Seismic stability of reinforced soil wall considering oblique pull – coherent gravity method

Pavan Kumar P V S N
Associate Professor, India

Madhira R. Madhav
Professor Emeritus, India

ABSTRACT: Conventional analysis and design of reinforced soil walls assume that the reinforcement is subjected to axial pullout. However, kinematics of reinforced soil structures demonstrates that the reinforcement is subjected to oblique pull. Mobilization of transverse force due to oblique pull depends on the stiffness of backfill and the interface friction angle. Few studies demonstrated an improvement in the factor of safety against pullout by considering the mobilized transverse force for static and seismic loads. In the present study the seismic stability of a reinforced soil wall is analyzed based on the coherent gravity failure mechanism. A bi-linear failure surface is considered and the tensile force in the reinforcement due to static and dynamic earth pressures quantified. Transverse force mobilized due to oblique displacement of failure wedge is computed along with the improved pullout resistance of sheet reinforcement. Variations of modified factor of safety against pullout due to horizontal seismic coefficient, backfill stiffness and oblique displacement are presented. Current study brings out the conservatism of existing seismic design and analysis methods based on consideration of axial pullout of reinforcement.

Keywords: Horizontal seismic coefficient, Transverse force, Oblique displacement, backfill stiffness, pullout

1 INTRODUCTION

Geosynthetic reinforced soil walls have performed well during Northridge and Hyogoken-Nanbu earthquakes compared to other conventional retaining walls (Tatsuoka et al., 1997 and White and Holtz, 1997). Tension developed in the reinforcement and displacement at the face of reinforced soil walls after construction is much smaller than implied by current design methods. Failure occurs at a much higher load than anticipated based on current design methods (Billiard and Wu, 1991). Rimoldi (1988) examined eight case histories involving reinforced soil walls and slopes using extensible reinforcement and concluded that the current design procedures are over conservative.

The conservatism in conventional design is provided because of uncertainties in construction control, strength loss in extensible reinforcement and empirical design methods that do not consider rational interactions between individual components of the wall system (Rowe and Ho, 1993). The static and seismic performance of reinforced soil walls was monitored through instrumentation of in service walls and large scale and laboratory scale model tests in centrifuge and shake table tests. The external and internal seismic stability of reinforced soil walls and water-front structures subjected to horizontal and vertical seismic accelerations and hydrodynamic forces were analysed for different modes of failure by horizontal slice method (Choudhury et al. 2007). These studies quantified the length and strength of geosynthetic reinforcement required for the stability of reinforced soil wall and angle made by the critical failure wedge with horizontal for cohesive and cohesion-less backfills.

The kinematics of failure of reinforced soil structures such as walls, embankments, slopes is such that the failure surface intersects the reinforcement obliquely resulting in oblique pullout of reinforcement instead of axial pull (Figure 1). Magnitude of oblique pull is maximum when wall reaches limit state of serviceability due to excessive loading or seismic event, poor quality of backfill, inadequate bond strength between reinforcement and soil, insufficient connection strength and poor construction practices. This oblique pull can be considered as a combination of transverse and axial pulls. Under the action of transverse force or displacement, the soil beneath the reinforcement mobilizes additional normal stresses as the reinforcement deforms transversely. As a result, a larger shear resistance is mobilized between reinforcement – soil interface. Direct shear tests were conducted on sand samples reinforced with natural and synthetic fibers, metal wires by Gray and Ohashi (1983).The fibers were aligned perpendicular and at different inclinations to the failure plane and the results indicate that reinforcement increased the peak shear strength and limited the post peak reduction of shear resistance in dense sand.

Madhav & Umashankar (2003a and b) studied the significance of subgrade stiffness on the transverse pullout of inextensible sheet reinforcement (Figure 2) assuming linear and non-linear subgrade responses respectively and full shear mobilization along the soil-reinforcement interface. The maximum transverse displacement considered in the study was limited to 1% of length of reinforcement.

