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Limit Analysis of Reinforced Embankments on Soft Soil: Electronic Annex 1

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Abstract
This document forms the electronic annex to the paper ‘Limit Analysis of Reinforced Embankments on Soft Soil’. It contains graphs that document a comprehensive parametric study into the stability of a reinforced embankment.

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1. Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$c'$</td>
<td>cohesion of the soil of embankment fill</td>
</tr>
<tr>
<td>$\phi'$</td>
<td>friction angle of soil of embankment fill</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>unit weight of soil of embankment fill</td>
</tr>
<tr>
<td>$c_u$</td>
<td>shear strength of soft soil</td>
</tr>
<tr>
<td>$R$</td>
<td>rupture strength of reinforcement per unit width</td>
</tr>
<tr>
<td>$H$</td>
<td>height of embankment</td>
</tr>
<tr>
<td>$D$</td>
<td>thickness of soft soil</td>
</tr>
<tr>
<td>$q$</td>
<td>surcharge</td>
</tr>
<tr>
<td>$n$</td>
<td>side slope gradient ($nH : 1V$)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>interface coefficient between reinforcement and soft soil/embankment fill</td>
</tr>
</tbody>
</table>
2. Design charts plotting $\phi'$ vs $c_u/\gamma H$ for low rupture strength $R/\gamma H^2 = 0.1$

2.1. Without surcharge $q/\gamma H = 0$

The following charts present the relationship between angle of shearing resistance $\phi'$ in the embankment fill required to prevent failure as a function of the normalised undrained shear strength of the soft soil $c_u/\gamma H$ for various values of $c'/\gamma H$, $H/D$, $n$. These charts relate to a reinforcement strength $R/\gamma H^2 = 0.1$ and a zero surcharge condition. Collapse is independent of the values of interface friction coefficient $\alpha$ studied (0.6, 0.8, 1.0).
Figure 1: Required soil properties for embankment without surcharge and low rupture strength reinforcement, \( n=2 \) (Note: Dash line part of the graph is unstable with \( c' = 0 \).)
Figure 2: Required soil properties for embankment without surcharge and low rupture strength reinforcement, \( n = 3 \).
Figure 3: Required soil properties for embankment without surcharge and low rupture strength reinforcement, \( n=4 \).
2.2 With surcharge $q/\gamma H = 0.1$

The following charts present the relationship between angle of shearing resistance $\phi'$ in the embankment fill required to prevent failure as a function of the normalised undrained shear strength of the soft soil $c_u/\gamma H$ for various values of $c'/\gamma H$, $H/D$, $n$. These charts relate to a reinforcement strength $R/\gamma H^2 = 0.1$ and a surcharge condition $q/\gamma H = 0.1$. Collapse is independent of the values of interface friction coefficient $\alpha$ studied (0.6, 0.8, 1.0).
Figure 4: Required soil properties for embankment with surcharge and low rupture strength reinforcement, $n=2$. 

$H/D=0.5, \ 1V:2H, q/\gamma H=0.1, R/\gamma H^2=0.1$

$H/D=1.0, \ 1V:2H, q/\gamma H=0.1, R/\gamma H^2=0.1$

$H/D=1.5, \ 1V:2H, q/\gamma H=0.1, R/\gamma H^2=0.1$
Figure 5: Required soil properties for embankment with surcharge and low rupture strength reinforcement, $n=3$. 
Figure 6: Required soil properties for embankment with surcharge and low rupture strength reinforcement, $n=4$. 

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3. Design charts plotting $\phi'$ vs $c_u/\gamma H$ for high rupture strength $R/\gamma H^2 = 1.0$

3.1. Without surcharge $q/\gamma H = 0$

The following charts present the relationship between angle of shearing resistance $\phi'$ in the embankment fill required to prevent failure as a function of the normalised undrained shear strength of the soft soil $c_u/\gamma H$ for various values of $c'/\gamma H$, $H/D$, $n$ and $\alpha$. These charts relate to a reinforcement strength $R/\gamma H^2 = 1.0$ and to a zero surcharge condition.
Figure 7: Required soil properties for embankment without surcharge and high rupture strength reinforcement, $n=2$, $H/D=0.5$ (Note: Dash line part of the graph is unstable with $c'=0$).
Figure 8: Required soil properties for embankment without surcharge and high rupture strength reinforcement, $n = 2$, $H/D = 1.0$ (Note: Dash line part of the graph is unstable with $c' = 0$).
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Figure 15: Required soil properties for embankment without surcharge and high rupture strength reinforcement $n=4$, $H/D=1.5$. 
3.2 With surcharge \( q/\gamma H = 0.1 \)

The following charts present the relationship between angle of shearing resistance \( \phi' \) in the embankment fill required to prevent failure as a function of the normalised undrained shear strength of the soft soil \( c_u/\gamma H \) for various values of \( c'/\gamma H, H/D, n \) and \( \alpha \). These charts relate to a reinforcement strength \( R/\gamma H^2 = 1.0 \) and a surcharge condition \( q/\gamma H = 0.1 \).
Figure 16: Required soil properties for embankment with surcharge and high rupture strength reinforcement $n=2$, $H/D=0.5$. 
Figure 17: Required soil properties for embankment with surcharge and high rupture strength reinforcement \( n=2, \ H/D=1.0 \).
Figure 18: Required soil properties for embankment with surcharge and high rupture strength reinforcement $n=2$, $H/D=1.5$. 
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Figure 22: Required soil properties for embankment with surcharge and high rupture strength reinforcement $n=4$, $H/D=0.5$. 
Figure 23: Required soil properties for embankment with surcharge and high rupture strength reinforcement $n=4$, $H/D=1.0$. 
Figure 24: Required soil properties for embankment with surcharge and high rupture strength reinforcement \( n=4, H/D=1.5 \).
4. Design charts plotting $c_u/\gamma H$ vs $R/\gamma H^2$ for various values of $H/D$

The following charts present the relationship between the normalised undrained shear strength of the soft soil required for stability plotted against normalised reinforcement strength.

![Figure 25: Required undrained shear strength for stability plotted against reinforcement strength for $c'/\gamma H = 0$, $\phi' = 30^\circ$, 1V:2H, and $\alpha = 0.8$. Thin lines indicate a bilinear fit. The maximum error in using this fit occurs approximately between 0.5 − 0.6$R_L$ and is around 8% in $c_u/\gamma H$ or 20% in $R/\gamma H^2$, where $R_L$ is the limiting (lowest) value of $R$ for any curve.](image)
Figure 26: Required undrained shear strength for stability plotted against reinforcement strength for $c'/\gamma H = 0.1$, $\phi' = 50^\circ$, 1V:2H, and $\alpha = 0.8$. Thin lines indicate a bilinear fit. The maximum error in using this fit occurs approximately between $0.5 - 0.6R_L$ and is around 15% in $c_u/\gamma H$ or 60% in $R/\gamma H^2$, where $R_L$ is the limiting (lowest) value of $R$ for any curve.