03 Jun 1993, 2:00 pm - 4:00 pm

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Proceedings: Third International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, June 1-4, 1993, Paper No. 3.35

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SYNOPSIS : The damage of the Draganesti earth dam on lower sector of the Olt river due to foundation liquefaction during 30 th May 1990, 0.12 g in site maximum acceleration, Vrancea earthquake is described. The dam is up to 20 m maximum height and border cross-wise and laterally the reservoir with 12.6 km length of the low head hydroelectric power station . The damage consisting of a large slide with about 60 m length at the dam downstream face and some cracks and lift-up of the reinforced concrete slabs at the corresponding upstream toe zone was placed in a zone where any special technology for increasing the relative density of the foundation loose sand layer was not applied . The natural relative density of the above mentioned layer having 1.20...7.00 m thickness was D_r=0.15...0.30, but it was increased up to 0.55...0.65 by vibrated-compacted gravel microcolumns technology, that was applied for over 80 % of dam foundation area. A comprehensive seismic backanalysis is performed in order to explain the damage mechanism.

INTRODUCTION

The Draganesti hydropower plant is located on the Olt river, which is the most important internal river in Romania (many years mean flow in site 165 cm/s), tributary of the Danube river. It is one of the six hydropower plants in cascade projected on lower sector of the Olt river (Fig. 1). Each hydropower plant of the cascade has a capacity of the 53 MW output for a head of 13.5m. The hydropower plant consists of a dam-powerhouse , spillway gate dam, position for potential navigation lock and earth dams bordering cross-wise and laterally on both banks the reservoir area . The total length of earth dams for only one hydropower plant is about 28 km and earth dams maximum height is 20 m.

A cross section of the earth dam typical for Draganesti hydropower plant is presented in Fig.2. It consists of reinforced concrete lining on upstream face, drainage blanket and sand-gravel compacted fill. This cross section is common for a lot of earth dams built in Romania and its performances in operation has been full satisfactory.

The foundation conditions for Draganesti earth dam and general speaking for all hydropower plants on lower sector of the Olt river were difficult ones.

The foundation soil profile in the site determined from surface to depth comprises the following layers:

- a vegetable layer of 0.00...0.50 m thickness , which was removed;

- a uniform, fine, loose sand layer thick of 1.20...7.00 m; this layer, with relative density

Fig. 1. Romania map with Vrancea epicenter and Draganesti hydropower plant site.

D_r=0.15...0.30 in natural condition is potential liquefiable;

- an alluvial sand-gravel and rare boulder layer of 3.50...7.00 m thickness; this material was used for earth dam body;

- bedrock consisting of levantine deposits of claystone and sandstone schists.

The dam region, according to Romania seismic zoning map, is of VII...VIII MM seismic intensity degrees. Under these conditions, the uniform, fine, loose sand layer from dam foundation soil profile, saturated by reservoir impounding raised numerous