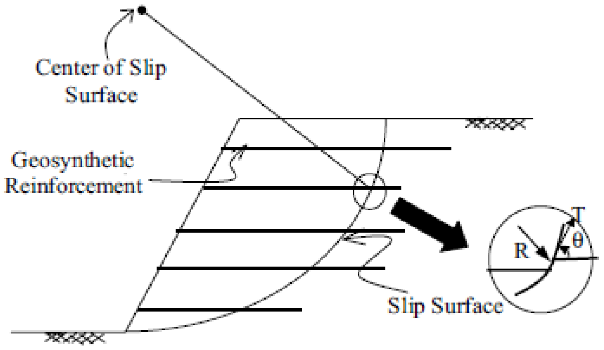

Figure 1. Kinematics of reinforced embankments (Madhav & Umashankar, 2003a)

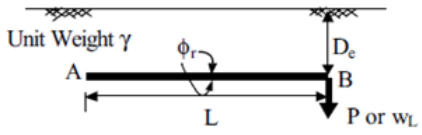

Figure 2 Reinforcement subjected to transverse force (Madhav & Umashankar, 2003a)

A generalized model for pullout of sheet reinforcement subjected to transverse downward pull upto 10% length of reinforcement was presented by Madhav & Manoj (2004). Analysis was carried out for extensible and inextensible reinforcement, rigid – plastic and elasto – plastic behaviour of sheet - backfill interface, and linear and non-linear subgrade responses. Kumar and Madhav (2006) studied the response of reinforcement subjected to transverse pull at an intermediate point. Pullout response of inextensible sheet reinforcement subjected to oblique end force was studied by Shahu (2007). The horizontal component of the oblique pullout force was found to increase by over 50% of the pure axial pullout capacity of the reinforcement for an obliquity of 60°.

Pseudo-static seismic stability of reinforced soil wall was analyzed by Reddy et al. (2008) based on horizontal slice method considering oblique displacement of failure wedge. Modified factors of safety against pullout increased with increase of oblique displacement of failure wedge and increase of backfill stiffness factor for different horizontal seismic coefficients. Pseudo-dynamic analysis of reinforced soil wall subjected to oblique pull was carried out by Reddy et al. (2009) to account for the effects of time and the body waves traveling through the reinforced soil wall.

Analysis of reinforced soil wall subjected to oblique pull and the improvement of factor of safety against pullout was studied based on coherent gravity design for inextensible reinforcement and tieback wedge method for extensible reinforcement by Kumar and Madhav (2008), Kumar and Madhav (2009) and Kumar et al. (2014). The oblique displacement of failure wedge in reinforced soil wall drastically increased the factor of safety against pullout. The mobilized transverse force increased the pullout resistance and reduced the tension developed in the reinforcement. Response of inclined reinforcement subjected to transverse force at shallow end was studied by Kumar and Madhav (2013) and quantified the mobilized transverse force for different inclinations of reinforcement. Shahu and Hayashi (2009) analyzed the extensible reinforcement subjected to oblique pull assuming elasto – plastic response of backfill and reinforcement-soil interface shear stress. Analysis predicted the critical height for the pullout and tension failure in a model reinforced soil wall constructed with extensible reinforcements and compared the results with Rankine’s method. Earlier studies indicate that the influence of oblique displacement on the seismic stability of reinforced soil wall considering coherent gravity failure mechanism was not analyzed and the present work brings out the significance of transverse force in the seismic stability reinforced soil wall.

2 PROBLEM DEFINITION AND ANALYSIS

A reinforced soil wall of height, H, retains granular backfill with an angle of shearing resistance, φ and unit weight, γ (Figure 3). Inextensible sheet reinforcement (n layers) of length, L and interface friction angle, φ_r are laid in the backfill. Reinforcement sheets have a uniform spacing of $S_v = H/n$ in the backfill with $S_v/2$ spacing at the top and the bottom of the wall. Reinforced soil wall is designed to satisfy external and internal stability requirements for static and seismic earth pressures.

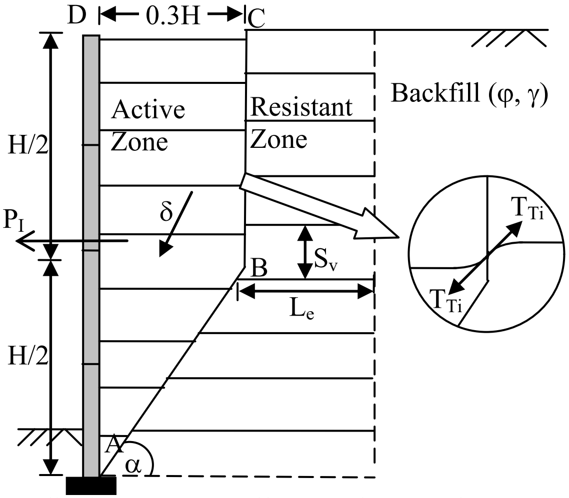

Figure 3 Oblique displacement of failure wedge – Coherent Gravity Method

2.1 *Conventional seismic analysis*

The location of maximum tensile force line in coherent gravity failure mechanism is bilinear in the static and seismic analysis as shown in Figure 3 (Berg et al. 2009). Reinforcement layers are intersected by the failure plane at different distances from the face of the wall dividing each layer into two parts, one segment lying within the failure zone while the other (external) segment lies outside the failure zone. L_{ei} is the effective length of the i^{th} layer of reinforcement located outside the failure zone, at a depth, z_i, from the top of the wall.

