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Predicting slake durability of carbonate rocks using geomechanical properties (Case study: Durood-Khorramabad highway, Iran)

Somaye Farashi [a], Gholamreza Khanlari [a, *], Fateme Naseri [b]

[a] *Department of Geology, Faculty of Sciences, Bu-Ali Sina University, Hamedan, Iran*

[b] *Department of Geology, Faculty of Sciences, Ferdowsi University of Mashhad, Mashhad, Iran*

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ABSTRACT

This study investigates the relationship between slake durability indices and geomechanical characteristics of five types of carbonate rocks situated in the west of Iran along the Doruod-Khorramabad highway. In this study, five types of limestone rocks were selected, including grey limestone (A), marly limestone (B, C, D), and sandy limestone (E). The geomechanical characteristics of the studied limestones were calculated based on the ISRM (1981) standard stimulations. Statistical approaches were executed to find the most influential geomechanical characteristics on slake durability indices and to find an appropriate slake durability cycle for interpreting rock behaviors. According to the simple regression analysis, the first and fourth cycles of slake durability can provide adequately good information for initial engineering/design works. Also, the correlation coefficients demonstrated nearly constant change after the fourth cycle. Geomechanical parameters, like Schmidt hammer and dry density, showed the highest correlation with the fourth slake durability cycle (R =0.98). On the other hand, uniaxial compressive strength revealed a poor correlation (R = 0.49) with this cycle. Apart from estimating the 4th durability cycle from geomechanical properties, it is possible to calculate the second to fourth cycles of slake durability using the results of the first durability cycle (R = 0.99–0.94). Consequently, a multivariate equation was developed based on water absorption, Schmidt hammer, effective porosity, and modulus of elasticity with R^2=0.89 using the best subset regression method.

Keywords : *Slake durability, Geomechanical characteristics, Carbonate rocks, Simple and multiple regressions*

1. Introduction

Limestones are the most common sedimentary rocks that serve as a foundation of many construction projects such as roads, dams, tunnels, railways, pipelines, bridges, and some other engineering structures in Iran [3, 10, 18, 31]. For studying the mechanical behavior of rocks, slake durability can be considered as an important parameter [6, 9, 20, 24, 28], as it is practical for soluble and weak rocks. By increasing the number of cycles in this test, the slake durability index diminishes. Based on some research studies, the slake durability test should be conducted for two cycles, while others [12, 21, 23, 25, 32, 33] believe that further cycles should be applied during this test. Many researchers assessed the durability of various types of rocks, e.g., sandstones, mudstones, and limestones, by more than two cycles [2, 26, 29]. Yagiz (2011) reported that the first and fourth cycles of the slake durability tests could be used in the pre-design phase of engineering practices, and the second and fourth cycles could be calculated by the 1st cycle of this test. Apart from the number of cycles, mineralogy and texture have great influences on slake durability as well [11]. The vulnerability of fine-grained rocks to degradability through the slake durability test is higher than that of coarse-grained ones. Sharma and Singh (2008) investigated the relationship between slake durability indices and geomechanical characteristics of different hard and soft rocks, such as sandstone, basalt, mica schist, coal, and shale. Also, many researchers have reported similar relationships for carbonate rocks [8, 16, 27, 34]. Bryson et al. (2012) developed a new durability index that could characterize the durability behavior of shales better than the standard slake durability index. Many researchers have applied geomechanical properties of rocks to predict the slake durability index using statistical (i.e., simple and multiple regressions) and numerical (i.e., adaptive neuro-fuzzy inference system, artificial neural networks) approaches [1, 25, 30, 35].

Accordingly, the main aims of the present study are: 1) choosing an appropriate cycle of slake durability for establishing geotechnical models in engineering-geological studies; 2) correlating the slake durability index and geomechanical parameters using the simple regression method; and finally 3) developing a multivariate statistical model for predicting the slake durability index based on geomechanical parameters using the best subset technique.

