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The Boolean Stochastic Generation method - BoSG: A tool for the analysis of the error associated with the simplification of the stratigraphy in geotechnical models

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ABSTRACT

In geotechnical modelling, some minor stratigraphic features are usually discarded in order to simplify the problem, avoiding to deal with further uncertainties about their position, thickness and lateral extent. The study proposes a new method based on the stochastic generation of different soil layers configurations, following a boolean logic: the material is either matrix or layer (i.e., gravel lenses in a clay-rich matrix).The method has been called BoSG (Boolean Stochastic Generation). The methodology allows to randomize the presence of a specific material interdigitated in a uniform matrix thus enabling to gather a dataset which could be analysed automatically, in order quantify the error associated with the adopted simplification.

The commercial codes FLAC and FLAC3D were used for the geotechnical modelling. A specifically-coded MatLab program allows to generate randomly the different soil configurations and then to automate the computation with the commercial software in order to maximize the sample number.

In this paper the methodology is applied with reference to a simplified slope in 2D and in 3D. Results show that within a low resistance matrix, the presence of layers with higher friction angle can significantly affect significantly the stability and the displacement pattern of an unstable slope. Therefore, a method to investigate the influence of the spatial distribution of these layers can be particularly useful.

1. Introduction

Quantifying uncertainty and reliability is one of the main problems in engineering (Whitman, 2000). Among all the engineering fields, geotechnics is atypical as most of the times it deals with natural materials whose properties and spatial distribution are not well-known (Baecher and Christian, 2005). Accounting for all the uncertainties would lead to unpractical and uneconomical technical designs (Beer et al., 2013b) therefore, since the dawn of the discipline, proper methods or useful turnarounds have been proposed to solve the problem.

Many of the most influential researches of geotechnics approached uncertainty as a fundamental issue for the field. In 1929 Terzaghi (Terzaghi, 1929) proposed the use of a combination of analogies with prior projects and continuous monitoring during construction in order to adjust design to the possible effects of uncertainties. Casagrande (Casagrande, 1965) introduced the term “calculated risk” using the probability theory to account for uncertainties in a field which was formerly focused only on deterministic methods. In 1969 Peck (Peck, 1969) expanded the Terzaghi concept of “learn as you go” which since then will be known as the observational method.

It has been said (Christian, 2004) that the observational method is related to the techniques of Bayesian updating since it reduces uncertainty on the basis of previous analyses. In this framework, we can also insert back analysis methods (Gioda and Sakurai, 1987) like the ones used for landslide characterization and modelling.

“Minor geological details” (Terzaghi, 1929) could have major impact on the performance and the stability of structures and slopes. For the geotechnical engineer the geometry and the properties of the materials implicated in the study are usually inferred on the basis of a small amount of data resulting from investigation and monitoring (Beer et al., 2013a). For example, the uncertainty in the determination of the stratigraphic profile of natural soils is linked to the punctual nature of the typical investigation procedure, i.e. boreholes. How to expand the stratigraphy in the other dimensions?

In theory, knowing the number of different geological units, their thickness and their spatial distribution is of crucial importance for the matching between actual phenomena and their mathematical representation (Phoon and Kulhawy, 1999). In practice, every engineer knows that a perfect match is unachievable and, moreover, unpractical. Thus, geotechnical practice is mostly a problem of optimization largely based on induction.

In this context, during the building of a geotechnical model it is generally common to discard some stratigraphic data in order to simplify the model itself, assuming that the significance of the results of the

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modeling procedure would not be greatly affected. The modeler relies mainly on expert knowledge in choosing what to dismiss and what to preserve (Kulhawy and Phoon, 1996). Moreover, the distribution of some elements in the landslide body can be too aleatory to be represented in detail. This leads to several problems for the modeler, as the quantification of the errors associated with the simplification of the stratigraphy is unknown. For example, if the strength parameters of the soils involved differ significantly, even a small rigid perturbation in the matrix may induce a different pattern of deformation in the slope. To address this problem many approaches have been proposed in literature, most of them relying on stochastic methods.

Uncertainties may be linked to inherent soil variability as soil is an aggregate of different materials and moreover there might be a fluctuation of soil properties even within a homogenous layer (Fenton, 1999; Heuvelink and Webster, 2001). To address these problems some methods which have been proposed rely on the stochastic variation of soil parameters following a set probability function (Fenton and Griffiths, 2002; Vanmarcke et al., 1986). Further research has focused on the evaluation of the Coefficient Of Variation (COV – standard deviation/mean) of soil properties (Phoon and Kulhawy, 1999), or on soil anisotropy (Zhu and Zhang, 2013). Other methods which account for the uncertainty of inherent soil variability follow a geostatistical approach (Breysse et al., 2005; Vargas-Guzmán and Jim Yeh, 1999). However, most of the times, the amount of available data to is usually too small and it is not possible to infer any reliable distribution (Elkateb et al., 2003).

