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Predictive model for uniaxial compressive strength for Grade III granitic rocks from Macao

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ABSTRACT

Determination of the uniaxial compressive strength (*UCS*) of rocks is an important task for rock and geotechnical engineering applications. Direct measurement is expensive, time consuming and even infeasible in some circumstances due to the difficulty in obtaining core samples. Therefore, empirical models are particularly favorable to engineers especially in the preliminary design stage. However, there is a lack of predictive *UCS* model for granite of weathering Grade III but it is well recognized to be crucial to the design of pile foundations on granitic bedrocks. In this study, a reliable predictive model will be developed under the Bayesian framework. An extensive experimental program was performed in this study to construct a comprehensive database of the measurements of uniaxial compressive strength, point load index, Schmidt rebound hammer value, *P*-wave velocity, effective porosity, specific gravity and dry density. It has been proven that the proposed model possesses satisfactory predictive performance.

1. Introduction

Uniaxial compressive strength (*UCS*) for rocks plays a vital role in both preliminary and final design stages of rock and geotechnical engineering projects such as dam, rock mass excavation, tunnel, slope stability and foundation of infrastructures (Bieniawski, 1975; Cargill and Shakoor, 1990). Besides, *UCS* is also an important parameter to assess rock material strength in Rock Mass Rating (*RMR*) for rock mass classifications. Inadequate or faulty information about the rock *UCS* can result in budget overrun and even failure of the corresponding structures.

For geotechnical design in granitic rocks such as rock-socket piles embedded into the bedrock stratum, the rock mass deformation modulus and uniaxial compression strength are the crucial parameters for estimating the settlement and ultimate bearing capacity of the piles respectively. The rock mass deformability modulus can be either determined by in-situ tests such as the dilatometer and pressure-meter or estimated empirically based on *UCS* (Gholamnejad et al., 2013) whereas the shaft resistance and end bearing of the piles are traditionally related to the *UCS* value (Rosenberg and Journeaux, 1976; Carter and Kullhawy, 1987; Zhang and Einstein, 1998; Ng et al., 2001) which can be evaluated experimentally or empirically. Besides, the Hoek–Brown failure criterion (Hoek et al., 2002) is also commonly used to predict the strength parameters of the rock masses in which *UCS* of the intact rock is one of the governing parameters for the prediction.

Nowadays, the use of in-situ pile load tests is popular for the estimation of pile capacities whereas the Osterberg load test method for rock-socket piles provides time and cost savings in the test performance over conventional pile load tests (Osterberg, 1984; Osterberg, 1994). However, there is no universal rule to define which tests should be performed for a given situation since each test possesses advantages and drawbacks. For the Osterberg load test method, its major limitation is that it is based on a patented system which requires professionals for installation and the load cell attached to each testing pile is generally considered as expendable and not retrievable after the test is completed. Besides, performance and applicability of this method is dependent on the soil conditions at the site. In some situations such as high variable bedrock stratum and/or the large size and high complexity of the project are encountered, the cost may be prohibitively high for a series of sacrificial test piles using Osterberg load cells for reliable estimation of pile capacities. Therefore, the use of empirical models with simple rock tests for estimating *UCS* is not only an appropriate alternative and economical approach for pile capacities estimation but also a supplementary tool for determining the representative locations for pile load tests and achieving more reliable estimation of pile capacities together with the limited pile load test results of a site.

Traditionally, the *UCS* of rocks is measured directly through laboratory uniaxial compressive test (UCT) (ASTM, 2001a; ISRM, 2007). However, the direct measurement process is costly and time consuming because it requires high-quality core samples, well-prepared specimens and highly skillful operator (Gokceoglu and Zorlu, 2004; Baykasoglu et al., 2008; Diamantis et al., 2009; Ceryan et al., 2012). Moreover, it is difficult or even infeasible to obtain rock core samples in some situations. For instance, there are formidable difficulties during the coring

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of weak and highly fractured rocks and equipment setup problems due to some physical constraints in congested urban areas and offshore regions in which the bedrock strata are usually located very deep under the sea water and soil layers. Therefore, reliable estimation of rock strength using direct measurement approach may not be achievable (Jaksa et al., 2005) and empirical formulae are useful.

Among various types of rock, granitic rocks are widely distributed throughout the earth crust and they are the most abundant bedrock that underlies the soil deposits (Campbell and Taylor, 1983; Alejano and Carranza-Torres, 2011). Considerable efforts have been devoted to the development of empirical models to predict the *UCS* for various types of rocks by linear regression analysis (Gunsallus and Kulhawy, 1984; ISRM, 1985; Ulusay et al., 1994; Karakus and Tutmez, 2006; Li and Wong, 2013; Heidari et al., 2012; Singh et al., 2012; Mishra and Basu, 2013; Kahraman, 2014) and other advanced computing techniques such as artificial neural networks, fuzzy inference systems and genetic programming (Meulenkamp and Grima, 1999; Singh et al., 2001; Gokceoglu and Zorlu, 2004; Yilmaz and Yuksek, 2008; Dehghan et al., 2010; Yagiz et al., 2012; Gurocak et al., 2012; Yesiloglu-Gultekin et al., 2013). However, it has been realized that there are only few studies focusing on granitic rocks, especially with explicit consideration of the weathering grades. Since rock is natural material, its properties are affected by many factors such as mineralogical compositions, grain sizes, textures and weathering degrees (Alejano and Carranza-Torres, 2011; Mishra and Basu, 2013).

