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ANALYSIS OF SEISMIC RESPONSE OF HIGH ARCH DAM ON THE BASIS OF ENERGY BALANCE

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SUMMARY

The subject of this paper is seismic analysis of arch dam including nonlinear behavior of contraction joints under the strong earthquake excitations. The energy balance for the dam-reservoir-foundation system, in function of time, is considered. The effects of different energy dissipater installed in the contraction joint on the seismic response of arch dam are investigated.

The behavior of energy dissipater under cyclic loads are modeled by nonlinear springs and dashpots. It is shown that the devices increase the capacity of the structure to dissipate energy and may significantly reduce the seismic response of the structure, but not the change its natural periods particularly. The aim of the investigation is to determinate the possibility of establishing a balance of introduced and dissipated energy before the construction is turned into a mechanism, as one of the criteria for the assessment of dam safety.

In order to increase the energy capacity of the estimation model, in stead of the friction dampers, the rubber dumpers with appropriate characteristics are included. The results of the estimations showed that with implementation of the energy absorbers in joints, the energy balance can be established

In the paper, vertical joints, which would be the most suitable for energy dissipation, programmed behavior of the dam and passive control of seismic response, were investigated. The parametric analysis of seismic response of the dam dependency on the characteristic of joints with regard to different levels of viscous damping and friction and rubber damper was done. Through parametric analysis the values of viscous and hysteretic damping of chosen joints were determined which are necessary for the establishing of energy balance. On the basis of the values obtained, it is possible to construct joints with suitable characteristics with respect to energy absorption.

INTRODUCTION

The analysis of behavior and calculation of seismic response to high arch dams are very complex problems. It is contributed by serious consequences caused by its demolishment, then complex geometric and geomechanic characteristics of the dam and its environment, as well as the stochastic nature of the earthquake.

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).

With the constructions exposed to the earthquakes, besides the force balance, there should also be the balance between the energy that is entered into the system from the ground and the energy capacity of the construction. In the case of the construction made from the rigid materials, energy is mainly spent on friction and it is often not possible to achieve the balance point. It is the case with the high arch dams.

The dam is built of concrete as row of vertical cantilever block, which are reciprocal, interconnected with contact joints, which don't receive tensile stress. The dam is performed by layers from arch segments where the concreting is interrupted and in that way horizontal joint is formed as well as the potential place for horizontal fissure. The quantization of dam body for all estimated models is done according to vertical and horizontal joints.

Blocks and joints behave in different way. Even during strong earthquakes, blocks stay in the linear area of strain, while plastic behavior and energy dissipation mainly occur in the joints. From this it follows that energetic capacity of the dam depends on the energetic characteristics of the joints.

In this paper, safety problem by the earthquake influence is examined as high concrete arch dam "Grancarevo" which was built 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.

Seismic analysis showed that dam satisfies stress-strain criteria for both levels of earthquakes. It is not the case with energy balance, because the rigid joints are week energy dissipaters. Energy capacity of the dam can only be increased by construction of joints with bigger ability of energy absorption. In the abstract it is presented that it is possible to accomplish it with the dampers, which can be embedded in the vertical joints and in the joint place between dam body and rock.

ENERGY BALANCE DURING EARTHQUAKE

With the constructions exposed to the earthquakes, besides the force balance, there should also be the energy balance between the energy that is entered into the system from the ground and the energy capacity of the construction.

The infinitesimal work dW of an SDF system is expressed as:

$$dW = \{m(\ddot{x} + \ddot{x}_o) + c\dot{x} + f(x)\}(\dot{x} + \dot{x}_0)dt = 0 \tag{1}$$

where, m is the mass, c the constant damping coefficient, $f(x)$ the restoring force of system, x the displacement of mass relative to the base, and $\ddot{x}_0$ the acceleration of earthquake ground motion.

The work dW done by inertia force $m(\ddot{x}+\ddot{x}_o)$, damping force $c\dot{x}$ and restoring force $f(x)$ through absolute velocity $(\dot{x}+\dot{x}_0)$ over infinitesimal time interval dt.