$$z_i = \left(i - \frac{1}{2}\right)\frac{H}{n} \tag{1}$$

For $z_i \le \frac{H}{2}$, $L_{ei} = L - 0.3 \times H$ (2)

and for $z_i > \frac{H}{2}$, $L_{ei} = L - \{0.6 \times (H - z_i)\}$ (3)

The active wedge is assumed to develop a dynamic inertia force, P_I, obtained as follows (Berg et al. 2009),

$$P_I = W_a K_h \tag{4}$$

where W_a is the weight of active wedge shown in Figure 4 and K_h is the horizontal seismic coefficient. P_I acts horizontally at the middle of the active wedge. This dynamic inertia force, P_I increases the tension developed in the reinforcement. In seismic design of RS wall each reinforcement layer is designed to withstand a part of the horizontal dynamic force, P_I in addition to the static force.

Tension in each layer of reinforcement is obtained as follows

$$P_{ai} = \sigma_{vbi} k_i S_{vi} + \frac{L_{ei}}{\sum_{i=1}^{n} L_{ei}} P_I \tag{4}$$

where σ_{vbi}, k_i and S_{vi} are the modified vertical pressure, coefficient of active earth pressure and spacing of reinforcement layers at i^{th} level. σ_{vbi} is the modified vertical stress on each reinforcement layer obtained as the ratio of total vertical force on the reinforcement layer to the reduced area considering the eccentricity of resultant load at each layer. In case of inextensible reinforcement the tensile strain in the rein-

forcement is limited to 1% and the reinforcement layer reaches peak strength at strains lower than the strain required for the backfill to reach its peak strength. Hence the strains are insufficient to generate active stress state (k_a) within the fill and the stress state within the reinforced mass varies from at rest state i.e. $k_i = k_0$ at the top of the reinforced soil wall reducing to the active state i.e. $k_i = k_a$ at a depth of 6 m below top of the backfill. The active state is assumed prevail below a depth of 6 m from top of the wall.
The seismic pullout resistance in each layer of sheet reinforcement is obtained from following equation

$$T_i = 2 \gamma z_i L_{ei} (0.8 \times \tan \varphi_r) \tag{5}$$

Berg et al. (2009) mentioned that seismic friction factor to be reduced to 80% of the static friction factor. The conventional factor of safety, FS_c, is the ratio of total pullout resistance to the total tension mobilized in all the layers of wall

$$FS_c = \frac{\sum_{i=1}^{n} T_i}{\sum_{i=1}^{n} P_{ai}} \tag{6}$$

2.2 *Analysis considering oblique/transverse pull*

Oblique displacement of the active wedge depends on the outward movement of wall face produced by sliding of soil within the active zone. This force causing sliding will in turn depend on intensity of earthquake load/external loads exerted on the wall. The magnitude of oblique displacement will also depend on the relative rigidity of the wall face and strength of connections.

The unstable wedge ABCD moves or slides along the failure surface ABC subjecting each reinforcement layer to the transverse/oblique displacement. Along BC, the failure surface is vertical and the reinforcement is subjected to a transverse displacement, δ. Along AB, the failure surface is inclined at an angle α with the horizontal and the reinforcement is subjected to an oblique pull of δ. The reinforcement at the end of active zone is subjected to an oblique displacement, δ, and pull, T_{Ti} (Figure 3). This oblique displacement, δ, is resolved into transverse and horizontal components, $\delta \sin\alpha$ and $\delta \cos\alpha$ respectively. The resultant of the normal stresses that gets mobilized due to transverse displacement, $\delta \sin\alpha$ on either side of failure plane at reinforcement – backfill interface is defined as transverse force, P_i (Figure 4). In the present work the effect of downward transverse force, P_i developed in the passive zone is considered and additional pullout resistance of reinforcement is evaluated.

