Innov. Infrastruct. Solut. (2016) 1:17
DOI 10.1007/s41062-016-0016-9

TECHNICAL NOTE

Updated relations for the uniaxial compressive strength of marlstones based on P-wave velocity and point load index test

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Received: 28 March 2016 / Accepted: 14 June 2016 / Published online: 4 July 2016

Abstract Although there are many proposed relations for different rock types to predict the uniaxial compressive strength (UCS) as a function of P-wave velocity (V_P) and point load index (*I*s), only a few of them are focused on marlstones. However, these studies have limitations in applicability since they are mainly based on local studies. In this paper, an attempt is therefore made to present updated relations for two previous proposed correlations for marlstones in Iran. The modification process is executed through multivariate regression analysis techniques using a provided comprehensive database for marlstones in Iran, including UCS, V_P and *I*s from publications and validated relevant sources comprising 119 datasets. The accuracy, appropriateness and applicability of the obtained modifications were tested by means of different statistical criteria and graph analyses. The conducted comparison between updated and previous proposed relations highlighted better applicability in the prediction of UCS using the updated correlations introduced in this study. However, the derived updated predictive models are dependent on rock types and test conditions, as they are in this study.

Keywords Updated models · Model performance · Marlstone · Prediction

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Introduction

Marlstones are calcium carbonate or lime-rich mudstones with variable amounts of clays and silt [35]. Generally, they are recognized by their inherent weak strength in rock engineering related projects (e.g. [7, 32, 46]). It was proved that the clay content is one of the main reasons for high observed deformations and settlements in marlstones (e.g. [4, 13, 22, 30, 36, 37, 42, 46]). As an important element in rock related engineering projects, access to an accurate high-quality laboratory database of engineering properties of these weak-strength materials will therefore be attractive [6, 7, 43].

The uniaxial compressive strength (UCS) is one of the main and most widely used rock mechanical properties in rock, civil and mining engineering projects which its standardized direct measurements due to destructivity and potential difficulties specially in weak strength rocks has been discussed by many researchers (e.g. [11, 24, 25]). Therefore, introducing and developing alternative nondestructive indirect methods can play a significant role in providing UCS predictive models [47]. Such nondestructive measurements (e.g. Schmidt hammer, Shore hardness, Los Angeles abrasion, slake durability, petrographical and structural property analyses, block punch strength index, core strangle test, point load index test, P-wave velocity and impact strength) with simpler and quicker procedures can be carried out both in field and laboratory conditions (e.g. [8, 10, 14, 21, 24, 27, 33, 34, 38–40, 45, 49]). Moreover, since less or no sample preparation is required and less sophisticated testing equipment is used, the economic aspects make them attractive alternative practical procedures to estimate the UCS.

In the recent years, various modeling methods such as statistical techniques and in particular multivariate regression analysis (MVRA), fuzzy inference system and neural network approaches have been applied to develop UCS predictive models in rock engineering (e.g. [17, 24, 26, 27, 47]). However, despite of some limitations such as inadequacies in simulating the process due to influencing auxiliary factors, the simple and MVRA techniques are commonly employed to establish a predictive model [27, 48]. Therefore, to provide a regression analysis, access to a strong laboratory database of rock mechanical properties is an important and very useful component to develop predictive models of rock properties and in particular for UCS as a function of indirect simpler tests.

Despite of vast distribution of marlstones in Iran, only a few limited and localized studies have been carried out [8, 16, 20, 28]. Moreover, several damages in engineering projects related to these weak rocks have been reported [7]. Therefore, lack of proposed models both in number and application as well as provide a developed predictive model to overcome some of the limitation of the available correlations, are the main reasons why marlstones were chosen.

In the current paper, the proposed predictive model for UCS as a function of P-wave velocity (V_P) and point load test index (Is) [24] has been updated for marlstones in Iran using a comprehensive database of 119 datasets of UCS, Is, V_P, elasticity modulus (E), porosity (n), water absorption (w) and density (γ). Among these measurements, the UCS, Is and V_P were considered for the modification and updating process. The procedure was performed using the MVRA and the updated relations were compared to previous proposed correlations for Iran. The performance of the updates was tested and evaluated using both different statistical criteria and analytical graph analyses which better predicting in UCS was observed using the updated relations.

