3-D DYNAMIC ANALYSIS OF TAIYUAN FLY ASH DAM

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SUMMARY

In this paper, the seismic stability of Taiyuan Fly Ash Dam in China is studied by using 3-D dynamic effective stress analysis method. The acceleration, dynamic shear stress and pore water pressure in the fly ash dam are calculated and the analysis of the seismic stability of the dam considering the seismic pore water pressure is given for different height of the dam.

INTRODUCTION

Taiyuan Fly Ash Dam is located in Shanxi province in China. The maximum height of the dam is 95.5m and the length between abutments at its crest is 258m, i.e., the crest length to height ratio is only 2.70 . In addition, the shape of the crest of the dam in plan is like letter L . Therefore, the response of the dam is of a 3-D nature, considerable judgment is required to estimate the overall dynamic response from that only computed for main section of the dam. The dynamic analysis of the dam is carried out with a 3-D FEM procedure. The hyperbolic model by Hardin and Drnevich is taken as stress-strain skeleton curve, Masing rule is used to determine unloading and reloading, and Masing-type curve is revised with damping by Hardin´s equation. The tendency to develop volumetric strains due to dynamic shear stress is taken into account by introducing a modified form of pore water pressure model presented by Seed into constitutional equation. The acceleration, dynamic shear stress and pore water pressure in the fly ash dam are calculated and the analysis of the seismic stability of the dam considering the seismic pore water pressure is given for different height of the dam.

Dynamic Properties

The material of the fly ash dam is regarded as nonlinear medium, the hyperbolic model by Hardin and Drnevich(1972) is taken as stress-strain skeleton curve, Masing rule is used to determine unloading and reloading, and Masing-type curve is revised with damping by Hardin and Drnevich ´s equation. After each load reversal, if stress is less than maximum stress occurred before, the tangent shear modulus is determined by

$$G = G_{ms} + \kappa(\gamma_m)\left\{\frac{G_{\max}}{\left[1+(\gamma-\gamma_a)/(2\gamma_r)\right]^2} - G_{ms}\right\} \tag{1}$$

where $G_{ms} = G_{max}/(1+\gamma_h)$, is secant modulus of the backbone curve at the point of maximum shear stress occurred before, $G_{max} = 6920k_{2max}(\sigma_m)^{0.5}$, is initial tangent shear modulus, $\gamma_h = \gamma/\gamma_r$, γ_r is so-called reference strain, γ_a is shear strain at the point of reversal, k_{2max} is maximum shear modulus coefficient of material, $\kappa(\gamma_m)$ is revision coefficient of damping ratio corresponds to maximum shear stress occurred before. The empirical equation proposed by Hardin and Drnevich for damping ratio is as

$$D = D_{\max}\frac{\gamma_h}{1+\gamma_h} \tag{2}$$

where, D_{max} is the maximum damping ratio. The values of k_{2max} , D_{max} and other indwx properties of fly ash dam materials are listed in Table 1.

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Table 1 Index Properties of Fly Ash Dam Materials

Materials	Clay	Gravel	Fly ash
Saturated Unit Weight γ (kN/m^3)	19.0	21.5	14.8
Effective Cohesion C' (kPa)	23.2	-	-
Angle of Internal Friction φ' (°)	23.0	35.0	29.0
Coefficient of Permeability k (m/s)	8.3×10^{-10}	2.1×10^{-3}	4.1×10^{-6}
Max. Shear Modulus coefficient k_{2max}	10.0	45.0	4.1
Max. Damping Ratio D_{max}	0.35	0.28	0.285

Formula for Pore Water Pressure Induced by Vibration

A modified form of pore water pressure model presented by Seed (Seed, et al., 1976) is used in analysis as follows:

$$\frac{u_g}{\sigma_m} = \frac{1}{2} + \frac{1}{\pi}\arcsin\left[\beta(\frac{N}{N_m})^{\frac{1}{\alpha}} - 1\right] \tag{3}$$

where, σ_m is the total mean stress, N is the number of loading cycles in t time, N_m is the number of loading cycles to cause maximum pore water pressure, α is the parameter related with dynamic shear stress ratio, β is the parameter related with static shear stress ratio.