The transverse force, P_i, mobilized by a displacement, w_L, at the free end in an inextensible reinforcement is obtained by Madhav and Umashankar (2003a). Additional stresses generated below the reinforcement due to the displacement are represented by a set of Winkler springs with linear stress – displacement response of the backfill. It is assumed that the shear resistance is fully mobilized (rigid-plastic) along the reinforcement – soil interface. The transverse force, P, is evaluated by integrating the soil reactions below the reinforcement as

$$P = \int_0^L k_s \, w \, dx \tag{7}$$

where k_s = initial tangent modulus of subgrade reaction, w = transverse displacement at distance, x, along the length of reinforcement. The transverse force is normalized to obtain

$$P^* = \frac{P}{\gamma D_e L} \tag{8}$$

where D_e is the depth of embedment of the reinforcement layer below the ground level. The above equation is simplified as

$$P^* = \frac{w_L}{L} \mu \int_0^1 W \, dX \tag{9}$$

where W is the normalized transverse displacement = w/w_L, X is the normalized distance = x/L and μ is the relative subgrade stiffness factor obtained from the contact stress developed along the reinforcement-soil interface due to the transverse displacement relative to the overburden pressure.

$$\mu = \frac{k_s L}{\gamma D_e} \tag{10}$$

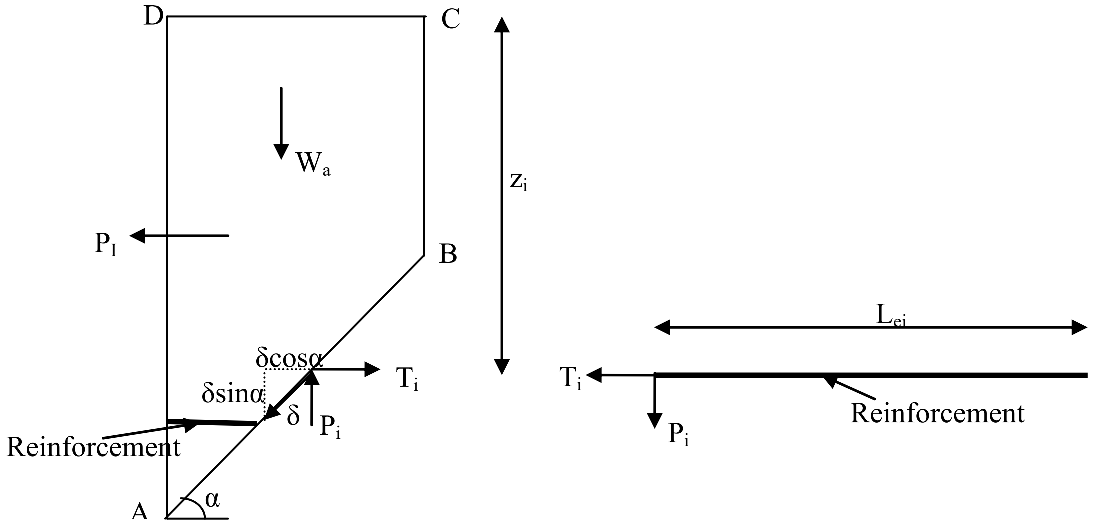

Figure 4 Kinematics of deformation of reinforcement

Depth of reinforcement, z_i, and effective length, L_{ei}, of each reinforcement layer are different in a reinforced soil wall and are obtained as follows.

Normalized transverse displacement of the i^{th} layer is obtained as follows

$$\text{For } z_i \le \frac{H}{2}, \quad \frac{w_L}{L_{ei}} = \frac{\delta}{L_{ei}} \tag{11}$$

$$\text{and for } z_i > \frac{H}{2}, \quad \frac{w_L}{L_{ei}} = \frac{\delta \sin\theta}{L_{ei}} \tag{12}$$

Relative backfill stiffness factor of i^{th} layer

$$\mu_i = \frac{\mu_{global} L_{ei} H}{L z_i} \tag{13}$$

In the above equation, μ_{global} - the global backfill stiffness factor of reinforced soil wall is the same as relative subgrade stiffness factor, μ defined by Madhav and Umashankar (2003a) and mentioned in equation 10. Substituting the above values of transverse displacement and relative subgrade stiffness factor in equation 9, the normalized transverse force, P^*_i is obtained while the transverse force is evaluated from

$$P_i = P^*_i \times \gamma \times z_i \times L_{ei} \tag{14}$$

The increase in the seismic pullout resistance due to the mobilized transverse force, P_i is obtained from

$$T_{iT} = 2\gamma z_i L_{ei} (0.8 \times \tan\varphi_r) + P_i \tan\varphi_r \tag{15}$$

Modified factor of safety considering the increased pullout resistance is obtained as

$$FS_T = \frac{\sum_{i=1}^{n} T_{iT}}{\sum_{i=1}^{n} P_{ai}} \tag{16}$$

3 RESULTS AND DISCUSSION

The variation of conventional factor of safety, FS_C considering only axial pullout and the modified factor of safety, FS_T considering increase in pullout resistance due to oblique/transverse pull are quantified for the following ranges of parameters. Seismic horizontal coefficient, k_h: 0 to 1, length of reinforcement, L: 0.6H to 0.9H, angle of shearing resistance of backfill, φ: 25° to 45°, interface friction angle, φ_r: 20° to 30°, number of reinforcement layers, n: 3 to 9, oblique displacement of failure wedge, δ: 0.001L to 0.05L and global backfill stiffness factor, μ_g: 50 to 10000.

