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CONSIDERATIONS CONCERNING EARTHQUAKE RESPONSE ANALYSIS OF ROCKFILL DAMS

RÉMARQUES SUR L'ANALYSE DE LA RÉPONSE SISMIQUE DES BARRAGES EN ENROCHEMENTS

BETRACHTUNGEN ÜBER EINER UNTERSUCHUNG DER ERDBEBENSEINFLUSS AUF DIE STEINDÄMME

Radu Priscu*, Dan Stematiu**, Lucian Ilie**

SUMMARY-RESUMÉ-ZUSAMMENFASSUNG

The earthquake response of rockfill dams is strongly influenced by different assumptions concerning fill behaviour and excitation mechanism. Starting from the results obtained for some Romanian dams, the paper emphasizes the influence of material dynamic properties and nonsynchronous excitation along the dams foundation. Also, it is shown the earthquake behaviour of a large rockfill dam during the Vrancea earthquake which hit Romania on 4-th of March 1977.

La détermination de la réponse au séisme des barrages en enrochements est en étroit rapport avec les hypothèses concernant le comportement des enrochements et le mode d'introduction de l'excitation sismique. À partir des résultats obtenus pour quelques barrages roumains on souligne l'influence des proprietes dynamiques des matériaux et du nonsynchronisme de l'excitation au long de l'emprise. On y expose également le comportement d'un grand barrage en Roumanie au récent tremblement de terre Vrancea, 4 mars, 1977.

Die Bestimmung des Einflusses eines Erdbebens auf die Steindämme ist direkt von einigen Voraussetzungen eingegriffen, betreffens des Steinschüttungskörpers und der Einführung der Erdbebenserregung. Ausgehend von den Ergebnissen bei den rumänischen Talsperren, in der Arbeit wird der Einfluss der dynamischen Eigenschaften der Werkstoffe und der Non-Synchronismus der Erregung längs der Grundrechtsbreite hervorgehoben. Gleichfalls, wird das Verhalten eines grossen Steindammes während des Erdbebens in Rumänien, von 4 März 1977 gezeigt.

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CONSIDERATIONS CONCERNING EARTHQUAKE RESPONSE ANALYSIS OF ROCKFILL DAMS

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In order to evaluate the rockfill dams stability at seismic loads it is necessary to know the value and the distribution of the accelerations induced into their bodies. The analysis of the earthquake response provides both kinds of data, yet the values obtained depend on the hypotheses concerning the behaviour characteristics of the materials as well as on the seismic excitation mechanism.

Current dynamic analyses accept the linear elastic behaviour of the fill materials. The earthquake analyses comprising the elasto - plastic [1] or viscous - elastic [2] behaviour of the rockfill body are yet at a preliminary stage as plastic and viscous deformation characteristics under dynamic loads are not entirely known. With an earthquake analysis in the elastic range the dam response is directly dependent on the Young's modulus and Poisson's coefficient. The deformation process, supposedly elastic, is characterized by dynamic deformation moduli dependent on the initial stress state and on the amplitude of the dynamic stresses [3]. Their values obtained by laboratory and field tests may be 2 to 20 times as big as that of static deformation moduli. As a result the dynamic response is greatly different if static or dynamic deformation moduli are taken into account.

The seismic load is usually introduced under the form of the inertia forces, the excitation accelerations being the same throughout the dam body and equal to ground acceleration. Under this form the excitation is called "synchronous" and confirms the hypothesis that the seismic wave velocity within the foundation ground and the dam body is infinite. As a matter of fact the seismic wave velocity has a finite value of 800 to 4000 m/s, according to the nature of the foundation ground. The earthquake displacements and accelerations will be different alongside the dam base, with a phase lag resulting from the finite propagating time of the wave front. Considering the dam body receives different excitation, according to the distribution of the accelerations along the foundation base, the excitation mechanism is called "nonsynchronous". In the case of rockfill dams the dam-foundation contact exposed to the earthquake waves has high values, up to hundreds of meters, which emphasizes the part played by the nonsynchronous character of the excitation in evaluating the seismic response.

As a result of some dynamic analyses carried out for some Romanian dams, both the effects introduced by the dynamic properties of the dam fill and the above mentioned excitation mechanism are pointed out bellow.

