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Structural safety evaluation of Karun III Dam and calibration of its finite element model using instrumentation and site observation

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ABSTRACT

In the present paper, a comprehensive finite element model of Karun III double curvature arch dam is calibrated based on the micro geodesies measurements and instrumentation. Thermal properties of concrete are obtained by transient thermal analysis and the results are compared with those obtained from thermometers. Thermal analysis features include air temperature, water layers temperatures, and the solar radiation on the exposed faces. Structural calibration features include thermal distribution within the dam body, dam self-weight, hydrostatic pressure, and silt load applied on the model of dam–reservoir–foundation system. Finite element model calibration provides updated information related to the current dam status and can be used for further safety evaluations.

Introduction

Arch dams are one of the most important infrastructures in which their failure may leads to catastrophic economical consequences on downstream facilities as well as loss of life. Periodic performance evaluation of concrete arch dams under the updated environmental conditions is an important issue in safe operation during their long life. The real behavior of an arch dam should be evaluated considering parameters like reservoir water and foundation rock effects, contraction joints behavior, thermal loads, dam-foundation-reservoir interaction and so on. Preparing an efficient and accurate numerical model which is capable of estimating the responses of concrete arch dam is of importance for future investigations. Developed numerical model should be calibrated with the data recorded in the dam site.

Different procedures have been proposed for finite element model calibration in both static and dynamic conditions. Daniell and Taylor [1] used ambient vibration test on a gravity dam to measure its modal properties. Excitation was provided by wind, by reservoir water cascading down the spillweir, and by the force of water released through outlet-pipes. They found that the ambient vibration testing can be used as an alternative to forced vibration testing when only the modal properties of a dam are required. Ghannat et al. [2] conducted a set of experiments on Longyangxia Dam by exciting the dam using large explosive charges in shallow water upstream from the dam. Dam displacement and acceleration responses were compared at the dam base. It was found that there is good agreement between the measured and computed responses. Alves and Hall [3] conducted a set of system identification studies to find the properties of the first two modes of Pacoima Dam using data gathered during 13 January 2001 earthquake. Sevim et al. [4] calibrated the finite element model of Berke

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Dam using operational modal testing. They used enhanced frequency domain decomposition technique in order to estimate natural frequencies, mode shapes and damping ratios. Hariri-Ardebili et al. [5] calibrated 3D finite element model of Dez Dam in thermal and static conditions using instrumentation data. Also, the static safety of the dam was investigated under various load combinations using the updated material properties.

In the present paper, a comprehensive finite element model of Karun III Dam is calibrated utilizing the data obtained from the instruments. Thermal properties of concrete are computed by transient thermal analysis and the results are compared with those obtained from thermometers. Concrete mechanical properties are also obtained by calibration of the structural model of the dam-foundation-reservoir system considering thermal distribution, dam self-weight, hydrostatic pressure, and the silt load. Finally, the safety of the dam is evaluated under the updated material and loading conditions.

Karun III Arch Dam

Karun III Dam is a 205 m high double curvature arch dam which is located within 610 km of Karun river mouth, in Khuzestan Province in Iran. The dam was commissioned in 2005. General characteristics of the dam are summarized in Table 1.

Thermal analysis and calibration

All meteorological data were gathered from Ize weather station near the dam site. Actual temperature values recorded in Ize station was used with the average daily temperature resolution. Weather temperature variations in Ize station is shown in Fig. 1(a). Upstream boundaries of dam body are under two different weather environments, i.e. water and the air temperature. The boundary between two environments is continuously fluctuating because water elevation changes in the reservoir. Variation of the water level is shown in Fig. 1(b). Upstream boundary temperature at various depths depends on its distance from the water surface and does not follow a fixed pattern at a particular time due to the fluctuating water level. In the current study, Bofang method [6] is utilized to obtain the distribution of temperature along the depth of the reservoir at a specific time.

Fig. 2(a) shows the downstream view of the all installed instruments within dam body. Totally, 386 embodied thermocouples were used to measure and control the temperature variation of mass concrete due to hydration and post-cooling stages. Only few thermocouples have remained sound after the installation and currently record concrete temperatures. Totally, 110 thermometers in 21 stations in the dam body are used in order to record temperatures on the upstream and central part through the block thickness at the installation level. Fig. 2(b) shows the location of thermometers in three central blocks of the dam schematically. Thermal characteristics of the mass concrete, which were used in numerical model for thermal transient analysis, are presented in Table 2.

