ANALYSIS OF EARTHQUAKE SAFETY OF A LARGE ARCH DAM

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SUMMARY

In this paper, safety assessment of high reinforce concrete arch dam, built in seismic active region thirty years ago, is analyzed. 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 massless foundation and compressible behavior of the reservoir.

Analysis consists of two parts. First part, linear analysis of the system dam-foundation-reservoir studied as an elastic continuum with viscous damping and uniform input (DBE-Design Basic Earthquake) with variable frequency range. Second part, nonlinear analysis, based on assumption of the dam as series of cantilever monoliths detached by contraction joints, for the illustration of occurrence of Maximal Credible Earthquake (MCE), relevant for the dam safety. In analysis, nonlinear effects of contraction joint movements and effects of concrete nonlinearity are included. Additionally, consequences of non-uniform motion of the canyon are investigated.The numerical model for the dynamic analysis of this dam included the dam body, foundation mass, reservoir water, real material mechanical characteristics and real seismic parametres of microlocation.

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

INTRODUCTION

The analysis of high arch dam safety considers two type of analysis, which is the result of different criterion for designing and object safety. The first one is related to optimal designing (optimum earthquake-resistant design) for which, as stability criterion, are not allowed cracks occurrences. It is to be done for case of external influence of authoritative earthquake type for designing (DBE-Design Basic Earthquake) in combination with other influences. The other level is object stability estimation (earthquake- resist design) for, which is allowed damages except the one who will endanger global object stability. Authoritative earthquake for this analysis is maximal credible earthquake (MCE-Maximal Credible Earthquake).

In this paper, safety problem by the earthquake influence is examined as high concrete arch dam “Grancarevo” 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.

CHARACTERITIC "GRANCAREVO" DAM

The "Grancarevo" dam has been analysed. It is a high arch concrete dam of double curvature. Basic

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geometric characteristics of the dam are:

- height 123.00 m
- Width at the top 4.6000 m
- Width at the bottom 26.914 m

The normal water level is 3.00 m below the spot of the dam crest. 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 "Grancarevo" 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 mode and damping capacity have been computed. Table 2 and Table 3 show the computed values of natural frequencies for the first five tremors.

Table 1

	E value (MPa)	ν	mass (t/m3)
Concrete	0.310 *106	0.20	2.45
Foundation rock	0.080 *106	0.20	2.90

Table 2

		mode 1	mode 2	mode 3	mode 4	mode 5
Natural freque. (Hz)	for LEVEL I	2.700	3.725	5.625	7.130	8.160
Natural freque. (Hz)	for LEVEL II	3.008	5.120	5.900	7.600	/
Damping (%)	for LEVEL I	1.190	1.910	1.310	2.070	1.670
Damping (%)	for LEVEL II	1.180	2.340	1.100	2.430	/

Table 3

		mode 1	mode 2	mode 3	mode 4	mode 5
Natural freque. (Hz)	for LEVEL I	2.510	4.450	6.840	/	/
Natural freque. (Hz)	for LEVEL II	2.840	4.810	7.120	/	/
Damping (%)	for LEVEL I	1.030	1.1030	0.840	/	/
Damping (%)	for LEVEL II	1.140	1.120	1.740	/	/

Examinations have been carried out for the two levels of the reservoir during the experiment, namely:

- LELEL I 8.00 m below the dam crest
- LEVEL II 29.00 m below the dam crest

For the reduced level of the reservoir water an increase of natural frequency for all oscillation shapes has been registered. If the second vibration tremor in the direction of the canyon is excluded, which probably presents a mistake in measurements, it is obvious that the greatest difference in frequencies occurs in first tremors. The reduction of amplitude of relative displacements has also been registered which shows that the reservoir water acts as a damper. 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.

SEISMIC PARAMETRES

Accelograms of the earthquake that took place on the Montenegrin Coast on 15 April 1979 have been used for the seismic analysis, namely:Petrovac, the "Oliva" hotel, and Titograd-2, Seismological station, and accelerogram El Centro 1940.All registered earthquakes have been reduced to the same intensity by scaling maximum acceleration of ground to the level of 0.20 g. for Design Basic Earthquake and 0.40 g for Maximal Credible Earthquake.

NUMERICAL MODEL

Differential equation of movement of dam-foundation-reservoir system for a discrete finite element model reads as follows (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 hydrodinamic 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 hydrodinamic pressures are unknown, and the second one, in which displacements are unknown. This solution imposes a presentation of hydrodinamic 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.

