EFFECT OF NONLINEAR SUBGRADE RESPONSE FACTOR ON OBLIQUE PULLOUT CAPACITY

Shantanu Patra ¹, J.T. Shahu ²

ABSTRACT

One of the major factors behind the popularity of geosynthetics reinforced earth retaining structures is that it can accommodate large deformation before failure. At large deformation the subgrade soil generally exhibits a nonlinear behaviour. In this paper, an analysis is presented for the evaluation of pullout capacity of an inextensible sheet reinforcement resting on nonlinear Pasternak subgrade and subjected to oblique pull. Two new factors namely, nonlinear subgrade response factor in shear and nonlinear subgrade response factor in vertical compression are introduced in the analysis and their effect on the pullout responses are studied. The reinforcement is assumed as inextensible rough membrane whereas a hyperbolic stress-strain relationship is assumed for the subgrade. The present study removes the drawback of the earlier oblique pullout model based on Winkler’s spring by considering the shear interaction between the neighbouring spring elements and gives more accurate prediction of end displacement, mobilized tension and its direction.

Keywords: Geosynthetics, reinforced soil structures, Pasternak model, Nonlinear subgrade, Oblique Pullout response, Finite difference method.

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ABSTRACT: One of the major factors behind the popularity of geosynthetics reinforced earth retaining structures is that it can accommodate large deformation before failure. At large deformation the subgrade soil generally exhibits a nonlinear behaviour. In this paper, an analysis is presented for the evaluation of pullout capacity of an inextensible sheet reinforcement resting on nonlinear Pasternak subgrade and subjected to oblique pull. Two new factors namely, nonlinear subgrade response factor in shear and nonlinear subgrade response factor in vertical compression are introduced in the analysis and their effect on the pullout responses are studied. The reinforcement is assumed as inextensible rough membrane whereas a hyperbolic stress-strain relationship is assumed for the subgrade. The present study removes the drawback of the earlier oblique pullout model based on Winkler’s spring by considering the shear interaction between the neighbouring spring elements and gives more accurate prediction of end displacement, mobilized tension and its direction.

INTRODUCTION

Geosynthetics reinforced earth retaining structures (Figs. 1a-b) has gained popularity over the last few decades for their ability to accommodate large deformation before failure as in the case of earthquake loading. At large deformation, the subgrade soil exhibits a nonlinear behaviour [1].

Kinematics of failure is another important aspect concerning the internal stability of reinforced soil structures [2] where the failure surface intersects the reinforcement obliquely thus causes an oblique pullout of the reinforcement (Figs. 1a-c).

Conventional methods, however, are empirical in nature and do not consider kinematics of failure, nonlinear response of the subgrade and proper soil-reinforcement interface behaviour thus gives a higher values of the factor of safety in the internal design [3].

To study the actual soil-reinforcement interface behaviour, the effect of a known value of the transverse end displacement was investigated first by Madhav & Umashankar [4]. Since the analysis does not consider the final deformed shape of the reinforcement, it is valid only for small end displacement [5]. However, a major limitation of these models lies in the assumption of the Winkler subgrade. Consequently, these analysis results in unrealistically high values of the pullout force and the end displacement, especially for weaker subgrade and higher obliquity of the pullout force.

The above shortcomings become possible to remove, by the assumption of the shear stiffness in the pullout analysis [6]. However, the analysis does not consider the nonlinearity exists in the actual soil-reinforcement behavior thus, is valid only for small end displacement and low angle of obliquity [6].

In this paper, an analysis is presented for the evaluation of pullout capacity of an inextensible sheet reinforcement resting on nonlinear Pasternak subgrade and subjected to an oblique pull. Two new factors namely, nonlinear subgrade response factor in shear and nonlinear subgrade response factor in vertical compression are introduced in the analysis and their effect on the pullout responses
are studied. The present study gives a better prediction of pullout response in terms of end displacement and horizontal pullout capacity.

FORMULATION AND MODEL CHARACTERISTICS

Problem definition
An inextensible sheet reinforcement of unit length is resting on a subgrade soil (Fig. 2a). The subgrade is having a normal stiffness factor \( \mu = k_s L / \gamma D \), shear stiffness factor \( G^* = GH / \gamma DL \), nonlinear subgrade response factor in vertical compression \( \beta = k_s L / q_{ult} \); and nonlinear subgrade response factor in shear \( \xi = G / \tau_{ult} \). The reinforcement is subjected to an oblique pullout force \( P \) at point B where the sliding mass intersects the reinforcement obliquely (see Figs. 1a-d). For the analysis, a nonlinear hyperbolic stress-deformation response [7] is assumed for the subgrade where a rigid plastic behavior is considered for the soil-reinforcement interface.

Governing Equations
Applying vertical and horizontal force equilibrium to the final deformed shape of an infinite reinforcement element [1,6] and after discretization, one gets the basic governing equations Eqs. 1 and 2 [7], where \( W_i \) and \( T_i^* \) are normalized displacement and reinforcement tension at node \( i \); respectively; and \( n \) is the number of elements into which the reinforcement strip is divided (i.e., \( \Delta X = 1 / n \)).

