ANALYSIS OF SEISMIC RESPONSE OF THE "MRATINJE" HIGH ARCH DAM

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ABSTRACT :

In this paper, safety assessment of a large concrete arch dam "Mratinje" on the river Piva in Montenegro, built in seismic active region thirty years ago, is analyzed. It is a high arch concrete dam of double curvature and height 200 m. For the seismic analysis of the dam, dynamic characteristics have been determined by experimental analyses, which in turn enabled the control of numerical model and its calibration. Research is based on numerical analysis of simultaneous interactive system dam-foundation-reservoir using 3-D finite elements. Dynamic analysis of the system is performed with assumptions about mass-less foundation. Analysis consists of two parts. First part, linear analysis of the system dam-foundation-reservoir is studied as an elastic continuum with viscous damping and uniform free-field ground motion with variable frequency range. Second part, nonlinear analysis is based on assumption of the dam as series of cantilever monoliths detached by contraction joints, under extremely strong earthquake action, which is relevant for the dam safety. The contraction joints can not transfer substantial tensile arch stresses, so they may open and close as the dam vibrates due to seismic ground motion. In this analysis, nonlinear effects arising from contraction joint movements and effects of concrete nonlinearity are included.

The results of numerical analysis are compared with the results of the experimental investigations, which resulted from the forced vibration in-site tests. Conclusions about dam safety assessments are presented.

KEYWORDS: arch dam, seismic analysis, dam-foundation-reservoir system

1. INTRODUCTION

The analysis of seismic response of high arch dams is very complex. This is due to the gravity of consequences that would occur upon its demolition as well as to the complex geometrical and geomechanical characteristics of the dam and the surrounding ground.

This model is a complex dynamical system composed of dam body, foundation as an infinite half-space and the reservoir water. As parts of an integral system, dam, foundation and reservoir are in simultaneous dynamic interaction when subjected to an earthquake. There are several simultaneous interactions of different nature, namely:

- Dam and foundation interaction
- Dam and water interaction
- Water and foundation (bottom of reservoir) interaction
- Dam and external earthquake effect interaction.

Based on this hypothesis is the mathematical formulation of modern models for the analysis of behavior of arch dams subjected to an earthquake. Besides, one should take into account the complexity of geometry and the domain boundaries, the change of physical properties and stochastic nature of dynamic stimulus.

In this paper, safety problem by the earthquake influence is examined as high concrete arch dam “Mratinje” which was build in seismic active region thirty years ago. Experimental investigation for this dam is in progress of realization and exploitation of determinate dynamic characteristic by which is possible to control and calibration of estimation model. Seismic analysis of the system dam-foundation-reservoir is performed on two levels with influence for linear and nonlinear area of deterioration and because of earthquake type Design basic Earthquake and Maximal Credible Earthquake.

2. CHARACTERISTIC “MRATINJE” DAM

The "Mratinje" dam has been analyzed. It is a high arch concrete dam of double curvature. While building the dam, an artificial lake was accumulated and its waters are used for producing electrical power in the Hydro Plant “Piva” next to the dam. The profile of the partition point is geometrically and geotechnically not symmetrical. The left side of the canyon is steeper than the right side. At the top of the right side deformation modules of the rocky mass have law values comparing to the rest of the profile. For this reason, the dam is constructed as non-symmetrical. In the top quarter of the right side it lays on the system of the horizontal piles on better partitions of the rocky mass, which has similar geotechnical characteristics, as well as on the appropriate levels on the left side. In the central part of the crest, there are three overflowing areas of 13 meters of width and 5 meters of height. The dam consists of up to 18 cantilevers and it has five revising galleries.

Basic geometric characteristics of the dam are:

- Building height 220.00 m
- Width at the top 6.46 m
- Width at the bottom 45.00 m
- Length in the crest along extrados 268.56m

Basic characteristics of concrete and rock in numerical model are assumed to be average. Values have been obtained on the basis of results of previous extensive research.

- Concrete 41000 MPa
- Foundation rock :

- Left side 10000 – 15000 MPa
- Right side from 5000 (7000) MPa until 15000 (16000) MPa

It is noticed that the right rocky side of the dam has poorer characteristics then the rest of the rocky mass. This side was individually analyzed in the static estimation.

