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Some factors affecting the structural performance of reinforced fills spanning voids

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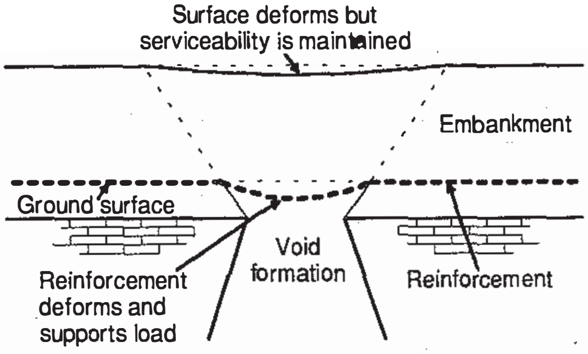
ABSTRACT: The use of basal reinforcement to prevent the collapse of fills following the formation of a foundation void is becoming an accepted foundation engineering technique. To evaluate the various factors that affect the structural performance of reinforced fills spanning voids a parametric study was performed using continuum methods based on the finite difference technique. The study shows the major parameters that affect structural performance are void size, fill height, foundation type, reinforcement strength and reinforcement stiffness. The results demonstrate that while reinforcement strength and bond may be the two criteria governing collapse, unique combinations of void size, fill height, reinforcement strength and reinforcement stiffness are required to meet serviceability criteria. In particular, reinforcement stiffness alone can only enhance serviceability by a limited amount. Furthermore, the loads carried by the reinforcement are not in proportion to its stiffness as some of the simplified analytical procedures would suggest. Multiple reinforcement layers also may be used, however, their effect on serviceability is the same as a single reinforcement layer.

1 INTRODUCTION

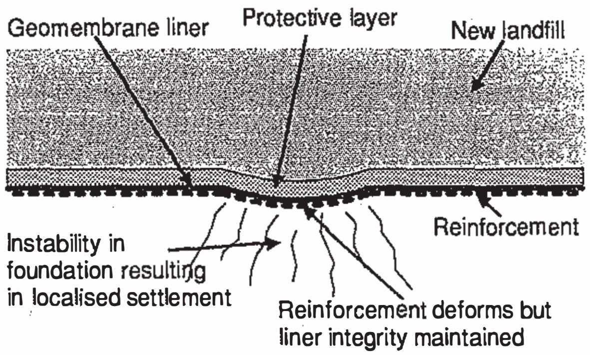
Over the last fifteen years basal reinforcement has been used increasingly as a means of controlling instability in earth structures when voids have formed in the foundation. Foundation voids may arise from either natural or man-made processes. Two examples of the use of this technique are shown in Figure 1. The first example, Figure 1a, shows the use of reinforcement to prevent the collapse of an embankment into a foundation void in a transportation-related application. In this application the reinforcement also may be required to ensure the surface of the embankment remains in a serviceable condition.

The second example, Figure 1b, shows the use of reinforcement to prevent distress in the basal liner system of a landfill when differential settlements occur beneath the liner system. Differential settlements may arise from instability or localised differences in compressive characteristics of the foundation material.

While the two applications shown in Figure 1 are identical from the viewpoint of the role of the reinforcement, there is one fundamental difference between them. In the case of the transportation-related application (Figure 1a) the reinforcement is required to restrict the amount of deformation at the surface of the embankment *at a height above the level of the reinforcement*, whereas in the landfill-related application (Figure 1b) the reinforcement is required

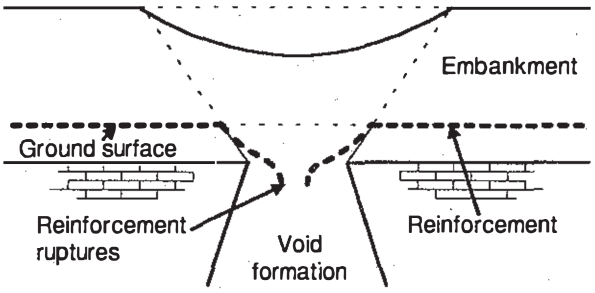


a) Basal reinforced embankments

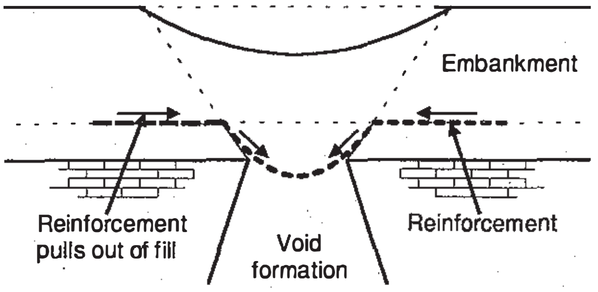


b) Basal reinforced landfill liner systems

Figure 1. Use of reinforcement to span foundation voids.

