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COMMENTS CONCERNING PRESENT REGULATIONS ON ARCH DAMS SEISMIC ANALYSIS.

A. POPOVICI, R. SARGHIUTA
Department of Hydraulic Structures, Technical University of Civil Engineering 124, Lacul Tei Bd., 72302 - Bucharest Romania
I. TOMA
Institute of Hydropower Studies and Design, 5-7, Vasile Lascar St., 79669 - Bucharest, Romania

ABSTRACT

Some limits of the presentday regulation on dams seismic analysis versus the capability of the advanced numerical methods are commented. The conclusions are based on comprehensive seismic analysis for DBE and MCE performed on Vafregan arch dam (H = 125 m, L_C/H = 144, Iran). A complete dam-reservoir-foundation finite element mesh was used for time history seismic response evaluation. The reservoir water was considered as a degenerated solid with shear modulus close by nought. The results confirm a general opinion that presentday regulations need to be improved based on new data obtained from case histories of arch dams subjected to strong earthquakes.

KEY WORDS

Earthquake numerical analysis, spectral method, time history seismic response, complete dam-reservoir-foundation finite element mesh, seismic stresses.

INTRODUCTION

The arch dams, as past experience emphasized, have high structural capacity to withstand to very strong earthquakes. Several arch dams built in various seismic regions behaved fairly well under strong earthquakes (Priscu *et al*, 1992)

However, the damage of the Pacoima dam (USA, H = 115 m) caused by strong San Fernando earthquake of 1971, has shown that arch dams could be damaged by seismic actions and which are also the possible damage patterns. The main damage consisted of disturbances occurred in the rock blocks on the left bank generating the shortened with 1.2 cm of the dam crest chord length and a vertical joint crack developed between dam abutment and the left bank support block. The field experience must be the main reference for developing the regulations for new projects, including seismic analysis models.

The presentday regulations concerning arch dams seismic analysis are based mainly on dam body stress criteria. The concrete compressive strengths are relatively high and even in the most severe earthquakes the compressive stress limits are very seldom reached. Instead the tensile strengths corresponding to a tenth from compressive ones are frequently reached, the concrete exhibiting in these cases brittle behaviour and the formation of cracks. Although the behaviour of the concrete and also of the foundation rock is significant nonlinear, the usual analyses are performed in the linear elastic range.

Additionally, some failure modes consisting of overturning or sliding-crushing failure of some concrete blocks are to be checked and also sliding of some selected foundation rock blocks must be taken into analysis.

Concerning the influence of the loading rate on the concrete maximum strength some tests carried out on 45 years old mass concrete samples, pointed out that under dynamic loads with high rate loading the ultimate strengths increase by 14% in compression and by about 72% in tension versus those under static loads. At the same time dynamic elasticity modulus increases by 33% in compression and by 24% in tension versus static one. The opinions to take into account these results are not convergent. The existence of some incipient cracks in the majority of concrete dams due to static, thermal loading, advises to caution in accepting of increased tensile strength in analysis of concrete dams under earthquake loading (Zienkiewicz *et al*, 1983).

The spectral analysis is usually applied for arch dams seismic response evaluation especially for DBE (design basis earthquake). The effect of the reservoir is included by added mass procedure. The estimation of the real response peaks by the probabilistic summation of the responses in the mode shapes can be considered in general as good. The number of mode shapes varies between 5 ... 50 depending of desired computation accuracy and performances of the software and hardware used. However, the nonlinear behaviour of materials, the effects of cracks or of dam-water- foundation interaction could not be modeled satisfactorily by this method. The later require the use of time history numerical integration methods.

Concluding this introduction one may point out that traditional methods for arch dams seismic analysis are unable to model significant phenomena associated to arch dams seismic behaviour especially under strong earthquakes. (Giuseppetti *et al*, 1993) (Carrere *et al*, 1993).

