Earth Reinforcement, Ochiai, Yasufuku & Omine (eds) © *1996 Balkema, Rotterdam. ISBN 90 5410 833 9*

Seismic analysis of nailed soil slopes – A pseudo-dynamic approach

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ABSTRACT: In this paper, seismic design of nailed soil slopes are presented based on pseudo-dynamic approach. This method incorporates a finite shear wave velocity based on the assumption that the shear modulus is constant and only the phase not the magnitude of acceleration is varying with depth. The results obtained are compared with pseudo-static approach. The effect of seismic force on the location on the failure plane has been presented. The effects of inclination of the nails and the coefficient of horizontal acceleration on the required reinforcement force have been studied.

1 INTRODUCTION

Soil nailing is a well known technique of reinforcing in-situ soil by passive inclusions, and can be used to retain excavations and to stabilise slopes by creating in-situ reinforced soil retaining structures. Several design methods of nailed soil slopes are available for static condition (Mitchell and Villet, 1987).

The design of retaining walls subjected to earthquake induced lateral force was first reported by Okabe(1924) and Mononobe and Matsuo, 1929(Das,1983). They developed a pseudo-static approach in which the lateral force is assumed to be a function of the weight of the sliding soil mass for a given coefficient of horizontal acceleration. The coefficient of horizontal acceleration is a function of the magnitude of earthquake and distance from the focus (Bonaparte et al. 1986). Bonaparte et al. (1986) studied the behaviour of slopes reinforced with polymer geogrid or geotextile and subjected to seismic forces, using pseudo-static method. Nozawa and Nasu (1985) developed a new method called sheet pile enclosure method to increase the earthquake resistance of embankments. Neelakantan et al. (1992) presented a balanced seismic design concept based on limit equilibrium method for anchored retaining wall. Steedman and Zeng (1990) studied the effect of finite shear wave velocity on the analysis of retaining walls for seismic codition and found that the finite shear wave velocity does not have significant influence on the magnitude of the total lateral earth pressure, but it has marked effect on the distribution of the dynamic increment of pressure.

In this paper, the seismic analysis of nailed soil slope has been presented based on pseudo-dynamic approach. The results obtained are compared with pseudo-static method. The effect of seismic force on the location of the failure plane has been studied. The effects of inclination of the reinforcement and the coefficient of horizontal acceleration on the required reinforcement force for equilibrium have been presented.

2 FORMULATION

In this section, the analysis of nailed soil slopes for seismic condition has been carried out based on pseudo-dynamic approach. The analysis based on pseudo-static approach is presented briefly.

2.1 Pseudo-dynamic analysis

In pseudo-static analysis, the soil is assumed to be rigid and the shear wave velocity is infinite. However, centrifuge modelling tests (Steedman and Zeng, 1990) show clearly the phase change in lateral acceleration in the backfill behind a retaining wall as shear waves propagates from the base of the model towards the ground surface. A pseudo-dynamic analysis incorporates a finite shear wave velocity based on the assumption that the shear modulus is constant with depth and only the phase and not the magnitude of the acceleration is varying.

For sinusoidal base shaking, the acceleration at depth, z, and time, t, is given by (Steedman and Zeng, 1990),

$$A(z,t) = K_h\, g \sin \omega[t-(H-z)/V_s] \quad (1)$$

where K_h = coefficient of horizontal acceleration, g = acceleration due to gravity, ω = angular velocity, H = height of the wall and V_s = shear wave velocity.

Fig. 1 shows a slope with wedge ABC, slope angle, β, wedge angle, θ, normal force, N, shear force, S, reinforcement force (pseudo-dynamic case), T_{rd}, inclination of the reinforcement, λ, and the horizontal inertia force P_h. Considering the mass of a horizontal wedge, the horizontal inertia force is given by

$$P_h = \int_0^H \rho(H-z)(\cot\theta - \cot\beta)\, A(z,t)\, dz \quad (2)$$

where ρ is the density of the soil. Evaluating the above integral.

