An updated discretization technique to evaluate oblique pullout capacity of inextensible reinforcement

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ABSTRACT: Reinforced soil structures such as reinforced soil walls, embankments and slopes being safe, economical, aesthetic and rapid in constructions are gaining popularity. However understanding of actual behavior of these structures at failure still remains unsettled. Present work deals with the internal stability of reinforced soil structures due to pullout of inextensible sheet reinforcement. Kinematics of failure is such that the failure surface intersects the reinforcement obliquely thus causing an oblique pullout of the reinforcement. On the other hand conventional methods of analysis considers only axial pullout of the reinforcement and do not consider complex reinforcement-soil interaction. In this paper, a novel approach is presented for a rational analysis of inextensible sheet reinforcement subjected to an oblique pullout force assuming a linear subgrade response and inextensible sheet reinforcement after taking proper soil-reinforcement interaction into account. An updated discretization technique is used to determine the actual pullout capacity for large end displacement and pullout angle. A new factor, length correction factor is introduced in the present analysis. The effect of this factor on the pullout capacity, mobilized maximum tension in the reinforcement and its direction is studied. A significant effect is observed for high values of obliquity and end displacement. Present analysis thus gives a more realistic analysis of the pullout of inextensible sheet reinforcement subjected to high end displacement and obliquity which in turn leads to a more rational design methodology of the reinforced soil structures.

INTRODUCTION

Reinforced soil structures such as reinforced soil walls and embankments are gaining popularity as sustainable alternatives to the conventional concrete retaining structures since, the design of these structures involves optimization of materials (recycle and reuse), energy efficiency (lowering carbon foot print and environment impact), and minimization of long term cost. However, stability of these structures is very important and depends on kinematics of failures which suggests that the failure surface intersects the reinforcement obliquely thus causing an oblique pullout of the reinforcement (Fig. 1). But, conventional methods of stability analyses consider only axial direction of the pullout force and do not consider kinematics of failure and complex soil-reinforcement interaction. Consequently, these methods fail to adequately predict the behavior of reinforced soil wall at pullout and gives highly conservative estimation of factor of safety.

The effect of kinematics of failure in the internal stability analysis of reinforced soil wall was first studied by Madhav and Umashankar (2004). The analysis is valid only for small end displacement because, overall equilibrium of forces was not applied to the final deformed shape of the reinforcement. Shahu (2007) presented a Winkler's based model for the pullout analysis considering the oblique end force. The model suffers from the inherent drawbacks of Winkler spring based model wherein the displacements occur only under the loaded area. Patra and Shahu (2012) presented a rational analysis for inextensible reinforcement resting on linear elastic Pasternak subgrade and subjected to oblique end force. However, the analysis does not consider the actual deformed length of the reinforcement and the horizontal displacement associated with the transverse component of oblique displacement. Thus, the analysis resulted in incorrect prediction of the pullout capacity of reinforcement especially for high obliquity and large end displacement.

In this paper, a novel approach is presented for a rational analysis of inextensible sheet reinforcement subjected to an oblique pullout force assuming a linear subgrade response and inextensible sheet reinforcement after taking proper soil-reinforcement interaction into account. An updated discretization technique is used to determine the actual deformed length of the reinforcement and pullout capacity of the reinforcement. A new factor, length correction factor is introduced in the present analysis. The effect of this factor on the pullout behavior of the reinforcement is also studied.