3-D DYNAMIC EFFECTIVE STRESS ANALYSIS

The dynamic analysis of the dam is carried out with a 3-D FEM procedure (Zhou Jian et al. 1991). The equations for finite-element approximation in incremental forms as follows:

$$[K]\{\Delta\delta\} + [Q]\{\Delta P\} + [C]\{\Delta\dot{\delta}\} + [M]\{\Delta\ddot{\delta}\} = \{\Delta F\} \tag{4}$$

$$[Q]^T\{\Delta\delta\} + [H]\Delta t\{p\} = \{\Delta\overline{F}\} \tag{5}$$

where, $[K]$, $[Q]$, $[C]$, $[M]$ and $[H]$ are stiffness matrix, couple matrix, damping matrix, mass matrix, respectively, $\{\delta\}$, $\{\dot{\delta}\}$ and $\{\ddot{\delta}\}$ are nodal displacement, velocity and acceleration vector, respectively. $\{F\}$ and $\{\overline{F}\}$ are nodal earthquake load vector and nodal seepage discharge vector, respectively.

The equation (3) and (4) is solved by the front solution method. The main steps are as follows:

1. Pre-front, form the identification vector for assembly and elimination of dynamic equation.

2. Compute the element matrices of dynamic equation and the loading vector.

3. Front solution, calculate nodal displacements, velocities, accelerations and pore water pressure at each time step.

4. Compute strain and stress field from nodal displacements, determine the new value of modulus G according to revised Masing rule.

5. Calculate seismic pore water pressure increment, and convert it into equivalent nodal force and add it into the loading terms of Eqs. (3).

6. Repeat step 2-5 until the end of earthquake motion.

7. Continue post –earthquake static analysis until no further dissipation of pore water pressure is taking place.

STABILITY ANALYSIS OF THE COAL FLY ASH DAM

The plan of Taiyuan Fly Ash Dam is shown in Fig.1. The dam is devided into 9 section for

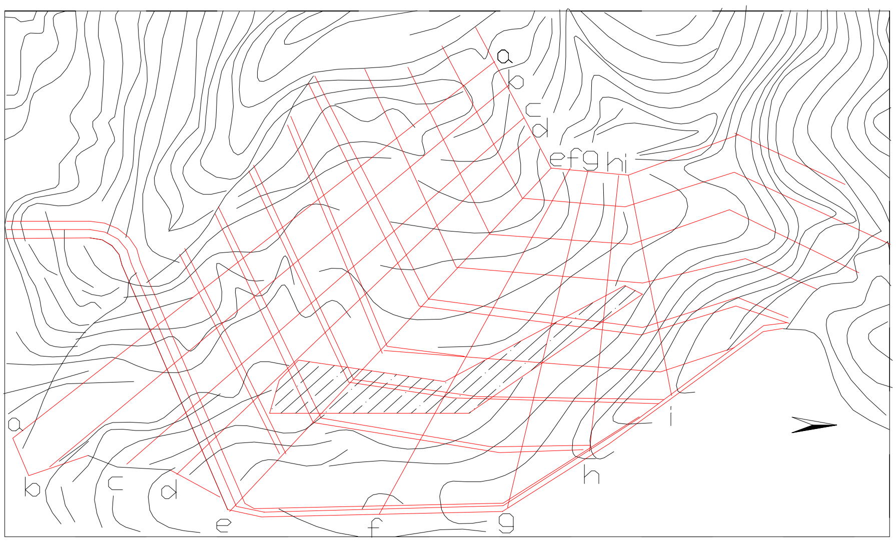


Fig.1 Element Plan (from section a-a to section i-i)

FEM analysis. An accelerogram of Haicheng (in China) Earthquake record is used as the input motion with the peak acceleration being scaled to 200 gal and the predominant period being prolonged to 0.55 second. (Fig.2).

