PRELIMINARY ANALYSIS OF DAMAGE TO
THE BAI RIVER AND THE CHIAO RIVER DAM

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SUMMARY

Causes for different earthquake performances of the facing layers on the Bai River Dam and the Chiao River Dam during the Tangshan earthquake are analysed primarily in the paper. Three methods for evaluating liquefaction potentials of the saturated cohesionless soil in a dam are proposed.

INTRODUCTION

Two main dams of Miyun Reservior near Beijing, the Bai River Dam and the Chiao River Dam, are earth dams covered with thin inclined clay wall. Both base deposits and dam bodies are composed of sandy gravel. The max. height of the dam and the max. deposit thickness are 65.3 m and 40 m for the Bai River Dam and 56 m and 20 m for the Chiao River Dam respectively. A typical cross section of the former is shown in Fig. 1. Variation of density of sandy gravel in the facing layer is quite large. Based on the 53 samples for the Bai River Dam and 32 samples for the Chiao River Dam taken from the dams, the sandy gravel content of the two dams are 63.4% and 49.3%, respectively. The mean dry unit weight of fine components are 1.61 t/m^3 and 1.68 t/m^3 and the corresponding relative densities, 32% and 53%, respectively. The secondary mean dry unit weight* are 1.53 t/m^3 and 1.61 t/m^3, the corresponding relative densities, 16% and 37% respectively.

During the Tangshan earthquake of July 28, 1976, the epicentral distance of the dams is almost the same, about 150 km, and the seismic intensity in the dam area is VI. Strong-motion records had been obtained by the accelerographs installed on the Bai River Dam. The max. horizontal acceleration is 0.057 g at the base and 0.16 g on the top of the dam. Slides of the facing layer of the Bai River Dam starting from the water level had taken place along the whole length of the dam. Inspection after the earthquake showed that inclined clay wall and the upper part of the facing layer above the water level still remained stable and there was no damage to the Chiao River Dam during the earthquake.

Aseismic stability of the facing layer was checked for earthquake of intensity XIII (early in the design of the dams), and for the Tangshan earthquake, after the earthquake by using the pseudo-static method. Result of computation shows the dams are safe enough. Therefore, the result is not in agreement with the earthquake performance of the dam.

The fact that the facing layer of the Bai River Dam may liquefy can be explained qualitatively as follows: 1) Slide of the facing layer occurred below the water level; 2) Seiving of the sandy gravel occurred

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* The secondary mean dry unit weight is the mean of the unit weights whose values are smaller than the mean dry unit weight.

during sliding; 3) The gravel contents of the sandy gravel in the facing layer of both dams are less than 70%. According to the vibration test result of the Chinese Academy of Hydraulics, the pore water pressure in such sandy gravel will increase obviously; 4) Excavation of the facing layer of the Bai River Dam above the water level showed that the gravel content did not form a continous skeleton, and seismic shearing stresses are mainly undertaken and transmitted by sands which are easily liquefied during earthquake.

Qualitative evaluation of liquefaction of the sandy gravel is made as follows.

TRIAXIAL CYCLIC LOADING LIQUEFACTION TEST OF THE FINE COMPONENTS

The mean grain sizes of materials for testing are 0.355 mm and 0.282 mm for the Bai River and the Chiao River Dam, respectively. Dry unit weights of the test samples are 1.65 t/m^3 and 1.70 t/m^3, and the corresponding relative densities are 40% and 49% for the Bai River Dam and 46.8% and 57.5% for the Chiao River Dam. Fig. 2 gives the liquefaction stress ratio, corresponding to 30 cycles. Fig. 3 shows the stress condition due to the triaxial test. Circle, O_s, is the consolidation stress circle, and circle, O_{sd}, is the resultant stress circle, formed by superimposition of the axial cyclic stress amplitude on the consolidation stress, and it is termed as the liquefaction stress circle. A tangent is drawn from the origin to the circle, O_{sd}, and the angle between the tangent and the abscissa is termed as liquefaction angel, φ_ℓ. After finding out the liquefaction stress ratios corresponding to mean dry unit weight and secondary mean dry unit weight from Fig. 2 by interpolation, it appears that the liquefaction stress ratio of the fine components in the facing layer of the Chiao River Dam is larger than that of the Bai River Dam.