Variation of modified factor of safety considering the mobilized transverse force, FS_T for different oblique displacements, δ, is presented in Figure 5. Factor safety increases by 147% with increase of oblique displacement, δ from 0.001L to 0.05L for different horizontal seismic coefficients, k_h ranging from 0 to 1. This clearly brings out the improved seismic performance of reinforced soil walls subjected severe shaking or displacements compared with conventional concrete retaining walls. Modified factor of safety, FS_T decreased by 104% with increase of horizontal seismic coefficient, k_h from 0 to 1 for a given oblique displacement. The increase of horizontal seismic coefficient increases the tension developed in the reinforcement. Modified factor of safety, FS_T increased by 35% with increase of global backfill stiffness factor, μ_g from 50 to 10000 for different horizontal seismic coefficients, k_h ranging from 0 to 1 (Figure 6). Global backfill stiffness factor is other significant parameter influencing the improvement of seismic stability of reinforced soil wall. Modified factor of safety, FS_T decreases by 104% with increase of horizontal seismic coefficient, k_h from 0 to 1 for a given global backfill stiffness factor.

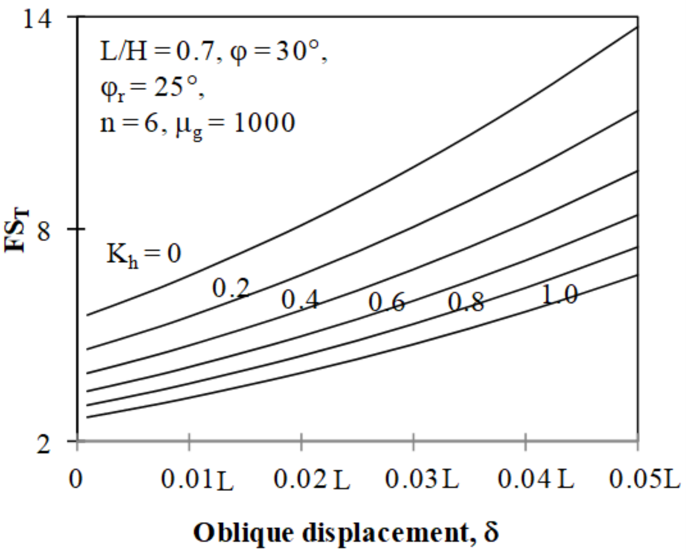

Figure 5 Variation of modified factor of safety, FS_T with oblique displacement, δ - Effect of K_h

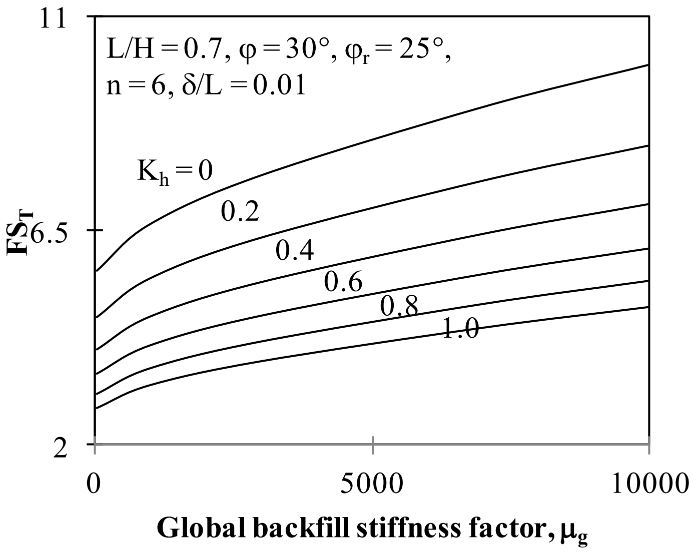

Figure 6 Variation of modified factor of safety, FS_T with global backfill stiffness factor, μ_g - Effect of K_h