For the reservoir water, compression modulus 2.07 $*10^6$ MPa and v = 0.00 have been assumed. Dynamical characteristics have been computed by experimental research of the "Mratinje" dam by forced vibrations. Resonant frequencies for the vibrations in the direction of the canyon (radial component) and transversally to the canyon (tangential component), natural shapes and damping capacity have been computed 11.00 m below the dam crest.

Table 1 Natural frequencies, measured value

		mode 1	mode 2	mode 3
Natural frequencies (Hz)	(for radial component)	2.80	4.56	5.34
Natural frequencies(Hz)	(for tangential component)	2.18	4.07	4.46

Table 1 show the measured values of natural frequencies for radial and tangential component. 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 law level of dynamic stimulus of the structure.

3. SEISMIC PARAMETERS

Accelerograms of the earthquake that took place on the Montenegrin Coast on 1979 have been used for the seismic analysis, namely:

- Petrovac, the "Oliva" hotel, component N-S,15.04.1979.
- Petrovac, the "Oliva" hotel, component N-S, 9 15.04.1979.
- Kotor, 24.05..1979.
- Budva, 24, 12.05.1979
- Titograd-2, Seismological station, component N-S, 15.04.1979.

All registered earthquakes have been reduced to the same intensity by scaling maximum acceleration of ground to the level of 0.25 g.

4. NUMERICAL MODEL

Differential equation of movement of dam-foundation-reservoir system for a discrete finite element model reads as follows equation 1:

$$\begin{bmatrix} M' & \rho G^T \\ 0 & M \end{bmatrix} \begin{Bmatrix} \ddot{P} \\ \ddot{u} \end{Bmatrix} + \begin{bmatrix} C' & 0 \\ 0 & C \end{bmatrix} \begin{Bmatrix} \dot{P} \\ \dot{u} \end{Bmatrix} + \begin{bmatrix} K' & 0 \\ -G & K \end{bmatrix} \begin{Bmatrix} P \\ u \end{Bmatrix} = \begin{Bmatrix} F' \\ F \end{Bmatrix} \tag{1}$$

Where M, C and K are the mass, damping and stiffness matrices of the dam-foundation foundation, and M', C' and K' are corresponding matrices of reservoir substructure. Radiation damping of water and conditions at the water-water boundary. In mass foundation model, the damping matrix (C) depends on the viscous damping (C') and radiation damping (Cr). Real damping is around 5% for linear analyses and 7%-10% for non-linear analyses. Vectors $\ddot{u}, \dot{u}$ and u are the acceleration, velocity and displacement, and $\ddot{p}, \dot{p}$ and p stand for corresponding values of hydrodynamic pressures in finite element nodes. Displacement and hydrodynamic pressures are basic unknowns. They commonly affect by Interaction matrices G and GT, so that (1) presents a system of simultaneous equations dependent on time. Their number equals the number of degrees of freedom in discrete structure nodes. In special cases when G=0 system (1) disintegrates into two independent systems: the first one in which hydrodynamic pressures are unknown, and the second one, in which displacements are unknown. This solution imposes a presentation of hydrodynamic pressures as incorporation of virtual mass of water on the upstream dam face. Free members F' and F are force vectors created as a result of ground displacement due to an earthquake.

For linear analysis seismic response system dam-foundation-reservoir are numerical model is based on numerical analysis of simultaneous interactive system dam-foundation-reservoir using 3-D finite elements. Dynamic analysis of the system is performed with assumptions about mass-less foundation and compressible behavior of the reservoir.

For the discrimination of the dam and foundation (rock) three-dimensional finite elements of (3D) continuum have been used with 24 degrees of freedom.

Discretion of dam body is done along the vertical and horizontal block joints. For dam body, is taken the thickness of the elements width in equal to a half of the dam thickness. In the numerical model for the foundation, the adopted width of the rock mass approximately equals 1.5h, where h is the dam height at the central cantilever. Elements of a prism shape gradually increasing their dimension upon entering the rock mass have been used. 3d finite element with eight gradients of freedom each has been used for the discrimination of the reservoir. The adopted part of the reservoir in the computational model equals the double height of the dam body. Damping in designed model is taken as replacing viscous damping with damping coefficient of 0.05.

