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Development of a multivariate empirical model for predicting weak rock mass modulus

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ABSTRACT

Estimating weak rock mass modulus has historically proven difficult although this mechanical property is an important input to many types of geotechnical analyses. An empirical database of weak rock mass modulus with associated detailed geotechnical parameters was assembled from plate loading tests performed at underground mines in Nevada, the Bakhtiary Dam project, and Portugues Dam project. The database was used to assess the accuracy of published single-variate models and to develop a multivariate model for predicting in-situ weak rock mass modulus when limited geotechnical data are available. Only two of the published models were adequate for predicting modulus of weak rock masses over limited ranges of alteration intensities, and none of the models provided good estimates of modulus over a range of geotechnical properties. In light of this shortcoming, a multivariate model was developed from the weak rock mass modulus dataset, and the new model is exponential in form and has the following independent variables: (1) average block size or joint spacing, (2) field estimated rock strength, (3) discontinuity roughness, and (4) discontinuity infilling hardness. The multivariate model provided better estimates of modulus for both hard-blocky rock masses and intensely-altered rock masses.

1. Introduction

Underground mines are increasingly being excavated in relatively deep and weak mineralized zones that are typically intensely-fractured and highly-altered with geotechnical properties resembling those of stiff soils, and civil engineering projects such as dams and tunnels are more frequently being constructed in geological domains that contain zones of highly-fractured rock. For example, most of the modern underground mines in Nevada, United States, are produced from Carlin-type deposits where disseminated gold and silver are hosted by intensely-fractured and moderately- to highly-altered sedimentary sequences. The host rocks are predominantly an assemblage of limestone, shale, volcanics, and breccias which have been fractured, folded, and locally hydrothermally altered resulting in a wide range of mechanical properties.

Given the cost and complexity of in-situ deformability tests, direct measurements of rock mass moduli are typically not performed at active mines, which make the use of empirical models attractive. However, the majority of published empirical equations are largely based on data sets with few measurements in weak and very weak rock masses. Additionally, common rock mass classification systems (i.e. Rock Mass Rating, RMR; Rock Tunneling Quality Index, *Q*) tend to be insensitive in these types of rocks, and geotechnical engineers at mines typically have relatively little geotechnical data to work with compared to civil engineering projects. Consequently, using predictive correlations in a mining environment can be difficult because of a lack of reliable input data.

For many civil engineering projects such as dams and tunnels, available locations or alignments may be sited in geologic domains that contain zones of highly-fractured or altered rock masses. While large civil engineering projects typically include in-situ rock mass modulus testing programs, these field tests are expensive and time consuming, and interpreting the resulting data can be ambiguous [1]. At the feasibility and preliminary (high-level) design stages, field testing of rock mass modulus typically cannot be justified, and as a result predictive empirical models are employed [2]. During these early stages, geotechnical data are likely limited to basic rock mass parameters that have been quantified by field mapping, a limited number of geotechnical core holes, or literature reviews. Consequently, the civil engineering

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sector also has a need for a reasonably accurate weak rock mass modulus correlation that requires only basic geotechnical parameters as inputs for feasibility analyses and preliminary designs.

Test data and geotechnical characterizations were obtained for stiff plate loading tests performed on heavily fractured rock masses at two underground mines in Nevada (United States), the Portugues Dam project in Puerto Rico (United States Territory), and the Bakhtiary Dam project in Iran. The weak rock mass moduli measured at civil and mining projects were combined to create a weak rock mass modulus database with associated detailed geotechnical characterizations. The moduli in the database were compared to several published rock mass modulus models to determine which, if any, are suitable for estimating weak rock mass deformation properties when limited geotechnical data are available. Based on the limitations identified in the published equations, an empirical multivariate model was developed, and the model only requires geotechnical parameters that could be easily quantified by field mapping or core logging.

2. Review of predictive models for weak rock mass modulus

An abundance of predictive empirical in-situ modulus models can be found in the literature, and one of the objectives of this study was to determine which, if any, of the existing models are adequate for predicting the moduli of weak rock masses when geotechnical data are limited. The mining environment and preliminary design stages of civil projects have unique limitations on available geotechnical data, and typically only lithological, rock mass classification (RMR, Q; or Geological Strength Index, GSI), and point load strength data may be available. Laboratory strength or deformability data for intact rock may be limited or nonexistent.

Eight rock mass modulus models were identified in the literature that are suitable for use when only basic geotechnical data are available (Table 1); these models: (1) were based on data sets that included at least some weak rock mass modulus measurements and (2) only require geomechanical data that can be quantified by field mapping or core logging. The Simplified Hoek and Diederichs [1] equation is based on a dataset of in-situ modulus tests performed in China and Taiwan. The dataset has a population of 494 data points with GSI values between 10 and 95, and excludes moduli measured with downhole deformation jacks and dilatometers, and in many cases GSI was calculated directly from RMR. The model requires a disturbance factor, D, to be estimated, which varies from zero to one. A value of zero represents a tightly interlocked rock mass, while one corresponds to a fully disturbed and loosened rock mass. The disturbance factor has proven difficult to estimate and at best is selected subjectively [1,3].