1. THE INFLUENCE OF THE DEFORMATION MODULUS ON THE EARTHQUAKE RESPONSE

During the deformation process of the rockfill body elastic movements of small value and reversible character, as well as remanent movements of an important value and with plastic and creep character do occur [4] . That is why in evaluating the rockfill dam displacements several deformation moduli ocuur each of them characterizing a certain type of loading.

For dam movements during construction sequences and reservoir impounding the analysis implies the consideration of global elastic moduli (E_s) when it is beeing carried out in the elastic range and an instantaneous loading is accepted; in the elasto-plastic range the analysis is carried out using zoned elastic moduli($E_{s,z}$) and construction sequences and reservoir impounding are properly simulated.

In the case of seismic loads, the perturbing effect of the induced accelerations and the initial stress state overlap. The value of connection forces between rockfill blocks depends on the value of the contact forces and, implicitly, on the stresses which actuating on the rock contacts. Provides the seismic action is moderate, the connections among the rock blocks are not affected and the rockfill behaves as a continuous and elastic body. The deformation modulus, called dynamic (E_d), has much higher values in this case.

Fig.1 shows the dependency of the dynamic and static moduli ratio (E_d/E_s) with the principal stresses in the dam body as it came out from the experiments carried out by HAYASHI, FUZIWARA and KOMEDA[3].

Thus in evaluating the earthquake response some serious errors occur and are due not only to the acceptation of the elastic behaviour of the dam body but mainly to the use of static deformation moduli, global or zoned, instead of dynamic ones. With a view to illustrating the deformation modulus influence on the dam response two Romanian dams have been analyzed in various hypothesis: Lotru (H=124 m, clay core rockfill) and Bolboci (H=51 m, reinforced concrete face rockfill).

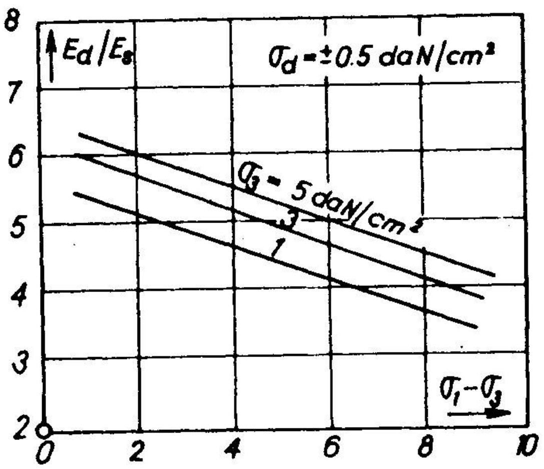

Fig. 1 The correlation between E_d/E_s ratio and the principal stresses in the dam body (after Hayashi, Fuziwara and Komeda).

Global elastic, zoned elastic and dynamic deformation moduli have been succesively considered. The zoned elastic moduli have been determined by simulating the construction sequences and the reservoir filling. For the deformation moduli the hyperbolic relations suggested by Duncan [5] have been admitted. The value of the tangent modulus depends on the internal friction angle and the stress level. Nonlinear stress-strain behaviour was approximated in the finite element analysis by assigning modulus values to each element consistent with the values of stress in that element. The analysis are performed using a step-by-step or incremental analysis procedure. During each step or increment the relationship between stress and strain for each element is assumed to be linear. Thus, at the end of the analysis the displacements,stresses and deformation moduli in the dam body have been obtained. The dynamic moduli have been determined with approximation in accordance with the static noduli previously determined, using the diagrams shown in Fig.1. The contours of the deformation moduli in dams cross sections for the three hypothesis considered may be followed in figures 3 and 4.