The effect of length of reinforcement on conventional and modified factors of safety for horizontal seismic coefficient, k_h varying from 0 to 1 is presented in Figure 7 for $\varphi = 30°$, $\varphi_r = 25°$, $n = 6$, $\mu = 1000$ and $\delta = 0.01L$. Increase of horizontal seismic coefficient, k_h from 0 to 1 increases the horizontal seismic inertia force in the sliding wedge and tension developed in the reinforcement layers and decreases the factors of safety (FS_C and FS_T). The increase of length of reinforcement, L from 0.6H to 0.9H increases the effective length and pullout resistance of reinforcement. Factors of safety increase by about 89% and 79% with increase of length of reinforcement, L from 0.6H to 0.9H for a horizontal seismic coefficient, $k_h = 0$ and 1 respectively. The effect of increase of length of reinforcement is more predominant in static stability of reinforced soil wall ($k_h = 0$) and decreases marginally with increase of horizontal seismic coefficient, k_h from 0 to 1. Modified factor of safety, FS_T obtained by considering the transverse force increases by about 22% compared with conventional factor of safety, FS_c for the length of reinforcement, L ranging from 0.6H to 0.9H and horizontal seismic coefficient, k_h from 0 to 1. Conventional and modified factors of safety, FS_C and FS_T decrease by 85% and 204% with increase of horizontal seismic coefficient, k_h from 0 to 1 for an angle of shearing resistance of backfill, $\varphi = 25°$ and 45° respectively (Figure 8). The increase of angle of shearing resistance, φ from 25° to 45° decreases the tension developed in the reinforcement and factors of safety increased by 140% and 46% for horizontal seismic coefficient, $k_h = 0$ and 1 respectively. Modified factor of safety, FS_T obtained by considering the increased pullout resistance due to transverse force increases by about 23% for different angles of shearing resistance of backfill and horizontal seismic coefficients.

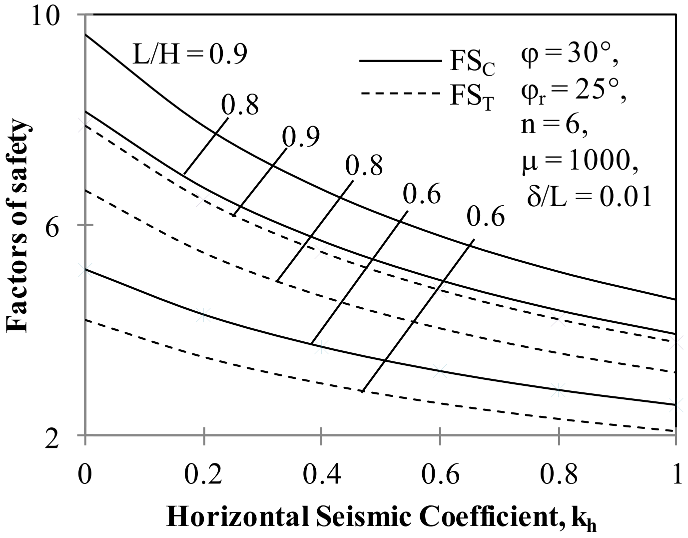

Figure 7 Variation of factor of safety with K_h - Effect of length of reinforcement

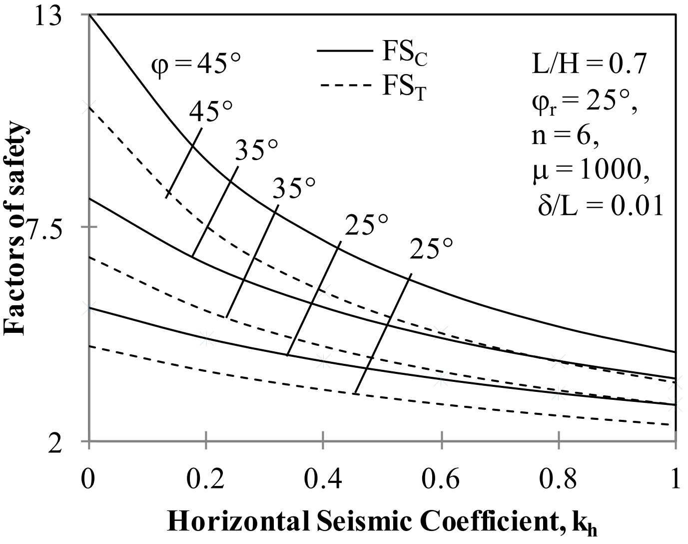

Figure 8 Variation of factor of safety with K_h - Effect of angle of shearing resistance

