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Technical note

Geosynthetic-reinforced soil structures with concave facing profile

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ABSTRACT

This paper presents a new method to determine the optimal profile of facing elements in geosynthetic-reinforced soil structures. Flexibility of some facing systems and advances in construction technology allow construction of reinforced soil structures with a non-planar cross section. In this study, the facing profile of a concave geosynthetic-reinforced soil structure (referred to as CGRSS) is idealized by a circular arc defined by a single variable, the Mid-Chord Offset (MCO). For a given setback and elevation change, the optimal facing profile is determined by seeking the MCO which, for a given margin of safety, yields the least tensile load in the reinforcement layers. The proposed procedure for finding the optimal facing profile is incorporated into a limit equilibrium-based log spiral formulation to determine the required tensile strength of the reinforcement. Results are presented in a set of charts showing the required unfactored tensile strength, MCO, and mode of failure for various friction angles, batter angles, and seismic coefficients. It is shown that CGRSSs can decrease the required tensile strength of the reinforcement by up to 30% under static and pseudo-static conditions. This observation justifies employing concave facing profiles in practice.

1. Introduction

Geosynthetic-reinforced soil structures (GRSSs), including geosynthetic-mechanically stabilized (MSE) walls and geosynthetic-reinforced slopes (GRS), are widely used for stabilizing steep slopes and walls. Well-established design methodologies, relative ease of construction, and satisfactory record of performance under normal and extreme loading conditions have established GRSS as an economically and technically viable choice for both public and private sectors. Main components of a GRSS include the reinforced soil, geosynthetic reinforcement layers, and a facing system. Various facing systems are available for GRSSs including geosynthetic wrap-around facing, masonry block units, gabions, welded wire mesh, vegetation, etc (e.g., FHWA, 2009). Facing systems provide protection against backfill sloughing and erosion, and in some cases, serve as drainage paths. Since facing elements are the only visible component of a GRSS, the choice of facing system will also influence aesthetics of the structure. Flexibility in the arrangement of a majority of facing systems has allowed construction of GRSS with multi-tiers or curved profile in longitudinal section. Using bi-linear and multi-tiered configurations can reduce tensile loads in reinforcement layers, especially for taller GRSSs. These configurations can enhance the aesthetics of the built structure and also can lead to a more economical design (e.g., Leshchinsky and Han, 2004; Ruan et al., 2015).

Several analytical and numerical studies have been conducted to optimize the number, arrangement, and strength of reinforcement layers in GRSSs (e.g., Basha and Babu, 2012; Leshchinsky, 2014; Xie and Leshchinsky, 2015). However, similar to other engineered slopes and earthen structures, GRSSs are commonly designed and built only with a planar facing profile in cross section. Inspired by some natural concave slopes, recent studies have shown that unreinforced slopes with a concave profile in cross section offer higher stability (e.g., Sokolovskiĭ, 1960; Utili and Nova, 2007; Jeldes et al., 2013) and better erosion resistance (e.g., Rieke-Zapp and Nearing, 2005; Schor and Gray, 2007; Jeldes et al., 2014) when compared with the equivalent planar slopes. Few attempts have been made to analyze concaves slopes and to quantify the contribution of such concave profiles to stability and erosion resistance of earthen slopes (e.g., Sokolovskiĭ, 1960; Utili and Nova, 2007; Jeldes et al., 2013). Sokolovskiĭ (1960) used the slip-line field theory and showed that the slope surface at the limit equilibrium (LE) state has a concave

