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Indirect estimation of the ultimate bearing capacity of shallow foundations resting on rock masses

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ABSTRACT

The success of a foundation design for structures is to precisely estimate the bearing capacity of underlying soils or rocks. To avoid the elaborate in-situ experimental methods, several approaches presented by various researchers for the estimation of the bearing capacity factor. Despite this fact, there still exists a serious need to develop more robust predictive models. The aim of this paper is to propose a novel formulation for the ultimate bearing capacity of shallow foundations resting on/in rock masses, using a powerful evolutionary computational technique, namely linear genetic programming. Thus, a comprehensive set of data is collected to develop the model. In order to evaluate the validity of the obtained model, several analyses are conducted and compared with those provided by other researchers. Consequently, the results clearly demonstrate the proposed model accurately characterize the bearing capacity factor and reach a notably better prediction performance than the traditional models.

1. Introduction

Shallow foundations support structures at a shallow depth below the ground surface and transmit applied loads to the underlying materials such as soils, rocks or intermediate geo-materials. In general, any foundation design must satisfy at least two important criteria [1–3]: (1) obtaining sufficient bearing capacity of underlying layer against ultimate failure, and (2) achieving acceptable total or differential settlements under working loads. Although, the design of foundations resting on or in rock masses is commonly controlled by the settlement criterion, the bearing capacity of rock mass must be estimated to evaluate the stability [4]. Therefore, in order to provide a precise and efficient design of a foundation, it is crucial to account for the bearing capacity of the rock mass beneath it. According to the rock mass properties and the beneath layer of it, the failure may occur in several mechanisms [5]. Bearing capacity failure in an overloaded rock foundation is one of them. The mode of bearing capacity failure mainly depends on the ratio of space between joints (S) to foundation width (B), joint condition (open or closed) and direction, rock type as summarized in Table 1and schematically represented in Fig. 1[5–7].

The most usually utilized approaches to determine the bearing capacity (q_{ult}) of foundations on rocks can be classified into four groups: (1) codes, (2) analytical methods, (3) semi-empirical methods, and (4) in-situ and full-scaled testing methods [4]. Codes often propose conservative values for estimating the allowable bearing pressure or ultimate bearing capacity [8–10]. These presumed values are derived from local experience and geology from a particular site, however, the engineer should ensure that they are applicable to the particular conditions relevant to the considered site [4]. On the one hand, analytical methods are based on bearing capacity theories, including limit equilibrium methods, using initial assumptions and relate q_{ult} to footing geometry and rock properties such as those equations provided by [6,11,12]. On the other hand, semi-empirical and empirical methods are often obtained by the correlation between q_{ult} and rock mass properties, based on empirical observations and experimental test results such as equations made by [13–15]. General forms of mostly utilized and traditional equations proposed by various researchers in the literature are summarized in Table 2[4,7–9].

As represented in Table 2, analytical methods include terms of physical and mechanical properties of rock mass and geometry of the foundation but not include terms of rock type, classification and qualitative parameters of rock mass Also, semi-empirical and empirical methods often relate q_{ult} to quantitative and qualitative of rock mass and are not prepared for the geometry of foundations or space between joints (Table 2).

The bearing capacity of a shallow foundation on a jointed rock mass mostly depends on geometry of foundation, the ratio of joint spacing to foundation breadth or loading width, as well as rock mass qualities such as joint conditions (open or closed), rock type

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Table 1
Bearing capacity failure modes in layered and jointed rock mass.

Ratio of joint spacing (S) to footing width (B)	Description	Joints	Direction	Bearing capacity failure mode
$\frac{S}{B} < 1$	Just jointed rock mass	Open	Vertical to sub-vertical	Uniaxial compression of the "rock columns"
$\frac{S}{B} < 1$	Just jointed rock mass	Closed	90° to 70°	General wedge shear failure
$\frac{S}{B} > 1$	Just jointed rock mass	Wide	Horizontal to sub-horizontal	Splitting failure
$\frac{S}{B} > 1$	Thick rigid layer of rock mass over weaker layer			Flexure failure
$\frac{S}{B} < 1$	Thin rigid layer of rock mass over weaker layer			Punching failure

and rock mass strength [5,12,15–18]. In regarding to the equations in the literature, there is not a comprehensive model including simultaneously both quantitative and qualitative parameters, such as foundation geometry and RMR. Thus, the complexity of analysis of bearing capacity behavior and accounting for the influences of different parameters on the bearing capacity factor implies that there is the necessity for a more comprehensive model.