EVALUATION OF THE STATIC AND THE SEISMIC STRESS IN THE FACING LAYER

A simplified method is used instead of FEM. Because the facing layer is too thin and located on the boundary, so FEM may introduce larger error in the calculation, besides, the input rock motion during the Tangshan earthquake is not yet known.

The static stress is determined by the method proposed in Ref. (1). The initial shearing stress ratio, α, in a horizontal plane, i.e. the ratio of the static shear stress to the normal stress, equals 0.18 when Poisson's ratio is taken as 0.35. Besides, a static principal stress ratio K_c =2.2 is obtained.

The seismic stress is determined as follows. Assuming that the acceleration of seismic motion in the facing layer is the same as that on the dam surface which can be evaluated from the strong-motion accelerogram recorded on the Bai River Dam, the ratio of equivalent seismic shearing stress amplitude to static normal stress in a horizontal plane of depth z can be determined as follows:

$$\tau_{xzd}/\sigma_{zs} = 0.65 \frac{a_{max}}{g}\left(1+\frac{1}{\gamma_B}\right) \tag{1}$$

where, a_{max} - maximum amplitude of acceleration on the dam surface; g - acceleration of gravity; γ_B - the submerged unit weight of soils.

METHODS OF DETERMINATION OF LIQUEFACTION POTENTIALS

H. B. Seed's method (2) and three methods presented by the writer are used to determine the liquefaction potentials of sandy gravel in the facing layer.

1. H. B. Seed's method. Three assumptions of the method are: a) liquefaction is induced by the seismic horizontal shearing stresses; b) the failure plane is the horizontal plane; c) the effective dynamic friction angle is equal to the effective static friction angle.

But, the writer has different opinions: a) It is not appropriate to assume that failure occurs in the horizontal plane for dams; b) As shown in Fig. 3, there are two points on the static stress circle, O_s, having the same value as the given initial shear stress ratio, α_E. Generally, static normal stress in the horizontal plane is larger than that in the lateral plane in dams, and therefore, it should correspond to the point on the right of the center of O_s. But the failure plane is situated on the left of the center actually; c) Static stress condition of a point cannot be determined exactly by the static normal stress and the initial shear stress ratio in the horizontal plane, except considering the static principal stress ratio. But it is seen from Fig. 2 that consideration stress ratio has an obvious effect on the liquefaction stress ratio, so that it should be regarded as an independent factor influencing the liquefaction; d) There is no sound basis for the assumption that the dynamic effective friction angle equals the static effective friction angle. In order to determine the position of the failure plane in circle O_s and O_{sd}, this assumption is not certain necessary. According to the total stress method, position of the failure plane in circle O_{sd}, is the tangent point F_d, shown in Fig. 3 and F_s in circle O_s.

2. Proposed method 1. Assuming that liquefaction is induced by the seismic horizontal shear stresses and the failure will occur in any plane other than the horizontal, a method for evaluating the stress condition in liquefaction is given in Fig. 4 and its main procedure is as follows: (Let K_{cE} be the static principal stress ratio in an element, and α_E be the initial shear stress ratio in the horizontal plane in the same element.) a) Determining the liquefaction stress ratio $(\sigma_{ad}/2\sigma_3)_{K_{cE}}$ due to K_{cE} and assuming a consolidation pressure σ_3, draw circle O_s and O_{sd}; b) Draw a straight line from the origin, making an angle equal to $\tan^{-1}\alpha_E$ with the abicissa and intersecting O_s at two points. If the horizontal plane corresponds with the point, A_s, on the right of O_s, then its position, point A_d on O_{sd} can be obtained by means shown in Fig. 4, where σ_s and τ_d represent the static normal stress and cyclic shear stress amplitudes respectively. The liquefaction stress ratio may be denoted by (τ_d/σ_s) in such a case. The following inequality specifies the condition that liquefaction cannot occur:

$$\tau_{xzd}/\sigma_{zs} < (\tau_d/\sigma_s) \tag{2}$$

This method fails in the neighborhood of the central axis of the dam due to the fact that the liquefaction stress ratio should be zero when the initial shear stress ratio becomes zero.

3. Proposed method 2 . Assuming again that liquefaction is induced by seismic horizontal shearing stresses, the main procedure of this method is shown in Fig. 5. a) Draw a straight line, ON, from the origin, making an angle equal to the liquefaction angle, φ_{lE}, determined by K_{CE}, with the horizontal axis and assume a consolidation pressure σ_3 . Then, find out the position of the horizontal plane A_s on O_s; b) If the stress circle, formed by superimposing the cyclic stress on static stress, is tangent to ON, liquefaction will occur. Since the horizontal shear stress is considered only to induce liquefaction so that the liquefaction stress circle O_{sd}, should be concentric with the circle O_s and tangent to ON also. In Fig. 5, components σ_s and τ_d of point A_s are static normal stress and cyclic shear stress respectively. Denoting the stress ratio by (τ_d/σ_s), Eq. 2 can be used as a criterion to determine the liquefaction potential.

Proposed method 3 . In this method, not only the horizontal shear stress but the other stress components are considered. Decompose a seismic stress into two part, the spherical and the deviatoric stress and assume that liquefaction is induced by the latter. After defining the liquefaction stress ratio in terms of octahedral stress, ($\tau_{octd}/\sigma_{octs}$) as a generalized liquefaction stress ratio, and finding the relation between the generalized ratio and the consolidation ratio from the cyclic triaxial loading tests, a threshold of liquefaction may be provided as

$$\tau_{octd}/\sigma_{octs} < \left(\tau_{octd}/\sigma_{octs}\right)_{K_{CE}} \qquad (3)$$

in which ($\tau_{octd}/\sigma_{octs}$) - a generalized liquefaction stress ratio corresponding to K_{CE}; τ_{octd}, σ_{octs} - octahedral cyclic shear stress and the static octahedral normal stress respectively. If Eq. 3 holds, liquefaction will not occur.

When only the seismic horizontal shear stress is considered, Eq. 3 reduces to

$$\tau_{xzd}/\sigma_{zs} < \frac{2+2\xi}{\sqrt{3}\,(K_{CE}+2)}\left(\sigma_{ad}/2\sigma_3\right)_{K_{CE}} \qquad (4)$$

where, ξ - the coef. of lateral pressure.

COMPUTATION RESULTS AND MAIN CONCLUSIONS

Strong-motion record obtained on the Bai River Dam is used in computing seismic stresses in the facing layer of the Bai River and the Chiao River Dams. The reasons are: a) the epicentral distances to these two dams and the direction of the dam axis to epicenter are almost the same; b) the dams are of the same type and almost the same height; c) the dams have the same base materials but different thickness. The thickness of base materials of the Bai River Dam at the section, on which the strong motion was recorded, is almost equal to the maximum thickness of base materials of the Chiao River Dam.

Letting the inequalities be equal, the distribution of maximum accelerations due to liquefaction along the height of the dam can be obtained by the above four methods. If the recorded acceleration is larger than the computed one, liquefaction will occur, or vice versa, as shown in Fig. 6 and Fig. 7.

