Stability Analysis of Reinforced Soil Wall under Seismic Loads: A novel Approach

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One of the major reasons for the popularity of geosynthetic reinforced earth retaining structures is their ability to perform better under seismic loading conditions. Pullout resistance is one of the most important factors that affect the stability of reinforced soil structures under seismic loading conditions. However, conventional methods do not consider the obliquity of the pullout force and consider only axial direction of the pull. In this paper, effect of oblique pullout on the seismic stability of a reinforced soil wall is presented where backfill is represented as a two-parameter Pasternak subgrade. The effect of various parameters on the pullout response is also studied under seismic loading conditions. The results are also compared with the conventional methods of analysis. The comparisons show that the present analysis gives a better estimation of the FOS against pullout as compared to the conventional methods of analysis thus brings out the importance of the present study.

KEYWORDS: Reinforced soil walls, oblique pullout response, pseudo-static analysis, Pasternak subgrade

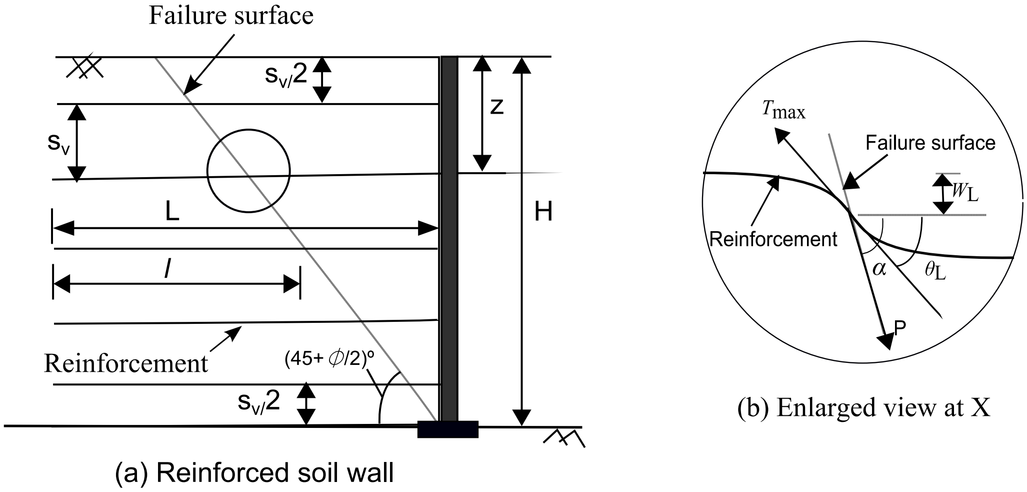
1. INTRODUCTION

One of the major reasons for the popularity of geosynthetic reinforced earth retaining structures such as reinforced soil walls (Fig. 1a) and embankments, is their ability to perform better under seismic loading conditions as they are inherently flexible. The other account could be the conservatisms associated in the existing design methods (Reddy et al. 2008). Whatsoever may be the reason; these structures are gaining popularity and being constructed extensively for highways, railways and other civil engineering structures. The internal stability of these structures is crucial especially during earthquake event considering the extent of its uses.

Kinematics of failure of reinforced soil walls plays an important role in internal stability of reinforced wall. Kinematics of failure suggests that the failure surface intersects the reinforcement obliquely (Fig. 1a) thus, causing an oblique pullout of the reinforcement (Figs. 1a and b). Under the oblique pull, the reinforcement deforms downward and mobilizes additional normal and shear stresses at the soil-reinforcement interface. Thus, the pullout capacity of the reinforcement may be considerably different compared to the axial one. However, conventional methods of analysis consider only axial direction of the pullout force and do not consider complex soil-reinforcement interaction and obliquity of the pullout force. Consequently, these methods give highly conservative values of factor of safety against pullout of the reinforcement (Rowe and Ho 1993).

Many researchers such as Bergado et al. (2000), Kumar and Madhav (2009), Madhav and Umashankar (2003), Shewbridge and Sitar (1989), Shahu (2007) and Patra and Shahu (2012) studied the effect of kinematics of failure and localized behavior of reinforcement orientation in the vicinity of failure surface. The first attempt to incorporate the kinematics of failure and obliquity of pullout force in the stability analysis was made by Madhav and Umashankar (2003). A Winkler based simplified model was proposed to study the effect of transverse component of oblique pullout force. A major limitation of Winkler based analysis is that the model is applicable only for small end displacement and does not account for shear stiffness of the subgrade. Consequently, the analysis gives a localized orientation of the reinforcement force equal to the obliquity of the pullout force, a fact not supported by the experimental findings (Bergado et al. 2000; Shewbridge and Sitar 1989).

