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REEVALUATION OF THE SEISMIC SAFETY OF A LARGE ARCH DAM COMMISSIONED THIRTY YEARS AGO

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ABSTRACT

Vidraru dam, H = 167 m, the highest arch dam in operation from Romania was commissioned in 1965. The new data concerning a seismic source in the neighbouring of the dam and nowadays seismic safety regulations imposed the seismic safety reassessment of the dam. The input data were acquisited by geophysical in situ investigations and by dam monitoring data processing. Synthetic accelerograms were generated. The analyses were performed by spectral method for DBE and time history linear elastic method for MCE. Some hypotheses with the dam damaged during MCE were also analysed. Special analyses by rigid block method concerning seismic sliding stability of the dam banks were performed. The study, pointed out the remarkable potential strength of the Vidraru dam to withstand strong earthquakes.

KEYWORDS

Earthquake numerical analysis; geophysical investigations; synthetic accelerograms; time history seismic stresses; dam banks sliding stability.

INTRODUCTION

The periodical safety evaluation of in operation dams is a current international practice. This is strictly necessary in order to prevent possible collapses or severe damage of these structures which are always associated with loss of human lifes, echological disasters and unmeasured material loss.

Ageing of dams, environment effects like strong earthquakes but also the new dam safety exigencies and the improvement analysis procedures are the main factors that required to carry out periodical evaluation of the safety of dams (Fanelli, 1980).

Vidraru dam, the highest arch dam in operation from Romania was commissioned in 1965 year. The layout of the dam and its central cross-section can be seen in Figure 1.

During dam design time the available data concerning seismic activity in the Vidraru dam site and neighbouring zone were limited. Also the mathematical methods for arch dam earthquake analysis were under development. In compliance with usual practice at that time, the seismic analysis of Vidraru arch dam was performed for an earthquake of VII MSK maximum intensity degrees (0.1 g; g - gravity) due to Vrancea focus. Vrancea focus generating subcrustal earthquakes is the most important for seismic activity in Romania area and is located at about 160 km from Vidraru dam site (fig. 2)

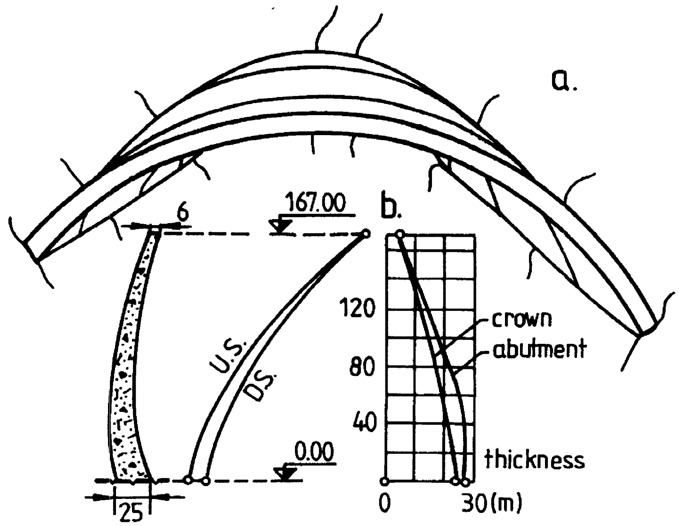

Fig. 1. Vidraru Dam: a-layout, b-central section with main geometrical characteristics

Until now, Vidraru dam was shaken by three strong Vrancea earthquakes, as follow: 4th March 1977 (M = 7.2), 31st August 1986 (M = 6.5) and 30th May 1990 (M = 6.5). However, due to long epicentral distance, the maximum intensities of the above mentioned earthquakes in the Vidraru dam site were evaluated between VI ... VII MSK degrees (0.15 g maximum acceleration). The dam behaviour under these seismic loads was very good; no cracks or damage in the dam body or dam foundation were noticed after these exceptional events.

