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ANALYTICAL STUDIES OF NONLINEAR BEHAVIOUR OF ARCH DAMS USING SHAKING TABLE TEST RESULTS OF AN ARCH DAM FRAGMENT

Ljubomir TASKOV[1] and Dimitar JURUKOVSKI[2]

[1]Assoc. Prof. Ph.D., Head of Dynamic Testing Laboratory, Institute of Earthquake Engineering and Engineering Seismology, University "Kiril and Metodij", Skopje, Yugoslavia
[2]Prof., Ph.D., Director, Institute of Earthquake Engineering and Engineering Seismology, University "Kiril and Metodij", Skopje, Yugoslavia

SUMMARY

Presented in this paper are the results obtained by analytical studies of the nonlinear behaviour of an arch dam fragment subjected to simulated earthquake conditions. For the analysis of the nonlinear response, a discrete mass model has been formulated. It has been considered the central cantilever block with the two contact zones formed by the neighbouring halves. The nonlinearity of the model is assumed as a consequence of the nonlinear behaviour of the vertical expansion joints between the blocks. The physical parameters which control the nonlinear behaviour of the model were analyzed using the parameter system identification technique in time domain. The obtained analytical results show successful simulation of nonlinear effects previously defined by the shaking table test.

INTRODUCTION

The nonlinear response of arch concrete dams subjected to strong earthquake motions is a problem which requires particular attention. Considering the fact that so far no arch dam failure due to strong earthquake has occurred, there is not such experience on a world-wide scale. However, it is known that in case of a strong earthquake the behaviour of the dam body would, mainly, depend on the behaviour of the vertical expansion joints between the concrete blocks. Therefore, it is rather difficult to accept the analytical consideration without experimental data on the mechanism of the dam failure due to vertical joints influence on the dam stability.

For the purpose of understanding the failure mechanism, both experimental and analytical studies has been carried out at the Institute of Earthquake Engineering and Engineering Seismology in Skopje. The experimental studies consist of shaking table tests on an arch dam fragment. The obtained results were presented on the Eight European Conference of Earthquake Engineering, held in Lisbon in 1986, and they are mainly used in this paper as input data for developing of a nonlinear mathematical model of an arch dam

MATHEMATICAL FORMULATION OF THE PROBLEM

For analysis of the nonlinear response, a discrete mass model has been formulated. It has been considered the central cantilever fragment with two neighbouring fragments, simulating the boundary conditions of the contact zones. Despite its relatively simple shape, the mathematical model is rather complex since it simulates several types of nonlinearities: sliding in the contact zones, joint opening and crushing in the contact (Fig. 1).

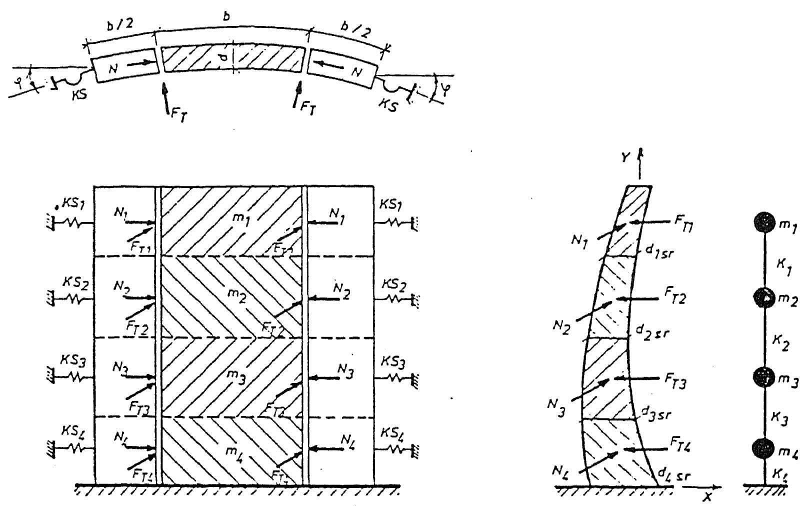

Fig. 1. Mathematical lumped mass model

To determine the dynamic response of nonlinear mathematical models it is suggested to apply direct integration of differential equations of motion (the step-by-step integration method) which enables to define the stiffness parameters of the system in each integration step, which are variable values as well as to simulate their nonlinear properties.

In literature there are various methods for numerical integration of the equations of motion. Their accuracy depends mainly on the integration step which should be small enough to to assure numerical stability of the solution.

The differential equation of motion of the central cantilever can be represented in the following matrix form:

$$[m]\{\ddot{x}\} + [c]\{\dot{x}\} + [k]\{x\} + 2\{F_T\}\ \mathrm{sign}(\dot{x}) = -[m]\{1\}\ \ddot{x}g \qquad (1)$$

The mass matrix $[m]$ is defined as a sum of the mass matrices of the dead weight $[m_o]$ and the added mass matrix $[m_a]$ of the hydrodynamic pressure:

$$[m] = [m_o] + [m_a] \qquad (2)$$

The stiffness matrix of the cantilever fragment is formed as a three diagonal matrix, adopting a single degree-of-freedom horizontal component of each mass so that while deriving the terms the effects of bending and shear in the cross-sections have been taken into account. The reduced degrees of freedom have been adopted because of load symmetry, the boundary conditions and the model geometry. The "x" direction, which is radial, is the predominant direction of deformations. The fragment is considered to be infinitely rigid in "y" direction, i.e., it is assumed that there is no rotation at the ends of the segment.