In this paper, a new analysis is presented for the internal stability analysis of reinforced soil walls against pullout considering an inextensible reinforcement resting on Pasternak subgrade (Selvadurai 1979, Patra and Shahu 2012) and subjected to oblique pullout force. The reinforcement is assumed as rough membrane whereas the subgrade soil is idealized as a Pasternak shear layer resting on a set of Winkler's springs. Use of Pasternak model as subgrade makes the analysis more realistic as it incorporates the effect of subgrade shear stiffness in the analysis. A modified factor of safety is defined, evaluated, and compared with the conventional one to establish the suitability and applicability of the present analysis in the design of reinforced soil walls. A parametric study is also conducted to study the effect of various geometrical and material properties on the stability of reinforced soil walls.



(a) Reinforced soil wall

(b) Enlarged view at X

FIG. 1. Reinforced soil wall and kinematics of failure.

2. PROBLEM DEFINITION AND ANALYSIS

A typical reinforced soil wall of height H is shown in Fig. 1(a). A granular material of unit weight γ and angle of frictional resistance ϕ is assumed as backfill material. The reinforcement as rough membrane of length L and interface frictional resistance ϕ_r are placed in horizontal layers with uniform vertical spacing S_v (= H/n where n is the number of reinforcement layer). The subgrade soil is idealized as a Pasternak shear layer resting on a set of Winkler's springs (Selvadurai 1979, Patra and Shahu 2012).

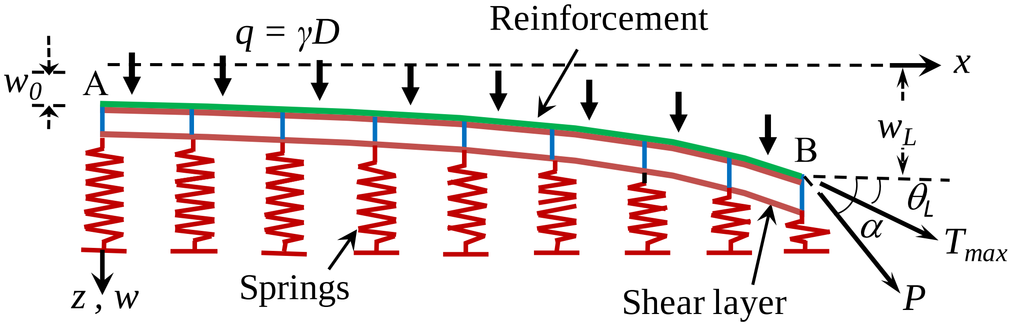


FIG. 2. Mechanistic model.

2.1 Conventional Approach

The internal stability of wall is conventionally verified considering a Rankine's failure surface passing through the toe of the wall and making an angle $\alpha = 45 + \phi/2^{\circ}$ with the horizontal (Fig. 1a). As the failure surface intersects reinforcements obliquely, the effective length l of reinforcement (inside the passive zone) also varies with the depth of reinforcement layer.

Effective length of the reinforcement at i^{th} layer of reinforcement may be obtained as

$$l_i = L - (H - z_i)\tan(45 - \phi / 2^{\text{o}}) \tag{1}$$

Tension T_i in the reinforcement at i^{th} layer is obtained as

$$T_i = \gamma z_i k_{a,i} S_{v,i} \tag{2}$$

Pullout resistance P_{i} at i^{th} layer is obtained as

$$P_i = 2\gamma z_i l_i \tan\phi_r \tag{3}$$

where γ = unit weight of backfill material; ϕ=angle of shearing resistance ; $k_{a,i}$ = the coefficient of active earth pressure; z_i = depth of reinforcement layer from the top; and $S_{v,i}$ = vertical spacing of the reinforcement, at i^{th} level of reinforcement.