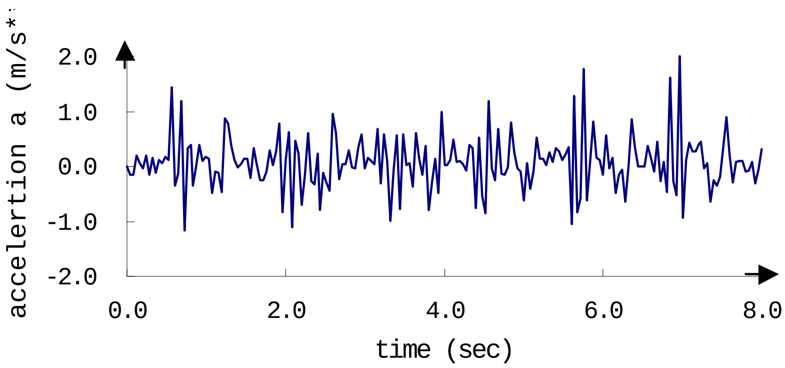
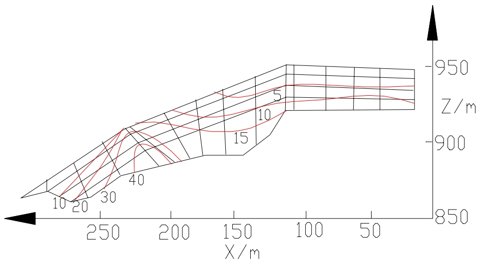


Fig.2 Input Motion

Fig. 3 and Fig. 4 show computed distribution of dynamic shear stress, τ_{xy} of section b-b for different seepage line(before and after stabilization), respectively, when the dam is constructed to designed height. Fig. 5 and Fig. 6 show the pore water pressure of section b-b, d-d, f-f and h-h before and after stabilization, respectively. It shows that liquefaction would occur near the crest and pore water pressure is obviously lower after stabilization.



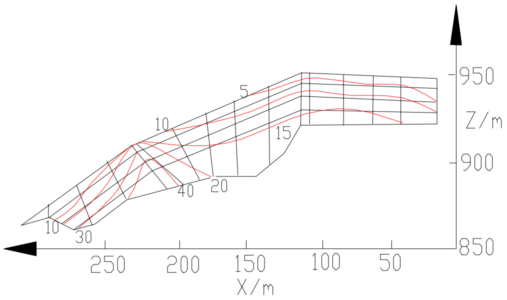


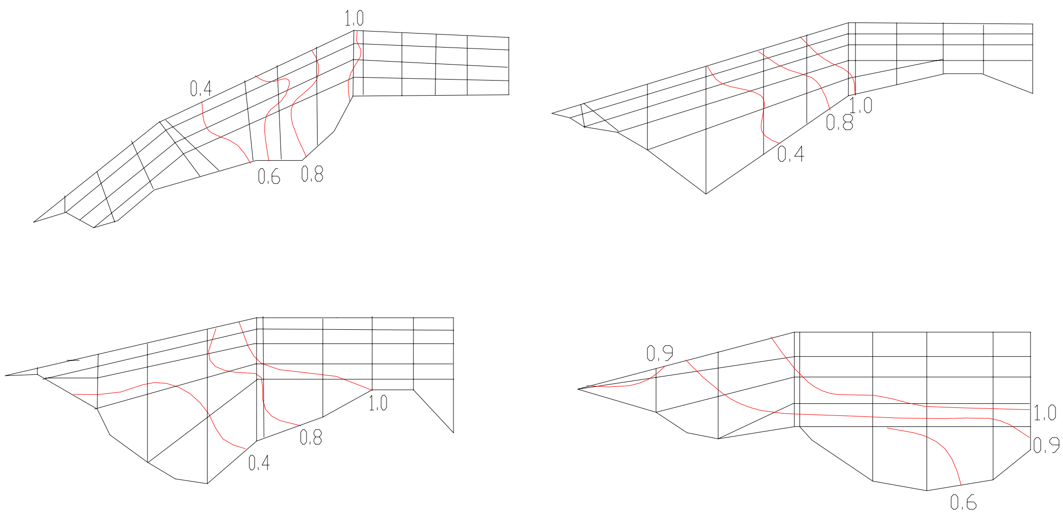
Fig.3 τ_{xy} **of Section b-b with High Seepage Line (before stabilization)**

Fig.4 τ_{xy} **of Section b-b with High Seepage Line (after stabilization)**

It is found from analysis that the initial start dam with height of 57m under an earthquake with intensity of VIII of modified Mercalli scale is stable. But it is not stable if the dam is higher than that height and the most effective measure to increase seismic stability of the dam is to drop the seepage face in the dam. Fig.7 (a,b) shows the result of stability analysis for critical section after the seepage face is droped and the slope of the dam is stabilized. In the region of stabilization, the strength parameters of materials should not be less than C'=10.5kPa, φ' =29.0° when the dam is accumulated to the height of the sixth stage, and not be less than C'=12.5kPa, φ' =29.0° when the dam is accumulated to the designed height.

