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Required unfactored geosynthetic strength of three-dimensional reinforced soil structures comprised of cohesive backfills

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ABSTRACT

Conservative design of Geosynthetic-reinforced soil structures (GRSSs) is commonly limited to two-dimensional (2D) conditions, ignoring the influence of possible cohesion in backfill material. However, the actual stability of GRSSs is directly influenced by the presence of cohesion – true or apparent – in backfill as well as three-dimensional (3D) effects. In this study, a 3D rational failure mechanism based on the kinematic approach of limit analysis is adopted to assess the stability of GRSSs comprised of cohesive backfills. Within this study, the influence of 3D effects, varying pore water pressures, varying backfill cohesion, and a range of slopes on long-term stability are illustrated in a series of convenient design charts. The results of 3D stability analyses for geosynthetic reinforced walls constructed with cohesive backfills are compared with the results obtained from design guidelines. As expected, when GRSSs are well-drained and relatively narrow in width - or when increasing levels of cohesion are present in the backfill - more stable conditions are realized. For practical scenarios, however, it is critical that cohesive soils should be utilized as backfill with great caution and reliable drainage conditions. Nonetheless, the presented solutions are directly useful towards the assessment of failures of real GRSSs, as they may be constructed with marginal fills that exhibit cohesion, accumulate pore water pressure and often exhibit failure conditions that are three-dimensional in nature.

1. Introduction

The cost-efficiency, ease of construction and good performance have made geosynthetic-reinforced soil structures (GRSSs) a common choice for earth retention and slope stabilization worldwide. Geosynthetic-reinforced soil structures (GRSSs) are commonly constructed with coarse-grained backfill soils to facilitate construction and sufficient drainage. Use of well-drained, coarse backfills often implies that the main mechanical interaction of backfill and reinforcements is cohesionless – that is, only frictional shear strength is considered in the long-term design of the structure. However, in some projects, the soils which displayed cohesive properties may be utilized as backfills due to cost or availability (Jones, 1990; Yang et al., 2012; Jones and Doulala-Rigby, 2014). Often, these soils exhibit a level of cohesion attributable to suction stemming from partial saturation (apparent cohesion) or cementation (true cohesion). This cohesion may result in a more stable structure when drainage is appropriate, but the use of these soils, termed as 'marginal fills' which have significant effects on the performance of GRSSs (e.g., Hatami et al., 2013; Esmaili et al., 2014), are generally discouraged because of its poor drainage (FHWA, 2009). Poor drainage in reinforced slopes constructed with marginal fills may result in a reduction in suction stress, leading to diminished shear strength within the soil and at the soil-reinforcement interface (e.g., Hatami et al., 2014, 2016; Esmaili and Hatami, 2015). Some design codes, such as BS 8006 (1995 and 2010) permit the use of cohesive frictional fill with a limitation of cohesion less than 5 kPa. More recently, AASHTO LRFD *bridge design specifications* (AASHTO, 2012) recommends that marginal fills that exhibit a level of cohesion may utilized as backfill when drainage requirements for GRSSs constructed with marginal fill are satisfactory to manage pore water pressures. With the development of electrokinetic techniques which can effectively transport water and increase the rate of dissipation of pore water pressure in cohesive soil (Glendinning et al., 2005), even cohesive soil with high water contents may be used as backfill in GRSSs (BS8006, 2011). Nevertheless, the most of current methods for designing the internal stability of GRSSs (e.g., Leshchinsky and Boedeker, 1989; Jewell, 1991; Bathurst et al., 2008) are limited to cohesionless backfills as it is the conventional practice, albeit not always employed.

Prior research focusing on using of cohesive backfills in GRSSs (e.g., Jones, 1990; Morrison and Clockford, 1990; Yang et al., 2017) have

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primarily been limited to plane strain conditions. Gular (1990) investigated the possibility of using lime stabilized cohesive soil as a backfill material for geotextile reinforced retaining structures through physical experiments and 2D numerical analysis. The result shows that the addition of lime increases the permeability and shear strength of cohesive soil while improving the stability of reinforced retaining structures. Guler et al. (2007) conducted 2D numerical finite element models to investigate the failure mechanism of GRSS comprised of cohesive backfills, finding that high levels of cohesion may cause external mechanisms to govern stability. Vahedifard et al. (2014) studied the influence of cohesion on seismic stability of GRSSs, demonstrating its influence on the thrust of realized lateral earth pressures. The results are applicable for both static and seismic design of GRSSs in cohesive soils, but are limited to plane strain conditions. More recently, Abd and Utili (2017) employed the kinematical approach of limit analysis (LA) to calculate the required tensile strength and embedment length of geosynthetics in reinforced slopes comprised of cohesive backfills. The results are presented as a series of solution charts applicable for evaluating internal stability design of GRSSs with cohesive backfill. Again, these analyses are limited to plane-strain conditions. Although cohesion provides more shear strength and consequently potential improved stability of GRSSs, many soils that exhibit cohesion are also prone to poor drainage. The presence of poor drainage may result in the accumulation of adverse pore water pressures and possibly unstable conditions. Hence, when cohesive soils are used as backfill in GRSSs, the influence of pore water pressure needs to be involved for long-term stability design.

According to various design codes (e.g., BS 8006, 1995; Hong Kong Geoguide 6, 2002), three-dimensional conditions need to be considered in design of reinforced earth structures. There are various sorts of the geometrical conditions with significant 3D effects in nature, such as turning corner, convex embankments, steep ravines (Lee et al., 1994) and structures of limited width which are not the focus of this study, but should be considered in future modifications of the proposed approach. Prior work focusing on 3D stability has primarily been limited to unreinforced cohesive slopes or GRSSs comprised of cohesionless backfill. Numerous prior studies on the stability analysis of 3D homogeneous slopes illustrate that the cohesion results in significant end effects, greatly increasing the observed stability and influencing the realized critical slip surfaces (e.g., Leshchinsky and Baker, 1986; Gao et al., 2013; Zhang et al., 2016). Gao et al. (2016) used the LA method to estimate the required tensile strength and embedment length of geosynthetics of 3D reinforced slopes constructed with cohesionless backfills. Application of a 3D approach resulted in less required strength and shorter reinforcement embedment length than 2D conditions. These results quantitatively illustrate the level of the conservatism implicit when assessing the stability of GRSS under plane strain conditions. In this study, the analytical model used by Gao et al. (2016) is extended to include the effects of cohesion and associated pore water pressures. By doing so, the presented results highlight the influence of considering 3D conditions on the required reinforcement strength required for long-term stability of GRSSs constructed with cohesive backfills.

2. Formulation

The kinematic LA approach is used in this study to determine the required tensile strength of geosynthetics for 3D reinforced slopes in cohesive backfills. Within the framework of LA, a kinematically admissible failure mechanism first needs to be established in 3D conditions. Michalowski and Drescher (2009) proposed a rotational 3D failure mechanism, which consists of a central cylinder with two end caps described by two log spirals. Gao et al. (2013) demonstrated the criticality of the postulated 3D mechanism for slope stability, therefore the mechanism is adopted here to assess 3D stability of reinforced slopes with cohesive backfills. Fig. 1 illustrates the 3D geometry of rotational failure mechanism for reinforced slopes limited to a width of

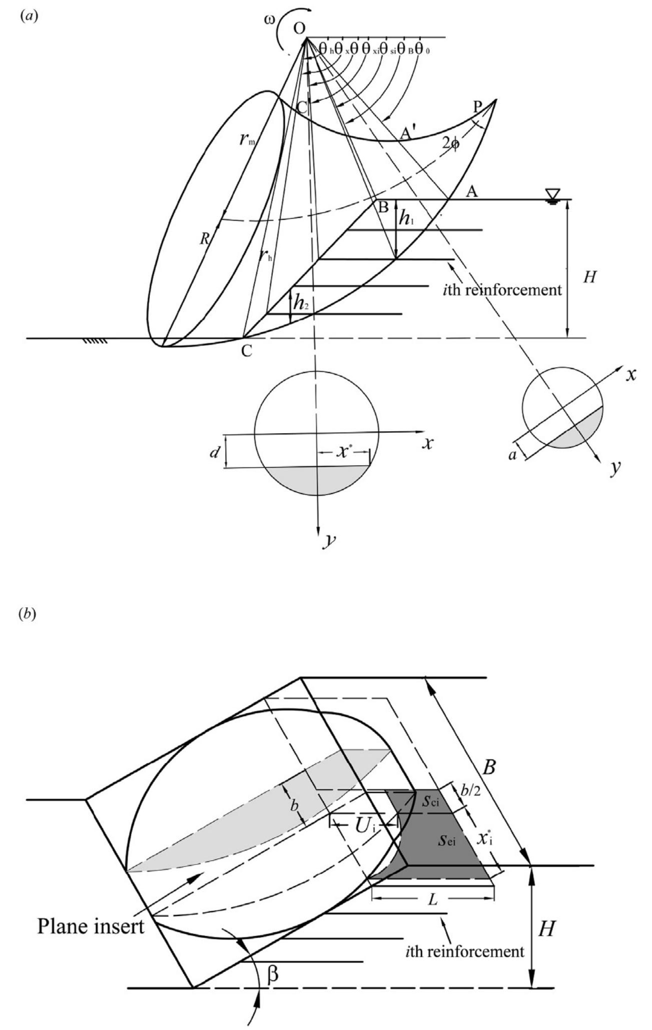

Fig. 1. 3D failure mechanism for reinforced slopes.

B. To formulate the problem, several assumptions are made:

(1) The Mohr-Coulomb failure criterion is used here and expressed as:

$$\tau = c' + (\sigma - u)\tan\varphi' \tag{1}$$

where τ = shear strength of soil; c' = effective cohesion of soil; u = pore water pressure; σ = normal total stress of soil and ϕ' = effective internal friction angle of soil.

(2) The cohesive backfill is homogenous and isotropic.
(3) The reinforcements are assumed to be embedded long enough, so that pullout failure is not considered.
(4) The foundation soil is competent and then the potential slip surface is not allowed to pass through the foundation.
(5) Horizontal, uniaxial reinforcement layers are assumed to contribute the required resistance, rendering a stable slope.
(6) The tensile strength of reinforcement layers can be distributed evenly along the height and width of the reinforced earth structures and the required average tensile strength K_t of reinforcement in an earth structure can be represented in a dimensionless form, defined as:

$$\frac{K_t}{\gamma H} = \frac{n\frac{B}{2}T_t}{\gamma\frac{B}{2}H^2} \tag{2}$$

where T_t = required tensile strength per unit width of a single reinforcement layer; n = number of reinforcement layers; B = width of