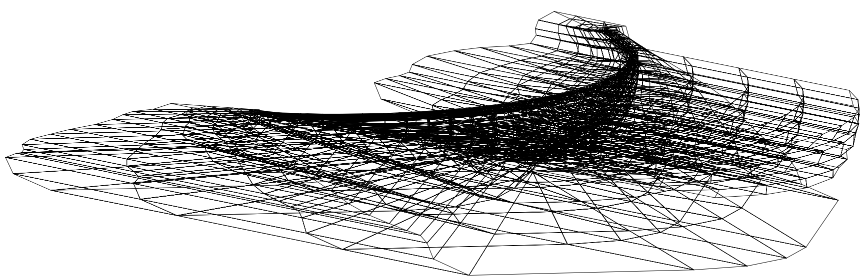


Fig. 1. Numerical MODEL B1 for coupled system dam-fundation-reservoir, elements plan

For linear analysis seismic respons system dam-foundation-reservoir are formed two numerical model (MODEL B1 and MODEL B2).

MODEL B1 (Figure 1) 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 massless foundation and compressible behavior of the reservoir. For the discretization of the dam and foundation (rock) three-dimensional finite elements of (3D) continuum have been used with 24 degrees of freedom.

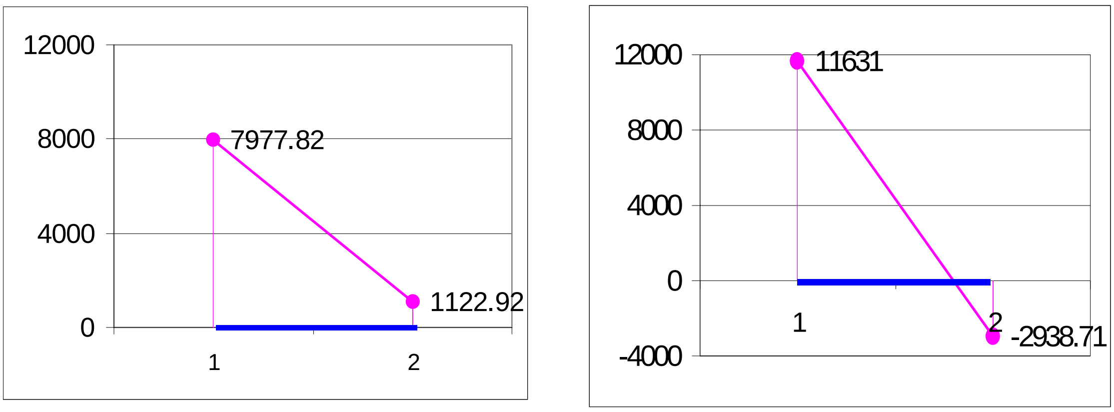
The elements width equalling one fourth of the dam width has been assumed for the dam body. In the numerical model for the foundation, the adopted width of the rock mass approximately equals 1.5h, where h is the dam height at the central cantilever. Elements of a prism shape gradually increasing their dimension upon entering the rock mass have been used. 3d finite element with eight gradients of freedom each has been used for the discretization of the reservoir. The adopted part of the reservoir in the computational model equals the double heigth of the dam body.

MODEL B2 is based on numerical analysis of simultaneous interactive system dam-foundation using 3D finite elements same as for MODEL B1. At this model is assumed that the matrix G (interactive matrix) is equal to zero. The influence of the water in impounding reservoir is approximate of water mass, which is attached by upstream dam face.

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 doesn’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 guantization 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.



a/ load hidrostatic + seismic (0.2 g) **b/ load hidrostatic + seismic (0.4 g)**

Fig. 2. Max principal stresses(33.00m under crown)

Modified model B2 is used for system of nonlinear analysis. Modification is consisted of entering model B2 nonlinear elements. They are set in horizontal and vertical joints between solid elements by which is quantizated dam body. It is performed in upper central part of the dam where, by linear analysis, max. intensity of ascertain tensile stress is 2938.71 kN/m2 (Fig.2)

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, cracs 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 echone of six interior deformation. Relation stress-deformation of these springs is independent one from another. On Fig. 3. are shown the springs for three deformations: axial, shearing add pure flexure in plane 1-2.

