Pseudo-dynamic analysis of reinforced soil wall-effect of kinematics of sliding mass considering linear backfill response

L'analyse pseudo-dynamique de l'effet renforcé de mur de sol de la cinématique et considérer linéaire remblayent la répo

G.V.Narasimha Reddy, M.R.Madhav and E.Saibaba Reddy
JNT University Hyderabad, India

Satyendra Mittal
IIT Roorkee, India

ABSTRACT

The failure surface in most cases intersects the reinforcement layers obliquely in most reinforced soil structures, subjecting the reinforcement to an oblique force instead of axial force by the sliding mass resulting in an additional bond resistance and a decrease in net destabilizing force significantly. The pseudo-dynamic method that considers the seismic inertia force based on the effect of phase difference in shear and primary waves propagating through the reinforced backfill is studied here instead of the approximate pseudo-static seismic earth pressure. This paper presents a more rational analysis of internal stability of reinforced soil structures considering the effect of kinematics of the sliding mass.

RÉSUMÉ

La surface d'échec dans la plupart des cas intersecte les couches de renfort oblique en la plupart des structures renforcées de sol, soumettant le renfort à une force oblique au lieu de la force axiale par la masse coulissante ayant pour résultat une résistance en esclavage additionnelle et une diminution de la force de déstabilisation de filet de manière significative. La méthode pseudo-dynamique qui considère la force séismique d'inertie basée sur l'effet de la différence de phase dans le cisaillement et les vagues primaires propageant par renforcé remblayent est étudiée ici au lieu de la pression séismique pseudo-statique approximative de la terre. Cet article présente une analyse plus raisonnable de la stabilité interne des structures renforcées de sol considérant l'effet de la cinématique de la masse coulissante.

Keywords : Kinematics, liner backfill response, pseudo-dynamic seismic analysis, reinforced soil wall

1 INTRODUCTION

Reinforced soil structures have gained wide popularity due to their cost-effectiveness and their superior performance during major earthquakes (Tatsuoka et al., 1997; White and Holtz, 1997 and Sandri, 1997). Better performance of these structures during a seismic event may be due to conservative conventional limit equilibrium methods.

Most of the methods available (Rowe and Ho, 1993) for the analyses of internal stability of reinforced soil walls consider only the axial resistance of the reinforcement to pullout and the destabilizing force to be independent of the provision of the reinforcement. The failure surface in reinforced soil walls intersects the reinforcement layers obliquely (Leschinsky and Reinschmidt, 1985; Leschinsky and Boedeker, 1989) subjecting the reinforcement to oblique force. The reinforcement subjected to transverse force (i.e., the vertical component of the oblique force) generates an additional normal force on the lower surface of the reinforcement that leads to a corresponding increase in the bond resistance. The mobilized transverse force counteracts the destabilizing force by the magnitude of the normal force mobilized. The mobilized additional normal force depends on the response of the soil to transverse displacement of the reinforcement. Analysis considering linear backfill response to the transverse displacement was proposed by Madhav and Umashankar (2003a&b).

In reinforced soil structures, the seismic force is assumed as constant throughout the depth of the backfill in most of the conventional approaches. Review of literature (Ling et al., 1997; Shahgholi et al., 2001; Nouri and Fakher, 2006) indicates that most of the seismic methods of analyses of reinforced soil structures, consider dynamic nature of earthquake loading through a pseudo-static seismic earth pressure without considering the effects of time and body waves traveling through the reinforced soil wall, thus providing an approximate and conservative solution. A more realistic pseudo-dynamic approach proposed by Steedman and Zeng (1990) and Choudhury and Nimbalkar (2006) that considers the above effects has been considered in this paper to study the stability of reinforced soil walls under seismic conditions. The proposed method is an extension to the method proposed in Narasimha Reddy et al. (2008).

2 PSEUDO-DYNAMIC SEISMIC ANALYSIS OF ...REINFORCED SOIL WALL

2.1 *Tensile Forces Generated in the Reinforcement due to Oblique Displacement*

A typical reinforced soil wall is depicted in Fig.1. The critical planar failure surface assumed independent of the provision of reinforcement, inclined at an angle α with respect to the horizontal is considered (Fig. 2). The angle, α, depends on the angle of shearing resistance, ϕ, and total seismic horizontal, Q_h, and vertical, Q_v, forces. Results of large number of laboratory shake table and centrifuge tests on models of reinforced slopes/walls, confirm the observed failure plane to be planar during a seismic event.