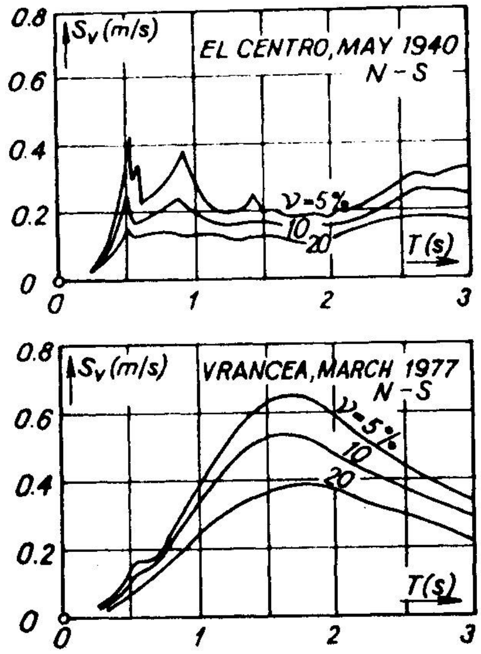

Fig. 2 The velocity spectra of the earthquakes El Centro and Vrancea, scaled to 0,1 g.

The earthquake behaviour has been determined by response spectrum analyses, for two earthquakes considered to be characteristics : EL CENTRO, May 1940 and Vrancea, March, 1977. The corresponding velocity spectra, scaled at the maximum acceleration of 0,1 g are presented in figure 2. One should notice that while the El Centro earthquake spectrum shows peaks within the range of quasirigid structures (with the first vibration periods of 0.3...0.5s), the Vrancea earthquake, that has recently occured in Romania, shows peaks within the period range of 1.5s.

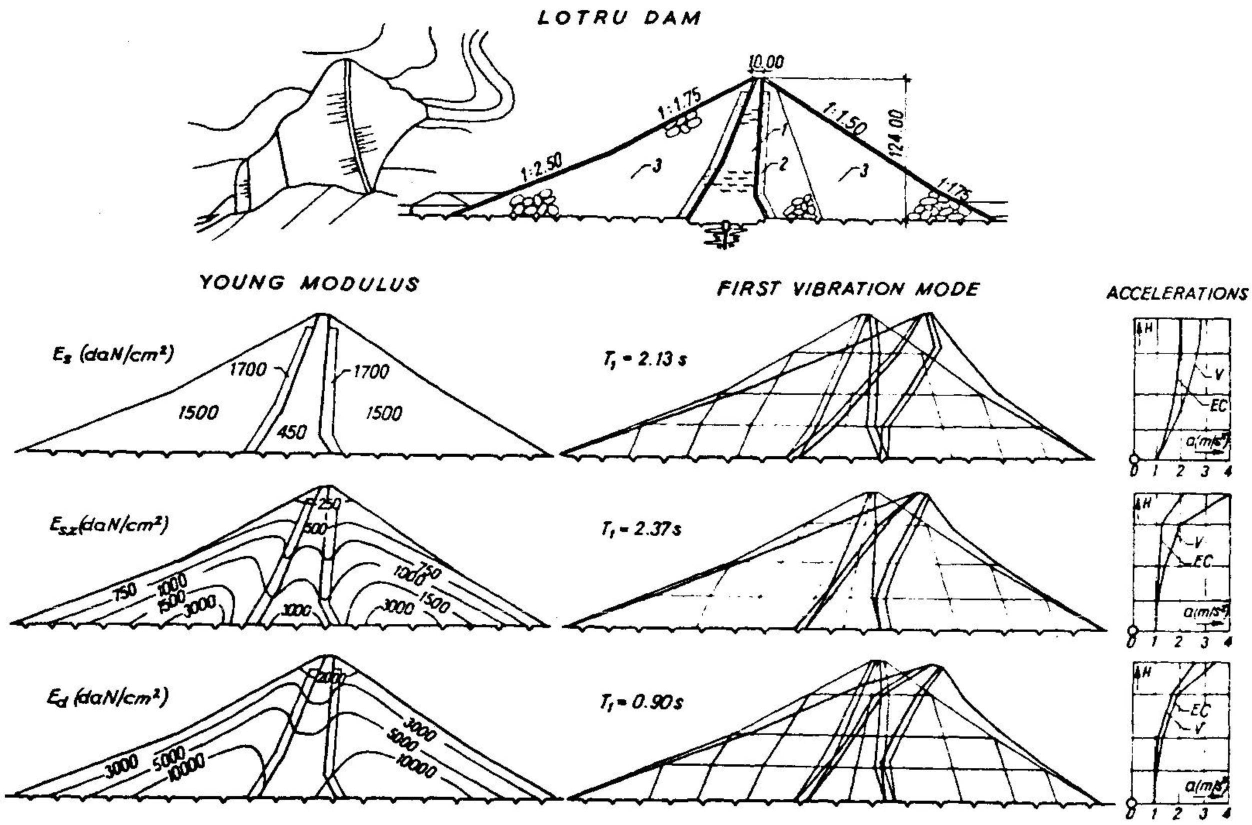

Fig. 3 Earthquake response of the Lotru dam:1-clay core,2-tranzition zone;3-rockfill.