According to Rayleigh, it is assumed that the damping matrix is dependent on the mass and stiffness matrices,

$$[c] = \alpha[m] + \beta[k] \; ; \quad \alpha = \frac{2\omega_1\omega_2(\lambda_1\omega_2-\lambda_2\omega_1)}{\omega_2^2 - \omega_1^2} \; ; \quad \beta = \frac{2(\lambda_2\omega_2-\lambda_1\omega_1)}{\omega_2^2 - \omega_1^2} \tag{3}$$

The friction force F_T is defined for two states: when it occurs in the contact where no sliding takes place and its maximum value when sliding takes place in the contact.

For the case: $k_f(x-x_L) < N.f_T \; ; \; F_T = k_f(x-x_L)$ (4)

$k_f(x-x_L) > N.f_T = F_T = N.f_T$

In the above expressions the notations have the following meaning:

k_f - local sliding stiffness in the contact,

x - displacement of the body subjected to friction,

x_L - sliding in the contact,

f_T - friction coefficient.

The last term of the differential equation (xg) refers to input acceleration:

$$\{P_G\} = -[m]\{1\}\ddot{x}g \tag{5}$$

The external force vector $\{P_G\}$ is expressed as a product of the mass matrix and the acceleration vector at the base. In this case the foundation of the physical model is considered as a base.

The solution of the system of differential equations of motion (1) was obtained applying the step-by-step direct integration using the constant acceleration method.

IDENTIFICATION OF MODEL RESPONSE PARAMETERS FOR DIFFERENT EARTHQUAKE EXCITATIONS

Applying the "brute force" method identification of the dynamic model response parameters is carried out in time domain for the following earthquake excitations: EL CENTRO SPAN 10 and BREGINJ SPAN 15. The vector of the parameters taken in the optimization process are of the following form:

$$\{\alpha\} = \{E, \gamma, F_s, \lambda, fT_o\}^T$$

The parameter symbols have the following meanings:

E - modulus of elasticity of the mixture (MPa)
γ - bulk density (kg/m^3)
F_s - factor of spring stiffness
λ - coefficient of viscous damping (%)
fT_0 - coefficient of static friction between blocks.

The flow chart of organization of the computer programs for the parameter identification and the model nonlinear response is given in Fig. 2.

For the El Centro Span10 earthquake the parameter identification of the model is carried out for linear range of behaviour. The linearity is due to the

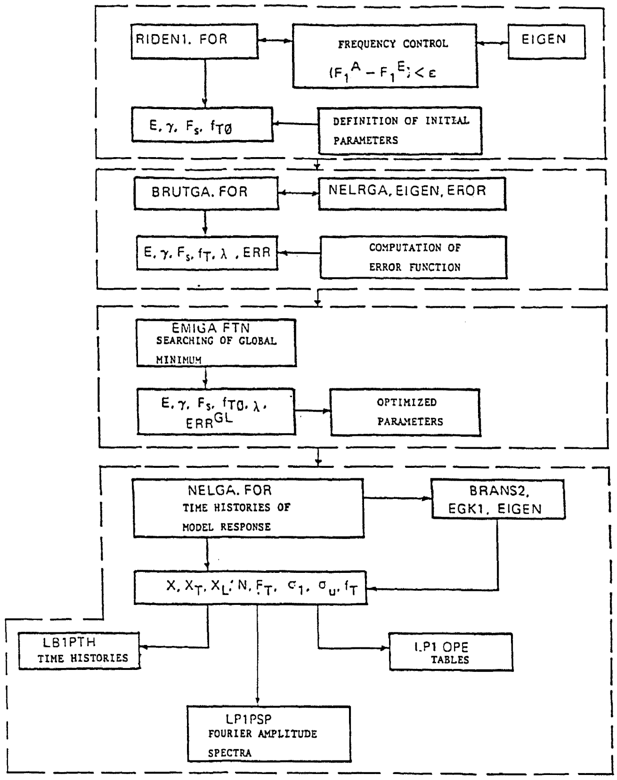

Fig. 2. Flow Chart of Organization of Computer Programs for Parameter Identification and Nonlinear Model Response