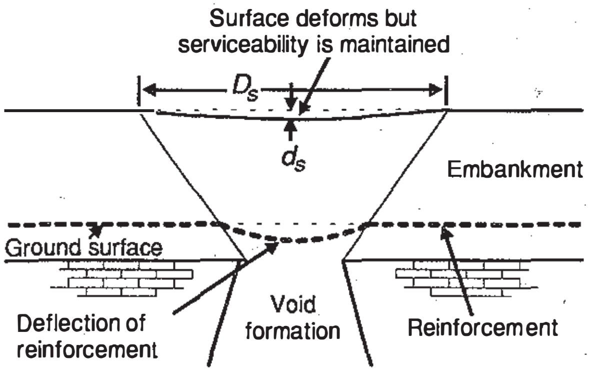


(i) Rupture of reinforcement



(ii) Reinforcement bond failure

a) Ultimate limit states



b) Serviceability limit state

Figure 2. Limit states for basal reinforced embankments spanning voids.

to restrict the amount of deformation in the liner system *adjacent to the reinforcement*. The need to maintain serviceability at a distance above the level of the reinforcement in the basal reinforced embankment application makes the analysis of this problem more complex than the landfill-related case. While the remainder of this paper concentrates on the transportation-related application, Figure 1a, some of the results presented also have relevance to the landfill-related application.

2 LIMIT STATES

The limit state approach is particularly applicable to reinforced soil design and a number of design codes are becoming available, e.g. BS 8006 : 1995. Ultimate limit states govern collapse modes of failure and serviceability limit states govern deformation modes. For reinforced embankments spanning foundation voids there are two ultimate limit states - rupture of the reinforcement and reinforcement bond failure, Figure 2a. One serviceability limit state exists - that of a maximum allowable differential deformation at the surface of the embankment, Figure 2b.

Because of the influence of the magnitude of reinforcement deformation on embankment surface deformation, fulfilling the serviceability limit state requirement is likely to impose a greater constraint on the properties of the reinforcement than either of the two ultimate limit state modes. Furthermore, simplified analytical methods are likely to give a conservative assessment of the required reinforcement properties for this limit state because of the geometrical complexity of the problem. To gain a better understanding of the influence of the various material and geometrical parameters on the structural performance of basal reinforced fills spanning foundation voids it was decided to perform a parametric study utilising an advanced modelling technique.

3 PARAMETRIC STUDY

The parametric study was performed using a continuum method based on the finite difference technique, FLAC 1995. The rationale for the use of this specific technique is published elsewhere, Lawson *et. al.* 1994. The problem geometry modelled is shown in Figure 3 where the basal reinforcement lies immediately above a rock foundation stratum. The embankment fill is above the reinforcement. Using a hard rock foundation would ensure maximum arching to occur in the embankment fill.

The problem was modelled under plane strain conditions and the various material parameters used are shown in Table 1. The rock foundation material parameters are similar to a medium to hard sandstone

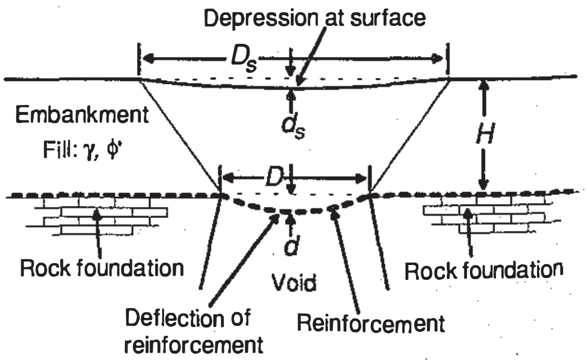


Figure 3. Material geometry used in the finite difference model.

material while the parameters used for the embankment fill are typical of a compacted granular soil. The reinforcement parameters varied but the relationship $J = 10T$ was maintained throughout to ensure consistency with current polymeric reinforcement materials.