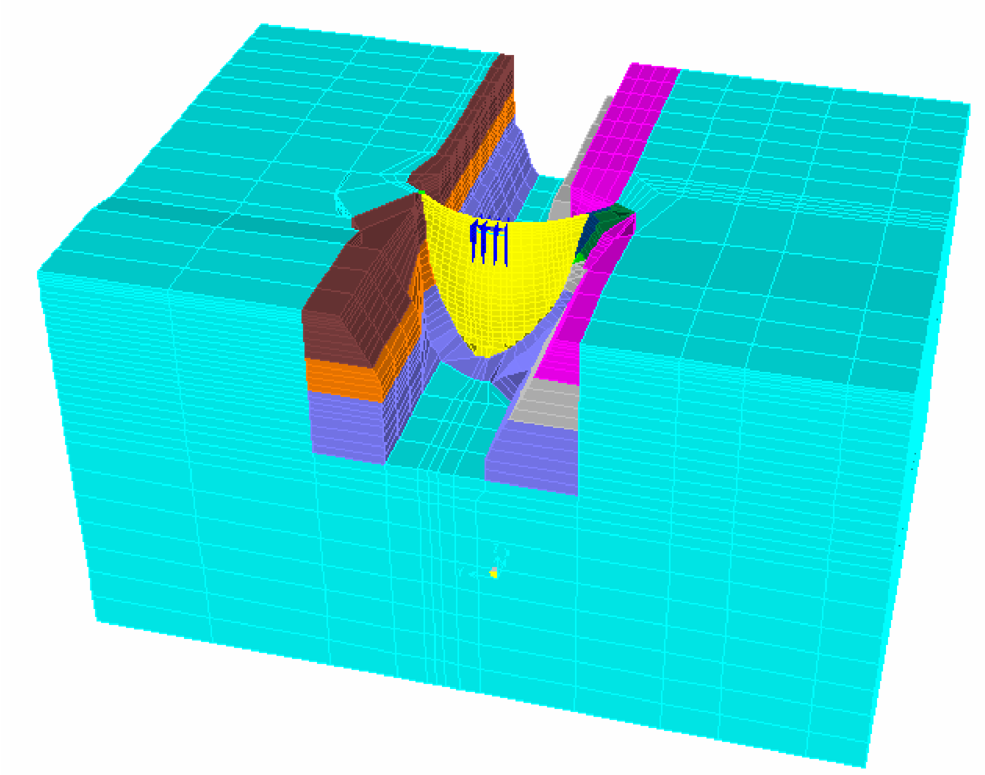


Figure 1 Numerical model for coupled system dam-foundation-reservoir, elements plan

Control and calibration of designed model is done with a control of its dynamics characteristics and comparing numerical and experimental results.

Model for nonlinear analysis is form on following principles:

The dam is performed in plane concrete as row of vertical cantilever block, which is reciprocal, attached with contact joints which don't reactive tensile stress. By upright is performed by layers from arch segments where is performed the interruption on setting in concrete and in that way is formed horizontal joint as well as the potential place for horizontal fissure occurrences. The quantization of dam body for all estimation models are done according to vertical and horizontal joints.
Because of concrete hardness exceeding on tightening, in joints, from origin monolith state dam body will be transformed into row of blocks with declined joints along coupling. Basis of nonlinear behavior is appearance, fissure expanding, and appearance of relative movements along the joints (opening, closing and shearing). Appearance of plastic deformity in blocks and joints is of secondary importance. Because of concrete hardness exceeding in joints on tensile from origin monolith state dam body will be transformed into row of blocks with declined joints along coupling.

Because of relatively low level of stress in the rocks, there are no fissures so the terrain foundation is treated as linear elastic as well as at nonlinear analysis.
Basis of nonlinear behavior is appearance, cracks expanding, and appearance of relative movements along the joints (opening, closing and shearing). Appearance of plastic deformity in blocks and joints is of secondary importance. For simulation of relative movements, contact elements of spring nonlinear type are applied, which are build in knot network of final elements along joints in zone and in surrounding zone, where the tightening is appeared. Each nonlinear element is composed of six nonlinear springs zero length for simulation of six interior deformation. Relation stress-deformation of these springs is independent one from another.

5. RESULTS AND DISCUSSION

There is a negligible difference between the computed dynamic characteristics of the dam on the chosen numerical model and those measured during the experimental. The computed and measured period of natural oscillations is shown in Table 2. and Table 3.

