International Journal of Mining Science and Technology 25 (2015) 23–30

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Prediction of representative deformation modulus of longwall panel roof rock strata using Mamdani fuzzy system

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ARTICLE INFO

Article history:
Received 2 March 2014
Received in revised form 15 April 2014
Accepted 15 July 2014
Available online 7 February 2015

Keywords:
Deformation modulus
Dilatometer test
Mamdani fuzzy system
Multivariable regression analysis

ABSTRACT

Deformation modulus is the important parameter in stability analysis of tunnels, dams and mining structures. In this paper, two predictive models including Mamdani fuzzy system (MFS) and multivariable regression analysis (MVRA) were developed to predict deformation modulus based on data obtained from dilatometer tests carried out in Bakhtiary dam site and additional data collected from longwall coal mines. Models inputs were considered to be rock quality designation, overburden height, weathering, unconfined compressive strength, bedding inclination to core axis, joint roughness coefficient and fill thickness. To control the models performance, calculating indices such as root mean square error (RMSE), variance account for (VAF) and determination coefficient (R^2) were used. The MFS results show the significant prediction accuracy along with high performance compared to MVRA results. Finally, the sensitivity analysis of MFS results shows that the most and the least effective parameters on deformation modulus are weathering and overburden height, respectively.

1. Introduction

Rock in nature is a discontinuous medium with natural fissures, fractures, joints, bedding planes, and faults. Deformability of rock mass depends upon the behavior of these discontinuities or weak planes. Both the frequency of joints and discontinuities, and their orientations with respect to the corresponding engineering structures and the roughness of the joints surfaces, play significant roles in the rock mass strength and load bearing capacity. Reliable characterization of the deformation behavior of jointed rocks is very important for the safe design of both mining and civil engineering structures (such as longwall mining, arch dams, bridge piers and tunnels). Hence, deformation modulus is one of the most important properties representing the mechanical behavior of rock masses, and it is used in various rock engineering projects including underground and surface structures [1]. In longwall mining, this parameter plays an important role in caving and fracturing of the panel roof rock strata and stress redistribution.

Commonly used approaches to estimate deformation modulus includes laboratory tests, in-situ loading tests and prediction by empirical equations. Researchers and scientific societies utilize various methods for determining the deformation modulus such as direct measurement using in-situ tests, indirect estimations based on rock mass classification methods, laboratorial result generalization for rock mass, etc [1–12]. The results obtained by all these methods are not of the same reliability; furthermore, the direct measurement method by use of in-situ test is ranked as the most reliable [7]. However, laboratory tests on limited size rock samples containing discontinuities cannot measure reliably values of deformation modulus due to the limitation of size of the testing equipment [8]. In-situ tests can provide direct information on the deformability of rock masses, however, as Bieniawski [9] noted, it is difficult to rely on one in-situ test alone as different results may be obtained even in a fairly uniform and good quality rock mass condition. Therefore, in order to obtain reliable results multi-tests are necessary which are expensive and time consuming.

Due to the difficulties encountered during the in-situ tests, developing of predictive models to estimate the deformation modulus based on the rock mass properties was always an attractive study domain among the rock engineers [11,12]. On the other hand, the mechanical properties of rock masses are not clear-cut, and most of the times are associated with uncertainties due to their complex and inhomogeneous nature. For example, prediction of in-situ deformation modulus from geomechanical properties of the rock masses is difficult and usually associated with error. In other words, determination of deformation modulus is highly influenced by the uncertainties related to mechanical properties of intact rock and rock mass parameters.

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http://dx.doi.org/10.1016/j.ijmst.2014.11.007
2095-2686/© 2015 Published by Elsevier B.V. on behalf of China University of Mining & Technology.

In recent years, predicting the rock mass properties by using artificial intelligence (AI) systems such as back propagation neural networks (BPNN), fuzzy systems, neuro-fuzzy systems and genetic algorithm (GA), has been an attractive research topic related to rock engineering practice [11–24]. Fuzzy inference systems (FISs) being one of the most capable branches of AI, which can cope with solution of complicated and ill-defined systems where many pertinent parameters have to be included. In the last two decades, an increase in fuzzy models applications in the field of geo-engineering, geosciences and engineering geomechanics has been observed [24–43].

Compared to other soft computing methods, the advantage of fuzzy systems used in this study is that they are able to describe complex and nonlinear multivariable problems in a transparent way. Moreover, fuzzy models can cope with non-probabilistic (i.e., semantic) uncertainties which are common in rock engineering. This paper describes two predictive models based on Mamdani fuzzy system (MFS) and multivariable regression analysis (MVRA). The results have been analyzed, interpreted, and compared with each other and with the in-situ measured values as well. For this purpose, the most effective geological parameters that could be considered in the designing problems of rock engineering (such as tunneling and mining projects) have been incorporated in the modeling.

