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ANALYSIS OF REINFORCED SOIL WALL CONSIDERING OBLIQUE PULL: BILINEAR FAILURE MECHANISM – LINEAR SUBGRADE RESPONSE I

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ABSTRACT: The available methods of analysis and design of reinforced soil walls consider only the axial pullout of the reinforcement. But, in practice, the reinforcement is subjected to oblique pull because of which the backfill below the reinforcement deforms transversely mobilizing normal stresses at the interface. As a result, the shear resistance mobilized along the reinforcement – backfill interface could be different and considerably more in case of oblique pull compared to the value corresponding to only axial pull. A new method to estimate the mobilized transverse forces in reinforced soil wall is presented. A modified factor of safety is defined, estimated and compared with the conventional one to establish the significance and contribution of the mobilized transverse forces. A parametric study quantifies the contributions of the global subgrade stiffness factor, length of reinforcement, the oblique or transverse displacement, and angle of shearing resistance of the backfill, interface friction angle and the number of reinforcement layers on the modified factor of safety and improvement ratio.

Keywords: Pullout resistance, oblique pull, conventional and modified factors of safety, improvement ratio, global subgrade stiffness factor

INTRODUCTION

In the design of reinforced soil walls, two primary forms of stability are investigated – external and internal. External stability is investigated assuming the composite backfill-reinforcement mass to behave as a rigid body (McGown et al., 1998). Internal stability is associated with tensile and pullout failure mechanisms of the reinforcement. For the latter, most of the studies presume that the reinforcement is subjected to only axial pull. However, the kinematics of failure establishes (Fig. 1) that the reinforcement is not pulled axially but obliquely, as the failure surface intersects the reinforcement either orthogonally or at an oblique angle resulting in a transverse or oblique displacement. The pullout resistance mobilized can be estimated by resolving the oblique displacement into axial and transverse components (Fig. 2). Most of the available studies consider the resistance mobilized only due to axial pullout and the contribution of transverse deformation is ignored or neglected.

The kinematics and obliquity of failure surface were considered by Gray and Ohashi (1983), Leschinsky and Reinschmidt (1985), Degencamp and Dutta (1989), Shewbridge and Sitar (1989), Leschinsky and Boedeker (1989), Athanasapoulous (1993), Burd (1995), Bergado

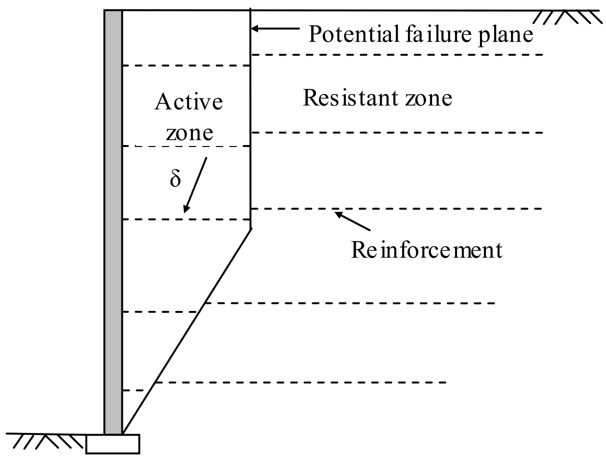

Fig. 1 Oblique pullout of reinforcement, bilinear failure mechanism

et. al. (2000), Madhav and Umashankar (2003), Madhav and Manoj (2004).

Madhav and Umashankar (2003) presented a new approach (Fig. 3) for the analysis of sheet reinforcement subjected to transverse force/displacement. Assuming a simple Winkler type response (Fig. 4) from the backfill/ground and the reinforcement to be inextensible, the resistance to transverse displacement is estimated. The inclination of the deformed reinforcement with the

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horizontal is considered to be small hence the formulation is applicable only for small deformations (transverse displacements up to 1% of the length of the reinforcement). The response to the applied force is shown to not only depend on the interface shear characteristics of the reinforcement but also on the relative stiffness of the backfill/ground. A relation is established between pullout resistance and the transverse free end displacement. Madhav and Manoj (2004) extended the response of geosynthetic reinforcement subjected to transverse force/displacement at free end to large displacements (10% length of reinforcement).

PROBLEM DEFINITION AND ANALYSIS

A reinforced soil wall (Fig. 5) of height, H, to retain a granular backfill of friction angle, φ, and unit weight, γ, is considered. Inextensible reinforcement sheets (n layers) of length, L, and interface friction angle, φ_r, are laid inside the backfill. The reinforcement sheets have a uniform spacing of $S_v = H/n$ in the backfill, with spacing

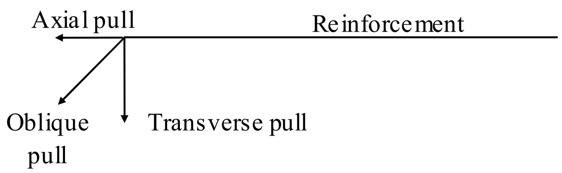

Fig. 2 Resolving oblique pull

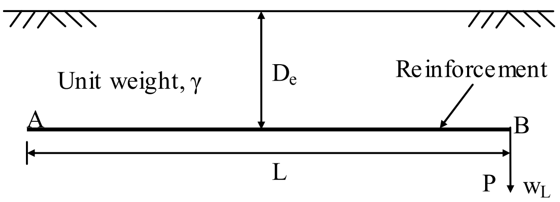

Fig. 3 Reinforcement subjected to transverse force (Madhav and Umashankar, 2003)