Table 2. Natural frequencies, measured and numerical value (for radial component)

		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 3. Natural frequencies, measured and numerical value (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

The results presented in this paper are considered to give a proper overview in order to illustrate characteristic effects.
At first, analyzing effects of earthquakes with different frequency ranges in order to choose the credible accelerogram, basic difference was noticed for certain earthquakes. Namely, on Fig.2 are shown comparative analysis of displacement in the dam central cantilever. It is obvious that, depending on a type of effect and position of cross section, accelerogram of earthquakes are paramount. Dynamic response of the model obtained by earthquakes with different frequency ranges, moves in very large limits and point of big importance of investigation of micro location seismic parameters. Moreover, it is clear that the extreme effects for complete dam body cannot be found according to synthetically designed earthquake.

The figure 2 shows the results of the dislocation of the central cantilever, obtained by linear and non-linear analysis. It is noticeable that the non-linear effects are the biggest in the central part of the dam body.

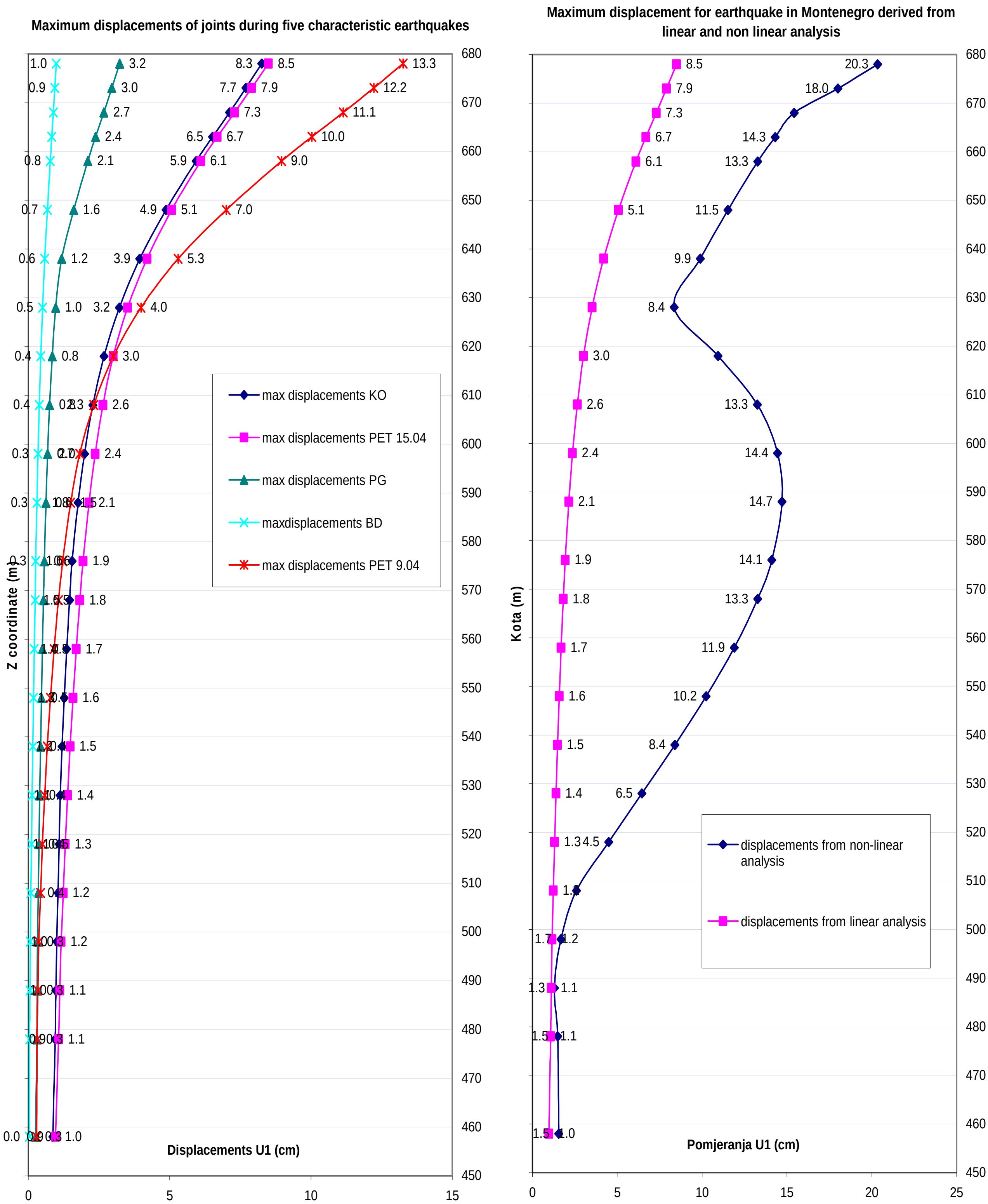
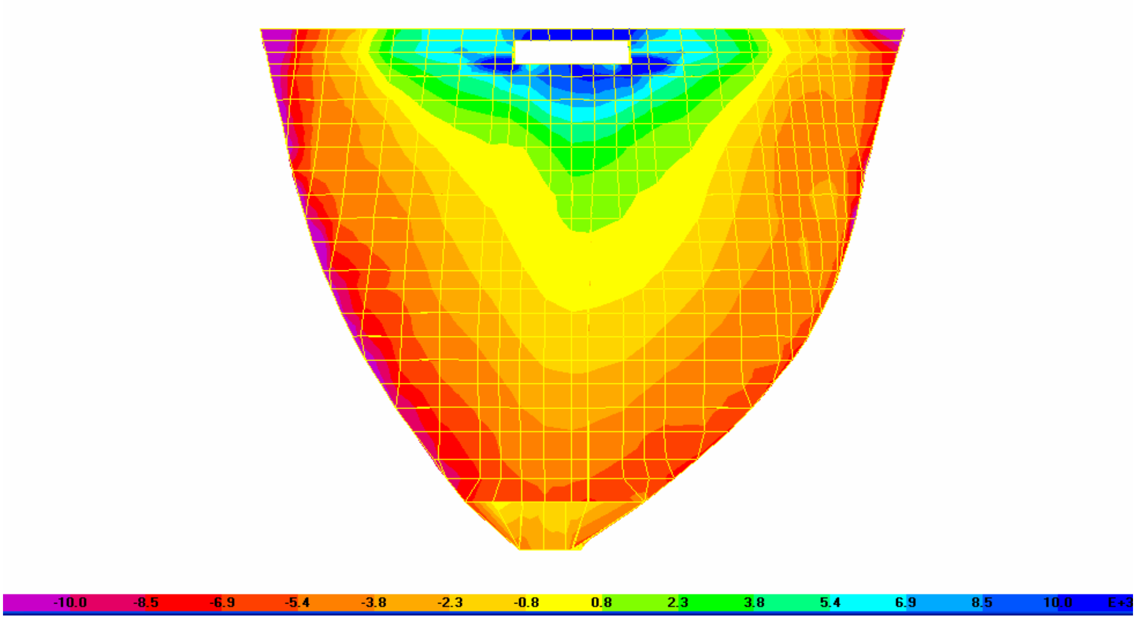
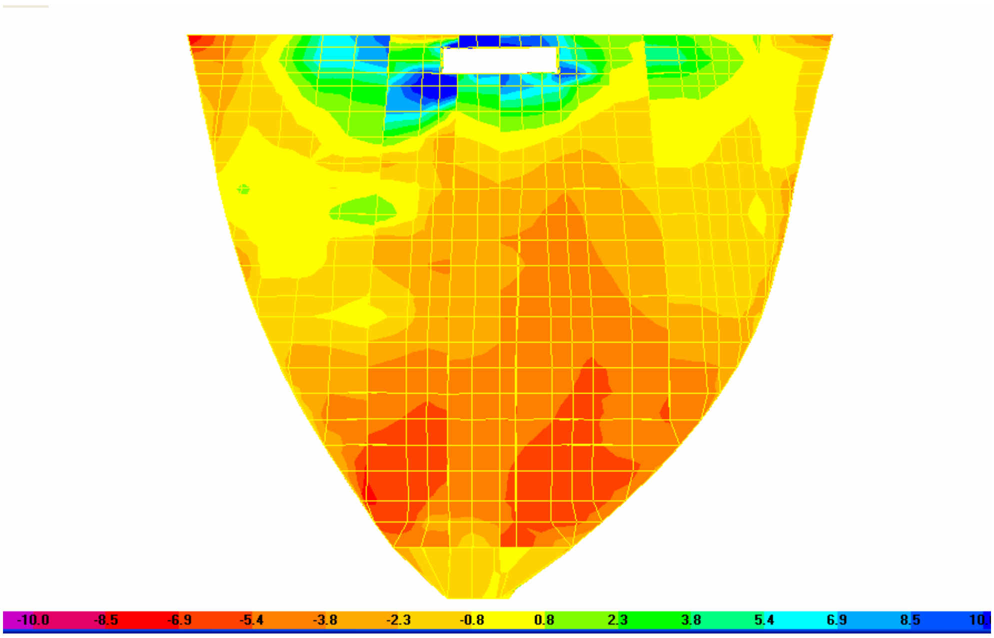