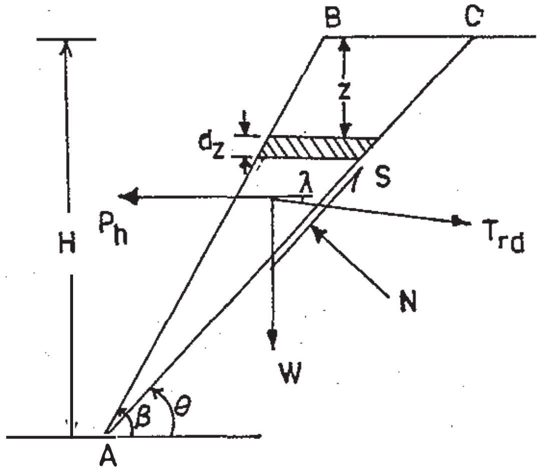

FIG. 1 FORCES ACTING ON THE FAILURE WEDGE(PSEUDO-DYNAMIC CASE)

$$P_h = \frac{\Lambda\gamma K_h\,(\cot\theta - \cot\beta)}{4\pi^2}\,[2\pi H \cos\omega\zeta + \Lambda(\sin\omega\zeta - \sin\omega t)] \quad (3)$$

where $\Lambda = V_s/f$, the shear wave length and $\zeta = t - H/V_s$, f = frequency(1/T), T = period.

Consider the equilibrium of the wedge ABC as shown in Fig. 1. Resolving the forces leads to an expression for total reinforcement force, T_{rd}, as

$$T_{rd} = 1/2\, \gamma H^2 K_{rd} \quad (4)$$

where K_{rd} is the coefficient of reinforcement force obtained from pseudo-dynamic analysis and is given by

$$K_{rd} = \frac{2P_h/\gamma H^2 + (\cot\theta - \cot\beta)\tan(\theta-\phi)}{\cos\lambda - \tan(\theta-\phi)\sin\lambda} \quad (4a)$$

Substituting for P_h from Eq.(3) in Eq.(4a) and simplifying, K_{rd} is seen to be a function of the dimensionless expressions, H/TV_s, t/T and wedge angle, θ. The maximum value of K_{rd} is obtained by maximizing K_{rd} with respect to t/T and θ, it is observed that K_{rd} is simply a function of H/TV_s.

2.2 Pseudo-static approach

The required reinforcement force by pseudo-static analysis (T_{rs}) can be derived assuming the soil as rigid. i.e as shear wave velocity, V_s tends to infinity, Eq. (4) can be expressed as

$$T_{rs} = 1/2\, \gamma H^2 K_{rs} \quad (5)$$

where K_{rs} is the coefficient of reinforcement force obtained from pseudo-static approach and is given by

$$K_{rs} = \frac{(\cot\theta - \cot\beta)[\tan(\theta-\phi) + K_h]}{\cos\lambda - \tan(\theta-\phi)\sin\lambda} \quad (5a)$$

3 RESULTS AND DISCUSSION

The pseudo-dynamic and pseudo-static methods for seismic analysis of nailed soil slopes are compared with respect to wedge angle and the required reinforcement force for equilibrium of the wedge. The effect of inclination of the reinforcement on the required reinforcement force has also been studied.

Fig. 2, shows the critical wedge angles obtained from pseudo-static and pseudo-dynamic approaches, for $\beta = 60°$, $H/TV_s = 0.3$, $\phi = 30°$ and $K_h = 0.2$. The wedge angle obtained from pseudo-static analysis is lower (about 3%). This indicates that the pseudo-static analysis is slightly conservative for finite shear wave velocity.

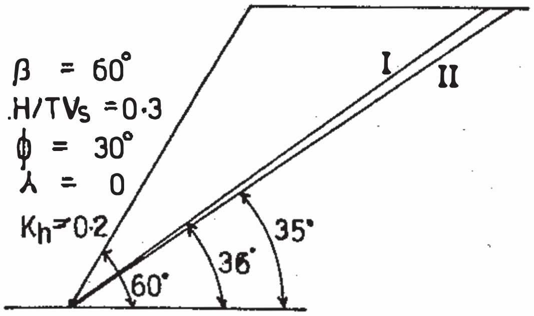

Fig 2 Wedge Angles, I - Pseudo dynamic, II - Pseudo-Static cases

The comparison of pseudo-static and pseudo-dynamic analyses have been presented in Fig. 3. It shows the variation of K_{rs} and K_{rd} with slope angle, for the values of K_h ranging from 0.0 to 0.2. It can be observed that the required reinforcement force obtained from Pseudo-dynamic approach would be smaller compared to Pseudo-static approach. For example, for $K_h = 0.2$ and $\beta = 60°$, the coefficient of reinforcement force required from Pseudo-static and Pseudo-dynamic methods are 0.245 and 0.225 respectively. The error involved in using pseudo-static approach is of the order of 10% for $K_h = 0.2$. However, it is evident from this figure that the differences in these two methods depend on the value of K_h. As K_h decreases, the differences in the values of K_{rd} and K_{rs} also decrease and when $K_h = 0.0$, both the methods will give the same results. Hence, it is preferable to use pseudo-dynamic approach when the value of K_h is greater than 0.2.

