dam site

Monthly temperature (°C)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	2 9	3 7	5 9	8 2	12.0	16 1	20 0	19 6	16.3	11 0	5.9	3 2

Table 4: Selection of temperature (°C) recorded on the dam's body during first impounding

Date Water level	7/2/90 Empty	26/4/90 el. 1280	26/12/90 el. 1293.6	31/01/90 el. 1296.5	22/03/91 el. 1311	04/05/91 el. 1316*
B3/DS/1283	8 7	10 2	8 9	7 8	9 8	11 3
B3/CE/1283	14 1	12 1	15 9	13 8	12.7	11
B3/CE/1309	3.8	7 8	3 9	2 8	5.3	8 3

* Full reservoir

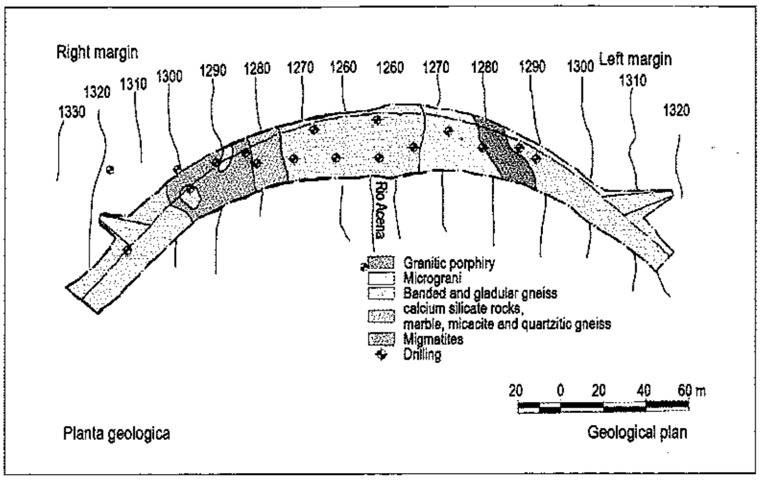


Fig 3 Geological characteristics of the foundation

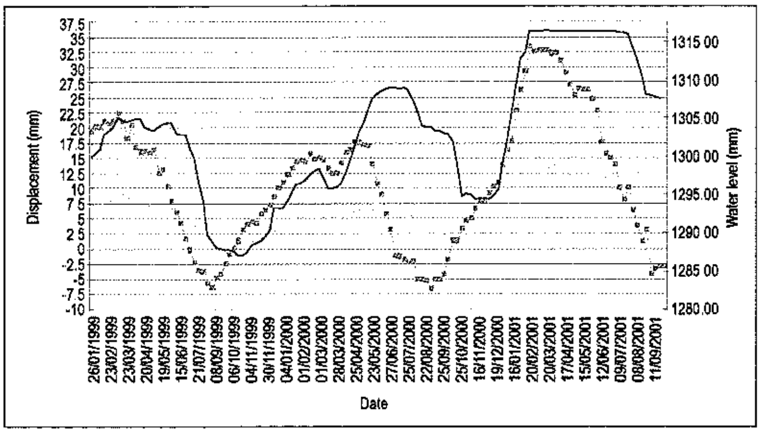


Fig. 4 Radial displacements from pendulum 3

the radial displacements measured by pendulum 3. In addition, Table 2 summarizes the static properties of the materials, Table 3 gives the historical monthly average temperatures near the dam site, and Table 4 is a selection of temperatures (°C) recorded on the dam body during first impounding.

Table 5: List of models and features

	Code	Deterministic model	Temperature model	Uplift
P1	SAP 2000	3D 53038 joints	Steady and linear	Yes
P2	CANT-SD	3D 53038 joints	Transient and with water temperature delay	No
P3	COQ-EF	3D 578 nodes	Stucky	-
P4	SOFiSTiK	3D 56638 nodes	Reproducing constuction records	-
P5	MERLIN	2D + 3D 4113 nodes	Steady and linear	Yes
P6	DIANA	3D 46304 elements	Transient	-
P7	ANSYS	2D + 3D 16772 elements	Transient	-

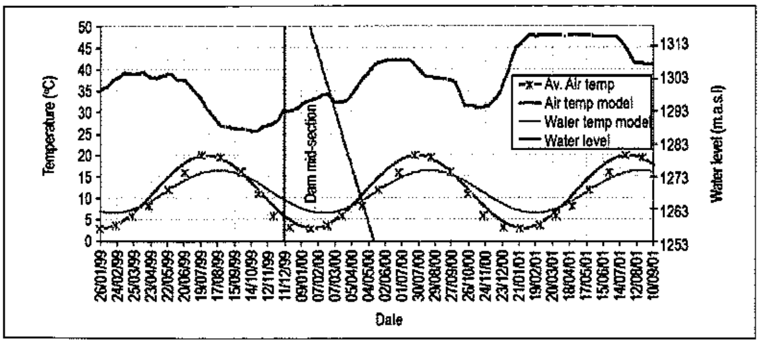


Fig 5 Example of input temperatures considered (P2).