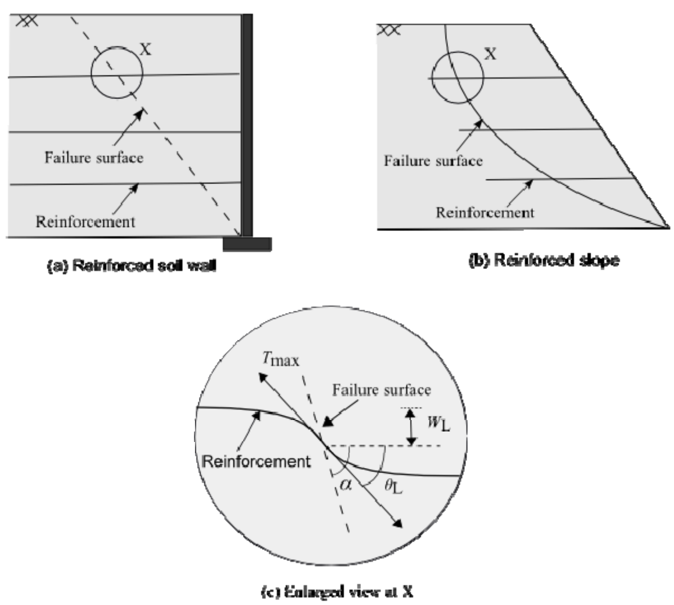


FIG. 1. Reinforced soil structures and kinematics of failure.

PULLOUT ANALYSIS AND UPDATED DISCRETIZATION

Problem Definition

An inextensible sheet reinforcement of length L embedded at depth D is resting on a linear elastic Pasternak subgrade having Winkler spring constant k_s and shear parameter G (Fig. 2b). The reinforcement is subjected to an oblique pullout force P at a point B with an obliquity α. Under the action of the oblique pullout force P maximum tension T_{max} is generated in the reinforcement at the point B and the reinforcement makes an angle θ_L with the horizontal (Fig. 2b). Normal and shear stresses at the top and at the bottom of the reinforcement are q, f_1 and p, f_2 respectively.

An updated discretization technique is adopted in the analysis to account the exact deformed shape of the reinforcement. In the earlier analysis (Shahu 2007; and Patra and Shahu 2012), the discretized length was assumed to be constant and equal to the initial length L of the reinforcement (Fig. 2). However, for large deformation, as the reinforcement undergoes transverse displacement, the horizontal projected length changes. Thus, the discretization is done over the updated horizontal projected length $L_H (= \int dx)$ of the reinforcement for each iteration (Fig. 2c).

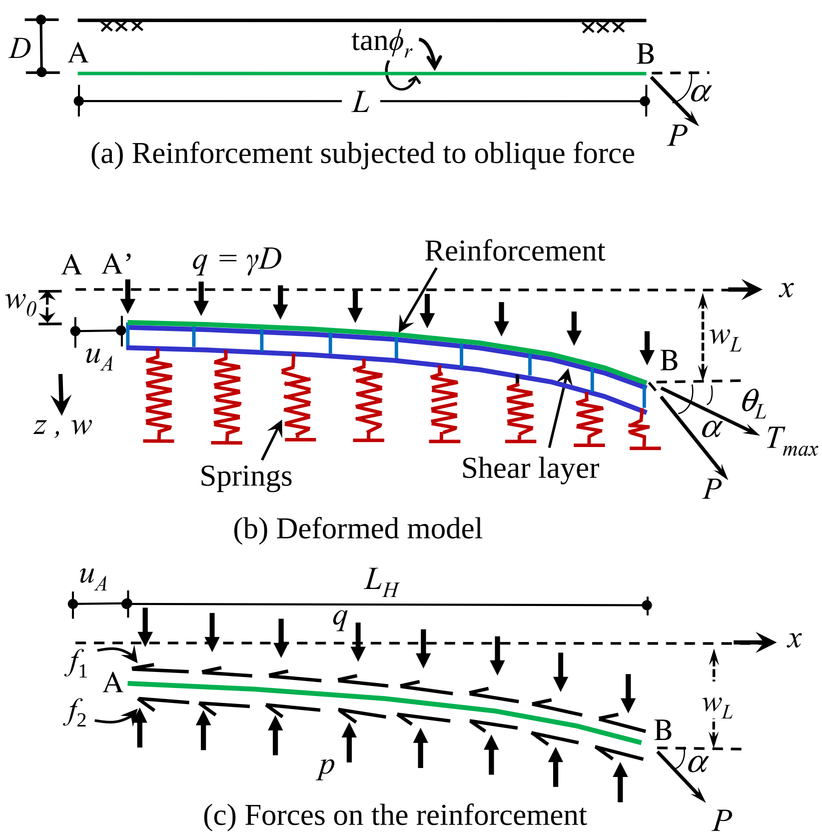


FIG. 2. Schematic of the model used.

