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SEISMIC ANALYSIS OF THE HIGH ARCH CONCRETE DAM OF THE WATER POWER PLANT "PIVA"

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Original scientific paper

This paper analyses the seismic strength of the high arch concrete dam of the Hydro-power plant "Piva" on the river Piva in Montenegro, which was built in the seismic active area almost forty years ago. This is the double curve concrete arch dam, 220 m high and it belongs to the group of very high dams, among the highest 25 in the world. Linear and nonlinear analysis was performed. These analyses are very complex because they should include simultaneous interaction of system dam-foundation-reservoir. Calculation model was prepared using 3D finite elements for linear and nonlinear seismic analysis. Normal stresses and displacements which are obtained by the linear and non-linear analysis are different by the values and distribution along the dam body. Stresses obtained by the non-linear analysis are significantly less than the stresses obtained by the linear analysis, but when the displacement is about there is inverse case. Linear analysis gives the satisfying results for lower levels of the dam stress. When the tension strength is exceeded in the joints among the blocks, the dam goes into non-linear state of behaviour and in that case non-linear analysis should be used.

Keywords: *arch dam; dam-foundation-reservoir system; seismic analysis*

Seizmička analiza visoko lučne betonske brane hidroelektrane "Piva"

Izvorni znanstveni članak

U radu se analizira seizmička otpornost visoko lučne betonske brane hidroelektrane "Piva" na rijeci Pivi u Crnoj Gori, izgrađenoj prije gotovo četrdeset godina u seizmički aktivnom području. To je betonska lučna brana s dva luka, 220 m visoka i spada u grupu vrlo visokih brana, među 25 najviših na svijetu. Provedena je linearna i nelinearna analiza. Te su analize vrlo složene jer bi trebale uključiti simultanu interakciju sustava brana-temelj-rezervoar. Proračunski je model pripremljen uz primjenu 3D konačnih elemenata za linearnu i ne-linearnu seizmičku analizu. Normalna naprezanja i pomaci dobiveni linearnom i ne-linearnom analizom su različitih vrijednosti i raspodjele duž tijela brane. Naprezanja dobivena ne-linearnom analizom znatno su manja od naprezanja dobivenih linearnom analizom, ali kada se radi o pomacima, slučaj je obrnut. Linearnom se analizom postižu zadovoljavajući rezultati kod nižih stupnjeva naprezanja brane. Kod prekomjerne vlačne ćvrstoće u spojevima između blokova, brana prelazi u ne-linearno stanje ponašanja i u tom je slučaju potrebno primijeniti ne-linearnu analizu.

Ključne riječi: *lučna brana; seizmička analiza; sustav brana-temelj-rezervoar*

1 Introduction

Seismic analysis of the high arch concrete dams is very complex, because this is a complex dynamic system that includes dam structure, surrounding terrain and water. On the other hand, these are the structures of the high risk, and damage of these structures would cause catastrophic results on the downstream areas. So, this analysis should give real response about the dam behaviour during the possible strongest earthquakes as well as be one of the most important parameters for the mark of its safety.

The calculated system consists of the dam body, foundation and the surrounding terrain as the infinite semi-space and water reservoir. This complex system, dam, foundation and accumulation are in the interaction when they are under the earthquake effects. In that case, there are several interactions of the different nature, that is:

- Interaction of the dam and foundation;
- Interaction of dam and water;
- Interaction of water and foundation (lower part of the reservoir);
- Interaction of dam and soil displacement during earthquake.

Taking in consideration these assumptions, actual mathematical models are formed for the analysis of the dam behaviour during the earthquake. Besides that, the complex geometry and technology for the construction of dam should be taken into consideration, as well as mechanical characteristics and stochastic nature of dynamic effects.

The high arch dam of Hydro Power Plant "Piva", Montenegro, which was built in seismic active area, is analysed in this paper. This dam is 220 m high and it is classified as very high dam, among the highest 25 dams in the world. The dam was built in 1976, and it has been in operation for a period of almost 40 years.

