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TWO DIMENSIONAL SLOPE STABILITY ANALYSIS UNDER SEISMIC LOADING

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1. Introduction

Among various methods of slope stability analyses and design, there is a method that estimates seismic loading induced permanent deformations of slopes. Assuming that failure surface is a circular one, constant acceleration required for safety factor FS=1 and geometry characteristics of failure surface is determined. Then with assumption that the soil mass above the circular surface is a rigid block, by using Newmark's method and exerting dynamic loading, permanent rotation of circular rigid sliding block is estimated by solving the equation of motion. Effect of input acceleration and time history, the natural frequency of the embankment, and the frequency of input wave are studied.

2. Critical Circular Slip Surface

A soil with slope angle of α strength parameter of c and ϕ is subjected to horizontal acceleration a(t)(Fig. 1). Assuming this acceleration is constant and using pseudo static limit equilibrium lead to calculating safety factor based on acceleration as a fraction of the acceleration g and geometry of circle. By changing the radius and the coordinates of the center of slip circle at certain acceleration, the minimum safety factor of that case will be find. Each constant acceleration has a special circle and FS. The minimum acceleration that makes minimum safety factor against rotation equal to 1, is yield acceleration in pseudo static method and the corresponding circle is the critical slip surface. As an example, some critical circular slip surfaces for various constant accelerations are shown in Fig. 2. While the constant acceleration is zero or near zero, the failure surface is deeper, and by increasing the acceleration, the depth of failure will decrease.

3. Displacement of Circular Rigid Sliding Block

The critical circular slip surface with FS=1 is chosen as a rigid block. This block is subjected to sinusoidal acceleration wave $a(t) = a_0 \sin \omega t$. Newmark's method and equations of motion is used for determining the angular velocity and rotation of the rigid block during a time history. The moment due to gravitational force and inertia force act as driving moment and the moment corresponding to cohesion and frictional force between interface of block and soil act as resisting moment.

$$M_D = mg(x_{cg} - x_c) + ma_0 \sin \omega t (y_c - y_{cg})$$

Where x_{cg}, y_{cg} are the coordinates of gravity center of circular block, and x_c, y_c are the coordinates of the center of circle.

$$M_{R2} = \frac{-\gamma a_0 \sin \omega t}{g} \tan \phi \left[\frac{x^3}{3} \tan \alpha - \frac{x^2}{2}(y_c + x_c \tan \alpha) + x x_c y_c - \frac{\left[R^2 - (x - x_c)^2\right]^{\frac{3}{2}}}{3} \right]_{x_1}^{x_2}$$

$$M_{R1} = R\gamma \tan \Phi \left\{ \left[\frac{x^2}{2} \tan \alpha - y_c x + \tfrac{1}{2}(x - x_c)\sqrt{R^2 - (x - x_c)^2} \right]_{x_1}^{x_2} + \tfrac{1}{2} R^2 (\beta_2 - \beta_1) \right\} + R^2 c(\beta_2 - \beta_1)$$

$$M_R = M_{R1} + M_{R2}$$

Where parameters are shown in Fig. 1. While the inertia force act in the direction of slope downward, M_{R2} is negative and decreases the total resisting moment. When the direction of the inertia force changed to slope upward, M_{R2} increases the total resisting moment. The equation of motion is given by:

$$R_{cg}^2 m \ddot{\theta} = M_D - M_R$$

Where $\ddot{\theta}$ is angular acceleration of rigid block, which caused rotation, and R_{cg} is distance between gravity center of block and center of circle. Initial condition for solving this equation makes angular velocity and rotation zero at t=0. Other condition makes it necessary while absolute value of driving moment is less than absolute value of resisting moment; there is no movement:

$$|M_D| \le |M_R| \Rightarrow \ddot{\theta} = 0$$

When $|M_D|$ becomes greater than $|M_R|$ sliding occurs and rotation will start and continue since inertia force reverse and also relative angular velocity between block and slope becomes zero. Fig. 3 shows plot of angular velocity $R\dot{\theta}$ and rotational displacement $R\theta$ versus time for a slope with α=25, ϕ=30,

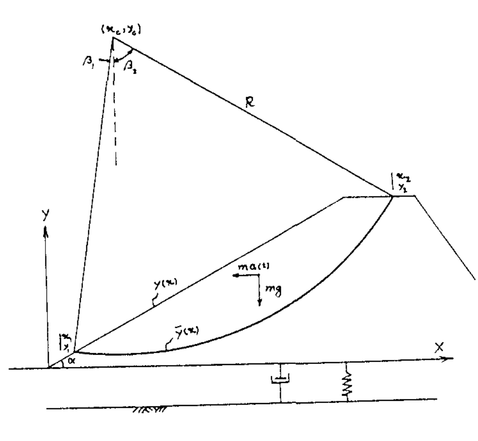

Fig. 1) Circular sliding block inside earth slope

c=40Kpa and input acceleration of 0.4gsinωt. this step by step plot shows when the acceleration reverse, the velocity in upward direction becomes zero and displacement remains constant. As time history of input acceleration increase, the displacement becomes more.