More refined numerical formulations based especially on finite element procedure for seismic analysis were developed in the last decades. They offer large possibilities to model of most earthquake response phenomena. For instance, in the arch dams seismic analysis field phenomena, nonlinear behaviour of the dam-foundation system materials, seismic cracks or dam joints opening, dam-reservoir-foundation interaction, damping rate variation, or variability of the seismic input along of the dam foundation can be modeled.

This paper tries to identify the ways for developing the arch dams seismic analysis regulations in compliance with the progress of numerical modeling. It is need to point out, too that problems concerning the prediction of earthquake motions or their probabilistic distribution in the site were not the subject of this paper. Consequently, we assume that DBE (design basis earthquake) and MCE (maximum credible earthquake) are apriori known at the bedrock level or at the dam base.

The support of comments are the results of some comprehensive seismic analysis for DBE and MCE performed for Vafregan arch dam (H = 125 m, Iran). The design of this dam was elaborated by Mahab Ghodss Consulting Eng. Co.-Tehran with technical cooperation by Romconsult Consulting Co.-Bucharest (Tarkeshdooz *et al*, 1991).

INPUT DATA AND MATHEMATICAL MODELS.

Vafregan arch dam with 125 m maximum height is located in almost symmetrically narrow gorge consisting of massive limestones, slated conglomerates and stratified limestones. The most significant geometrical data about Vafregan arch dam are presented in Table 1.

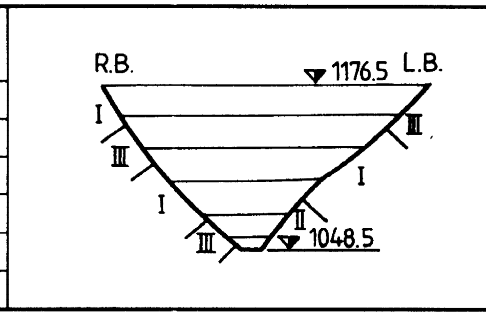
Table 1

Maximum height	125 m
Crest length	264 m
Crest cord length	224 m
Central section thickness at crest level	6.00 m
Central section thickness at dam base	20.00 m
Concrete volume of the dam	320.000 cm

The mechanical characteristics of the dam-foundation system materials are illustrated in Table 2, including elevation distribution of that three types of rock qualities existent in the dam foundation.

Table 2

Type of materials	Young moduli (MPa)		Poisson ratio	
	Static	Dynamic	Static	Dynamic
Concrete	20000	26500	0.17	0.21
Rock I type	7500	12000	0.25	0.30
Rock II type	5000	8000	0.30	0.35
Rock III type	3000	5600	0.40	0.45



