Pseudo-static Seismic Stability of Basal Reinforced Embankment with Oblique Pull

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ABSTRACT
Seismic stability of embankments on soft soils has been addressed by many researchers in the past with approximation for pseudo-static condition with and without reinforcement but based on consideration of axial pull in the reinforcement. The kinematics of deformation of typical failure of reinforced embankment dictates oblique pull in the reinforcement due to sliding mass. This oblique pull mobilizes additional normal stresses resulting in higher shear resistance and addition normal force than mobilized with consideration of axial pull only. This paper analyses seismic stability with oblique pull for a basal reinforced embankment on non-homogeneous soft soil based on pseudo-static approach. Results indicate that the stability of the embankment is underestimated in the conventional approach that uses axial pull.

1. INTRODUCTION
Stability is a concern for embankments on soft ground because of the low strength of the foundation soil. A layer of geosynthetics material extending for the full width of the embankment is provided in basal reinforced embankments at the interface of the embankment and ground. The basal reinforcement resists some or all of the destabilizing forces and restricts the lateral deformations of the foundation (Jewell 1988).

Stability of Geosynthetic - Reinforced Embankment on Non-homogeneous Soils
Limit equilibrium methods developed have been used to assess short term (undrained) stability of reinforced embankments constructed on soft foundations. Geometry of embankment and thickness of soft soil, drainage conditions, rate of construction of embankment, strain in and tensile strength of reinforcement, type of soil, etc. influence the stability of the embankment (Rowe et al. 2005).

Seismic Stability of Embankments
Pseudo-static and pseudo-dynamic analyses are commonly adopted for analyzing stability of embankments under seismic conditions. In pseudo-static analysis the earthquake induced forces (inertia forces) are represented by a constant horizontal/vertical force equal to the weight of the potential sliding mass multiplied by a non-dimensional seismic coefficients, $k_h$ and $k_v$ (Ling et al. 1997). Pseudo-dynamic analysis is carried out considering the phase difference in shear and primary waves (Nimbalkar et al. 2006). These studies are limited to internal stability without considering displacement and reduction of soil strength.

2. KINEMATICS OF REINFORCEMENT-BACKFILL RESPONSE -OBLIQUE PULL
Kinematics of deformation (Fig. 1) dictates typical failure of reinforced soil structures. At failure of soil mass the reinforcement is subjected to pull. Almost all the available design methods incorporate only the axial pullout mechanism (Fig. 2). However, in actual case at failure reinforcement is subjected oblique pull (Fig. 3). Under the action of oblique force or displacement, the soil beneath the reinforcement mobilizes additional normal stresses as the reinforcement deforms transversely. Madhav and Umashanker (2003, 2005) developed the governing equations for linear and nonlinear sub grade responses. Normalized normal component of tensile force in the reinforcement is computed for normalized free end displacement ratios ranging from 0 to 0.1. The contribution of oblique pull in reinforcement on the stability of geosynthetic reinforced wall is quantified by Narasimha Reddy et al. (2008).
3. PROBLEM STATEMENT AND ANALYSIS

A basal reinforced embankment of height, \( H \), equal to 4.5 m rests on non-homogeneous foundation soil 10 m thick. The non-homogeneity of foundation soil is expressed with its strength increasing with depth, \( z \), as \( c_u(z) = c_u(0)\{1+ \alpha z/H \} \) where \( c_u(z) \), \( c_u(0) \) and \( \alpha \) are the undrained strength at any depth \( z \), undrained strength at the top, and non-homogeneity parameter respectively. Stability of the embankment is computed with reinforcement tensile capacity, ‘T’ available at the fill-foundation soil interface for the full base width. Seismic conditions under different acceleration coefficients are considered. GeoSlope program using Bishop’s method is used to compute the factor of safety and to identify critical slip circle for both unreinforced and reinforced embankment considering only axial force in the reinforcement. Cross-section of the embankment and the ranges of properties considered are given in Figure 4 and Tables 1-5.

### Table 1: Embankment Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top width</td>
<td>20 m</td>
</tr>
<tr>
<td>Bottom width</td>
<td>38 m</td>
</tr>
<tr>
<td>Side slope (1:n)</td>
<td>1:2</td>
</tr>
<tr>
<td>Height of embankment, ( H )</td>
<td>4.5 m</td>
</tr>
</tbody>
</table>

### Table 2: Embankment Fill Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_e )</td>
<td>37°</td>
</tr>
<tr>
<td>Unit weight, ( \gamma_e )</td>
<td>20 kN/m²</td>
</tr>
</tbody>
</table>

### Table 3: Foundation Soil Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness ( H )</td>
<td>10 m</td>
</tr>
<tr>
<td>( c_u(0) )</td>
<td>25 kPa</td>
</tr>
<tr>
<td>Unit weight, ( \gamma )</td>
<td>17 kN/cu.m</td>
</tr>
</tbody>
</table>

Non-homogeneity Parameter, \( \alpha \): 0, 0.5 & 1 kPa/m
Modulus of subgrade reaction, \( K_s \): 5000 kN/m²

### Table 4: Reinforcement Details

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>interface of fill and ground</td>
</tr>
<tr>
<td>Length</td>
<td>entire base</td>
</tr>
<tr>
<td>Tensile capacity(T)</td>
<td>100 kN/m</td>
</tr>
<tr>
<td>Transfer efficiency</td>
<td>100%</td>
</tr>
<tr>
<td>Interface friction, ( \phi_r )</td>
<td>37°</td>
</tr>
</tbody>
</table>

### Table 5: Seismic Coefficients

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal coefficient, ( \alpha_h )</td>
<td>0, 0.05, 0.1, 0.15</td>
</tr>
<tr>
<td>( \alpha_h/\alpha_0 )</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Analysis for Basal Reinforcement - Transverse Pull

As shown in Figure 5, the geosynthetics layer, at the intersection with slip surface, deforms at an oblique angle \( \alpha \) due to kinematics. The vertical component of the force, T,
causes transverse displacement, while the horizontal component is the axial pullout. This vertical component of T, i.e., the normal reaction develops additional normal stresses on the reinforcement.

