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Numerical modelling of geosynthetic reinforced fills over voids

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Abstract. Voids may form under thin fills and embankments due to karstic terrain, mining operations, permafrost thawing, pipe failure or local subsidence at the surface of a landfill closure. A strategy that can be used in anticipation of void formation is to introduce a geosynthetic reinforcement layer at the base of the fill at the time of construction that can temporarily support the fill over the void until remediation. This paper describes a series of numerical models of the reinforced fill over a void problem using the finite difference method (program 2DFLAC). The rate-dependent hyperbolic isochronous load-strain model for the reinforcement developed by the writers is used to model the polymeric geosynthetic reinforcement layer.

1 Introduction

Voids may form under thin fills and embankments due to karstic terrain, mining operations, permafrost thawing, pipe failure or local subsidence at the surface of a landfill closure. A strategy that can be used in anticipation of void formation is to introduce a geosynthetic reinforcement layer at the base of the fill at the time of construction that can temporarily support the fill over the void. The problem of a reinforced fill over a void is conventionally addressed using analytical solutions for reinforcement tensile strength and strain limit states (e.g., Giroud et al., 1990; BS 8006-1 2010). These solutions have the disadvantage that the influence of rate-dependent (load-strain-time) behaviour of the reinforcement is not considered. Furthermore, the coupled behaviour of the reinforcement and fill layer are ignored. For example, there is the expectation that as the reinforcement stiffness increases the vertical deflection of the fill will decrease. This paper describes a series of continuum numerical models of the reinforced fill over a void problem that capture the coupled effect of the reinforcement, soil materials, and problem geometry using the finite difference method (program 2DFLAC – Itasca 2011).

2 Numerical model

The general arrangement and domain for the long void (plane-strain) numerical model is shown in Fig. 1. Details of the modelling approach can be found in Naftchali and Bathurst (2024). To simplify numerical modelling and focus attention on the influence of the fill

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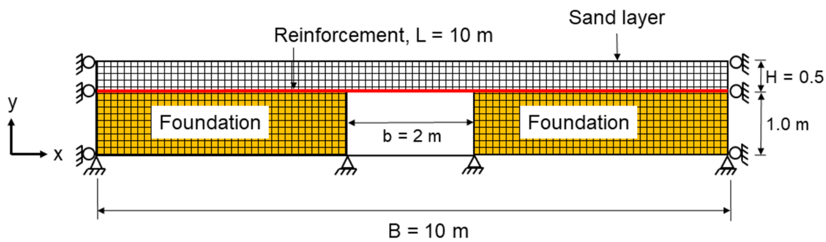

Figure 1: Base case problem domain. Note: Numerical grid dimensions are illustrative only. Finer grid node spacing was used in the vicinity of the reinforcement where stress gradients are greater.

materials, problem geometry and the reinforcement, the foundation was taken as rigid rock. Geosynthetic reinforcement products are rate-dependent materials meaning that their stiffness is load-, strain- and time-dependent. The relationship between tensile load and strain for a particular isochronous time t and strain ε can be expressed as:

$$T(\varepsilon,t) = J(\varepsilon,t) \times \varepsilon \tag{1}$$

Here, J is the creep-adjusted secant stiffness at elapsed (isochronous) time and tensile strain. The non-linear hyperbolic isochronous stiffness model described by Bathurst and Naftchali (2021) is used in this study. In this model, the reinforcement secant stiffness is:

$$J(\varepsilon,t) = \frac{1}{\dfrac{1}{J_o(t)} + \dfrac{1}{\chi(t)}\varepsilon} \tag{2}$$

Here, $J_o(t)$ is the initial tangent stiffness of the isochronous curve for time t, and $\chi(t)$ is a parameter that captures the curvature of isochronous load-strain and stiffness curves with strain ε. Reinforcement materials with $\chi(t) = \infty$ represent idealized elastic behaviour at each isochronous time. The tangent stiffness ($J_t(\varepsilon,t)$) is required in the 2DFLAC numerical code. Differentiating Eq. 2 gives:

$$J_t(\varepsilon,t) = \frac{1}{J_o(t)\left[\dfrac{1}{J_o(t)} + \dfrac{1}{\chi(t)}\varepsilon\right]^2} \tag{3}$$

The full parametric study from which some results are extracted here included a range of fill heights H = 0.25 to 9 m, void widths from b = 0.25 to 7 m, four different sand fills and six geosynthetic reinforcement products with combinations of $J_o(t)$ = 500 to 10,000 kN/m and $\chi(t)$ = 20 to ∞ kN/m. The latter represents an idealized linear elastic material.

3 Example results

Some example results are shown in Fig. 2. The reinforcement deflection, surface deflection, reinforcement load and strain increase as the void width increases when all other parameters remain the same. This is not unexpected. Fig. 2b shows that maximum surface deflections for b = 3 m are large and likely beyond acceptable performance limits for a road surface, but are shown here to illustrate trends in numerical outcomes. It is difficult to quantify the width of the surface deflection bowls in these numerical simulations because the surface gradients beyond the edge of the void are very shallow. Nevertheless, from Fig. 2b for the same void width, the width of the deflection surface (D_s) does not appear to be influenced by the reinforcement stiffness. Fig. 2c can be used to check that the strength limit strength for a

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candidate reinforcement product is not exceeded, i.e., the allowable tensile strength is greater than the maximum tensile load in the reinforcement i.e., $T_{al} \geq T_{max}$. The allowable tensile strength is computed as $T_{al} = T_{ult}/RF$ where parameter RF is the combined strength reduction factor due to creep, installation damage and durability mechanisms. A value of RF = 3 is reasonable for PET geogrids. A value of RF = 5 may be appropriate for polyolefin geogrid materials that tend to exhibit greater creep than PET geogrids of similar strength and when all other conditions are the same (Bathurst and Naftchali 2021; Naftchali and Bathurst 2023). Fig. 2d shows cases with the maximum reinforcement strains exceeding or approaching 5%. The largest strains and loads (Fig. 2c and 2d) were at the void edges for b ≥ 2 m. This may be due to the formation of a soil arch above the void that transfers the fill soil weight to the edges of the void. Reinforcement strains are judged to be excessive for b ≥ 2 m and χ (t) = 50 kN/m, and for b = 3 m and $\chi(t) = \infty$.