Pullout failure

The conventional factor of safety against pullout of the reinforcement is the ratio of the total pullout resistance to the total tension in the reinforcement as given by

$$(\text{FOS})_{\text{conv}} = \Sigma P_i \big/ \Sigma T_i \tag{4}$$

2.2 Kinematics of failure and oblique pullout analysis

Figs. 1a and b show kinematics of failure of the wall. As the active wedge moves downward along the failure surface, it intersects the reinforcement obliquely causing an oblique pullout of the reinforcement. Under the oblique pull the reinforcement undergoes transverse deformation (Fig. 2) and mobilizes additional normal and interface shear stresses. Consequently, the pullout capacity is not the same as obtained in conventional method of analysis.

The oblique pullout capacity of the reinforcement at i^{th} layer may be obtained as

$$P_{\text{i}} = 2\,\gamma D l \tan\phi_{\text{r}} P_i^* \tag{5}$$

Normalized pullout capacity P_i^* for each reinforcement layer is obtained as (Patra and Shahu 2012)

$$P_i^* = \frac{1}{2n\cos\alpha}\sum_{k=1}^{N}\left(\mu W_L W_k - G^* W_L \frac{\partial^2 W_k}{\partial X^2} + 2\right)\cos\theta_{ck} \tag{6}$$

where $\mu = k_S l/\gamma D =$ subgrade normal stiffness factor; $G^* = GH/\gamma Dl =$ subgrade shear stiffness factor; $W_L = w_L/l =$ normalized end displacement; $T^*_{x,ck} = T^*_{ck}\cos\theta_{ck} =$ horizontal component of tension in the reinforcement element; and $\theta_k = \left(\theta_{ck} + \theta_{ck-1}\right)/2$.

Pullout failure

Modified factor of safety against pullout is defined as

$$(\text{FOS})_{\text{mod}} = \Sigma P_{H,i} / \Sigma T_i \tag{7}$$

where horizontal pullout capacity $P_{H,i} = P_i \cos\alpha$,

Improvement factor R_T

$$R_T = (\text{FOS})_{\text{mod}} / (\text{FOS})\text{conv} \tag{8}$$

A trial and error procedure is first adopted to determine the oblique pullout capacity P_i at each layer. Following ranges of parameters are used in the analysis: E = 25000–81000 kPa, ϕ=30–40°. ϕ_r = ϕ–2/3ϕ, L=0.5–0.8H (where H=6 m) and n = no of reinforcement layer = 4–6. Subgrade normal stiffness μ = 500–20000 and shear stiffness factor G^* =20–5000 are obtained as described in Patra and Shahu (2012).

3. RESULTS AND DISCUSSIONS

Fig. 3 shows variation of factor of safety against pullout vs L/H ratio (where L is total length of the reinforcement and H is height of the wall). As L/H ratio increases, the factor of safety increases (Fig. 3). The increase in the factor of safety is due to the mobilization of soil-reinforcement interface frictional resistance over greater length of the reinforcement.

