Geotextiles and Geomembranes xxx (2017) 1–11

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

journal homepage: www.elsevier.com/locate/geotexmem

Limit state design framework for geosynthetic-reinforced soil structures

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ARTICLE INFO

Article history:
Received 4 March 2017
Received in revised form
9 August 2017
Accepted 12 August 2017
Available online xxx

Keywords:
Geosynthetics
MSE walls
Reinforced steep slopes
Limit equilibrium
Slope stability

ABSTRACT

Conventional design of geosynthetic-reinforced soil structures is divided into two categories, walls and slopes, based on the batter of its facing system. Internal stability, characterized as sufficient reinforcement anchoring and strength, is performed using earth pressure-based design criteria for reinforced walls while reinforced slopes are founded on limit equilibrium (LE) based slope stability analyses. LE analyses are also used to assess the global or compound stability of both types of structures, accounting for the geometry of the reinforced, retained and foundation soils. The application of LE-based methods typically results in determination of a slip surface corresponding to the lowest attained Safety Factor (*SF*), known as the Factor of Safety (*Fs*); however, it yields little information about reinforcement loading or connection load. In this study, use of the analyzed spatial distribution of slip surfaces known as a *Safety Map*, is modified to discretize reinforcement layers and the required tensions to attain a prescribed constant *Fs* at any location in the reinforced soil mass. This modified framework, implemented through an iterative, *top-down* procedure of LE slope stability analyses originating from the crest of a reinforced structure and exiting at progressively lower elevations on the facing, enables the determination of a *Tension Map* that illustrates the required distribution of reinforcement tension to attain a prescribed limit state of equilibrium. This tension map is directly constrained by a pullout capacity envelope at both the rear and front of each reinforcement layer, providing a unified, LE-based approach towards assessing an optimal selection of mutually dependent strength *and* layout of the reinforcement. To illustrate the utility of the Limit State framework, a series of instructive examples are presented. The results demonstrate the effects of facing elements, closely-spaced reinforcements, secondary reinforcement layers, and is compared to conventional design approaches.

1. Introduction

Geosynthetics have been widely used as an economical means of soil reinforcement in both walls and slopes in recent years. Current design of reinforced soil structures in the United States distinguishes between slopes and walls using the batter angle as a criterion. When the inclination of the face is equal to or less than 20°, the structure is defined as a reinforced wall. Conversely, when the batter is greater than 20°, it is defined as a reinforced slope (Berg et al., 2009; AASHTO, 2012; NCMA, 1997). These different soil structures employ different design methodologies, potentially leading to significantly different outcomes. This inclination-based design distinction simplifies the design of walls, requiring a synthesis of basic, semi-empirical calculations to evaluate internal and external stability (with the exception for global or compound stability). While the aforementioned approach to wall design results in safe structures, it is not consistent with traditional and well-established geotechnical design of similar structures that are 'arbitrarily' differentiated by batter: slopes. Evaluating design of reinforced slopes and walls can be considered as a subset of slope stability that considers traditional slope problem with the added forces of elements such as reinforcements and facing, constructed over a foundation soil (Leshchinsky and Reinschmidt, 1985; Leshchinsky and Boedeker, 1989; Wright and Duncan, 1991, Leshchinsky et al., 1995). In these analyses, slope inclination (or batter) is just a typical design variable, not a delineator of calculation convenience. Use of a unified approach in limit state design of reinforced 'walls' and 'slopes' reduces confusion related to the

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http://dx.doi.org/10.1016/j.geotexmem.2017.08.005

Please cite this article in press as: Leshchinsky, D., et al., Limit state design framework for geosynthetic-reinforced soil structures, Geotextiles and Geomembranes (2017), http://dx.doi.org/10.1016/j.geotexmem.2017.08.005

mechanics behind design. It offers consistency regardless of the structure being considered thus lessens the level of judgment and subjectivity associated with designs, especially of structures having complex geometries and non-uniform soil profiles – both realistic scenarios for reinforced soil structures.

Limit equilibrium (LE) analysis has been used successfully in the design of complex and critical structures (e.g., tall dams) for many decades. The LE formulation requires governing assumptions in statics and/or geometry of failure (i.e. kinematics). Hence, there are a variety of LE methods, each of which is based on different assumptions (Duncan, 1996). The simplicity and demonstrated performance of LE approaches have cemented it as a mainstream design tool in the US.