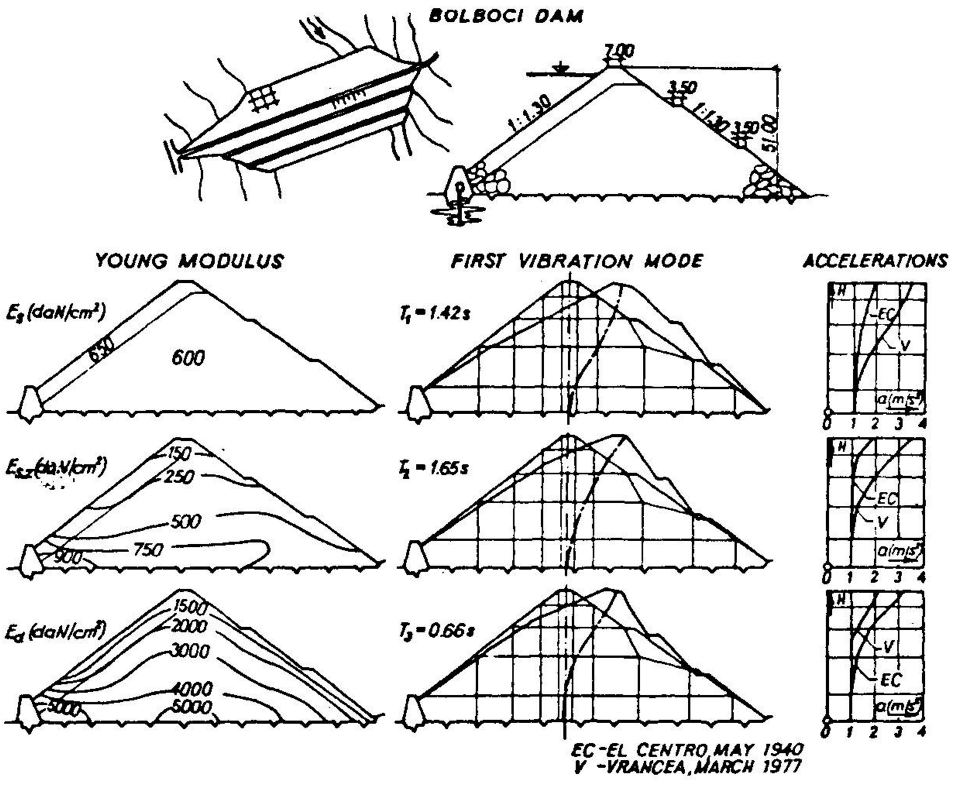

Fig. 4 Earthquake response of the Bolboci dam.

The analysis results are shown in figures 3 and 4. For both dams not only an important change of the vibration fundamental period is obvious but also the shape of the first vibration mode according to the deformation modulus used. In the case of dynamic moduli the fundamental period is about 2.5 times less and the displacements corresponding to the first mode shape are more reduced in the lower half of the dam height, presenting increases twoards the crest. As a result, the distributions of the induced accelerations into the dam body by the two considered eartquakes, for a damping of 10% of the critical one, is different in its turn. While in the case of static moduli, the Vrancea earthquake, a slower one, leads to higher values of the response accelerations, in the case of the dynamic moduli the situation is reverse. At the same time in the case of dynamic moduli, the distribution over the dam height shows important increases in the upper third of the dam only, as it has been noticed according to the field records of the earthquake response of some rockfill dams [6] .