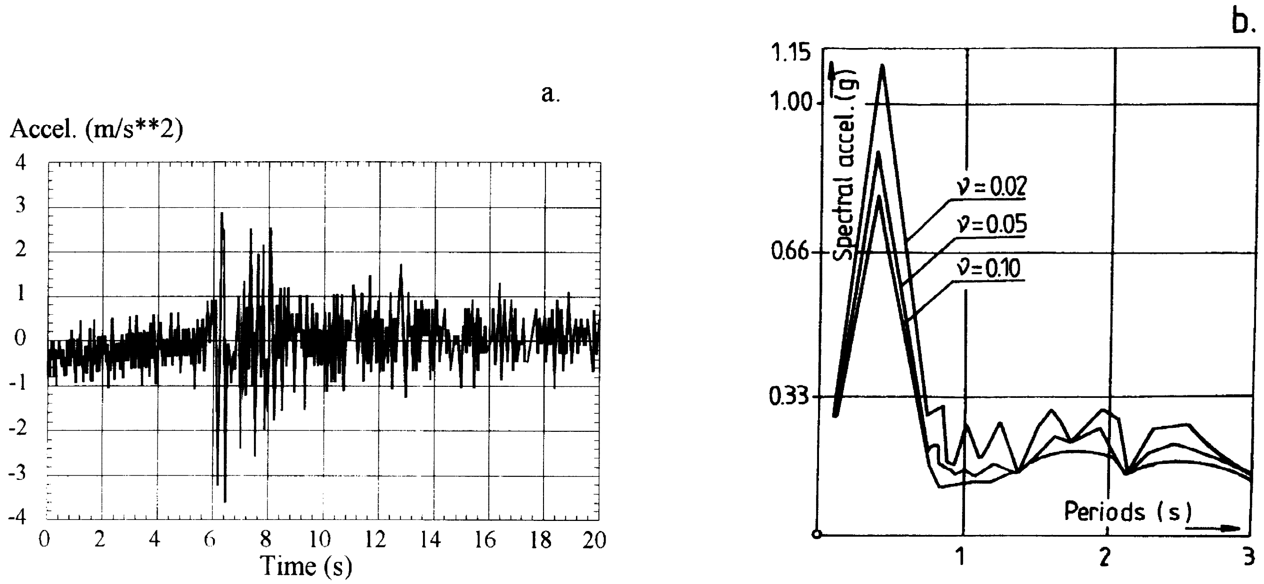


Fig. 1. Input seismic data: a- MCE accelerogram; b-seismic response spectrum corresponding to MCE accelerogram.

The seismic hazard of the site was evaluated by regional earthquake history analysis and also was based on two probabilistic methods, namely, seismic linear model for main faults associated to dam site and asymptotic distribution method (Gumbel III, extreme values) by seismic events of the XXth century processing. The maximum seismic accelerations were 0.25 g (g - gravity) for DBE and respectively 0.36 g for MCE. A regional recorded moderate earthquake scaled for MCE and associated response spectrum, which were used in seismic analyses can be seen in Figure 1.

Various mathematical models for dam static, thermal or seismic analyses were used for various stages of the dam design or construction. The models were based on finite element procedures or TLM (trial load method). Some well known international computer codes like ANSYS 5.0, SAP IV and SAP90 or others elaborated by authors were applied in various stages for performing the dam seismic analyses. More details about the hypotheses accepted in these models will be given in the next items.

RESULTS BY SPECTRAL ANALYSIS.

This method was used in the dam seismic analysis for DBE. The main assumptions considered in the dam spectral analysis were the following:

- incompressible water in reservoir, the water effect being modeled by added mass procedure; the influence of the dam-reservoir system geometry on added mass coefficient was taken into account by Popovici method (Priscu *et al*, 1985);
- massless but flexible foundation with isotropic characteristics but varying from zone to zone;
- seismic response spectrum ν = 5% and 10 % (ν - fraction of critical damping) compatible with DBE accelerogram applied on horizontal upstream-downstream direction;

