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# The counteracting effects of rate of construction on reinforced embankments on rate-sensitive clay

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ABSTRACT: Previous research has shown that for conventional soils, a slower construction rate leads to higher embankment stability, while for rate-sensitive soils faster construction mobilizes higher short-term strength as a result of soil viscosity. Thus for rate-sensitive soils, the critical period with respect to the stability of the embankment is after the end of construction. This paper examines the effects of construction rate and PVDs on the short-term failure height and the role pore pressure dissipation during the construction can have on stability. The interaction between pore pressure dissipation and geosynthetic reinforcement is investigated. The implications with respect to (a) the construction rate and design of PVDs, as well as (b) the development of reinforcement strains and the selection of reinforcement are discussed. Practical implications are highlighted.

## 1 INTRODUCTION

The behaviour of reinforced embankments constructed on typical soft soils has been extensively studied. However, the effect of the viscous behaviour of rate-sensitive foundations on the short-term and long-term performance of reinforced embankments has only received limited attention.

A study by Rowe et al. (1996), on the behaviours of the Sackville test embankment, showed that in order to accurately predict the responses of embankment on the rate-sensitive soil, a constitutive model considering the viscous behaviours of the soil is essential. Rowe & Hinchberger (1998) proposed and demonstrated that an elasto-viscoplastic constitutive model could adequately describe the behaviour of the Sackville test embankment. Rowe & Li (2002) showed that the long-term stability of the reinforced embankment on the rate-sensitive soil decreases after the end of construction due to delayed build up of excess pore water pressures as a result of soil viscosity. Installation of prefabricated vertical drains (PVDs) has potential to reduce the effect of delayed excess pore pressures. However, the effect of PVDs on the performance of reinforced embankments on the rate-sensitive soil has not been studied.

The objective of this paper is to perform a parametric study of the combined effects of PVDs and geosynthetic reinforcements on the behaviour of embankments on soft rate-sensitive soils. The short-term stability of the reinforced embankment will be compared with the result from the conventional elasto-plastic model. The influence of factors such as the stiffness of reinforcement, rate of construction and spacing of PVDs will be examined with respect to the time-dependent responses of excess pore pressure and reinforcement strains.

## 2 FINITE ELEMENT MODELING

The finite element program AFENA (Carter & Balaam, 1990), previously modified by Rowe & Hinchberger (1998) to incorporate an elasto-viscoplastic constitutive model, was adopted in this study. Drainage elements (Russell, 1990) implemented by Li & Rowe (2001) were utilized for studying the effects of PVDs. The results presented here were obtained for embankments with 2H:1V side slopes overlaying 15 m of soft rate-sensitive clay above the rigid and permeable sand layer. A typical mesh is shown in Figure 1.

The finite element mesh included a total of 1815 six-noded linear strain triangular elements, with 4003 nodes to discretise the embankment and foundation soils. Two-noded bar elements were used for modeling the reinforcement and two-noded interface joint elements (Rowe & Soderman, 1985) were used for modeling the interfaces. For PVDs modeling, two-noded drainage elements (Li, 2000) were utilized.

The centerline of the embankment and far field boundary, located 100 m away from centerline, were taken to be smooth-rigid boundaries. The bottom boundary of the finite element mesh was assumed to be free draining and rough-rigid. The embankment construction was simulated by gradually turning on

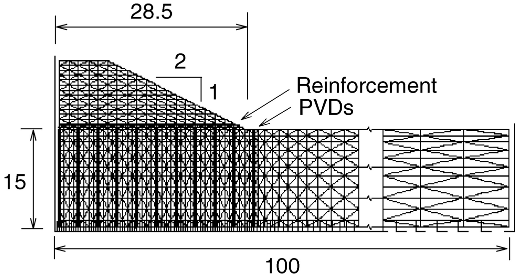

Figure 1. Finite element mesh discretisation.

the gravity of the embankment in 0.75 m thick lifts at a rate corresponding to the construction rate of the embankment. The PVDs fully penetrated the 15m thick clay layer and were arranged in a square pattern with three different spacing; S = 1 and 3 m. Zero excess pore water pressure was assumed along drainage elements. The details of the elasto-viscoplastic constitutive model and drainage element are presented in the previous papers by Rowe & Hinchberger (1998) and Li & Rowe (2001), respectively.

## 3 CONSTITUTIVE PARAMETERS

### 3.1 *Foundation soil properties*

The soft rate-sensitive soil examined is denoted here as soil CR1. Constitutive parameters used for soil CR1 are similar to the estimated soil foundation properties at the Sackville test embankment (Rowe & Hinchberger, 1998). The various parameters for CR1 are listed in Table 1.

The hydraulic conductivity of soft rate-sensitive clay was taken to be a function of void ratio as detailed in Rowe & Hinchberger (1998).

### 3.2 *Backfill properties and construction rate*

The purely frictional granular soil is used to model the embankment fill. The assumed properties are friction angle $\o' = 37°$, dilation angle $\psi = 6°$ and unit weight $\gamma = 20\,\mathrm{kN/m^3}$. The non-linear elastic behaviour of the fill was modeled using Janbu's (1963) equation:

$$\frac{E}{P_a} = K\left(\frac{\sigma_3}{P_a}\right)^m \tag{1}$$

where $E$ is the Young's modulus; $P_a$ is the atmospheric pressure; $\sigma_3$ is the minor principle stress and $K$ and $m$ are material constants selected to be 300 and 0.5, respectively.

The construction rates for the two cases examined in this study were 2 m/month and 6 m/month.

Table 1. Details of foundation soil properties.

| Soil parameter | Soil CR1 |
|---|---|
| Failure envelope, $M_{N/C}(\o')$ | 0.96 (29°) |
| Cohesion intercept, $c_k$ (kPa) | 0 |
| Failure envelope, $M_{O/C}$ | 0.75 |
| Aspect ratio, $R$ | 1.25 |
| Compression index, $\lambda$ | 0.16 |
| Recompression index, $\kappa$ | 0.034 |
| Coefficient of at rest earth pressure, $K'_o$ | 0.75 |
| Poisson's ratio, $\upsilon$ | 0.3 |
| Reference hydraulic conductivity, $k_{vo}$ (m/s) | $2 \times 10^{-9}$ |
| Hydraulic conductivity ratio, $k_h/k_v$ | 4 |
| Unit weight, $\gamma$ (kN/m$^3$) | 17 |
| Initial void ratio, $e_o$ | 1.50 |
| Viscoplastic fluidity, $\gamma^{vp}$ (1/hour) | $2.0 \times 10^{-5}$ |
| Strain rate exponent, $n$ | 20 |

### 3.3 *Interface parameters and reinforcements*

Rigid-plastic joint elements (Rowe & Soderman, 1985) were used to model the fill/reinforcement and fill/foundation interface. The fill/reinforcement interface was assumed to frictional with $\o' = 37°$. The fill/foundation interfaces had the same shear strength as the foundation soil at ground surface.

Geosynthetic reinforcements were modeled as an elastic material with tensile stiffness, $J$, of 0 (no reinforcement), 500 and 1000 kN/m.

## 4 RESULTS AND DISCUSSIONS

### 4.1 *Effects of reinforcement and construction rate on the short-term stability of embankment*

The stability of the embankment can be assessed in term of the fill thickness at which the net embankment height above the original ground surface reaches a maximum value as illustrated in Figure 2.

For the four cases examined in Figure 2, the response is initially linear and this is then followed by a non-linear response and eventually failure. The fill thicknesses giving rise to short-term embankment failure are 3.5, 5.8, 6.0 and 7.2 m for case I, II, III and IV respectively. In case I, the unreinforced embankment was constructed on the rate-insensitive foundation having the same properties as those of other cases except for the viscoplastic characteristics to illustrate the effect of rate-sensitivity on short-term behavior. The results from case II and III demonstrate the effects of construction rate on the short-term failure height of the embankment. The faster construction rate resulted in higher short-term failure height of the embankment due to soil viscosity.

The short-term failure height of embankment was significantly improved by using geosynthetic reinforcement. The results from case III and case IV

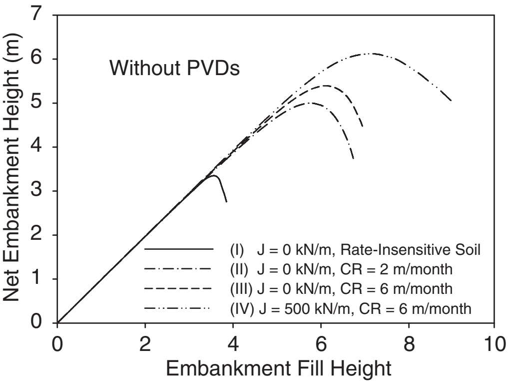

Figure 2. The effects of reinforcement and construction rate on the short-term stability of embankment.

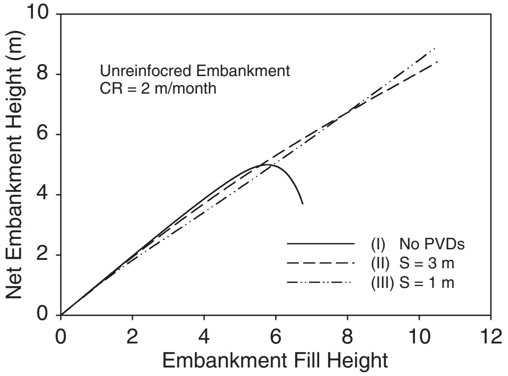

Figure 3. The effect of PVDs on the short-term stability of the embankment.

show that the failure height of reinforced embankment was improved 20% compared to the unreinforced embankment.