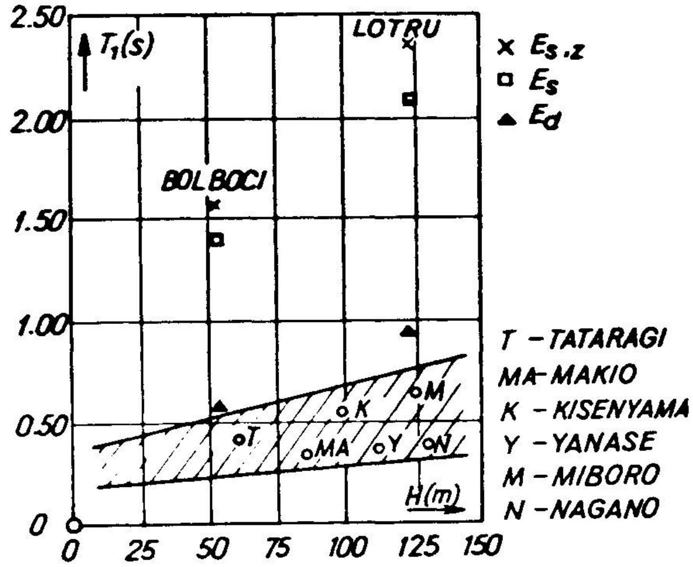

Fig. 5 The first vibration periods determined for Lotru and Bolboci dams comparatively with those measured for several Japanese rockfill dams (after Okamoto).

According to the above presented results as well as to other similar analyses it is evident that the use of the static moduli, zoned or not, the dynamic analysis leads both to erroneous evaluation of the response and to a wrong choice of the type of earthquake (slower or faster) acting upon the rockfill dams which are to be studied.

2. THE EFFECT OF THE NONSYNCHRONOUS CHARACTER OF EXCITATION

As it has been shown in the case of nonsynchronous exitation the excitation accelerations in the dam body are different from one point to onather according to the seismic accelerations of the dam base. By neglecting the dam-foundation interraction the seismic accelerations along the dam base are dependent on the position of the seismic wave. The motion equations have, then, the formula [8] :

$$[M]\{\ddot{\delta}\} + [C]\{\dot{\delta}\} + [K]\{\delta\} = - [M]\,[R]\,\{\ddot{u}\} \qquad (1)$$

in which [M] , [C] and [K] are the mass, damping and stiffness matrices, $\{\delta\}$, $\{\dot{\delta}\}$ and $\{\ddot{\delta}\}$ are the displacement velocity and acceleration vectors along the dynamic degrees of freedom, and:

[R] is a matrix of the influence coefficients;

$\{\ddot{u}\}$ - the vector of the seismic accelerations in the dam base.

The term R_{ij} of the matrix [R] stands for the displacement of the (i) - degree of freedom, when a unitary displacement of the (j)-foundation point takes place. The matrix [R] is a rectangular one with the number of rows equal to the dynamic degrees of freedom and the number of columns equal to the number of the foundation degrees of freedom.

The solution of the equations of motion, Eqs (1), can be obtained by direct integration. The integration is carried out by the step by step procedure, modifying the $\{\ddot{u}\}$ vector at each time step according to the position and the magnitude of the seismic wave.

The influence of the nonsynchronous character of the excitation on the earthquake response of the Lotru dam, previously presented, may be followed in figure 6. The same El Centro and Vrancea earthquakes scaled up to a maximum acceleration of 0,1g have been considered; their accelerograms are figured in Fig.6 as accelerations of the point E of the foundation. The damping was this time considered to be 20%. The deformation moduli are the dynamic ones and the seismic wave velocity in the foundation ground is of 1200 m/s. The induced accelerations into the dam body are represented as accelerograms over a period of 4.5s,herein considered to be characteristic. The full line marks the accelerations obtained in the synchronous excitation hypothesis and the dotted line marks the accelerations obtained in the nonsynchronous excitation hypothesis.