As many participants remarked after analysing the given data, it was anticipated that the measurements provided might not be sufficient to obtain an accurate interpretation of the dam's behaviour. In particular, inadequacies in the following data were highlighted:

- Inflow/outflow seasonal regime of the reservoir (water temperatures to assign to the wet face of the dam model, and so on.)
- The influence of thermal radiation and daily air temperatures, given particular dam face exposures.
- The shortness of the observation period, which might compromise the ability to identify trends and repeatable situations
- The synthetic and generic nature of measurements relevant to the first impounding, particularly those relevant to joint displacements, such as the maximum joint 'movement' recorded was 1.88 mm, but no information on either the type of movement (opening or sliding) or the external conditions of its occurrence were provided. Also, the exact locations of the thermometers inside the dam body were not reported, making it difficult to identify the internal temperature patterns inside the body within the first impounding period.
- The eventual spatial variability of the elastic parameters of the dam and its foundation.

3. Characteristics of the models

Despite the fact that the formulators provided a particular model geometry generated from the software SAP2000, all participants used different codes, and many of them changed the features of the mesh. These main features are briefly commented on below:

- The P1 Solution is based on an analysis carried out with SAP 2000 NL V.7.0. The model was built based on 53 038 joints, 11 654 within the dam body, and 45 740 elements, 9327 within the dam body. The element used is defined as 'solid': an eight joint and six plane faces element. The size of the element has been defined by the need to be able to reproduce the thermal gradient through the thickness of the dam body. The width has been divided into five elements, thus implying an average size of 3 m for the element.
- P2 Contributors used their in-house developed FEM Code CANT-SD to analyse the linear-elastic FEM model of the dam-foundation system. The same FEM mesh as the one provided by the formulators was used for all analyses.
- P3 Team carried out the structural model with the help of the software COQEF, developed by Coyne et Bellier. COQEF models the dam using thick shell elements. The elements of the mesh are made up of rectangles defined by eight nodes and triangles defined by six nodes. Foundation elements are VOGT elements defined by a line with three nodes. To obtain a reasonable mesh size, only 578 nodes were selected to build the dam model.
- P4 used the computer software SOFiSTiK for stress-strain analyses. The finite element mesh was generated using SOFiSTiK automatic mesh generator. Three types of element were used to model the dam body: BRIC, QUAD and SPRING. The BRIC element is a general six-sided element with eight nodes. The plane element, QUAD, is a general quadrilateral element with four nodes. To simulate the behaviour of the interfaces of the dam (joints between concrete blocks, dam-foundation interaction), SPRING elements were also introduced. This complex modelling of the dam

resulted in a finite element mesh with 10 383 finite elements and 56 638 nodes.

- The P5 analysis was done using by the computer code MERLIN, which has the support of a window-based pre-processor, KUMONOSU, used to generate the 2D and 3D meshes. In the stress analysis, interface elements were used between the dam and the foundation (it was assumed that the monoliths were rigidly connected). For the most elaborate model (3D including joints), the total number of nodes was 33 871, with 16 163 being inside the dam body.
- P6 conducted the study using DIANA finite element software and Midas FX+ as DIANA pre-/post-processor. The dam body was initially schematized by a parameterized cylinder at the upstream face, a parameterized cone at the downstream face, and a parameterized ring at the top. Boolean operators applied to these parameterized geometrical shapes led to the final geometry of the dam body. The element size was set at 2 m for the elements in the dam, and at 25 m for the elements at the boundaries of the foundation. A tetrahedron mesh was generated automatically. The mesh contained 32 562 elements in the foundation, and 12 742 elements in the dam.
- P7 used the ANSYS computer code. The finite element back-analysis of the dam's behaviour was carried out in bi-(2D) and three-dimensional (3D) hypotheses. The dam body was discretized with the SOLID 45 element type, using four rows of elements across the width of the dam. This element is defined by eight nodes and is linear, isoparametric with incompatible modes included. The volume of rock foundation extended in every direction was about 1.5 Hd (Hd – dam maximum height), and was meshed with tetrahedral solid element (SOLID45). Finally, the total number of SOLIDS used in the 3D model was 16 772.

Concerning the load hypothesis, basic differences were found among the teams which did or did not consider uplift pressure as an acting force, and also among those which modelled temperatures in different ways (see Fig. 5 as an example provided by P2). Another difference factor was that some of the participants also carried out a statistical model to analyse the given recorded data. The main characteristics of the load hypothesis, together with the just- reviewed model features, are summarized in Table 5.

Fig. 6 provides an overview of all the models described above.

4. Comparison of numerical results

A comparison of the various numerical results obtained by the teams using the set of given parameters is given in Fig. 7 and Table 6.

Fig. 8 and Table 7 compare the best fit results achieved by the teams after they had carried out their sensitivity analyses.

5. Lessons learned from the sensitivity analyses

The main findings from the various participants who conducted a sensitivity analysis are summarized below.

- P1. Two parameters were varied to explain the behaviour of the dam better: the Young's Modulus of the concrete and taking into account, or not, uplift pressure. It was found that, when the Young's Modulus was divided by two, the results of the analy-

