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SYNOPSIS: A nonlinear stress-strain static evaluation model and an equivalent visco-elastic dynamic evaluation model, which can simulate well the static and seismic behaviors of the ash deposit, as well as the methods for analyzing the dynamic response and for improving the earthquake-resistance of the ash-retention dam are presented and illustrated through a practical engineering project in the paper.

INTRODUCTION

About 300 million tons of coal ash is produced annually by coal-burning power plants in the world recently. The safe, environmentally acceptable and economic disposal of this waste is a multi-discilinary activity especially in earthquake area. In general the unfavourable engineering properties of coal ash deposit are: high water content, large void ratio, and very low mass density. Moreover, the grain size of ash is fine, its distribution is uniform and the specific gravity of ash grain is smaller than that of soil grain. Hence, the liquefaction of the ash deposit is likely to happen and to damage the ash-retention dam during an earthquake.

Although there have been a large number of contributions on the dynamic stability analysis and earthquake-resistant improvement for earth dam in literature. But the differences between earthfill dam in reservior and ash-retention dam in coal ash lagoon are so great that the dynamic response analysis should take account of ash deposit with ash-retention dam, as well as, the numerical analysis model and improvement method should be suitable for ash which is much different from soil. The major objectives of the studies reported herein are to open the way for solving above mentioned problems.

DYNAMIC RESPONSE ANALYSIS METHOD OF ASH-RETENTION DAM

The main points of the dynamic response analysis method of the ash-retention dam are as follows:

1. At first a nonlinear incremental static analysis based on Biot consolidation theory is carried out before starting of dynamic analysis. The analysis can simulate the construction process of the initial dam and the sub-dams and the disposal process of the coal ash. The analysis will reveal the stress and pore water pressure distribution including undissipated excess hydrostatic pore water pressure distribution of the ash deposit.

2. The dynamic response analysis method of the ash-retention dam is based on effective stress principal. A true earthquake record is selected at first. The maximum acceleration and time history of the selected record are then modified based on the magnitude of the earthquake which will happen mostly. The continuance time is divided to more than 10 time sections. It is supposed that the soil and ash in every time section are visco-elastic medium. The dynamic pore water pressure increment and residual deformation increment in each time section are evaluated with empirical formulas. Both of the above-mentioned increments are transformed into the initial stress, which is then changed into the node load based on a fundamental principle. It is that

the direction of residual shear strain increment coincides with the direction of principal shear stress. Afterwards, the nonlinear incremental static analysis will be carried out again to get a new stress distribution. Then the dynamic evaluation for the next time section will begin.

Because the dynamic shear modulus and damping ratio are dependent on the amplitude of dynamic shear strain which is not known yet, the dynamic evaluation in every time section should be iterated at least twice or thrice. The dynamic equation will be step-by-step integrated by Wilson's linear acceleration method.

The accumulated excess pore water pressure and permanent deformation caused by the earthquake will be obtained by above-mentioned methods. The liquefied zone will be judged and the stability analysis using Bishop's method will be carried out based on above results.

EVALUATION MODEL

A nonlinear stress-strain model is used in static analysis as follows:

$$E_t = E_i(1 - R_f R_s)^2 \tag{1}$$

$$M_t = K_m P_a\left(\frac{\sigma_1'}{P_a}\right)^m \tag{2}$$

$$E_i = K P_a\left(\frac{\sigma_3'}{P_a}\right)^n \tag{3}$$

in the above equations, P_a is atmospheric pressure, σ_1' and σ_3' are effective principal stress, E_t is tangent Young's modulus, M_t is tangent modulus of compressibility, R_f is failure ratio, K and n are coefficient and power of Young's modulus respectively (R_f, K and n are the same in Duncan model), K_m and m are coefficient and power of modulus of compressibility, R_s is static stress level as follows:

$$R_s = \frac{\sigma_1' - \sigma_3'}{2\sigma_s \sin\Phi} \tag{4}$$

$$\sigma_s = \frac{1}{2}(\sigma_1' + \sigma_3') + c \cot\Phi \tag{5}$$

An equivalent visco-elastic model is used in dynamic response analysis as follows:

