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Analysis of Reinforced Soil Wall: Effect of Kinematics and Non-linear Backfill Response

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ABSTRACT

Analysis of reinforced soil wall considering kinematics and incorporating non-linear (hyperbolic) backfill response to transverse displacement using Horizontal Slices Method is presented. The stresses developed in the backfill are limited to the ultimate bearing resistance. Parametric studies quantify the effects of nonlinear backfill response for different wall, backfill and reinforcement parameters on the factor of safety of the reinforced wall considering both the increase in bond resistance and the additional normal force in the reinforcement due to oblique displacement.

1. INTRODUCTION

Numerous methods are available for the analysis of stability of reinforced soil walls. All these methods consider only the axial resistance of the reinforcement to pullout, e.g., Jewell (1992), Alfaro et al. (1995), Ochiai et al. (1996), etc. whereas, in a reinforced soil structure, the failure surface of the sliding mass of soil intersects the reinforcement layers obliquely. This effect of oblique pull/displacement on the analysis of reinforced soil structures has been considered only by few researchers, e.g., Gray and Ohashi (1983), Leshchinsky and Reinschmidt (1985), Shewbridge and Sitar (1989), Leshchinsky and Boedecker (1989), Athanasopoulos (1993) and Bergado et al. (2000).

The failure surface is oblique to the reinforcement. Hence, the reinforcement subjected to transverse force (i.e., the vertical component of the oblique force) generates an additional normal stresses on the lower surface of the reinforcement that lead to a corresponding increase in the bond resistance. The mobilized transverse force counteracts the destabilizing force and hence, the net destabilizing force decreases 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. The increase in the pullout resistance due to this oblique pull and mobilized additional normal stress on the reinforcement based on linear response (Fig. 1a) have been reported by Narasimha Reddy et al. (2008, 2009). The stresses developed in the backfill can increase neither linearly nor indefinitely with the displacement but are limited to the ultimate bearing resistance of the backfill.

2. ANALYSIS

Figure 2 depicts a reinforced soil wall of height, $H$, with inextensible reinforcements of length, $L$, in a backfill with unit weight, $\gamma$ and angle of shearing resistance, $\phi$. The angle of interface friction or the bond resistance between the reinforcement and the backfill, is $\phi_r$. The backfill is reinforced with 'm' layers of sheet reinforcement. Thus the spacing, $S$, between the layers of reinforcement is $H/n$. 

![Stress-Displacement Response of Backfill](image)

The improvement in factor of safety of reinforced soil walls is studied using the horizontal slices method of Shahgholi et al. (2001) incorporating the model developed by Madhav and Umashanker (2003), to quantify the mobilized transverse force for different values of free-end displacements and relative stiffnesses of the backfill.
except for the top and bottom layers which have a spacing of \( S/2 \). Failure surface, AC, independent of the provision of reinforcement, inclined at an angle, \( \alpha \), with respect to the horizontal is considered.

The backfill is divided (Fig. 3a) into ‘\( n \)’ number of horizontal slices with a layer of reinforcement at the center of each horizontal slice. The depth to the \( j^{th} \) layer of reinforcement is \( h_j \), from the top. The sliding mass of soil moves along the plane AC. The movement is oblique to the alignment of the reinforcement. Hence an oblique displacement, \( \delta \), is considered along the failure surface to estimate the additional resistance mobilized. \( \delta \cos \alpha \) and \( \delta \sin \alpha \) are the axial and transverse displacements respectively due to the displacement along Coulomb’s planar surface. A resisting force, \( P_j \), gets mobilized as a result of the transverse displacement, \( ds \sin \alpha (=w_j) \), of the reinforcement with respect to the backfill (Fig. 3b). The mobilized transverse force that depends on the normal stress-displacement response is evaluated for non-linear backfill response.