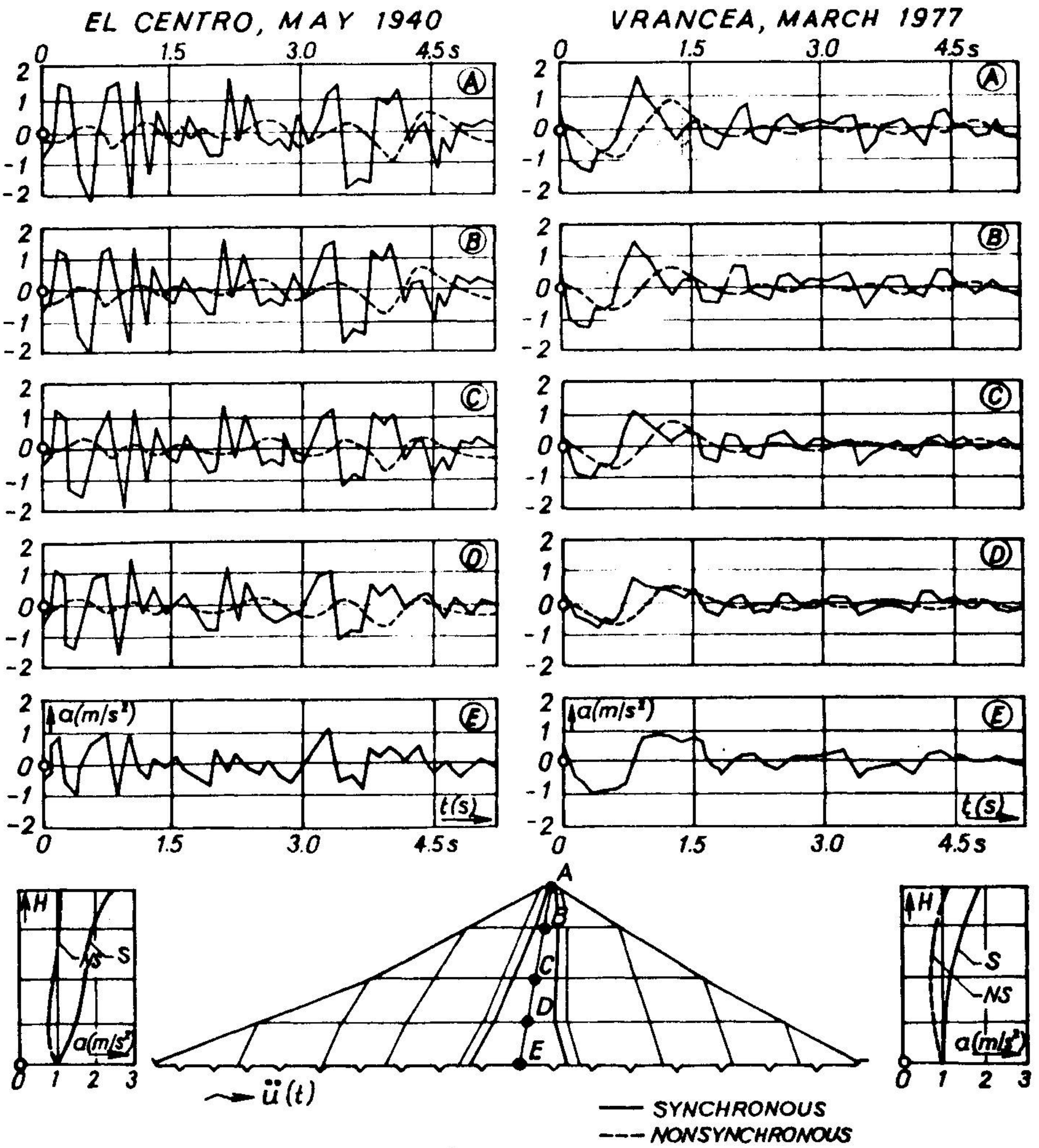

Fig. 6 The influence of the nonsynchronous character of the excitation on the earthquake response of Lotru dam.

Mention should be made of the much lower values of the accelerations obtained in the nonsynchronous excitation hypothesis and the tendency to damp down the response within the range of high frequencies. The distribution of the accelerations over the dam height at its peak shows a fairly constant value in the case of nonsynchronous excitation and a quite important amplification towards the crest in the case of synchronous excitation. There is no evidence of the increase of the response in the upper third of the dam which is obvious in the measured earthquake responses for some existing dams [6] . The discrepancy is due to the fact that actually the behaviour of the embankment towards its crest is no longer elastic.

