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Technical Note

Pullout of Inclined sheet Reinforcement in Reinforced Earth Wall

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Key words

Inclined reinforcement, angle of inclination, reinforced soil wall, pullout resistance, factor of safety.

Abstract: The conventional practice of construction of reinforced soil walls involves aligning metallic/polymeric reinforcement horizontally. Use of inclined reinforcement is not adopted or limited due to difficulties in construction. The present work analyses RE wall with sheet reinforcement inclined downward to the horizontal at an inclination ranging from 0 to 10° and predicts the factor of safety against pullout of inclined reinforcement. Further, its application to the stability of reinforced earth (RE) wall is investigated by quantifying the improvement of factor of safety against the factor of safety for conventional wall with horizontal reinforcement. The variations of factor of safety with length of reinforcement, angle of shearing resistance of backfill, number of reinforcement layers, interface friction angle, intensity of surcharge and different failure mechanisms are studied. Reinforced soil walls with reinforcement oriented marginally downward offer improved resistance against pullout compared with walls with horizontal reinforcement.

Introduction

Geosynthetic reinforcement is aligned commonly horizontally but transversal to the application of gravity stresses in reinforced earth structures such as embankments, slopes, retaining walls and foundation beds. The mechanism of horizontal geosynthetic reinforcement is to restrain the tensile strains in the soil and thus increase the shear resistance of the composite medium through interfacial bond resistance limited by its own tensile strength. Inclined reinforcement in the form of grouted nails are employed commonly (Juran et al. 1990) for excavation support for high rise buildings and underground facilities, stabilizing railroad and highway cut slopes, tunnel portals in steep and unstable stratified slopes, etc. The grouted nails reinforce the soil and improve the overall shear strength of in situ soils as passive inclusions by creating a coherent gravity structure and restraining the displacements in soil.

Most of the available studies for the analysis and design of reinforced earth structures consider only the axial resistance of reinforcement against pullout (Flower, 1982, and Jewell, 1992). The reinforcement force was considered to act tangential to slip surface by Quast (1983) and along a direction between the alignment of the reinforcement and the tangent to the slip surface by Rowe and Soderman (1984), Bonaparte and Christopher (1987), Huisman (1987) and Rowe (1992). Madhav and Umashankar (2003) and Madhav and Manoj (2004) studied the kinematics of failure of reinforced soil structures and established that reinforcement is subjected to oblique pull (combination of axial and transverse pull) rather than a pure axial pullout. Numerical models developed establish a relationship between transverse displacement and pullout resistance for different subgrade responses and for extensible and inextensible reinforcements. Madhav and Kumar (2007) studied the effect of oblique pull/mobilized transverse force in improving the pullout resistance of reinforcement in reinforced soil wall with horizontal reinforcement. In the present work the pullout resistance of inclined reinforcement is quantified.

Problem Definition

A typical reinforced soil wall (Figure 1) of height 'H' with 'n' number of inclined sheet reinforcement of uniform length 'L', backfill unit weight of 'γ', and angle of shearing resistance, φ, is considered for analysis. The interface friction angle or bond resistance between soil and reinforcement is characterized by 'φ_r'. Reinforcement layers are arranged at uniform spacing of 'S_v' at an inclination of 'α' with the horizontal. Reinforced soil wall is subjected to a uniform surcharge pressure of intensity 'w'.

The depth, z_i, of the i[th] layer of reinforcement from the top of the wall is

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

Tension, P_{ai}, developed in i[th] layer of reinforcement is

$$P_{ai} = k\sigma_{vi}S_{vi} \tag{2}$$

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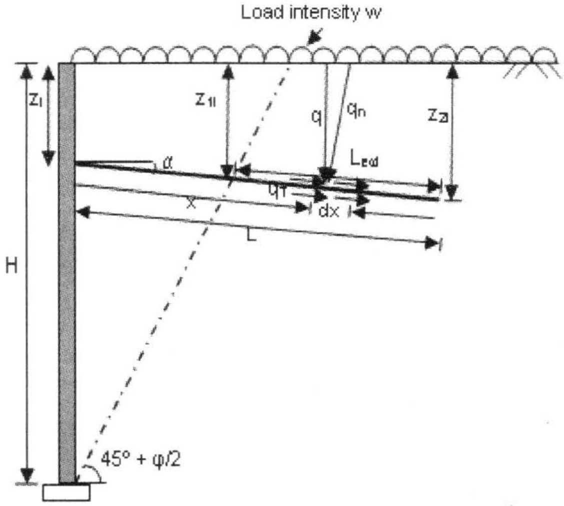