Factors of safety decrease by 110% and 104% with increase of horizontal seismic coefficient, k_h from 0 to 1 for the number of reinforcement layers n = 3 and 9 respectively (Figure 9). The increase of number of reinforcement layers in the reinforced fill from 3 to 9 increases the factors of safety by 191% and 199% respectively for horizontal seismic coefficient, $k_h = 0$ and 1. The increase of number of reinforcement layers in reinforced fill improved the factor of safety against pullout in extreme seismic events. Modified factor of safety, FS_T increases by 22% over the conventional factor of safety, FS_c for the number of reinforcement layers, n varying from 3 to 9 and horizontal seismic coefficient, k_h from 0 to 1. The conventional and modified factors of safety decrease by 104% with increase of horizontal seismic coefficient, k_h from 0 to 1 for the interface friction angle,φ_r ranging from 20° to 30° (Figure 10). The increase of interface friction angle between backfill and reinforcement increases the pullout resistance of reinforcement and transverse force mobilized due to oblique pull. The conventional factor of safety, FS_c and modified factor of safety, FS_T, increase by 59% and 66% respectively with increase of interface friction angle, φ_r from 20° to 30° and horizontal seismic coefficient, k_h from 0 to 1. The construction of reinforced soil wall with higher interface friction between reinforcement and soil improves the factor of safety against pullout during earthquakes.

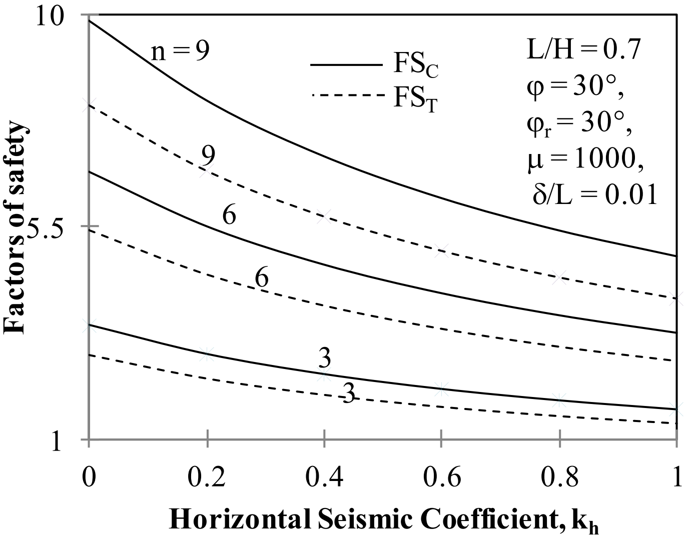

Figure 9 Variation of factor of safety with K_h - Effect of number of reinforcement layers

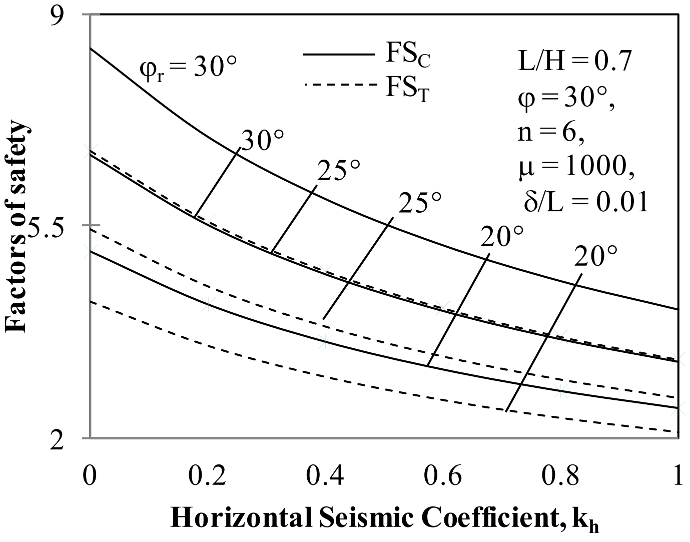

Figure 10 Variation of factor of safety with K_h - Effect of interface friction angle

4 CONCLUSION

Seismic stability of reinforced soil wall subjected to axial and oblique pullout is analyzed based on coherent gravity method and the modified factor of safety against pullout is quantified considering the mobilized transverse force. Modified factor of safety increases by 147% with increase of oblique displacement, δ from 0.001L to 0.05L and by 35% with increase of global backfill stiffness factor, μ_g from 50 to 10000. These results highlight the hidden conservatism in the reinforced soil walls which is not accounted for in the conventional static and seismic analysis and design of these structures. Modified factor of safety considering the oblique pullout is about 22% higher than the conventional factor of safety from axial pullout for a global backfill stiffness factor, $\mu_g = 1000$, oblique displacement, $\delta = 0.01L$ and interface friction angle, $\varphi_r = 25°$. Conventional and modified factors of safety increase with increase of length of reinforcement, angle of shearing resistance of backfill, interface friction angle between reinforcement and soil, number of reinforcement layers and decreased with horizontal seismic coefficient.