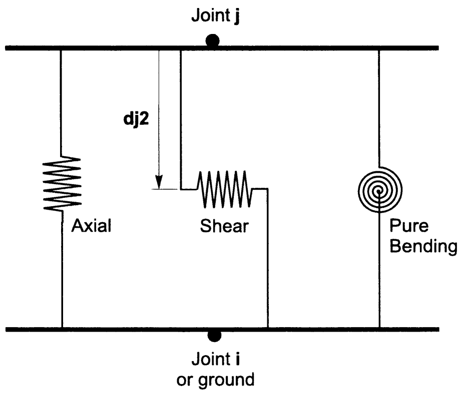


Fig. 3. Nonlinear element in plane 1-2

Other three springs, which aren’t on Fig. 3, are for other three deformations left: torsion, shearing and flexure in plane 1-3. For each spring the relation stress-deformation, which direct elements behavior is included.

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RESULTS AND DISCUSSIONS

Calculated dynamic dam characteristics on selected estimated model and calculation in course of experimental investigation have small difference. Calculated and estimated periods of own fluctuation are shown in table 4.

Table 4

	mode 1	mode 2	mode 3	mode 4	mode 5
Natural frequ. for level III(numerical values,MODEL B1)	2.720	2.750	3.850	4.590	4.910
Natural frequ. for level III(numerical values, MODEL B2)	2.060	2.320	3.330	3.600	4.440
Natural frequ. for level I (measured values)	2.510	2.700	3.725	4.450	5.625
Natural frequ. for level II (measured values)	2.840	3.008	4.810	5.120	5.900

- level I water in reservoir 8.00 m belov the dam crown
- level II water in reservoir 23.00 m belov the dam crown
- level III water in reservoir 3.00 m belov the dam crown

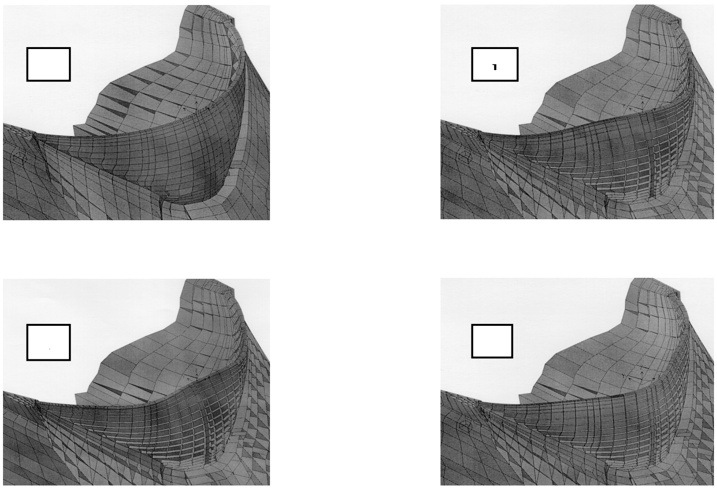
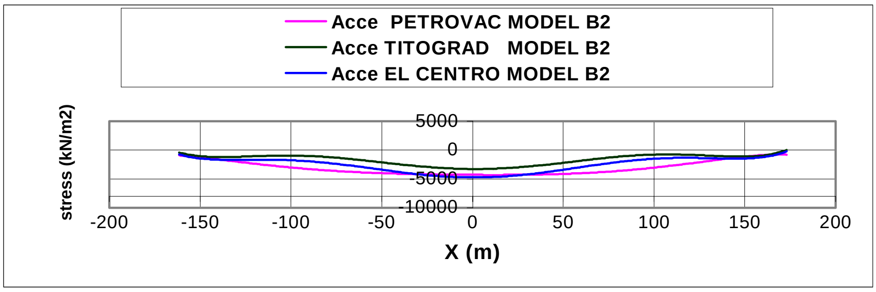


Fig.4. Numerical model B2, a/ undeformed model, b/ mode 1, c/ mode 2 , c/ mode 3

a/ upstream face (crown)



b / upstream face (33.00 m under crown)

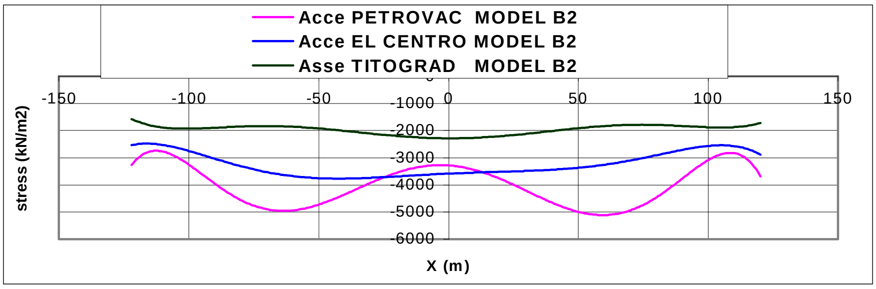


Fig.5. Time-history analysis, max principal stress (linear analysis)