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Notation

A_1	log spiral constant
c	design cohesion
D	height of the line of action of the resultant force from toe
D_i	height of the line of action of the ith reinforcement force from toe
FS	factor of safety
H	slope/wall height
I	arc angle
k_h, k_v	horizontal and vertical seismic coefficients
LC	long cord
MCO	mid-chord offset
$\mathrm{MCO}_{\max}$	maximum MCO forming a vertical tangent at the crest
$\mathrm{MCO}_{\mathrm{opt}}$	MCO representing the optimum concavity (i.e., yielding the minimum T)
M_{R_h}	moment due to R_h
M_q	moment induced to the uniform surcharge q
n	number of reinforcement layers
q	uniform surcharge
R_c	circular arc radius
R_h	horizontal resistance of the facing at the bottom of the slope
R	log spiral radius
S_v	vertical spacing between reinforcement layers
T	resultant of all reinforcement forces
$T_{\max\text{-}i}$	maximum tensile force in the ith reinforcement
W	weight of failure mass
x, y	coordinates of any point along the curved facing profile
x_{cc}, y_{cc}	coordinates of the center of the curved facing profile
x_F, y_F	coordinates of any point along the log spiral failure surface
x_{CG}, y_{CG}	coordinates of the center of gravity of the failure mass
x_{CL}, y_{CL}	coordinates of the pole of log spiral
Y_e	height where the slip surface exits the facing profile
α	backslope angle
γ	unit weight
ΔA	soil volume reduction per unit length of the slope
β_1, β_2	angle of rotation to the points where the log spiral exits and enters the slope
ζ	angle between toe and circular arc of the planar facing profile
ψ	$\tan(\phi)$
ϕ	design internal angle of friction
ω	batter (=90° − Average slope angle)

profile. Jeldes et al. (2013) used the Sokolovskiĭ solution for a weightless medium and presented an approximate solution representing the optimal concave profile of slope. Jeldes et al. (2014) used the latter approximate solution along with an erosion model and showed that concave slopes yield 15–40% less sediment than alternative planar slopes with the same factor of safety. Utili and Nova (2007) used two log spirals: one spiral to represent the concave slope surface and the other for the slip surface, in the context of the upper bound limit analysis (LA) method. All the aforementioned methods only investigated concave profiles for unreinforced slopes under static loading.

Flexibility of some facing systems (e.g., wrapped-faced, masonry block units) and advances in construction technology allow us to take advantage of the higher stability of concave profiles in reinforced soil structures and to build GRSS with concave facing profiles. In this study, the facing profile of a concave GRSS (referred to as CGRSS) is idealized by a circular arc defined by a single variable, the Mid-Chord Offset (MCO). The effects of using concave facing profile under static and pseudo-static conditions are studied by implementing the proposed concave profile into a LE-based log spiral formulation. Theoretically, this study shows the impact of face geometry on the stability and required tensile strength of reinforcement in GRSSs. To the best of the authors' knowledge, this impact has not been investigated for reinforced earthen structures yet. Practically, the proposed procedure for employing concave profiles can potentially lead to more economical designs by decreasing the required tensile strength of reinforcement and/or backfill volume. The proposed approach is developed by employing a conventional design procedure (i.e., LE), suggesting that it can be readily implemented in practice.

2. Formulation of concave facing profile

The concave facing profile of a CGRSS for given height is formulated using a circular arc defined by a single parameter, MCO. The optimal facing profile is determined by seeking the MCO that yields the least tensile load in the reinforcement. An optimization problem is defined based on the consideration that the locations of toe and crest are prescribed by the project.

Fig. 1 shows the notation and details of the idealized circular arc geometry which is used to idealize the concave facing profile. As shown in Fig. 1b, the curvature of the arc is controlled via MCO, which is a commonly used term in surveying to define circular arcs. The single parameter MCO is the distance between Points 4 and 5 in Fig. 1b.

It is desired to obtain the coordinates of any point along a concave profile as a function of MCO, the batter, ω, and the slope/wall height, H. Note that ω is defined as the orientation of a straight line connecting the toe (Point 1 in Fig. 1a) to the crest (Point 3 in Fig. 1a) relative to the vertical axis. For the given CGRSS geometry, the Long-Chord (LC) is known, which is defined as the straight line between Points 1 and 3 (i.e., the length of the equivalent planar profile). According to Fig. 2b, MCO and LC can be defined as:

$$\mathrm{MCO} = R_c\left(1 - \cos\left(\frac{I}{2}\right)\right) \tag{1}$$

$$\mathrm{LC} = 2R_c \sin\left(\frac{I}{2}\right) \tag{2}$$

where R_c and I are the arc radius and the arc angle, respectively, and can be determined as:

$$R_c = \frac{H^2}{8\mathrm{MCO}}\left(1 + \tan^2\omega\right) + \frac{\mathrm{MCO}}{2} \tag{3}$$

$$I = 4\tan^{-1}\left(\frac{2\mathrm{MCO}\cos\omega}{H}\right) \tag{4}$$

The center of the circular arc (x_{cc}, y_{cc}) is located on the bisector of LC and can be defined as: