Computers and Geotechnics 70 (2015) 178–189

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Slope stability analysis by means of finite element limit analysis and finite element strength reduction techniques. Part II: Back analyses of a case history

F. Tschuchnigg [a,*], H.F. Schweiger [a], S.W. Sloan [b]

[a] Computational Geotechnics Group, Institute for Soil Mechanics and Foundation Engineering, Graz University of Technology, Austria
[b] ARC Centre of Excellence for Geotechnical Science and Engineering, School of Engineering, University of Newcastle, Australia

ARTICLE INFO

Article history:
Received 4 May 2015
Accepted 4 July 2015
Available online 21 August 2015

Keywords:
Finite element limit analysis
Finite element method
Strength reduction technique
Slope stability
Non-associated plasticity
Back analysis

ABSTRACT

This paper deals with a back analysis of a slope failure. The case history investigated is located in an alpine environment in central Europe and is characterized by a very steep original terrain, indicating *in situ* soil with high strength. To study the factor of safety, two different approaches applying the so-called φ'/c' reduction are used, namely finite element limit analysis and strength reduction finite element analysis. Comparison of a strength reduction technique with rigorous finite element limit analysis confirms that the factors of safety (FoS) obtained are very similar for associated plasticity, an intrinsic assumption of limit analysis. For non-associated plasticity, a modified version of the so-called Davis approach has been applied because it has been shown that the original formulation proposed by Davis works well when the FoS is defined in terms of loads but is not appropriate when the FoS is defined in terms of soil strength. The results show that, with the modified Davis parameter, both strength reduction finite element analyses and finite element limit analyses provide very similar factors of safety. The key advantage of limit analysis, however, is that the value of the FoS can be bracketed from above and below with upper and lower bound calculations.

1. Introduction

The case history investigated is a slope failure located in the alpine region of central Europe. It concerns a geotextile reinforced embankment on a steep slope. It has to be mentioned that the studies presented are based on a real boundary value problem, but the geometrical conditions are slightly modified for the purpose of this study. Nevertheless, the findings and conclusions are valid for steep slopes found frequently in alpine regions.

The original design of the project was done with Limit equilibrium analyses (LEA), as proposed e.g. by Janbu [9], Bishop [1], Morgenstern and Price [15] and Spencer [20]. An overview of various limit equilibrium methods and a discussion of their shortcomings and merits can be found in Duncan [7] and Krahn [12]. Due to their widespread use, an informed awareness of the limitations of these methods in practice seems to have been lost. However, other procedures for calculating factors of safety, such as strength reduction techniques performed with the displacement-based finite element method (e.g. [2,8,6]), are increasingly being benchmarked against limit equilibrium methods. For slope stability analysis a reasonable agreement between these two types of methods is usually found (e.g. [4]). Nonetheless, the limit equilibrium method (which for slopes is based on the method of slices) does not yield unique factors of safety due to the inherent assumptions that underpin it. These assumptions include the need to define the distribution of the inter-slice forces, as well the shape of the failure surface, in advance and may result in the computed failure mechanism not being kinematically admissible. Finite element limit analysis, on the other hand, provides rigorous upper and lower bounds on the factor of safety (see, e.g. [16,17,18,13,14,10,19]) and is therefore used in this paper to give reference solutions for comparison with those from the displacement finite element strength reduction technique. As limit analysis implicitly assumes an associated flow rule, the approach suggested by Davis [5], as well as modified versions of the Davis approach that are explained in Part I of this paper, are used for non-associated plasticity.

In geotechnical engineering no unique definition for the factor of safety exists. Indeed, in bearing capacity problems it is common

* Corresponding author at: Computational Geotechnics Group, Institute for Soil Mechanics and Foundation Engineering, Graz University of Technology, Rechbauerstraße 12, A-8010 Graz, Austria. Tel.: +43 (0)316 873/6729; fax: +43 (0)316 873/6232.

E-mail address: franz.tschuchnigg@tugraz.at (F. Tschuchnigg).
URL: http://www.soil.tugraz.at/ibg/cgg (F. Tschuchnigg).

http://dx.doi.org/10.1016/j.compgeo.2015.07.019

Nomenclature

c'	effective cohesion
$c'_{mob.}$	mobilized effective cohesion during SRFEA
c^*	reduced cohesion according to Davis [5]
$l_{spacing}$	spacing between the anchors
u	total displacements
α_S	slope angle
γ	unit weight
ε_1	major principal strain
ε_3	minor principal strain
φ'	effective friction angle
$\varphi'_{mob.}$	mobilized effective friction angle during SRFEA
φ^*	reduced friction angle according to Davis [5]
ν'	Poisson's ratio
ψ'	dilatancy angle
$\psi'_{failure}$	dilatancy angle at failure
Λ	amount of non-associativeness ($\varphi' - \psi'$)
E'	Young's modulus of the soil
EA	axial stiffness
EI	bending stiffness
F_{max}	ultimate anchor capacity
FoS	factor of safety
FoS_{UB}	factor of safety obtained with upper bound analysis
FoS_{LB}	factor of safety obtained with lower bound analysis

practice to define the factor of safety in terms of the load capacity, whereas in slope stability problems the safety factor is usually defined with respect to the soil strength. The latter definition is used throughout this paper.