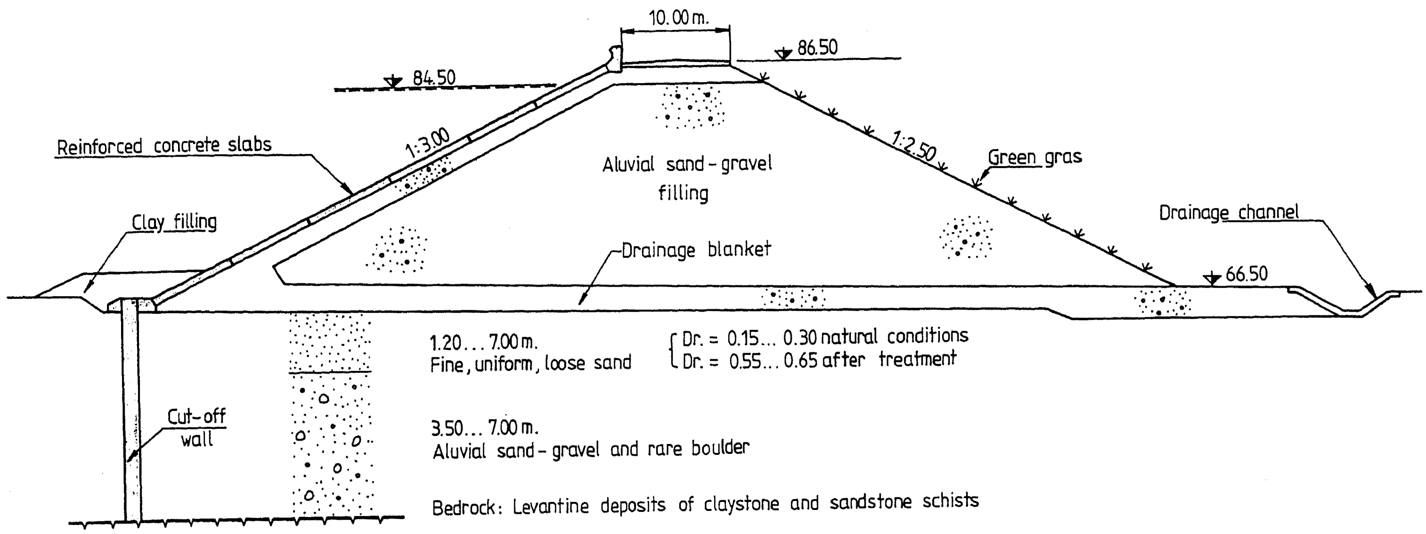

Fig. 2. Typical cross section of the Draganesti earth dam and geological profile in the dam area.

problems concerning liquefaction risk as is commented by Popovici et.al. (1982), Popovici et.al. (1984), Luca et.al. (1991).

During dam project studies, some constructive solutions had been analysed in order to reduce the liquefaction risk of the loose sand layer above mentioned. The removal of this layer from dam foundation area was considered too, but it was not accepted because of the large volume of the excavation necessary to be carried out. In these conditions, the constructive solutions have been selected in order to achieve simultaneously the increase of relative density of the sand layer as well as the increase of its permeability coefficient. A technology based on repeated vibropressing of a truncated pyramid metallic form up to 4 m depth, filling of the inside pyramid voids with gravel permeable material up to refuse was succesfully applied for over 80% of the Draganesti earth dams foundation area. The penetration tests associated with specific laboratory determinations, carried out before and after applying the above mentioned treatment solution confirmed it. The relative density, determined between the gravel permeable microcolumns increased up to D_r = 0.55...0.65 and the permeability coefficient increased 50...100 times.

The foundation and construction works at Draganesti hydropower plant started in 1985 year. The four generator-turbine groups of the hydropower plant have been put in operation during 1987-1989 years. At 30th May 1991 and 31th May 1991 , two Vrancea earthquakes of magnitude M=6.7 and respectively M=6.1 have shaken this zone. Although this zone is located at about 250 km from Vrancea epicenter, due to big depth of the hypocenter evaluated at 150...180 km underground, the peak ground acceleration in the dam site was important and it was appreciated at 0.12 g (g-gravity). First of the two above mentioned earthquakes provoked some damage at left bank side of the Draganesti earth dam. They are presented in the following.

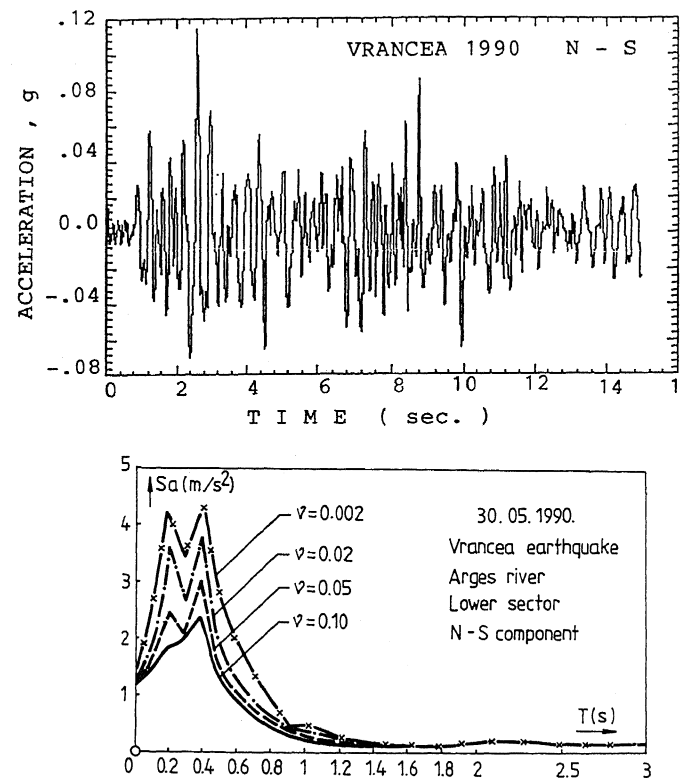

Fig. 3. Recorded accelerogram and seismic response spectrum of the 30th May 1990 Vrancea earthquake , Lower Arges river sector place.