The dam was analysed with the numerical procedures which were at the designer disposal in the moment of designing at the late of 60 years. Because of the modest possibilities for the calculation of the dam, the preliminary testing was performed on model of the dam. The dam was designed according to the results obtained from model testing and static analysis.

Development of actual numerical methods, before all the development of the method of finite elements, made it possible to get more detailed and more reliable insight in the state of stress and deformations in the dam body and foundation from static, and especially seismic effects.

Large amount of data obtained from technical observation of the dam as well as performed dynamic tests on the dam were used for calibration of the numerical model as well as for comparative analysis of obtained results.

For the reasons mentioned above, the Faculty of Civil Engineering in Podgorica was engaged to perform Special Study on static and dynamic behaviour and safety of this dam. The data from the mentioned study were used for this paper.

Figure 1 Layout of dam

2 Basic characteristics of the dam "PIVA"

The dam WPP "Piva" is high arch dam, of the double curves (Fig. 1). The profile of parting the river is geometrically and geotechnically nonsymmetrical. The left side of the canyon is steeper than the right. In the top of the right side, modulus of deformation for the rock mass is lower than of the left side. For that reason the dam was built as nonsymmetrical. Taking into consideration the mentioned, the support was formed for the upper quarter of the right side over the system of horizontal piles. They are placed on better parts of the rock mass, which has almost the same features as at the adequate level on the left side. In the middle part of the dam there are three overflowing fields 13 m wide and 5 m high. The dam consists of 18 consoles which are connected with joints and they have five revision galleries.

The basic characteristics of the dam are:

- height 220 m
- arch thickness in the crown 6,46 m
- dam thickness in the bottom 45,00 m
- arch length in the crown 268,56 m.

Mechanical and deformational characteristics of the dam concrete in the existing state are defined according to the performed tests, and the following results are obtained:

- average compressive strength 45,60 MPa
- tensile strength 2,85 MPa
- modulus of concrete elasticity 41 000 MPa.

In order to define mechanical and deformation characteristics of the rock mass the available technical documents are analysed from the period of testing works, designing, construction and long-time observations of structures and terrains in the zone of structure. The following moduli of deformability are established:

- left side 10 000 ÷ 15 000 MPa
- right side from 5000 (7000) MPa to 15 000 (16 000) MPa.

For the water reservoir, the modulus of compression is supposed to be $2{,}07\times10^6$ MPa and $\nu = 0{,}00$.

Dynamic characteristics of the dam were determined from experimental research with the forced vibration on the dam. During that, the frequencies for the radial vibrations (in the direction of the canyon) and tangential vibrations (transversal to the canyon) were measured for the different water levels in accumulation.

3 Seismic parameters

Five ground motions were used for the seismic analysis, which occurred in the Montenegrin seaside in 1979:

- Petrovac Hotel "Oliva2", component NS 15.04.1979. (PET 15.04.)
- Petrovac Hotel "Oliva", component NS 09.04.1979. (PET 09.04.)
- Kotor 24.05.1979. (KO)
- Budva 24.05.1979. (BD)
- Titograd - 2, Seismologic station, component NS, 15.04.1979. (TG)

Abbreviations in parentheses are used further in the paper. All registered ground motions were scaled to the same intensity by scaling to the maximal ground acceleration of 0,25 g.

4 Numerical model

Differential equation of the system dam-foundation-reservoir for the discreet model of finite elements presents the system of simultaneous equations dependant on time. This equation has the following form:

$$\begin{bmatrix} \boldsymbol{M'} & \rho\boldsymbol{G}^{\mathrm{T}} \\ 0 & \boldsymbol{M} \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{P}} \\ \ddot{\boldsymbol{U}} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{C'} & 0 \\ 0 & \boldsymbol{C} \end{bmatrix} \begin{Bmatrix} \dot{\boldsymbol{P}} \\ \dot{\boldsymbol{U}} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K'} & 0 \\ \boldsymbol{G} & \boldsymbol{K} \end{bmatrix} \begin{Bmatrix} \boldsymbol{P} \\ \boldsymbol{U} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{F'} \\ \boldsymbol{F} \end{Bmatrix},$$

where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are matrices of masses, damping and rigidity of dam – foundation substructure, and $\boldsymbol{M'}$, $\boldsymbol{C'}$ and $\boldsymbol{K'}$ are corresponding matrices of the reservoir substructure. The real damping is about 5 % for linear analysis and 7 ÷ 10 % for nonlinear analysis.