Properties of provided database

The provided database for this study was compiled from published papers [7, 8, 16, 20, 28] as well as other validated relevant sources [1, 44]. The database includes a total of 119 datasets of mechanical and geotechnical tests of marlstones comprising the Is, V_P, γ, n, w as well as UCS and E. However, in this paper only the UCS, Is and V_P have been used. The locations of tested samples, scattering and histograms of employed data as well as their statistical

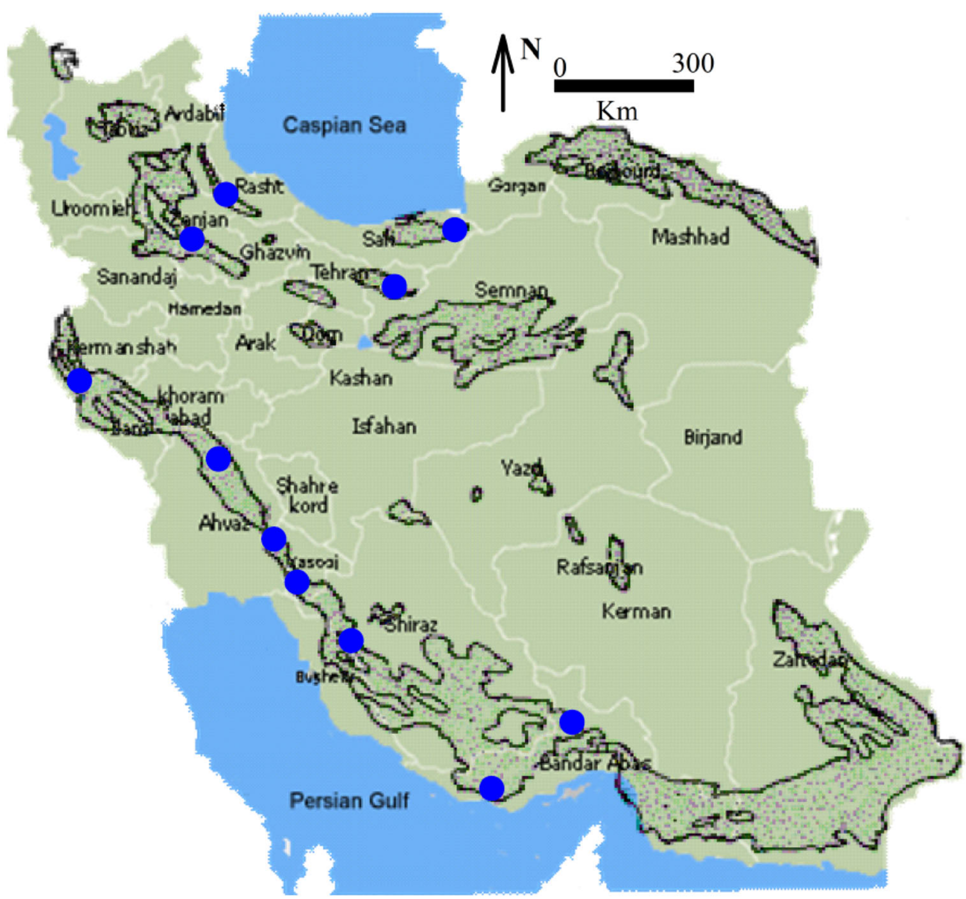

Fig. 1 Overlap of marlstones distribution in Iran [16] and location of tested areas