DESCRIPTION OF THE DAMAGE AND REMEDIAL MEASURES

Priscu et.al. (1985) , have presented in their book the plain zones from Romania affected by

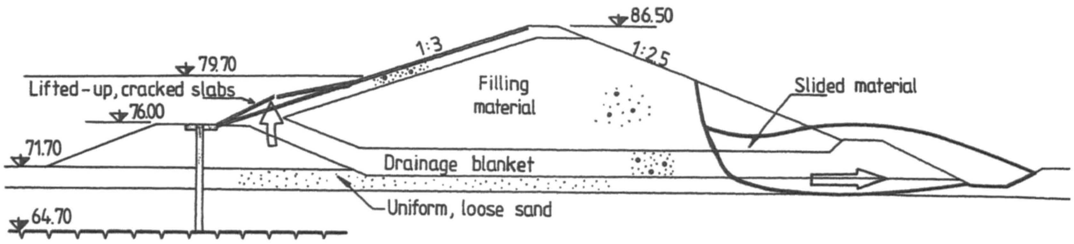

Fig. 4. Sketch of the Draganesti earth dam damage due to 30th May 1990 Vrancea earthquake.

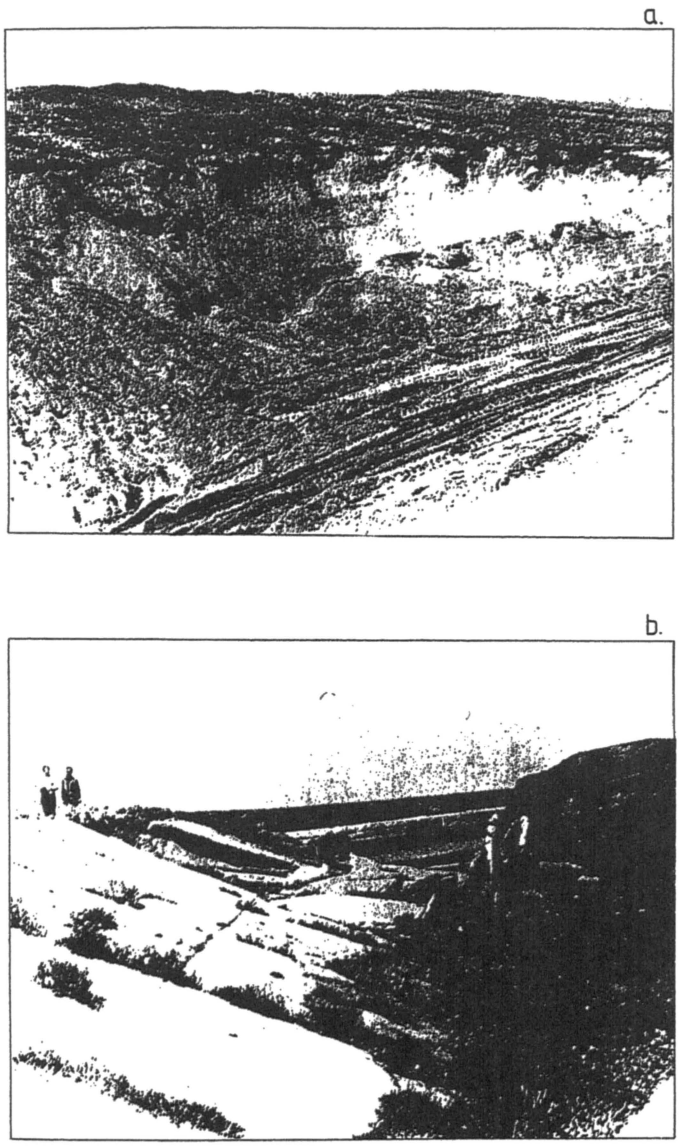

Fig. 5. Pictures of the damage : a- dam downstream face; b- dam upstream face.

liquefaction phenomena during destructive earthquakes . The seismic activity in Romania is provoked mainly by subcrustal intermediate earthquakes of Vrancea epicenter. The lately strong Vrancea earthquakes from 4th March 1977 (M=7.2), 31th August 1986 (M=6.9) and respectively 30th May 1990 (M = 6.7) confirmed the appearance of liquefaction phenomenon in numerous zones from Romania, located especially along the plain river banks . One of them was left bank of the lower sector of the Olt river.