2. Materials and methods

2.1. Geology of Case Study

The Khoramabad city, with a surface area of 6322 km², is situated in the central part of the Lorestan province, west of Iran. From the geological point of view, the study area consists of four main lithological units: conglomerate, sandstone, and siltstone (Amiran and Kashkan Formations), Limestone (Asmari and Shahbazan Formations), marl and shale (Gurpi Formation), and low-level piedmont fan and valley terrace deposits [17]. The study area is located in the longitude 48° 23' to 48° 55' East and the latitude 33°29′ to 33° 35' North, along the Dorud - Khorramabad highway.

* Corresponding author. Tel: +98-8138381460, Fax: +98-8138381460. *E-mail address:* khanlari_reza@yahoo.com (Gh. Khanlari).

2.2. Rock Sampling

In this research study, five types of limestone rocks were collected from the Dorud - Khorramabad highway in western Iran (Fig. 1). In order to provide standard testing specimens, each sample was examined for being homogeneous, unweathered, and free of visible joints. Anisotropic properties were not observed in the studied rocks. These limestone specimens include:

(A) A Cretaceous dark grey to grey limestone outcropped within the Dorud - Khorramabad highway.

(B) A Cretaceous marly limestone from the Chaghalvandy Formation at the inlet of the Dorud - Khorramabad highway.

(C) A Cretaceous marly limestone from the Chaghalvandy Formation outcropped 40 km from the Dorud - Khorramabad highway.

(D) A Cretaceous marly limestone of the Chaghalvandy Formation in the Zaghe area.

(E) An Oligocene marly-sandy limestone from the Abkot area

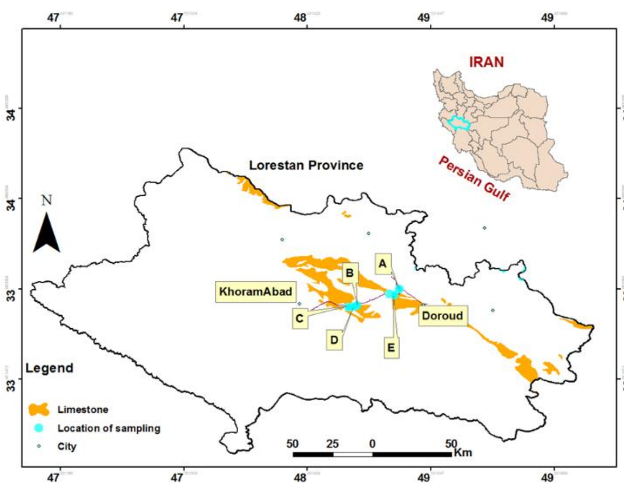

Fig. 1. Sampling locations and distribution of limestone sample in the Lorestan Province.

Table 1. Geomechanical properties of the studied samples.

Lithotype	γ_{dry} (kN/m^3)	N	UCS (MPa)	Vp (km/s)	E (GPa)	n´ (%)	W (%)	Id_2 (%)
A	26.25±0.36	44±5	64.53±18.61	6.48±0.051	22±4	0.37±0.11	0.14±0.04	99.69±0.03
B	25.62±0.12	39±5	46.7±18.4	5.28±0.25	13±4	0.15±0.05	0.06±0.01	99.47±0.04
C	26.20±0.09	44±5	51.32±17.07	6.32±0.22	21±8	0.17±0.18	0.06±0.07	99.77±0.05
D	25.95±0.16	43±3	49.01±15.29	5.41±0.42	17±6	0.17±0.08	0.06±0.03	99.80±0.03
E	26.32±0.36	45±6	72.77±8.20	6.53±0.036	27±2	0.83±0.27	0.31±0.08	99.81±0.07

γ_d =dry density, N: Schmidt hammer rebound number, UCS =uniaxial compressive strength, Vp =p-wave velocity, E= Young's modulus, n´= effective porosity, W= water absorption by weight, Id_2= slake durability index.

2.3. Laboratory Studies

In order to conduct petrographic studies, a thin section was prepared for each carbonate type. An optical polarizing microscope was employed to describe the mineralogical and textural properties of the limestones.

(A) The dark grey to grey limestone had a sparite/calcite cement. This dense rock had a comparatively low porosity with a dark brown color. It also had fossils filled with a sparite cement (Fig. 2-A).