For granitic rocks, different weathering degrees can be found in various regions, e.g., in humid sub-tropical and tropical areas such as Hong Kong, Macao, Malaysia and Brazil (Ng et al., 2001; Chiu and Ng, 2014). It has been concluded in previous studies that the rock strength is closely related to the weathering degrees (Kulhawy and Prakoso, 2007; Basu et al., 2009). In most cases, the foundations of structures rest on weathered rocks and the Grade III material is regarded to support the loads of the superstructures. The term Grade III material herein is based on the weathering grade classification (i.e., I—Fresh; II—Slightly Weathered; III—Moderately Weathered; IV—Highly Weathered; V—Completely Weathered; and VI—Residual Soil) according to ISRM (ISRM, 2007). It has been reported that the *UCS* and weathering degrees of the bedrock are the governing factors for the bearing capacity and the depth of foundation (Zhang and Dasaka, 2010; Dasaka and Zhang, 2012). Some empirical models have been established by considering the weathering degrees (*WD*) for predicting the rock masses deformation modulus (e.g., Kayabasi et al., 2003; Gokceoglu et al., 2003). These *WD*-dependent models can be applied to rocks with different weathering degrees. Nevertheless, *WD* is not included for the model development in this study because an extensive database is required in which large amount of rock samples with different weathering degrees have to be taken for training and testing. Due to the lack of rock samples with other weathering degrees and the importance of Grade III material in foundation design, this study focuses on the model development for Grade III granite. On the other hand, it is believed that weathering degree specific models are more reliable because quantitative assessment of *WD* is sometimes questionable due to lack of data for all the weathering degrees. For optimum designs of rock-socketed piles in granitic rocks, the *UCS* of Grade III granite is possibly more critical than Grade I and Grade II. In this regards, reliable estimation of the *UCS* for grade III granite is vital to the success to the foundation design. However, there is still a lack of empirical model for predicting the *UCS* for Grade III granite. Therefore, a robust and reliable predictive model with suitable complexity is particularly favorable to practicing engineers.

It should be emphasized that there are two critical issues to be addressed in the formulation of an empirical model: 1) identification of the most influential rock properties or index parameters; and 2) selection the best model among relationships with different complexity (Yan et al., 2009). It is noted that an oversimplified empirical model will result in large estimation uncertainty. In contrast, a more complicated model contains more adjustable/free parameters and it is not surprising to result in smaller fitting error. However, the over-complicated models may over-fit the data and they are sensitive to measurement noise and modeling error (Yuen, 2010a). It is realized that the above problems are difficult to be addressed using traditional methods (Meulenkamp and Grima, 1999; Kahraman, 2001). One of the drawbacks of using multi-variate linear regression analyses for the established empirical relationships is that it provides only the mean estimation of the targeted parameter (e.g., *UCS*) but not the associated uncertainty. In this case, it may lead to overestimation of the low targeted parameter as well as underestimation of the high targeted parameter values (Kahraman, 2001; Meulenkamp and Grima, 1999). Another drawback of the least-squares regression analysis is that an empirical model with more free parameters will normally result in smaller fitting error. However, the models that are unnecessarily too complicated may over-fit the data and they are sensitive to measurement noise and modeling error (Yuen, 2010b). As a result, the reliability and applicability of the previous relationships is questionable. For the Artificial intelligence-based techniques such as artificial neural network analysis (ANN) there are some shortcomings for data analysis (e.g., ANN possesses slow rate of learning and getting trapped in local minima) (Momeni et al., 2014).

In recent years, Bayesian probabilistic approach has shown exceptional performance in various aspects such as structural mechanics (Yuen et al., 2007; Yuen and Mu, 2012), soil and rock engineering (Yan et al., 2009; Chiu et al., 2012; Cao and Wang, 2014a; Cao and Wang, 2014b; Feng and Jimenez, 2014; Ng et al., 2014; Wang and Aladejare, 2015; Yan and Yuen, 2015). In contrast to the traditional parametric identification that identification of unknown parameters is proceeded under a prescribed model class, the Bayesian model class selection approach refers to the more challenging problem without a prescribed model class.

It has been proven that this approach has been successfully applied to various mechanics problems and geotechnical site characterization before, such as identification of underground stratification (Wang et al., 2013). In the present paper, Bayesian model class selection will be utilized to identify the most significant parameters affecting *UCS* of Grade III granite based on a series of measured rock properties and index parameters from an extensive experimental program.

A large amount of rock core samples of granite from the bedrock stratum were acquired from various locations of Macao. Using the rock core samples of Grade III granite, an extensive experimental program were conducted to obtain the uniaxial compressive strength together with fundamental rock physical properties and indices such as point load index, Schmidt rebound hammer value, *P*-wave velocity, effective porosity, specific gravity and dry density. Finally, the predictive performance of the proposed model was examined using an independent testing database. It has been proven that the predictability and overall performance of the proposed model is promising so the proposed model can be used for *UCS* estimation for Grade III granite.

2. Testing program

2.1. Rock samples and classification

Granite of weathering Grade III is typically found from the bedrock in Macao. In order to compile a representative database suitable for the analysis, a number of rock core samples with diameter of 54 mm (NX-size) were collected and their rock physical properties and index parameters were determined. All samples were extracted from the bedrock stratum approximately 30 m below the ground level from various sites in Macao (Fig. 1).

The weathering grade of these granite samples was identified on the basis of the ISRM weathering classification method and only those with Grade III were used for the development of the model. Table 1 shows the