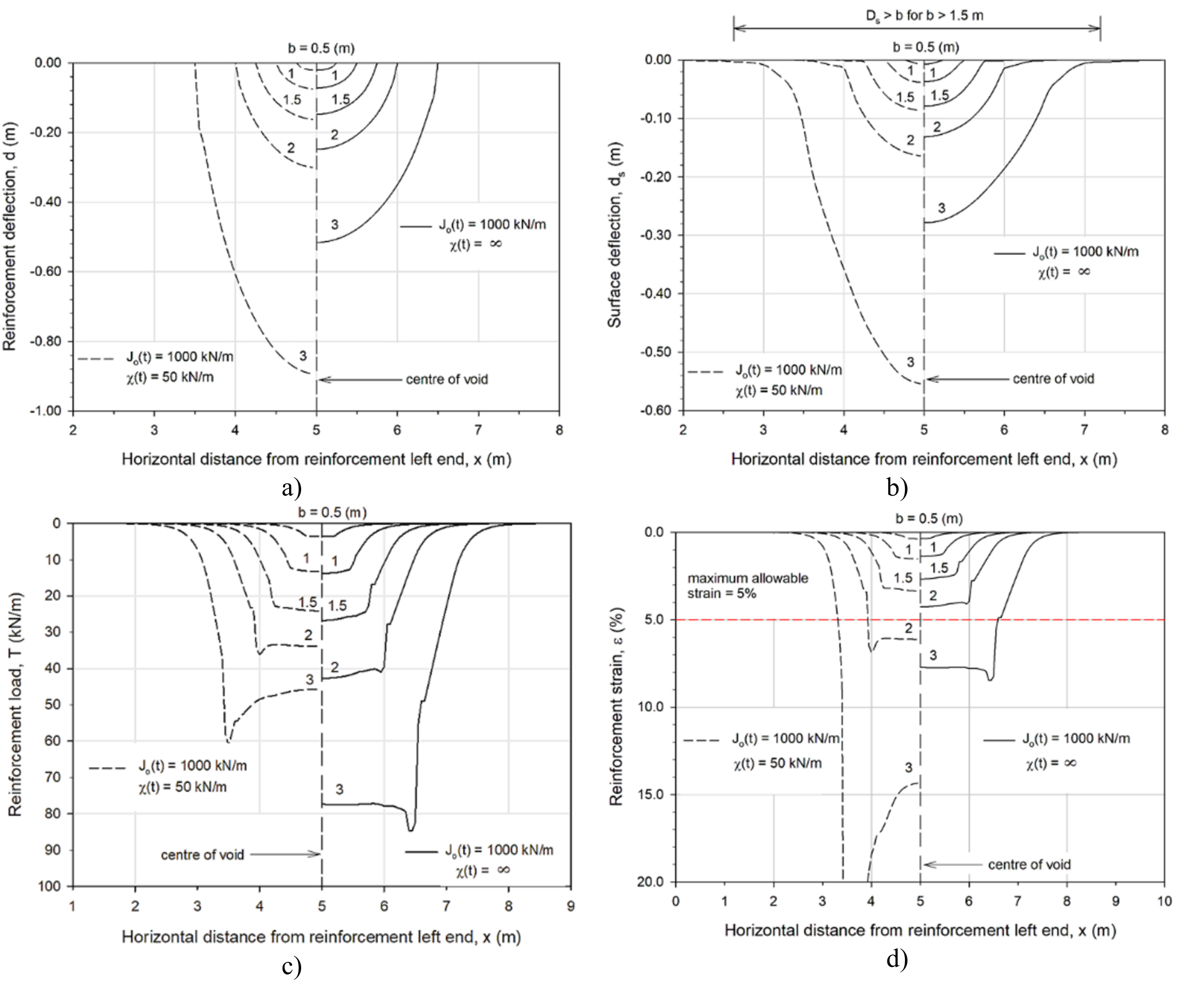

Figure 2: Influence of width of void on numerical outcomes for H/b = 1 and reinforcement stiffness $J_o(t)$ = 1000 kN/m and parameter $\chi(t) = \infty$ and 50 kN/m: a) reinforcement deflection; b) surface deflection; c) reinforcement load, and; d) reinforcement strain. H = height of fill layer and b = width of void.

4 Conclusions

For the range of parameters investigated in the numerical modelling study by Naftchali and Bathurst (2024) the following observations were made:

1. Maximum reinforcement tensile strains and loads occur directly above the centre of the void if the maximum reinforcement strain does not exceed 5%.
2. For reinforcement materials with $J_o(t)$ < 5000 kN/m there are detectable differences in numerical outcomes. The influence of reinforcement rate-dependency (creep) is greater for wider voids (b > 2 m).
3. For sheet reinforcement geosynthetics with little or no rate-dependency, there is a limiting performance benefit for single-layer reinforcement with isochronous secant stiffness greater than $J_o(t)$ = 5000 kN/m for void widths up to 3 m.
4. The rate-dependency of reinforcement materials with the same value of $J_o(t)$ is largely captured by parameter $\chi(t)$. As parameter $\chi(t)$ decreases (i.e., the reinforcement material becomes more rate-dependent), the reinforcement deflections, fill surface deflections, and reinforcement strains increase, and the reinforcement loads decrease. This is because the effective stiffness of the geosynthetic material decreases, leading to the same qualitative behaviour as rate-independent reinforcement ($1/\chi(t) \rightarrow 0$) and decreasing $J_o(t)$.
5. Increasing the void width resulted in an increase in reinforcement deflection, surface deflection, and maximum reinforcement tensile load and strain.
6. The influence of the fill height to void width (H/b) on reinforcement deflection, load and strain in the reinforcement is judged to be small. However, increasing H resulted in decreasing surface deflection.
7. The maximum surface and reinforcement deflections, reinforcement tensile strains and loads decreased with increasing compaction of the granular fill soil in these simulations, when all other parameters were the same.

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