Fig.1 Pullout resistance for inclined reinforcement

where k, σ_{vi}, and S_{vi} are the coefficient of earth pressure, the vertical stress and the spacing between the reinforcement layers at ith level respectively. The vertical stress obtained as a combination of gravity force and moment due to lateral force, is

$$\sigma_{vi} = \frac{R_{vi}}{L - 2e_i} \tag{3}$$

where R_{vi} and e_i are the weight of reinforced fill above ith layer and eccentricity respectively. The eccentricity, e_i, of the resultant force is

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

where M_{ri} and M_{oi} represent the resisting and overturning moments at the ith layer.

The reinforcement aligned horizontally is subjected to a uniform gravity stress and respective pullout resistance, T_i, at depth z_i is obtained as

$$T_i = 2\gamma z_i L_{ei} \tan\varphi_r + 2wL_{ei} \tan\varphi_r \tag{5}$$

where L_{ei} is the effective length of reinforcement beyond the failure surface. The factor of safety against pullout of horizontal reinforcement, is

$$F_0 = \frac{\sum_{i=1}^{n} T_i}{\sum_{i=1}^{n} P_{ai}} \tag{6}$$

The inclined sheet reinforcement of length 'L' placed at an angle 'α' with the horizontal is intersected by the Coulomb failure surface shown in Figure 1. Reinforcement is subjected to overburden pressure increasing from γz_i to γz_{1i} to γz_{2i} from the wall to the point of intersection with the failure plane and to the farthest end where z_{1i} and z_{2i} are respectively the depths below ground surface of the point of intersection with the plane of failure and the tip of the inclined reinforcement at ith level. z_{1i} and z_{2i} are obtained as

$$z_{1i} = z_i + \frac{(H - z_i)\sin\left(45° - \frac{\varphi}{2}\right)}{\sin\left(45° + \frac{\varphi}{2} + \alpha\right)} \tag{7}$$

$$z_{2i} = z_i + L\sin\alpha \tag{8}$$

The overturning moment, stabilizing moment, modified vertical stress and subsequently the tension developed in the ith layer of reinforcement are obtained for an average depth of reinforcement $\frac{z_i + z_{2i}}{2}$ similar to that for the horizontal reinforcement.

The vertical stress acting on an infinitesimal length 'dx' at a distance x measured along the reinforcement from the facing (Figure 1) is

$$q = \gamma(z_i + x\sin\alpha) + w \tag{9}$$

Stresses normal, q_n, and tangential, q_t, to the alignment of the reinforcement are

$$q_n = (\gamma(z + x\sin\alpha) + w)\cos\alpha \tag{10}$$

$$q_t = (\gamma(z + x\sin\alpha) + w)\sin\alpha \tag{11}$$

Tangential stress, q_t, directly offers resistance against pullout of reinforcement and an additional frictional resistance is mobilized due to increase in normal stress component, q_n. The total pullout resistance mobilized in the resistant zone is

$$T_{imp} = \int_{L-L_{ei\alpha}}^{L} 2(\gamma(z + x\sin\alpha) + w)\cos\alpha\tan\varphi_r\,dx + \int_{L-L_{ei\alpha}}^{L} 2(\gamma(z + x\sin\alpha) + w)\sin\alpha\,dx \tag{12}$$

$$T_{imp} = (\gamma(z_{1i} + z_{2i}) + 2w)\cos\alpha\tan\varphi_r L_{ei\alpha} + ((\gamma(z_{1i} + z_{2i}) + 2w)\sin\alpha L_{ei\alpha} \tag{13}$$

where $L_{ei\alpha}$ is the effective length of inclined reinforcement.

$$L_{ei\alpha} = L - \left[\frac{(H - z_i)\tan\left(45 - \frac{\varphi}{2}\right)}{\cos\alpha} \times \left[1 - \frac{\sin\left(45^\circ - \frac{\varphi}{2}\right)\sin\alpha}{\cos\left(45^\circ - \frac{\varphi}{2} - \alpha\right)} \right] \right] \quad (14)$$