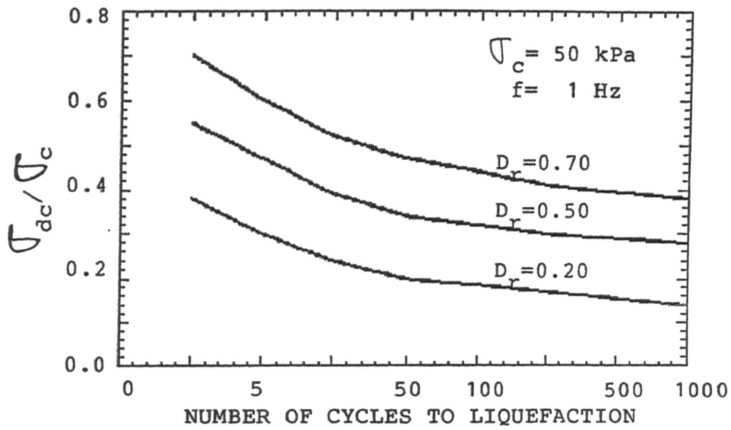

Fig. 6. Results of cyclic loading triaxial tests on Draganesti undisturbed samples (tests performed by INCERC-Bucharest).

Some recording accelerograms and seismic response spectra of the 30th May 1990, Vrancea earthquake are illustrated in Figure 3. They were recorded in the lower sector of the Argesriver in a geologic profile likewise with that from Draganesti earth dam site. The peak ground acceleration of the 30th May 1990, Vrancea earthquake in Draganesti earth dam zone was appreciated to 0.12 g.

A sketch of the along the river earth dam damaged zone is presented in Figure 4. This zone was about 60 m length , on the left bank of the Olt river, placed between km 3.900 and km 4.000 upstream from cross main dam (see Fig. 1,b) . The reservoir level, during earthquake, was 4.80 m under reservoir normal operation level, respectively 6.80 under dam crest level.

The slide from the dam downstream face had a crack plane quite vertically beginning from half of the dam slope. In horizontal plan, the slide shape at upstream and downstream ends are circular arches closed in the dam downstream bench. Some diffuse water seepage were detected in this zone, which after sliding concentrated in two

