

The interaction between reinforcement and drains and their effect on the performance of embankments on soft ground

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ABSTRACT This paper reviews the behaviour of reinforced embankments on both typical soft cohesive (rate-insensitive) soil and rate-sensitive soil. The interaction between geosynthetic reinforcement and prefabricated vertical drains (PVDs) is examined and it is demonstrated that the combination of PVDs and the tension mobilized in reinforcement can substantially increase the stability of embankments. The paper also provides a brief explanation of a recent design approach for embankments on soft rate-insensitive soil, considering the combined effect of reinforcement and PVDs. The effect of creep/relaxation of geosynthetics and rate sensitivity of the foundation soil on embankment performance is discussed and it is shown that they can have a significant effect on the failure height of reinforced embankments. The results suggest the need for considerable care when the foundation soil is rate-sensitive.

1 INTRODUCTION

Geosynthetics reinforcement and prefabricated vertical drains (PVDs) have revolutionized many aspects of the design and construction of embankments on soft ground and provide a cost effective alternative to traditional techniques. The behaviour of reinforced embankments on typical soft deposits is now well understood and many design procedures have been proposed. However, while these design methods may be conservative for conventional (rate-insensitive) soils, they may be quite unconservative for less conventional (rate-sensitive) soils (Rowe & Li 2005; Li & Rowe 2008 and Rowe & Taechakumthorn 2008a).

The beneficial effects of PVDs for accelerating the gain in soil strength are well recognized (e.g. Taechakumthorn & Rowe 2008; Sinha et al. 2009 and Saowapakpiboon et al. 2009). For example, when PVDs are used in conjunction with basal reinforcement, the presence of PVDs can substantially reduce the long-term creep deformation while allowing more rapid construction than could be safely considered without the use of PVDs (Li & Rowe 2001 and Rowe & Taechakumthorn 2008a).

Thus, the objective of this paper is to review research relating to the effects of the basal reinforcement and PVDs on the design and construction of embankments over soft ground. This paper also summarizes a design approach, which considers the interaction between reinforcement and PVDs, for embankments on typical soft clay deposits. A number of parametric studies are used to highlight some design considerations and potential problems that might be anticipated during the construction. This paper follows two previous keynote papers (Rowe and Li 2005 and Rowe and Taechakumthorn 2008b) and while it covers some of the same basic material as those papers, it also provides new insights based on the most recent research in the field up to November 2009.

2 REINFORCED EMBANKMENT ON SOFT GROUND

When embankments are constructed on soft foundations, the lateral earth pressure within the embankment fill imposes shear stresses on the foundation reducing its bearing capacity and hence embankment stability (Jewell 1987). The role of the basal reinforcement is to absorb some, or all, of the earth pressure from the fill and to resist the lateral deformations of the foundation, thereby increasing embankment stability. Reinforced embankments are typically designed based on consideration of: (a) bearing capacity, (b) global stability, (c) pullout or anchorage, and (d) deformations (Leroueil & Rowe 2001). The significant role that geosynthetic reinforcement can play in increasing embankment stability on traditional soft clay deposits was first clearly demonstrated from a theoretical perspective by the analysis of the Almere test embankments (Rowe & Soderman 1984). They clearly demonstrated that the reinforcement does very little (and there are negligible strains) while the soil remains elastic. Strains begin to develop as the plastic zone grows and they develop rapidly when there is contiguous plastic failure in the soil and the reinforcement is all that is maintaining the embankments stability.

3 PARTIALLY DRAINED BEHAVIOUR OF REINFORCED EMBANKMENTS

The observed construction-induced excess pore water pressures from a large number of field cases suggest that partial consolidation of the foundation may occur during embankment construction at typical construction rates (Crooks et al. 1984; Leroueil & Rowe 2001). This applies to natural soft cohesive deposits that are typically slightly overconsolidated. Also, it has been reported that there can be a significant strength gain due to partial consolidation during embankment construction (e.g. Chai et al. 2006 and Saowapakpiboon et al. 2009).