The energy balance is equivalent to the equilibrium of dynamic forces. The energy balance is considered for a finite time interval whereas the equilibrium is considered at each instance. As the response is influenced by the past history, the concept of energy balance may give some insight into the response characteristics.

The incremental work dW done over duration t_1 to t_2 is evaluated for equation (1),

$$\int_{t_1}^{t_2} m\ddot{x}\dot{x}dt + \int_{t_1}^{t_2} c\dot{x}^2 dt + \int_{t_1}^{t_2} f(x)\dot{x}dt = \int_{t_1}^{t_2} m\ddot{x}_0\dot{x}dt \tag{2}$$

or

$$E_k + E_d + E_a = E_i \tag{3}$$

$$E_a = E_s + E_h \tag{4}$$

$E_k + E_d + E_a = E_k + E_d + E_s + E_h = E_i$
(5)

Next, we group energy terms, according to physical nature, into the folloving categories:

E_k = kinetic energy

E_k = viscous damper energy

E_a= absorbed energy

E_a= recoverable elastic strain energy

E_a= irrecoverable hysteretic energy

E_I = total earthquake input energy

Overall energy capacity of the construction equals to the total of E_k, E_d, E_s and E_h.

An important omission in this approach is that effects of soil-structure interaction ore ignored, and because of that significant energy loss mechanisms (nonlinear response of the and radiation damping) are the neglected. Total earthquake input energy that must be absorbed by the construction is decreased for the part which is going back from the construction to the soil.

The input energy decreases the increment with the increase of movement. Energy capacity increases because of the energy absorption in post-elastic phase. If the balance point does not occur before the

construction changes into mechanism, the construction will brake. The designing criteria of seismic resistant constructions stems from this, on the basis of the energy balance.
In the case of the rigid constructions, the energy is mainly spent on the dry friction and often it is not possible to achieve the balance point. With the ductile constructions, with the ability of huge plastic strain and energy absorption, before the final loss of stability, the possibility of achieving the energy balance in significantly higher, even in the case of strong earthquakes.

CHARACTERISTICS “GRANCAREVO” DAM

Introductory The "Grancarevo" dam has been analyzed. It is a high arch concrete dam of double curvature. Basic geometric characteristics of the dam are:

Construction height	123.00 m
Thickness on the top	4.600 m
Thickness on the bottom	26.914 m
Length in crown along the extrudes	349.31 m

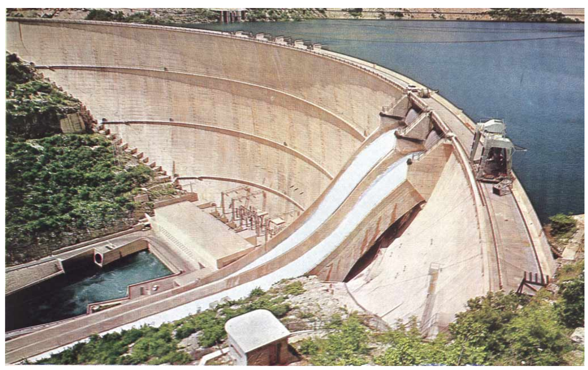


Fig. 1. –"Gran~arevo" dam

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.

SEISMIC PARAMETERS

Accelograms of the earthquake that took place on the Montenegrin Coast on 15 April 1979 have been used for the seismic analysis, 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

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.

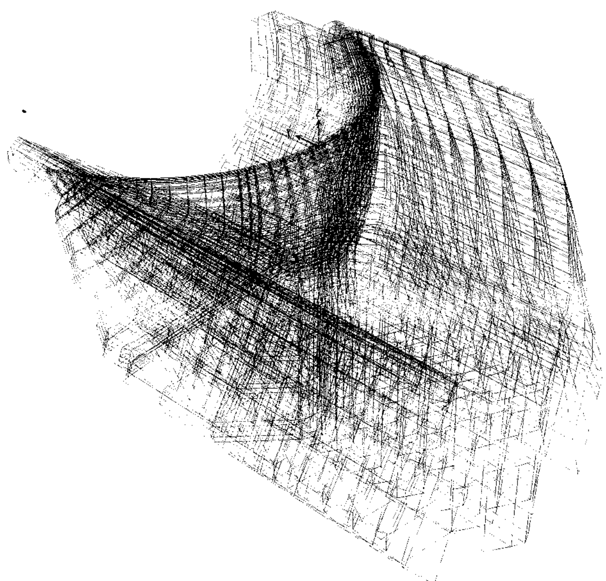


Fig. 2. Numerical model for coupled system dam-foundation-reservoir, elements plan

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 formed 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 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.