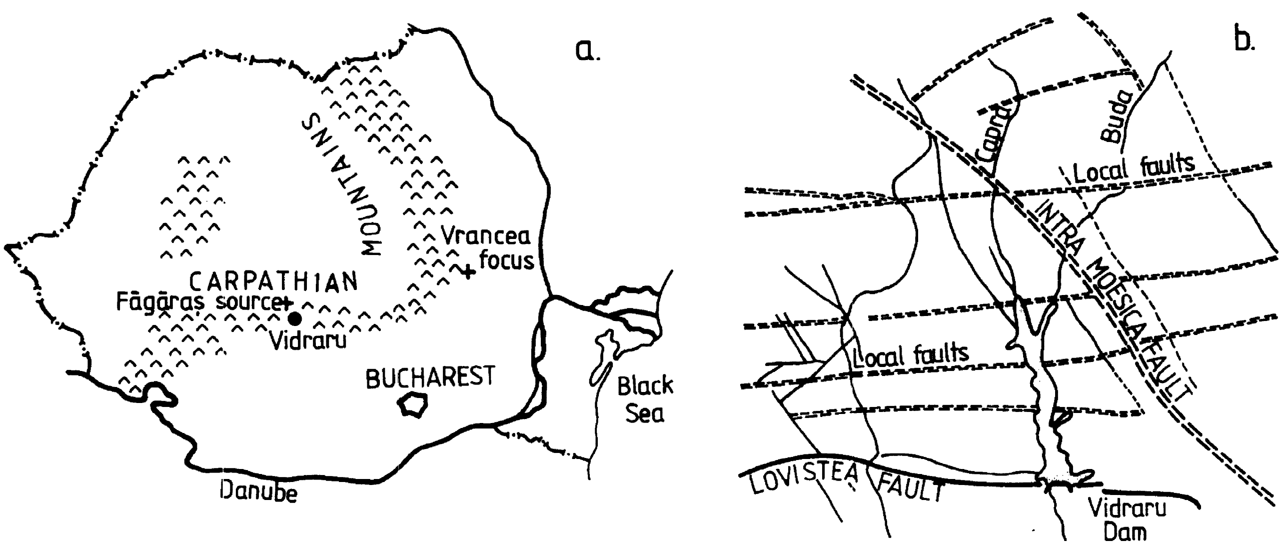

Fig. 2. The main seismic sources generating earthquakes in Vidraru dam site:
a-Vrancea, b-Fagaras (Lovistea fault)

The knowledge concerning arch dams behaviour under seismic loads were large developed in the last years, after Vidraru dam commissioning. New regulations for dam seismic protection were elaborated in this period by ICOLD and also by Romanian government authority. They concretised a valuable experience gained from large dams that were subjected to strong earthquakes, from in situ and laboratory testings concerning dam seismic behaviour or from results of the seismic analyses performed by numerical mathematical methods based on finite element technics (Priscu *et al.*, 1985).

On the other hand, seismological studies had shown that for Vidraru dam safety more concerning than Vrancea focus seismic activity is the Fagaras seismic source located at the upstream tail of the Vidraru reservoir, about 15 km from the dam (fig. 2). This source located on a major regional fault generates very destructive crustal earthquakes with return period of about 85 years. The last destructive Fagaras earthquake has been in 1916 (M = 6.5) and it provoked some slides in the mountainous neighbouring zone of the epicentre.

The recent seismological site studies concluded that seismic activity due to Fagaras source generates an increased seismic level in Vidraru dam site more than that considered in its design. The nowadays national regulations concerning dam seismic safety required a reassessment of Vidraru arch dam seismic safety. This analysis has benefited by the richness of data acquisited during the 29 years of the dam monitoring as well as the spectacular progress of the numerical analysis methods developed in this time. Some main results of this comprehensive analysis are presented in this paper.

GEOLOGICAL AND SEISMOLOGICAL DATA

Vidraru dam site is located in the narrow gorge of the Arges river from Southern Carpatian chain. The foundation rock for the dam is a hard and compact ocular gneiss with allowable strengths of 8 MPa on the left bank and respectively of 6 MPa on the right one. The valley becomes large open at about 500 m upstream of the dam, where sedimentary rocks (marlstone, gritstone claystone schists) are prevalent.

On the contact between sedimentary deposits and crystalline zone near the dam site there is Lovistea fault, which is the source of the crustal Fagaras earthquakes, the most concerning for the dam. Ten kilometres East of the dam there is another important regional fault, named Intramoesica. Other three major faults are crossing this zone North from the dam (fig. 2).

The analysis of macroseismic events has shown that Vidraru dam site is subject to earthquakes generated by two main sources, as follows:

- subcrustal earthquakes from Vrancea zone (focal deeps: 60 ... 174 km, epicentral distances: 130 ... 183 km);
- crustal earthquakes from Fagaras zone (focal deeps: 5 ... 33 km, epicentral distances less than 50 km).

The strongest earthquake observed in Vidraru dam site seems to have been Fagaras earthquake from 26.01.1916 with about VII + MSK intensity degrees in the dam site.

The seismic monitoring of Vidraru dam started in 1975 when a fixed seismic station was installed. Two years later, three telemetric seismic stations were installed around the reservoir. In 1981 year, 4 new accelerographs SMA-1 were installed, three of them in the dam cross-section and one in the free field on the river left bank.

The processing of the data recorded by Vidraru dam site seismic monitoring during 1981 ... 1993 years conducted to the following conclusions (Toma *et al*, 1994):

- ❑ in the area with 50 km radius around the dam site were registered in this period 15 earthquakes, the most important being of M = 4.1 (maximum intensity I_0 = IV MSK degrees) in 20.05.1984;
- ❑ temporal variation of the magnitude pointed out a constant feature;
- ❑ generally, the seismic activity in this period may be characterised as being of low level.

The seismological recorded data associated with regional tectonics and historical seismic data, especially the earthquake from 26.01.1916, allowed to make predictions on Fagaras earthquakes for both DBE (design basis earthquakes) and respectively MCE (maximum credible earthquakes) levels.

The geological profile used for the convolution of the base rock nonstationar white noise signal, in order from the surface, consisted of the following layers:

- surface layer consisting of clay and gravel with 2.5 cm thickness and G_{max} = 18 MPa, V_S = 100 m/s (G - shear modulus, V_S - velocity of shear waves);
- alluvium layer with 10.00 m thickness and G_{max} = 290 ... 700 MPa, V_S = 400 ... 620 m/s ;
- crystalline schists layer with some altered rocks inserted, thick of 85 m and G_{max} = 2140 ... 7600 MPa, V_S = 1000 ... 1800 m/s;
- hard rock of crystalline type thick of 400 m and V_S = 2000 ... 2750 m/s.

The base rock white noise signal was processed in order to consider the influence of crustal focuses and especially of the Fagaras earthquake from 26.01.1916. The signal convolution through above mentioned layers placed over base rock was performed taking into consideration the non-linear compatible curves between shear strains (γ %) and dynamic shear moduli (G), respectively fractions of critical damping (D %).

The free field synthetic accelerogram at the soil surface resulted with maximum value of 0.26 g for DBE and respectively 0.53 g for MCE. The maximum acceleration values were consequently 2.6 time higher than had been considered in the dam design.

The design spectra for both DBE and MCE were built as envelope spectra of the seismic response spectra for six synthetic accelerograms. The spectral values were compared and correlated with those recommended by International Agency for Atomic Energy from Vienna (50-SG-51,1980).

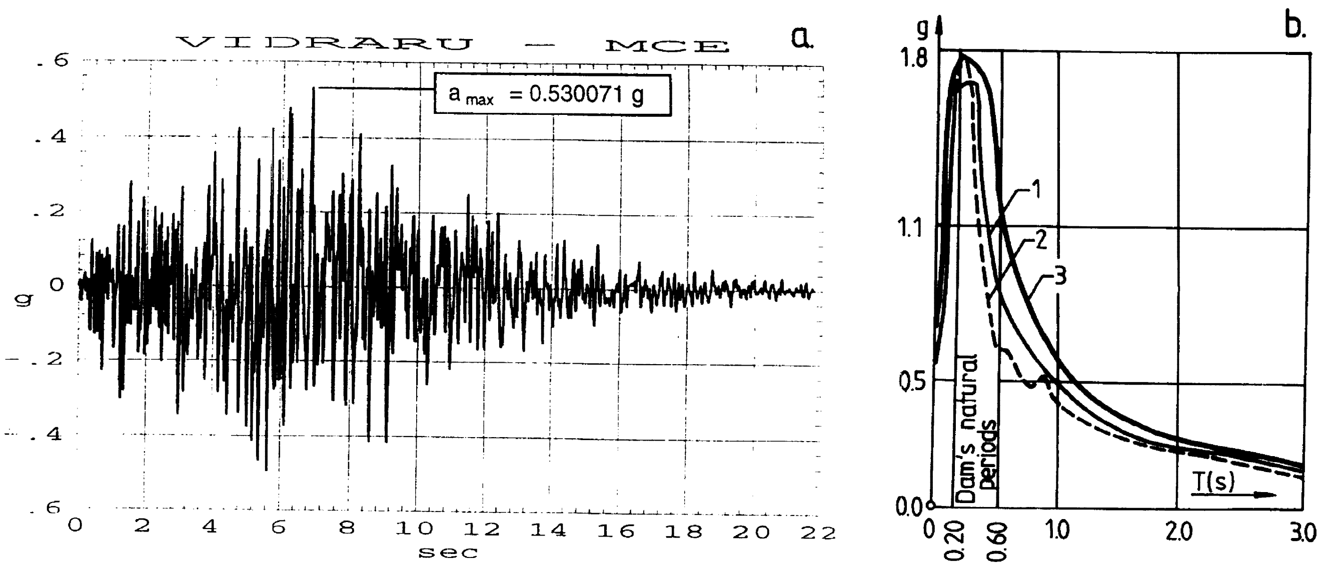

Fig. 3. Input seismic data: a-MCE Fagaras accelerogram; b-MCE horizontal direction, D=5% response spectrum: 1-according to r61.60/INFP, 2-envelope synthetic accelerograms, 3-global envelope.

In figure 3 are presented the MCE horizontal upstream-downstream direction accelerogram and corresponding response spectrum for damping rate v=0.05 both of them used in the dam seismic analysis

INVESTIGATIONS IN SITE IN ORDER TO CALIBRATE MATHEMATICAL MODELS.

Vidraru dam during its construction time and before commissioning was equipped with numerous surveying equipment in order to perform a comprehensive monitoring. Some direct and inverse pendulums, horizontal clinometers, rockmeters, deformeter marks, teleformeters, teledilatometers, hydrometers, telepresmeters, telependulums, flowmeters, bank's slide stability marks allowed for to collect a lot of data concerning dam behaviour. Their processing pointed out a normal behaviour of the dam for all its different operation stages. They allowed also for a better calibration of the mathematical models for static and dynamic analysis of the dam (Popovici *et al*, 1992).

Some geophysical investigations were carried out in Vidraru dam site during 1993 year in order to evaluate dynamic mechanical characteristics of the dam body and of the foundation rocks. These investigations were carried out by refraction method in different accessible zones from dam site as follows: both dam banks at the crest level, dam downstream face at four levels corresponding to existent footbridges, dam downstream base, upstream and downstream walls of those nine horizontal galleries crossing the dam body. Some results of these investigations can be seen in Table 1 (the values of parameters are the average ones).

Table 1

	V_p (m/s)	V_s (m/s)	E_{dyn} (MPa)	G_{dyn} (MPa)	μ_{dyn}
Left bank	3900	1950	25700	9520	0.33
Right bank	4325	2275	33700	12900	0.31
River bed	4800	2750	47600	18900	0.26
Dam body	4890	2820	49800	19920	0.25

V_p - velocity of primary waves, V_s - velocity of shear waves
E_{dyn} - dynamic Young modulus, G_{dyn} - dynamic shear modulus
μ_{dyn} - dynamic Poisson coefficient.

In situ natural vibration tests were carried out periodically both during dam construction and during its operation, for empty reservoir case and also for full reservoir one. The vibrations were generated by small blasts carried out nearby the dam or by heavy traffic on the dam crest. Also during in site moderate earthquakes from 1986 and 1990 years due to Vrancea focus, the recordings of the seismic stations supplied important data concerning dam dynamic characteristics. Through these records one could identify the lower natural frequencies and associated mode shapes and also the critical damping ratios for the natural modes

The results pointed out an increase versus time of the dam global stiffness, associated with the concrete age in the first year after pouring and especially with joints grouting. The fractions of critical damping in all the tests had values of 0.005 ... 0.022, consequently very small values justified by very low level of excitations.