Vectors $\ddot{\boldsymbol{U}}$, $\dot{\boldsymbol{U}}$ and $\boldsymbol{U}$ are accelerations, velocity, displacement, and $\ddot{\boldsymbol{P}}$, $\dot{\boldsymbol{P}}$ and $\boldsymbol{P}$ are corresponding values of hydrodynamic pressure in joints of finite elements. $\boldsymbol{G}$ and $\boldsymbol{G}^{\mathrm{T}}$ are interaction matrices. Displacements and hydrodynamic pressures are the basic unknowns. The upper equation presents the system of equations depending on time. Their number is equal to the number of degrees of freedom in the discreet structure joints. In special cases when $\boldsymbol{G} = 0$ the system falls in to two independent systems: the first one where hydrodynamic pressures are unknown, and the second one where displacements are unknown. This solution imposes taking hydrodynamic pressures like virtual mass of water to the upstream dam face. Free members $\boldsymbol{F'}$ and $\boldsymbol{F}$ are vectors of forces which appear as a result of the soil displacement during the earthquake effects.

For the linear analysis, seismic response of the system dam-foundation-reservoir numerical model is based on the numerical analysis of simultaneous interactive system of dams-foundation-reservoir using 3-D finite elements. Dynamic analysis of the system is performed with the suggestion about the foundation without mass, incompressible behaviour of the water in the reservoir and zero value of the mass interaction ($\boldsymbol{G} = 0$).

Three-dimension finite elements of the elastic continuum are used for discretization of the dam and foundation with 24 degrees of freedom.

Discretization of the dam body was performed along the vertical and horizontal block joints. It is adopted that the elements width is equal to the quarter of the dam thickness. The width of the rock mass about 1,5 h is adopted for the foundation, where h is the dam height in the central console. Elements of the soil are of the prismatic shape with the gradual increase of their dimensions after coming into the rock mass. 3-D finite elements with eight degrees of freedom are adopted. The part of the reservoir equal to the double height of the dam body is included for water quantization in the reservoir in the calculated model. Damping is taken in the model as viscous damping with the damping coefficient of 0,05. Numerical model for the system dam-foundation-reservoir is presented in Fig. 2.