(B) The first marly limestone had a calcite cement, some of which were coarse that filled the micro-joints, reducing the durability of the rock. It also had stylolite filled with iron oxide cement (Fig. 2-B).

(C) The second marly limestone had some microcracks filled with calcite crystals. The joints were crosswise in several directions (Fig. 2-C).

(D) The third marly limestone had some microcracks filled with calcite crystals. It had a calcite cement, with a fine to medium grain size and without organic contents. It also had stylolite filled with iron oxide cement (Fig. 2-D).

(E) The marly-sandy limestone had a fine-grained sparite/calcite cemented texture. It had random stylolites, microcracks with voids filled with calcite. It had a higher organic content compared to the other samples (Fig. 2-E).

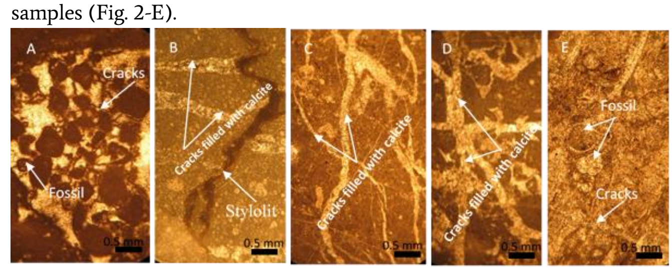

Fig. 2. The photomicrographs of the studied rocks.

3. Rock testing procedures

For the laboratory studies, homogeneous, unweathered and free of observable joint samples were selected. A total of seven large blocks were collected, of which five core samples and 50 spherical specimens were prepared. Schmidt hammer rebound number (N), effective porosity (n´), uniaxial compressive strength, P-wave velocity (V_p), slake durability index, water absorption by weight (w), dry density (γ_{dry}), and also modulus of elasticity (E) were examined on the five samples, whose results are listed in Table 1.

The uniaxial compressive strength (UCS) and modulus of elasticity (E) tests were performed following ISRM (1979) stipulation, which requires the core samples drilled with a 54 mm diameter and an L/D ratio of 2-2.5. Unconfined compressive tests were applied on core samples, with a uniform loading rate of 0.5–1 MPa. The L-type Schmidt hammer with an impact energy of 0.735 Nm was applied following ISRM (1981). P-wave value (Vp), water absorption (w), effective porosity (n´), and dry density (γ_{dry}) were also determined following ISRM (1981). Ten samples from each lithotype were tested for fifteen cycles of slake durability test [7] (Fig. 3). The Id test was repeated 15 times, and the average results are listed in Table 2.

Table 2. Averaged Id results for the studied lithotypes (Id is the slake durability index, and the numbers show the slake durability cycle).

Lithotype	Id_1	Id_2	Id_5	Id_{10}	Id_{15}
A	99.79	99.69	99.56	99.35	99.05
B	99.71	99.47	99.05	98.44	97.75
C	99.88	99.77	99.52	99.18	98.84
D	99.9	99.80	99.49	99.04	98.58
E	99.87	99.81	99.64	99.42	99.17

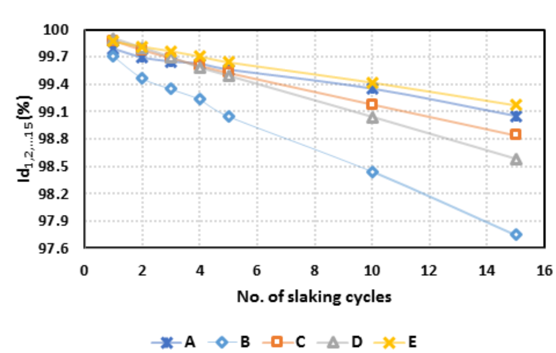

Fig. 3. Comparing the slake durability indices for the selected limestone samples (Id is the slake durability index, and the numbers show the slake durability cycle)

4. Regression analysis

4.1. Simple regression analysis

Until now, different methods have been proposed by other researchers to investigate the empirical relationships between rock properties. One of the acceptable methods is regression analysis. In this study, linear (y = ax + b) and nonlinear (y = axb) regression analyses, exponential (y = aex) and logarithmic (y = a + ln x) relationships between the slake durability indices and relevant rock properties were undertaken to develop the most reliable empirical equations. The results of the regression analysis are shown in Fig. 3. The linear regression analysis gives the best correlations between the variables with 90% confidence (Table 3).