In the first step, the recorded temperatures by the thermometers are assigned to the nearest nodal point on the model by geometrically interpolation and the actual temperature history of the nodes are plotted. Determination of the primary temperature distribution in dam body is the most important issue in thermal analysis. Due to continuation of concreting in 2004 and also concrete hydration and post-cooling effect, beginning of the year 2005 is selected as starting time of the thermal calibration procedure. The conventional method in determination of the initial temperature is assigning annual average temperature to the all nodes and then conducting the time-dependent analysis on finite element model to reach a stability response during the transient analysis. With this method the initial temperature is calculated to be 18 °C. After calculation of the initial temperature at the beginning of the year 2005, thermal analysis is repeated for the years 2005–2007 and the results are compared with the actual recorded values. The one day time step is used for thermal analysis. The daily average air temperature and reservoir levels are applied to the dam. Three blocks of the dam are selected as benchmarks which are No. 13 (middle block), No. 9 and No. 17 as seen in Fig. 2(b). Also, Fig. 3 shows the temperature variation in the central thermometer for blocks No. 9 and No. 13 at the highest and lowest levels. As seen, there are acceptable consistencies between the calculated and recorded temperatures in the considered locations.

Table 1
Main characteristics of Karun III Dam.

Crest level	850 m asl*
Maximum height above the foundation	205 m
Crest length	462 m
Crest width	5.5 m
Dam thickness at the base	29 m
Concrete volume (body and spillway)	1.3 Mm^3
Normal operation level	845 m asl
Minimum operation level	800 m asl
Reservoir capacity in normal operation level	2970 Mm^3
Reservoir capacity in minimum operation level	1250 Mm^3

* Above sea level.

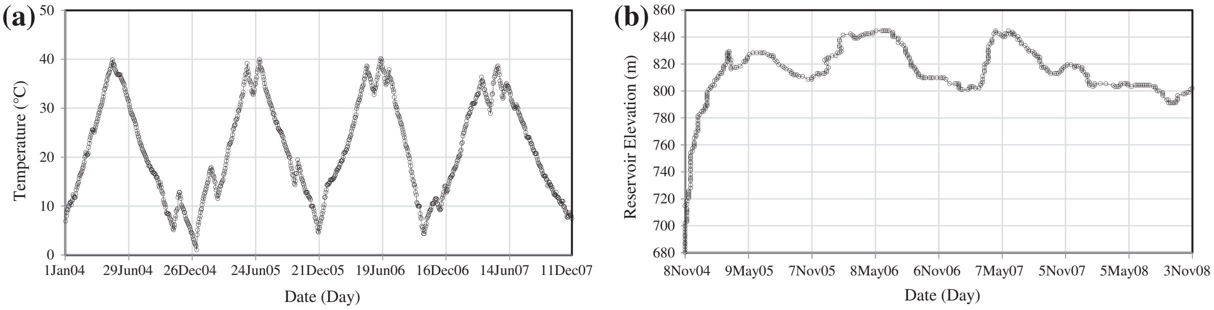

Fig. 1. (a) Weather temperature variations in Ize station and (b) variation of reservoir water level.