Factor of safety against pullout with inclined reinforcement,

$$F_\alpha = \frac{\sum_{i=1}^{n} T_{iimp}}{\sum_{i=1}^{n} P_{ai}} \quad (15)$$

Results and Discussion

The variations of factors of safety against pullout of horizontal and inclined reinforcement presented in the previous section are evaluated for range of parameters. The analysis is carried out for 6 m high wall with length of reinforcement, ranging from 0.5H to 0.8H. Unit weights of reinforced and retained fill are 18 kN/m^3. Angle of shearing resistance for both fills assumed to be equal is varied from 25° to 40°. Number of reinforcement layers ranged from 4 to 8 and the interface friction angle varied from $\varphi/3$ to φ. Intensity of surcharge ranged from 0 to 20 kPa. The rupture strength of reinforcement and connection strength are assumed sufficiently high such that the only possible mode of failure is pullout of reinforcement. Inclination of reinforcement α varied from 0 to 10°. Factors of safety for tie-back wedge and coherent gravity methods are also determined and compared.

The factor of safety, F_α, increases from 5.06 to 7.25 with increase in inclination of reinforcement from 0 to 10° for a length of reinforcement of 0.6H (Figure 2). The increase of factor of safety is due to increase of overburden stress on the reinforcement in the resistant or passive zone. The factor of safety, F_α, increases from 4.22 to 10.06, a 250% increase, with increase in length of reinforcement from 0.5H to 0.8H for an inclination of reinforcement of 5°. The increase in length of reinforcement increases the effective length of reinforcement in the resistant zone and thereby provides higher anchorage against pullout of reinforcement.

The increase of angle of shearing resistance of reinforced fill limits the extension of failure wedge into the backfill and reduces the lateral stresses to be resisted in the reinforced fill. The factor of safety, $F\alpha$ increases linearly from 5.70 to 7.89, i.e., by about 1.4 times, with increase in inclination of reinforcement, α from 0° to 10° for a friction angle of backfill, φ = 30°. The use of inclined reinforcement in a dense granular backfill offers a higher frictional restraint against pullout compared to horizontal reinforcement. Therefore the factor of safety, F_α increases from 5.09 to 12.21, a 240% increase, with increase in angle of shearing resistance of reinforced fill/backfill, φ, from 25° to 40° for an inclination of reinforcement, α = 5° (Figure 3).