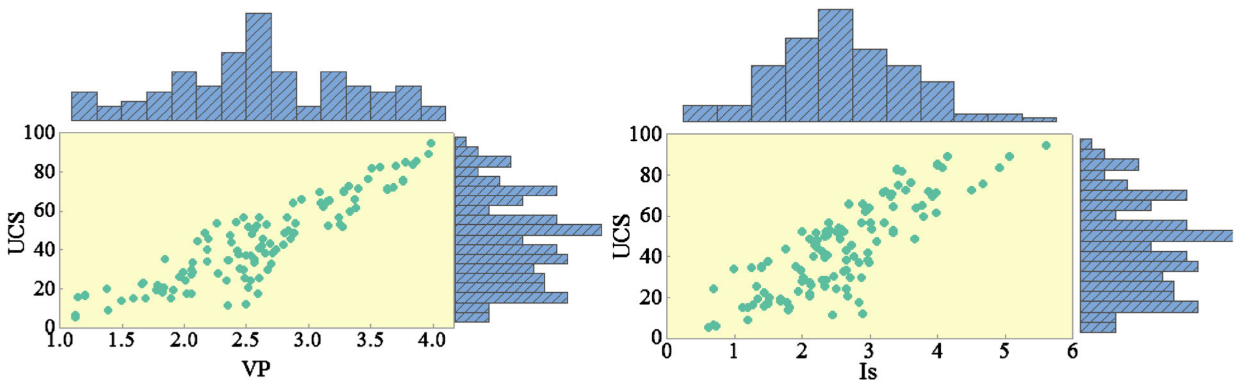

Fig. 2 Marginal and histogram plots of UCS, V_P and *Is* of the provided database

Table 1 Statistical analyses of 119 datasets used in this study

Parameter	Average	Standard deviation	Maximum	Minimum
V_P (km/s)	2.61	0.715	3.79	1.22
Is (MPa)	2.59	0.96	5.6	0.61
UCS (MPa)	44.40	22.43	94.26	5.1

parameters are presented in Figs. 1, 2 and Table 1, respectively. The American Society for Testing Material (ASTM) and the International Society of Rock Mechanics (ISRM) are the two main accepted standard procedures for measurement of UCS, V_P and *Is*. In this paper all of the data for V_P has been measured according to ASTM, whereas the *Is* was based on ISRM. For the UCS, only Moradian and Behnia [28] used the ISRM, while the other UCS values were obtained by testing according to the ASTM standard. Obtaining all data using acceptable and uniform standardized testing procedures thus minimizes concerns about the database uncertainties. The UCS and V_P have been tested according to standards using NX size cylindrical samples whereas for *Is* the diameter of the specimens were 50 mm.

Updating process

Although several problems and limitations related to V_P, and in particular for *Is*, have been reported when the UCS are predicted using correlations based on these parameters (e.g. [9, 12, 15, 18, 19, 23, 24, 29]) but these tests have widely been used by many researchers to indirectly predict the UCS [8]. The measured strength in the *Is* test is a function of the platen load at failure [14], whereas in V_P the rock mechanical parameters can be determined using simpler nondestructive tests without changing the internal structure of the samples at relatively low costs respected to static tests. Although the *Is* test is biased towards stronger samples and varies with the shape of the specimen [31], but the V_P is related to the quality of the materials and also depends on rock type, density, grain size and shape, porosity, anisotropy, pore water pressure, clay content, confining pressure and temperature. However, the influence of weathering, alteration, bedding planes and joint properties consisting of roughness, filling material, water, dip and strike has also been examined [24]. Therefore, errors up to 100 % should be expected in various size corrections when the compressive strength is predicted from *Is* tests [23].

The possibility to improve and update the proposed relation by Kahraman [24] ($\mathrm{UCS} = 9.95Vp^{1.21}$; $\mathrm{UCS} = 23.62Is - 2.69$) for marlstones in Iran is the main objective of this paper. The relation by Kahraman [24] was obtained using 48 different rock types which marlstones were also included. Moreover, the observed scattering in predicted values by Kahraman [24] with respect to the exact line (1:1 slope line) can be another indication for possible improvement to update the relations (Fig. 3a–d). The operation for updated relations has been executed through the MVRA and the result after modification is presented in Fig. 3c, d. In this process, the UCS was calculated using the Kahraman [24] relation and the MVRA was then conducted between the measured and predicted UCS values.