$$G = \frac{K_2}{1 + K_1\gamma_c} P_a\left(\frac{\sigma_s}{P_a}\right)^{1/2} \tag{6}$$

$$\lambda = \lambda_{max} \frac{K_1\gamma_c}{1 + K_1\gamma_c} \tag{7}$$

$$\triangle\varepsilon = C_1\overline{\gamma_d}^{C_2} \exp(-C_3 R_s^2) \frac{\triangle N}{1 + N_e} \tag{8}$$

$$\triangle\gamma = C_4\overline{\gamma_d}^{C_5} R_s^2 \frac{\triangle N}{1 + N_e} \tag{9}$$

in these equations, G is dynamic shear modulus, λ is damping ratio, $\triangle\varepsilon$ and $\triangle\gamma$ are residual volumetric strain and shear strain produced in $\triangle N$ number of vibrations respectively, $\triangle N / 1+N_e$ is increment of number of relative vibrations in the mentioned time section, N_e is effective loading number as follows:

$$N_e = \frac{\Sigma(\gamma_d)_i}{\overline{\gamma_d}} \tag{10}$$

where $\Sigma(\gamma_d)_i$ is cumulative increment of dynamic shear strain at the beginning of the mentioned time section, $\overline{\gamma_d}$ is mean amplitude of shear strain in the mentioned time section.

The residual volumetric strain will be converted into the pore water pressure $\triangle u$ in undrained condition, which is able to be computed by

$$\triangle u = M_u \triangle\varepsilon \tag{11}$$

$$M_u = K_u P_a\left(\frac{\sigma_s}{P_a}\right)^m \tag{12}$$

where M_u is bulk modulus of resilience, K_u is coefficient of bulk modulus of resilience.

R_f, K, n, K_m, m and K_u are static parameters, which can be determined by static triaxial compression test and one-dimenional compression test. λ_{max}, K_1, K_2, C_1, C_2, C_3, C_4, and C_5 are dynamic parameters, which can be determined by dynamic triaxial compression test and resonant column test.

EXAMPLE OF ANALYSIS

We selecte a large coal ash-retention dam of the largest power plant in China as an example of above-mentioned static and dynamic analysis.