2. Data set

Some data were collected from Bakhtiary dam site which is located in the southwest of Iran, 70 km away from northeast of Andimeshk city (Khuzestan province) and 65 km away from southwest of Dorud city in Lorestan province, Iran. This dam site is located in the folded Zagros tectonic-sedimentary zone. Its bed rock consists of limestone and marly limestone, containing nodules of siliceous limestone (or chert). The limestone also may occasionally contain dolomitic material. In this case study, deformation modulus of rock mass was measured based on the dilatometer test. Dilatometer test is known as one of the most reliable, economical and simple in-situ tests for measuring the deformation modulus of rock mass and is widely used in a great number of major engineering projects. It has been applied for measuring deformation parameter of rock mass in a borehole. Some of important advantages of this test are low cost, repeatability of test at several depths of borehole in situation close to intact condition and probability of anisotropy assessment. The dilatometer model which used in Bakhtiary dam site is Interfels model, that is, the Slotter test model. However, performing tests and interpretation of data and result have been carried out based on ISRM suggested method [44].

The rest of data obtained from the in-situ longwall panel roof rock measurements were reported in literatures. It should be noted that the geological characteristics of those coal mine sites are rather similar to those of the Bakhtiary dam site. Accordingly, these collected data is added to measured data in Bakhtiary dam site to build a database. In this study, parameters including overburden height, rock quality designation, weathering, unconfined compressive strength, bedding inclination to core axis, joint roughness coefficient and fill thickness were collected and then evaluated to develop Mamdani fuzzy system (MFS) and multivariable regression analysis (MVRA) models. For this purpose, 84 datasets were prepared for constructing the models. About 64 series of the datasets were used in developing the models and the rest of them were kept for testing the models. In selecting testing datasets, a sorting method was utilized. Statistical characteristics and variation of applied parameters in the modeling as well as their respective symbols are shown in Table 1. Also, Table 2 shows some of the datasets used in the modeling.

Table 2
Sample of data used in the modeling.

No	H (m)	RQD (%)	W (%)	UCS (MPa)	I (°)	JRC	FT (mm)	E_m (GPa)
1	20.4	93	83	125	52	4	1.5	30.6
2	45.5	100	60	69	75	5	1.5	3.47
3	169.25	100	85	106.5	20	7	1.5	11.9
4	431.9	100	75	94	45	7	0.5	15.38
5	138.6	80	65	94	85	19	0.5	2.35
6	174.3	73	25	25	55	17	3	3.73
7	459.4	100	78	87.5	40	9	0.5	22.38
8	192.25	100	85	106.5	80	11.5	1	20.3
9	174.3	42	70	96.5	42	13	1	2.02
10	121.5	57	20	19	36.25	10.5	1	13.47

3. Fuzzy systems

Fuzzy set theory was introduced by Zadeh (1965) to deal with the conception of the uncertainty due to imprecision and vagueness [45]. It provides a strict mathematical framework in which vague conceptual phenomena can be precisely studied. It can be considered as a suitable modeling language for vague and imprecision conceptual relations, criteria and phenomena. Imprecision here is meant in the sense of vagueness rather than the lack of knowledge about the value of a parameter [46]. In fact, it is a natural way to deal with imprecision problems by definition of class which represents continuum grades of membership. Therefore, a much wider scope of applicability in the field of pattern classification and information process is accessible by fuzzy sets [45]. Moreover, it performs numerical computation by using linguistic labels stipulated by membership functions [47]. In this way, contrary to a classical set in which the elements belong to, or not belong to a set, a fuzzy set degree of membership for each element is assigned in the unit interval between 0 and 1.

This theory can also be used for developing rule-based models which combine expert knowledge and numerical data [25]. Zadeh [48,49] was the first to introduce the idea of analysis and system modeling by using linguistic terms, and since then, it has been the subject of considerable investigations [50–52]. A fuzzy system

Table 1
Description of input and output parameters used in the modeling.

Type of data	Parameter	Unit	Symbol	Minimum	Maximum
Input	Overburden height	m	H	6	459.4
	Rock Quality Designation	%	RQD	42	100
	Weathering	%	W	100	20
	Unconfined Compressive Strength	MPa	UCS	19	125
	Inclination to core axis	°	I	2.5	85
	Joint roughness coefficient		JRC	3	19
	Fill thickness	mm	FT	0	4
Output	Deformation modulus	GPa	E_m	1.49	30.6