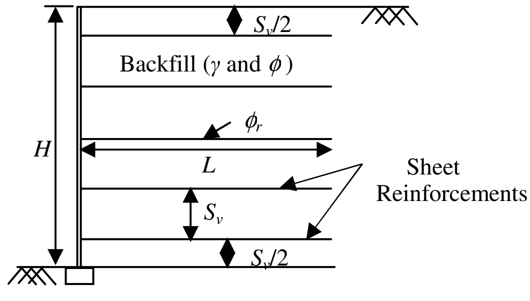

Fig. 1. Reinforced Soil Wall - Definition Sketch

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Horizontal Slices Method proposed by Shahgholi et al. (2001) is adapted to analyse the pseudo-dynamic seismic stability of reinforced soil wall. The backfill is divided into 'n' number of horizontal slices each with a layer of reinforcement at its middle (Fig. 2). The j^{th} layer of reinforcement is at a depth, h_j, from the top. This analysis considers the mobilized additional normal force in the reinforcement, P_j, in response to transverse displacement as shown in Fig. 2. A transverse force, P_j, gets mobilized as a result of the transverse displacement, w_L,(=$\delta\sin\alpha$), of the reinforcement with respect to the backfill (Fig. 2).

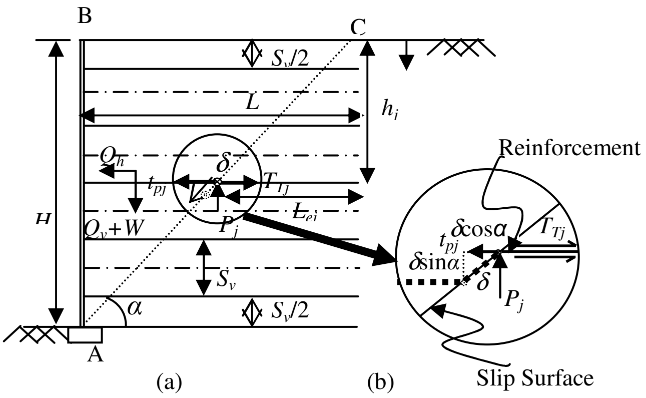

Fig. 2 .Reinforced Soil Wall with Kinematics of Deformation

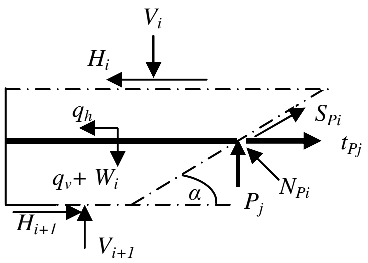

Fig. 3. Forces Acting on a Horizontal Slice Subjected to Pseudo-Dynamic Seismic Forces and Mobilized Transverse Force.

Forces acting on a typical horizontal slice considering pseudo-dynamic seismic forces are shown in Fig. 3 and the tensile force generated in the reinforcement is evaluated considering the mobilized transverse force, P_j, due to transverse displacement (component of oblique displacement) in addition to the forces that generally act on a typical horizontal slice.

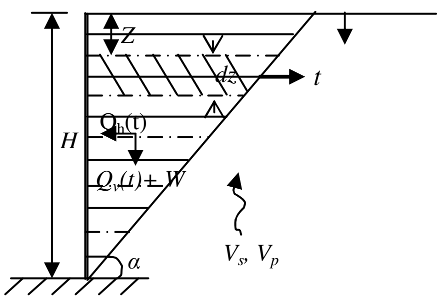

Fig. 4 . Reinforced Soil Wall Considering Pseudo-Dynamic Forces.

A typical reinforced soil wall (Fig.4) assumed fixed at the base is considered with the base subjected to harmonic horizontal and vertical seismic accelerations of amplitudes $a_h=K_hg$ and $a_v=K_vg$ (where g is the acceleration due to gravity) respectively for period of time, T, with shear and primary wave velocities of V_s and V_p, respectively. In the present analysis the velocity of primary wave is considered as 1.87 times that of shear wave. It is assumed that the shear modulus of the backfill is constant with depth and that only the phase and not the amplitude of acceleration varies with depth. It is assumed that both the horizontal and vertical waves with accelerations (a_h and a_v) start exactly at the same time and no phase shift exists between these two waves thus giving a critical condition for the design.