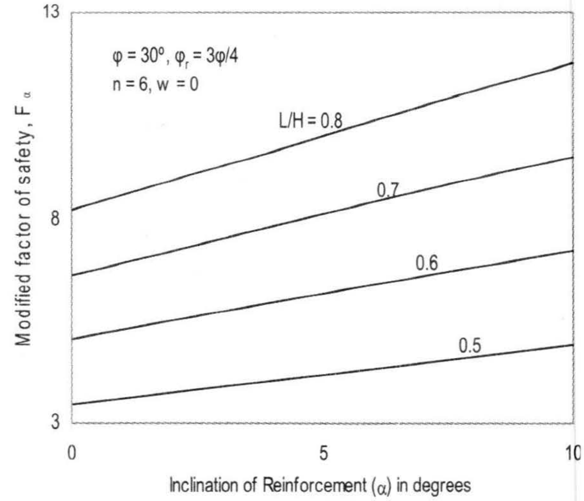

Fig.2 Variation of F_α with α - Effect of L/H

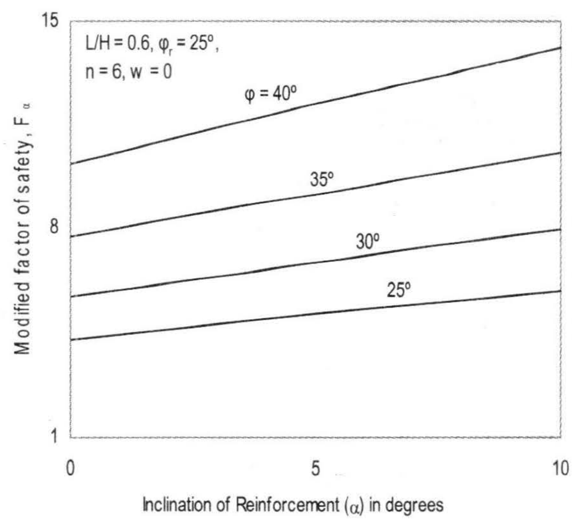

Fig.3 Variation of F_α with α - Effect of φ

The factor of safety, F_α increases linearly from 5.06 to 7.25, an increase of 1.43 times, with increase in inclination of reinforcement, α from 0 to 10° for six layers of reinforcement (Figure 4). The increase of number of reinforcement layers or decrease of spacing between the layers reduces the tension developed in each layer. Therefore, the factor of safety, F_α increases from 4.11 to 8.26 with increase in number of reinforcement layers, n from 4 to 8 for an inclination of reinforcement, α = 5°. The downward inclination of reinforcement induces higher normal stresses compared with those with horizontally arranged reinforcement. Increase in number of such inclined reinforcement layers improves the overall pullout resistance much more significantly. Hence, the rate of improvement of factor of safety, F_α, with inclination of reinforcement increases with increasing number of reinforcement layers from 4 to 8.

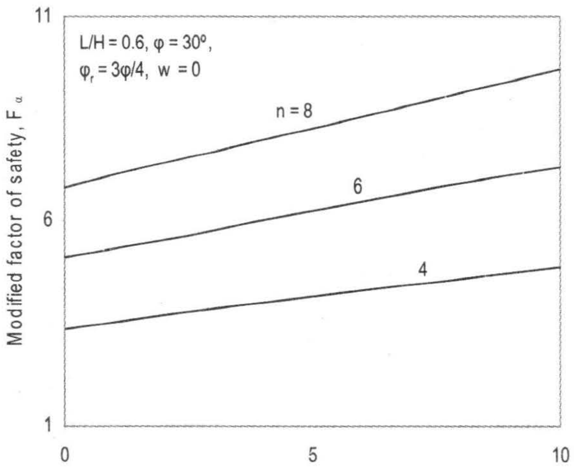

Fig.4 Variation of F_α with α - Effect of n

The effect of inclination of reinforcement is to mobilize higher frictional resistance and mobilize passive resistance against pullout. Consequently, the factor of safety, F_α increases from 4.45 to 6.63 with increase in inclination of reinforcement,α from 0 to 10° for an interface friction angle, φ_r = $2\varphi/3$. The response of inclined reinforcement to axial/horizontal pullout significantly depends on the soil - reinforcement interface friction angle. An increase in the roughness of geotextile sheet and a combination of surface roughness and bearing resistance in the case of geogrid improve the pullout resistance. Hence factor of safety, F_α, increases from 3.25 to 8.20 with increase of interface friction angle, φ_r from $\varphi/3$ to φ for 5° inclination of reinforcement (Figure 5). Interestingly, the rate of improvement of factor of safety with inclination of reinforcement is nearly constant (three lines are mutually parallel) with increase of interface friction angle, φ_r from $\varphi/3$ to φ.

The magnitude of surcharge pressure acting on the backfill affects the tensile force developed in the reinforcement (Figure 6). The factor of safety, F_α increases from 4.71 to 6.76 with increase of inclination of reinforcement from 0 to 10° at a surcharge pressure, w = 10 kN/m². The factor of safety decreases from 6.19 to 5.46 with increase in surcharge from 0 to 20 kN/m² for an inclination of reinforcement, α = 5°. The rate of improvement of modified factor of safety with increasing inclination of reinforcement is constant for surcharge pressure ranging from 0 to 20 kN/m².

The coherent gravity method assumes that at-rest pressure conditions prevail over the top half of the wall against active earth pressures in tie back wedge method. Thus large tensions develop in reinforcement based on coherent gravity method than tie back wedge method. Hence the factor of safety increases from 5.07 to 7.25 and 3.40 to 4.73 for tie back wedge method and coherent gravity method with increase in inclination of reinforcement, α from 0 to 10° respectively (Figure 7). The rate of improvement of factor of safety with increasing inclination of reinforcement is relatively higher for the tie-back wedge method compared to coherent gravity method.