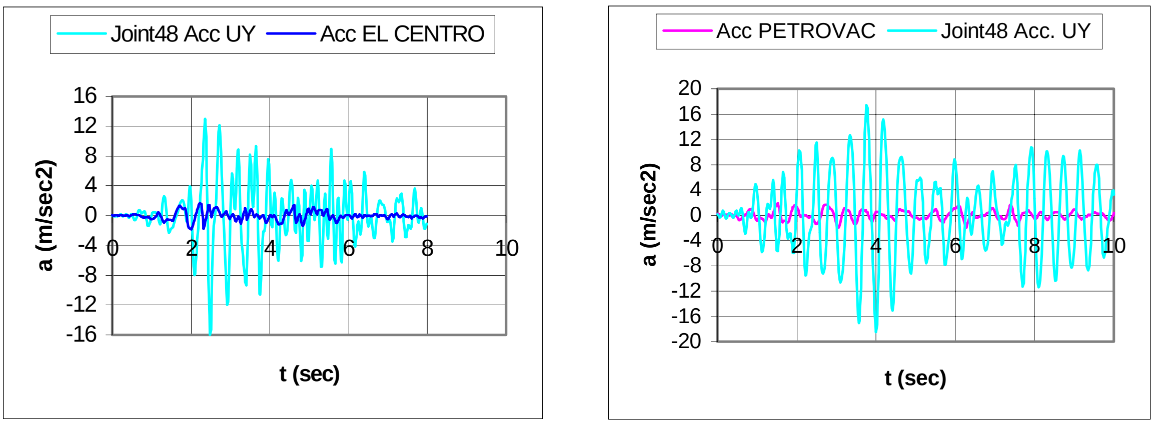
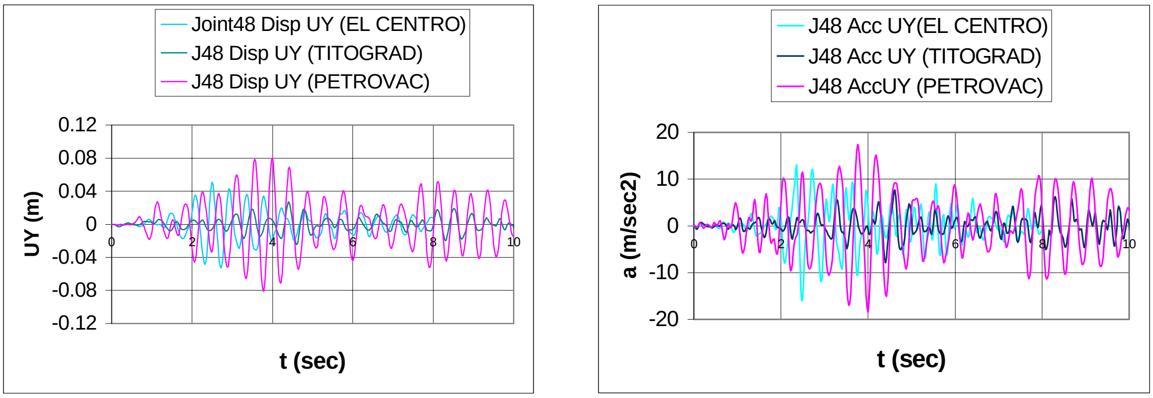


Fig.6. Time history of acceleration at crest of central cantilever in radial direction(linear analysis)



a/ displacement b/acceleration

Fig.7. Time history of displacement and accelerationat dam crest in radial direction (linear analysis)