The acceleration at any depth, z, and time, t, below the top of the wall can be expressed as

$$a_h(z,t) = a_h \sin\omega\left[t-(H-z)/V_s\right] \tag{1}$$

$$a_v(z,t) = a_v \sin\omega\left[t-(H-z)/V_p\right] \tag{2}$$

The horizontal and vertical inertia forces (q_{hi} & q_{vi}) at a depth, h_i, acting on the i^{th} slice having mass, m_i, are

$$q_{hi} = m_i a_h(z,t) \tag{3}$$

$$q_{hi} = m_i\ a_h\ \sin\ \{\omega[t-\ (H-h_i)/V_s]\} \tag{4}$$

Simplifying the above equations and substituting $\xi=H/TV_s$, $m_i= W_i/g$ and $K_h=a_h/g$,

$$q_{hi} = W_i K_h \sin\left\{2\pi\left[\frac{t}{T}-\xi+\frac{h_i}{TV_s}\right]\right\} \tag{5}$$

The total vertical inertia force, q_{vi}, with $K_v=a_v/g$ is

$$q_{vi} = W_i K_v \sin\left\{2\pi\left[\frac{t}{T}-\frac{\xi}{1.87}+\frac{h_i}{TV_p}\right]\right\} \tag{6}$$

The vertical force equilibrium for the i^{th} slice (Fig.3) with the additional mobilized normal force, P_j, can be expressed as

$$V_{i+1}-V_i-W_i-q_{vi}+S_{pi}\sin\alpha+N_{pi}\cos\alpha+P_j=0 \tag{7}$$

where $P_j = \gamma h_j L_{ej} P_j*$ is the transverse force in the j^{th} layer of the reinforcement due to transverse displacement, P_j* - the normalized transverse force in the j^{th} layer of the reinforcement and it is estimated based on linear backfill response (Madhav and Umashankar, 2003a).

Shear force, S_{pi}, upon the base of each slice is

$$S_{pi} = N_{pi}\tan\phi / FS_{sr} \tag{8}$$

Substituting for S_{pi} from Eq. (8) into Eq. (7) and solving for normal force due to mobilized transverse force, N_{pi}, on the base of each slice, one gets

$$N_{pi} = \frac{V_i - V_{i+1} + W_i + q_{vi} - P_j}{\dfrac{\tan\phi}{FS_{sr}}\sin\alpha + \cos\alpha} \tag{9}$$

The horizontal force equilibrium for the whole sliding mass considering the mobilized transverse force is

$$\sum F_{xj} = 0$$

$$\sum_{j=1}^{m} t_{pj} - \sum_{i=1}^{n} N_{pi}\sin\alpha + \sum_{i=1}^{n} S_{pi}\cos\alpha - \sum_{i=1}^{n} q_{hi} = 0 \tag{10}$$

S_{pi} and N_{pi} are determined from Eqs. (8) and (9) for FS_{sr}=1.

$\sum_{j=1}^{m} t_{pj}$ determined using Eq. (10) can be rewritten as

$$\sum_{j=1}^{m} t_{pj} = \sum_{i=1}^{n} N_{pi}\sin\alpha - \sum_{i=1}^{n} S_{pi}\cos\alpha + \sum_{i=1}^{n} q_{hi} = 0 \tag{11}$$

where,

$$N_{pi}\sin\alpha = \left(\begin{array}{l}\left(\dfrac{\sin\alpha.FS_{sr}}{\tan\phi.\sin\alpha + FS_{sr}\cos\alpha}\right)\left(1+K_v\sin\left\{2\pi\left[\dfrac{t}{T}-\dfrac{\xi}{1.87}+\dfrac{h_i}{TV_p}\right]\right\}\right)\\ \left(\gamma h_i l_i - \gamma h_{i+1}l_{i+1} + \dfrac{\gamma H}{2n}(l_i + l_{i+1}) - P_j\right)\end{array}\right)$$

$$S_{pi}\cos\alpha = \left(\begin{array}{l}\left(\dfrac{\tan\phi.\cos\alpha}{\tan\phi.\sin\alpha + FS_{sr}\cos\alpha}\right)\left(1+K_v\sin\left\{2\pi\left[\dfrac{t}{T}-\dfrac{\xi}{1.87}+\dfrac{h_i}{TV_p}\right]\right\}\right)\\ \left(\gamma h_i l_i - \gamma h_{i+1}l_{i+1} + \dfrac{\gamma H}{2n}(l_i + l_{i+1}) - P_j\right)\end{array}\right)$$

$$q_{hi} = \frac{\gamma H}{n}\left(\frac{l_i + l_{i+1}}{2}\right)K_h\sin\left\{2\pi\left[\frac{t}{T}-\xi+\frac{h_i}{TV_s}\right]\right\} \quad (12)$$

