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Design of geosynthetic-reinforced slopes in cohesive backfills

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ABSTRACT

Currently, geosynthetic reinforcements for slopes are calculated assuming the ground strength to be purely frictional, i.e. without any cohesion. However, accounting for the presence of even a modest amount of cohesion could allow using locally available cohesive soils as backfills to a greater extent and less overall reinforcement. But cohesive soils are subject to the formation of cracks that tend to reduce slope stability so their presence has to be accounted for in the design of the slope reinforcement. In the paper, limit analysis was employed to derive a semi-analytical method for uniform $c-\phi$ slopes that provides the amount of reinforcement needed as a function of ground cohesion, tensile strength, angle of shearing resistance and of the slope inclination. Both climate induced cracks as well as cracks that form as part of the slope collapse mechanism are accounted for. Design charts providing the value of the required reinforcement strength and embedment length are plotted for both uniform and linearly increasing reinforcement distributions.

From the results, it emerges that accounting for the presence of cohesion allows significant savings on the reinforcement to be made, and that cracks are often significantly detrimental to slope stability so they cannot be overlooked in the design calculations.

1. Introduction

Since the 1980s the use of geosynthetics with the aim of increasing the shear strength of cohesive soils has been investigated (Fourie and Fabian, 1987; Ingold, 1981; Ingold and Miller, 1983; Ling and Tatsuoka, 1994). In the 1990's Zornberg and Mitchell in their review papers on cohesive backfills (Mitchell and Zornberg, 1995; Zornberg and Mitchell, 1994) state that the use of cohesive backfills has led to substantial savings in areas where granular materials are not locally available. More recently, substantial experimentation has been performed to investigate the behaviour of geotextile reinforced cohesive slopes (Hu et al., 2010; Noorzad and Mirmoradi, 2010; Wang et al., 2011). In particular nonwoven geotextiles and geogrids have shown to be effective at increasing the strength of cohesive soils and improving drainage (*e.g.* Portelinha et al., 2013; Portelinha et al., 2014). However, in the methods currently available in the literature, reinforcements are still calculated assuming soils to be cohesionless (de Buhan et al., 1989; Jewell, 1991; Leshchinsky and Boedecker, 1989; Leshchinsky and Hanks, 1995; Michalowski, 1997). This conservative assumption is due to the fact that geosynthetics were initially conceived for cohesionless granular soils and that the first design guidelines published for geosynthetic reinforced earth structures disregard the beneficial effect of cohesion (*e.g.* Jewell, 1996). However, the sixth edition of AASHTO LRFD *bridge design specifications* (AASHTO, 2012), allows for the inclusion of cohesion in the design of geo-reinforced slopes although unfortunately no formulae are provided for this purpose. The AASHTO revisit was prompted by the work of Anderson et al. (2008) which, for example, shows that an amount of cohesion as small as 10 kPa can reduce the thrust against an earth structure of up to 50–75% for typical design conditions. In light of these findings, Vahedifard et al. (2014) have investigated the beneficial effect of cohesion on geosynthetic reinforced earth structures based on limit equilibrium concluding that '*the results clearly demonstrate the significant impact of cohesion on the K_{ae} value*' (K_{ae} being the design seismic active earth pressure coefficient). Unlike Vahedifard et al. (2014), this paper is concerned with the stability of geo-reinforced slopes in the absence of any retaining structure. One of the objectives of this

