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Research Paper

Strength reduction method in Barodesy

Barbara Schneider-Muntau*, Gertraud Medicus, Wolfgang Fellin

Division of Geotechnical and Tunnel Engineering, University of Innsbruck, Technikerstr. 13, 6020 Innsbruck, Austria

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ABSTRACT

Strength reduction analysis are very common in geotechnical engineering to define a factor of safety of structures, e.g. slopes. Usually, the Mohr-Coulomb strength parameters friction angle φ' and cohesion c' are reduced until limit equilibrium is reached. This method is only applicable to material models which utilize a Mohr-Coulomb or similar (e.g. Drucker-Prager) failure criterion. In this article a strength reduction method for the barodetic material model is introduced and the results of slope stability calculations compared with the results with an elasto-plastic material model (Mohr-Coulomb) and with the results of an analytical analysis according to Bishop are presented. The strength reduction method for barodesy has been implemented in the Finite Element code Abaqus.

1. Introduction

One of the main issues in geotechnical engineering is the calculation of factors of safety in order to assess a construction. The calculations are often made with analytical methods, for instance rigid body motions. The factor of safety is then defined as ratio between driving and retaining forces or moments. Alternatively the so called φ'-c' reduction can be used, with φ' and c' being the parameter of the Mohr-Coulomb failure criterion. The shear strength parameters are reduced until limit equilibrium is reached, which means in terms of rigid body motions that driving forces equal resisting forces. In addition to the limit equilibrium methods, Finite Element calculations nowadays allow deformation analyses. The φ'-c' reduction method is common for stability calculations with Finite Element Methods and also implemented in commercial Finite Element programs, such as plaxis. The φ'-c' reduction method obviously implies the use of material models which include the Mohr-Coulomb failure criterion, this reduction procedure can though be applied to other frictional models like Drucker-Prager. In this article an alternative strength reduction method for barodesy is proposed and applied to a slope stability analysis.

1.1. Peak strength: relationship between Mohr-Coulomb parameters φ' and c' and the void ratio e

Peak strength envelopes are dependent on density (i.e. the initial void ratios), cf. Fig. 1(a). The lower the initial void ratio is, the higher is the peak strength, e.g. [1,16]. The strength envelope belonging to a certain void ratio can be approximated with the Mohr-Coulomb parameters c' and φ', see Fig. 1(b). For highly overconsolidated soils, when the void ratio e is smaller than the critical void ratio e_c, the approximation gives a cohesion $c' \neq 0$ and a friction angle $\varphi' < \varphi'_c$ with φ'_c being the critical friction angle. For normally consolidated and slightly overconsolidated soil, we get no cohesion ($c' = 0$) and the friction angle equals the critical friction angle $\varphi' = \varphi'_c$. Triaxial compression tests on Weald clay with a mean stress p'= const. are simulated with barodesy for clay[1] [13,15] in Fig. 1(c) with material parameters from Table 1. As long as the soil is highly overconsolidated, the peak strength (line with dots) is higher than the critical strength. The simulations with barodesy in Fig. 1(c) correspond to critical state soil mechanics according to Fig. 1(c). How apposite Mohr-Coulomb parameters c' and φ' can be obtained from simulations with barodesy is shown in Appendix B.

The peak states of unconventional drained triaxial tests are shown in Fig. 2. The experiments by Bergholz [2] were carried out on saturated, reconstituted Dresden clay [3]. All samples were isotropically consolidated with 800 kPa and unloaded to 100 kPa and 200 kPa respectively. After starting with a conventional drained triaxial test, at a certain point the pore pressure was increased (p' was decreased). Consequently, the peak strength at low stress levels could be investigated. The stress paths and the peak states are shown in the p'-q plot in Fig. 2(a). The maximum mobilized friction angle $\varphi'_{mob} = \arcsin\frac{\sigma'_1 - \sigma'_2}{\sigma'_1 + \sigma'_2}$ is plotted versus the mean stress p' in Fig. 2(b). Due to the preconsolidation pressure of 800 kPa, the samples are highly overconsolidated (i.e. $e < e_c$). Therefore, the mobilized friction angle exceeds the critical friction angle of $\varphi'_c = 35°$, see Fig. 2(b). The lower the mean stress p' at failure (i.e. the higher the overconsolidation ratio), the higher is the mobilized friction angle. The solid symbols refer to

* Corresponding author.
E-mail address: barbara.schneider-muntau@uibk.ac.at (B. Schneider-Muntau).

[1] In the open access article by Medicus & Fellin [13] the equations of barodesy for clay and a detailed description of the model can be found.