2.2 *Bond Resistance along the Reinforcement due to Oblique Pull*

The method of estimation of pullout force in the reinforcement considering mobilized transverse force due to oblique displacement of sliding mass is similar to the conventional method except that in the pseudo-dynamic seismic analysis of reinforced soil wall, the inclination of the failure plane varies with the seismic forces (Q_h and Q_v) in addition to the angle of sharing resistance (ϕ). Increase in bond resistances due to transverse forces mobilized in the different reinforcement layers (i.e. considering local factors) are considered based on linear backfill response. The total normalized bond resistance mobilized in the reinforcement layers is

$$\sum_{j=1}^{m} T_{Tj} = \sum_{j=1}^{m}\left(2+P_j^{*}\right)\gamma h_j \tan\phi_r\left[L-\left(H-h_j\right)\tan(90-\alpha)\right] \quad (13)$$

The factor of safety, FS_{TP}, considering both the additional normal force in the reinforcement and the increase in bond resistance due to transverse displacement considering horizontal and vertical seismic inertia forces is obtained using Eqs. (11) and (13) as

$$FS_{TP} = \sum_{j=1}^{m} T_{Tj} / \sum_{j=1}^{m} t_{pj} \quad (14)$$

3 RESULTS AND DISCUSSION

The factor of safety, FS_{TP}, considering both additional normal force and increase in bond resistance is evaluated considering linear backfill response for the different seismic, wall, backfill and reinforcement parameters.

3.1 *Comparison of Results of Pseudo-Dynamic with Pseudo-Static Approaches*

The effect of angle of shearing resistance, ϕ, on the variation of factor of safety considering only the axial pullout, FS_C, with horizontal seismic coefficient, K_h, for pseudo-static and pseudo-dynamic (ξ=0.3) approaches is presented in Fig 5. The factor of safety decreases with increase in K_h for pseudo-static and pseudo-dynamic approaches due to increase in destabilizing force. FS_C based on pseudo-dynamic case is more than the value from the pseudo-static approach due to more realistic application of seismic inertia force based on the effect of phase difference in shear and primary waves propagating through the reinforced backfill.

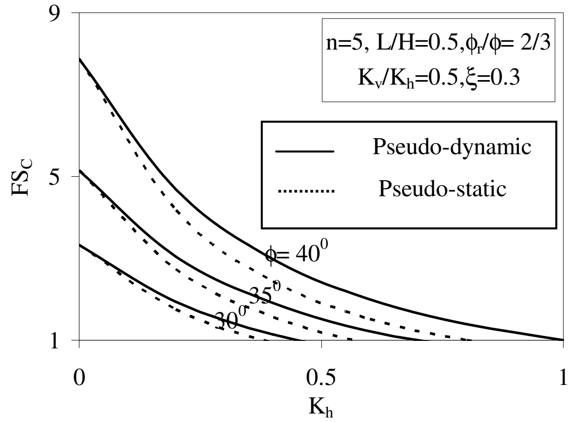

Fig 5. Variation of Factor of Safety, FS_C, with Horizontal Seismic Coefficient, K_h,- Effect of ϕ.

3.2 *Effect of Normalized Displacement*

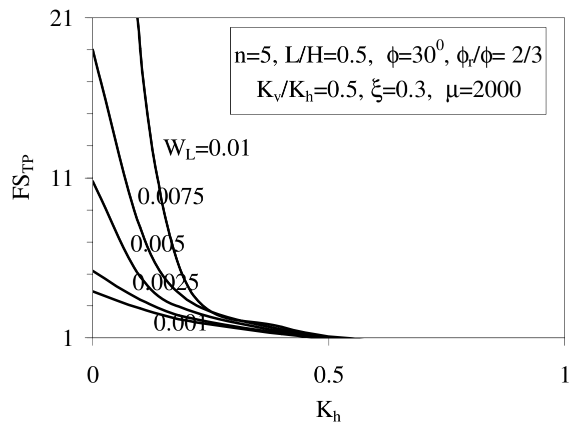

Fig. 6. Variation of FS_{TP} with K_h - Effect of Normalized Displacements, W_L.