Discussion

The error measurement criteria can be employed to evaluate the accuracy of the prediction and the model's performance [2, 3]. However, the possible problems in interpretation of these criteria should be notified, particularly when working with low-volume data or trying to assess accuracy across multiple items. In the current paper, the performance of the updated models has been examined and evaluated by mean absolute percentage error (MAPE), variance account for (VAF), root mean square error

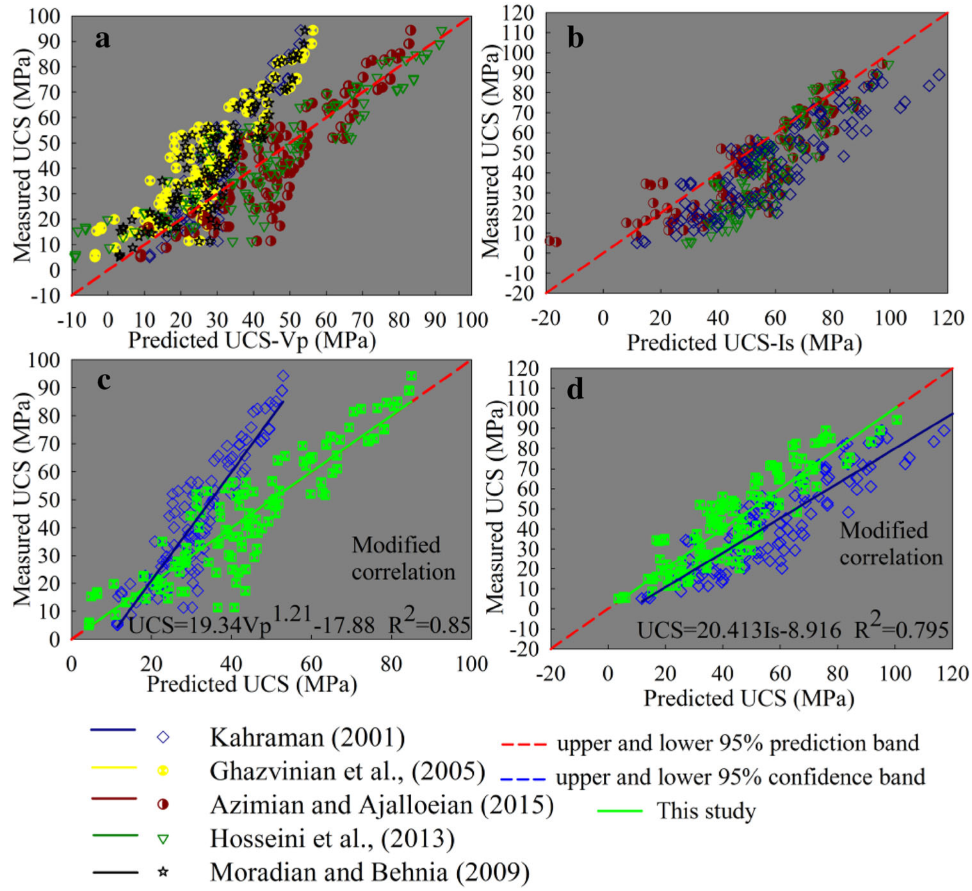

Fig. 3 Data scattering of used correlations in this paper with respect to 1:1 slope line (**a**, **b**), comparison between the predicted values using proposed relation by Kahraman [24] before and after modification regarding to 1:1 slope line (**c**, **d**)

Table 2 Results of statistical analyses criteria to evaluate the performance of the updated and previous proposed correlations in this study