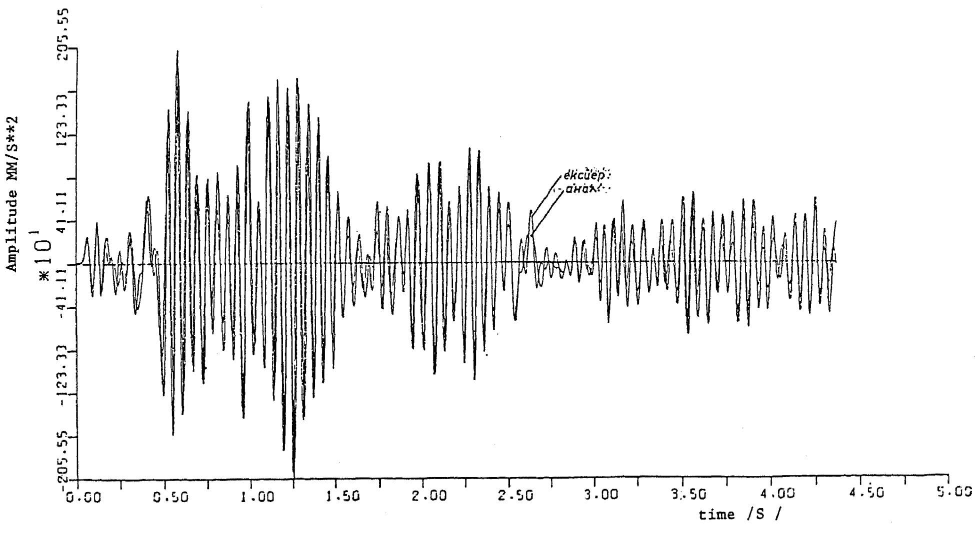

Fig. 3. Joint Presentation of Experimental and Analytical Acceleration Time Histories at the Top of the Model (El Centro Span10)

intensity of the input earthquake excitation, having a peak acceleration of $\ddot{x}g$ = 0.045 g. Fig. 3 shows a joint presentation of the experimental and analytical acceleration time history response at the top of the model.

For the Breginj Span15 earthquake the parameter identification refers to a typically nonlinear dynamic response of the model. The maximum peak acceleration of the input excitation is approximately 0.45 g.

Fig. 4 shows a joint presentation of both experimental and analytical acceleration time history at the top of the model.

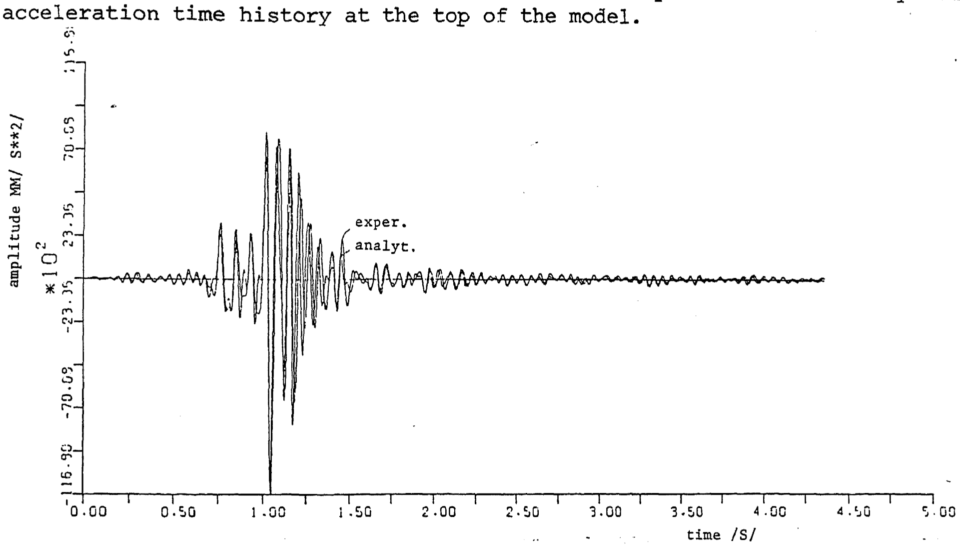

Fig. 4. Joint presentation of experimental and analytical acceleration time histories at the top of the model (Breginj Span15)

CONCLUSIONS

Based on the results obtained from the analytical studies with respect to mathematical model formulation and the applied parametric identification procedure, the following conclusions can be stated:

- The main concept of the model consists in simulation of partial failure of the joints depending upon the vibration intensity due to dynamic excitation. Accordingly, three representative stages of the dynamic response can be analyzed: linear response state (undisturbed contact joints), nonlinear response state (partly disturbed contact joints) and a state of failure.

- The following effects have been defined as more significant: sliding in the contact, crushing in the contact zone, opening of joints and friction reduction in the contact, depending on the level of input acceleration.

- Nonlinearity effects have successfully been investigated using the parametric identification applying the "brute force" method.
  Finally, based on the complete study presented in this paper a general explanation of the nonlinear behaviour mechanism of the model during a strong earthquake is possible, and can be applied to the prototype.

- In case of an intensive earthquake excitation, arch dams can sustain considerable stresses in the arches leading to partial physical disattachment of the vertical blocks along the contact zone. This mechanism of joints opening is further followed by crushing in the contact zone or increase in tensile stresses at the upper part of the cantilevers (1/2 to 1/3 the height) which may cause a partial or total failure of the dam.

The investigations presented in this study do not give complete answers to all the questions related to the problems of nonlinear behaviour of arch dams during strong earthquakes. Yet, the obtained results should be considered as a basis for further definition of the phenomena offering possibilities for improvement of the methods for aseismic design of arch dams.

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