Table 1. Material parameters used in the finite difference analyses.

Material type	Parameter	Value
Rock foundation	Friction, ϕ'	42°
	Cohesion, c'	7,000 kPa
	Dilation, ψ	12°
	Bulk modulus, K'	27,600 MPa
	Shear modulus, G'	11,100 MPa
	Density, γ	24 kN/m^3
	Tensile strength, T	2 MPa
	Void diameter, D	varies
Embankment fill	Friction, ϕ'	35°
	Cohesion, c'	0 kPa
	Dilation, ψ	0°
	Bulk modulus, K'	70 MPa
	Shear modulus, G'	25 MPa
	Density, γ	20 kN/m^3
	Embankment height, H	varies
Reinforcement	Stiffness, J	varies
	Tensile strength, T	varies

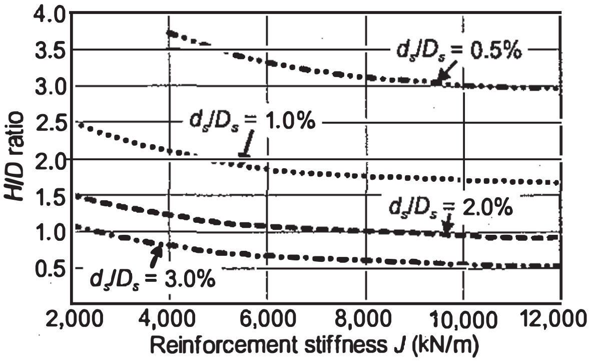
3.1 *Effect of reinforcement stiffness on surface differential deformation*

For serviceability the maximum allowable differential deformation at the surface of the embankment must be established - d_s/D_s in Figure 3. In general, d_s/D_s should be less than or equal to 1% in order for vehicles to pass at speed over a deformed area, or d_s/D_s should be less than or equal to 2% for vehicles to pass at moderate speed, Parry 1983. Greater values of d_s/D_s may be acceptable depending on the restrictions placed on vehicle passage.

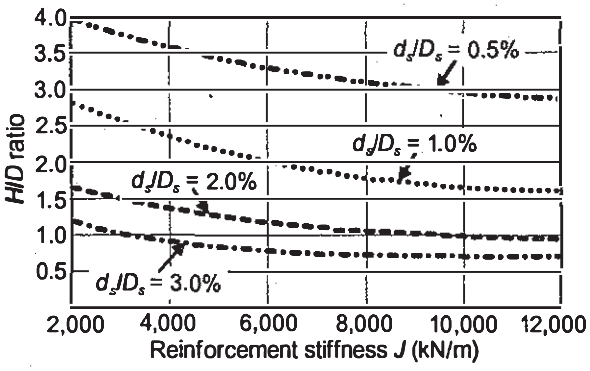
A common view of the role of the reinforcement in preventing embankment collapse is that the stiffer the reinforcement the lower the differential deformation (d_s/D_s) at the embankment surface. Consequently, reinforcement stiffness is considered to have a fundamental effect on serviceability. Figure 4 shows the results of the parametric study relating to this aspect.

In Figure 4a the surface differential deformation d_s/D_s is plotted against reinforcement stiffness J and H/D ratio, which defines the problem geometry, for a void diameter $D = 1$ m. The results show clearly that H/D ratio has a major effect on reducing surface differential deformation with reinforcement stiffness having a relatively minor secondary effect. Increasing the H/D ratio increases the amount of arching in the embankment fill, especially for H/D ratios greater than 1.5. This increase in arching reduces the surface differential deformation significantly. Conversely, a relatively large increase in reinforcement stiffness is required to reduce the surface differential deformation significantly.