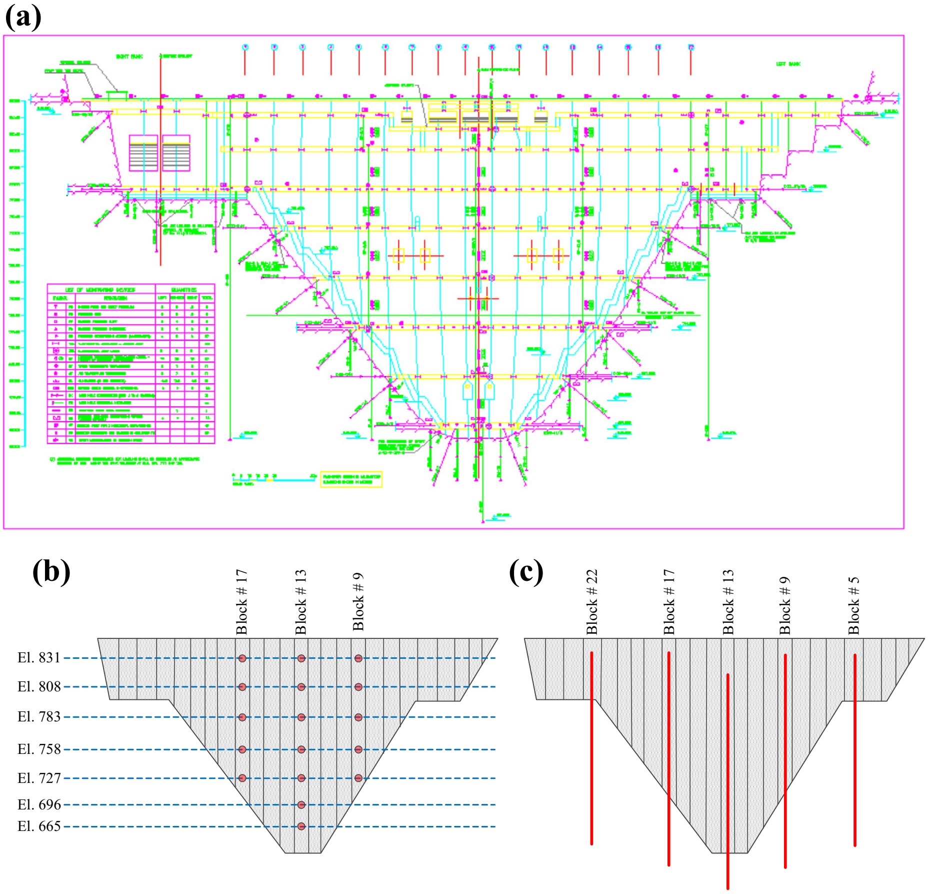

Fig. 2. (a) Downstream view of the installed instruments in Karun III Dam, (b) schematic view of the embodied thermometers locations, and (c) schematic view of pendulums locations.

ANSYS finite element software [7] was used for thermal analysis considering thermal distribution in the dam body under environmental variations such as air and reservoir temperature and the effects of solar radiation. The provided finite element model should have adequate accuracy for thermal loads sensitivity and be able to capture all the small changes in loading condition. Accordingly, sensitivity analysis was performed on elements size and number both in thickness and height of the dam. The final finite element model consists of 9800 eight-node elements for thermal analysis. In this model, the dam is divided into five layers through the thickness and the foundation modeling is ignored in thermal analysis.

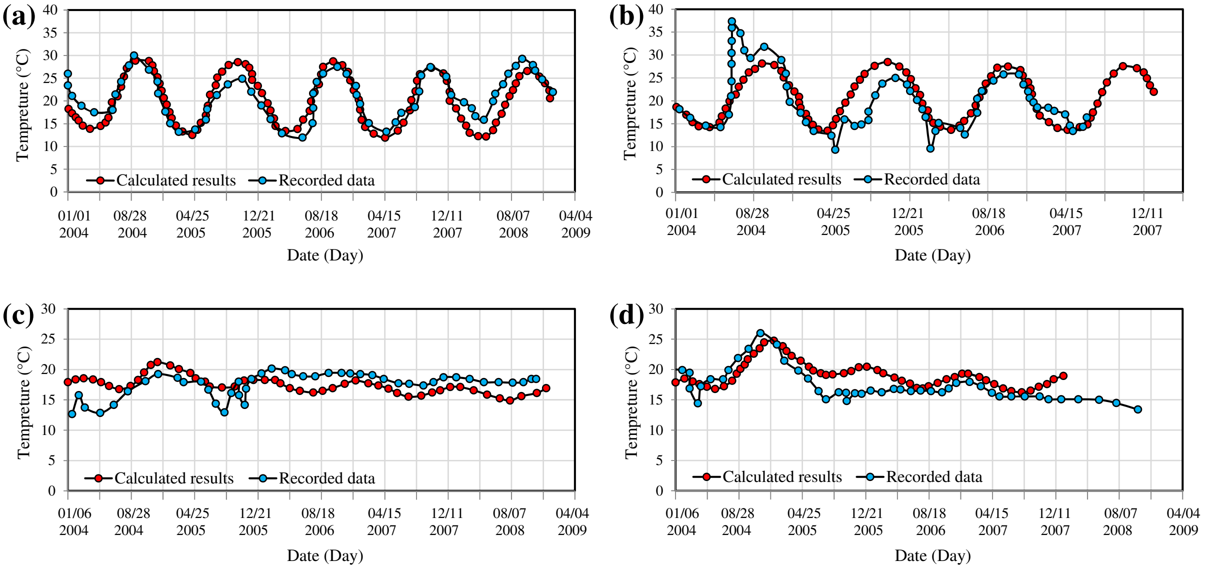

Fig. 3. Comparison of the calculated results and thermometers record at (a) level 831 m, Block No. 9, (b) level 828 m, Block No. 13, (c) level 726 m, Block No. 9, and (d) level 726 m, Block No. 13.