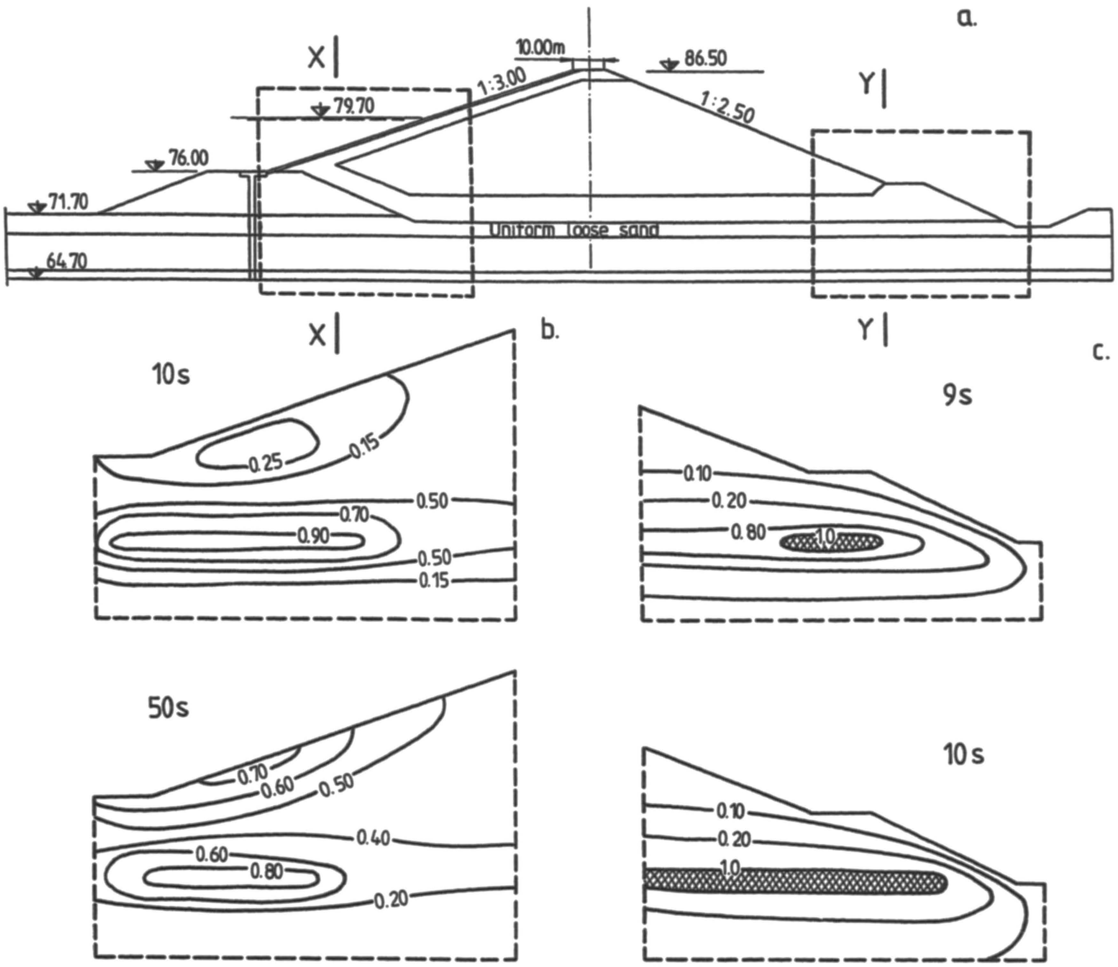

Fig. 7. Contours of the ratio u/σ'_v for different time steps during and after earthquake : a- dam-foundation system; b- dam upstream toe zone; c- dam downstream toe zone.

springs of about 2...3 l/s. The site investigation has not detected any dam-foundation material erosion. The sliding material filled up the drainage channel from the dam downstream toe.Some cracks were noticed on the dam downstream bench in the slide neighbouring adiacent zones.

The investigations carried out at dam upstream face corresponding to slide zone from downstream face have shown some important cracks and lift-up of the reinforced concrete slabs. Immediately after earthquake, the reservoir level was scheduled to be decreased with 0.5...1 m/24 hours speed. In this rate, the reservoir was partial emptyed in the about next two weeks.

Some pictures of the dam damage at downstream and respectively upstream face can be seen in Fig. 5.

The judgement of the collected data from in-situ investigations, previous laboratory testings and computing numerical analysis conducted to conclusion that accident was due to liquefaction of the uniform, loose sand layer from dam foundation . Although a technology for improving the quality of this layer was applied for over 80% of the dam foundation area, it was not applied in the accident zone. That special technology was not applied in the zones were sand layer thickness was under 1.5 m. In this case the compaction by vibrating roller of 160 kN was considered to be sufficient for a satisfactory increase of the small natural relative density of the sand layer. The accident shows that the expected performances did not carried out.

The remedial measures at the dam downstream face consisted of removing in the first stage of the slided material. In the second stage, the slide void volume was filled with drainage material compacted in layers of 0.5 m thikness by 160 kN liess roller excluding shaking. A stabilization bench of 10 m width was erected at the dam downstream face up to half of dam height in an old river bed zone. At the dam upstream face the joints sealing was repaired, the slab cracks were filled with epoxi resines and some slabs very damaged were replaced. The remedial works were carried out in two months.

SOME RESULTS IN BACKANALYSIS

Some numerical analyses based on finite element method, by using well known computer codes like

ANSYS, SIMEX, SHAKE, FLUSH were performed in order to explain the presented above phenomenon. The liquefaction was modeled according to GADFLEA computer code elaborated by Booker et.al.(1976). More information concerning the applied methods may be found in the books by Priscu et.al.(1985) and Popovici at.al.(1992).

Figures 6...8 illustrate some input and output data. The results of cyclic loading triaxial tests on undisturbed samples of the Draganesti-Olt sand are presented in Figure 6. The cell of the dynamic triaxial apparatus had 50mm diameter and 100 mm height. The consolidated undrained samples are initial compressed by axial vertical pressure σ_1 and radial confining pressure σ_3 . A dynamic cyclic stress $\pm\ \sigma_{d,c}$, modeled by a piston with double action, is added at the initial stress state. The initial σ_1, σ_3 stress state of the sample is according to the tested material place in the dam-foundation system. The dynamic cyclic stress $\pm\ \sigma_{d,c}$ is computed according to earthquake characteristics. For the 30th May 1990 Vrancea earthquake with M=6.7 and peak ground acceleration in Draganesti dam area of 0.12g, the equivalent cyclic loading considered was 10 cycles of 1 Hz.
The dynamic cyclic stresses (σ_{dc}) for each sample were computed after Seed recommendation with the following equation:

$$\sigma_{dc} = 2\,\tau_{mc} = 2.\ 0.65\ \sigma_v\ \frac{a_{max}}{g}(0.8...1.0)$$

where τ_{mc} is cyclic mean shear stress, σ_v - initial vertical stress ($\sigma_v \simeq \sigma_1$), g - gravity. The number 0.65 makes equivalence between uniform mean shear stress considered in equation and maximum shear stress and, respectively, 0.80..1.00 is due to stress reduction by the soil deformability.