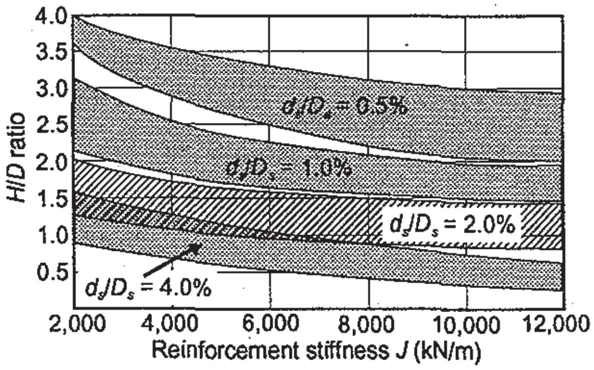
Figure 4b shows the same parameters plotted but for a void diameter $D = 4$ m. The results are very similar to the 1 m diameter void case shown in Figure 4a. Of particular note is the similarity in magnitude of the H/D ratios for the same d_s/D_s plots. Thus, void



a) For void diameter $D = 1$ m



b) For void diameter $D = 4$ m



c) For all void diameters less than or equal to 8 m

Figure 4. Effect of reinforcement stiffness on surface differential deformation

diameter, as a singular parameter, has only a minor influence on surface differential deformation when H/D ratios are also used as the basis for defining the problem geometry.

Figure 4c shows the same parameters plotted for all void diameters less than or equal to 8 m. Regions of different surface differential deformation are readily identified according to H/D ratio and reinforcement stiffness. H/D ratio has a dominant effect on surface differential deformation with reinforcement stiffness having a secondary effect.

From the results shown in Figure 4 it is observed that serviceability solutions in terms of values of d_s/D_s can be obtained by using unique combinations of *both* H/D ratio and reinforcement stiffness. It is to be noted that reinforcement stiffness alone may not provide the required degree of serviceability.

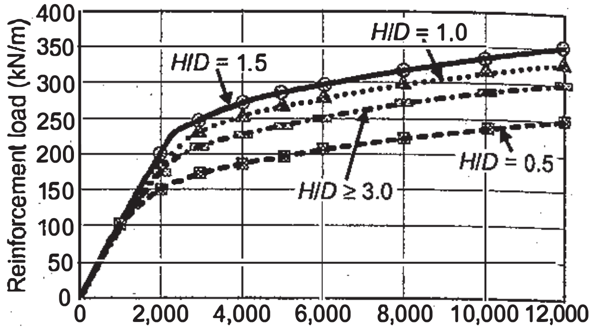
3.2 *Effect of reinforcement stiffness on reinforcement load*

Use of the various analytical models available, e.g. BS 8006 : 1995, Giroud *et al.* 1990, suggest that the load carried by the reinforcement is in proportion to its stiffness. Thus, very stiff reinforcements would attract very high loads compared to less stiff reinforcements. The results of the parametric study relating to this aspect is shown in Figure 5.

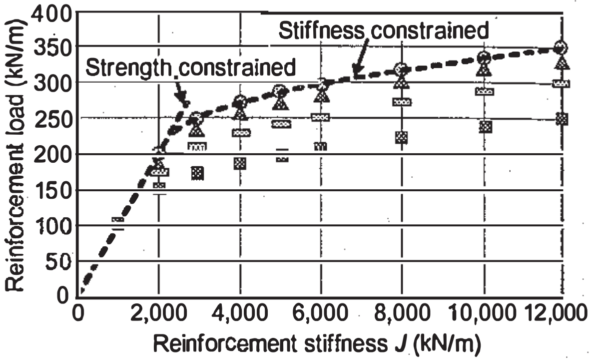
Figure 5a shows the relationship between reinforcement stiffness and reinforcement load for various H/D ratios at a void diameter $D = 4$ m. The results show an increase in load carried by the reinforcement for H/D ratios increasing from 0.5 to 1.5 where it reaches a maximum. For $1.5 < H/D < 3.0$ there is a reduction in load carried by the reinforcement, and for $H/D \geq 3.0$ the load carried by the reinforcement is constant. These results are consistent with those obtained from arching theory where the maximum vertical stress at the base of an arching soil occurs at $H/D \approx 1.5$.

Figure 5a also shows the effect of reinforcement stiffness on load carried by the reinforcement for void diameter $D = 4$ m. Up to a reinforcement stiffness approximating 2,000 kN/m the reinforcement load is proportional to reinforcement stiffness. However, for reinforcement stiffnesses greater than 2,500 kN/m increases in reinforcement load are no longer proportional and are relatively small compared to the increase in reinforcement stiffness.

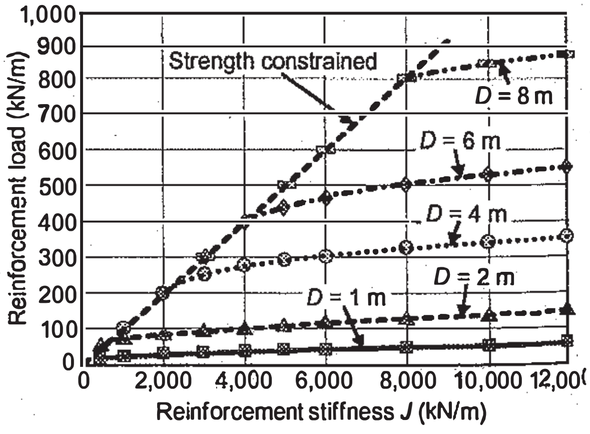
The plots shown in Figure 5a may be divided into two regions - a strength constrained region and a stiffness constrained region. These are shown in Figure 5b for $H/D = 1.5$, yielding the maximum reinforcement load, and void diameter $D = 4$ m. In the strength constrained region reinforcement load is proportional to reinforcement stiffness, and defines the reinforcement strength/stiffness relationship used in the analyses - in the analyses the relationship $J = 10T$ was maintained as described previously. In the stiffness constrained region reinforcement load is not proportional to reinforcement stiffness and increases much more slowly. In this region specific combinations of reinforcement stiffness and reinforcement load may be chosen to satisfy a given set of structural performance criteria. The intersection of the strength constrained and the stiffness constrained regions is the *minimum possible load* that is carried by the



a) Load in reinforcement for void diameter $D = 4$ m



b) Strength and stiffness constrained regions at $H/D = 1.5$ for void diameter $D = 4$ m



c) Reinforcement load versus stiffness at $H/D = 1.5$ for void diameters $D \leq 8$ m

Figure 5. Effect of reinforcement stiffness on reinforcement load

reinforcement for a specific problem geometry and reinforcement type.

Figure 5c contains plots of reinforcement load versus reinforcement stiffness at $H/D = 1.5$, yielding the maximum reinforcement loads, and void diameters $D \leq 8$ m. The reinforcement strength constrained boundary adbering to $J = 10T$ is also plotted. As would be expected the larger the void diameter the higher the load carried by the reinforcement. While changes in the H/D ratio has an effect on reinforcement load (see Figure 5a) this is relatively small compared to the influence of void diameter. For simplicity, it may be warranted to assume a conservative reinforcement load based on a H/D ratio of 1.5 for most problem geometries and void diameters.

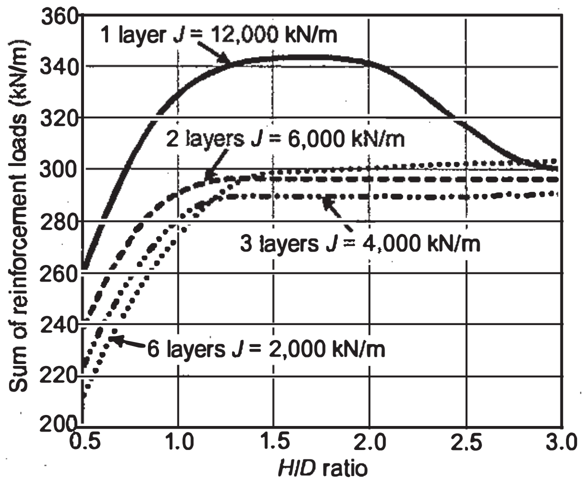
3.3 *Effect of multiple reinforcement layers on structural performance*

It has become fairly common practice to include multiple layers of reinforcement in the base of embankments in order to fulfil the load carrying requirements. However, in doing this little attention is paid to the overall stiffness requirements of the basal reinforcement. Figure 6 shows the results of the parametric study relating to this aspect.