Acording to the results presented as well as to some other similar analyses it follows that in the case of embankment dams with bread foundation surfaces the effect of the nonsynchronous character of the excitation is important, leading to a reduction of the response and thus emphasizing the capacity of such dams to withstand earthquakes.

3. THE BEHAVIOUR OF THE LOTRU DAM DURING THE VRANCEA EARTHQUAKE, MARCH, 1977.

Of the two dams under consideration, Lotru and Bolboci,it is only the former to have faced the recent earthquake in Romania , the latter being still at the design stage.

The magnitude of 7.2 places the Vrancea earthquake, March 4-th 1977, among the strongest earthquakes to have occured in Europe in the last few decades. The earthquake focus was located at about 100 km depth in Vrancea region, an area with a well known high earthquake activity. From the point of view of the dam shaking it is interesting to point out that on March 4-th 1977 as well as in the previous earthquakes the maximum intensities were felt towards South-South West of the epicenter. In Fig.7 a sketch of the most affected zone within the Romanian territory is presented;it also shows that Lotru dam, located at about 200 km away from the epicenter, was outside the impact zone (the earthquake intensity at the site was estimated to be VI on the MM scale).

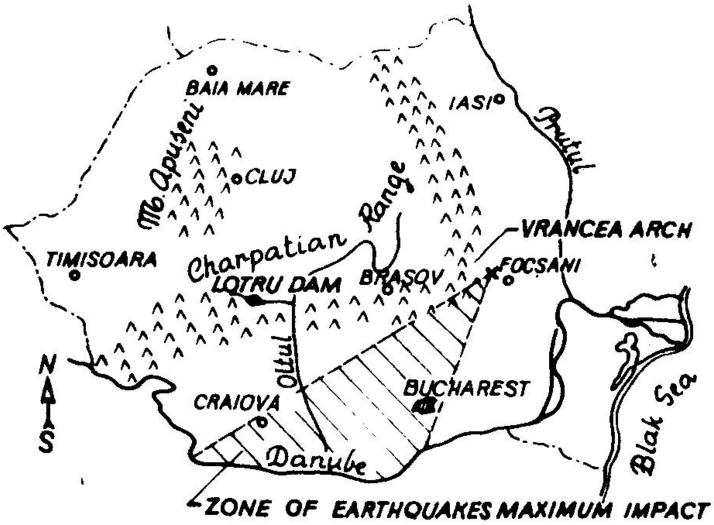

Fig. 7 The Lotru dam location as to the maximum impact zone of the Vrancea earthquake, March 1977.

Unfortunately this dam as well as other important dams in Romania were provided with seismic recording equipment for induced earthquakes only. During the earthquake the seismic devices ran out of the previously set measuring range so that no recordings of the precise data about the excitation and the dam response could be obtained. A engineering team checked out the state of the dam after the earthquake and established the dam behaved normally, that there was no evidence of deformations, unreversible displacements, cracks or increase of seepage. Besides this dam had been designed to withstand an earthquake with a seismic acceleration of 0.05 g which was not surpassed by the 4-th of March 1977 earthquake. The analyses presented in the paper point out the fact that, by the effect of the nonsyncronous character of the excitation the induced accelerations are not higher than the base ones, and that the dam stability is not affected, even for earthquake accelerations up to 0,1g.

4. CONCLUDING REMARKS

- The above-mentoned analysis of the rockfill dam earthquake response, refers to the effect of the deformation moduli and the excitation mechanism upon the induced accelerations.

- The evaluation of the response in the hypothesis of the elastic behaviour of the rock-fill body can lead to results similar to those recorded in the field if the deformation dynamic moduli are considered. Systematically, the induced accelerations are fairly constant along the two thirds of the dam height and amplified on the upper third.

● The analyses carried out for two earthquakes with different characteristics show an important influence of the site spectrum characteristics upon the dam earthquake response.

● The introduction of the non-synchronous character of the excitation leads to a lowering of the induced accelerations, thus pointing out the strength resources of the embankment dams subject to earthquakes.

● The rock-fill dam mathematical models of the dynamic analysis lead to correct evaluations of the earthquake response inasmuch as laboratory and field tests can provide the dynamic characteristics of the foundation ground behaviour as well as of the rock-fill body.

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