The contours of the ratio between pore water pressure (u) and effective stress (σ'_v) for different time steps during and after 30th May equivalated Vrancea earthquake are presented in Figure 7. More details concerning the variation of this ratio are illustrated in Figure 8 for two vertical longitudinal sections placed in the upstream and downstream toe zones of the Draganesti earth dam.

The results of the backanalysis conducted to the conclusion, that the dam downstream face slide was due to the uniform, loose sand layer liquefaction, existant in the dam foundation area.The layer liquefaction, according to the computed data, begins at 9 s after eartquake starting.The time moment of the slide seems to be at the end of the eartquake or at few seconds after earthquake ceasing.

The damage at the dam upstream face seems to be provoked by the earthquake excessive uplift pressure. In the foundation corresponding zone the generated maximum ratio u/σ'_v resulted 0.9, but the seal of the upstream face stoped the dissipation of the earthquake generated pore pressures. Consequently, uplift pressures generated on internal face of the concrete lining provoked the lift-up of slabs, associated to joints sealing breaks and cracks.

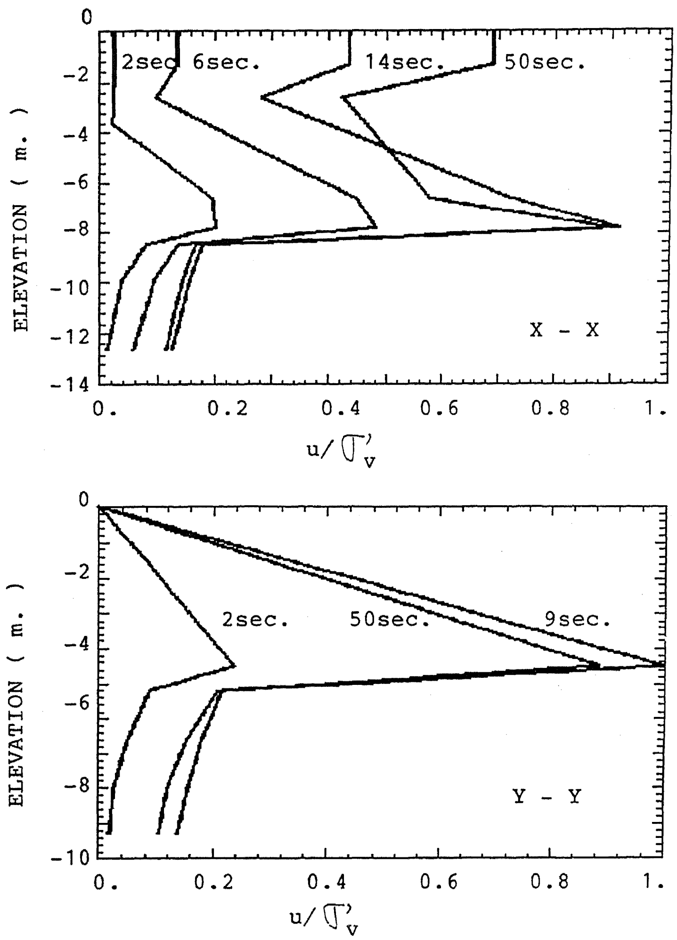

Fig. 8. Variation of the ratio u / σ'_v for different time steps during and after earthquake in longitudinal vertical sections X-X and Y-Y (see Fig. 7).

CONCLUDING REMARKS

The described accident points out once again the very unfavourable effects that liquefaction phenomena can provoke in earth dam-foundation systems during or after violent earthquakes . The damage of the Draganesti earth dam is a typical accident due to foundation liquefaction.

The investigations performed in order to evaluate the influence of different factors on accident have shown the efficiency of the technology based on vibrating-pressed gravel microcolumns for avoiding liquefaction risk. This technology was used in over 80% of the Draganesti earth dam foundation area, but unfortunately it was not applied in the accident zone.

The information gained by in-situ investigations, laboratory tests, computer backanalysis associated to accident analysis will be very useful for the future projects in this area. In this way the accident can be considered a lesson for the future.

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