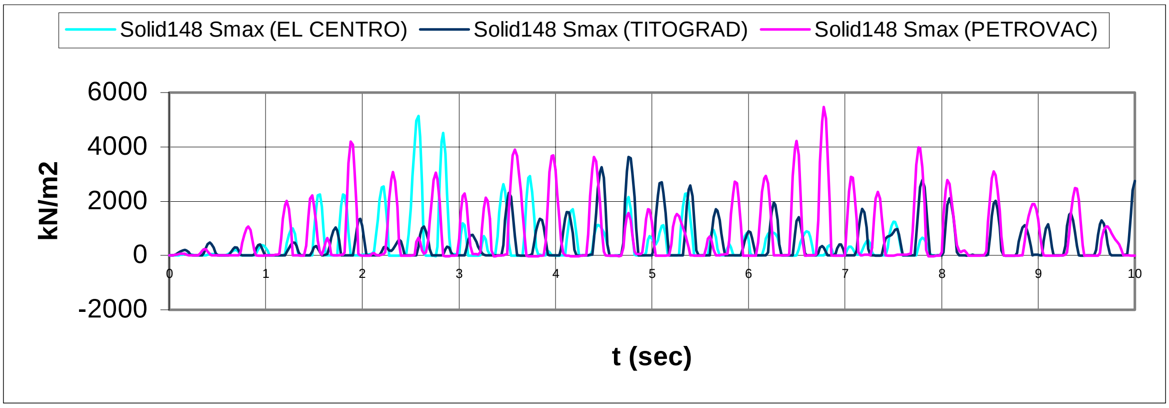
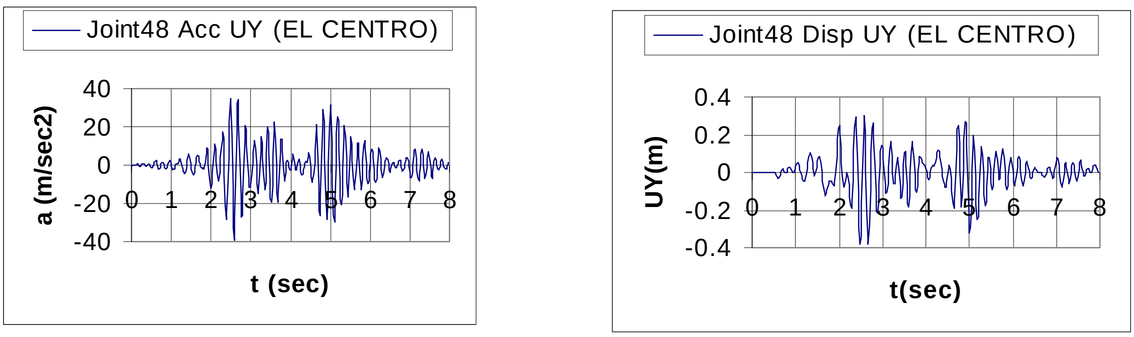


Fig.8 Time history of max. principal stress at dam crest (linear analysis)



a/ displacement /acceleration

Fig.9. Time history of displacement and accelerationat dam crest in radial direction (nonlinear analysis)

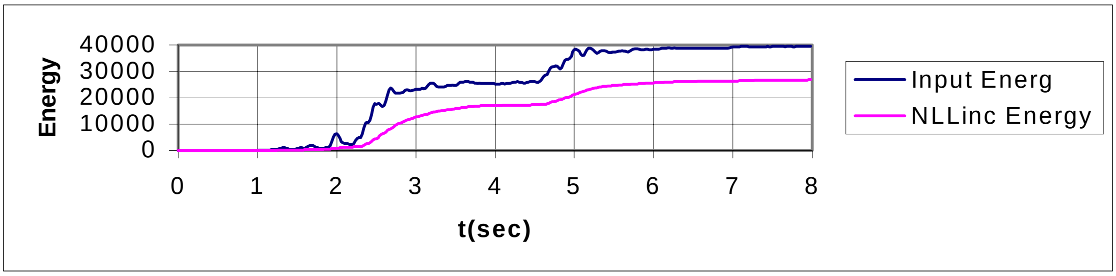


Fig.10. Time history ofenergy bilans dam crest in radial direction (nonlinear analysis)

Maximum principal tensile stresses in the dam due to dead load, water load and DBE (peak acc. up to 0.4g) are under allowable tensile stress (2 MPa) of mass concrete.

Unlike DBE, which does not cause excessivetensile stresses, MCE accelerations (peak acc. over 0.4g) with dead load and water load cause tensile stresses which exceed the dynamic tensile strenght of mass concrete. The zones of the highest tensile stresses are in the upper central portionof the dam and along the dam – foundation boundary.

The results of nonlinear analysis carried out in this paper for MCE (peak acc. 0.4g) has shown a remarcable difference from the corresponding results linear analysis.

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