A way to calibrate mathematical models for dynamic analysis is based on the coincidence between values of computed natural periods and of associated recorded ones. In the Table 2 are synthetized some results on this subject.

The global analysis of data obtained from varied investigations justified to perform the Vidraru seismic analysis using the value of 29000 MPa for concrete dynamic Young modulus (E_{dyn}). As is known, the rate between E_{dyn} and corresponding static Young modulus E_{st} for concrete is cca 1.25 ... 1.35 in compression and 1.1 ... 1.25 in tension. Consequently, a concrete static Young modulus of 22500 MPa was considered in the dam static analysis. Both, static and dynamic analyses were performed in the linear elastic hypothesis of materials behaviour from dam-foundation meshed system (Popovici *et al*, 1987).

Table 3

Periods	Computed values (s)				Values resulted from recordings (s)		
E_{dyn} (MPa)	26500		37000				
Hypothesis about reservoir	empty	full level 831	empty	full level 831	1964..66 empty	1986 level 775	1995 level 795.3
T_1	0.4537	0.6042	0.2940	0.5128	0.42	0.52	0.55
T_2	0.3673	0.5504	0.2800	0.3100	0.37	0.46	0.48
T_3	0.2635	0.3446				0.36	0.38
T_4	0.2253	0.3029				0.28	0.32
T_5	0.2229	0.2707				0.18	0.18

The structural analyses were performed with ANSYS5.0 computer code. STIF45, isoparametric C° class finite elements including incompatible modes for bending modelling having 6 ... 8 nodes per element, each of them with 3 translation degrees of freedom, were used for both dam body and foundation solid mesh.

In order to obtain a satisfactory accuracy of the numerical results, three lines of STIF45 elements were considered in the dam thickness. An axonometric view of the dam-foundation finite element mesh can be seen in Figure 4.

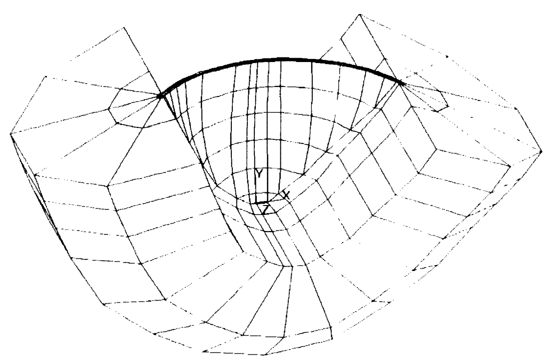

Fig. 4. Axonometric view of the finite element mesh

The seismic analyses were carried out by spectral analysis method for DBE and by time history method based on numerical integration of the system motion equations for MCE. The reservoir influence on dam seismic response was considered by added mass procedure. They were evaluated in compliance with system geometry, earthquake direction and system degrees of freedom directions. The damping matrix was evaluated by linear Rayleigh model (Priscu *et al*, 1985).

According to linear elastic materials behaviour accepted for all of structural analyses, the superposition of the stresses due to various loads was possible. Consequently, the seismic stresses were algebraically added to the existent static stresses at the earthquake starting. The static stress state was due to dam weight load (dead load), hydrostatic pressures due to reservoir water and environmental temperatures effect load. It can be remarked that dam weight load was applied only on dam cantilevers, taking into account that dam joints were grouted at the and of the dam erection (Popovici *et al*, 1992)

Two extreme loading combinations were considered in the stress analyses including MCE. They were the following (Popovici *et al*, 1995):

C1: dead load + hydrostatic pressures for normal design reservoir elevation + environmental temperatures associated to the mean August month (summer warmest month) + MCE a_{max} = 0.53 g applied horizontally upstream-downstream;

C2: dead load + hydrostatic pressures for normal reservoir elevation + environmental temperatures associated to the mean January month (winter coldest month) + MCE a_{max} = 0.53 g applied horizontally upstream-downstream.

RESULTS CONCERNING DAM BODY SEISMIC STRESSES.

Maximum horizontal upstream-downstream relative displacement of the dam due to MCE (see fig.3) reaches 1.25 cm in the central section at the crest level. In the analysis was neglected the nonsynchronism of the seismic wave's action.

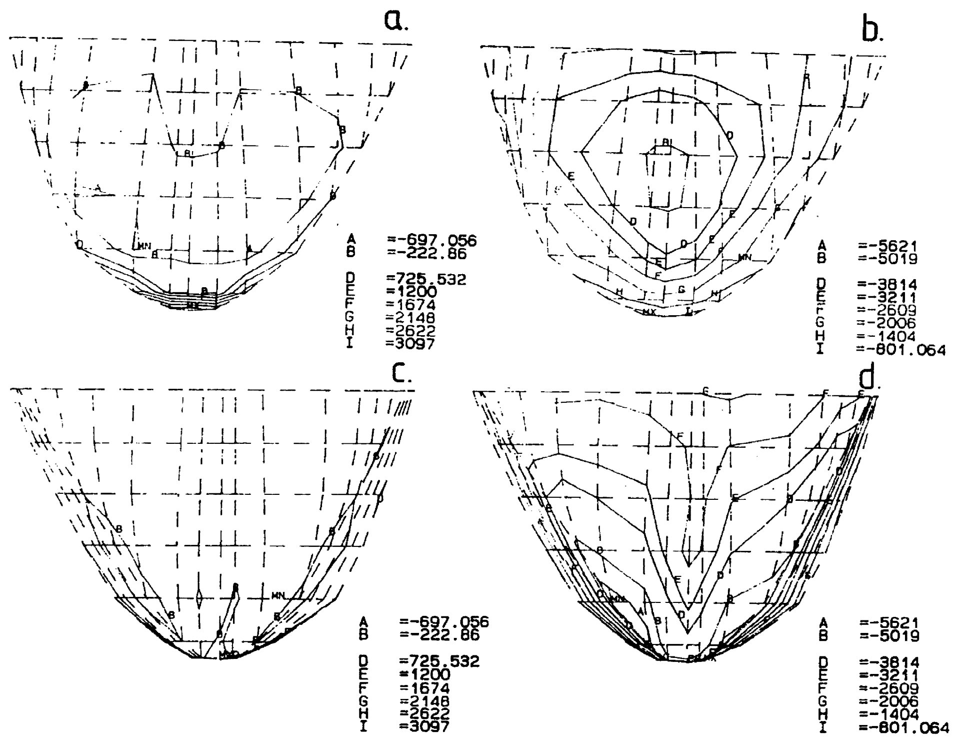

Fig. 5. Vidraru dam - contours of principal stresses due to MCE a_{max}=0.53g, horizontally, upstream-downstream: a-σ_1 upstream face, b-σ_3 upstream face, c-σ_1 downstream face, d-σ_3 downstream face (values in KPa)

The contours of the maximum values σ_1 and σ_3 due to MCE on upstream and downstream faces of the dam are presented in Figure 5. σ_1 tensile maximum stress reach up to 3.097 MPa on upstream toe of the dam central section. σ_3 compressive maximum stresses reach up to 5.621 MPa on downstream toe of the dam central section. Maximum shear stresses τ_{max} reach up to 2.670 MPa in the same zone.

The maximum seismic stresses due to MCE were combined with initial static stresses according to C1 and C2 combinations.

The maximum vertical total stresses in the dam central section for both C1 and C2 combinations are illustrated in Figure 6. The highest tensile vertical total stresses occur in the dam central section upstream toe zone. They reach up to 4.7 MPa. MCE during summer time is comparatively more dangerous than the corresponding one during winter time, because for a large area of the dam upstream face the tensile bending stresses reach 1.5 ... 2.0 MPa.

The dam downstream face which is, more or less under compression from static loads is less exposed to high tensile stresses due to MCE variable stresses. The highest compressive vertical stresses occur in the dam central section at the downstream toe zone; they reach 10 MPa during MCE winter time and respectively 12 MPa during MCE summer time.

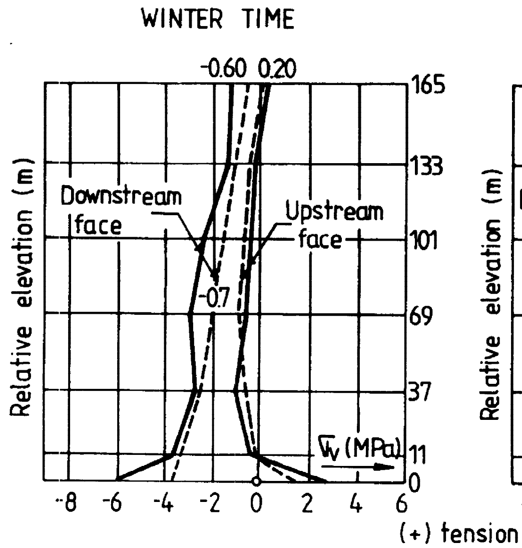

Fig. 6. Vidraru dam - vertical stresses in central section due to MCE a_{max}=0.53g, horizontally, upstream-downstream (dashed line) and dead load + hydrostatic pressures for normal design level of the reservoir + temperature (winter/summer) + MCE a_{max}=0.53g (solid line)

Some analyses were performed taking into account the effects of some possible cracks provoked by MCE in the highest tensioned zones of the dam body. Generally, the potential horizontal cracks at dam upstream toe would not be dangerous for dam safety. They provoke some dam body stresses redistribution. Higher negative effects on the cantilever could be amplified by cracks or opening of the grouted vertical joints.

RESULTS CONCERNING DAM BANKS SLIDING STABILITY

A special attention was paid to the effects of earthquakes on dam abutment sliding stability, especially left bank with morphological prominence and complex geological disturbances. According to local geological map concerning faults, cracks, soft zone insertions and other discontinuities, a number of potential sliding rock volumes were selected. They were analysed about potential failure mechanisms, kinematically possible.
The safety factors at sliding were computed according to Londe procedure (rigid block method). The loads taken into account were the following: rock volume own-weight, interstitial pressures due to seepage from reservoir and seismic inertia forces.

Two rock volumes, from the left bank, selected for performing the above mentioned analysis, are schematically illustrated in Figure 7. A volume of 84908 m^3, with faces limited by F3, F8, F9 faults and the outer rock surface, was analysed to sliding on CDFE plane, EC and FD edges, all of them kinematically possible. This volume resulted the most sensitive to sliding phenomenon specially on FD edge. Some synthetic results concerning safety coefficients of the ABCDEF volume sliding on FD edge can be seen in diagrams from Figure 8. The diagram from Figure 8 points out that the influence of the interfaces cohesion (unit cohesion c = 0.03 MPa) concerning an increasing of the sliding safety coefficient, is a moderate one. During MCE the analysed volume keeps stability if $m \leq 0.08$ and $\varphi \geq 35°$ or $m = 0$ and $\varphi \geq 30°$, only (m - reduction coefficient of the interstitial pressure due to seepage from reservoir considered at normal design level; φ - friction angle on sliding surfaces). This conclusion emphasizes the essential importance of the curtain grouting and drainage network of the dam foundation on the banks seismic sliding stability.