Limit state analysis, including LE, assumes that the *design* strength of the soil in consideration is mobilized. The degree of mobilization (or utilization) signifies the margin or factor of safety, *Fs*. Reinforcement is installed in slopes that otherwise are inherently unstable. That is, at an actual limit state the *design* strength of the soil is fully mobilized (i.e. $Fs = 1.0$) and stability hinges upon the mobilized tensile resistance of the reinforcement. At that state, design should ensure that the long-term strength of the reinforcement will be available throughout the reinforcement (e.g., Leshchinsky et al., 2016). An implicit assumption in this concept is that the reinforcement will not rupture as the soil deforms during mobilization of its strength (e.g., Liu, 2016). Often this phenomenon is referred to as compatibility. Geosynthetic reinforcements are generally ductile ('extensible'), capable of developing substantial strain (typically >8%) before rupture. Such planar strains are much larger than those needed for granular compacted backfill to mobilize its strength (i.e., to form an 'active' mass). From this perspective, combined with experimental and numerical investigations reviewed by Leshchinsky et al. (2016), the limit state concept and LE in particular are suitable for design of geosynthetic reinforced slopes/walls. This assertion is supported by the performance of numerous reinforced slopes designed and constructed over the past three decades as reported in proceedings of many relevant conferences. However, reported experimental and numerical confirmation of relatively brittle (i.e., 'inextensible') reinforcement, designed based on limit state analysis, is scarce (Leshchinsky et al., 2016). Hence, the question of compatibility of inextensible reinforcement in the context of limit state still remains. Consequently, the scope of this study is limited to extensible reinforcement that exhibits ductile behavior relative to the soils involved.

Note that while LE is employed to analyze the limit state in this study, one may use alternative approaches, such as *limit analysis*, LA, of plasticity (Rowe and Ho, 1992; Xie and Leshchinsky, 2015; Smith and Tatari, 2016). Furthermore, numerical methods that can deal with limit state, such as finite element (FE) and finite difference (FD) analyses may also be implemented within the context of the framework (Leshchinsky and Han, 2004; Leshchinsky and Vulova, 2001; Mohamed et al., 2014; Ambauen et al., 2015). However, while continuum mechanics-based numerical methods are insightful, implementation of these approaches in ordinary design may add unnecessary complexity.

2. Safety map

Although various LE stability analyses have been developed for design of reinforced slopes (e.g. Duncan and Wright, 2005), few discuss specific, yet practical details associated with mobilized tensile resistance along reinforcements. Baker and Klein (2004a, 2004b) modified the top-down approach by Leshchinsky (1992) using planar surfaces. Han and Leshchinsky (2006) used an alternative approach to Baker and Klein (2004a) considering more efficient load distribution among reinforcement layers. Leshchinsky et al. (2014) used log spiral surfaces to calculate the required tensile resistance along the reinforcement, including at the connection to the facing, providing considerations for a LE design framework. The use of log spiral enabled examination of non-vertical reinforced slopes as planar surfaces then become less critical. Modification and generalization of this framework to deal with realistic problems is presented in the *Tension Map* section followed by a section of *Illustrative Examples*.

It is noted that stability of reinforced soil structures is a subset of slope stability problems and some design codes allow for LE-based design of such structures (Leshchinsky et al., 2016). FHWA and AASHTO require LE design of reinforced *slopes*, arbitrarily defining it as having a maximum inclination of 70°, while requiring LE assessment of global stability of reinforced *walls* (i.e., inclination $\geq 70°$) as a final design step. LE analysis is recognized by FHWA and AASHTO as a legitimate strength limit state design tool; however, its implementation is lacking.

Use of LE for slope stability (reinforced or unreinforced) requires iteration of multiple slip surfaces until a failure surface that corresponds to a critical, minimum *Fs* is determined. One means of demonstrating this process graphically is the *safety map* methodology (Baker and Leshchinsky, 2001). In addition to illustrating the relative spatial stability of a given geotechnical problem, the distribution of shear surfaces can inform the relative tensile mobilization of reinforcements in a reinforced soil structure using an LE approach. The safety map is used within this study to select a satisfactory layout and strength of reinforcements. It is presented through an instructive simple example.

The safety map, in context of reinforced soil, indicates whether the assumed strength and length of reinforcement produces adequate stability. The specified strength of reinforcement along its length is illustrated in Fig. 1. Note that at any location along the reinforcement, its strength is limited by either its long-term intrinsic rupture strength or its pullout resistance, whichever value is smaller. Pullout resistance is a function of the overburden

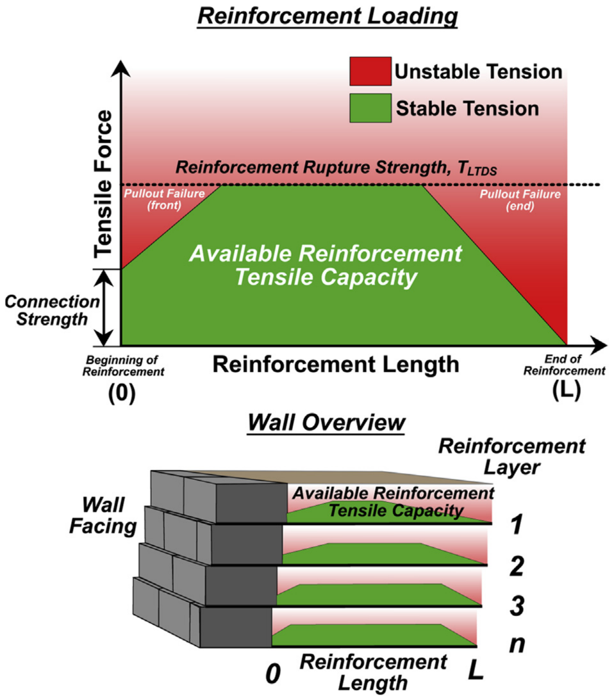

Fig. 1. Available tensile resistance along reinforcement in current design.

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