Fig. 5: Kinematics of Basal Reinforced Embankment

The transverse downward force at the end B (Fig. 6) in the normalized form is (Madhav & Manoj 2003)

\[ P^* = \frac{P}{\gamma D L} = \mu \frac{W_n L}{n} \left[ \frac{W_1}{2} + \frac{1}{n} \sum_{i=2}^{n} W_i \right] \]  

(1)

The horizontal component of maximum tension (i.e., the pullout force) is non-dimensionalised as

Fig. 6: Definition Sketch for Transverse Pull (Madhav and Manoj 2003)

\[ T_{\text{max}} \cos \theta_{n+1} = \frac{T_{n+1} \cos \theta_{n+1}}{2 \gamma D L \tan \phi} = T_{n+1} \cos \theta_{n+1} \]  

(2)

The normalized normal component of maximum tension is

\[ T_{\text{max}} \sin \theta_{n+1} = \frac{T_{n+1} \sin \theta_{n+1}}{\gamma D L} = 2 T_{n+1} \sin \theta_{n+1} \tan \phi \]  

(3)

Computations of Factors of Safety with Transverse Pull (Fig. 7).

For the critical circle in axial pullout case knowing the geometry of slip circle, intersection point of reinforcement with slip surface, effective length of reinforcement, L, transverse force and additional axial force are computed. For various rotations ranging from 0.001rad to 0.01 rad normalized transverse displacements, \( w_o \) and transverse force, \( P \), are computed from the expressions given above. Additional axial force due to \( P \) will be obtained as \( 2P \tan \phi r \) for double shear. Additional resisting moments due to these forces are computed from the lever arm with respect to center. The following are the notations used for different factors of safety along with their computations:

\[ F_{su} \] - Factor of safety for unreinforced embankment.
\[ F_{sc} \] - Factor of safety for reinforced embankment with conventional axial pull.
\[ F_{(Addi. Axial)} \], \( F_{(Addi. Axial+Transverse)} \), \( F_{sAP} \) = \( \frac{(M_R + M_A) + M_P}{M_D} \)

where \( M_R \) = Resisting moment developed with conventional axial pull; \( M_A \) = Resisting moment with addi. Axial force; \( M_P \) = Resisting moment with addi. Axial+Transverse force; and \( M_D \) = Driving moment developed with axial pull.

4. RESULTS AND DISCUSSION

The variations of \( F_{su}, F_{sc}, F_{sA}, \text{ & } F_{sAP} \) with seismic coefficient \( k_h \) are shown in Figures 8 and 9. To quantify the effect of oblique pull over conventional axial pull, ratios, \( R_f \), as defined below are computed and the results shown in Figure 10.

\[ R_{(TT)} = \frac{F_{sc}}{F_{su}}, R_{(TP)} = \frac{F_{sAP}}{F_{sc}}, R_{\text{oblique}} = \frac{F_{sAP}}{F_{su}}, R_f = \frac{F_{sA}}{F_{su}} \]

Fig. 8: \( F_{su} \) variation with \( k_h \) - Effect of Non-homogeneity

Fig. 9: Variation of \( F_{su} \) with \( k_h \) - Effect of Rotation for \( \alpha=0 \)
The variation of factors of safety with the horizontal seismic coefficient is presented in Figures 8 and 9. From Figure 8, it is observed that due to seismic effect, the factor of safety for unreinforced embankment on homogeneous ground decreases from 1.56 to 0.86 and from 1.66 to 0.94 & 1.74 to 1.01 respectively for non-homogeneous ground for $\alpha$ equal to 0.5 and 1.0. The effect of non-homogeneity factor $\alpha$ on $F_s$ is considerable. $F_s$ (unreinforced) increases from 1.563 to 1.73 due to increase of $\alpha$ from 0 to 1.0. Similar trend is observed for reinforced embankment also.

The effect of oblique pull on $F_s$ is evident from Figure 9 for both static and seismic cases. $F_s$ increases significantly with rotation. The increase in $F_s$ with rotation is because of mobilization of larger forces in the reinforcement. For homogeneous soil under static condition $F_{s\alpha}$ increases from 1.671 to 2.19 while $F_{s\alpha A}$ increases from 1.67 to 2.63. Similar trend is observed for increasing $\alpha$ value. Similar trend is observed for seismic condition also.

Figure 10 details the quantification of oblique pull over conventional axial pull. Due to oblique pull $F_s$ increases up to 1.3 to 1.6 times over $F_s$ considering axial pull and 1.07 to 1.7 than that for unreinforced case.

(i) The induced oblique force in reinforcement contributes to increase of $F_s$ over conventional axial pull. An increase of 1.3 to 1.7 times axial pull is observed with oblique pull.

(ii) The effect of seismic coefficient on $F_s$ ratio $R_f$ is almost linear and marginal. The transverse force contribution is significant over additional axial force.

**REFERENCES**