Figure 2. Displacement in the dam central cantilever



Load case: combination ST+HS1+T1+HD+Z2
Figure 3. Stress in tangent direction: S22 max (upstream) linear analysis



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

Figure 4.Stress in tangent direction: S22 max (upstream) non linear analysis

The figure 5 presents acceleration of joint at the dam crest during earthquake „Petrovac" which was calculated on non-linear model. The factor of amplification of acceleration during this earthquake is big and it is 15.6. which demonstrates the sensitiveness of the dam on the effect of the earthquake.

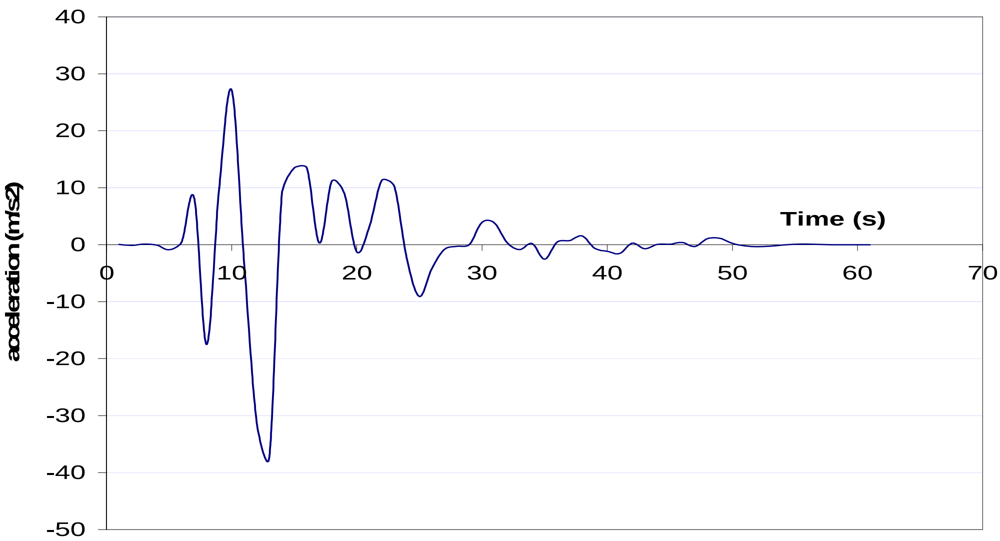


Figure 5.Acceleration of joint at the dam crest

The effects obtained by linear and non-linear analysis are significantly different, not only by value, but also by the distribution of the stress in the dam body. To illustrate mentioned differences on figures 3 and 4, the overview of the radial component of normal stresses is presented. The figure 3 presents normal stress in dam body under mutual influence of its own weight, hydrostatic and hydrodynamic influence of the water in reservoir and the influence of the earthquake obtained by linear analysis; and on figure 4 nonlinear analyses. Comparing to the values obtained by linear analysis, the stresses obtained by non-linear analysis and significantly smaller.

Comparing the results of seismic dam analysis calculated on the model for linear analysis and on experimental results measured on dam, we could conclude that selected dam model, which includes interaction dam-rock-water with real mechanical properties of material, is suitable and acceptable for finding out dynamic characteristics of static and dynamic response of dam-foundation-reservoir system.

Dynamic response of designed model, obtained by the effects of the different frequency range earthquakes, is within very large limits and cannot be determined with the sufficient accuracy, based on designed synthetic earthquake.

Non-linear analysis shows a big reduction of influences after dam enters the non-linear area of strain. It is shown that dam has required stability regarding the stress and strains for the conditions of accepted designed earthquake and maximal possible earthquake., while the dam energy capacity is insufficient because of the small absorption capacities of the fragile joints.

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