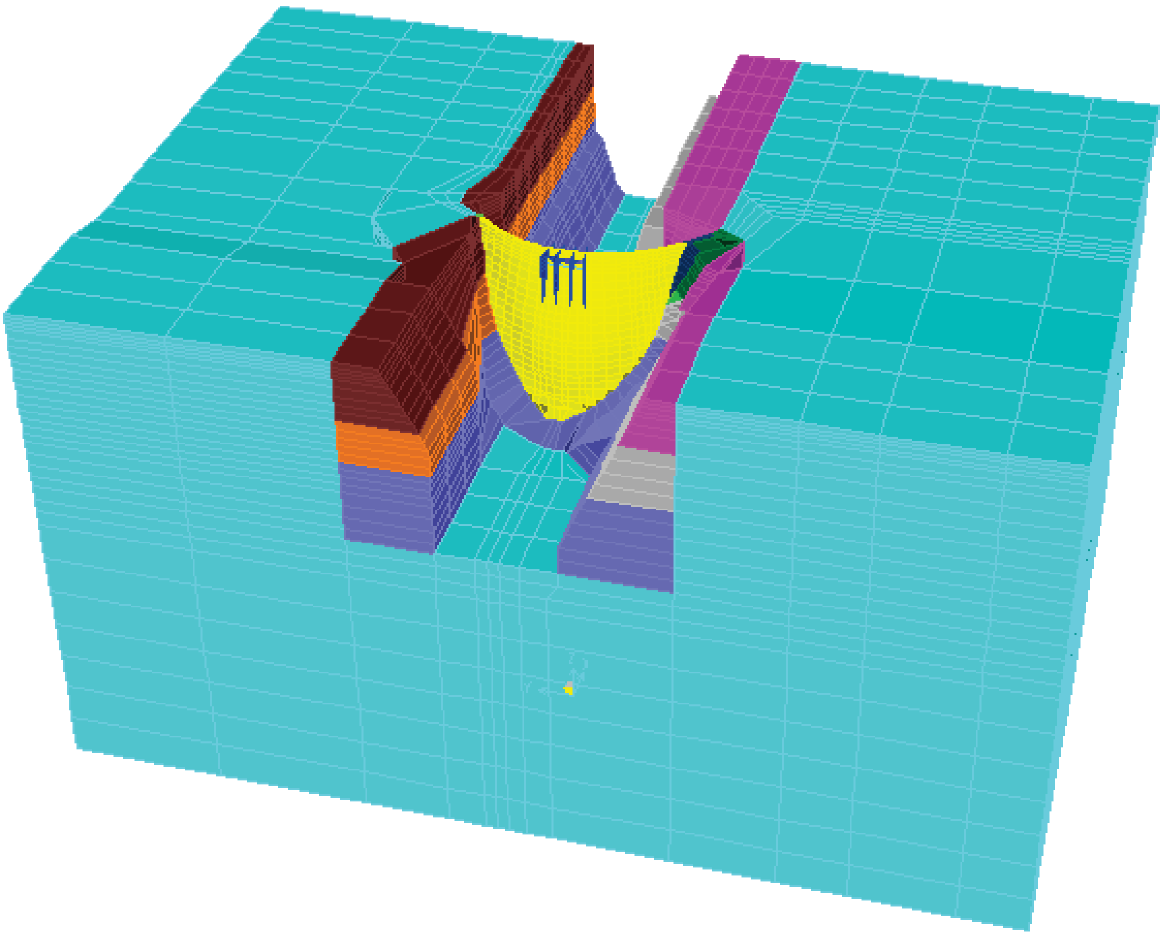


Figure 2 Numerical model for the system dam-foundation-reservoir elements layout

Model for nonlinear analysis is based on the principle that the dam consists of series of concrete vertical console blocks, which are mutually connected with the contact joints which cannot receive the tension so they present the potential place for the occurrence of cracks and fissures. The dam was constructed vertically in the layers from the arch segments where breaks in concreting were made, and consequently horizontal working joints are formed. Modelling of dam body for both models is performed with elements and mesh was generated in accordance with vertical and horizontal joints.

Transition from linear to nonlinear area of deformations occurs in joints where the concrete tension strength is exceeded. Dam will be transformed from monolithic state to the series of blocks with the nonlinear bonds along the joints.

Contact elements with nonlinear spring type are used for the simulation of nonlinear behaviour. They are placed in the joints of finite elements mesh along the zone of vertical joints and around this zone where the tension in concrete has appeared. Each nonlinear element consists of six nonlinear springs of zero length for the simulation of six inner deformations. The simplicity is adopted, the relation stress – deformations of these springs is mutually independent one from the other. There are springs for three deformations in Fig. 3: axial, shear and bending in the plane.

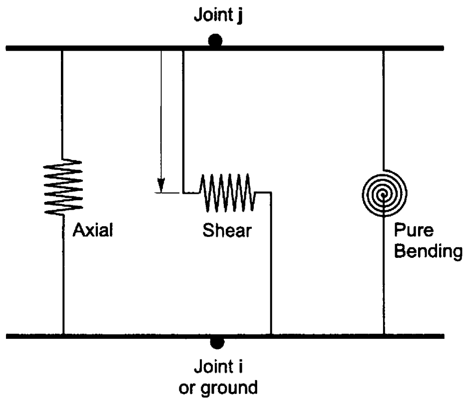


Figure 3 Scheme of nonlinear element

Because of relatively low values of stresses in rock, no fissures will appear in the rock mass and it will be treated as linear-elastic material also for nonlinear analysis.