Table 2
Parameters used in thermal transient analysis.

Item	Common range	Present model
Specific heat [J/(kg/°C)]	870–1088	879
Thermal conductivity [J/m/day/°C]	160,000–300,000	276,000
Convection coefficient [W/m^2/K]	Related to wind speed	1,336,000
Solar absorption	0.5–0.65	0.6
Emissivity	0.62–0.9	0.88

Structural analysis and calibration

There are eight direct and five inverses pendulums in Karun III Dam that have been installed in blocks No. 5, No. 9, No. 13, No. 17 and No. 22, as shown in Fig. 2(c). Calibration procedure for static response was conducted based on the load combinations represented in Table 3 by comparing the data resulted from analysis and the measured displacement using various pendulums at the considered time.

Structural finite element model of the dam, foundation and the reservoir (Fig. 4) were provided based on the as-built drawings and calibrated utilizing data recorded at several stations of the plumb-lines embodied in the mass concrete corresponding to the times represented in Table 3.

Primary point coordinates of the dam body, horizontal and vertical arch attributes were used to model the body and the main appurtenant structures like the spillway, the left and the right thrust blocks. Accordingly, the reservoir length was considered about 3.5 times of the dam height in the upstream direction. It is worth mentioning that the reservoir was modeled with the prismatic fixed section along its length. According to the particular topography of the region, the surrounding foundation rock was extended twice of the dam height in all directions.

Eight-node solid elements and eight-node fluid elements were used for modeling the dam body, appurtenant structures, foundation medium and the reservoir water. Pressure at the reservoir free surface was assumed to be zero. In the numerical model, there are 3958 elements in the dam body and appurtenant structures, 21848 elements in the foundation medium,

Table 3
Considered time for structural finite element model calibration.

No.	Date	Water level	Consideration
1	21 Apr 2007	844.78	Maximum water level and moderate ambient temperature
2	05 Dec 2007	817.02	Moderate water level and moderate ambient temperature
3	06 Sep 2008	790.15	Minimum water level and warm ambient temperature

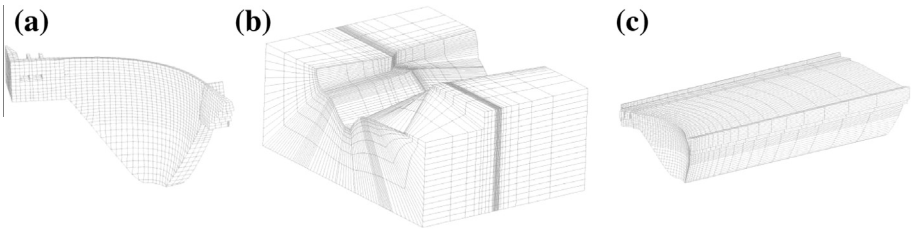

Fig. 4. Finite element model of (a) the dam body, (b) the foundation rock, and (c) the reservoir medium.

Fig. 5. Stage construction of the dam body.

and 2302 elements in the reservoir. Also, 1684 three-dimensional node-to-node contact element [7] were used for modeling the contraction joints. In the numerical model of Karun III Dam, four stage constructions were considered for applying the self-weight of the dam body as shown in Fig. 5. At the design phase, concrete with the compressive strength of 35 MPa was used for the outer face of the dam body while the concrete in the inner parts has the compressive strength of 25 MPa.

The utilized three-dimensional contact elements can support compression in normal direction to the plane of interface and shears in the tangential direction. Although, normal and tangential stiffness have some effects on each other during movement of adjacent planes, in the present study it is assumed that they act independently. Generally, determination of exact values for normal compression (K_n) and tangential (K_s) stiffness of contact elements is impossible because there are many unknown parameters in interaction and contact of two surfaces. So, for determining the best values for K_n and K_s, a large range of values were assumed for them and sensitivity of the results for these parameters were investigated. Fig. 6 shows opening at the crest of the crown cantilever for various normal stiffness values. As seen, considering 300 GPa/m for normal stiffness leads to opening about 1 mm at the crest which confirms the results obtained from joint-meter at this level. In addition, tangential stiffness was supposed to be 30 GPa/m (10% of the normal stiffness), which is reasonable value in concrete arch dams.