The result of nonlinear static analysis is shown

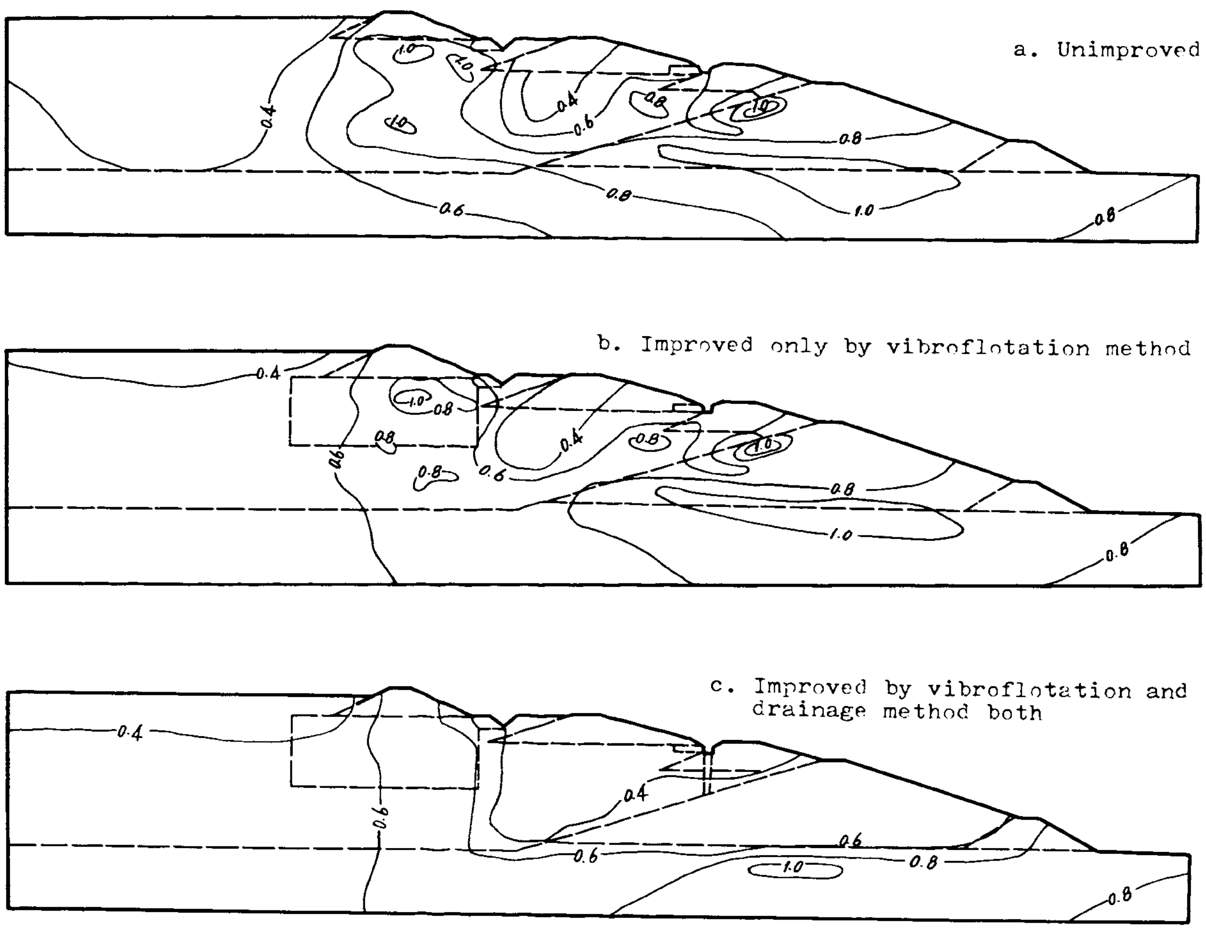
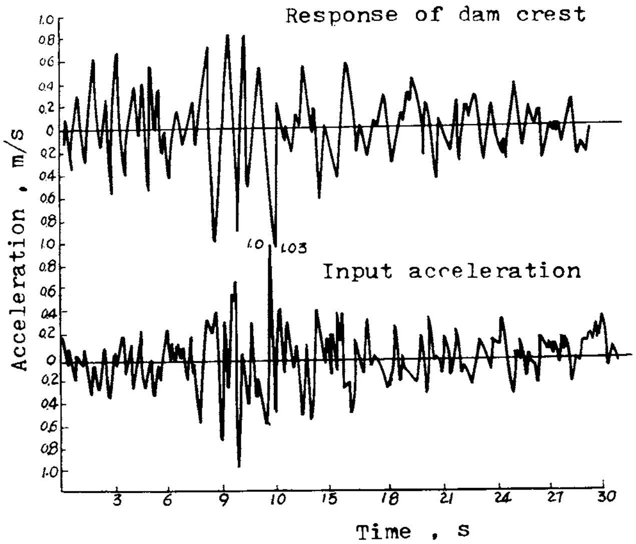


Fig. 1. Shear stress level before earthquake.

in Fig.1. It is known from Fig.1 that non evident excess hydrostatic pore water pressure exists in coal ash deposit, that is to say, the ash deposit has consolidated mostly in static condition because the construction process and wet disposal process of coal ash are not quick enough to produce the excess hydrostatic pore water pressure. But a large shear zone, in which stress level is more than 0.8, exists in the initial dam foundation and the third sub-dam foundation. We can find from Fig.1 the stress level in a part of the shear zone reaches 1.0, that is to say, in which the soil fails in shear. The reason is that the strength of soil in the initial dam foundation and the density and strength of ash deposit are very low. It is obvious that the problem should be paid attention to and should be solved.

The dynamic response of the third sub-dam crest from dynamic response finite element analysis is shown in Fig.2. It will be known from Fig.2, the dynamic magnification of the dam crest exists obviously only before 9 second. After the time the dynamic response of the dam crest will reduce because the free vibration period of the dam increases to 4.2 second from 1.3 second at the beginning of the earthquake, in other words, the free vibration period of the dam will run away far and far from the predominant period of the input earthquake wave.

