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Limit analysis of reinforced embankments on soft soil

Colin C. Smith*, Alireza Tatari

Department of Civil and Structural Engineering, The University of Sheffield, Mappin Street, Sheffield, S1 3JD, UK

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ABSTRACT

Previous research into the stability of reinforced embankments founded on soft soil has presented limited studies based on a narrow range of assumed failure mechanisms. In this paper comprehensive parametric studies of reinforced and unreinforced embankments were conducted using the general purpose computational limit analysis approach Discontinuity layout optimisation (DLO). Comparisons with previous Limit Equilibrium and FE results in the literature showed good agreement, with the DLO analysis generally able to determine more critical failure mechanisms. Simplified, summary design envelopes are presented that allow critical heights and reinforcement strengths to be rapidly determined based on soft soil strength and depth, and show how the balance between soft soil strength and reinforcement strength combines to affect overall stability.

1. Introduction

The use of a basal geosynthetic reinforcement for an embankment constructed on soft soils can significantly enhance stability and allow construction to heights substantially higher than could be achieved without reinforcement (Rowe and Soderman, 1987). Two common analysis methods used by geotechnical engineers to check the stability of embankments over soft soil are (i) conventional limit equilibrium such as Coulomb wedge or the method of slices and (ii) the finite element (FE) method. The general concept of the former method is to find the most critical slip surface with the lowest factor of safety. This may be defined as the shear strength of the soil divided by shear stress required for equilibrium, Duncan (1996).

Most limit equilibrium methods indirectly model the reinforcement as a single representative force which acts at the intersection between the reinforcement and the failure mechanism. The failure mechanism may be modelled as a slip-circle using the method of slices e.g. Rowe and Soderman, 1985, Hird, 1986, Sabhahit et al., 1994, or as a log-spiral e.g. Leshchinsky, 1987, Leshchinsky and Smith, 1989 or using a translational mechanism e.g. Jewell, 1988.

While limit equilibrium is simple and straightforward it makes an assumption about the nature of the failure mechanism which can lead to inaccuracy. In contrast FE methods can accurately model both working conditions and failure modes, representing the reinforcement as a structural membrane with an axial stiffness and negligible flexural rigidity. More recent work in the literature has focused on this method e.g. Rowe and Soderman (1985, 1987); Duncan and Schaefer (1988); Hird and Kwok (1989); Hird et al. (1990); Chai and Bergado (1993); Rowe and Hinchberger (1998); Rowe and Li (2005) and Zhang et al. (2015). However, modelling the embankment problem by finite elements typically requires significant time and is more complex with regard to choosing the problem parameters in comparison with limit equilibrium methods (Duncan, 1996).

Recently the advent of numerical direct methods has allowed the rapid solution of limit analysis problems in a fully general way. These provide a middle way between the simplification in limit equilibrium analysis and the relative complexity of the FE method. An elasto-plastic analysis typically requires many increments in order to find the critical factor of safety in contrast to a computational limit analysis approach which can directly determine the collapse state through optimization. One of the main advantages of limit analysis over FE methods is it requires only two strength parameters for any material modelled: the cohesion, c' or c_u, and the angle of shearing resistance, ϕ', of the soil. Computational limit analysis approaches have been recently used to analysis a range of reinforced soil problems e.g. Leshchinsky et al. (2012), Clarke et al.

* Corresponding author. Tel.: +44 114 2225717.
E-mail addresses: c.c.smith@sheffield.ac.uk (C.C. Smith), a.tatari@sheffield.ac.uk (A. Tatari).

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(2013) and Vahedifard et al. (2014). These papers utilise the discontinuity layout optimisation method (Smith and Gilbert, 2007), which is adopted in this paper to undertake a parametric study of embankment stability.

The aim of this paper is to illustrate how reinforced embankments can be modelled in limit analysis; to investigate the range of failure modes that can occur and to produce a series of non-dimensional design charts for different geometries of embankment which allows the necessary minimum embankment soil strength and reinforcement strength required for stability to be determined in terms of the embankment geometry, base soil strength, soil/geotextile interface coefficient and surcharge. This provides a significantly more comprehensive set of charts compared to previous works that have utilised Limit Equilibrium such as Leshchinsky and Smith (1989), Duncan et al. (1987), Leshchinsky (1987) and Hird (1986) without using an analysis which typically adopts only one mode of failure.