REFERENCES

Berg R.R, Christopher B.R, Samtani N.C. 2009. Design and construction of mechanically stabilized earth walls and reinforced soil slopes Volume 1. Publication No. FHWA-NHI-10-024. Washington, D.C.: U.S. Department of Transportation, Federal Highway Administration.

Billiard, J.W. & Wu, J.T.H. 1991. Load test of a large-scale geotextile-reinforced retaining wall. Proc. Geosynthetic '91 Conf., New Orleans, U.S.A., Vol.2: 537-548.

Choudhury, D., Nimbalkar, S.S. and Mandal, J.N. 2007. External stability of reinforced soil walls under seismic conditions. Geosynthetics International, 14(4), 211 –218.

Gray, D.H. and Ohashi, H. 1983. Mechanics of fiber Reinforcement in Sand. Journal of Geotechnical Engineering, ASCE, 109:335-353.

Kumar, P.V.S.N.P. and Madhav, M.R. 2006. Pullout Resistance of Geosynthetic Reinforcement due to Transverse displacement at intermediate point. International Symposium on Lowland Technology, Saga, Japan: 177 – 182.

Kumar, P.V.S.N.P. and Madhav, M.R. 2008. Analysis of RE wall using oblique pull for linear subgrade response: Coherent gravity approach. New Horizons in Earth Reinforcement, Japan: 491 – 496.

Kumar, P.V.S.N.P. and Madhav, M.R. 2009. Analysis of Reinforced Soil Wall Considering Oblique Pull: Bilinear Failure Mechanism – Linear Subgrade Response I, Lowland Technology International, IALT, 11(1): 1-11.

Kumar, P.V.S.N.P. and Madhav, M.R. 2013. Inclined Reinforcement – Backfill Interactions to Transverse Pull. Proceedings 18th ICSMGE, Paris: 202 – 213.

Kumar, P.V.S.N.P., Madhav, M.R. and Kumar, M. 2014. Analysis of Oblique in Reinforced Soil Wall – Coherent gravity and Tieback wedge method. 9th International Symposium on Lowland Technology, Saga, Japan: 340 - 347

Madhav, M.R. and Umashankar, B. 2003a. Analysis of inextensible sheet reinforcement subject to transverse displacement/force: linear subgrade response. Geotextiles and Geomembranes, 21(2): 69–84.

Madhav, M.R. and Umashankar, B. 2003b. Analysis of inextensible sheet reinforcement subject to downward displacement/force: non-linear subgrade response, Geosynthetics International, 10(3): 95-102.

Madhav, M.R., and Manoj, T.P. 2004. Response of geosynthetic reinforcement to transverse force/displacement with linear subgrade response. Proceedings of International Conference on Geotechnical and Geoenvironmental Engineering, Mumbai, India: 13 – 18.

Shahu, J.T. 2007. Pullout Response of Inextensible Sheet Reinforcement Subject to Oblique End Force. Journal of Geotechnical and Geoenvironmental Engineering, 133(11): 1440 – 1448.

Shahu, J.T. and Hayashi, S. 2009. Analysis of Extensible Reinforcement Subject to Oblique Pull. Journal of Geotechnical and Geoenvironmental Engineering, 135(5): 623 – 634.

Reddy, G.V.N., Madhav, M.R. and Saibaba Reddy, E. 2008. Pseudo-static seismic analysis of reinforced soil wall—Effect of oblique displacement. Geotextiles and Geomembranes, 26(5): 393–403.

Reddy, G.V.N., Choudhury, D., Madhav, M.R. and Saibaba Reddy, E. (2009). Pseudo-dynamic analysis of reinforced soil wall subjected to oblique displacement. Geosynthetics International, 16(2): 61 –70.

Rowe, R.K. and Ho, S.K., 1993. Keynote lecture: a review of the behaviour of reinforced soil walls. In: Ochiai, H., Hayashi, S., Otani, J. (Eds.), Earth Reinforcement Practice. Balkema, Rotterdam, pp. 801–830.

Tatsuoka, F., Koseki, J. and Tatayama, M., 1997. Performance of reinforced soil structures during the 1995 Hyogo-Ken Nanbu earthquake. In:Ochiai, H., Yasufuku, N., Omine, K. (Eds.), Earth Reinforcement. Balkema, Rotterdam, pp. 973–1008.

White, D.M. and Holtz, R.D., 1997. Performance of geosynthetic-reinforced slopes and walls during the Northridge, California earthquake of January 17, 1994. In: Ochiai, H., Yasufuku, N., Omine, K. (Eds.), Earth Reinforcement. Balkema, Rotterdam, pp. 965–972.