Considering masses and spring system for connecting earth slope to the ground, the effect of natural frequency of embankment and frequency of input wave will be appeared. If the natural frequency f_n is assumed 2 Hz and time history of dynamic loading is 10 sec Fig. 4 shows plot of circular block rotation after 10 sec versus different frequency of input waves. It can be seen that the rotational displacement will increase when input frequency is close to natural frequency. Maximum displacement is corresponded to $f=f_n$ (i.e. resonance condition). Even if the input acceleration is less than the acceleration due to critical circular slip surface which found in previous section, there will be failure and considerable rotation in the slope under resonance condition and some frequency near natural frequency. This means pseudo static solutions do not give acceptable results at least when the frequency of input waves is sufficiently near to the natural frequency.

4. Effect of Damping

Viscous damping will affect on the rotation if a dashpot is added to mass spring system. In a small displacement, the coefficient of damping is usually considered less than 5%. But because of very large displacement and shear strain, it is not correct to limit coefficient of damping to 5% or 10%. However, by utilizing graphs and equations presented by Hardin and Drnevich (H.D method), the coefficient of damping is calculated. For this purpose changing displacement and consequently shear strain value in each step of displacement versus time plot (Fig. 3) is estimated. Based on this shear strain, the amount of damping coefficient is computed by H.D. method. Then the shear strain value of that step is estimated again by using damping coefficient. This iteration will continue until satisfying both equation of motion and H.D. equations. Fig. 5 shows comparison between displacement-time curves for three cases: without damping, with 5% damping and self control damping by using H.D. method. Displacement after 10 sec versus input frequency for the same three cases is compared in Fig. 6.

5. Concluding Remarks

By comparing results in this study it can be concluded that one of the important parameters effected on failure of slopes is relation between frequency of seismic loading and natural frequency of slopes. This is usually ignored in pseudo static analysis and determining of dynamic safety factor. It may cause results far from reality. Increasing in each term like time history of seismic loading, strength parameters of soil, maximum amplitude, and decreasing the angle of slope will increase the permanent displacement.

Reference

1)Hardin; Drenevich (1972). "Shear Modulus and Damping Soils: Design Equation and Curves" ASCE, 98 (SM7)

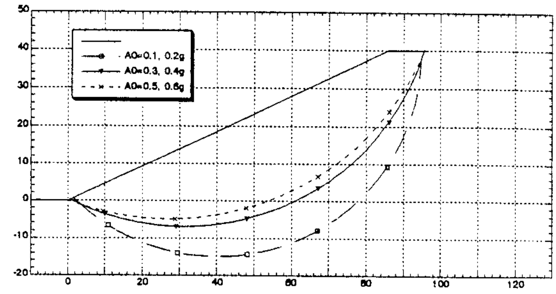

Fig. 2) Critical slip surface for various acceleration

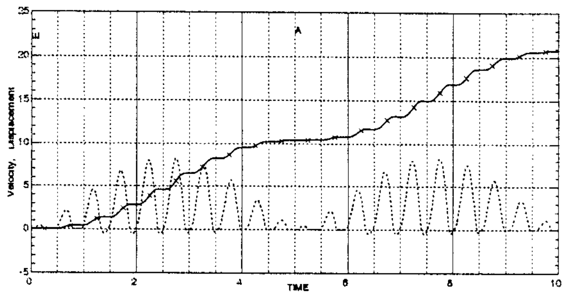

Fig. 3) angular velocity and displacement during shaking

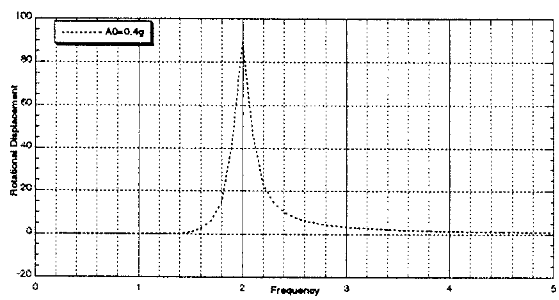

Fig. 4) Effect of frequency on displacement after 10 sec

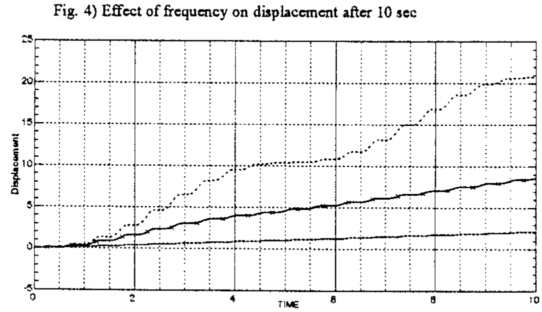

Fig. 5) Comparison between displacement diagram for three cases

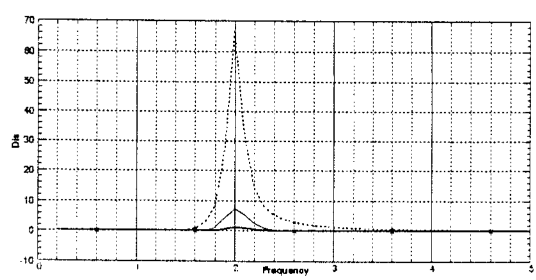

Fig. 6) Displacement after 5 sec versus frequency for three cases