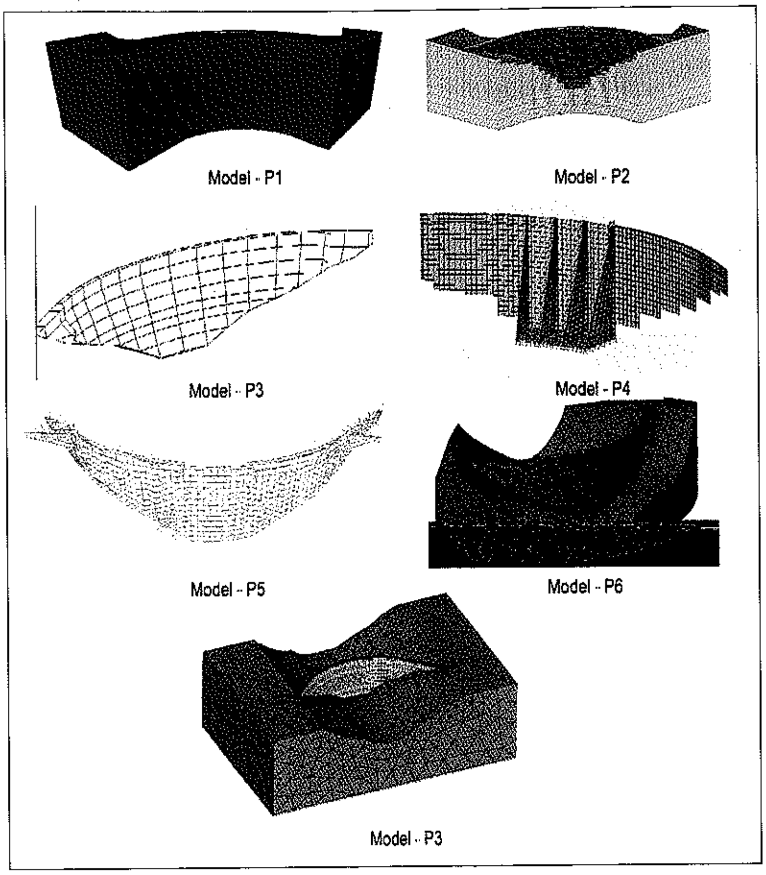


Fig 6. View of the models

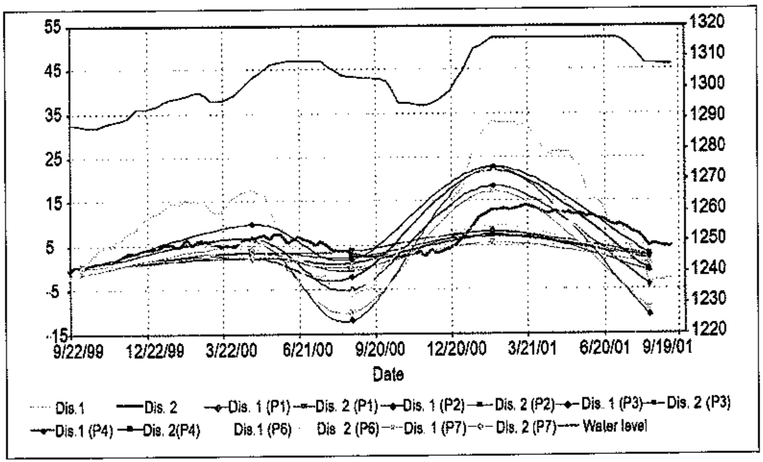


Fig 7. Comparison of the numerical results (using the given parameters)

Table 6: Numerical results (using the given parameters)

Date/Displacement (mm)	6/10/99	25/4/00	22/8/00	6/2/01	14/8/01
Recorded D Crest	0.00	17.50	-6.50	33.30	-4.40
Recorded D Gallery	0.00	6.30	3.00	12.90	4.60
P1 - Crest	0.00	6.30	-11.93	22.77	-10.85
P1- Gallery	0.00	3.61	-0.53	8.43	-0.75
P2 - Crest	0.00	10.00	2.00	23.00	3.00
P2 - Gallery	0.00	3.50	2.50	7.50	2.50
P3 - Crest	0.00	6.63	-4.97	18.58	-3.85
P3 - Gallery	0.00	3.18	3.90	8.11	2.92
P5 - Crest	0.00	2.20	-2.10	22.10	-0.70
P5 - Gallery	0.00	2.40	1.20	7.20	2.00
P6 - Crest	0.00	5.80	-5.50	21.90	-8.20
P6 - Gallery	0.00	3.10	0.80	9.50	1.40
P7 - Crest	-1.30	4.40	-10.10	17.40	-9.40
P7 - Gallery	0.00	2.20	0.10	5.70	0.90

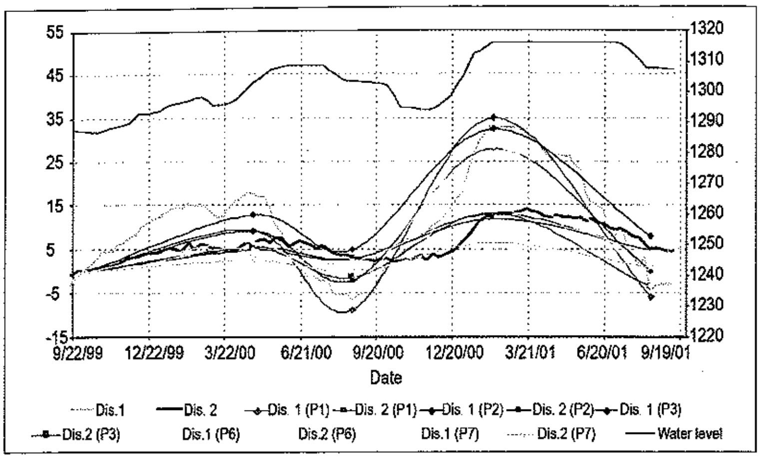


Fig 8 Comparison of numerical results (based on best-fit)

Table 7: Numerical results (best fit)