Although field cases suggest the importance of considering partial drainage, they do not allow a direct comparison of cases where it is and is not considered. Finite element analyses provide a powerful tool for comparing the behaviour of reinforced embankments constructed under both undrained and partially drained conditions (Rowe & Li 2005).

When soft foundations do not initially have the strength to safely support a given embankment, stage construction may be employed to allow sufficient consolidation and strength gain to support the final embankment load. Li and Rowe (2001) showed that geosynthetic basal reinforcement may eliminate the need for stage construction or, in cases where staging was still needed, reduce the number of stages required. Their results also implied that there may be benefits arising from the combined use of reinforcement with methods of accelerating consolidation, such as PVDs, as discussed in the following section.

4 INTERACTION BETWEEN REINFORCEMENT AND PVDs

Since the first prototype of a prefabricated drain made of cardboard, PVDs have been widely used in embankment construction projects because of the benefits in terms of reduced construction costs and improved ease of construction (e.g. Holtz et al. 2001; Bergado et al. 2002; Chai et al. 2006; Sinha et al. 2009 and Saowapakpiboon et al. 2009). PVDs accelerate soil consolidation by shortening the drainage path and taking advantage of the naturally higher horizontal hydraulic conductivity of the foundation soil. This technique improves embankment stability by allowing strength gain in the foundation soil associated with the increase in effective stress due to consolidation.

The combined effects of reinforcement and PVDs have been investigated by Li and Rowe (2001) and Rowe and Taechakumthorn (2008a). It has been shown that at typical construction rates, the use of PVDs results in relatively rapid dissipation of excess pore pressures and this can be enhanced by the use of basal reinforcement. For example, Figure 1 shows the variation of net embankment height (fill thickness minus

maximum settlement) with embankment fill thickness from finite element simulations, where S is the spacing of PVDs in a square pattern. For this particular foundation soil (see insert in Figure 1) and PVDs at a spacing of 2 m, the unreinforced embankment can be constructed to a height of 2.85 m. If reinforcement with tensile stiffness $J = 250$ kN/m is used, the failure height increases to 3.38 m. It is noted that, for these assumed soil properties and a construction rate of 2 m/month, failure of the embankment due to excessive settlement of the foundation soil will not occur if the reinforcement stiffness is greater than 500 kN/m.

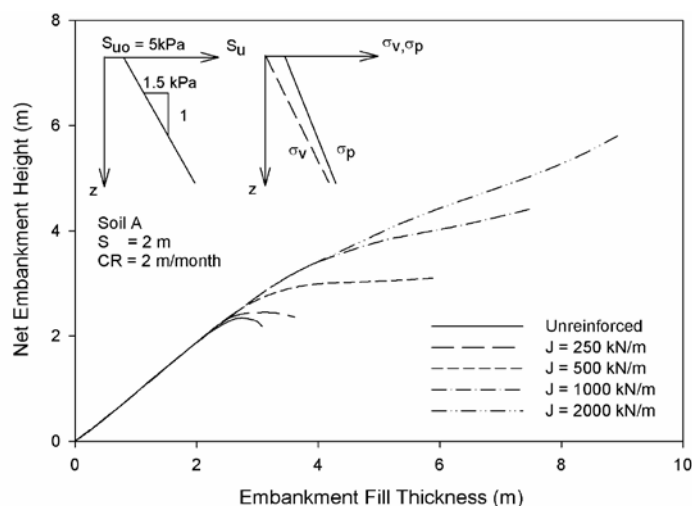


FIGURE. 1 The combined effect of reinforcement and PVDs on the short-term stability of an embankment (modified from Rowe & Li 2005)