The vertical force equilibrium for the \( i^{th} \) slice incorporating additional mobilized normal force, \( P_j \), is as given in Eq.(1):

\[
\sum F_i = 0
\]

i.e., \( V_i = V_i - W_i + S_{pi} \sin \alpha + N_{pi} \cos \alpha + P_j = 0 \) (1)

where \( P_j (= \gamma h_j L_j P^* \) is the transverse force in the \( j^{th} \) layer of the reinforcement due to transverse displacement where \( P^* \) is the normalized transverse force in the \( j^{th} \) layer of the reinforcement determined based on nonlinear backfill responses (Madhav and Umashanker, 2003).

Shear force considering mobilized transverse force, \( S_{pi} \), upon the base of each slice is as given in Eq. (2):

\[
S_{pi} = \frac{N_{pi} \tan \phi}{FS_{pi}}
\]

Substituting for \( S_{pi} \) from Eq. (2) into Eq. (1) and solving for the normal force due to mobilized transverse force, \( N_{pi} \), on the base of each slice, one gets Eq. (3),

\[
N_{pi} = \frac{V_i - V_{i_{+1}} + W_i - P_j}{\tan \phi + \sin \alpha + \cos \alpha}
\]

The horizontal force equilibrium for the whole sliding mass is as shown in Eq. (4).

\[
\sum F_{pi} = 0 \quad \text{i.e.,}
\sum_{j=1}^{m} t_j - \sum_{i=1}^{n} N_{pi} \sin \alpha + \sum_{j=1}^{m} S_{pi} \cos \alpha = 0
\]

Sum of the tensile forces generated in a reinforced soil wall considering mobilized transverse force is determined using the Eq. (4).

The tension mobilized in \( j^{th} \) layer of the reinforcement gets modified due to the additional normal force, \( P_j \), (Eq. 5)
\[ T_{nj} = 2 \gamma_j L_{nj} \tan \phi_j + P_j \tan \phi. \quad (5) \]

The total bond resistance mobilized in the reinforcement layers’ considering oblique displacement is (Eq. 6)

\[ \sum_{j=1}^{m} T_{nj} = \sum_{j=1}^{m} 2 \gamma_j L_{nj} \tan \phi_j + \sum_{j=1}^{n} P_j \gamma_j \tan \phi_j. \quad (6) \]

The factor of safety, \( FS_{tp} \) (Eq. 7), considering both the additional normal force in the reinforcement and the increase in bond resistance due to transverse displacement is obtained using Eqs. (4) and (6) as

\[ FS_{tp} = \frac{\sum T_{nj}}{\sum P_j} \quad (7) \]

3. RESULTS AND DISCUSSION

Relative bearing resistance factor, \( \beta = L/H_{d_{al}}=0 \) represents linear backfill response. The nonlinearity of backfill response increases with increasing \( \beta \). The variation of \( FS_{tp} \), with normalized displacement, \( W_{L} \), for different values of relative bearing resistance factor, \( \beta \), for \( n=5, L/H=0.5, \phi = 30^\circ, \phi/\phi = 2/3 \) and \( \mu = 2000 \) is presented in Figure 5. \( FS_{tp} \) increases significantly with normalized displacement for different relative bearing resistance factors. Increase in \( FS_{tp} \) with \( \mu \) is gradual for soft backfill (\( \mu < 1000 \)) and exponential for stiffer backfills (\( \mu > 1000 \)) for relative bearing resistance factor, \( \beta < 500 \). Increase of \( FS_{tp} \) with \( \mu \) is gradual for soft and stiff backfills for \( \beta > 500 \). \( FS_{tp} \) increases from 7.95 to 37.87 with decrease in \( \beta \) from 1000 to 100 for \( \mu = 5000 \).