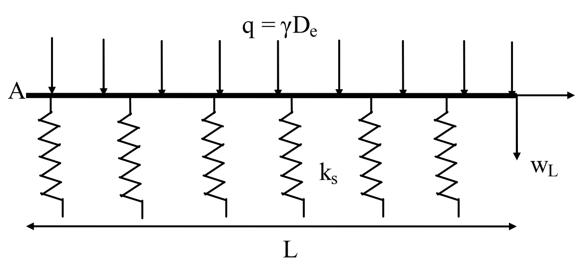

Fig. 4 Winkler type response of subgrade (after Madhav and Umashankar, 2003)

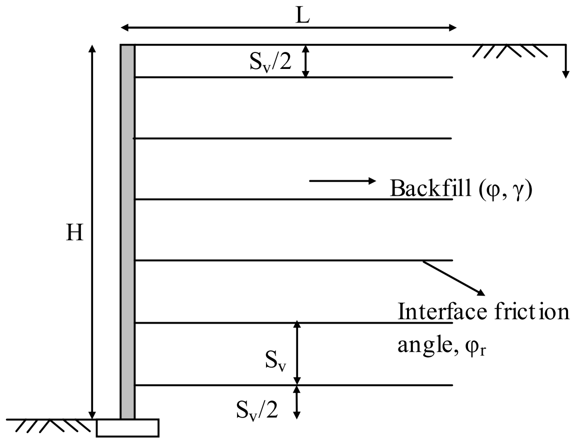

Fig. 5 Reinforced soil wall

of $S_v/2$ at the top and the bottom of the wall. The RS wall is designed to satisfy "external" stability requirements, which include sliding, overturning and bearing capacity. In addition reinforced soil walls must satisfy the "internal" stability requirements. With reference to the reinforcing elements there are three potential modes of failure: the reinforcing element may be pulled out of the soil behind the wall (bond failure), the elements may rupture (tensile rupture) and the connections between the reinforcing elements and the facing unit may fail. These potential failure modes depend on the geometry of the wall, the properties of the backfill, the reinforcement and the facing.

Conventional Approach

A bilinear wedge failure mechanism (Fig. 6) is considered for the analysis. The 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

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

and for

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

Tension in each layer of reinforcement is obtained from the following steps

- Calculate the overturning moment (M_{oi}) due to the backfill
- Calculate the resisting moment (M_{ri}) due to the weight of the retained material
- Determine the weight of reinforced fill (R_{vi}) above the respective layer
- Obtain the eccentricity of the resultant load from the center of the fill for each layer from the following equation

$$e_i = \frac{L}{2} - \left(\frac{M_{ri} - M_{oi}}{R_{vi}} \right) \tag{4}$$

- Calculate the modified vertical stress (Meyerholf pressure) in each layer as follows

$$\sigma_{vbi} = \frac{R_{vi}}{L - 2e_i} \tag{5}$$

Obtain the tension in each layer:

$$P_{ai} = \sigma_{vbi}\, k_i\, S_{vi} \tag{6}$$

where k_i and S_{vi} are the coefficient of active earth pressure and spacing of reinforcement respectively at i^{th} level of reinforcement .

The pullout resistance in each layer of reinforcement is obtained from following equation