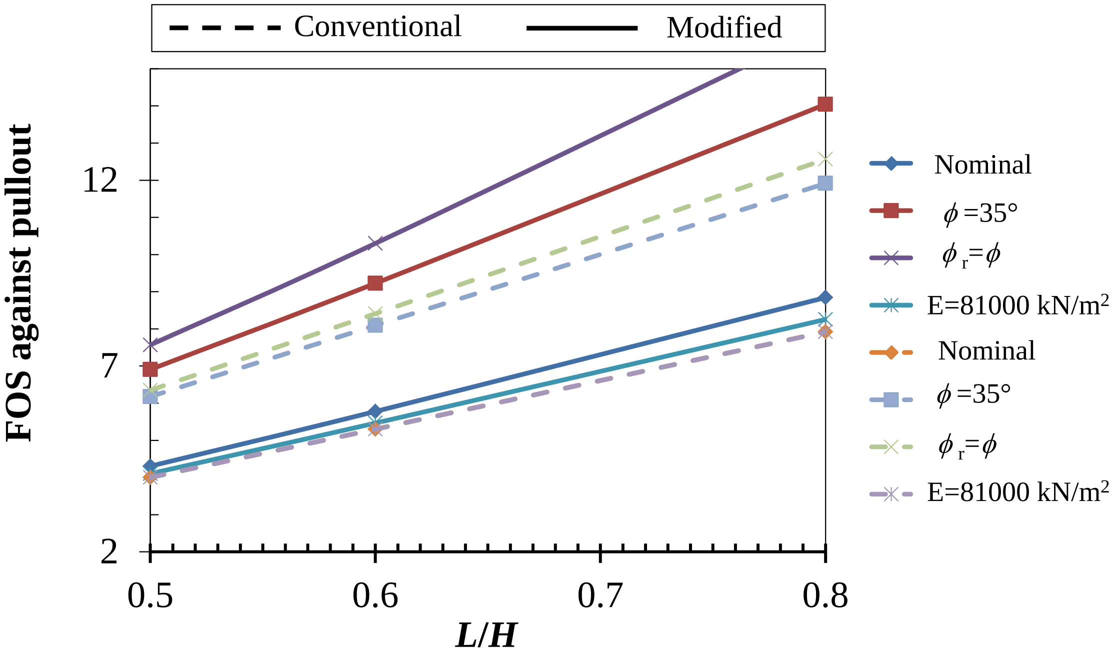


FIG. 3. FOS against pullout vs *L*/*H* – effect of *E*, ϕ, and ϕ_r (nominal case: *E*=25000 kN/m^2, ϕ=30°, ϕ_r=2/3ϕ, and *n*=6.

The effect of number of reinforcement layer on FOS against pullout is shown in Fig. 4. As the number of reinforcement layer increases, the pullout resistance increases for each additional layer of reinforcement. Consequently, the factor of safety against pullout increases.

The effects of various other parameters such as modulus of elasticity *E*, angle of shearing resistance ϕ, soil-reinforcement interface frictional resistance ϕ_r, etc., on the stability of reinforced soil wall are also studied (Figs. 3-5).

The effect of angle of shearing resistance ϕ and soil-reinforcement interface friction ϕ_r is such that as ϕ and ϕ_r. increases, the factor of safety against pullout also increases and the rate of increase is more for higher values of ϕ and ϕ_r (Figs. 3 and 4). However, the modulus of elasticity *E* of backfill material has no significant effect on the factor of safety (FOS) against pullout (Figs. 3 and 4).

The present analysis gives higher values of factor of safety against pullout as compare to the conventional method of analysis. It is also evident from Figs. 3-5 that for the range of parameters used in the analysis, the modified values of factor of safety are greater than the conventional values of factor of safety.

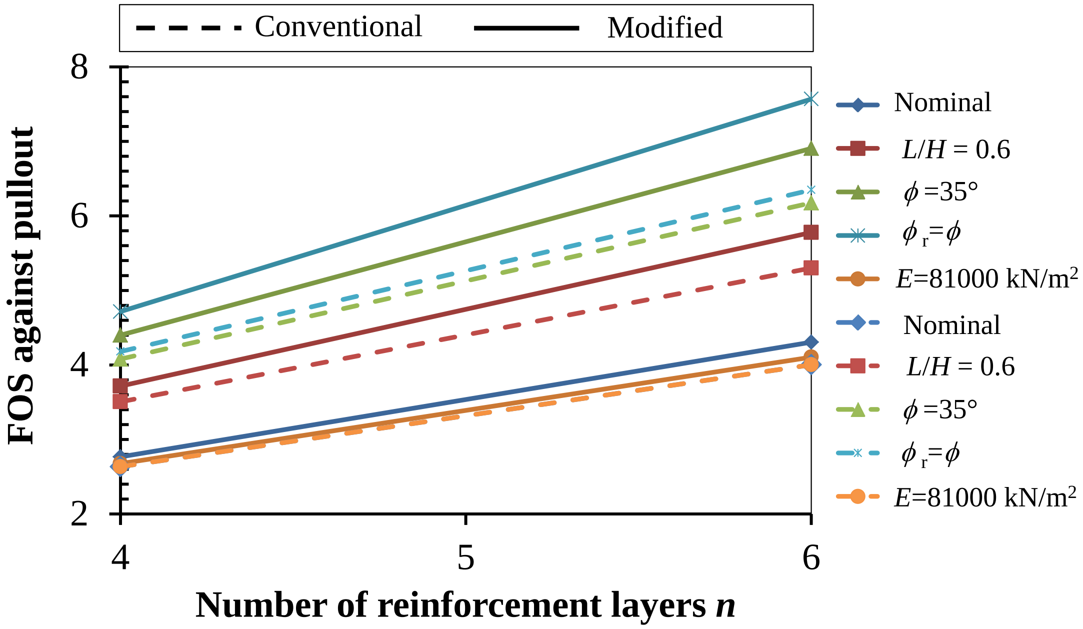


FIG. 4. FOS against pullout vs *n* – effect of *E*, *ϕ*, and ϕ_r (nominal case: *E*=25000 kN/m^2, *ϕ*=30°, ϕ_r=2/3*ϕ*, and *L*/*H*=0.5.