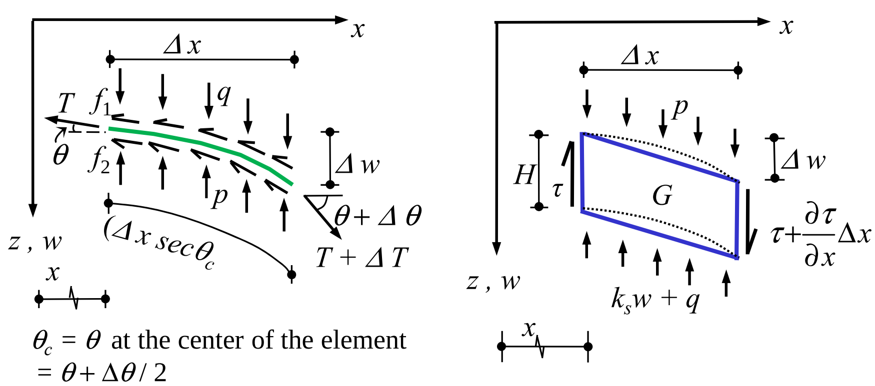
Formulations

An infinitesimal reinforcement element of horizontal length dx and unit width is considered in Fig 3(a). The reinforcement tensions and inclinations at horizontal distances x and ($x+\Delta x$) are T and θ, and ($T+\Delta T$) and ($\theta+\Delta\theta$), respectively. Applying vertical and horizontal force equilibrium to the deformed shape of the reinforcement element and using basic governing equation for Pasternak subgrade (Fig. 3b), and then nondimensionalizing and discretizing, and finally simplifying, one gets (Patra and Shahu 2012)

$$T_{i+1}^{*}=T_{i}^{*}+\frac{0.5}{n}\left[\left\{\mu W_i W_L - n^2 G^{*} W_L \left(W_{i+1}-2W_i+W_{i-1}\right)\right\}\left(\frac{\tan\theta_i}{\tan\phi_r}+1\right)+2\right] \quad (1)$$

$$W_i=\frac{n^2\left(W_{i+1}+W_{i-1}\right)\left(2T_i^{*}\tan\phi_r\cos^2\theta_i+G^{*}\right)}{\mu+2n^2\left(2T_i^{*}\tan\phi_r\cos^2\theta_i+G^{*}\right)} \quad (2)$$

where $\mu = k_s L/\gamma D$ = subgrade stiffness factor; $G^{*} = GH/\gamma DL$ = shear stiffness factor; $W_L = w_L/L$ = normalized end displacement, = w/w_L, $T^{*} = T/T_{HP}$ where T_{HP} = $2\gamma D\, L\, \tan\phi_r$ is the axial pullout capacity of the reinforcement, $X = x/L$ and i is the number of elements into which the reinforcement sheet is divided (i.e., $\Delta X = L_H^{*}/n$, where $L_H^{*} = L_H/L$, length correction factor).



(a) Reinforcement element (b) Pasternak layer element

FIG. 3. Stresses on infinitesimal elements (Patra and Shahu 2012).

The assumed boundary conditions are:

at $X = 0$, $\frac{dW}{dX} = 0$ and $T^* = 0$; and at $X = L_H^*$, $W = 1$. (3)

Considering the overall equilibrium of forces on the deformed reinforcement and after nondimensionalizing, discretizing and simplifying, one gets (Patra and Shahu 2012)

$$\tan\alpha = \frac{\left[\frac{1}{\tan\phi_r}\sum_{i=1}^{n}\frac{\mu W_i W_L}{\cos\theta_{ci}} + \sum_{i=1}^{n}\left\{\mu W_i W_L + 2 - n^2 G^* W_L\left(W_{i+1} - 2W_i + W_{i-1}\right)\right\}\sin\theta_{ci}\right]}{\sum_{i=1}^{n}\left[\left\{\mu W_i W_L + 2 - n^2 G^* W_L\left(W_{i+1} - 2W_i + W_{i-1}\right)\right\}\cos\theta_{ci}\right]} \tag{4}$$

$$P^* = \frac{1}{2n\cos\alpha}\sum_{i=1}^{n}\left[\left\{\mu W_i W_L + 2 - n^2 G^* W_L\left(W_{i+1} - 2W_i + W_{i-1}\right)\right\}\cos\theta_{ci}\right] \tag{5}$$

where $P^* = P/T_{HP}$, $\theta_{ci} = \tan^{-1}\left[nW_L\left(W_{i+1} - W_i\right)\right]$ = value of θ_c for element i; and $\theta_i = \left(\theta_{ci} + \theta_{ci-1}\right)/2$

Solutions and Range of parameters

Solving Eqs. (1) and (2) in conjunction with the boundary condition (Eq. 3) and overall equilibrium equations (Eqs. 4 and 5) W_i and T_i^* at any node i, are obtained. A trial and error procedure is adopted for the solution. For each successive iteration, the discretization is redone with respect to the new projected length $L_{H,\ new}$ till $L_{H,\ new}$ is equal to L_H, where $L_{H,\ new}$ is given as

$$L_H, new = L L_H \Big/ \sum \frac{L_H^*}{N}\sec\theta_{ci} \tag{6}$$

Based on the practical consideration following ranges of parameters are considered for the analyses: μ = 50-1000 and G^* = 0-50, interface frictional angle ϕ_r = 20-40^o (Patra and Shahu 2012).

Results and Discussions

A detailed parametric study has been carried out to study the effect of various parameters such as subgrade shear stiffness factor G^*, subgrade normal stiffness factor μ, interface frictional resistance ϕ_r and obliquity α on the pullout response of the reinforcement. The effect of length correction factor on the pullout capacity is also quantified.

Fig. 4 shows that with the increase in shear stiffness G^*, the pullout capacity reduces. However, as subgrade stiffness μ and interface frictional resistance ϕ_r increases, the pullout capacity increases. The effect of length correction is found to be predominant for lower G^* and μ, and higher ϕ_r and α.

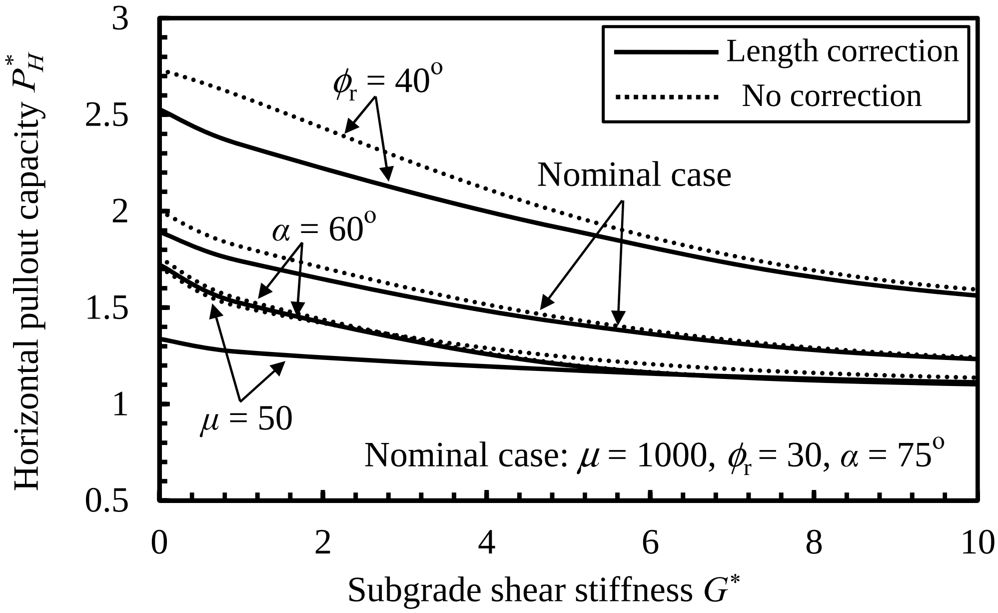


FIG. 4. P_H^* versus G^* – effect of μ and length correction.

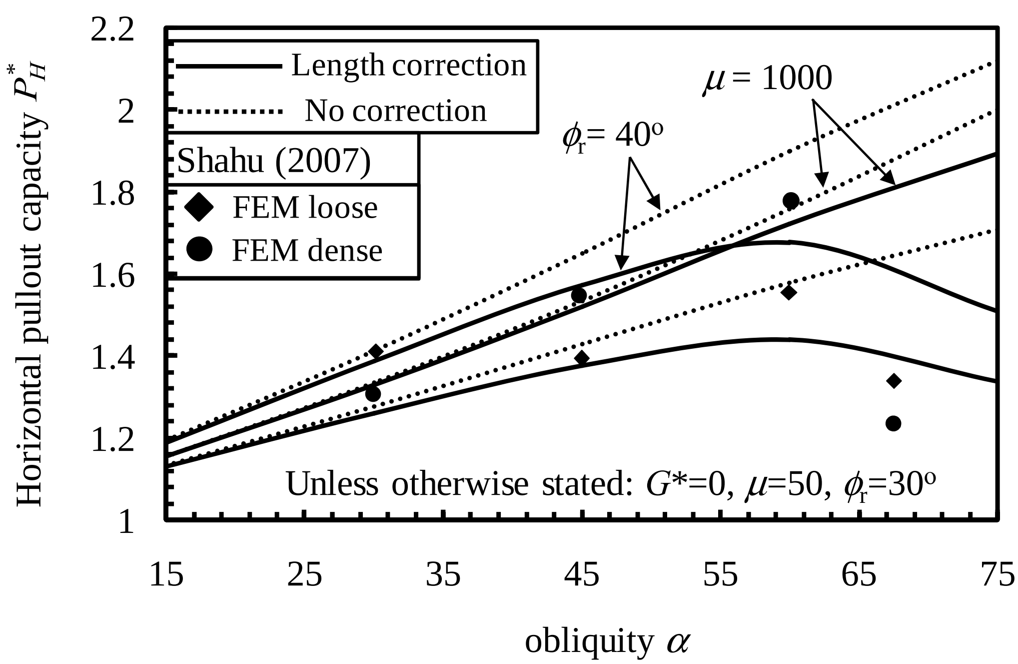


FIG. 5. P_H^* versus α – effect of μ and length correction.

Fig. 5 shows that as the obliquity α increases, pullout capacity increases. However, after a particular value of obliquity α (> 60^{o}) the pullout capacity again reduces which is also evident from the finite element analysis results (Shahu 2007). But, earlier analysis (Shahu 2007; and Patra and Shahu 2012) has failed to capture this behavior as it did not incorporate the length correction thus the pullout capacity increases even for $\alpha > 60^{o}$. It can be explained as follows: as the angle of obliquity increases, the reinforcement deforms more transversely and eventually the increase in pullout capacity due to the increase in interface shear stresses is surpassed by the decrease in pullout capacity due to the reduction in horizontal projected length of the reinforcement.

CONCLUSIONS

In this paper, a novel approach is presented for the stability analysis of sustainable retaining structures such as reinforced soil walls and embankments by considering an inextensible sheet reinforcement resting on linear elastic Pasternak subgrade and subjected to oblique pullout force. An updated discretization technique is used to determine the pullout capacity of the reinforcement more accurately. A new factor, length correction factor is introduced and its effect on the pullout capacity is studied. The analysis shows a significant effect of the length correction factor on the pullout response particularly for high values of obliquity and end displacement. Thus, the present analysis gives a more realistic prediction of the pullout capacity which ultimately leads to the sustainable design of retaining structures.

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