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Numerical model for evaluating the seismic response of earth dams

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ABSTRACT: Attempting to determine the permanent deformations of earth dams to earthquakes,the paper presents a model of analysis in which the material behavior is described in accordance with the concepts of plasticity theory on the basis of an yield criterion.The yield function for materials is connected with their resistance characteristics and can be expressed by using the Mohr-Coulomb relation with some corrections.The saturated granular material with water is modelled as a coupled bi-phasic medium.The two phases are coupled by the volumic deformations.The mathematical model is conveyed by means of effective stress.The numerical results are presented for a dam built in Romania.

1 INTRODUCTION

It is very important to predict permanent deformations of earth dams during earthquakes, because the large settlement of earth dam means the reduction of freeboard, possibly leading to overtopping.A comprehensive approach to the determination of earthquake induced deformation of an earth dam must include an analysis of both the initial stresses acting throughout the dam and the superimposed cyclic stresses together with the pore pressure generated by deformation history.In earthquake analysis, therefore, we cannot avail the "limit equilibrium" methods to predict the extent of damage.In the same vein, linear analysis using idealized material properties is not in general applicable.

The correct determination of permanent deformations of earth dams cannot be made without considering the effect of pore water pressure since this can produce the liquefaction phenomenon.This problem can be solved assuming the coupled effect "effective stress -pore pressure"(see Zienkiewicz, Leung, Hinton and Chang (1981), Dikmen and Ghaboussi (1984),Ghaboussi and Dikmen (1984)) or by separate solution (see Seed, Lee, Idriss and Makdisi (1973)).

In the last ears, the most of non-linear models for dynamic analysis of earth dams often are based on the plasticity theory. Even if it cannot express the whole complexity of material behavior, these models are leading to the solutions having an acceptable degree of approximation.Such a model of analysis constitutes the subject of this paper.As is commonly used , the liquefaction phenomenon refers to a state of zero or residual effective stress in a region within the soil mass.Obviously, in a liquefied region of sand the pore pressure is equal to or slightly less than the total mean stress.The liquefied soil has very little shear resistance and capable of undergoing flow and large deformations.The criterion for the onset of liquefaction can therefore be stated as the effective stresses reaching a specified residual value. Upon liquefaction the modulus of material in the liquefied region must be reduced to a fraction of this original value.

Prior to liquefaction, as the pore pressure are increasing, the stress state (shear stress and effective stress) reaches a condition of "near failure".Such a stress state in a monotonic drained test would be considered failure stress.However, under cyclic stresses complete failure has not occurred but the strain amplitudes start increasing.Clearly at such a state of "near failure" the effective stress have not vanished and the material cannot be considered as liquefied but under additional cycles of stress, the material is well on its way towards liquefaction.This state of "near failure" will be refereed to as "initial liquefaction".Complete liquefaction usually follows the initial liquefaction.However, it is important to recognize the existence of such state as a critical intermediate point on the path to complete liquefaction.

2 THEORETICAL BACKGROUND

The saturated material bellow the water level is modeled as a coupled two phase medium; the two phases are the porous deformable granular solid and the pore water. These two phases are coupled through volumetric strains.D'Arcy How law is assumed to govern the flow of pore water through the porous elastic solid, with the material constant for this process being the coefficient of permeability. We have adopted the

Zienkiewicz ,Leung, Hinton and Chang's (1981) assumption that the most important feature of cyclic strain response is that of the cumulative densification which is responsible for such phenomena as liquefaction and loss of strength. We have included this aspect in our model.

Therefore,for the strain increment $d\varepsilon$ we can write:

$$d\varepsilon = d\varepsilon_s + d\varepsilon_d \quad (1)$$

where $d\varepsilon_s$ is the part of strain increment directly related to stress and $d\varepsilon_d$ is the additional densification strain increment which is related to cumulative densification phenomenon; it is volumetric nature.

The component $d\varepsilon_s$ can be divided into elastic and plastic parts, i.e. :

$$d\varepsilon_s = d\varepsilon_s^e + d\varepsilon_s^p \quad (2)$$

Now, the elastic-plastic constitutive equation for the effective stress increment $d\sigma'$ has the expression :

$$d\sigma' = D \cdot d\varepsilon_s = D \cdot (d\varepsilon - d\varepsilon_d) \quad (3)$$

in which D is tangent modulus matrix.

To determine the plastic strain component $d\varepsilon_s^p$, the concepts of plasticity theory have been used.

The densification strain increment $d\varepsilon_d$ must be related to the total strain history and the level of the stresses; Zienkiewicz, Leung, Hinton and Chang (1981) offer a such model and allow the simplest correlation between ε_d and the measured pore pressure changes for standards tests conducted under cyclic loads. We have adopted that model in our coupled two-phase analysis.

3 PLASTICITY MODEL

In attempting to model the nonlinear behavior of soils by plasticity concepts, the best known resistance characteristics of soils, the cohesion c and friction angle φ, must be used. They characterize the critical behavior by on envelope of Mohr's circles. Therefore, for a plane state of deformation the yield function for soils connected with their resistance characteristics can be expressed by using the modified Mohr-Coulomb relation :

$$F = a_c(1-\sin\varphi)\frac{\sigma_1-\sigma_3}{2} + \sigma_1 \cdot \sin\varphi - c \cdot \cos\varphi \quad (4)$$

The coefficient a_c ($a_c < 1$) suggests the including of a plastic potential for the stress states after limit of elasticity but preceding the failure, where $a_c = 1$.

Details of this model are presented in an earlier paper (see Moroianu, Breaban, Topa, Paduraru (1983)).