$$T_i = 2\gamma\, z_i\, L_{ei} \tan\varphi_r \tag{7}$$

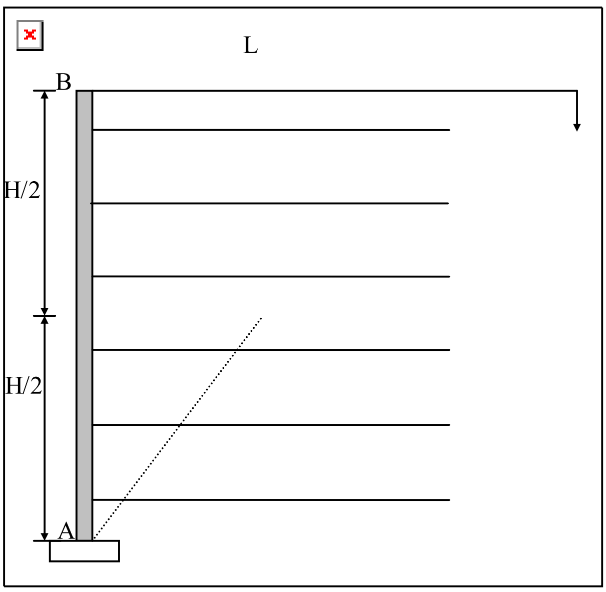

Fig. 6 Analysis of reinforced soil wall - conventional approach

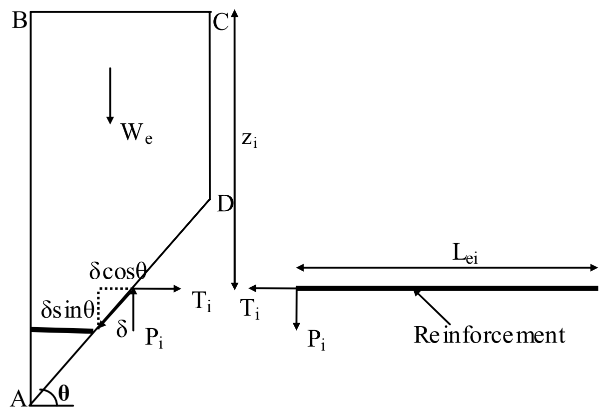

Fig. 7 Kinematics of deformation of reinforcement

The conventional factor of safety, FS_{conv}, is the ratio of total pullout resistance to the total tension mobilized obtained as follows

$$FS_{conv} = \frac{\sum_{i=1}^{n} T_i}{\sum_{i=1}^{n} P_{ai}} \tag{8}$$

Analysis Considering Oblique/Transverse Pulls

The 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 external loads exerted above the wall. The magnitude of oblique displacement will also depend on the relative rigidity of the wall face, strength of connections, etc.

The unstable wedge ABCD moves or slides (Fig. 7) along the failure surface ADC subjecting each reinforcement layer to transverse/oblique displacement. Along DC, the failure surface is vertical and the reinforcement is subjected to a transverse displacement of δ. Along AD, the failure surface is inclined at an angle θ with the horizontal and the reinforcement is subjected to an oblique pull of δ. This oblique pull is resolved into transverse and horizontal components $\delta\sin\theta$ and $\delta\cos\theta$ respectively.

The resultant of the normal stresses that gets mobilized due to transverse displacement on either side of failure plane at reinforcement – backfill interface is defined as transverse force, P_i (Fig. 7). In the present work the effect of 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 (2003) and

Madhav and Manoj, (2004) for the problem identified in Fig. 3. Additional stresses generated below the reinforcement due to the displacement are represented by a set of Winkler springs (Fig. 4) 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

$$P = \int_0^L k_s \, w \, dx \tag{9}$$

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

$$P^* = \frac{P}{\gamma D_e L} \tag{10}$$

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

$$P^* = \frac{w_L}{L} \mu \int_0^1 W \, dX \tag{11}$$

where w_L is the transverse displacement at the end of reinforcement 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.

$$\mu = \frac{k_s \; L}{\gamma D_e} \tag{12}$$

$$W = \frac{w}{w_L} \tag{13}$$

$$X = \frac{x}{L} \tag{14}$$

Where W = normalized transverse displacement and X = normalized distance.

The depth of reinforcement, z_i, and the effective length, L_{ei}, of reinforcement are different for each layer in a reinforced soil wall. These values are evaluated and substituted in Eq. 13 and 12 to arrive at the modified transverse displacement and relative subgrade stiffness factor for each layer.

Normalized transverse displacement of the i^{th} layer:

$$\text{For } z_i \le \frac{H}{2}, \quad \frac{w_L}{L_{ei}} = \frac{\delta}{L_{ei}} \tag{15}$$

$$\text{and for } z_i > \frac{H}{2}, \quad \frac{w_L}{L_{ei}} = \frac{\delta \sin\theta}{L_{ei}} \tag{16}$$

Relative subgrade stiffness factor of i^{th} layer

$$\mu_i = \frac{\mu_{global} \, L_{ei} \; H}{L \, z_i} \tag{17}$$

In the above equation μ_{global} is the global subgrade stiffness factor of the wall same as relative subgrade stiffness factor, μ defined by Madhav and Umashankar (2003) and mentioned in Eq. 12. The global sugbrade stiffness factor depends on the stiffness of the backfill, length and depth of embedment of reinforcement. The stiffer the subgrade, larger the length of the reinforcement, shallower the depth of embedment, larger will be the global subgrade stiffness factor, μ_{global}, and vice versa. Substituting the above values of transverse displacement and relative subgrade stiffness factor in Eq. 11, the normalized transverse force (P^*_i) is obtained and the transverse force is evaluated from the following equation

$$P_i = P^*{}_i \times \gamma \times z_i \times L_{ei} \tag{18}$$

The active wedge will remain in equilibrium under the weight of wedge (W_e), active thrust (P_a) and the total transverse force mobilized by all the reinforcement layers in the wall (Fig. 8). The increase in the pullout resistance due to the mobilized transverse force, P_i is obtained from following equation

$$T_{iT} = 2\gamma \, z_i \, L_{ei} \; \tan\varphi_r + P_i \; \tan\varphi_r \tag{19}$$