Table 3. The correlation coefficient (R) between geomechanical characteristics and the first ten slake durability indices.

R	Id_1	Id_2	Id_3	Id_4	Id_5	Id_6	Id_7	Id_8	Id_9	Id_{10}	Relations
N	0.70	0.88	0.94	0.98	0.98	0.99	0.98	0.98	0.99	0.99	Linear
UCS(MPa)	0.21	0.47	0.60	0.70	0.69	0.72	0.76	0.77	0.79	0.78	Linear
Vp(km/s)	0.34	0.57	0.67	0.78	0.78	0.84	0.91	0.91	0.88	0.87	Linear
γ_{dry}(kN/m3)	0.62	0.81	0.88	0.95	0.95	0.98	0.99	0.99	0.98	0.98	Linear
n´(%)	0.24	0.44	0.54	0.59	0.58	0.60	0.61	0.61	0.64	0.64	Linear
w(%)	0.24	0.43	0.54	0.59	0.58	0.60	0.61	0.62	0.64	0.64	Linear
E(GPa)	0.57	0.76	0.84	0.89	0.88	0.91	0.93	0.92	0.93	0.93	Linear

In this research, after four cycles of drying/moisturizing, it was concluded that the variation of the coefficient correlation between slake durability indices and geomechanical characteristics (i.e., w, n´, Vp, E, and UCS) is nearly constant and can be disregarded (Fig. 4). Yagiz et al. (2012) reported that the slake durability index of four cycles (Id_4) provides more accurate results to evaluate the mechanical properties of carbonate rocks. Id_4 is one of the reliable input variables for the estimation of the UCS and E in carbonate rocks.

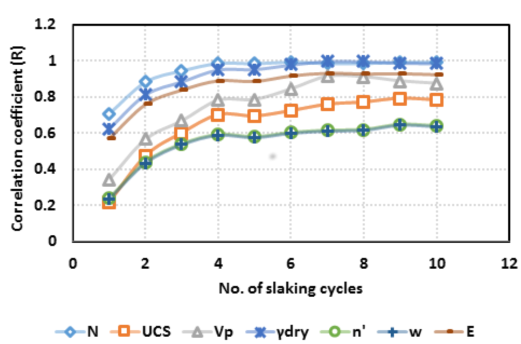

Fig. 4. Relationship between R values and geomechanical characteristics in different slaking cycles.

The relationship between Id_4 and the properties of the index rock is given in Fig. 5. As seen, the highest and lowest correlation coefficients were recorded between Id_4, N, and UCS, respectively (Fig. 5).

The second to fourth cycles of slake durability indices were empirically predicted from the results of the 1st cycle of the slake durability index, as shown in Table 4.

Table 4. The relationships between Id_1 and other slake durability indices.

Equations	R	T test	
		Calculated value	Tabulated value
Id_2 = 1.7151 Id_1 - 71.492	0.99	15.69	2.132
Id_3 = 2.1618 d_1 - 116.13	0.97	11.01	2.132
Id_4 = 2.2479 Id_1 - 124.8	0.96	7.66	2.132
Id_5 = 3.0725 Id_1 - 207.17	0.94	6.16	2.132