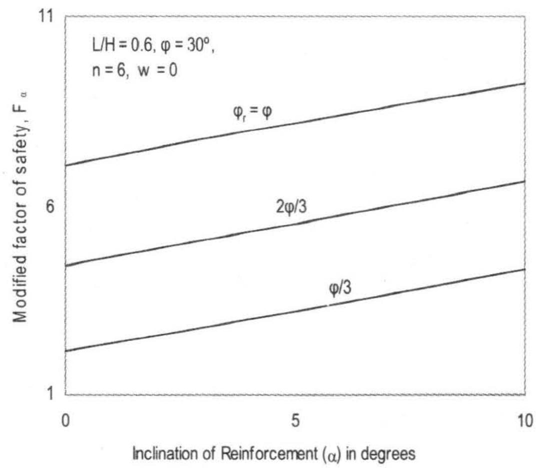

Fig.5 Variation of F_α with α - Effect of φ_r

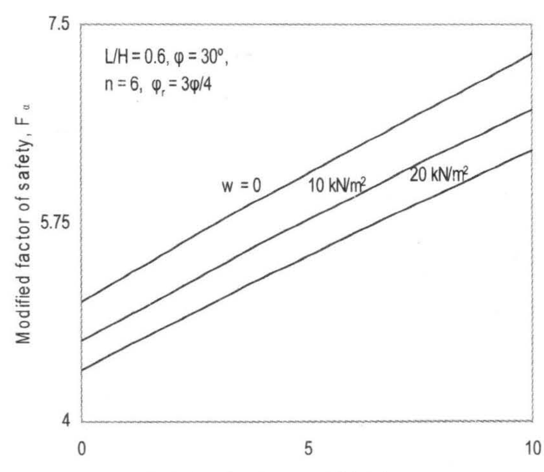

Fig.6 Variation of F_α with α - Effect of w

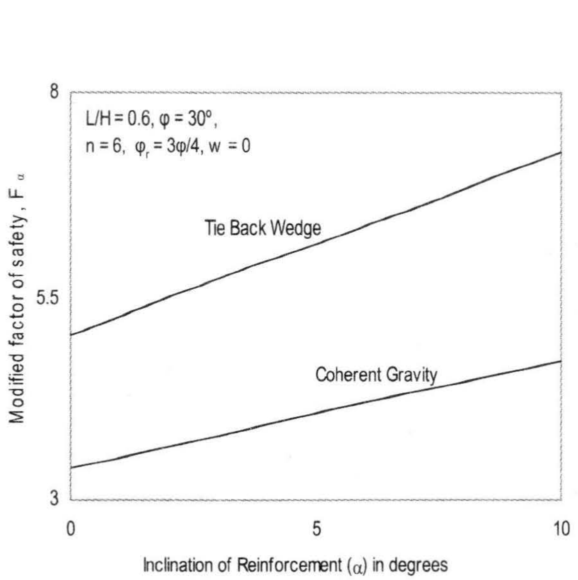

Fig.7 Variation of F_α with α - Effect of failure mechanisms

Conclusions

The improvement of factor of safety of inclined reinforcement compared with that for horizontal reinforcement increases linearly by 12%, 23% and 45% for inclinations of reinforcement of 2.5, 5 and 10° respectively for average parameters considered in the analysis. This increase in the factor of safety is due to higher pullout resistance of inclined reinforcement due to a combination of additional shear resistance mobilized and the increase of normal stress exerted on the reinforcement. The use of inclined reinforcement reduces the length and number of required reinforcement layers and/or permits use of backfills with smaller friction angle and lower soil - reinforcement interface friction angle.

The factor of safety for a given inclination of reinforcement increases markedly with length of reinforcement, angle of shearing resistance of backfill, number of reinforcement layers and interface friction angle. The factor of safety decreases with increase in the surcharge pressure but still remains higher than that for horizontal reinforcement. Hence the use of inclined reinforcement is advantageous over horizontal reinforcement for structures with higher surcharge pressures. The factor of safety obtained for tie-back wedge method is higher compared to that for coherent gravity method. A typical design of reinforced earth wall is illustrated to quantify the significance of inclined reinforcement. The use of reinforcement at a marginal downward inclination to the horizontal is advocated for improved internal stability of reinforced soil walls.

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