The modified factor of safety is obtained by considering the increased pullout resistance

$$F_T = \frac{\sum_{i=1}^{n} T_{iT}}{\sum_{i=1}^{n} P_{ai}} \tag{20}$$

The improvement ratio obtained by considering the increased pullout resistance

$$R_T = \frac{F_T}{FS_{conv}} \tag{21}$$

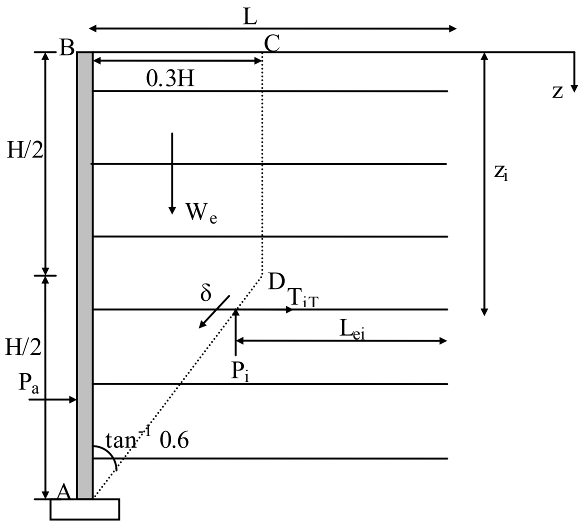

Fig. 8 Reinforced soil wall with oblique pull

RESULTS AND DISCUSSION

Based on the formulation presented in the preceding section, the conventional and modified factors of safety and improvement ratio are estimated for a wide range of parameters such as global subgrade stiffness factor, μ_{global} = 10 - 3000, length of reinforcement, L = 0.5H - 0.8H, oblique displacement, δ = 0.01L - 0.04L, friction angle of backfill, φ = 30º - 35º, interface friction angle, φ_r = (2/3)φ - φ and number of reinforcement layers, n = 3 - 6.

The conventional and modified factors of safety increase linearly with length of reinforcement (Fig. 9). The conventional factor of safety increases from 2.21 to 5.11 with increase in length of reinforcement from 0.5H to 0.8H for φ = 30º. Increase in the length of reinforcement leads to a direct increase in the effective length of reinforcement (L_{ei}) which in turn results in increased pullout resistances. Values of FS_{conv} and their rate of increase with L/H increase with increasing values of φ.

Considering the effect of oblique pull, the increase in length of reinforcement induces larger normal stresses on reinforcement mobilizing higher shear resistance along the soil reinforcement interface. Thus, the modified factor of safety, F_T, increases from 2.67 to 6.10 with increase in length of reinforcement from 0.5H to 0.8H for friction angle of backfill, φ = 30º (Fig. 9).

The increase in the friction angle of backfill, φ decreases the active earth pressure force. Hence the conventional factor of safety increases from 2.4 to 3.62 with increase of friction angle of backfill from 30º to 35º for 3 layers of reinforcement (Fig. 10). The increase in number of reinforcement layers provide a better restraint against lateral spreading of soil within the reinforced fill. Hence conventional factor of safety increases from 2.4 to 4.71 with increase in number of reinforcement layers from 3 to 6 for friction angle of soil, φ = 30º (Fig. 10).

The modified factor of safety also increases with friction angle of backfill due to additional pullout resistance mobilized along soil - reinforcement interface due to oblique pullout of reinforcement. F_T increases from 2.9 to 4.46 with increase in φ from 30º to 35º for 3 layers of reinforcement (Fig. 10). The increase in number of reinforcement layers present in the wall increases the overall pullout resistance due to oblique pull out effect and thereby increases the modified factor of safety. F_T increases from 2.9 to 5.66 as the number of reinforcement layers increase from 3 to 6 (Fig. 10).

The increase of soil reinforcement interface friction angle improves the pullout resistance of reinforcement from passive zone, hence the conventional factor of safety increases from 2.88 to 4.63 with increase of φ_r from (2/3)φ to φ, for length of reinforcement of 0.5H

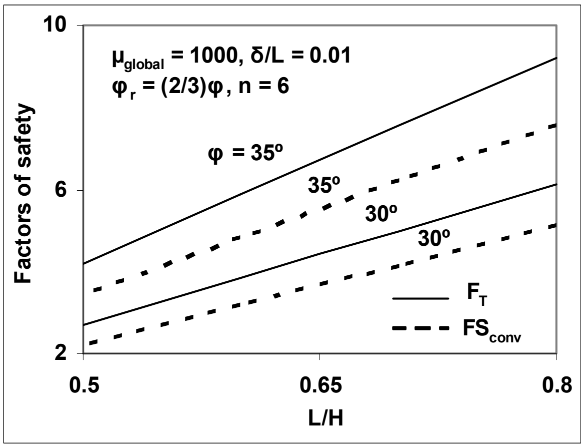

Fig. 9 Variation of factors of safety with L/H – Effect of φ

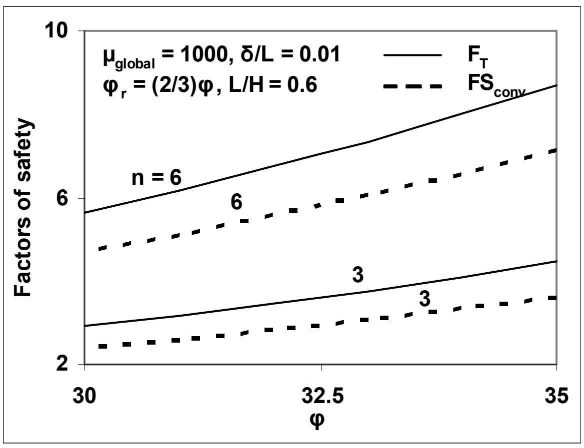

Fig. 10 Variation of factors of safety with φ – Effect of n

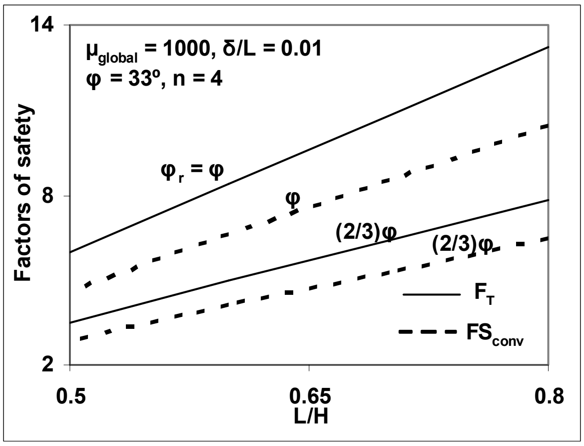

Fig. 11 Variation of factors of safety with L/H – Effect of φ_r

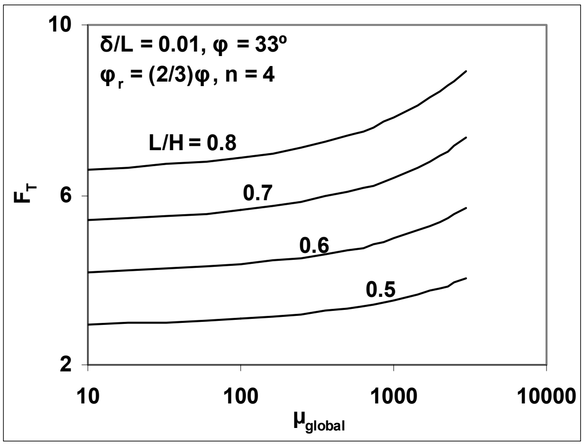

Fig. 12 Variation of F_T with μ_{global} – Effect of L/H

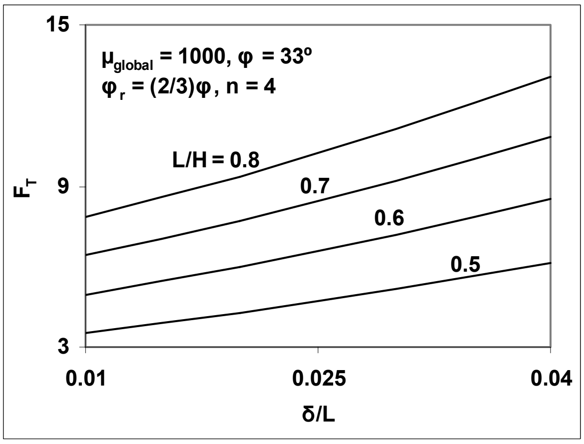

Fig. 13 Variation of F_T with δ/L – Effect of L/H

(Fig. 11). Considering the effect of oblique pull, the analysis is based on the assumption that full shear resistance is mobilized along sheet soil interface and the mobilized shear resistance is proportional to the interface friction angle, φ_r. Hence increase in interface friction angle further improves the pullout resistance. The modified factor of safety increases from 3.52 to 5.96 with increase in φ_r from (2/3)φ to φ for length of reinforcement 0.5H (Fig. 11).

The transverse force required to mobilize a given oblique displacement increases with increase in global subgrade stiffness factor, μ_{global}. The modified factor of safety, F_T, increases marginally from 2.9 to 3.2 with increase in μ_{global}, from 10 to 300 for length of reinforcement 0.5H (Fig. 12). With further increase of μ_{global} beyond 300, the modified factor of safety increases sharply from 3.19 to 4.06. A similar behavior is observed for other lengths of reinforcement.

The transverse force mobilized increases with increase in magnitude of displacement for a given stiffness of subgrade. The modified factor of safety increases from 3.52 to 6.11 with increase of δ from 0.01L to 0.04L for a length of reinforcement of 0.5H (Fig. 13). The rate of increase of the modified factor of safety increases with increase in length of reinforcement from 0.5H to 0.8H. The conventional factor of safety will not vary with subgrade stiffness factor and oblique displacement, since the conventional design methods do not consider the influence of above parameters.

Both the conventional and the modified factors of safety were observed to increase with length of reinforcement (Fig. 9) and their improvement with length of reinforcement is comparable. Hence the improvement ratio, R_T is nearly constant at 1.20 with increase in length of reinforcement, L from 0.5H to 0.8H, for φ = 30º (Fig. 14).

The improvement ratio, R_T, marginally increases from 1.2 to 1.22 with increase of friction angle of soil from 30º to 35º for six layers of reinforcement (Fig.15). Similar to the variation with length of reinforcement, the improvement ratio, R_T, remains constant at 1.21 with increase in number of reinforcement layers from 3 to 6 (Fig. 15).

The improvement ratio, R_T, increases from 1.22 to 1.29 as the interface friction angle increases from (2/3)φ to φ for length of reinforcement of 0.5H (Fig.16).

The global subgrade stiffness factor, μ_{global}, has significant influence on improvement ratio for an oblique displacement δ = 0.01L (Fig. 17). The improvement ratio increases marginally from 1.02 to 1.06 for μ_{global}, increasing from 10 to 100. With further increase of global subgrade stiffness factor from 100 to 3000 the improvement ratio increases drastically from 1.06 to 1.41. The curves for different lengths of reinforcement are close to each other indicating the fact that effect of length of reinforcement is secondary compared with the effect of global subgrade stiffness factor on R_T.

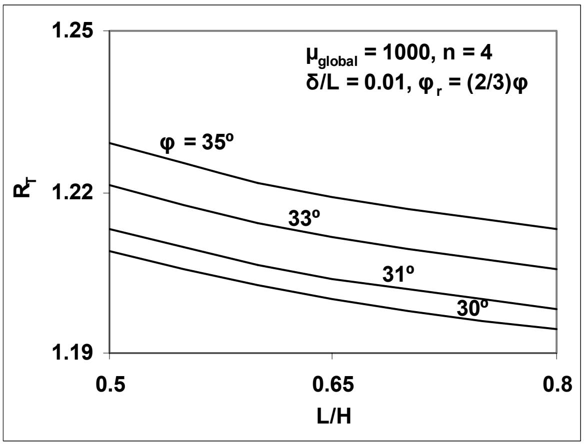

Fig. 14 Variation of R_T with L/H – Effect of φ

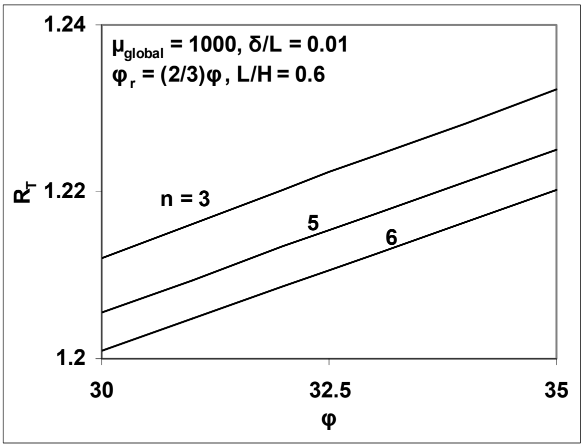

Fig. 15 Variation of R_T with φ – Effect of n

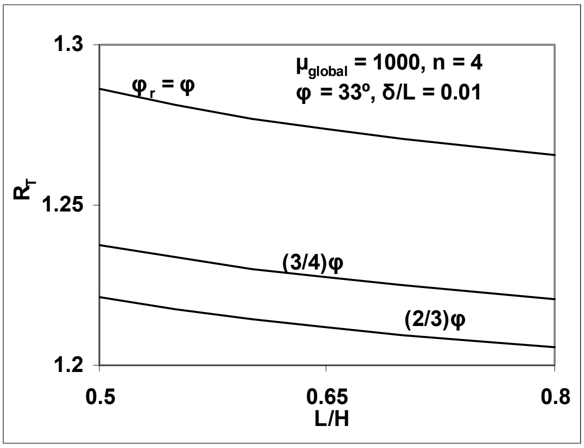

Fig. 16 Variation of R_T with L/H – Effect of φ_r

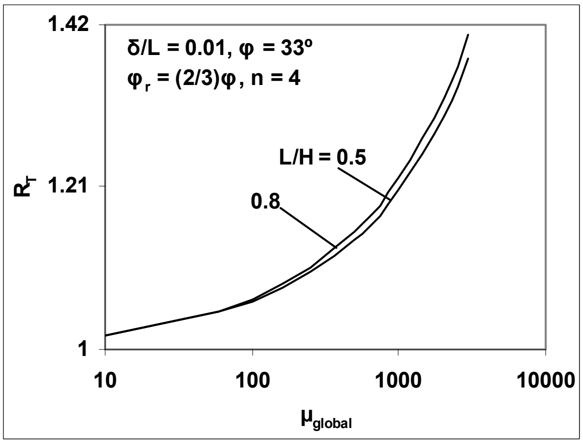

Fig. 17 Variation of R_T with μ_{global} – Effect of L/H

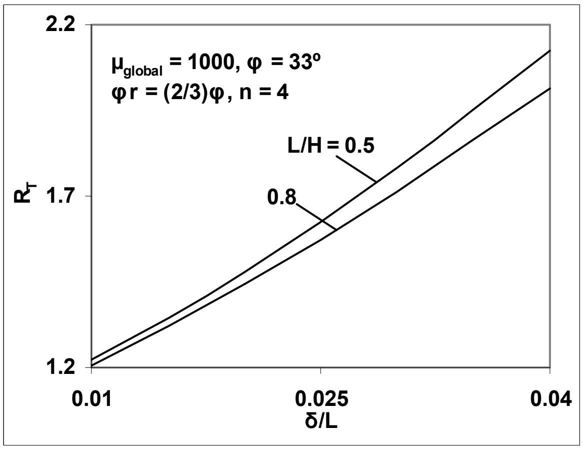

Fig. 18 Variation of R_T with δ/L – Effect of L/H

The improvement ratio is very sensitive to the magnitude of oblique displacement (Fig. 18). The improvement ratio increases from 1.2 to 2.1 due to increase of oblique displacement of active wedge, δ, from $0.01L$ to $0.04L$ for μ_{global} = 1000. The effect of length of reinforcement on improvement ratio is secondary compared to the effect of oblique displacement since the curves for different lengths of reinforcement are close to each other.

TYPICAL DESIGN OF REINFORCED SOIL WALL

In this section a typical design of reinforced soil wall is presented along with computation of the conventional, modified factors of safety and improvement ratio.

Design Parameters

Height of wall (H)	: 6.0 m
Unit weight of wall fill and backfill (γ)	: 18 kN/m^3
Friction angle of soil (φ)	: 30º
Interface friction angle (φ_r)	: $\frac{2}{3}\varphi = 20°$
Allowable bearing pressure	: 200 kPa
Sliding coefficient (ff)	: 0.47
Allowable tension in	: 60 kN

reinforcement (T_D)

Relative global subgrade stiffness factor (μ_{global}) : 1000

Oblique displacement (δ) : 0.01L

Assume length of reinforcement (L) = 3.0 m

External Stability Calculations

Coefficient of active earth pressure (k_a) : $\frac{1}{3}$

Lateral force acting on the reinforced block (P_a) : $\frac{1}{2}\times\frac{1}{3}\times 18\times 6^2 = 108$ kN

Total vertical force (R_v) : $18\times 6\times 3 = 324$ kN

Overturning moment about base (M_o) : $\frac{1}{2}\times\frac{1}{3}\times 18\times 6^2\times\frac{6}{3} = 216$ kN-m

Resisting moment about toe of wall (M_R) : $18\times 6\times 3\times\frac{3}{2} = 486$ kN-m

Factor of safety against overturning : $\frac{486}{216} = 2.25$ (> 2.0, safe)

Eccentricity of load (e) : $\frac{3}{2}-\left(\frac{486-216}{324}\right) = 0.66$m (> $\frac{3}{6}$ = 0.5m, unsafe)

The eccentricity check is not satisfied and length of reinforcement is increased to 3.5m.

Lateral force acting on the reinforced block (P_a) : $\frac{1}{2}\times\frac{1}{3}\times 18\times 6^2 = 108$ kN

Total vertical force (R_v) : $18\times 6\times 3.5 = 378$ kN

Overturning moment about base (M_o) : $\frac{1}{2}\times\frac{1}{3}\times 18\times 6^2\times\frac{6}{3} = 216$ kN-m

Resisting moment about toe of wall (M_R) : $18\times 6\times 3.5\times\frac{3.5}{2} = 661.5$ kN-m

Factor of safety against overturning : $\frac{661.5}{216} = 3.06$ (> 2.0 safe)

Eccentricity of load (e) : $\frac{3.5}{2}-\left(\frac{661.5-216}{378}\right) = 0.57$m

Bearing pressure : $\frac{378}{3.5-(2\times 0.57)} = 160.17$ kN/m^2 (< 200 kPa, safe)

Base frictional resistance : $0.47\times 378 = 177.66$ kN

Factor of safety against sliding : $\frac{177.66}{108} = 1.65$ (> 1.5 Hence safe)

Internal Stability Calculations

The layout of reinforcement is shown in Fig. 19 with six layers of reinforcement having an allowable tension of 60 kN/m arranged at following depths: 0.5m, 1.5m, 2.5m, 3.5m, 4.5m and 5.5m. Tables 1 to 3 illustrate the internal stability analysis of reinforced soil wall for the proposed arrangement of reinforcement.

Table 1 Calculation of earth pressure and destabilizing moment (M_{oi}) for each layer

Layer No (i)	z_i, m	σ_{vi} kN/m^2	k_a	Earth pressure kN/m^2	R_{hi} kN	M_{oi} kN-m
1	0.5	9	0.33	3	0.75	0.13
2	1.5	27	0.33	9	6.75	3.38
3	2.5	45	0.33	15	18.75	15.63
4	3.5	63	0.33	21	36.75	42.88
5	4.5	81	0.33	27	60.65	91.13
6	5.5	99	0.33	33	90.75	166.38

(where σ_{vi} is the vertical stress at i^{th} layer, k_a is coefficient of active earth pressure and R_{hi} is the lateral force acting at i^{th} layer)