## 4.2 *Effects of PVDs on the short-term stability of embankment*

The main function of PVDs is to increase rate of excess pore water pressure dissipation by reducing the length of the drainage path. The consequence is an increase degree of partial consolidation as well as shear strength of the foundation soils. As shown in Figure 3, the short-term stability of embankment was improved drastically using PVDs and no failure occurred for fill thicknesses up to 10.5 m.

During the initial stage of construction, the smaller PVDs spacing (case III) resulted in larger settlement due to the higher degree of partial consolidation. This higher degree of partial consolidation also resulted in smaller overstress developed in the foundation and accordingly less viscoplastic deformation was generated. Thus, as the fill thickness approached 10 m, the net embankment in case III was higher than for case II.

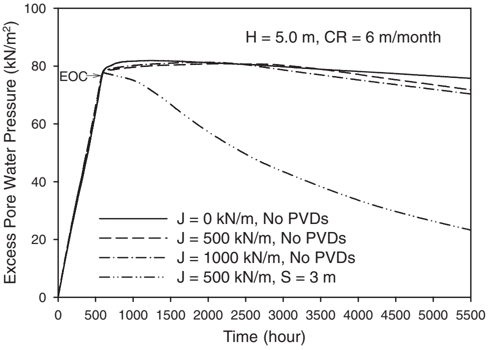

Figure 4. The effects on excess pore water dissipation.

## 4.3 *Effects on the excess pore water pressure dissipation*

In order to investigate the long-term behaviour of the embankments, a number of embankments were numerically constructed to 5 m on a rate-sensitive soil. The calculated excess pore pressures at 5 m below the original ground surface under the embankment crest are given in Figure 4. These results show that the excess pore pressures kept increasing even after the end of construction, when the external fill load was constant. This phenomenon is similar to that observed at the Sackville test embankment (Rowe & Hinchberger, 1998).

The inclusion of reinforcement slightly reduced the maximum excess pore pressure and resulted in greater apparent dissipation. This is due to less generation of pore pressure resulting from less overstress and hence less creep induced pore pressure. The effect increased with increasing reinforcement stiffness, although the overall effect was not large in this case.

The use of PVDs resulted the peak pore pressure occurring at the end of construction and this was followed by relatively rapid dissipation of the excess pore pressures.

## 4.4 *Effects on the reinforcement strain*

The constructions of three 5 m height reinforced embankments were simulated in order to study the effects of PVDs and construction rate on the reinforcement strain as shown in Figure 5.

Results from Cases I and II show the effect of construction rate on the mobilized reinforcement strains. Case I (slower construction rate) resulted in larger reinforcement strain at the end of construction because

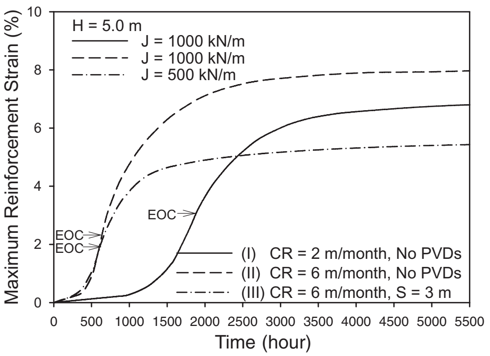

Figure 5. The effects on mobilized reinforcement strain.

soil tended to transfer more load to the reinforcement since it had lower strength at the lower strain rate. However, the slower construction rate allowed greater degree of partial consolidation and this reduced the amount of overstress in the soil and consequently reduced the long-term viscoplastic deformations in the soil. Accordingly, smaller long-term reinforcement strains were mobilized. Commonly designers aim to limit reinforcement strains to 5%–6%. The results for Cases I and II correspond to long-term reinforcement strains of 6.8% and 8.0%, respectively.

The effect of PVDs on the reinforcement strain is also presented in Figure 5. The use of PVDs allowed the use of lower stiffness reinforcement and also limited the long-term mobilized reinforcement strains, due to the fact that PVDs significantly increased the rate of excess pore water pressure dissipation which, in turn, reduced the amount of overstress in the system as well as the long-term reinforcement strains.

## 5 CONCLUSIONS AND DISCUSSIONS

For the rate-sensitive soil, a faster rate of construction resulted in higher short-term stability of the embankment. However a larger amount of overstress was generated in the soil and this resulted in large viscoplastic deformations. The excess pore water pressures continued to increase and reached its maximum value after the end of construction. Thus the critical period regarding the stability for these embankments may occur after the end of construction. The use of reinforcement resulted in less overstress in the soil for a given embankment fill thickness and this resulted in less viscoplastic deformation of the soil. The use of PVDs significantly increased the rate of excess pore water pressure dissipation; minimizing the effects of overstress and the long-term reinforcement strain.

This study demonstrates that the behaviour of rate-sensitive soil can have significant effects on the engineering performances of the reinforced embankment, especially after the end of construction. Therefore, the viscosity and viscoplastic characteristic of the soil should be considered in the design and construction of earth structures on the rate-sensitive soil.

## ACKNOWLEDGEMENTS

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