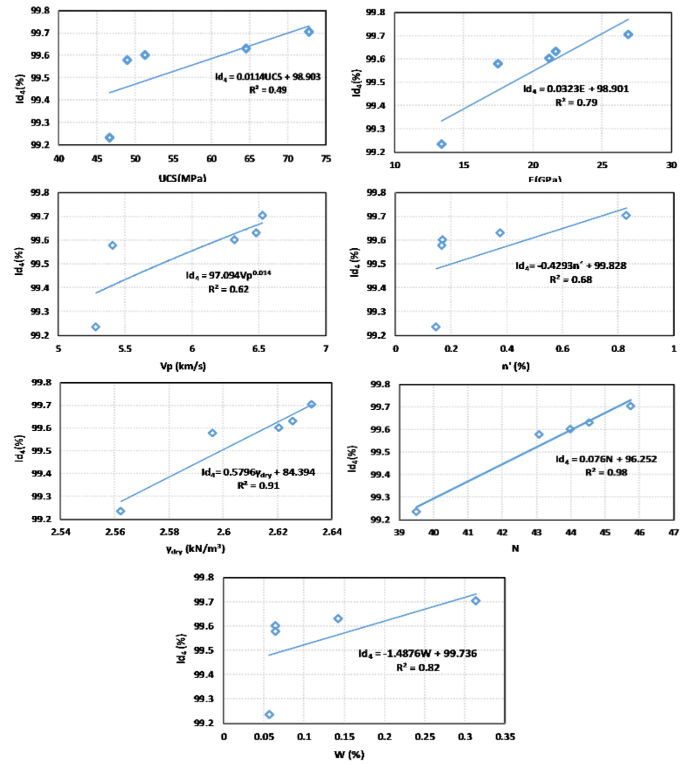

Fig. 5. Relationship between Id_4 and geomechanical properties of the studied rocks.

This method can be used to reduce the testing duration. Correlation coefficient values of higher than 0.94 were obtained from the results of the t-test, indicating a meaningful correlation between the variables. The empirical relationship between Id_1 and both Id_2 and Id_4 is adequately acceptable to be employed in the primary stages of engineering/design projects.

4.2. Multiple regression analysis

In this research, the slake durability index was statistically investigated and correlated with seven geomechanical parameters, including UCS, E, Vp, N, W, n', and γ_{dry} (Table 1). In order to assess the combined influence of rock properties, multiple regression analysis was executed using the best subsets technique. In other words, a multivariate linear statistical approach was used to evaluate the influences of the predictors (geomechanical properties) on the response of the model (slake durability index) [26], which is defined theoretically by the following equation:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + e \quad (1)$$

Where, Y is the response of the model, Xi (i=1,...,k) are the predictors, βi defines the coefficient of Xi, and e determines the noise [38].

The best subsets technique is an efficient way to select variables for the most suitable statistical model and achieve goals with as few predictors as possible [4].

In this study, the Minitab 17 statistical software [4] was employed to accomplish our goald and construct the best subsets regression. Two evaluation criteria, including the adjusted R^2 and Mallow's Cp should be measured for the selection of the most suitable subset. The adjusted R^2 is a modified version of R^2, which reveals how well data points fit a curve or line, but modifies for the number of predictors in a model [15]. It is calculated by the following equation:

$$Adjusted\ R^2 = 1 - \frac{(1-R^2)(N-1)}{N-P-1} \quad (2)$$

Where, p is the number of the predictors, and N is the total size of the sample [19].

In order to select a proper multiple regression model among all the presented models by the software, Mallows' Cp statistic can be a practical asset [15].This criterion can identify the best alternative because it can compare the precision of a full model to those with a different number of parameters. It is calculated through the following equation:

$$C_p = \frac{RSS_P}{\sigma^2} + (2P - n) \quad (3)$$

Where, RSS_p is the residual sum of squares for a model with p predictors and $\hat{\sigma}^2$ is an estimate of the variance of noise [19].

The best response in this technique should have the lowest C_p and the highest R^2 values. The best subsets regression results are given in Table 5. As shown, the best fit includes water absorption, modulus of elasticity, Schmidt hammer, and effective porosity. Therefore, the aforementioned properties are the most reliable parameters for predicting the four-cycle slake durability index from geomechanical properties. The descriptive statistics of multiple regression analysis are shown in Table 6. According to the results of Table 5, the multiple regression equation is developed as follows:

$$Id_4 = 97.057 + 0.383wt + 0.0119E + 0.0255N + 0.1995n' \quad (4)$$

Table 5. The best subsets regression models for predicting Id_4 based on geomechanical properties.