For considering the correspondence between the theoretical and measurements, the second load combination as presented in Table 3 was taken as the reference one. Consequently, the results of the structural analyses corresponding to the first and third load combinations (based on Table 3) were used for model verifications. Fig. 7 shows the results obtained from the conducted analyses and the comparison with the measurements along the considered blocks. As seen, there is a good agreement between the analytical and measured results. Considering the conducted analysis in the calibration procedure, typical values in the similar dams, and engineering references, the material properties for concrete and foundation were obtained as summarized in Table 4.

Static safety evaluation

For evaluation of the static safety of the dam, load combinations specified by FERC [8] were considered as governing combinations. Table 5 represents these load combinations which are based on the operating data available at the dam site. It

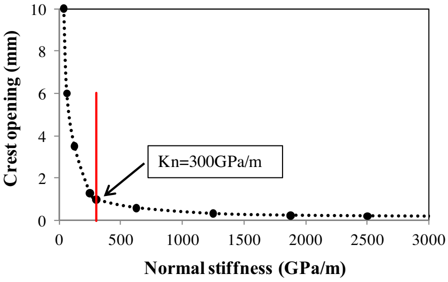

Fig. 6. Stiffness sensitivity analysis of vertical joints in Karun III Dam.

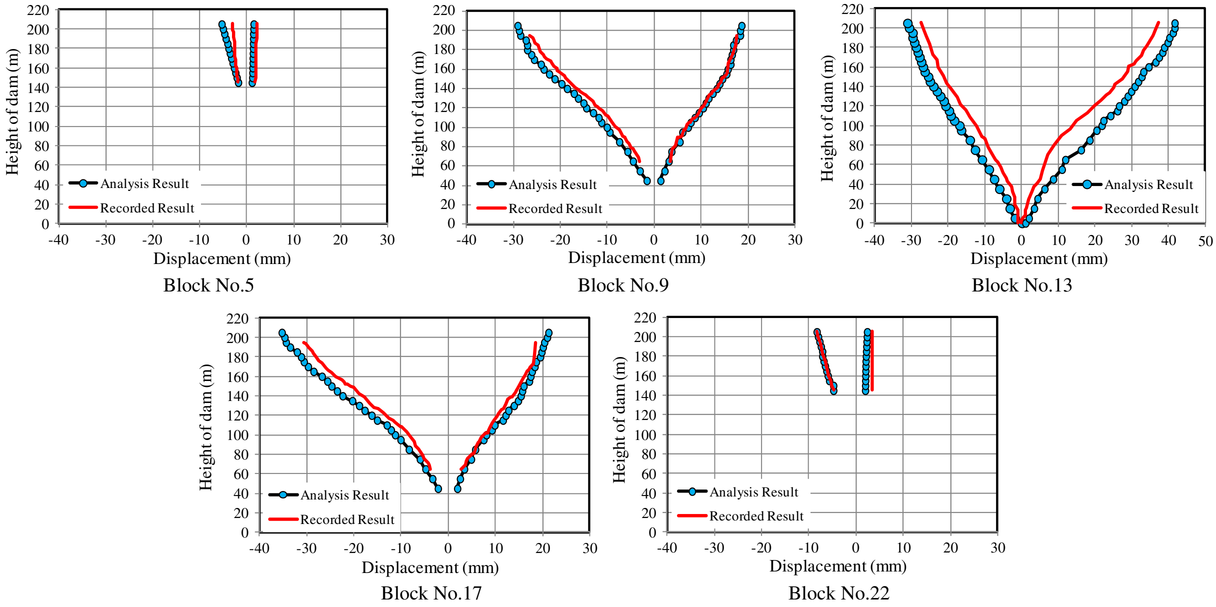

Fig. 7. Results of the structural calibration in different blocks of the dam.

Table 4
Concrete and foundation parameters used in the finite element model calibration.

Concrete mass density	2400 kg/m^3
Concrete modulus of elasticity	30 GPa
Concrete Poison's ratio	0.2
Concrete thermal expansion coefficient	6e-6 1/°C
Grouting temperature	18 °C
Foundation deformation modulus	14 GPa
Foundation Poison's ratio	0.2

Table 5
Static load combinations for Karun III Dam.