2. General information

2.1. Project overview

Of concern is the construction of a connection road between a main road and a valley. Due to the geological conditions it was necessary to construct geotextile reinforced embankments on the downhill side of the connection road. The preliminary design consisted of a geotextile reinforced embankment with a total height of approximately 25 m and a slope inclination α_s of 60°. In parts with constricted space, rock fill constructions with higher slope inclinations were also designed. This paper focuses solely on the geotextile reinforced embankment on the downhill side, therefore construction details are provided only for these parts of the project. Fig. 1a shows a top view of the project while Fig. 1b illustrates details of the construction along cross section A-A, which is the highest and thus the most critical cross section.

2.2. Soil conditions

The soil profile for the numerical simulation is based on the site investigations consisting of trenches, dynamic probing (DBM) and core drillings with depths down to 25.0 m from the surface. These investigations showed sandy gravel material with a medium to dense density. Due to the fact that the inclination of the original terrain is almost 40°, the *in situ* strength parameters of the soil must be relatively high. The proposed parameters given in the geotechnical report are a unit weight γ of 22.0 kN/m^3, an effective friction angle φ' of 40°, and an effective cohesion c' of 0–3.0 kPa. Fig. 2 shows the *in situ* conditions along cross section A-A. The data of the original terrain is based on an intense geodetical measurement program. The average inclination of cross section A-A is 34.2° and the maximum inclination at the upper part of the slope is 39.7°.

2.3. Slope failure

During the construction of the geotextile reinforced embankment the slope failed. Fig. 2 illustrates the situation at failure (embankment height) and the embankment after failure. A detailed investigation of the failure mechanism, in combination with a comprehensive study of the measurement data before and after the failure, led to the conclusion that the failure mechanism (slip surface) occurred within the sandy gravel material behind the geotextile reinforced embankment. Fig. 3 shows a front view of the embankment including the visible parts of the failure surfaces.

The Figs. 1b and 2 illustrate the assumed slip surface (based on the measurement data) along cross section A-A. At collapse, roughly 90% of the total embankment height was constructed, but an additional surface load of 30 kPa had to be taken into account on top of the embankment.

3. Numerical methods used for comparison of factors of safety

3.1. Strength reduction method with displacement finite element method (SRFEA)

The finite element code Plaxis [3] is used for all displacement finite element analyses discussed in this paper. This finite element code obtains the factor of safety (FoS) by means of the strength reduction method (SRM), i.e. an analysis is performed with characteristic strength properties for the friction angle φ' and the cohesion c', followed by an incremental decrease of $\tan\varphi'$ and c' (assuming a Mohr–Coulomb failure criterion). This procedure leads to the following definition of the factor of safety:

$$\mathrm{FoS} = \frac{\tan\varphi'}{\tan\varphi'_{\mathrm{mobilised}}} = \frac{c'}{c'_{\mathrm{mobilised}}} \tag{1}$$

where the 'mobilised' subscript denotes mobilised strength quantities. In the standard strength reduction procedure, as used by most commercial finite element programs, the dilatancy angle ψ' is kept constant (as long as $\varphi' > \psi'$). All analysis referred to as SRFEA in this paper are performed with a modified strength reduction method where the dilatancy angle is reduced in the same manner as the effective friction angle (see also Part I of this paper). Thus the obtained factor of safety is defined as:

$$\mathrm{FoS} = \frac{\tan\varphi'}{\tan\varphi'_{\mathrm{mobilised}}} = \frac{c'}{c'_{\mathrm{mobilised}}} = \frac{\tan\psi'}{\tan\psi'_{\mathrm{failure}}} \tag{2}$$

In Section 7, the difference between the standard φ'/c' reduction and the modified version, where $\tan\psi'_{\mathrm{failure}} = \tan\psi'/\mathrm{FoS}$, is presented.

3.2. Factor of safety obtained from finite element limit analysis (FELA)

Finite element limit analysis (FELA) are performed using the methods described in Sloan [16], Sloan [17], Sloan and Kleeman [18], Lyamin and Sloan [13], Lyamin and Sloan [14], and