It can be seen from Fig. 6 that if the liquefaction indices corresponding to the mean density are used in computation, liquefaction does not occur in the Bai River Dam at all. If those corresponding to the secondary mean density are used, Seed's method will give the result that liquefaction only occurs near the water level, while proposed method No. 1 will give the conclusion that a liquefied zone will extend down to 29-30 m from the water level, in good agreement with the practical zone, Method 2 concludes that liquefaction may occur down to 9-10 m, and the conclusion of Method 3 is the same as Seed's method. Whereas, no liquefaction will occur in the Chiao River Dam, determined by all methods. The conclusion is in agreement with the actual condition.

Three conclusions may be made from the above results. 1) Different earthquake performance of the two dams may be due to the fact that the relative density of fine components is higher in the Chiao River Dam than in the Bai River Dam. But this is a complicated problem, perhaps, there exist other causes also. 2) All four methods may give an actual conclusion provided that an appropriate index for liquefaction is selected. Practically, in a dam, the density variation may be quite large so that it is reasonable to take it into consideration in seismic stability computations. Experience shows that, if the liquefaction indices including the secondary mean density are used, a better result will obtain. 3) The facing layer of inclined wall type dam and the upstream embankment of core wall type dam are the most instable parts in liquefaction during earthquakes, even though the intensity of which is as low as VI or VII. In order to increase seismic stability, it is better to increase the density of filling as high as possible. If the filled materials are to be sandy gravel, the gravel content should be more than 70%.

REFERENCE

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2. Seed, H. B., Idriss, I. M., Lee, K. L. and Makdisi, F. I., 1975, "Dynamic analysis of the slide in the lower San Fernando Dam during the earthquake of February 9. 1971", Journal of Geotechnical Engineering Division, ASCE, Vol. 101, No. GT9, Proc. Paper 11541, pp. 889-991.

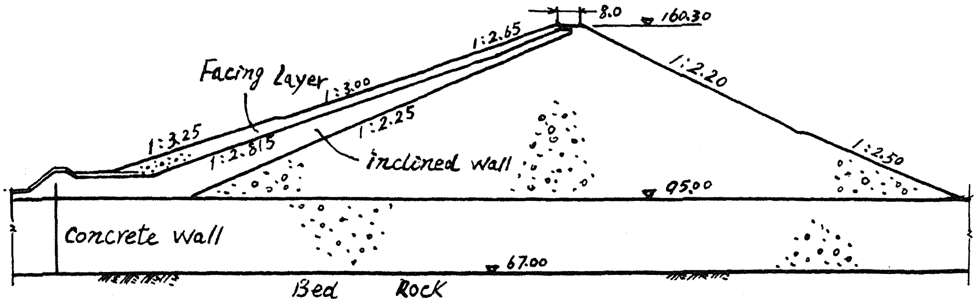

Fig.1 A Typical Section of the Bai River Dam

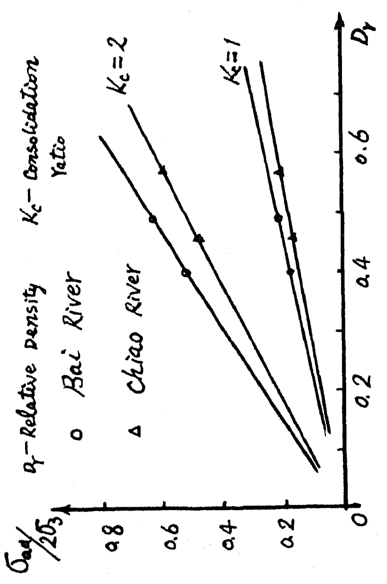

Fig.2 The Stress Ritio for Liquefaction (N = 30)

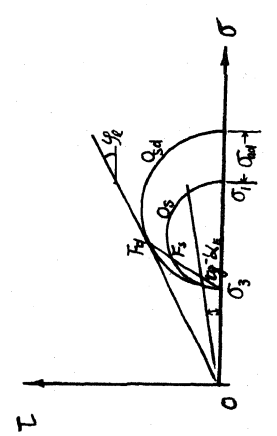

Fig.3 The Stress Condition of Triaxial Test and the Definition of Liquefaction Angle