Predictive equation	Researcher(s)	R^2	RMSE	MAPE	VAF
$UCS = 56.939 \text{Ln}\,(Is) + 1.655$	Azimian et al. [8]	0.59	0.531	14.91	71.27
$UCS = 14.847 Is + 19.887$	Hosseini et al. [20]	0.57	0.579	15.76	68.54
$UCS = 20.44 Is - 8.92$	Direct correlation	0.78	**0.314**	**9.12**	85.93
$UCS = 20.413 Is - 8.916$	Updated in this paper	**0.795**	**0.314**	**9.12**	**86.27**
$UCS = 23.62 Is - 2.69$	Kahraman [24]	0.43	0.611	16.23	59.09
$UCS = 7.55 V_P^{1.789}$	Direct correlation	0.83	**0.229**	**8.96**	91.35
$UCS = 0.021 V_P - 27.163$	Azimian and Ajalloeian [7]	0.80	0.315	9.88	85.02
$UCS = 0.026 V_P - 20.47$	Ghazvinian et al. [16]	0.26	0.782	17.91	56.32
$UCS = 0.0353 V_P - 48.748$	Hosseini et al. [20]	0.61	0.341	11.02	82.96
$UCS = 165.05 e^{(-4451.07/V_P)}$	Moradian and Behnia [28]	0.35	0.573	15.95	62.78
$UCS = 9.95 V_P^{1.21}$	Kahraman [24]	0.37	0.486	12.98	64.53
$UCS = 19.34 V_P^{1.21} - 17.88$	Updated in this paper	**0.85**	**0.229**	8.98	**91.88**

Bold values indicate better performance of used statistical criteria

(RMSE), correlation coefficient (R^2) and residual (Re) statistical error indices. The results are then compared to previous proposed relations for marlstone in Iran (Table 2; Fig. 4a, b). It can be found in statistical contexts that the smaller values of MAPE, Re and RMSE as well as higher values of R^2 and VAF will address for better performance in fitting.

In this paper only the modification is taken into account and the direct correlations are not the subject of the study. However, the results of direct correlations using the available data are also presented. The updated correlations were validated using a randomized selection of 20 % of the datasets. Comparison of prediction accuracy for the updated correlations with previous proposed

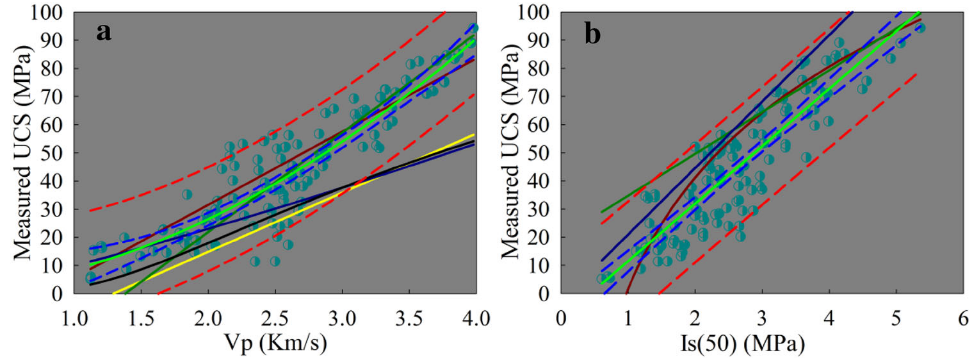

Fig. 4 Comparison of the updated correlations in this study with previous proposed relations regarding upper and lower 95 % prediction and confidence band. The definition of *colors* is the same as Fig. 3