4 APPLICATION

The Draganesti Dam is located on the Olt river; it is 15.00 m high and was constructed by using the local materials of the type of sandy-clayly soils. The dam is founded on the alluvial soil foundations. The finite element mesh is extended until the depth of 10.00 m (fig.1). The characteristics of material are

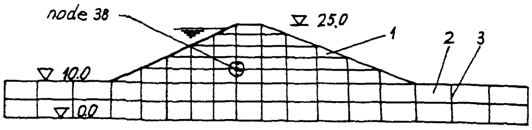

Figure 1. Draganesti Dam

presented in Table 1. In an earlier paper, Breaban and Moroianu (1986) have analyzed the non-linear response for this dam without influence of pore water pressure. The Draganesti Dam is situated in an area with important seismicity.

Table 1. Draganesti Dam. Characteristics of materials

Material zone	E daN/cm^2	μ	φ	c daN/cm^2	γ KN/m^3	a_c
Sandy fill	1000	0.3	28	0.3	20	0.2
Sand	1000	0.3	28	0.3	20	0.2
Gravels sand	2000	0.3	35	0.	19	0.3

The seismical loads where assumed by means of accelerogram (Fig.2) obtained by numerical way as series of samples of a stationary random process, accounting for the macroseismical conditions and for the geological features of the side.

Because of very high computational costs, the analysis was made only for 4.5 seconds of input accelerogram and for the last 0.5 seconds the ordinates are zero.

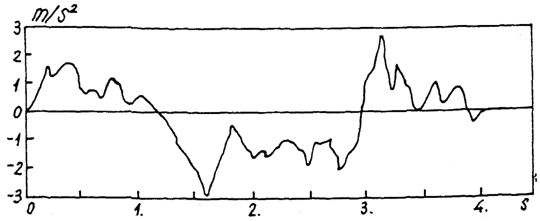

Figure 2. Freefield accelerogram

In Figures 3-6 are presented some aspects about the calculated response : accelerations, displace-

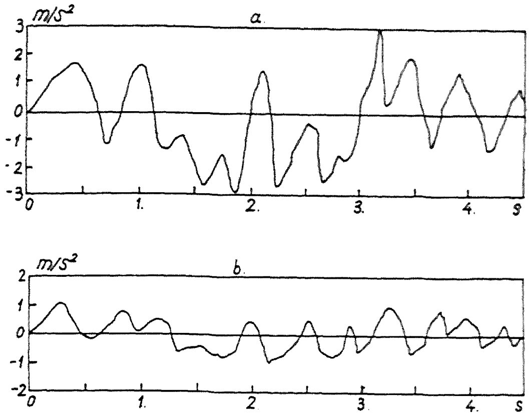

Figure 3. Acceleration response at the top of dam
a. horizontal, b. vertical

ments, pore water pressure.

The first finding appearing out of analysis is that the response accelerations at the crest of dam are mitigated, as an effect of non-linear behavior of materials and saturated pore water presence. The permanent deformations are noticeable. In Figures 5-6 is shown that in the dam appears a limited zone where exists conditions for an initial liquefaction. It should be noted that in the analysis, the zones under the dam are assumed permeable.

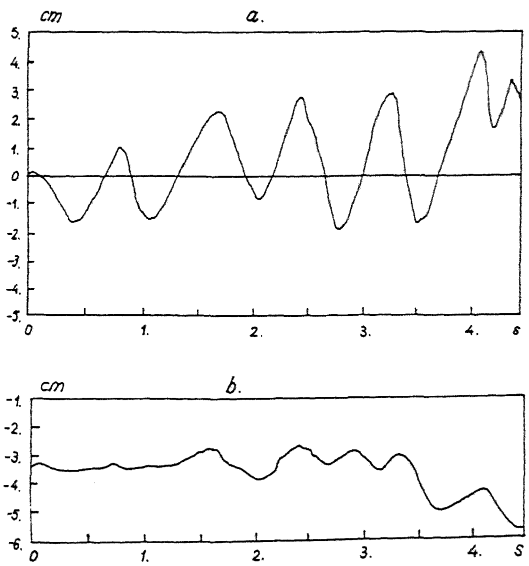

Figure 4. Displacement response at the top of dam
a. horizontal, b. vertical

5 CONCLUDING REMARKS

An effective stress method of analysis for determination of seismic response of earth dams has been presented. The material is modeled as saturated porous deformable media and the dynamic coupled solutions are solved. For solid skeleton, an elasto-plastic model has been used.

The model uses the best known characteristics of soils associated with the critical Mohr-Coulomb surface.

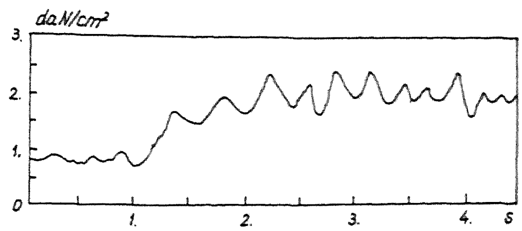

Figure 5. Pore water pressure response in n.p.38

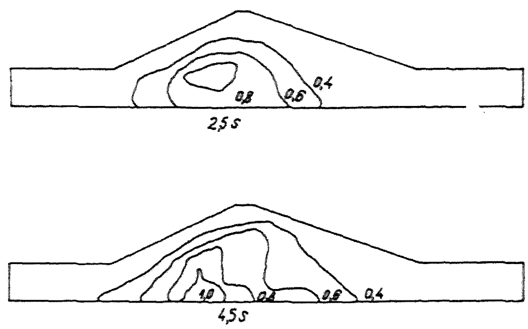

Figure 6. Pore water pressure at 2.5s and 4.5s

The results presented validate the possibilities of both analytical model and the computer program.

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