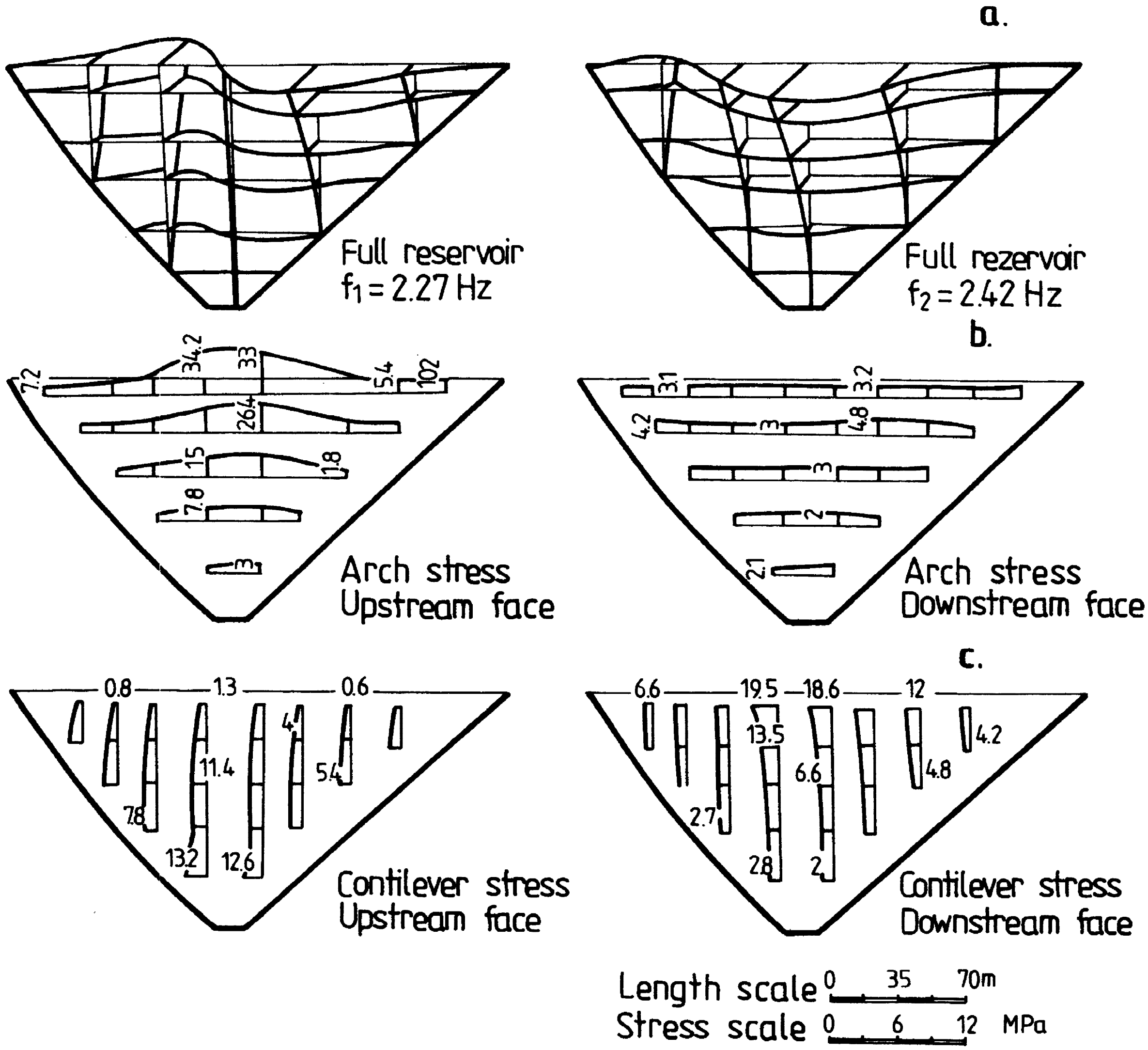


Fig. 2. Vafregan dam - spectral analysis: a-mode shapes; b-seismic arc stresses due to horizontally U/D response spectrum ν = 10%; c-seismic cantilever stresses in the same conditions

Table 3 and figure 2 illustrate some results obtained by this analysis. The maximum seismic stresses in dam body are placed in the superior upstream face central zone. In this zone the normal stresses on horizontal direction reach up to 3.3 ... 3.4 MPa. The combination of dead load + hydrostatic pressure + DBE earthquake leads to maximum compressive stresses of 7.1 MPa and to maximum tensile stresses of 1.5 MPa. The stresses are important but taking into account the dynamic, transient, short time character of the seismic stresses, it was concluded that dam can withstand DBE free of damage.

The strong influence of the damping rate on seismic stresses level was pointed out be spectral analysis. For instance, the increase of ν from 5 % to 10 % led to decrease of corresponding seismic stresses with about 50%. The dams damping properties, as is known, are in large limits depending of particularly characteristics of each dam site and dam body itself and also direct proportionally with the amplitude of seismic shocks. Consequently, an important parameter conditioning the dam body seismic stresses level is usually evaluated only by coarse approximation.

Table 3.