Date/Displacement (mm)	6/10/99	25/4/00	22/8/00	6/2/01	14/8/01
Recorded D Crest	0 00	17 50	-6.50	33.30	-4 40
Recorded D Gallery	0 00	6 30	3.00	12.90	4 60
P1 - Crest	0 00	9 43	-8.70	35.10	-5 72
P1- Gallery	0 00	5 36	-1.31	13.36	-3 42
P2 - Crest	0 00	13 00	5.00	32 50	8 25
P2 - Gallery	0 00	5 50	3.00	12 00	5 00
P3 - Crest	0 00	9.30	-2.02	28 13	0 23
P3 - Gallery	0 00	4 92	2.86	13.08	4 71
P6 - Crest	0 00	6 70	-3 20	28 40	-3 10
P6 - Gallery	0 00	3.80	2.30	13 70	4 20
P7 - Crest	-1.50	5.10	-11.60	20.00	-10 8 0
P7 - Gallery	0.00	2.60	0.10	6.60	0 90

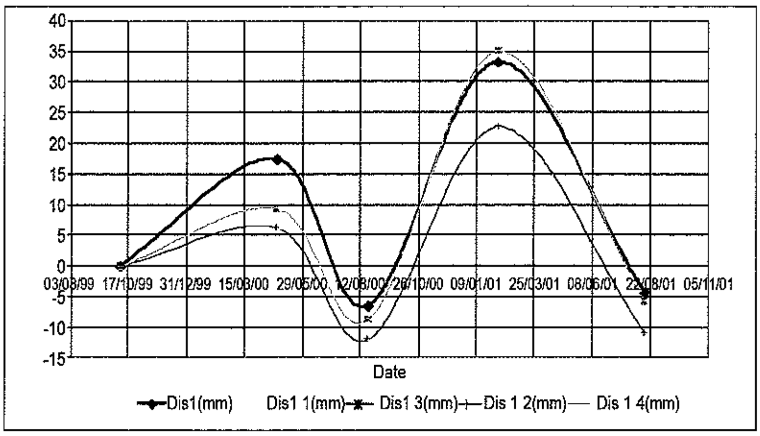


Fig 9 Results of the P1 sensitivity analysis

Table 8: Results of P1 sensitivity analysis

Date	Comparison of obtained displacements in the crest (mm)*				
	Dis 1	Dis 1.1	Dis 1 2	Dis 1.3	Dis 1.4
6/10/99	0.00	0.00	0.00	0 00	0.00
25/4/00	17/50	6/30	9.42	6.30	9.42
22/8/00	-6 50	-11.93	-8 69	-11.93	-8 69
6/2/01	33/30	22 77	35 09	22 77	35 09
14/8/01	-4 30	-10 85	-5 72	-10 82	-5 73

* Where:
Dis 1 (mm) = monitoring data from plumbline 3
Dis 1 1 (mm) = Dis 1 obtained using given data
Dis 1 2 (mm) = Dis 1 obtained without considering uplift effect
Dis 1 3 (mm) Dis 1 obtained using Young's Modulus divided by two
Dis 1 4 (mm) = Dis 1 obtained without considering uplift effect and using Young s Modulus divided by two

sis were quite similar to the real measurements; consequently, the variation of this parameter captures the structural behaviour of the dam. In addition, since the uplift effect was found not to be very significant, its influence on the final result was considered negligible. The results of these analyses are presented in Table 8 and Fig. 9.

- P2. This team altered the given stiffness, so that the Young's Modulus both of the dam and of its foundation was halved. In the results presented in Figs 10 and 11, it appears that some non-linear effects may have been activated in the upper part of the dam during particular periods (summer), which may be in accordance with measurements of joint movements recorded during the first reservoir impounding, and these indicate the need to include the joints' behaviour in a future model adequately.
- P3 This team determined the best set of coefficients corresponding to the smallest differences between the recorded and the calculated displacements by the least-squares method. The best simulation was obtained with a concrete Young's Modulus of Ec = 11 8 GPa, with a standard deviation equal to 1.8 GPa, a concrete Young's Modulus/rock Young's Modulus ratio unchanged (so that the rock Young's Modulus was defined by E_r = 5.9 GPa), and a coefficient of thermal expansion $\sigma = 9.5 \times 10^{-6}$ °C^{-1} with a standard deviation of 1.5×10^{-6} °C^{-1}. As a result, the dam demonstrates a more flexible behaviour than the behaviour corresponding to the assumed material mechanical properties. The real amplitude of movements of this arch-gravity dam can be modelled only with a large increase in the dam's flexibility (that is, with a considerable decrease in its concrete Young's Modulus); thus, a non-linear phenomenon may appear in the behaviour of the dam and may be responsible for this increase in flexibility.

Table 9 and Fig 12 present the results of calculations with these adjusted mechanical properties.

- P5. This team considered a series of variations for the Young's Modulus in 2D models: 5000 MPa, 10 000 MPa, and 20 000 MPa in the foundation; 15 000 MPa, 20 000 MPa and 5000 MPa in the dam. However, a 3D parametric study was not done and only two cases were analysed. Relative displacements of pendulum 3 for this analysis are shown in Fig. 13.

Case 01_01 corresponds to Young's Modulus of dam = 15 000 MPa and Young's Modulus of the foundation = 5000 MPa, while Case 02_02 corresponds to Young's Modulus of dam = 20 000 MPa and Young's Modulus of foundation = 10 000 MPa.

An additional analysis was carried out for a range of concrete coefficients of thermal expansion from 0 7 to 1.3×10^{-5}/oC, while keeping the other parameters equal to those of Case 01_01. The results are shown in Fig. 14. It is worth noting that an increase in the coefficient of thermal expansion results in little change in the relative displacement from the intermediate to the lower gallery. It is suspected that this is because of the assumed constant water temperature on the upstream face.