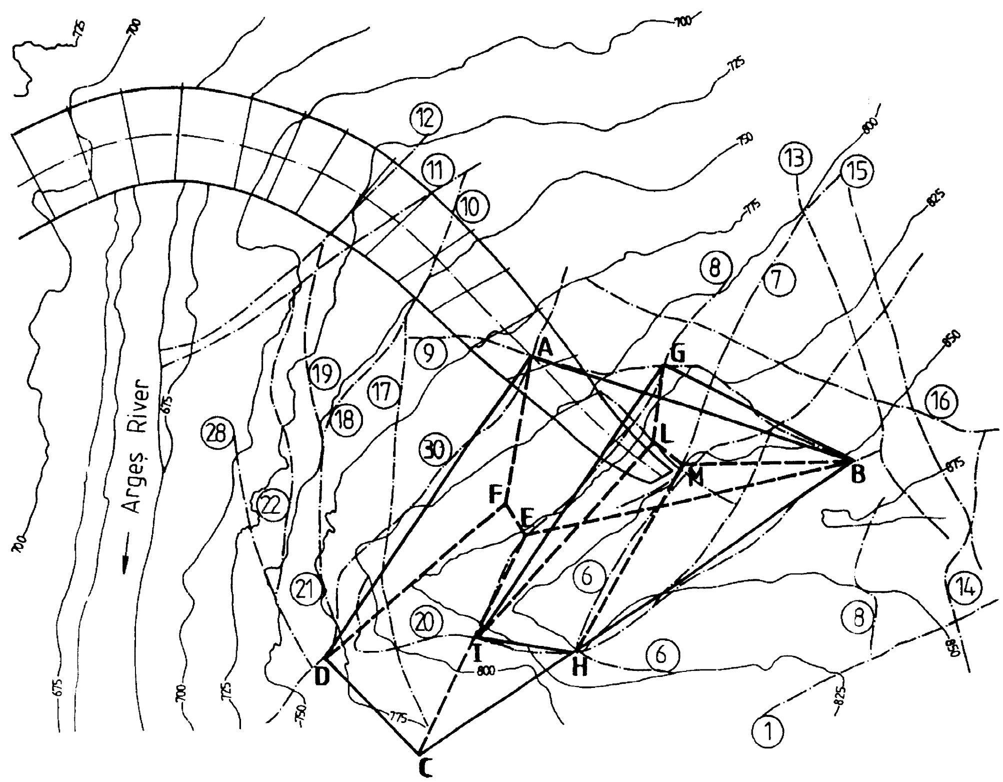

Fig. 7. Plan view of two potential sliding blocks from left bank

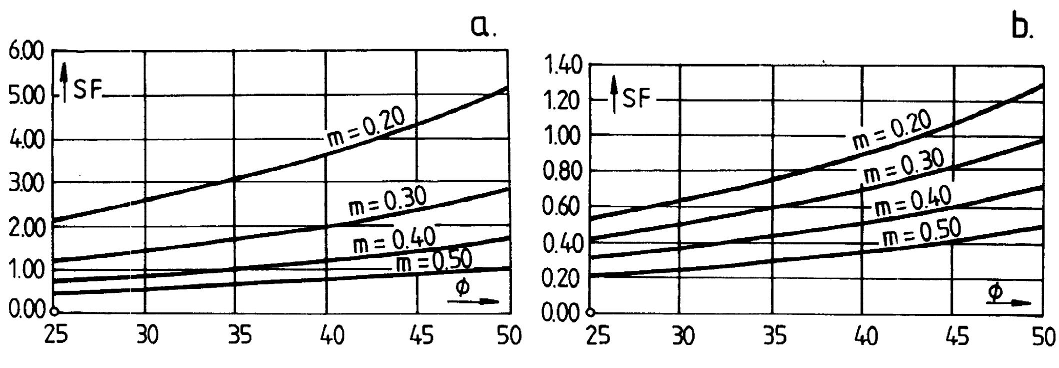

Fig. 8. Parametric study concerning sliding stability of the block ABCDEF: a-free of earthquake, b-with MCE (SF-safety factor, m-interstitial pressure reduction coefficient, Φ-frictional angle on sliding edge)

CONCLUDING REMARKS

The nowadays regulations concerning dam seismic safety, the new seismic data acquisition after dam commissioning (1965 year) required reassessment of the hazards associated with seismicity for Vidraru dam, H = 167 m, the highest arch dam in operation from Romania.

In compliance with the up to date knowledge the levels of the seismic input at the dam foundation were 0.26 g horizontal maximum acceleration for DBE and respectively 0.53 g for MCE, much higher than they had been considered in the dam design (0.1 g).

The new seismic analyses pointed out the remarkable potential strength of the Vidraru dam to withstand strong earthquakes. Some damage of the dam such as cracks, partial opening of some vertical grouted joints or spelling of concrete should be expected during MCE, but the dam will remain intact and uncontrolled release of water from reservoir will not occur.

A special attention was paid on dam abutment seismic sliding stability. This analysis was performed by rigid block method. A parametric study was preferred in order to quantify the influence of various parameters. Some tendencies to rock release at the left bank for pessimistic input data could develop during MCE. The analysis pointed out the essential importance of the curtain grouting and drainage network and the corresponding survey in order to avoid the above mentioned disturbances.

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