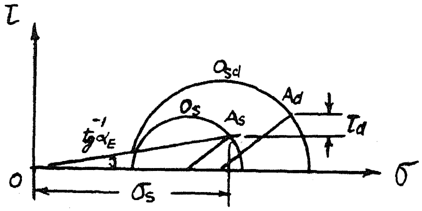

Fig. 4 The Liquefaction Stress Condition — Method 1

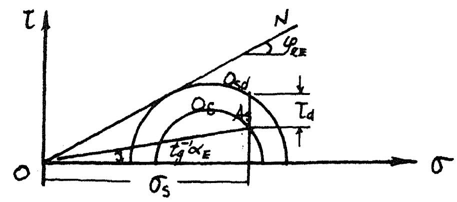

Fig. 5 The Liquefaction Stress Condition — Method 2

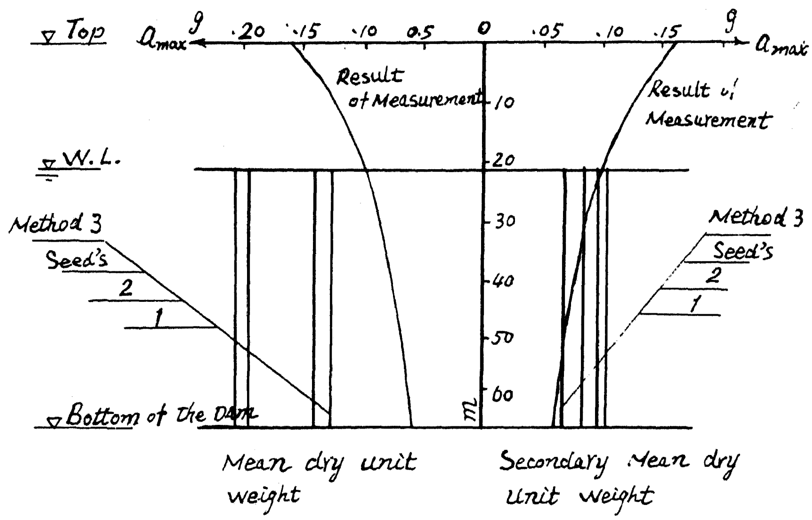

Fig. 6 The Results of Computation for the Bai River DAm

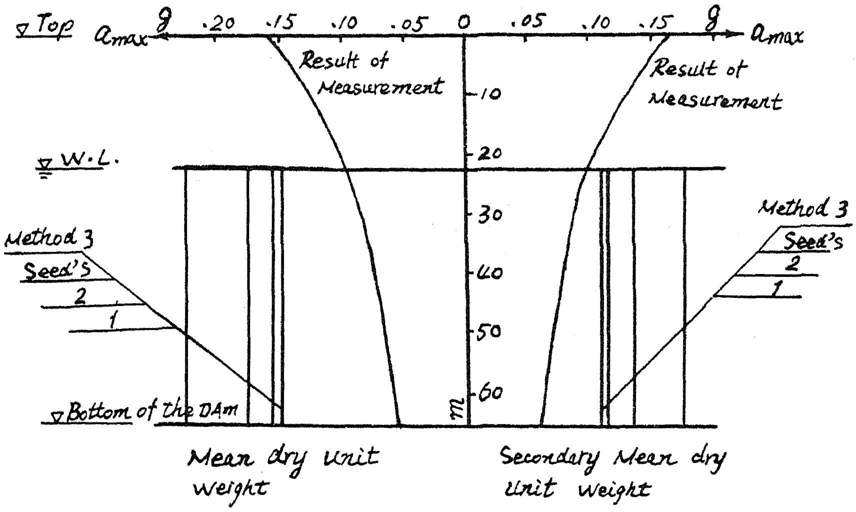

Fig.7 The Results of computation for the Chiao River Dam