- P6. To achieve a better fit for the measured displacements, some parameters of the model were varied as follows: a lower stiffness of the foundation was considered; the temperature of the dam was assumed to be constant throughout the year in the core of the dam; and, the water temperature was varied throughout the year.

First, the stiffness of the foundation was assumed to be equal to 0.2 GPa. In this case, the calculated relative horizontal displacements showed reasonable agreement with the measured target displacements. The largest differences occurred at the load situation corresponding to 25/04/2000. These differences may have been caused by an erroneous assumption concerning the water temperature or the ambient temperature. For example, the month of April in 2000 may have been colder than the average over the years, as is considered in the analysis.

The corresponding calculated horizontal displacements are summarized in Table 10.

Second, the temperature in the core of the dam body was assumed to be constant and equal to 11° C throughout the year. The core of the dam body was defined as the portion of the volume at a distance greater than 3 m from the outer surfaces of the dam. In this case, the temperature was assigned to all the nodes falling within the core of the dam body, while the temperature at the nodes falling outside were determined from the steady-state thermal analysis. As can be seen in Table 11, the differences between these results and results obtained with the original model are small, especially for the relative displacement between the bottom gallery and the crest of the dam.

Third, the water temperature was considered to be 14°C at the load situations on 06/10/1999, 22/08/2000 and 14/08/2001 (in the summer or close to summer), and 5°C at the load situations on 25/04/2000 and 06/02/2001 (in the spring or in winter). Nevertheless, the assumption of variable water temperature throughout the year does not lead to a better fit of the measured displacements. The calculated displacements are given in Table 12:

- P7. To reduce the difference between recorded/computed displacements, the stiffness of the dam-foundation system was reduced, using new material mechanical characteristics to the lower limit usually accepted for this type of dam. The new mechanical characteristics are shown in Table 13. The displacements computed with the new material mechanical characteristics are given in Table 14. However, the new results did not reach the recorded displacements, except for Dis1 on 22.08.2000 and 14.08.2001. The performance of the computed displacements versus the recorded ones would be improved by taking into account a better evaluation of the dam body temperatures.

6. Some lessons learned by statistical modelling

Statistical models, which correlate structural behaviour variables and external factors, have been used increasingly in recent years. Their use is not as complex as deterministic models, making forecasting of future behaviour easier for various load situations. They are also very useful for checking the consistency of data or identifying abnormal values of any variable values over time.

Only participants one (P1) and three (P3) used statistical modelling, and the main characteristics of these models together with relevant knowledge gained through such modelling are given next.

P1 first used software, AUSMODEL (developed by OFITECO), which calculates the set of empirical relationships which explain the so-called 'control variable' readings better (for example, movements, pore pressures, strains, seepage, and so on) in terms of time (from a chosen origin), head water, temperature and rainfall.

Effects on the control variable related to time (irrecoverable), or to any of the other external variables, can be isolated. The programme also allows for identification of 'unexplained' behaviour and its tendency. The results, as given in Fig. 15 for displacements from the foundation to the gallery, did not show irrecoverable movements.

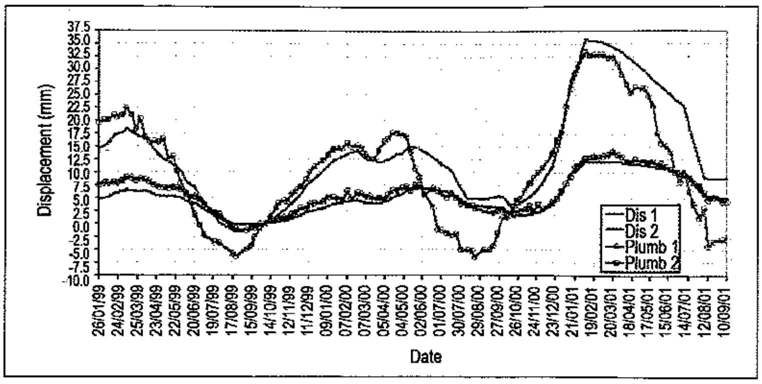


Fig. 10 Displacements calculated for pendulum 3 (both E divided by 2) Dis1 (from the lower gallery to the crest) and Dis 2 (from the lower to the intermediate gallery).

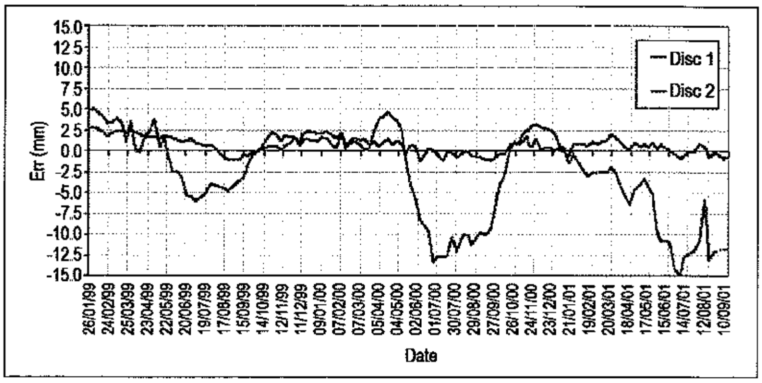


Fig. 11. P2 Error for pendulum 3 (module E divided by 2). The difference between measured and calculated displacements (Dis1 and Dis 2).