Load combination	Description	
Static usual	SU1	S[a] + T[b](summer) + NWL[c] + Silt
	SU2	S + T(winter) + NWL + Silt
Static unusual	SUN1	S + T(summer) + FWL[d] + Silt
	SUN2	S + T(winter) + FWL + Silt
	SUN3	S + T(summer) + MWL[e] + Silt
	SUN4	S + T(winter) + MWL + Silt

[a] Dead load.
[b] Temperature.
[c] Normal water level.
[d] Flood water level.
[e] Minimum water level.

should be mentioned that the safety factor for compressive stresses is considered to be 2.0 and 1.5 under the usual and unusual load combinations, respectively [8]. Safety factor for tensile stresses is always equal to 1.0. Allowable stresses for compressive stresses are 17.4 and 23.3 MPa and for tensile stresses are 3.4 and 3.4 MPa under the usual and unusual load combinations, respectively.

Fig. 8 shows envelope of the first principal stresses on the upstream and downstream faces of the dam body extracted from static load combinations pointed in Table 5. Also the same plots are depicted in Fig. 9 for third principal stresses. Considering the allowable stresses for tensile and compressive stresses, it can be seen that in all cases the values obtained from analyses are in acceptable range and the dam is evaluated to be safe at the current condition.

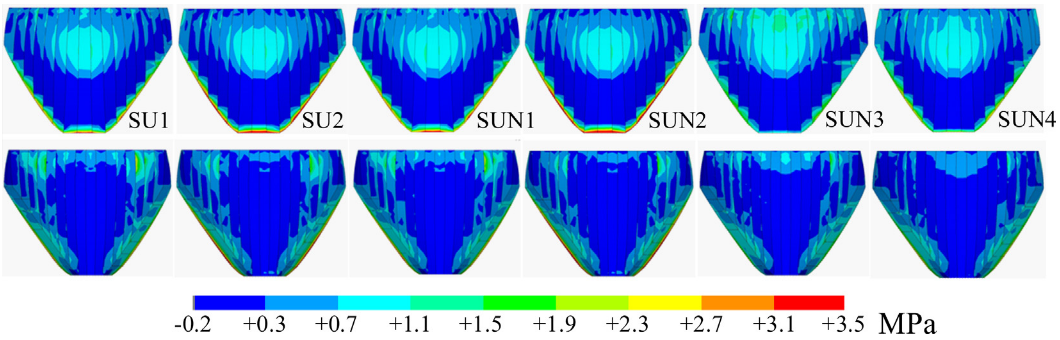

Fig. 8. Envelope of first principal stress in static condition.

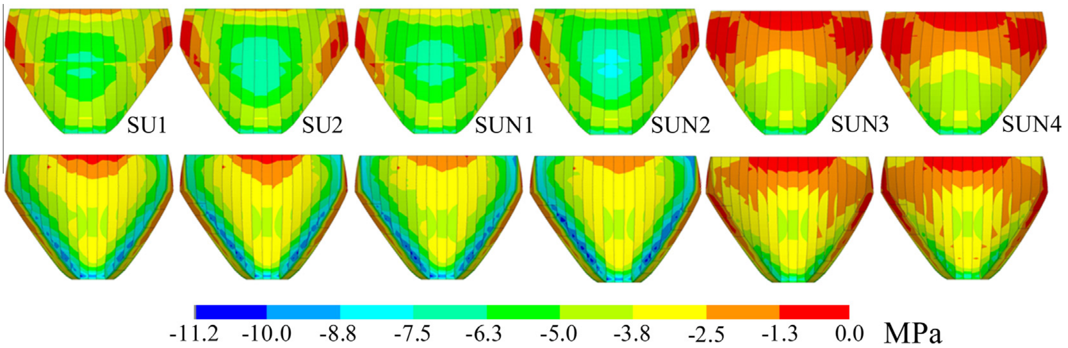

Fig. 9. Envelope of third principal stress in static condition.

Conclusion

In the present paper, a standard procedure for static safety evaluation of a high arch dam is reported. The thermal finite element model of the dam was calibrated using available data obtained from thermometers. All the main features affecting the thermal distribution within the dam body such as air and water varying temperatures and solar radiation were taken into account. The provided model for static analysis includes all the main features such as contraction joints between the dam blocks, foundation flexibility, and the stage construction effects. The calibration procedure was performed based on the measurements recorded at the dam site. It was found that the current calibration procedure leads to estimation of the reasonable material properties. Finally, static safety evaluation of the dam was conducted based on the referred load combinations and it was shown that the considered dam is safe under the current updated loading conditions.

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