Control and calibration of numerical model is performed in accordance with the results of experimental investigation of dynamic characteristics of dam.

5 Results and their analysis

Among the multitude of computational and experimental results obtained from the study, typical results that illustrate the behaviour of the dam were selected in this paper.

Calculated dynamic characteristics of dam from numerical model and values from experimental research are presented in Tab. 1 and Tab. 2. Natural shapes and damping capacity have been computed at water level 11,00 m below the dam crest. Experimental research has confirmed a theoretical assumption that the reservoir water affects the added mass to the dam body. The computed damping values range between 1,030 ÷ 2,430 %. Small damping is the result of a low level of dynamic stimulus of the structure. Results obtained from these analyses are in good concordance.

Table 1 Measured and calculated values of frequencies (for radial components)

	mode 1	mode 2	mode 3
Natural frequencies (Hz) (measured)	2,80	4,56	5,34
Natural frequencies (Hz) (numerical)	2,72	4,00	4,35

Table 2 Measured and calculated values of natural frequencies (for tangential component

	mode 1	mode 2	mode 3
Natural frequencies (Hz) (measured)	2,18	4,07	4,46
Natural frequencies (Hz) (numerical)	2,12	3,64	4,35

Analysis of results for selected ground motions with different frequency range shows that there is a big difference in action effects. Namely, in Fig. 4a there is a comparative analysis of displacement in the central dam console of all five selected ground motions. It is obvious that depending on the type of action and position of cross section, ground motions have a special effect. Dynamic response of the model during the ground motions with different range of frequencies has a big range of results which refer to great importance of investigation of micro seismic parameters of the location.

Fig. 4b shows the results of displacement of the central console, obtained according to the linear and nonlinear analysis of ground motion PET 15.04. It is noticeable that nonlinear effects are biggest in the central part of the dam body.

In Fig 5, there is acceleration of the joint in the central console on the dam crown for the ground motion PET 15.04., which is determined in nonlinear model. The factor of amplification of acceleration of this ground motion is very high, which shows the dam sensibility to the earthquake of these frequency characteristics.

The action effects obtained by linear and nonlinear analysis are significantly different, not only by the value, but also by the disposition of stresses in the dam body. In order to illustrate the mentioned differences in Figs. 6 and 7 radial component of the normal stresses is presented. Fig. 6 presents the normal stress in the body dam during the effects from self-weight load, hydrostatic and hydrodynamic load from water in the reservoir and earthquake effects obtained from the linear analysis; and Fig. 7 from the nonlinear analysis. The stress values obtained from non-linear analysis are significantly less than the values obtained by linear analysis.