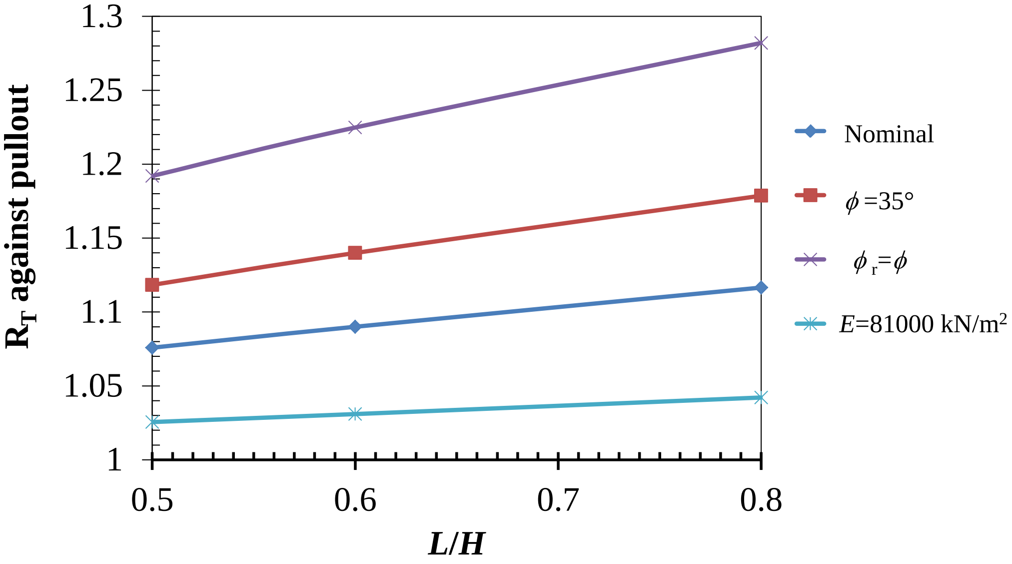


FIG. 5. Improvement Ratio R_T against pullout vs *L*/*H* – effect of *E*, *ϕ*, and ϕ_r (nominal case: *E*=25000 kN/m^2, *ϕ*=30°, ϕ_r=2/3*ϕ*, and *L*/*H*=0.5.

Fig. 5 shows the improvement ration R_T of the modified FOS against pullout over conventional factor of safety. The improvement ratio increases with the increase in L/H ratio, ϕ and ϕ_r. For the range of parameters used in the present study improvement ratio up to 1.3 have been achieved.

4. CONCLUSIONS

A new analysis is presented for internal stability analysis of reinforced soil walls considering an inextensible reinforcement resting on Pasternak subgrade and subjected to oblique pullout force. The reinforcement is assumed as a rough membrane with a rigid-plastic interface behaviour and the subgrade soil is idealized as a Pasternak model. The following conclusions can be drawn from the present study:

(1) For all the cases, the present analysis gives a higher value of factor of safety against pullout as compared to conventional method of analysis. The increase in factor of safety is more for higher values of L/H ratio and number of reinforcement layers. For the range of parameters used in the present study, improvement ratios upto 1.3 have been achieved (i.e. 30% increase).

(2) As the friction angle ϕ, of the backfill material increases, soil-reinforcement interface frictional resistance ϕ_r and obliquity α of pullout forces increases which results in higher factor of safety against pullout. The increase in obliquity of pullout forces and angle of shearing resistance result in higher normal and shear stresses at the soil-reinforcement interface, which results in higher pullout capacity.

(3) The length of the reinforcement to height of the wall ratio (L/H) has significant effect on the stability of reinforced soil wall against pullout. FOS against pullout increases with higher values of L/H, and higher numbers of reinforcement layers n.

(4) Modulus of elasticity E has negligible effect on the factor of safety against pullout as compared to the angle of shearing resistance ϕ of backfill material.

(5) The present analysis gives a better prediction of factor of safety against pullout as compared to the conventional method of analysis, which yield much lower FOS against pullout out failure and could be interpreted as highly conservative.

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