In addition, as another way to estimate how external variables such as water level and temperature influ-

Table 9: Results of P3 sensitivity analysis

Date	Water level (el.)	Air temp (°C)	Dis 1 recorded (mm)	Dis 1 calculated (mm)	Dis 2 recorded (mm)	Dis 2 calculated (mm)
6/10/99	1287.4	9.82	0.00	0.00	0.00	0.00
25/4/00	1303.09	7.57	17.50	8.32	6.30	4.18
22/8/00	1303.61	19.36	-6.50	-3.48	3.00	2.02
6/2/01	1316.2	5.80	33.30	25.27	12.90	11.12
14/8/01	1307.73	20.16	-4.30	-1.41	4.60	3.52

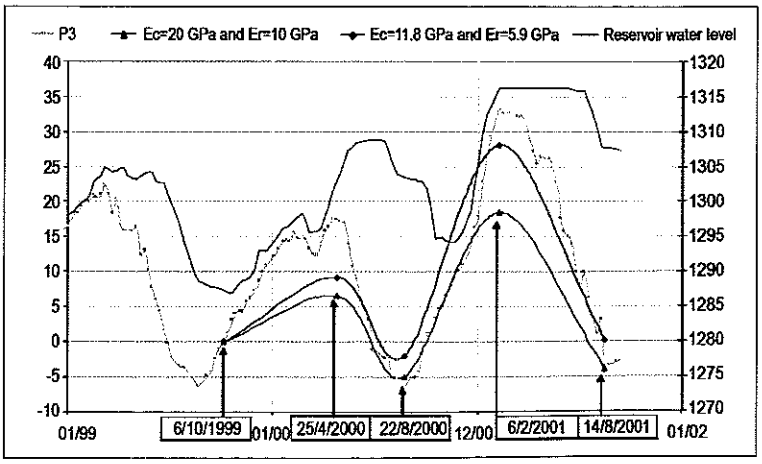


Fig. 12 Results of the P3 sensitivity analysis.

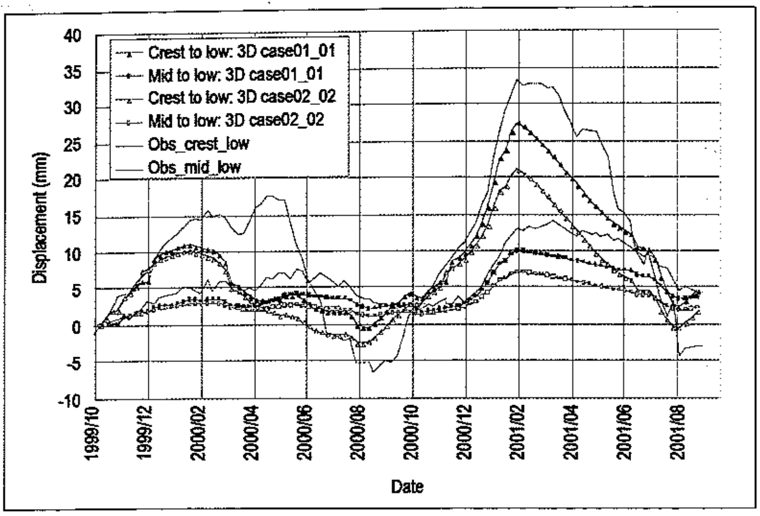


Fig 13. Relative displacements of pendulum 3D

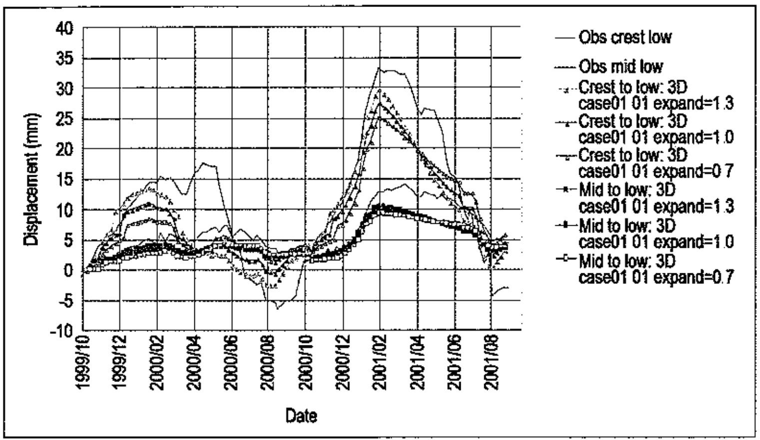


Fig 14. P5 Relative displacements (3D) for the parameter of the coefficient of thermal expansion

Table 10: P6 Relative horizontal displacements (in mm) between the bottom gallery and the crest (D1) and between the bottom and middle galleries

Date	Target (D1)	Target (D2)	Analysis (D1)	Analysis (D2)
6/10/99	0.0	0 0	0 0	0 0
25/4/00	17 5	6 0	6 7	3 8
22/8/00	-5 0	3.0	-3 2	2.3
6/2/01	32.0	13.0	28 4	13.7
14/8/01	1 0	7 5	-3 1	4 2

Table 11: P6 Relative horizontal displacements (in mm) between the bottom gallery and the crest of the dam (D1) between the bottom and middle galleries

Date	Target (D1)	Target (D2)	Analysis (D1)	Analysis (D2)
6/10/99	0.0	0 0	0 0	0.0
25/4/00	17.5	6 0	5.6	2.8
22/8/00	-5.0	3.0	-5.4	1 1
6/2/01	32.0	13.0	21.3	9.0
14/8/01	1 0	7 5	-7.7	1.9