Modified for linear analysis is used for system of nonlinear analysis. Modification is consisted of entering model nonlinear elements. They are set in horizontal and vertical joints between solid elements and in the contact points of the dam and rock.

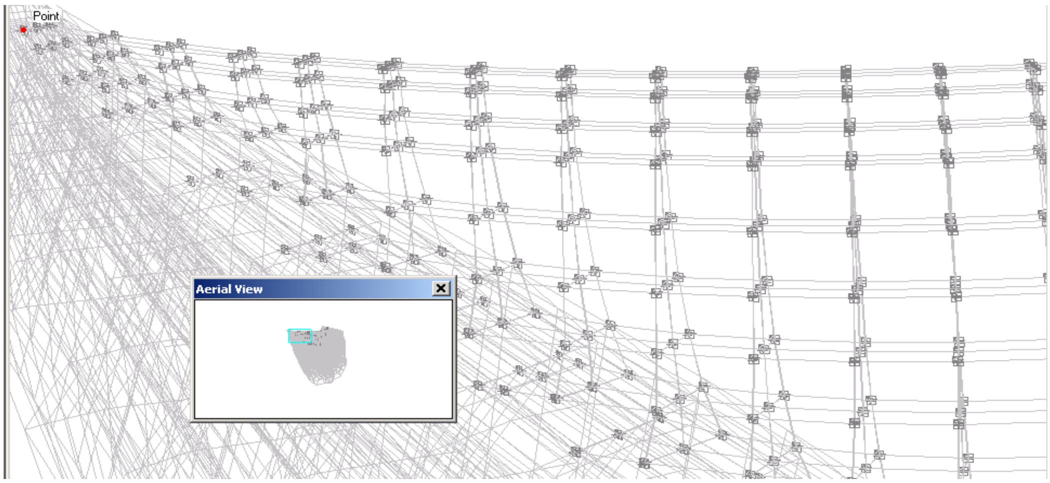


Fig. 3. Numerical model for coupled system dam-foundation-reservoir, elements plan (fragment)

Basis of nonlinear behavior is appearance, cracks expanding, and appearance of relative movements along the joints. Appearance of plastic deformity in blocks and joints is of secondary importance (Fig. 3.). For simulation of relative movements, contact elements of spring nonlinear type are applied. The adopted elements are those that can accept only compression. Each nonlinear element is composed of six nonlinear springs for echini of six interior strains.