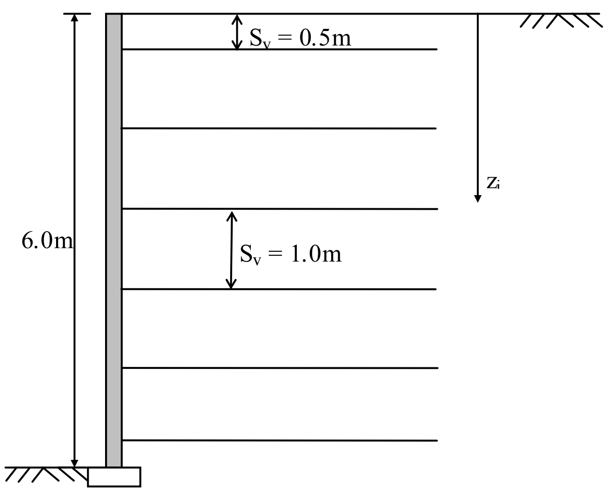

Fig. 19 Typical design of a Reinforced soil wall

Table 2 Calculation of modified vertical stress (σ_{vbi}) on each layer

Layer No (i)	z_i m	R_{vi} kN	M_{ri} kNm	e_i m	σ_{vbi} kN/m^2
1	0.5	31.5	55.13	0	9
2	1.5	94.5	165.38	0.04	27.63
3	2.5	157.5	275.62	0.10	47.73
4	3.5	220.5	385.87	0.19	70.67
5	4.5	283.5	496.12	0.32	99.12
6	5.5	346.5	606.38	0.48	136.42

Table 3 Calculation of tension (P_{ai}) and pullout resistance (T_i) for each layer

Layer No.	z_i m	S_{vi} m	P_{ai} kN	L_{ei} m	T_D kN	FS_{ri}	T_i kN
1	0.5	0.5	1.5	1.7	60	40	11.14
2	1.5	1.0	9.21	1.7	60	6.51	33.41
3	2.5	1.0	15.91	1.7	60	3.77	55.69
4	3.5	1.0	23.56	2.0	60	2.55	91.72
5	4.5	1.0	33.04	2.6	60	1.82	153.30
6	5.5	1.0	45.47	3.2	60	1.32	230.61
		$\sum P_{ai}$ =	128.69			$\sum T_i$ =	575.87

FS_{ri} is the factor of safety against rupture of reinforcement at ith level

The maximum tension mobilized in reinforcement located at a depth of 5.5 m is 45.47 kN/m which is less than the allowable tension (60 kN/m). Hence the proposed arrangement is safe against rupture.

The factor of safety against pullout defined as

$$FS_{conv} = \frac{\sum T_i}{\sum P_{ai}} = \frac{575.87}{128.69} = 4.47$$

which is greater than 1.0 and the arrangement safe against pullout of reinforcement.

Effect of Oblique Pullout of Reinforcement

Considering an oblique pull of 0.01L and global subgrade stiffness factor of 1000, the transverse displacement and relative stiffness factor for each reinforcement layer is computed. The normalized transverse force, P^*_i, transverse force, P_i, and the modified pullout resistance, T_{iT}, in each layer of reinforcement is evaluated (Table 4) for an interface friction angle, φ_r =2/3φ.

$$\text{Modified factor of safety, } F_T = \frac{\sum T_{iT}}{\sum P_{ai}} = \frac{692.04}{128.69} = 5.38$$

Table 4 Calculation of transverse force and modified tension in each reinforcement layer

Layer No	z_i m	T_i kN	P_i kN	T_{iT} kN
1	0.5	11.14	25.06	20.26
2	1.5	33.41	39.90	47.93
3	2.5	55.69	50.10	73.92
4	3.5	91.72	53.39	111.15
5	4.5	153.30	68.05	178.07
6	5.5	230.61	82.71	260.71
			$\sum T_{iT}$ =	692.04

and improvement ratio,

$$R_T = \frac{F_T}{FS_{conv}} = \frac{5.38}{4.47} = 1.20$$

CONCLUSIONS

Conventional method of analysis and design of reinforced soil walls consider only axial pullout of reinforcement. But in practice, the displacement of the failure wedge is oblique to the alignment of reinforcement layers which is usually horizontal. In the present study the effect of oblique displacement of the bilinear wedge with linear subgrade response is considered by evaluating the transverse displacement at each reinforcement layer. The effect of transverse displacement is to increase the normal stress on the reinforcement which directly increases the pullout resistance of the reinforcement. Variations of conventional and modified factors of safety against pullout for a range of the following parameters are quantified: length of reinforcement, number of reinforcement layers, friction angle of soil, global subgrade stiffness factor of backfill and interface friction angle. The variations of F_T and FS_{conv} with the above parameters are very similar. The modified factor of safety, F_T, increases significantly with the magnitude of oblique displacement and the global subgrade stiffness factor. The improvement ratio, R_T, ranges from 1.08 to 2.0 for different lengths of reinforcement, friction angle of soil, number of reinforcement layers and interface friction angle. The increase in R_T depends significantly on the global subgrade stiffness factor and the oblique displacement. Thus the considered improvement is most significant for well compacted granular backfills. An illustrative design of a reinforced soil wall is presented to record the significance of considering the kinematics of the sliding mass and oblique pullout.

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