Fig. 4 depicts the variation of coefficient of reinforcement force obtained from Pseudo-dynamic approach, with slope angle for inclination of the reinforcement varying from 0° to 12° with the horizontal. The effect of inclination of the reinforcement is negligible for lower slope angles. But, for higher slope angles, the coefficient of required reinforcement force increases with increase in inclination of the reinforcement with the horizontal. Thus, the horizontal placement of the reinforcement would result in minimum required reinforcement force.

4 CONCLUSIONS

In this study, a pseudo-dynamic approach has been used for the seismic analysis of nailed soil slopes and the results are compared with the pseudo-static approach.

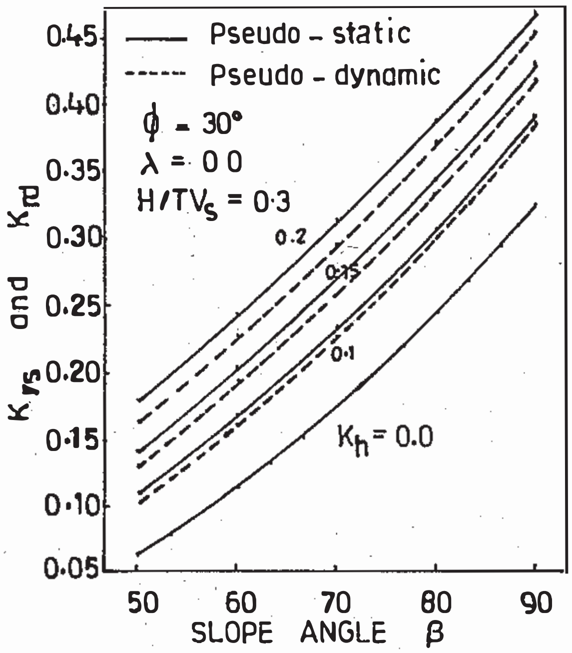

Fig 3 Comparison of Pseudo-Static and pseudo-dynamic analysis

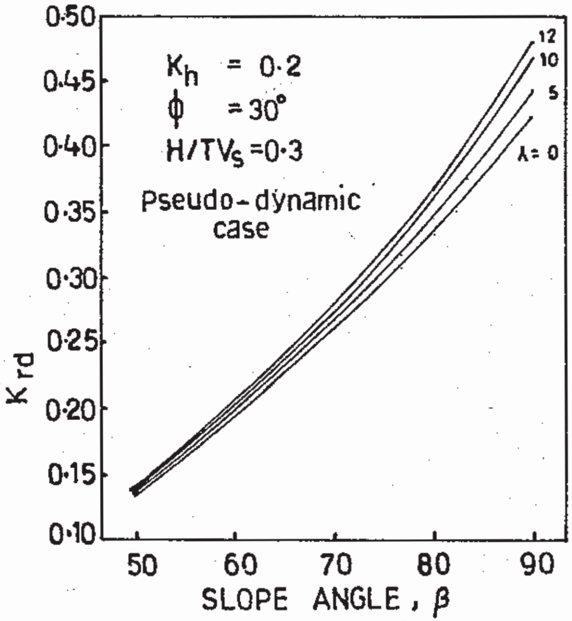

Fig 4 Effect of Inclination of the reinforcement

The following conclusions are drawn from this study:

1. The pseudo-static method can be used for coefficient of horizontal acceleration, K_h less than 0.2, as the error involved is less than 10%. However, for K_h greater than 0.2, it is preferable to use pseudo-dynamic analysis.

2. The horizontal placement of the reinforcement requires minimum reinforcement force for equilibrium. Hence, it is preferable to place the reinforcement in the horizontal direction.

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