	Vafregan dam - Natural frequencies in Hz					
Number of the frequency Hypothesis	1	2	3	4	5	6
Empty reservoir	2.99	3.37	4.63	5.62	6.12	6.30
Full reservoir	2.27	2.42	3.37	3.52	3.71	4.02

RESULTS BY TIME HISTORY ANALYSIS.

The analysis was performed in three-dimensional finite element mesh of the dam-reservoir-foundation system illustrated in Figure 3. The reservoir water was considered as a degenerated solid with shear modulus close by nought; compressive modulus of the water was 2000 MPa. The same type of three-dimensional element SOLID 45 with 4 ... 8 nodes - according to ANSYS 5.0 computer code - was used in meshing of the dam foundation and reservoir. In order to model the absorbent effect of the reservoir sediments some dampers COMBIN14 were considered at the reservoir bounds.

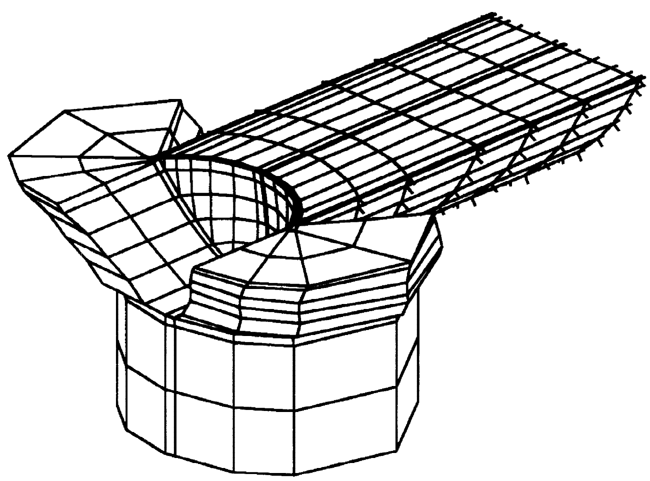


Fig. 3. Axonometric view of the finite element mesh used in time history response analysis

The structural damping matrix was evaluated in compliance with linear Rayleigh model. The parameters of the model were compatible with the fraction of critical damping of 0.05 in first and second natural modes of the dam in full reservoir hypothesis. A sequence between 4.0...9.0s of the accelerogram presented in Figure 1, with 0.36 g maximum acceleration was synchronically applied horizontally upstream-downstream at the bottom nodes of the system. The numerical integration time step was variable of about 0.02 s.

Other hypotheses in this analysis were the following:

- linear elastic behaviour of the concrete and of the foundation rock materials ;
- small strains and displacements ;
- massless foundation ;
- take into account of the water compressibility and of the absorbent effect of the reservoir sediments;
- take into account of same cracks or vertical grouted joints opening effects on dam body stresses redistribution;

Some results obtained in this analysis are shown in Figures 4..6.