By progressing in computational software and hardware systems, several computer-aided modeling and soft computing techniques such as artificial neural networks (ANNs), adaptive neuro-fuzzy system (ANFIS), fuzzy inference system (FIS), support vector machine (SVM) and genetic programming (GP) have been realized by various researchers in several civil engineering domains. Such computing techniques have a lot of features that have made them attractive choice for predicting different problems. The first feature is they are data-driven self-adaptive methods. That means they do not require many prior assumptions about the models of the problem under study. They automatically learn from data to determine the structure of a prediction model. These techniques become more attractive because of their capability of information processing, such as non-linearity, high parallelism, robustness, fault and failure tolerance and their ability to generalize. Besides, these techniques have been successfully employed to solve problems in civil engineering field [19–29].

The aim of this paper is to utilize a powerful branch of genetic programming (GP), namely linear genetic programming (LGP), to derive a more comprehensive predictive model for the ultimate bearing capacity of shallow foundations resting in/on jointed rock masses. A comprehensive and reliable set of data including 102 rock socket, centrifuge rock socket, plate load and large-scaled footing load test results are collected to develop the model. In order to verify the robustness of the obtained model several validation and supplementary study phases are conducted.

2. Genetic programming

Genetic programming, as a subset of evolutionary computational intelligence approaches, considers the synthesis of Darwinian ideas of genetic inheritance, natural variation and selection to solve complicated problems. In general, in genetic programming (GP), inputs and corresponding output data samples are known and the main goal is to generate predictive models relating them without any prior assumptions [30,31]. Typically in GP, a population of individuals initialized and members of the population are ranked according to a fitness function. Those members with the highest fitness ranking are given a higher chance to become parents for the next generation, the offspring. The approach that is utilized to generate offspring from the parents, is termed the reproduction heuristic. Then selected members are transformed, by chance, into new members via mutation and recombination or crossover. These steps repeat until the convergence conditions are satisfied and the fittest member is selected [32,33].

2.1. Linear genetic programming

There are several branches of GP where individuals, i. e. programs or encoded solutions, are represented in different ways. These are tree-shaped, graph-shaped and linear encodings [30]. Tree-shaped expressions or encodings typically define a root node that represents the output. Each node can have one or more child nodes. Some nodes represent operations on children, unary operations such as abs, exp, and log, or binary operations such as add (+), mult (×), and div (/). Nodes without children are called leaf nodes (or terminals) that represent input values or evolved constant values within the system. The graph-based expressions are similar to the tree-shaped ones, but child nodes are no longer unique or multiple nodes may refer to the same node as their children [34].

Linear genetic programming (LGP) is a new subset of GP with a linear structure similar to the DNA molecule in biological genomes. In LGP, expressions of a functional programming language (such as LISP) are substituted by programs of an imperative language (such as C/C^{++}) [31,35]. Fig. 2 represents a comparison of structure of a program evolved by (a) tree-based, (b) graph-based GP, and (c) Linear GP. As shown in this figure, a linear genetic program can be seen as a data flow graph generated by multiple usage of register content. In classical tree-based and graph-based

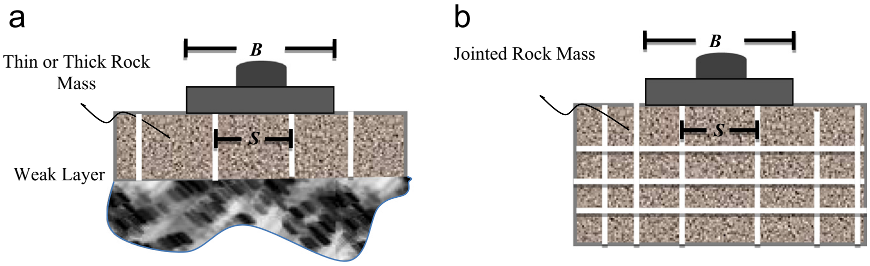

Fig. 1. A typical sketch of a shallow foundation resting on a (a) layered or (b) jointed rock mass.