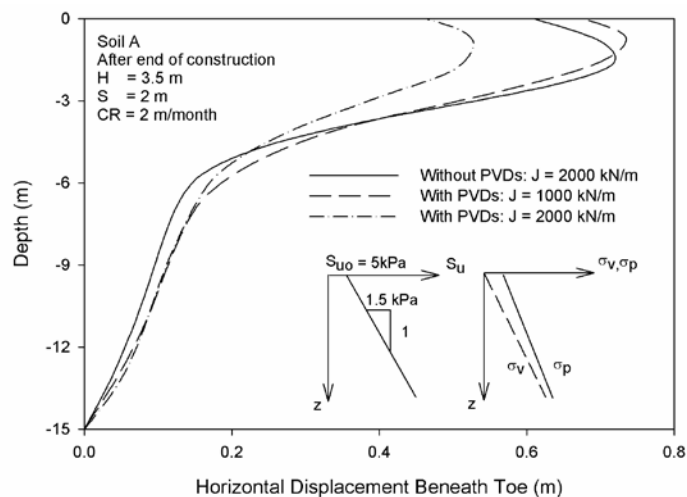


FIGURE.2 The combined effect of reinforcement and PVDs on lateral deformation beneath the toe of an embankment at the end of construction (modified from Rowe & Li 2005)

When PVDs are used in conjunction with basal reinforcement, they can enhance the beneficial effect of the reinforcement in reducing the horizontal deformations of the foundation soil below the embankment as illustrated in Figure 2. With the use of PVDs, less stiff reinforcement can be employed while still providing about the same lateral deformation as when the stiffer reinforcement is used without PVDs.

5 DESIGN OF EMBANKMENTS ON SOFT GROUND CONSIDERING THE INTERACTION BETWEEN BASAL REINFORCEMENT AND PVDs

In design, the effects of reinforcement and PVDs are usually treated separately even if both are used. Li and Rowe (2001) proposed a design method for reinforced embankments that incorporates the effect of strength gain due to consolidation of the foundation soil. This design method was based on a limit state design philosophy using an undrained strength analysis suggested by Ladd (1991). The design procedure consists of four steps as described below.

First, the design criteria and representative soil parameters have to be selected including embankment geometry, soil profile (i.e. undrained shear strength, preconsolidation pressure, vertical effective stress, and coefficient of consolidation in both the normally consolidated and overconsolidated state, as well as vertical and horizontal hydraulic conductivity), longest vertical drainage path, embankment fill properties, and the anticipated average construction rate and hence the time available for consolidation. Second, one must select the configuration of the PVDs (pattern: triangular or square, spacing and length of PVDs). Then the method proposed by Li and Rowe (2001) can be utilized to calculate the average degree of consolidation at any specific time. Third, this information is used to calculate the increase in undrained shear strength along the potential failure surface using the SHANSEP method (Ladd 1991) as described by Li and Rowe (2001). Finally, using this undrained shear strength, the limit equilibrium analysis can be employed to determine the reinforcement force required to give an adequate factor of safety and the required reinforcement stiffness is then calculated based on the magnitude of the required force and the allowable reinforcement strain. This then allows the selection of the required geosynthetic reinforcement. If reinforcement having the required stiffness and strength is not readily available, the process can be repeated deducing the spacing between the PVDs until a suitable combination of PVDs and reinforcement is identified. Full details of this approach and an example associated with the design approach summarized above are provided by Li and Rowe (2001).

This approach can be easily applied for a stage construction sequence by adding the consolidation during the stoppage between stages when calculating the average degree of consolidation, while keep the other steps the same. To ensure embankment stability during construction, it is important to monitor the development of reinforcement strains, excess pore pressure, settlement, and horizontal deformation to confirm that the observed behaviour is consistent with the design assumptions (Rowe & Li 2005).