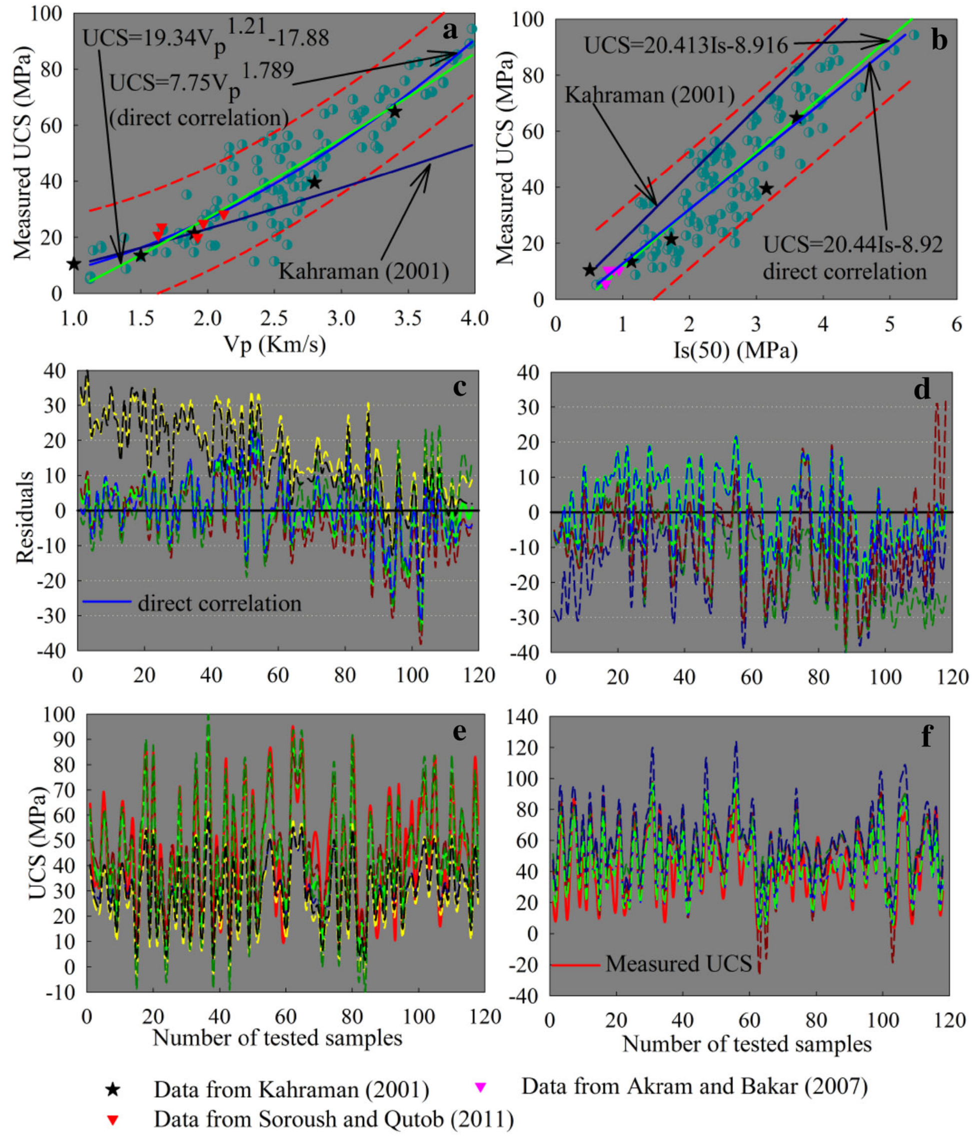

Fig. 5 Comparison of updated correlations with direct regression analyses and relation proposed by Kahraman [24] with respect to 95 % prediction bands (**a**, **b**), The calculated residuals of indicated correlations in Table 2 (**c**, **d**) and comparison of predicted UCS using the V_P (**e**) and *I*s (**f**) as shown in Table 2. The colors are the same as in Fig. 3. The applicability of updated correlations for new external data is also presented in **a** and **b**

correlations (Fig. 4a, b) indicates that almost all of the estimated values of UCS using the updated correlations fall in the 95 % prediction bands. The conducted comparison between the updated correlations with Kahraman [24] and those obtained by regression analysis is shown in Fig. 5a, b. The calculated residual for all of the used correlations are also presented (Fig. 5c, d). In addition, a comparison between predicted UCS values using the implemented correlations [7, 8, 16, 20, 24, 28] as well as direct regression analysis is shown in Fig. 5e, f.

Moreover, the applicability of the updated correlations was examined using other data [5, 24, 41] which was not employed in the updating process (Fig. 5). The observed agreement with the updated relations indicates the usefulness of the relations.

Conclusion

Dependency on rock type is one of the main limitations in developing empirical relationships between the UCS and other mechanical parameters such as V_P and *I*s. Thus whether there is possibility for updating, these relations can be developed for another area with other rock types. Hence, finding such these probable updates will help for better application of the relation and searching for them can be a reasonable investigation. In this paper the proposed relation by Kahraman [24] was updated for marlstones in Iran and comparison of the results indicated better applicability in the introduced updated relation. The performance and accuracy of the updated correlations were controlled by several statistical indices and graph analyses in which significant improvement was observed with respect to the previous proposed relations as well as moderate improvement with respect to the results of direct correlations.

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