The dynamic excess hydrostatic pore pressure distribution in the ash deposit at the end of



the earthquake from the dynamic response analysis is shown in Fig.3. We can find that the maximum increment of pore water pressure is 40 kPa and a liquefied zone occures in upstream ash deposit of the third sub-dam.

Then the stability of ash-retention dam is evaluated using Bishop's simplified procedure in effective stress method. The result shows that the safety factor of the stability of the third sub-dam is only 0.84 if the third sub-dam is built on existing ash deposit as illustrated in Fig.4.

From the above results we have good reason to say it is impossible to build the third sub-dam on original ash deposit. A large liquefied zone of ash deposit will cause the third sub-dam to be damaged if an earthquake happens. Therefore, the ash deposit should be improved.

EARTHQUAKE-RESISTANT IMPROVEMENT

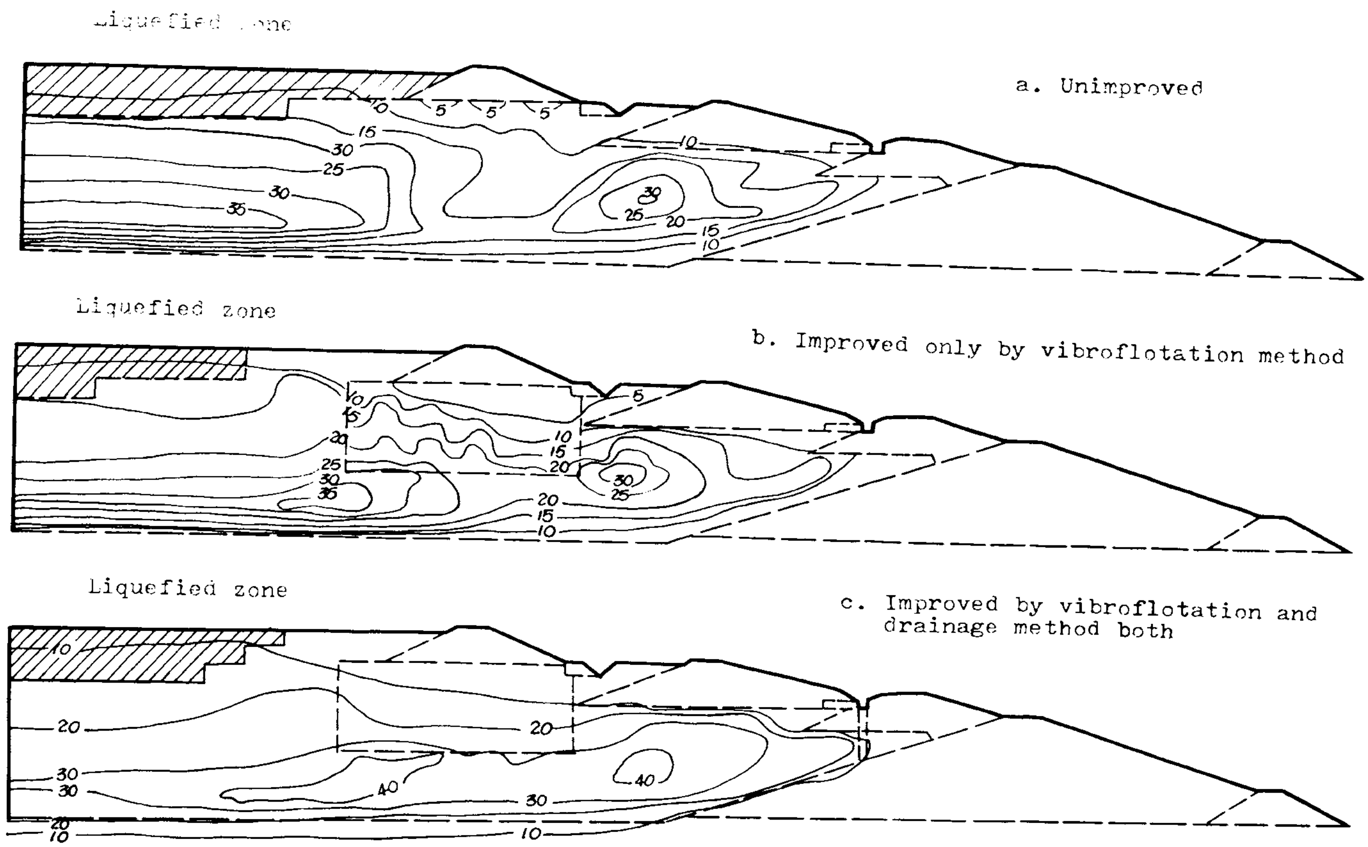


Fig. 3. Distribution of earthquake-induced pore water pressure in ash deposit.

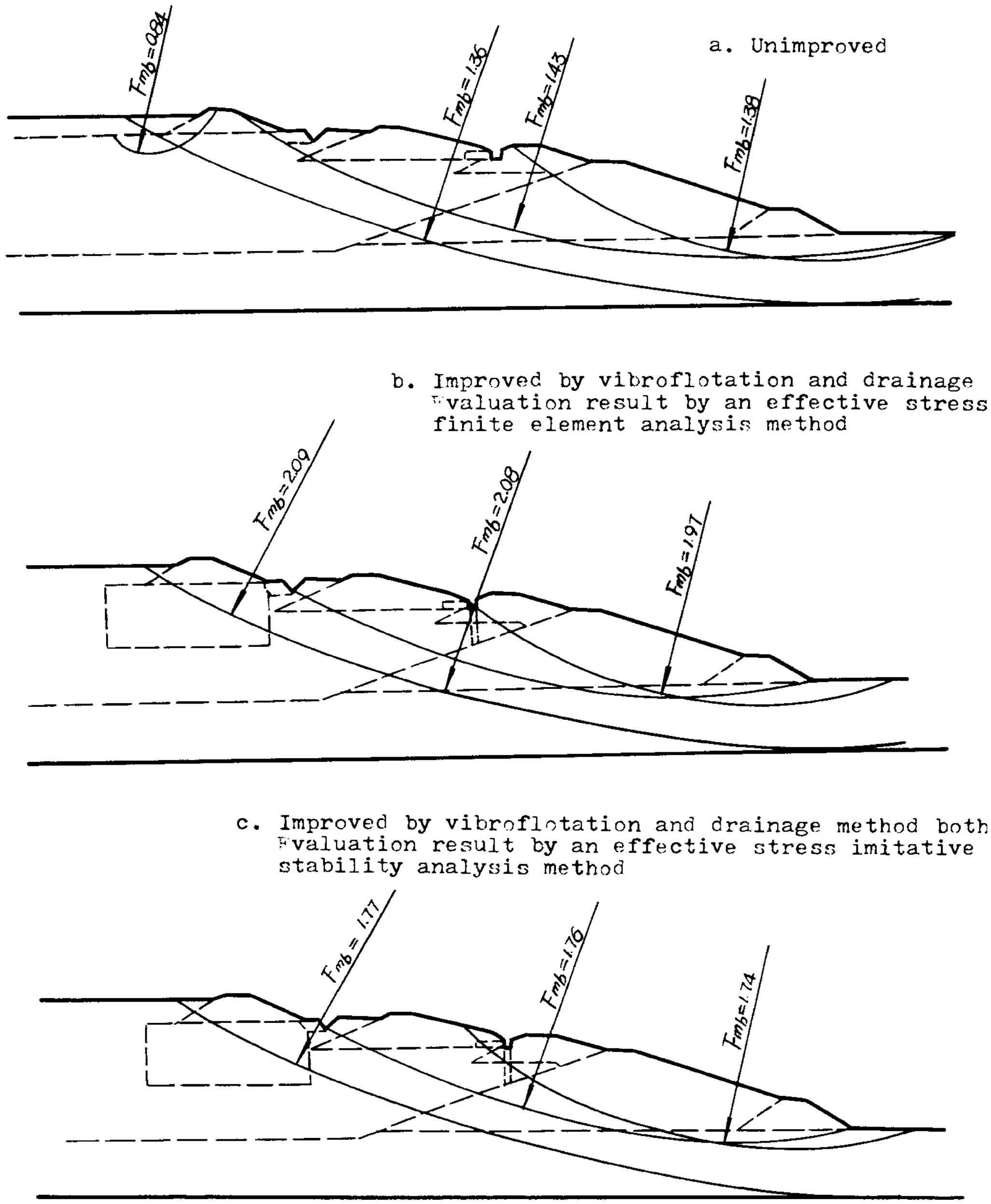


Fig. 4. Results of seismic stability analysis.

As shown above, the earthquake-resistant improvement is necessary to strengthen the ash foundation of the sub-dam and to minimize the liquefied zone. Making a comparison between the effects of some different improvement methods by above-mentioned dynamic response analysis we can find the best two improvement methods as follows:

1. Vibroflotation method
The density of ash deposit will increase obviously by vibroflotation. The in-situ investigation shows that the relative density will increase to 0.65 from 0.09 and the strength of the improved ash will be much larger than that of original loose ash. By vibroflotation about 30 percent volume of ash deposit is replaced with stone co-

lumn, hence the strength of ash-stone composite foundation will be much larger than that of unimproved ash deposit. So that the sub-dam on the ash-stone composite foundation will be stable even when an earthquake happens as shown in Fig. 4. The laboratory test shows that the anti-liquefaction ability of ash increases with increasing of density. In addition, the stone column is a good drainage path. Therefore, the excess pore water pressure decreases and the area of liquefied zone becomes small and goes far away from the third sub-dam, and so the seismic stability increases obviously by vibroflotation as shown in Fig.3 and 4.

2. Drainage method

As the phreatic water surface is very high and the strength of soil in the original dam and the dam foundation is very low, the stress level of the original dam and its foundation is high and up to 1.0. The problem could not be solved by vibroflotation. For this purpose, we choose a kind of drainage method. We have set a longitudinal drainage channel to change the seepage condition of the ash lagoon. The seepage analysis shows that the phreatic water surface will draw down 8 m by the drainage method as shows in Fig. 5. Therefore, the stress level before earthquake will decrease so much that the shear zone, in which the stress level is up to 1.0, will become very small and the seismic stability of the ash-retention dam will be much higher than that of unimproved ash-retention dam as shown in Figs.1 and 4.

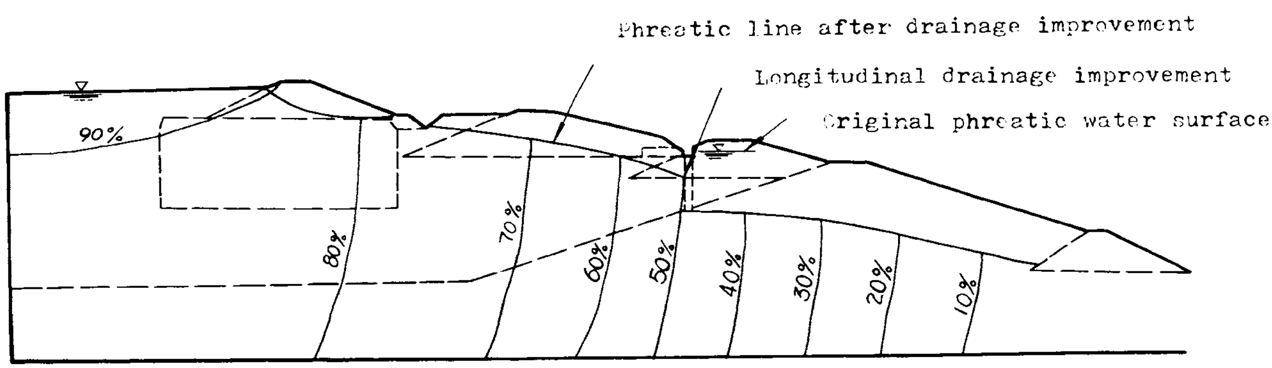


Fig. 5. Result of seepage analysis.

CONCLUSIONS

As the results of the study the following conclusions could be reached:

1. A nonlinear stress-strain static evaluation model and an equivalent visco-elastic dynamic evaluation model can simulate well the static and seismic behaviors of the ash-retention dam and coal ash deposit.

2. Both vibroflotation and drainage methods are effective earthquake-resistant improvement method.

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