The variation of \( FS_{tp} \) with relative stiffness of backfill, \( \mu \), for different values of relative bearing resistance factor, \( \beta \), for \( n=5, L/H=0.5, \alpha=30^\circ, \alpha/\alpha = 2/3 \) and \( W_{L} = 0.005 \) is presented in Figure 6. \( FS_{tp} \) increases significantly with normalized displacement for different relative bearing resistance factors. Increase in \( FS_{tp} \) with \( \mu \) is gradual for soft backfill (\( \mu < 1000 \)) and exponential for stiffer backfills (\( \mu > 1000 \)) for relative bearing resistance factor, \( \beta < 500 \). Increase of \( FS_{tp} \) with \( \mu \) is gradual for soft and stiff backfills for \( \beta > 500 \). \( FS_{tp} \) increases from 7.95 to 37.87 with decrease in \( \beta \) from 1000 to 100 for \( \mu = 5000 \).

The variation of \( FS_{tp} \) with relative bearing resistance factor, \( \beta \), for different values of relative bearing resistance factor, \( \phi \) for \( n=5, L/H=0.5, \phi/\phi = 2/3, \mu = 2000 \) and \( W_{L} = 0.005 \) is presented in Figure 7. Factor of safety, \( FS_{tp} \) increases significantly with increase in angle of shearing resistance due to increase in mobilization of transverse force and this rate increases with increase in angle of shearing resistance. Decrease in \( FS_{tp} \) with \( \beta \) is exponential and sharp for \( \beta \) up to 1000, and gradual for \( \beta > 1000 \).

**Fig. 5:** Variation of \( FS_{tp} \) with Normalized Displacement \( W_{L} \) - Effect of \( \beta \)

**Fig. 6:** Variation of \( FS_{tp} \) with Relative Stiffness of Backfill, \( \mu \) - Effect of \( \beta \)

**Fig. 7:** Variation of \( FS_{tp} \) with Relative Bearing Resistance Factor, \( \beta \) - Effect of Angle of \( \phi \)

The \( FS_{tp} \) decreases with increase in angle of shearing resistance due to significant decrease in mobilized transverse force. Hence, \( FS_{tp} \) decreases from 10.3 to 4.4.
with increase in $\beta$ from 0 to 3000 for $\phi=30^0$ and increases from 3.0 to 20.0 with increase in $\phi$ from 25$^0$ to 40$^0$ for $\beta=1000$.

The variation of the factor of safety $FS_{TP}$ with relative bearing resistance of backfill, $\beta$, for different angles of interface friction or bond resistance, $\phi$, for $n=5$, $L/H=0.5$, $\phi=30^0$, $\mu=2000$ and $W_r=0.005$ is shown in Figure 8. The rate of increase in the factor of safety, $FS_{TP}$, due to transverse displacement with relative bearing resistance, decreases sharply with relative bearing resistance of backfill for $\beta < 500$ and decreases marginally thereafter. $FS_{TP}$ increases with increase in angle of interface friction. The mobilized transverse force increases with increase in angle of interface friction and counteracts the destabilizing force reducing the net destabilizing force by the magnitude of the normal force mobilized. $FS_{TP}$ decreases from 13.4 to 7.4 with increase in $\beta$ from 0 to 500 and from 7.4 to 5.1 with increase in $\beta$ from 500 to 3,000 for $\phi/\phi=3/4$.

![Figure 8: Variation of $FS_{TP}$ with Relative Bearing Resistance Factor, $\beta$-Effect of $\phi$.](image)

### 4. CONCLUSIONS

The stability of reinforced soil wall considering the kinematics of displacement is analyzed. The reinforcement layers are subjected to oblique force/displacement due to the sliding mass. The factor of safety, $FS_{TP}$, decrease sharply with increase in the relative bearing resistance factor of the backfill for relatively incompressible soils (i.e. $\beta <1000$) for different wall, backfill and reinforcement parameters due to the sharp decrease in mobilized transverse force with increase in bearing resistance factor of backfill. But, the factor of safety, $FS_{TP}$ decreases marginally with increase in the relative bearing resistance factor of the backfill for compressible soils (i.e. $\beta >1000$) for different wall, backfill and reinforcement parameters due to the marginal decrease in mobilized transverse force with increase in bearing resistance factor of backfill.

### REFERENCES