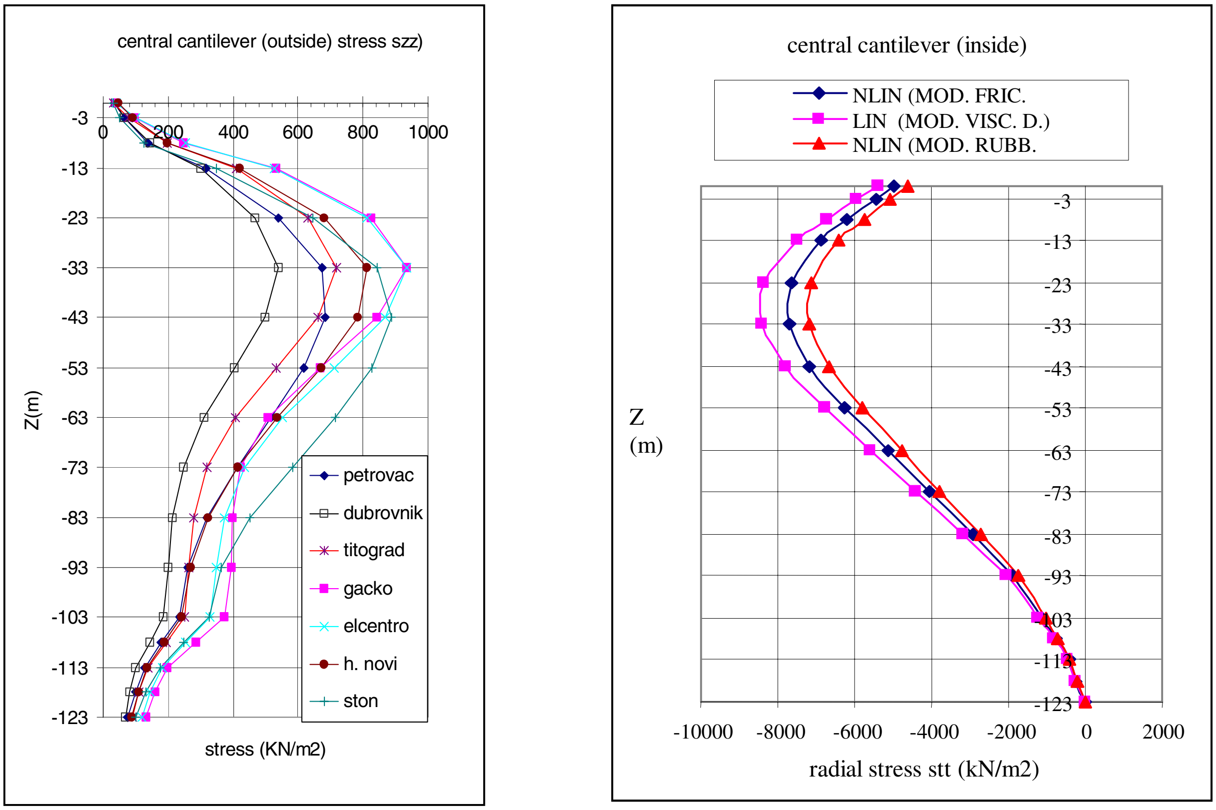
For energy capacity modeling, in the joints of the model and in the contact points of the dam and rock, different dissipaters of energy are embedded, and they are: friction dumpers and rubber dampers

RESULTS AND DISCUSSIONS

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 accelogram, basic difference was noticed for certain earthquakes. Namely, on Fig.4a. are shown comparative analysis of normal stresses along the axis Z $\mathbf{s_{zz}}$ in the central cantilevers. It is obvious that, depending on a type of effect and position of cross section, accelogram of earthquakes “Petrovac”, “Gacko”, “Ston” and “Herceg Novi” 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.

Accelogram “Petrovac” is accepted here as representative one for presenting the results of energy balance of this paper.



a/ for selected earthquakes b/for total load

Fig. 4. Radial stress σ_{tt} on central cantilevers (inside)

On linear analysis model with DBE earthquake effect, it is shown that fractures do not occur in dam body and that established criteria for dam stability is achieved. On the same model it is shown that with MSE earthquake in the combination with the other effects, the excess of concrete solidity on tension occurs.

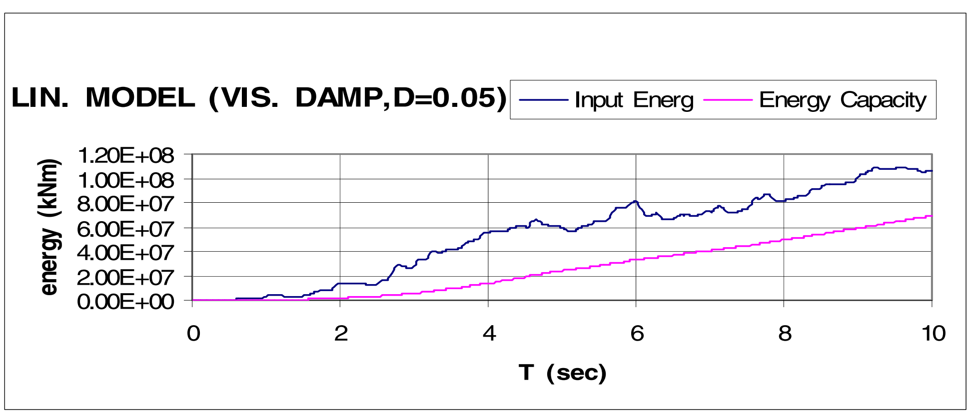


Fig.5. Time history of dam energy balance (linear analysis, viscous damping)

On linear analysis model, on which the joints are modeled with elements that can only accept the pressure stress, the reduction of the stress after dam entrance in non-linear area of strain is recorded (Fig. 4b.) It is shown that also with the MCE effect, the dam has the necessary stability regarding the stress and strains.