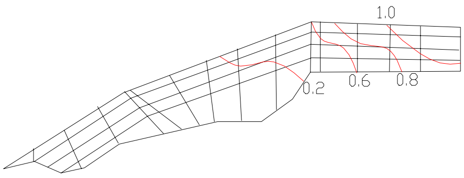
Fig.8 (a,b) shows the stabilized region of fly ash and the result of stability analysis for section b-b. In the region of stabilization, the strength parameters of fly ash should not be less than

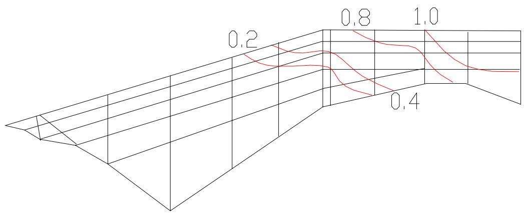
Section b-b **Section d-d**



Section f-f **Section h-h**

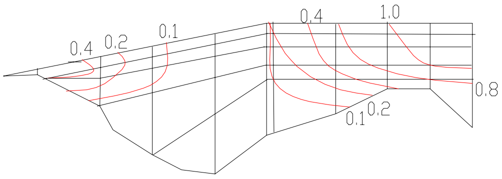
Fig.5 Distribution of Pore Water Pressure Ratio before Stabilization





Section b-b **Section d-d**

Section f-f **Section h-h**



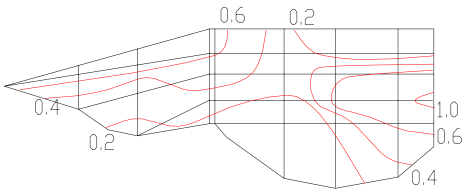
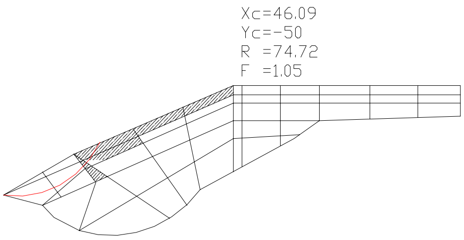
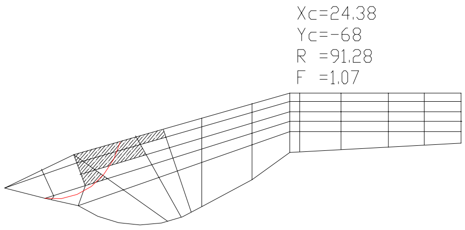


Fig.6 Distribution of Pore Water Pressure Ratio after Stabilization

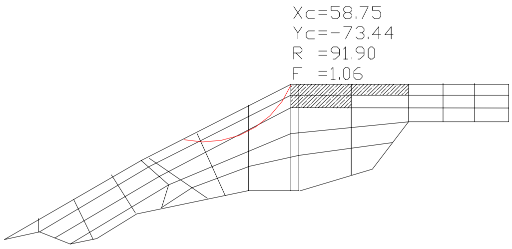


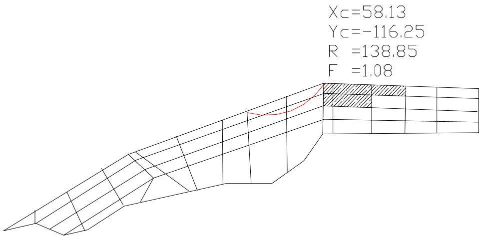


(a) height of sixth stage **(b) disigned height**

Fig.7 Stabilization Region and Safety Factor of the Critical Section

C'=6.5kPa, φ' =29.0° when the dam is accumulated to the height of the sixth stage, and not be less than C'=7.5kPa, φ' =29.0° when the dam is accumulated to the designed height. .





(a) height of sixth stage **(b) disigned height**

Fig.8 Stabilized Region of Fly Ash and Safety Factor of Section b-b

CONCLUSION

It is concluded that the maximum pore water pressure ratio occurs near the crest of the dam and these areas are more sensitive to liquefy. The initial start dam with height of 57m under an earthquake with intensity of VIII of modified Mercalli scale is stable. But it is not stable if the dam is higher than that height and it is found from analysis that the most effective measure to increase seismic stability of the dam is to drop the seepage face in the dam. Some suggestion of stabilization is given.

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