FS_{TP} considering both the additional normal force in the reinforcement and the increase in bond resistance due to mobilized transverse force decreases (Fig. 6) with K_h slightly for small normalized displacements (W_L <0.0025) and significantly at large displacements (W_L >0.0025), due to decrease in net destabilizing force with the significant contribution of the mobilized transverse force for lesser pseudo-dynamic seismic forces (K_h<0.3). FS_{TP} decreases sharply for normalized displacements up to K_h =0.3 and marginal thereafter. FS_{TP} increases from 2.1 to 4.3 for K_h =0.2 and 1.2 to 1.7 for K_h =0.4 with increase in W_L from 0.001 to 0.01. Failure of reinforced soil wall is imminent with further increase in the horizontal seismic coefficient.

3.3 *Effect of Relative Global Stiffness of Backfill*

FS_{TP} increases exponentially (Fig. 7) with increase in relative stiffness, μ, due to significant contribution of mobilized transverse force. This significant effect of μ on FS_{TP} decreases sharply with increase in horizontal pseudo-dynamic seismic force for K_h< 0.3 and marginally with further increase in K_h. FS_{TP} increases from 2.03 to 5.9 with increase in μ from 50 to 10,000 for K_h =0.2 while FS_{TP} decreases from 10.8 to 1.4 with increase in K_h from 0 to 0.4 for μ = 2,000.

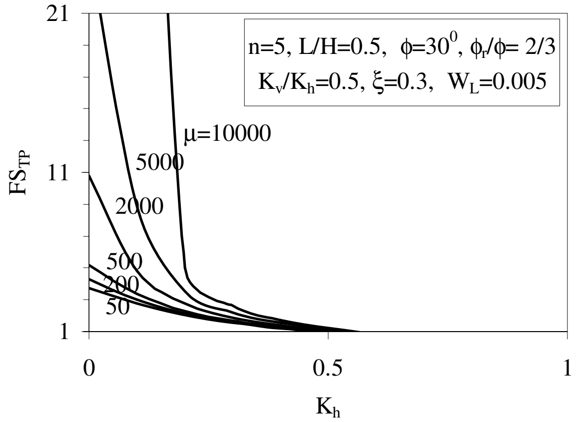

Fig. 7. Variation of FS_{TP} with Horizontal Seismic Coefficient, K_h, - Effect of Relative Stiffness, μ..

3.4 *Effect of Normalized Time of Travel of Shear Wave*

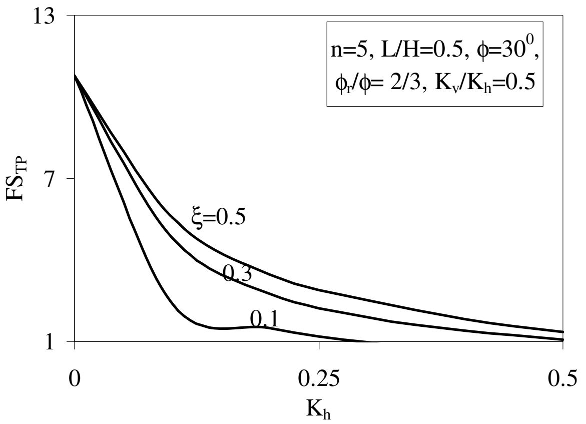

Fig. 8. Variation of Factor of Safety, FS_{TP}, with Horizontal Seismic Coefficient, K_h, - Effect of Effect of ξ (= H/TVs).

Fig. 8 shows the variation of factor of safety, FS_{TP}, with the horizontal seismic coefficient, K_h for different values of ξ for n=5, L/H=0.5, ϕ=30^0, ϕ_r/ϕ = 2/3, μ=2,000, W_L=0.005, and K_v/K_h=0.5. Factors of safety, FS_{TP} decrease with decrease in ξ (i.e. increase in period of lateral shaking, T, or faster rate of shear wave, t (=H/Vs)). FS_{TP} using pseudo-dynamic approach is 10.8 for K_h =0.0 and 2.5 for K_h= 0.4 for ξ= 0.5, and 10.8 for K_h =0.0 and 1.0 for K_h= 0.6 for ξ= 0.1.

4. CONCLUSIONS

The conventional approach of assuming destabilizing force independent of provision of reinforcement and considering only axial pullout of the reinforcement layers leads to conservative design of reinforced soil wall. Present realistic approach results in phenomenal improvement (i.e. about 10 fold) in factor of safety by considering both the additional normal force in the reinforcement and the increase in bond resistance due to transverse displacement. The pseudo-dynamic approach gives higher factors of safety than pseudo-static approach due to more realistic consideration of the application of the seismic inertia force. Factors of safety, FS_{TP} from pseudo-dynamic approach decrease with decrease of the parameter ξ (i.e. increase in period of lateral shaking or faster shear wave).

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