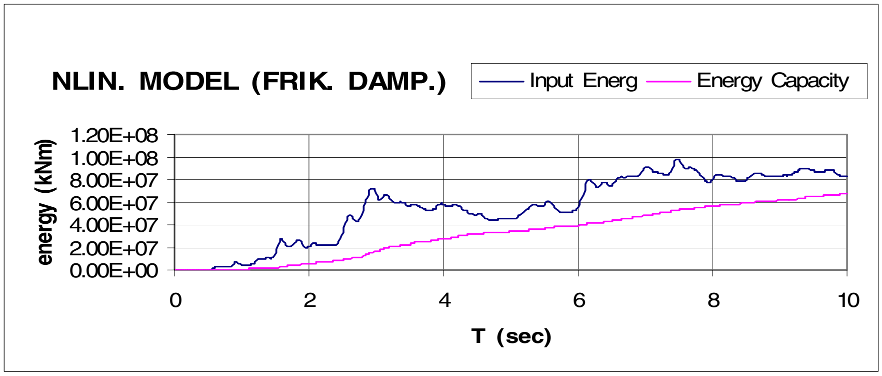


Fig.6. Time history of dam energy balance (nonlinear analysis, friction damping)

On the previous models, the dam stability is not proved regarding the energy balance. It is shown that with the earthquake effect, the dam input energy is higher than energy capacity. On linear analysis model, the damping is accepted as replaceable viscous damping of 5%, which is insufficient for establishing the energy balance. In estimated non-linear analysis model, besides viscous damping, friction damping is included, which occurs in rigid joints, after the fractures appear in them. This is simulated by the friction dumpers placed in the vertical joints. It appeared that the dam energy capacity is insufficient because of the small absorption capacities of the fragile joints.

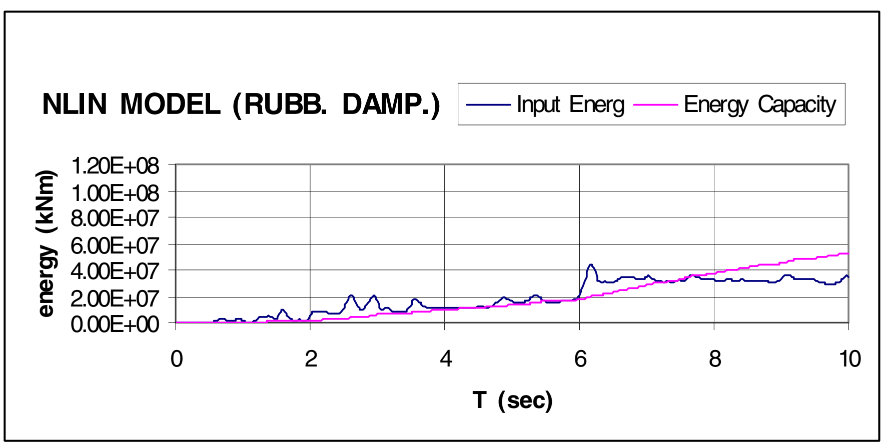


Fig.7. Time history of dam energy balance (nonlinear analysis, rubber damping)

In order to increase the energy capacity of the estimation model, in stead of the friction dampers, the rubber dumpers with appropriate characteristics are included. The results of the estimations showed that with implementation of the energy absorbers in joints, the energy balance can be established (Fig.7.).
Besides that, the earthquake effect is decreased for more than 50%, as well as decrease of the total stresses due to proper load of around 10 %.

CONCLUSION

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 a 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.

In block joints, there is a big dissipation of implicated energy, which could be increased by appropriate construction of block joints with abilities of damping. The results of the estimations showed that with implementation of the energy absorbers in joints, the energy balance can be established

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