Table 1
Rock mass modulus models that are applicable to weak rock masses and can be used when only limited geotechnical data are available.

Model	Dependent variable	Applicability	Equation (GPa)
Hoek and Diederichs Simplified [1]	GSI	20<GSI<90	$E = 100\left(\frac{1-D/2}{1+e^{[(75+25D-\mathrm{GSI})/11]}}\right)$
Palstrom and Singh [2]	Q	$1 < Q < 30$	$E = 8Q^{0.4}$
Galera et al. [4] (Linear)	RMR	10 < RMR < 50	$E = 0.0876\mathrm{RMR}$
Galera et al. [4] (Exponential)	RMR	10 < RMR < 80	$E = e^{(\mathrm{RMR}-10)/18}$
Serafim and Pereira [5]	RMR	30 < RMR < 50	$E = 10^{(\mathrm{RMR}-10)/40}$
Read et al. [7]	RMR	20 < RMR < 80	$E = 0.1(\mathrm{RMR}/10)^3$
Gokceoglu et al. [3]	RMR	20 < RMR < 85	$E = 0.0736e^{0.0755\mathrm{RMR}}$
Gokceoglu et al. [3]	GSI	15 < GSI < 77	$E = 0.1451e^{0.0654\mathrm{GSI}}$

Palstrom and Singh [2] assembled a database of in-situ modulus from 42 tests performed at hydroelectric projects in India, Bhutan, and Nepal. Rock types included gneiss, granite, mica schist, sandstone, mudstone, siltstone, and dolerite, and RMR varied between 46 and 75 ($1.1 \leqslant Q \leqslant 30$). Correction factors of up to 7.5 were applied to moduli to account for effects of blast damage and volume of rock tested. Even with these corrections, previously published models over-predicted moduli of the lower quality rock masses in their dataset. Palstrom and Singh [2] suggested a new Q-based correlation that has some applicability for rock masses with Q-values near 1.

Galera et al. [4] assembled a database of in-situ moduli values from downhole dilatometer and pressure meter tests. Tests with moduli less than 0.5 GPa or that were performed on highly-weathered rock masses were censored from the database to eliminate "soil behavior", which resulted in 427 data points that included rock mass modulus, RMR, and Rock Quality Designation (RQD). Their analyses indicated RMR was a better predictor of rock mass modulus than RQD and that lithology was not a significant parameter. Based on the censored dataset, they developed linear and quadratic models.

Serafim and Pereira created a relationship based on a combination of their own data and the dataset presented by Bieniawski [5,6]. The field test methods were not specified. The dataset overall has RMR values from 23 to 85, and the resulting model is exponential in form. The relationship by Read et al. was a re-fitting of the Serafim and Pereira and Bieniawski datasets with rock mass modulus constrained to equal 100 GPa when RMR was 100 [5–7]. This constraint was imposed to prevent the correlation from predicting unrealistically high modulus values when RMR approached 100.

Gokceoglu et al. created a new rock mass modulus database by combining the results of 58 situ deformability tests with 57 moduli originally published by Kayabasi et al. [3,8]. The data were generated from dilatometer and plate loading tests were conducted at the Deriner Dam site and Ermenek Dam site in Turkey. The tests were performed on quartz diorite, limestone, and heavily-jointed marl, and RMR varied between 20 and 85 with 17 tests in weak rock masses. Each data point includes RMR, GSI, RQD, uniaxial compressive strength of the intact rock, elastic modulus of the intact rock, and discontinuity properties. Gokceoglu et al. [3] developed new single variable and multi-variable models. For the single input equations, they evaluated linear, logarithmic, power, and exponential models; for both GSI and RMR the exponential correlations had the highest coefficients of regression. Multivariate regression analyses indicated intact rock modulus, uniaxial compressive strength, RQD, and discontinuity weathering degree were the most significant variables for predicting rock mass modulus. However, this multivariate model can be difficult to use when geotechnical data are limited because reliable measurements of intact rock properties may not be available, and in weak rock masses RQD is typically zero or near zero.

3. Database of weak rock mass modulus

3.1. Overview of data sources

A database of weak rock mass modulus was assembled for the results of stiff plate loading tests performed at two underground mines in Nevada, the Bakhtiary Dam and Hydroelectric Project in Iran, and the Portugues Dam in Puerto Rico. In-situ modulus was calculated from the reload portions of the force–displacement plots, and geotechnical parameters were determined from core logs following the guidelines developed in Section 3 or by window mapping.