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Nomenclature

List of symbols

c'	effective cohesion (parameter of the Mohr-Coulomb failure criterion)
CSL	Critical State Line
e	void ratio
e_c	critical void ratio
e_{ini}	initial void ratio
E	Youngs modulus
NCL	isotropic Normal Compression Line
N	ordinate intercept of the NCL
N_{min}	minimum ordinate intercept of the NCL, corresponding to the minimum OCR of the overall problem
OCR	$=\frac{p'_e}{p'_{ini}}$; overconsolidation ratio
p'	mean effective stress
p'_e	$=\exp\left(\frac{N-\ln(1+e)}{\lambda^*}\right)$; *Hvorslev equivalent pressure*
p'_{ini}	isotropic consolidation pressure
q	deviatoric stress
X	number of elements
γ'	effective unit weight
γ_s	$=\sqrt{\frac{2}{3}\,\varepsilon:\varepsilon}$; second strain invariant
$\gamma_{s_{pl}}$	$=\sqrt{\frac{2}{3}\,\varepsilon_{pl}:\varepsilon_{pl}}$; equivalent plastic strain
δ	correction factor for Mohr-Coulomb parameters
ε	strain tensor
$\dot{\varepsilon}$	stretching tensor
η	reduction factor
κ^*	slope of the unloading line under isotropic compression in the $\ln p'$ - $\ln(1+e)$ plot (parameter of barodesy)
λ^*	slope of the NCL in the $\ln p'$ - $\ln(1+e)$ plot (parameter of barodesy)
ν	Poisson's ratio
σ'	effective Cauchy stress
$\mathring{\sigma}'$	objective effective stress rate
σ'_1	maximum principle effective stress
σ'_2	minimum principle effective stress
σ^*	reference pressure
φ'	effective friction angle (parameter of the Mohr-Coulomb failure criterion)
φ'_c	effective critical friction angle
φ'_{mob}	$=\arcsin\frac{\sigma'_1-\sigma'_2}{\sigma'_1+\sigma'_2}$; mobilized effective friction angle
ψ	dilatancy angle

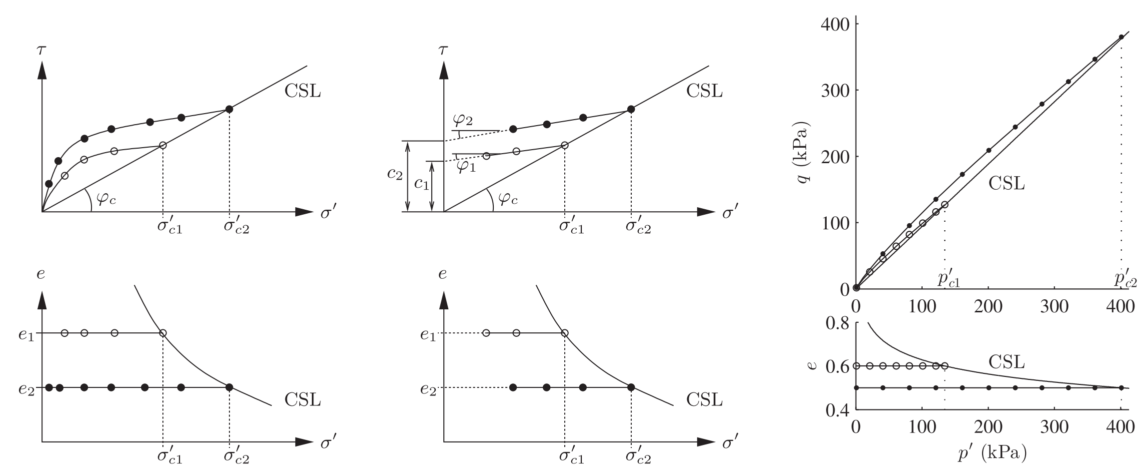
experimental data of Dresden clay from Bergholz & Herle [3], the open symbols and lines to simulations with barodesy.

2. Strength reduction in barodesy

Potts & Zdravkovic [17] describe a general procedure for strength reduction analysis for elasto-plastic models. They include the partial factor as an additional state variable in the yield function and make strength reduction analyses applicable for elasto-plastic models which do not include c' and φ'.

Barodesy and hypoplastic models do not use the standard notations of elasto-plasticity, such as yield function, flow rule or plastic potential. They are formulated as a single rate equation to describe incremental soil response, i.e. the objective stress rate $\mathring{\sigma}' = \mathbf{h}(\sigma', \dot{\varepsilon}, e)$ as a function of the actual effective Cauchy stress σ', the stretching $\dot{\varepsilon}$ and the void ratio e. Therefore, the strength reduction procedure described in [17] cannot be applied.

In this Section a strength reduction method with barodesy for clay is explained. To the authors' knowledge strength reduction calculations have not so far been conducted for hypoplastic models or barodesy. In Mohr-Coulomb models, high overconsolidation ratios are considered



(a) Peak strength envelopes dependent on the initial void ratio. The lower the initial void ratio, the higher the peak strength. Figure adapted from Atkinson [1].

(b) The strength envelope for certain void ratio approximated with the Mohr-Coulomb parameters c' and φ'. Figure slightly adapted from Atkinson [1].

(c) Triaxial compression tests of Weald clay with $p' =$ const. simulated with barodesy for clay [13] for initial void ratios $e_1 = 0.6$ and $e_2 = 0.5$. As long as the soil is highly overconsolidated, peak strength (line with dots) is higher than critical strength.

Fig. 1. Peak states: Highly overconsolidated soil has a higher peak strength than the critical strength, which applies to the strength of normally consolidated and slightly overconsolidated soil. The stresses σ'_{c1} and σ'_{c2} (p'_{c1},p'_{c2} respectively) are stresses on the critical state line (CSL) corresponding to the initial void ratios e_1 and e_2, respectively.