Table 12: P6 Relative horizontal displacements (in mm) between the bottom gallery and the crest (D1) and between the bottom and middle galleries

Date	Target (D1)	Target (D2)	Analysis (D1)	Analysis (D2)
6/10/99	0.0	0.0	0 0	0 0
25/4/00	17 5	6.0	2 7	2 5
22/8/00	-5 0	3.0	-4 6	0 3
6/2/01	32.0	13.0	18.7	9.0
14/8/01	1.0	7.5	-7.2	0 1

Table 13: P7 New material mechanical properties considered

Property	Foundation	Dam body
E (Young's Modulus)	7000 MPa	18 000 MPA
Poisson's ratio	0 2	0 2
Coefficient of thermal expansion	0	$1\ 2 \times 10^{-5}\ °C^{-1}$

Table 14: Results of P7 sensitivity analysis

Date	Computed 3D analysis, new material mechanical characteristics	
	Dis 1 (mm)	Dis 2 (mm)
6/10/99	-1 5	0 0
25/4/00	5/1	2 6
22/8/00	-11.6	0 1
6/2/01	20 0	6 6
14/8/01	-10 8	0 9

ence the structural behaviour of the dam, three statistical analyses were carried out with 'Statgraphics plus V 5 0' (water level and temperature separately and coupled) The results of the regression analysis of the joint influence of water level and ambient temperature on the displacements from foundation to crest (Dis 1) are defined by the equation which fits the model:

$$\mathrm{Dis1} = 207864.0 - 318\ 952 w_{lev} + 0\ 122366 w_{lev}2 - 5.10044 \mathrm{Temp} + 0\ 739249 \mathrm{Temp2} - 0\ 0555234 \mathrm{Temp3} + 0\ 00137341 \mathrm{Temp4}$$

where 'w_{lev}' is water level and 'Tem' is external temperature

Since the P-value in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99 per cent confidence level. The R-Squared statistic indicates that the model as fitted explains 84 1215 per cent of the variability in Dis1. It is noteworthy that the coupled effect of thermal and hydraulic loads explains a significant amount of the movement of La Aceña dam However, the remaining 15 per cent should be explained by other variables

P3 applied the HST method (developed by Coyne et Bellier) for the three displacements recorded by pendulum 3: horizontal displacement from the lower gallery to the crest, (Dis1); horizontal displacement from lower to intermediate gallery, (Dis2); and horizontal displacement from the intermediate gallery to the crest (Dis3).

For the first displacement, 343 observations were available between 03/01/1996 and 11/09/2001. For the others, only 130 observations were available, between 01/01/1996, and 11/09/2001 CONDOR software (developed by Coyne et Bellier) calculates the best model for each displacement, using hydrostatic functions (Z, Z2, Z3, and Z4), seasonal functions (cosS, sinS, sin2S and sinS × cosS), temporal functions (T, exp. (-T) or the discontinuous step function. The best models were composed with one 'H' function Z and all four seasonal 'S' functions For all the models, the temporal functions did not improve the interpretation of dam movements. Specifically:

- The residual standard deviation for the displacement Dis1 is equal to 2 8 mm, which corresponds to a correct explanation coefficient of 75 5 per cent. The models for the other displacements, Dis2 and Dis3, have residual standard deviations, as high as 0 8 mm and 2 4 mm respectively,. Their explanation coefficients are equal to 78 per cent and 70 5 per cent.

- The influence of the seasonal effect on Dis1 is 27 mm, with the maximum at mid-August and the minimum at the beginning of February The influence of the hydrostatic effect is 44 mm when the reservoir water level varies from el. 1253 (empty) to el. 1316 (full).
- For Dis2, the influence of the seasonal effect is 3 7 mm, with the maximum at the end of August and the minimum at the beginning of March. The influence of the hydrostatic effect is 22 mm for the same range of reservoir water level as Dis1.
- The influence of the seasonal effect on Dis3 is 20 mm, with the maximum at the beginning of August and the minimum at the beginning of March The influence of the hydrostatic effect is 18 mm.

On the other hand, CONDOR detected an anomaly in the horizontal displacement from the lower gallery to the crest (Dis1), which occurred between 18/08/1999 and 28/09/1999, inclusive. The explanation for this phenomenon may be that the reservoir water level was very low during the summer of 1999. The water level elevation went down from 1299.65 to 1288.05 between 06/07/1999 and 08/08/1999 As a result, the dam recorded an important displacement in the upstream direction, probably as a result of the thermal effect. After November 1999, the reservoir level rose to a usual elevation, and the corrected value of Dis1 became normal again

6. Conclusions

All independent teams have reached the series of conclusions given below. Alhough they are, in a sense very similar, some particular points which enrich the overall conclusions are presented here

- P1. Although the statistical analysis of the input data shows that 85 per cent of the movement of the dam can be explained by the combined action of water pressure and temperature, the results of the analysis emphasize the fact that there must be other factors influencing the mechanical behaviour of the dam. In particular, the numerical model represents well the trend in the actual movements of the dam, but the real magnitude is captured only if the stiffness assumed for the concrete is reduced.
- P2. The main conclusion to be drawn from the comparison of numerical results and recorded data indicates the need to ensure that joint behaviour is included in a future FEM model. Such a simulation might be approached gradually, starting, for instance, by considering that the central dam blocks are free to move as independent cantilevers, and modelling the actual non-linear effects of the structural joints with appropriate FEM elements. A comparison of calculated and measured behaviour should include the joints' relative displacements, if the relevant measurements are available. If not, monitoring them in terms of opening, sliding and extension is strongly recommended. Finally, in cases where the comparison is still not considered acceptable, the assumptions made on the external temperatures models should be reviewed critically.
- P3. After carrying out statistical modelling in advance to check for abnormalities in the records, the structural model provided an explanation of the non-linear behaviour of the dam It could not, however, be used alone to describe the non-linear phenomena, possibly because of the opening of joints under exceptional hydrostatic loads, and the high deformability of the foundation rock Monitoring and a precise investigation into the displacements of the joints and foundation will be necessary to complete and perfect the understanding of non-linear response of the arch-gravity dam.

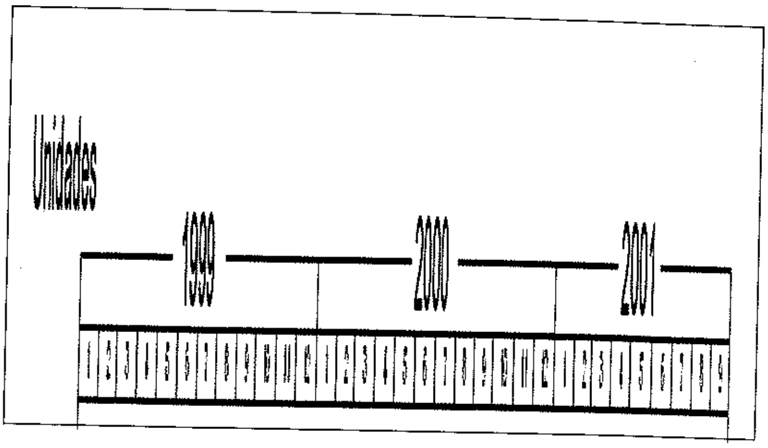


Fig. 15. Model fit by AUSMODEL to movements from the foundation to the gallery

- P4. To explain the dam's complete behaviour and to answer all questions, it is necessary to undertake very complex modelling, including simulation of the real construction procedure, introduction of all joints between the concrete blocks with non-linear constitutive law, application of all loads with the real loading history, and, while at the same time, calibrating the model using the measured data. In our opinion, fulfilment of these requirements is possible, but the process requires a major investment of time and effort.
- P5. The two main conclusions are: (1) 2D analysis captured the dam response almost exactly, except for the time period 04/2000 and 10/2000, when it appeared that the arch effect was clearly operating; and, (2) results for the relative displacement from the intermediate to the lower gallery in 2D analysis indicated the need for a smaller elastic modulus Improved results could be obtained with the availability of an exact history of the air temperature, the dam body temperature (including summer values), and more information regarding local radiation.
- P6. Regarding the displacements measured in the dam, a major role was played by the effect of thermal expansion, which dominates the effect of hydrostatic loading. Temperature distribution in the core of the dam body has a relatively minor effect. A reduced stiffness of the foundation results in a better fit of the measured displacements, which can be reasonably well predicted even under the simplistic assumptions of linear elastic material behaviour. In any case, better results can be expected when more detailed information concerning the input parameters are available, such as the real profile of the ground surface, foundation stiffness, development of water temperature, and environmental temperature.
- P7. The computed displacements in the 3D finite element model using the ANSYS computer code and mechanical/thermal material characteristics recommended by the formulator are generally smaller than the corresponding displacements recorded at pendulum 3. The computed displacements in the 2D model are closer to the corresponding displacements recorded at pendulum 3, than those computed in the 3D model. After improving the results by diminishing the stiffness properties, it can also be concluded that data on the dam body temperatures are a very coarse approximation of the actual temperatures.

In summary, despite all the various assumptions, load hypothesis, models, and so on, the conclusions of almost all participants include the following:

- Either the dam body and/or foundation rock may be less stiff than expected
- Temperatures could not be modelled properly with the available data
- Non-linear effects, particularly sliding in the joints, may be influencing the behaviour.
- Irrecoverable movements have not been identified

Finally, the authors (formulators) wish to note that Canal de Isabel II, in accordance with the recommendations of the ‘First Review And General Analysis Of The Safety Of The Dam’ [Ofiteco, 2004], is undertaking an extension of the investigation of this dam, by providing topographical control of the movements and by drilling the dam core and the foundation to gain information on the mechanical parameters of the materials

The results of the Benchmark Workshop strongly support the need for, and efficiency of both actions. ◊

Acknowledgements

Special thanks are given to all the participants and their Companies or institutions for their valuable and major efforts, and to the Canal de Isabel II, which provided a very interesting case study. Also, special thanks to Dr Glagovski, as the responsible representative of the Benchmark organization, and to the other members of the ICOLD Committee on Computational Aspects of Analysis and Design of Dams (chaired by Mr Alain Carrère and vice-chaired by Mr Guido Mazzà). Finally, the first author has been able to participate in the Benchmark in the context of the project “Aplicacion del analisis de riesgos a los programas de conservacion, mantenimiento, rehabilitacion y gestion de la seguridad de presas y embalses. BIA2006-08948” sponsored by the Spanish Ministry of Education and Science (30 per cent) and FEDER funds of the European Union (70 per cent)

All seven individual papers with the contributions from the participants will be ready by the end of 2007, as part of the “Proceedings on the Ninth International Benchmark Workshop on Numerical Analysis of Dams (Russia, 2007)

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