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Notation

c	cohesion
$\dot{D}$	total energy dissipation rate
$\dot{D}_{r(B-C)}$	energy dissipation rate within the reinforcement along B-C.
$\dot{D}_{r(C-D)}$	energy dissipation rate within the reinforcement along C-D.
$\dot{D}_{s(B-C)}$	energy dissipation rate within the soil along B-C due to crack formation
$\dot{D}_{s(C-D)}$	energy dissipation rate within the soil along C-D.
$d\dot{D}_r$	infinitesimal energy dissipation rate within reinforcement
$f_1, f_2, f_3, \ldots, f_6$	functions to calculate the external work rate made by soil weight
f_b	bond coefficient between the soil and geosynthetic-reinforcement
f_w	function to evaluate the external work rate done by the pore water pressure
g_1	function for the dissipated energy rate made by the soil along the log-spiral slip surface (C-D)
g_2	function for the dissipated energy rate made by the reinforcement along the log-spiral slip surface (C-D)
g_3	function for the dissipated energy rate made by the soil along the crack (B-C)
g_4	function for the dissipated energy rate made by the reinforcement along the crack (B-C)
H	slope height
h	crack depth
h_w	height of water within the crack
i	denotes ith layer of reinforcement
j	number of reinforcement layers that pull-out
K	generic average tensile strength of reinforcement
K_t	average tensile strength of a uniformly distributed reinforcement
$L_{c(i)}$	length of reinforcement layer i as illustrated in Fig. 2a
$L_{e(i)}$	effective length of reinforcement layer i resisting pull-out failure
L_r	total length of the reinforcement layers
l_1, l_2	lengths defined in Fig. 2a
n	number of reinforcement layers
r	generic radius for the log-spiral slip surface (C-D)
r_c	distance from point P to any point along the crack (B-C)
r_u	pore pressure coefficient
r_χ	reference radius of the log-spiral slip surface (C-D)
r_ζ	distance from point P to the crack tip
r_υ	distance from point P to the slope toe
T	tensile strength of a reinforcement layer
t	dimensionless coefficient representing the soil tensile strength
$\dot{\boldsymbol{u}}$	displacement rate along the log-spiral slip surface (C-D)
$\dot{\boldsymbol{u}}_{\boldsymbol{c}}$	displacement rate along the crack
w	width of shear band along the log-spiral slip surface (C-D)
w_c	width of crack (B-C)
$\dot{W}$	total external work rate
$\dot{W}_1, \dot{W}_2, \dot{W}_3, \ldots, \dot{W}_6$	external work rates for different regions
$\dot{W}_s$	external work rate done by the soil weight
$\dot{W}_w$	external work rate done by the pore water pressure
x	horizontal distance measured from slope toe to the crack (B-C)
y	vertical upward coordinate departing from the slope toe
$z_{(i)}$	depth of reinforcement layer i below the slope crest
$z^*_{(i)}$	overburden depth of reinforcement layer i which for gentle slopes can be less than z_i
β	slope face inclination
γ	unit weight of soil
δ	angle made by line P-I, see Fig. 9a
$\dot{\varepsilon}$	strain rate in the direction of the reinforcement layer
ζ	angle between line P-C and the horizontal
η	angle between the crack and the reinforcement layer
$\dot{\theta}$	angular velocity
$\theta_{(i)}$	angle related to the intersection of the failure surface with the i-layer
θ	generic angle of the log-spiral part of the failure surface
θ_{1-2}	angle marking the boundary between zone 1 and 2 of the slope in Fig. 11.
λ	angle between the displacement rate vector u_c and the crack
μ	angle between line P-B and the horizontal
σ	normal stress
σ_t	soil tensile strength
σ_t^{M-C}	uniaxial tensile strength consistent with the Mohr Coulomb failure criterion
σ_c^{M-C}	uniaxial compressive strength consistent with the Mohr Coulomb failure criterion
τ	shear stress
υ	angle between line P-D and the horizontal
ϕ	angle of shearing resistance
χ	angle between line P-F and the horizontal

paper is to provide a method for the design of slope reinforcements where the effect of cohesion is accounted for that may feed into future new guidelines for geosynthetic reinforced slopes. The value of cohesion exhibited by the backfill is likely to change over time due to weather action, *e.g.* cycles of wetting – drying (Take and Bolton, 2011). The determination of suitable values of cohesion and its degradation over time are discussed in detail in section 4.

In general, cohesive soils manifest limited, if not negligible, tensile strength so they are subject to the formation of cracks. The development of cracks in $c-\phi$ geo-reinforced slopes leading to slope instability has also been observed in post-earthquake deformations (e.g Ling et al., 2001) as well as in experiments in geotechnical centrifuge *e.g.* Porbaha and Goodings (1996). Moreover, Baker (1981), Michalowski (2013) and Utili (2013) investigating unreinforced slopes conclude that when the presence of cracks is neglected, slope stability may be significantly overestimated. In this paper, it will be shown that in order to safely design the geo-reinforcement of a slope accounting for the beneficial effect of cohesion, the possibility of the onset of a single crack forming as part of the slope failure mechanism as well as the