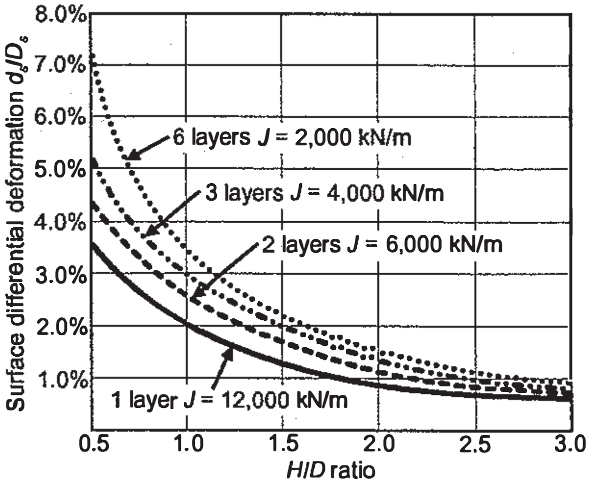
In the parametric study the relationship between reinforcement stiffness and reinforcement strength was maintained at $J = 10T$ which is consistent with practice inasmuch as when lower strength reinforcements are used their stiffnesses are invariably reduced proportionately. When modelling the effect of multiple reinforcement layers equivalent gross reinforcement strengths were maintained. For example, two layers of reinforcement had half the strength per reinforcement layer compared to a single layer of reinforcement and three layers of reinforcement had one third the strength per reinforcement layer compared to a single layer of reinforcement. Because of the maintenance of $J = 10T$ throughout this same relationship applies to reinforcement stiffness. Thus, a reinforcement having half the strength of another reinforcement will also have half the stiffness. A constant vertical spacing of 300 mm was used between adjacent reinforcement layers in all cases.

Figure 6a shows the sum of the reinforcement loads for multiple reinforcement layers at various H/D ratios and a void diameter $D = 4$ m. Where the single layer of reinforcement is used the load carried by the reinforcement rises to a maximum at $1.5 < H/D < 2$ and then reduces to a constant value for $H/D \geq 3$. This trend is identical to that shown in Figure 5a. Where multiple layers of reinforcement are used the sum of the reinforcement loads increase to a maximum at $H/D \approx 1.5$ and then remain constant for increasing H/D ratios. This difference in shape of the load curves is thought to be due to the difference in stress distribution caused by the presence of the multiple reinforcement layers within the embankment fill.

As expected, the stiffer single reinforcement layer attracts a greater total load than the less stiff multiple reinforcement layers, although the total reinforcement loads are identical for $H/D \geq 3$. Where multiple reinforcement layers have been used the total reinforcement load is very consistent, e.g. the two, three and six layers of reinforcement shown in Figure 6a all exhibit very similar total reinforcement loads over the range of H/D ratios. Also, where multiple reinforcement layers have been used the tensile load in the bottom reinforcement layer is always greater than in the top layer although the magnitude of the difference changes depending on the magnitude of the H/D ratio.



a) Sum of loads carried by multiple reinforcement layers



b) Surface differential deformation due to multiple reinforcement layers

Figure 6. Effect of multiple reinforcement layers on structural performance for void diameter $D = 4$ m

Figure 6b shows the effect of multiple reinforcement layers on surface differential deformation. The results show clearly that the stiffer single reinforcement layer reduces the surface differential deformation compared to the less stiff multiple reinforcement layers. The magnitude of the difference varies according to the *H/D* ratio, but for *H/D* ≤ 1.5 the differences are significant.

Comparison of the results in Figure 6b with those in Figure 4b show clearly that multiple reinforcement layers have the same effect on surface differential deformation as a *single reinforcement layer of the same stiffness*. Thus, no additional improvement in surface differential deformation is gained when using multiple reinforcement layers.

4 CONCLUSIONS

The use of basal reinforcement to maintain the performance of fills spanning foundation voids is becoming accepted practice. The problem involves a complex interaction between fill/foundation properties, fill/void geometry and reinforcement properties. The analysis of this problem is best performed by continuum methods especially where serviceability criteria are to be considered.

Reinforcement stiffness has a limited effect in reducing the differential deformation at the surface of the embankment. The dominant factor influencing the surface differential deformation is the *H/D* ratio which denotes the degree of arching present. Reinforcement stiffness has a secondary effect on surface differential deformation and relatively large increases in reinforcement stiffness are required to reduce the surface differential deformation significantly. Solutions that limit surface differential deformation must contain unique combinations of *both H/D* ratio and reinforcement stiffness.

Because of the complex interaction between embankment fill and reinforcement spanning a void the load carried by the reinforcement is not in proportion to its stiffness. Unlike the more conservative analytical models continuum methods provide a more accurate means of assessing reinforcement loads that satisfy given performance criteria.

Multiple reinforcement layers may be used as a means of carrying the reinforcement loads. However, the stiffness of the multiple reinforcement layers has the same effect on embankment serviceability as a single reinforcement layer of the same stiffness.

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