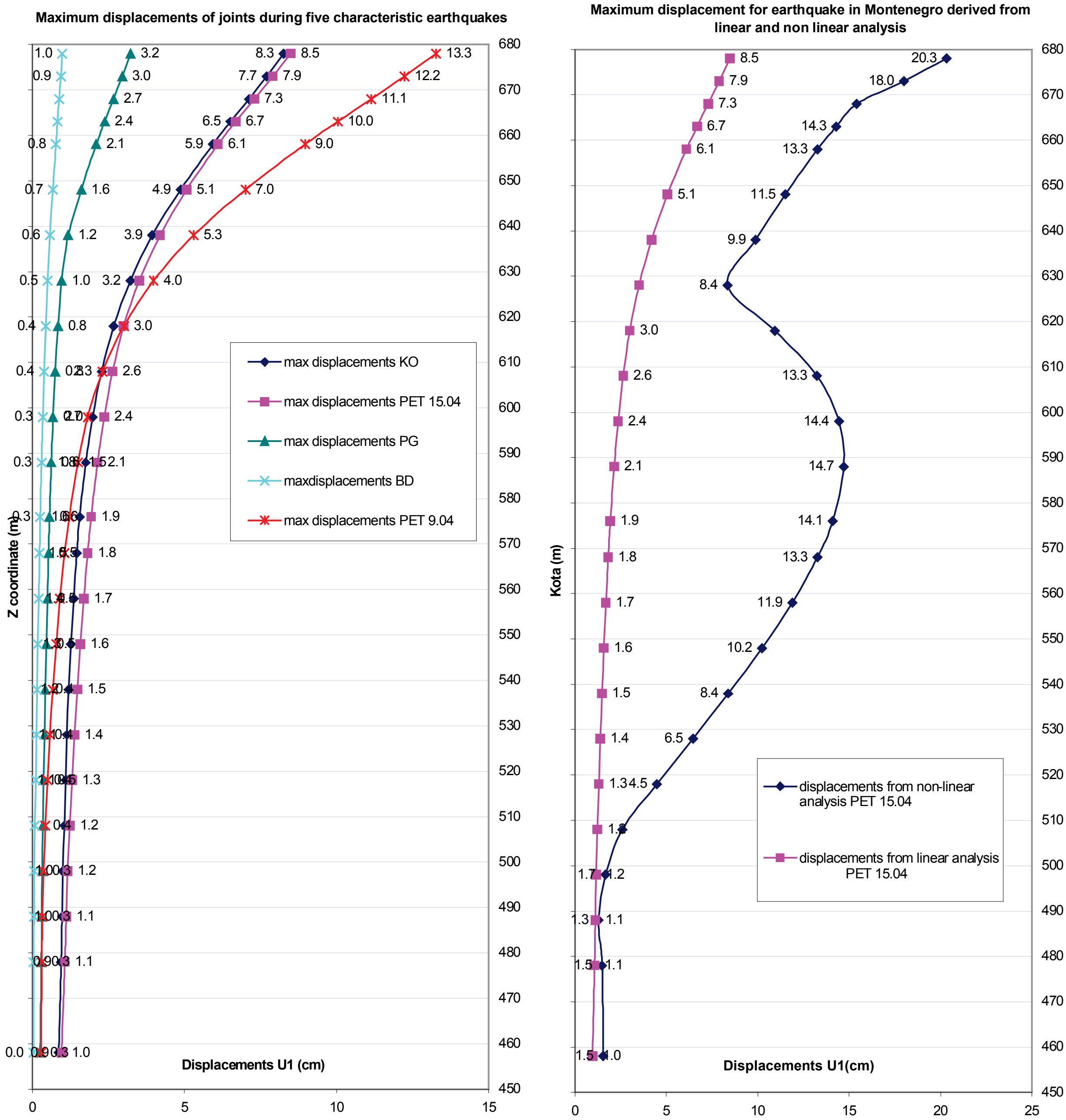


Figure 4 Displacement in the dam central cantilever

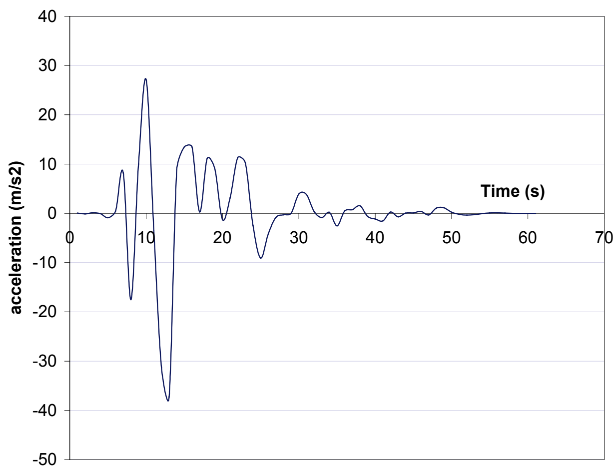
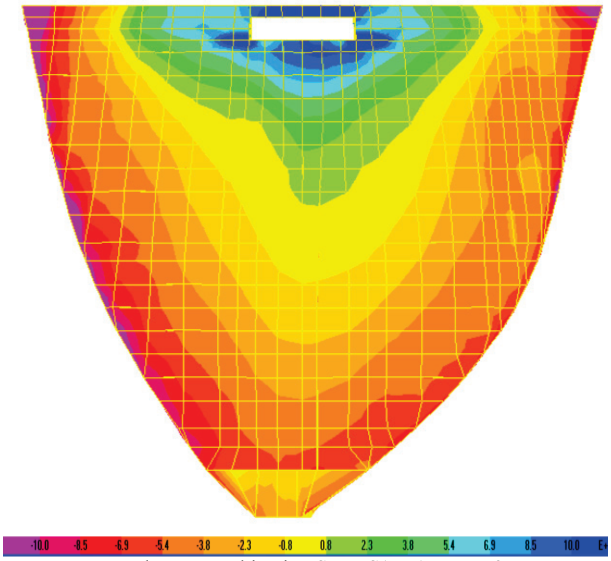