Another kind of uncertainty is connected to the fact that most of the data obtained by in situ investigations, are punctual or linear and anyhow not spatially distributed (Koike and Matsuda, 2005). In fact modeling requires to formulate a hypothesis on the subsurface distribution of the soil layers counting on few stratigraphic data (Phoon and Kulhawy, 1999). For this reasons, understanding the geological history of the investigated site may be a crucial information which would allow to decide how to approach uncertainty and select the most appropriate modeling strategy (Christian, 2004; Christian et al., 1994). Geostatistical methods are usually used to address this problem (Deutsch, 2002). Other techniques include object-based methods which have been used for modeling shales (Dubrule, 1989) or to study fluvial depositional processes (Deutsch and Tran, 2002). Object-based methods, also known as boolean models (Baecher et al., 1977), allow approaching the sedimentary architecture of the investigated area through a chrono-stratigraphic prospective, generating facies that mimic the natural depositional processes.

Probabilistic geotechnical analysis (Griffiths et al., 2002), approaches uncertainty directly in the geotechnical model, generating different distributions of soil parameters and loads in order to determine the worst-case scenario or assess the reliability of a structural work (Breyсse et al., 2007; El-Ramly et al., 2002; Griffiths and Fenton, 2007). Within these methods, model input parameters are assumed as random variables which can be written in the form of a probability density function.

One of the most important approaches relies on random fields theory (Vanmarcke et al., 1986) and is known as Stochastic Finite Element Method (SFEM) (Beacher and Ingra, 1981).

This method is based on the spatial correlation in soil layers, which is the tendency for each soil zone to be more correlated to the closer ones than the distant ones. It addresses inherent soil variability within layers through a statistical approach (Vanmarcke, 1977).

Random FEM is an evolution of stochastic FEM in which random fields are combined with FEM through a Monte Carlo simulation. In this case many soil configurations with a known mean, standard deviation and spatial correlation length, are applied to the finite element mesh. It was used to study foundation settlements (Griffiths and Fenton, 2009; Paice et al., 1996), to assess the stability of a simple slope (Griffiths and Fenton, 2004) and for landslides treated as infinite slopes (Griffiths et al., 2011).

Other numerical methods use Monte Carlo simulations to address the problem of uncertainty within the models. The main modeling strategy is to assign soil parameters through a Monte Carlo simulation and then address the reliability of the structure or the stability of a slope. Usually these methods are applied to simple models (Niandou and Breysse, 2007) or to limit equilibrium slope stability models (Greco, 1996; Malkawi et al., 2001; Jiang et al., 2015;) even though some examples of application were proposed for the study of large landslides (Sciarra et al., 2006).

In this work a methodology will be introduced which estimates the uncertainty linked to marked soil heterogeneity. With the proposed technique it is possible to quantify the error through the generation of different configurations and the automatic analysis of the results. After the description of the methodology, two example applications are shown with reference to slope stability modelling of simple slopes made up loose soils with different mechanical behavior i.e., prevailing fine clay-rich matrix and sparse coarse gravel layers. The examples will help to display the typical results and delineate the potentiality of the method.

2. Method

The Boolean Stochastic Generation method (BoSG) stochastically generates through a Monte Carlo simulation different soil distributions following a boolean logic: the material is either *matrix* or *layer* (i.e., gravel lenses in a clay-rich matrix). Differently from other approaches, the mechanical parameters of the soils are fixed and defined, but their distribution in the slope is randomly generated. The method, therefore, is suitable for areas where a significant differentiation of soil properties is expected. Usually, in the building of the geotechnical model, some stratigraphic elements are discarded to simplify the problem and to reduce additional uncertainties about the spatial extent of these layers. It is usually hypothesized that results would not be substantially affected. However, the presence of layers with different properties might influence the dynamic of the whole geotechnical problem and it is nonetheless important to quantify the error associated with such practice. Through the generation of different soil configurations it is possible to gather a dataset which could be analysed automatically in order to quantify the error associated with the adopted simplification.

BoSG method has been implemented for the geotechnical commercial codes FLAC (Itasca Consulting Group, I., 2008) and FLAC 3D (Itasca Consulting Group, I., 1997). Specifically designed routines in MatLab were programmed in order to generate the soil configurations and to automatize the procedure.

2.1. The computational algorithm

The algorithm to generate, calculate and automatically analyse the stochastically generated soil configurations follows these steps:

1. The geometry of the problem and the size of the elements are designed in FLAC.
2. A MatLab program automatically generates a text file with all the soil configurations.
3. The computation of FLAC for each soil configuration is automatic; therefore, with just one command, the calculation of a large number of configuration is possible in order to generate a large dataset of results.
4. A MatLab program automatically analyses the results; in this way it is easier to select the "most likely" soil configuration for a back-analysis or to calculate the errors.
5. The integrity of the dataset is preserved allowing further analyses on all configurations with FLAC.

In the following sections each step of the algorithm is explained for 2D and 3D models.

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