6 REINFORCED EMBANKMENT ON RATE-SENSITIVE SOIL

It has been recognized by many researchers (Lo & Morin 1972; Vaid & Campanella 1977; Vaid et al. 1979; Graham 1983; and Leroueil 1988) that natural soft deposits exhibit significant time-dependent behaviour and the undrained shear strength of the natural soft clay is strain rate dependent (rate-sensitive). The performance of reinforced embankment constructed on the rate-sensitive soil also has been investigated by both field studies and numerical analysis (Rowe et al. 1996; Hinchberger & Rowe 1998; Rowe & Hinchberger 1998; Rowe & Li 2002; and Rowe & Taechakumthorn, 2008a,b). Rowe et al. (1996) showed that in order to accurately predict the responses of the Sackville embankment on a rate-sensitive soil, it was essential to consider the effect of soil viscosity. Rowe and Hinchberger (1998) proposed an elasto-viscoplastic constitutive model based on the concept of overstress viscoplasticity using fluidity parameters to model the effect of soil viscosity and demonstrated that the model could adequately describe the behaviour of the Sackville test embankment.

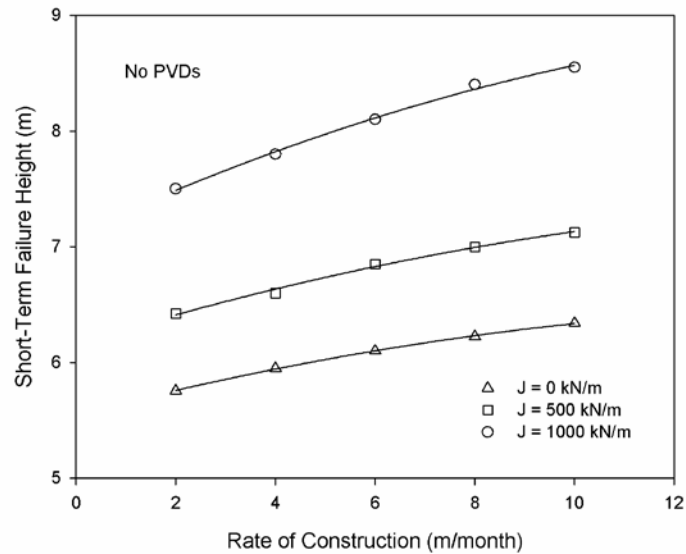


FIGURE.3 The effect of construction rate and reinforcement stiffness on short-term stability of an embankment (modified from Rowe & Taechakumthorn 2008a)

For rate-sensitive soils, the undrained shear strength is highly dependant on the rate of loading (i.e. rate of embankment construction); the faster the loading rate, the stronger the soil appears. For that reason, the loading rate is an important factor when conducting an analysis of embankment performance on a rate-sensitive soil. The effect of construction rate and geosynthetic reinforcement on the short-term stability of reinforced embankments is illustrated in Figure 3. A series of reinforced embankments with axial stiffness of 0 (unreinforced), 500 and 750 kN/m were numerically constructed at different construction rates until failure. The effect of construction rate is evident with the faster construction rate resulting in a higher short-term embankment failure height for all cases. Also, the use of basal reinforcement has been shown to improve embankment stability. Until a limiting stiffness is reached, the stiffer the reinforcement the higher confining force to the system and hence the higher the short-term failure height (Figure 3). However, this short-term benefit hides a long-term problem as will be discussed later.

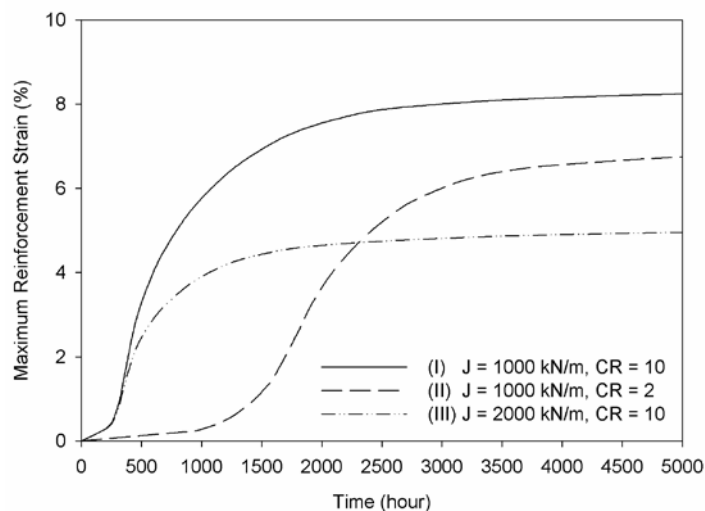


FIGURE.4 The effect of construction rate and reinforcement stiffness on mobilized reinforcement strains (modified from Rowe & Taechakumthorn 2008a)