Figure 5 Acceleration of joint at the dam crest (Pet 15.4)

Comparing the results from the seismic analysis of linear model of the dam with experimental results measured on the dam, it can be concluded that the chosen dam model that includes interaction dams-rock-water with the real mechanical characteristics of material, is suitable and acceptable for defining the dynamic characteristics as well as static and dynamic response of the system dam-foundation-reservoir.

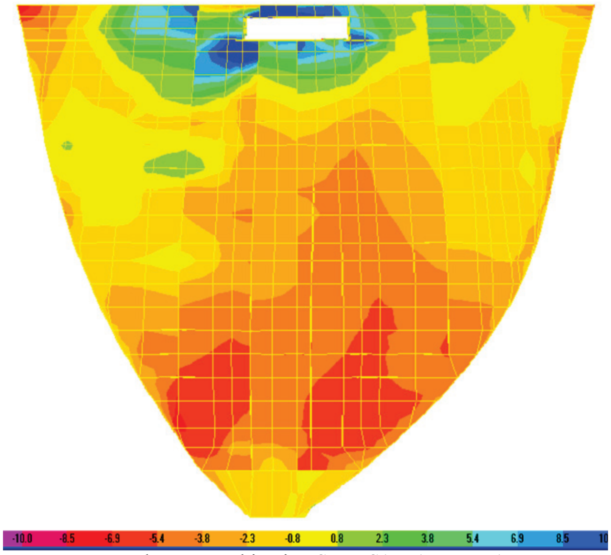
Dynamic response of dam model, obtained from different frequency range of ground motions, is within very large limits and because of that greater number of ground motions should be used.

Nonlinear analysis shows a great reduction of stresses, after the dam elements have entered in nonlinear range of behaviour.



Load case: combination ST+HS1+T1+HD+Z2

Figure 6 Stress in tangent direction: S22 max (upstream) linear analysis



Load case: combination ST+HS1+T1+HD+Z1

Figure 7 Stress in tangent direction: S22 max (upstream) nonlinear analysis

6 Conclusion

Based on results obtained from linear and nonlinear analyses and comparison of results from experimental and numerical analysis the following conclusions can be presented:

- There is negligible difference between calculated and measured dynamic characteristics of the dam which confirms that the numerical model of the dam is correctly produced, and the obtained results are realistic.
- The previous statement is confirmed with the results from linear and nonlinear analysis, which are in accordance with the results obtained from measurement and geodetic osculation of dam.
- After the dam enters in nonlinear range of behaviour, a great reduction of stresses occurs, in relation to the linear range, which is showed by the conducted nonlinear and linear analyses.
- Dynamic response of the dam, obtained from numerical model with ground motions with different frequency range is within a large range. Because of these reasons it is necessary to perform investigation of micro location seismic parameters.
- Normal stresses and displacements obtained by the linear and non-linear analysis are significantly different not only by the values but also by the distribution along the dam body. Stresses obtained by non-linear analysis are significantly less than those obtained by the linear analysis, but when it is about displacement there is the inverse case.
- Linear analysis gives the satisfactory results up to the level of the dam stress which causes the exceeding of the permitted tensile stresses in joints among the blocks. After that the dam goes into non-linear range of behaviour when non-linear analysis should be used.

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