2. Mechanics of reinforced embankments

Manceau et al. (2012) recommend three ULS states should be considered as follows: (i) deep-seated failure, (ii) lateral sliding (iii) extrusion. While deep seated failure requires an analysis such as method of slices or equivalent, the latter two mechanisms can be analysed relatively simply using limit equilibrium. Jewell (1988), presented simple analytical equations based on force equilibrium for the analysis of reinforced and unreinforced embankments of geometry depicted in Fig. 1 and described by the parameters listed in Table 1 (in the analysis $c' = 0$ was assumed). These provide useful equations for calibration and a conceptual model of two of the main mechanisms of collapse.

In Fig. 2a, the reinforcement provides resistance against lateral failure of the embankment itself with friction on the upper reinforcement surface of $\alpha_s \tan\phi'$ where α_s is the reinforcement interface coefficient. Equilibrium analysis gives the following required side slope gradient n for stability:

$$n > \frac{K_a}{\alpha_s \tan\phi'}\left(1 + \frac{2q}{\gamma H}\right) \tag{1}$$

where the design value of active earth pressure coefficient, $K_a = (1 - \sin\varphi')/(1 + \sin\varphi')$.

In Fig. 2b the reinforcement provides shear resistance against lateral squeezing of the soft soil beneath the embankment. Equilibrium analysis of the deep failure mechanism gives the factor of safety F_s on the soft soil strength as follows:

Table 1
Reinforced embankment analysis parameters.

Symbol	Definition
c'	Cohesion intercept of the embankment fill
ϕ'	Friction angle of embankment fill
γ	Unit weight of embankment fill
c_u	Shear strength of soft soil
R	Rupture strength of reinforcement per unit width
H	Height of embankment
W	Width of top of embankment
D	Thickness of soft soil
q	Surcharge
n	Side slope gradient ($1V{:}nH$)
α_c	Interface coefficient between reinforcement and soft soil
α_s	Interface coefficient between reinforcement and embankment fill

$$F_s = \frac{c_u}{q + \gamma H}\left(4 + (1 + \alpha_c)\frac{nH}{D}\right) \tag{2}$$

The minimum force R within the reinforcement required to provide the stability for the failure mechanism in Fig. 2b is given by Eq. (3):

$$R = \gamma H^2\left(\frac{\alpha n D}{4D + (1 + \alpha)nH} + \frac{K_a}{2}\right) \tag{3}$$

Jewell also presented the following equation for checking the stability of an unreinforced embankment (the failure mechanism is not present here):

$$F_s = \frac{c_u}{\gamma H}\left(\frac{8D + 2nH}{2D + K_a}\right) \tag{4}$$

Such limit equilibrium equations have the value of simplicity and clarity but it is not necessarily clear whether these are conservative or non-conservative in all cases.

3. Discontinuity layout optimisation (DLO)

3.1. Geotechnical analysis

Discontinuity layout optimisation is a computational limit analysis method which is able to identify the critical failure mechanism and collapse load for any geotechnical stability problem. Examples of this analysis approach applied to soil only problems (with no reinforcement) may be found in Smith and Gilbert (2007, 2013) and Leshchinsky (2015). Fig. 3 illustrates the stages in the DLO procedure for finding the layout of sliplines that form

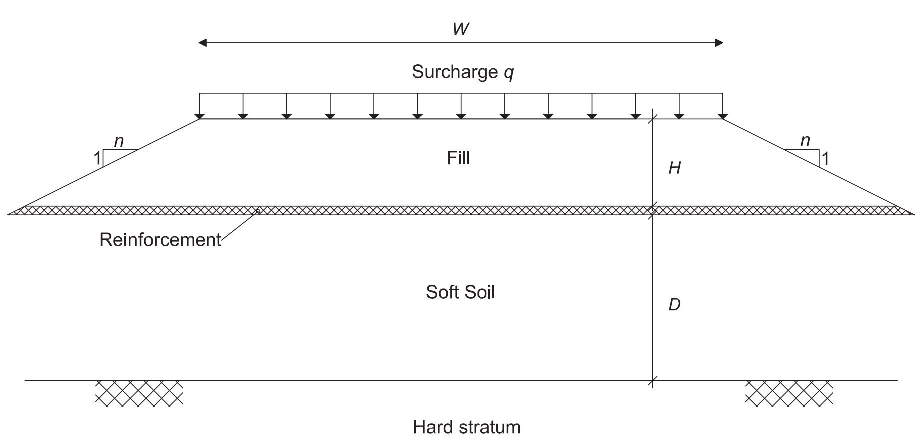

Fig. 1. Geometry of embankment model.