Non-dimensional parameters are obtained as follows: \( X = x / L \), \( W = w / w_L \), \( W_L = w_L / L \), \( P^* = P / T_{HP} \), \( T^* = T / T_{HP} \), \( P_{HP}^* = P_{HP} / T_{HP} \), \( T_{HP} = 2 \gamma DL \tan \phi_t \) = axial pullout capacity of the reinforcement and \( W_L = w_L / L = \) normalized end displacement.

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![Diagram](image-url)

**Fig. 1** Kinematics of failure of reinforced structures

**Fig. 2** Schematic of the proposed model
Where, the boundary conditions is

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

Applying overall equilibrium of external forces one gets (refer [7])

\[
\tan \alpha = \frac{\sum_{i=1}^{n} \left( \frac{\mu W_i L W_i}{1 + \beta W L W_i} \right) \sec \theta_{ci} + \tan \theta_{ci} \tan \phi_r}{\sum_{i=1}^{n} \left( \frac{\mu W_i L W_i}{1 + \beta W L W_i} \right) \sin \theta_{ci} \tan \phi_r}
\]
where \( \theta_i = (\theta_{ci} + \theta_{ci-1})/2 \). The horizontal pullout capacity \( P_H^* \) is then evaluated as \( P_H^* = P^* \cos \alpha \).

**Solution and range of parameters**

Eqs. 1 and 2 are solved in conjunction with the boundary conditions (Eq. 3) and overall equilibrium equations (Eqs. 4 and 5) to obtain \( W_i \) and \( \tau_i^* \) at all nodes. A trial and error procedure is adopted for the solution [6]. Ranges of parameters used for the analyses are shown in Table 1.

**Table 1 Ranges of parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G^* )</td>
<td>0 – 1000</td>
</tr>
<tr>
<td>( \mu )</td>
<td>500 – 5000</td>
</tr>
<tr>
<td>( \xi )</td>
<td>0 – 1000</td>
</tr>
<tr>
<td>( \beta )</td>
<td>0 – 1000</td>
</tr>
<tr>
<td>( \phi )</td>
<td>15 – 45</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>0 – 85</td>
</tr>
</tbody>
</table>

Note: parameters are non-dimensional

**RESULTS**

**Effect of nonlinear subgrade response factor in shear \( \xi \)**

Fig. 3 shows that as the nonlinear subgrade response factor in shear \( \xi \) increases, the horizontal component of the pullout force \( P_H^* \) increases. For a smaller value of \( \xi \) (<20), the increase in \( P_H^* \) is very sharp however after a particular value of \( \xi \) (>20) the increase is almost negligible.

As the pullout force increases (Fig. 3) with \( \xi \), the end displacement \( W_L \) also increases as shown in Fig. 4. Thus, end displacement \( W_L \) may become very high and exceed the allowable limit. For all practical applications, therefore, the allowable end-displacement should be the guiding factor in determining the design pullout capacity.

**Effect of nonlinear subgrade response factor in vertical compression \( \beta \)**

Fig. 5 shows that as nonlinear subgrade response factor in vertical compression \( \beta \) increases, the horizontal component of the pullout force \( P_H^* \)
As the pullout force decreases (Fig. 6) with $\beta$, the end displacement $W_L$ also decreases as shown in Fig. 6.

The effect of obliquity $\alpha$ and angle of interface friction $\phi_r$ on the pullout response is such as $\alpha$ and $\phi_r$ increases horizontal component of pullout capacity $P_H^*$ and end-displacement $W_L$ increases (Figs. 3-6).

CONCLUSIONS

This paper presents a mechanistic model for the analysis of an inextensible sheet reinforcement, resting on a nonlinear Pasternak subgrade and subject to an oblique pullout force. The analysis considers a non-linear hyperbolic stress-strain relationship for the subgrade soil, and the obliquity of the pullout force. Following conclusions are drawn:

1. As nonlinear subgrade response factor in shear $\xi$ increases, the horizontal component of the pullout force $P_H^*$ increases.
2. As nonlinear subgrade response factor in vertical compression $\mu$ increases, the horizontal component of the pullout force $P_H^*$ decreases.
3. For higher $\xi$, end displacement $W_L$ also become higher and may exceed the allowable limit. Thus, for all practical applications, the allowable end-displacement should be the guiding factor in determining the design pullout capacity for weaker subgrade.
4. As nonlinear subgrade response factor in vertical compression $\mu$ increases, the horizontal component of the pullout force $P_H^*$ decreases. As the pullout force decreases, the end displacement $W_L$ also decreases.
5. The present study removes the drawback of the earlier oblique pullout model based on Winkler’s spring by considering the shear interaction between the neighbouring spring elements and gives more accurate prediction of end displacement $W_L$, and horizontal component of the pullout force $P_H^*$.

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