To investigate the effect of the various parameters such as reinforcement stiffness, construction rate and the effect of PVDs on the long-term behaviour of reinforced embankments on rate-sensitive soil, a

series of 5 m high reinforced embankments were numerically constructed on rate-sensitive foundation soil A. The results from Case I and Case II (Figure 4) show the effect of construction rate. The reinforcement strains at the end of the construction were 1.6% and 2.6% for Cases I and II, respectively. The reinforcement strain for the slower construction rate (Case II) was higher because the soil exhibited lower short-term strength and transferred more load to the geosynthetic reinforcement. However, this slower construction rate allowed a higher degree of partial consolidation and reduced the amount of overstress in the soil. Consequently, there was less creep and stress relaxation in the soil following construction. This resulted in smaller long-term reinforcement strains. The results from Case I and III (Figure 4) show the effect of reinforcement stiffness and as expected the stiffer reinforcement (Case III) gave smaller strains both at the end of construction and long-term.

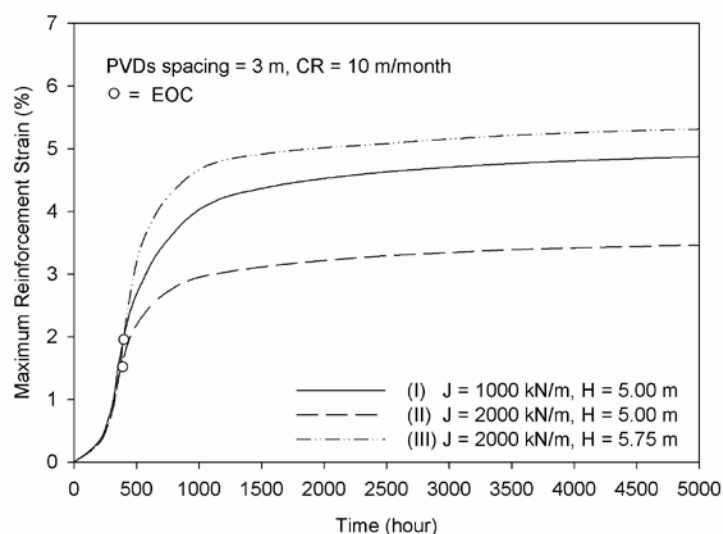


FIGURE.5 The effect of PVDs and reinforcement stiffness on mobilized reinforcement strains (modified from Taechakumthorn & Rowe 2008)

The rate of excess pore water dissipation and the consequent rate of shear strength gain in the soil can be increased using PVDs. Results in Figure 5 show that with the use of PVDs, the long-term mobilized reinforcement strain can be significantly reduced. For the 5 m high reinforced embankment with the reinforcement stiffness $J = 1000$ kN/m, even a construction rate as low as 2 m/month gave rise to a long-term reinforcement strain of 6.9% which exceeds the typical allowable limit of about 5% (Figure 4). However, with PVDs at 3 m spacing, numerical construction of the embankment to the same $h = 5$ m height at 10 m/month gave a maximum long-term reinforcement strain of 4.6% (Case I, Figure 5). With stiffer ($J = 2000$ kN/m) reinforcement, PVDs reduced the long-term reinforcement strain from 4.9% to 3.3% (Case III in Figure 4 and Case II, Figure 5). With a reinforcement stiffness of 2000 kN/m, a reinforced embankment could be constructed up to 5.75 m without the long-term reinforcement strain exceeding about 5% (Case III, Figure 5).

7 EFFECTS OF CREEP/RELAXATION OF REINFORCEMENT STAINS

Experimental studies have shown that geosynthetics typically made of polyester (PET), polypropylene (PP) and polyethylene (PE) are susceptible to creep/relaxation (Jewell & Greenwood 1988; Greenwood 1990; Bathurst & Cai 1994; Leshchinsky et al. 1997; Shinoda & Bathurst 2004; Jones & Clarke 2007 and Kongkitkul & Tatsuoka 2007). The importance of considering creep/relaxation of geosynthetics reinforcement, to understand the time-dependent behaviour of the reinforced embankments on soft ground

has been highlighted in the literature (Rowe & Li 2005; Li & Rowe 2008 and Rowe & Taechakumthorn, 2008b).

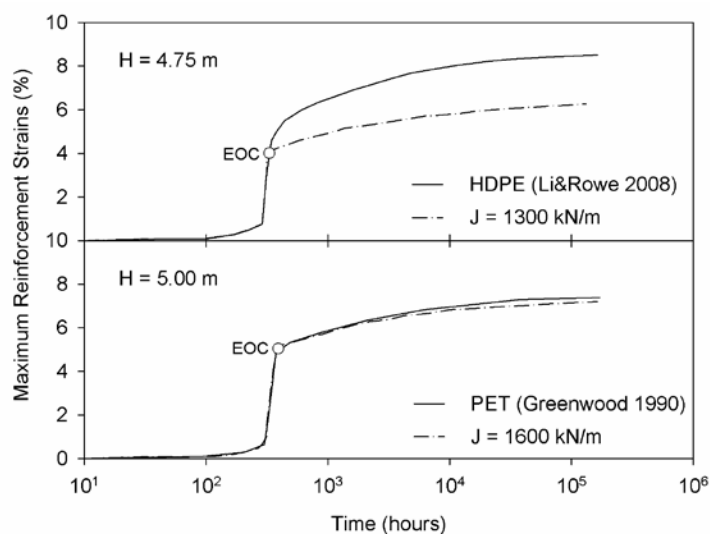


FIGURE.6 Variation of reinforcement strain with time during and following the embankment construction over a rate-insensitive soil (modified from Rowe & Li 2005)

For creep-sensitive reinforcement, in some cases the reinforcement strain may significantly increase with time after embankment construction (Rowe & Li 2005). Figure 6 shows (solid lines) the development of reinforcement strain with time up to 98% consolidation for embankments reinforced with high density polyethylene, HDPE, (upper figure) and PET (lower figure) geosynthetics. Also shown (dashed lines) are the strains that would be developed if the reinforcement was assumed elastic with stiffness selected such that, at the end of construction, the reinforcement strain is the same as that developed in the viscous reinforcement. Thus, the difference between the solid and dashed lines represents the creep strain due to the viscous nature of the reinforcement.

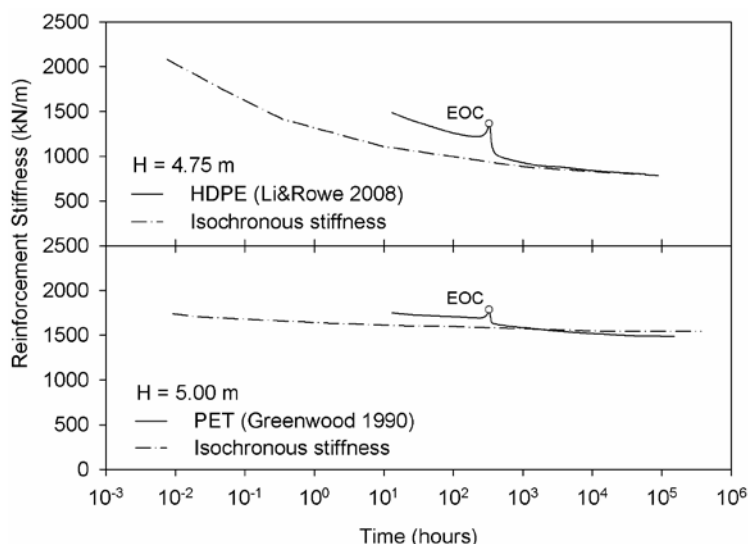


FIGURE.7 Variation of reinforcement tensile stiffness with time during and following the embankment construction (modified from Rowe & Li 2005)

Rowe and Li (2005) demonstrated that the isochronous stiffness deduced from standard creep tests can reasonably represent the stiffness of geosynthetics reinforcement at the critical stage, for rate-insensitive foundation soils. The study also recommended that the isochronous stiffness should be used in

design to estimate the mobilized reinforcing force at the end of embankment construction. Figure 7 compares the mobilized reinforcement stiffness with isochronous stiffness deduced from in-isolation creep test data during and after the construction of the HDPE geogrid and PET geosynthetic-reinforced embankments. The mobilized stiffness decreases with time and very closely approaches the isochronous stiffness in the long term. This also agrees with the finding of Li and Rowe (2008) and Rowe and Taechakumthorn (2008b) for the case of rate-sensitive foundation.

The time-dependence of the mobilized reinforcement stiffness shown in Figure 7 also implies that the force in the reinforcement following the end of embankment construction may be significantly lower than expected in design owing to the viscous behaviour of geosynthetic reinforcement during embankment construction. This highlights the need for care when applying tensile stiffness from standard load–strain tests to deduce the design tensile force. In addition to creep effects, consideration should be given to potential effects of construction damage to the reinforcement.

8 CONCLUSIONS

The behaviour of reinforced embankments and the current design approaches have been examined for a number of different situations. The results show that the use of geosynthetic reinforcement can substantially increase the failure height of embankments over soft ground. The finite element method has proven to be an effective tool to analyze the behaviour of reinforced embankments. The results showed that the performance of the reinforced embankment can change significantly, depending on the type of geosynthetic used and/or the nature of the foundation soil. Therefore, careful consideration must be given to the selection of the constitutive relationships to model each component of a reinforced embankment. Basal reinforcement can improve the stability of the embankment on both conventional (rate-insensitive) as well as rate-sensitive soil. Furthermore, the effect of partial consolidation during embankment construction can enhance the effect of reinforcement which encourages the combined use of reinforcement with methods of accelerating consolidation, such as PVDs. When stage construction is required, the use of reinforcement can reduce the number of stages needed. With the presence of PVDs, the design method proposed by Li and Rowe (2001) can be employed to address the interaction between the effect of strength gain, associated with the partial consolidation, and the reinforcement.

For reinforced embankments constructed over rate-sensitive soil, although the viscoplastic nature of the foundation can increase the short-term stability of the embankment, it significantly degrades the long-term embankment stability following the end of construction. The use of reinforcement provides a confining stress to the system and limits creep in the foundation. PVDs can provide a significant enhancement to the performance of reinforced embankments on these soils. For example, because PVDs allow a higher degree of consolidation during and following the construction, the overstress and consequent creep in the soil is reduced, resulting in less differential settlement and lateral movement as well as smaller long-term reinforcement strains.

As a result of the time-dependent nature of the geosynthetic reinforcement, reinforcement stiffness at the end of construction is less than that provided by the standard tensile test. This implies that the reinforcement force used in the design may not represent what has been mobilized in the field. The isochronous stiffness measured from a standard creep tests appears to reasonably, and conservatively, represent the reinforcement stiffness in the field at the end of construction. The results also suggest that reinforcement creep and stress-relaxation allow an increase in the shear deformations of the foundation soil which will degrade the long-term performance of the reinforced embankment and may even lead to long-term failure, if the foundation soil is rate sensitive. Considerable care must be taken in the design of embankments when dealing with both creep-susceptible reinforcement and a rate-sensitive foundation soil.

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