R	R^2	R^2_{adj}	Mallows Cp	UCS (MPa)	w (%)	γ_{dry} (kN/m³)	E (GPa)	Vp (km/s)	N	n´ (%)
88.20	77.8	76.8	15.2				X			
74.56	55.6	53.7	51.5						X	
90.88	82.6	81	9.5						X	X
89.49	80.1	78.3	13.4	X			X			
93.11	86.7	84.8	4.7				X		X	X
92.79	86.1	84.1	5.7	X	X		X			
94.23	88.8	86.5	3.3		X		X		X	X
93.48	87.4	84.8	5.7	X	X		X	X		
94.44	89.2	86.3	4.7	X	X		X		X	X
94.23	88.8	85.9	5.3		X	X	X		X	X
94.65	89.6	86.1	6	X	X		X	X	X	X
94.44	89.2	85.7	6.6	X	X	X	X		X	X
94.65	89.6	85.3	8	X	X	X	X	X	X	X

Table 6. The descriptive statistics of multiple regression analysis.

Predictor	Coef.	Std. Err.	T-Value	P-Value
Cons.	97.06	0.61	158.73	0
w	0.383	0.202	1.9	0.072
E	0.012	0.004	2.62	0.016
N	0.025	0.006	3.9	0.001
n´	0.12	0.062	3.23	0.004

The R value of Eq. (4) was 0.94, which can be relied on as an acceptable estimate for the slake durability index. In order to validate the best regression model, an analysis of variance was executed, as presented in Table 7. Moreover, the proposed model is significant at a 90% confidence level (p-value <0.1) for all of the predictors in this model.

The measured and calculated Id_4 values from equation (4) were correlated, whose result is presented in Fig. 6. As seen, Eq. (4) is a suitable calculation for the measured Id_4, which is able to reliably predict the response.

Table 7. Variance analysis of the regression model for Id_4.

Source	df	SS	MS	F-Value	P-Value
Regression	4	0.70	0.18	39.54	0.000
w	1	0.02	0.02	3.62	0.072
E	1	0.03	0.03	6.87	0.016
SHR	1	0.07	0.07	15.21	0.001
n´	1	0.05	0.05	10.42	0.004
Residual	20	0.09	0.00		
Total	24	0.80			

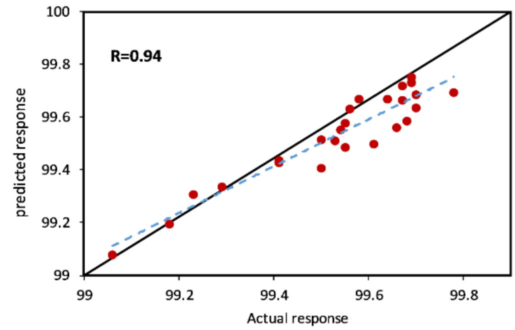

Fig. 6. The relationship between actual and calculated values Id_4.

5. Conclusions

In this research, an effort was made to investigate and add more information to the relationship between the slake durability index and geomechanical characteristics of five types of carbonate rocks. Geomechanical characteristics, such as Schmidt hardness and dry density of carbonate rocks, showed the highest correlation with Id_4 (R = 0.98 and 0.96). It seems that in carbonate rocks, the results of the slake durability test with four cycles are interpreting the behavior of the rocks more appropriately than those of the slake durability test with two cycles.

Based on the simple regression analysis, it seems that after the fourth cycle, the slake durability index remains constant with the change of effective porosity, modulus of elasticity, P-wave velocity, and water absorption. Furthermore, it is possible to calculate the results of the second to fourth cycles of slake durability from the results of the 1st durability cycle for carbonate rocks (R = 0.99–0.94). Finally, the result of multiple regression analysis demonstrated that effective porosity, Schmidt hardness, modulus of elasticity, and water absorption have the potential to estimate four-cycle slake durability with R=0.94 and p-value <0.01, which is statistically reliable. Also, this research indicates that the obtained results can be more practical in the early stages of engineering projects.

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