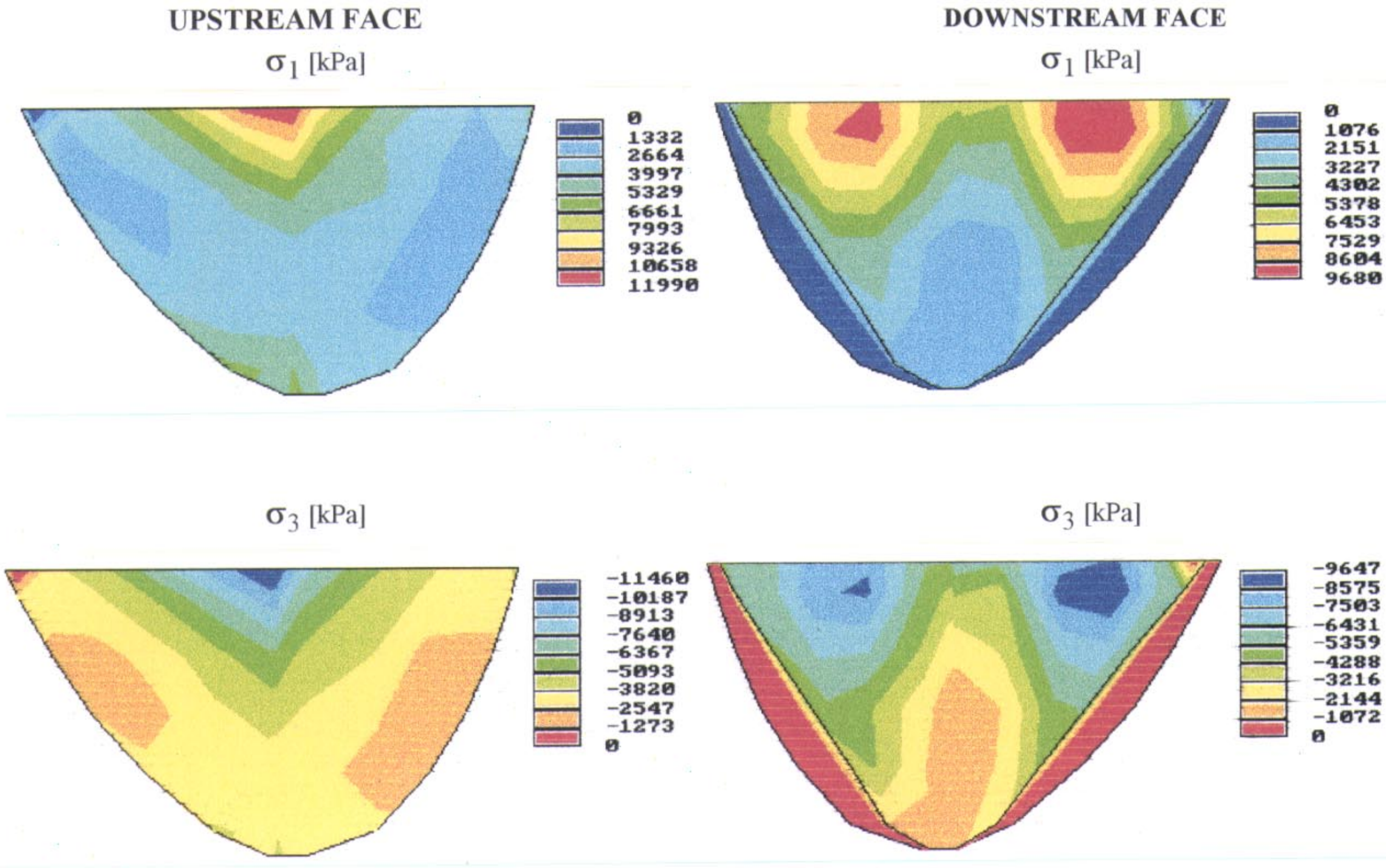


Fig. 4. Vafregan dam - contours of the maximum principal stresses due to MCE a_{max}=0.36g, horizontally U/D

The contours of maximum σ_1 and σ_3 seismic stresses point out that dam crest central zone is the most exposed to loss its integrity during MCE (fig. 4). The maximum seismic tensile stresses in this zone reach 11.9 MPa on upstream face. Of course, the accepted hypotheses as linear elastic behaviour of materials or damping rate of only 5% for first and second natural modes are very conservative. On the other hand, the analyses performed taking into account some cracks in dam body or grouted joints opening stressed the high capacity of the dam to withstand in condition of stresses redistribution.

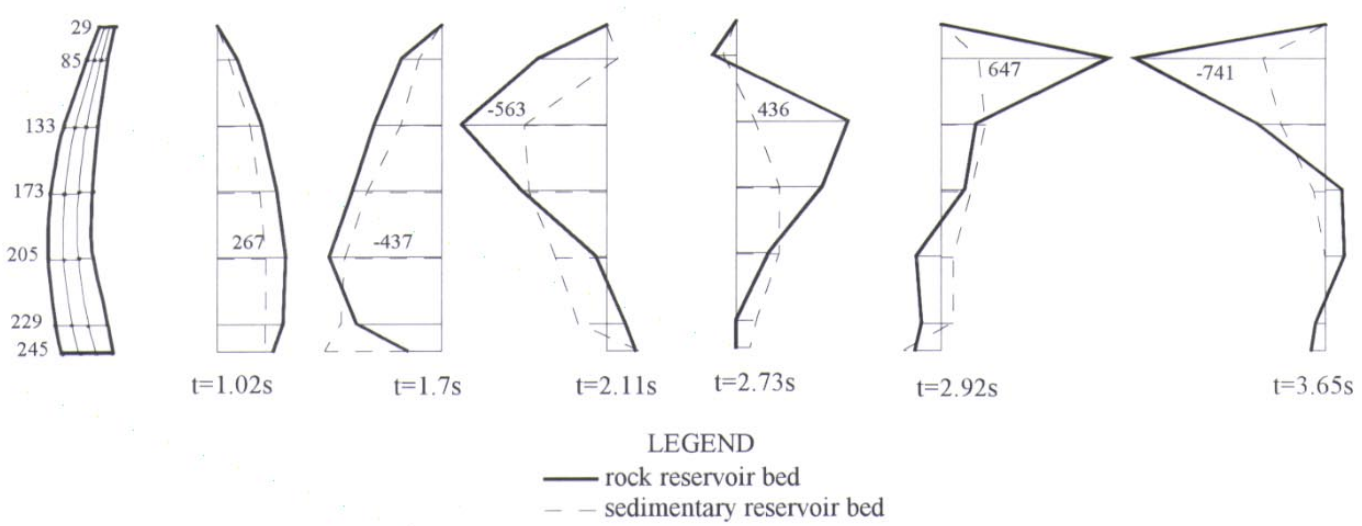


Fig. 5. Hydrodynamic pressures diagrams at various time instant on dam upstream face-central section due to MCE applied horizontally U/D (results in kPa)

The diagrams of hydrodynamic pressures at various time instants during MCE (fig. 5) emphasize the very important damping effects of the sediments from reservoir bed. The reduction ratio of the correspondent values is about 0.5 versus rock reservoir bed. Moreover, the diagram shapes taking into account the dam-water interaction and water compressibility are much different versus well known Westergaard diagram.

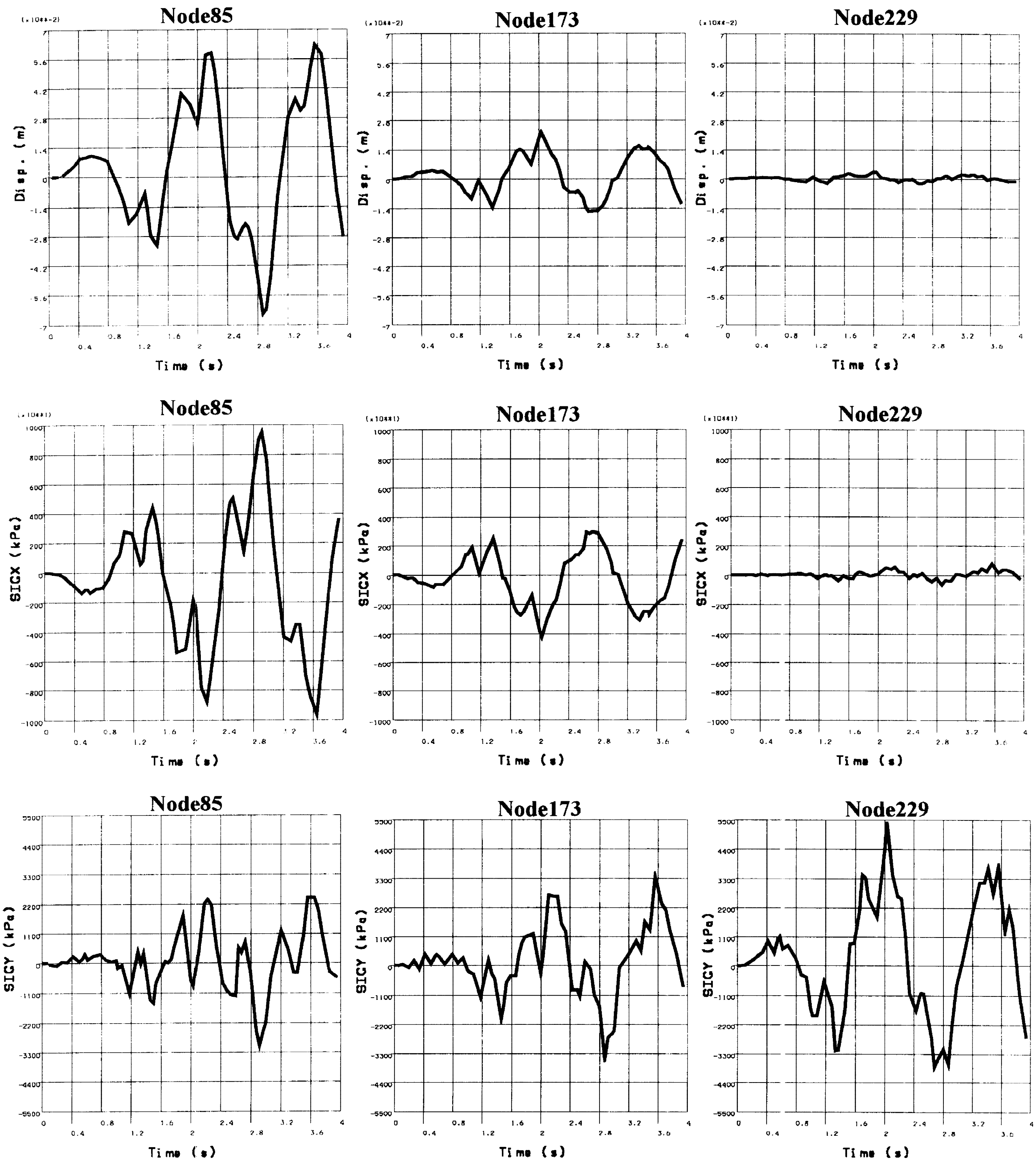


Fig. 6. Time history response oscillograms due to MCE applied horizontally U/D (see nodes in Fig. 5)

As a general conclusion, which can be formulated according to above presented seismic analysis as well as past experience of the arch dams subjected to strong earthquakes is that some cracks in the dam body or dam foundation can occur due to MCE but this does not lead to uncontrolled release of water from the reservoir.

COMMENTS AND FINAL REMARKS.

The progresses in numerical methods associated to software and hardware spectacular development offer to design engineer large possibilities to analyse by mathematical models the most complex problems previously totally intractable.

The applications presented in this paper illustrated the capacity of the presentday numerical methods based on finite element procedure to offer solutions in some complex problems concerning arch dams seismic analysis as follows: dam-reservoir-foundation complete interaction, effects of dam body cracks or of vertical joints opening, effects of water compressibility and of absorbing energy on the reservoir bed and so on. They pointed out the remarkable potential of the analysed arch dam and generally of arch dams to withstand at strong earthquakes.

However the question arising is about confidence in these results supplied by advanced mathematical models but frequently built on input data less or only approximately known as material characteristics or input accelerograms. We think that selection of the mathematical models must be directly connected to degree of input data knowledge. Consequently, it is not recommended to choose sophisticated method of analysis beyond of knowledge of the physical parameters available but it is equally imprudent to expect all answers from the analysis which ignore important features of the problem.

Moreover, the presentday regulations concerning arch dams seismic analysis need to be improved based on new data obtained from case histories of existent dams subjected to strong earthquakes. In fact, the results of some computations according to presentday regulations concerning arch dams seismic safety can be in contrast with the actual state; many of the existent arch dams have proved remarkable potential to withstand strong earthquakes.

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