International Research Journal of Earth Sciences ISSN 2321–2527
Vol. **2(9),** 7-14, October **(2014)** *Int. Res.J. Earth Sci.*

Prediction of Rock Mechanical Parameters as a Function of P-Wave Velocity

Abbas Abbaszadeh Shahri[1, 3*], Arsham Gheirati[2] and Maria Espersson[3]
[1]Faculty of Civil Engineering, Islamic Azad University, Rudehen Branch, Rudehen, Tehran, IRAN
[2]Department of Geophysics, Islamic Azad University, Chalous branch, Chalous, IRAN
[1,3]Uppsala University, Box 534, Construction Engineering Department, SE-75121 Uppsala, SWEDEN

Available online at: www.isca.in, www.isca.me
Received 21th June 2014, revised 24th September 2014, accepted 13th October 2014

Abstract

Due to non destructive and easy method of P-wave velocity (V_P) measurements in field and laboratory conditions, and also its relation to mechanical parameters of the material, it has increasingly been conducted to determine the physical properties of rock materials. In this paper an experimental study of the measurement of P-wave velocity, uniaxial compressive strength (UCS), Schmidt hammer test (N), porosity (n), saturated and dry density (γ) and elasticity modulus (E) for two types of rocks including the sandstone and schist at a selected site in West of Iran in Hamedan province were performed. According to available reports of Geological Survey of Iran (GSI), in most of areas of Zagros fault zone including our selected area, particularly in Sanandaj – Sirjan zone, the majority of rock types are consisting of sandstones and metamorphed Jurassic rocks in green schist. Therefore, in the present paper, we aim to determine reliable empirical predictive models as a function of P-wave velocity to estimate the rocks properties for these two rock types. For this purpose, 30 samples consisting of 9 schist and 21 sandstones were tested in laboratory. By application of statistical analysis and student t-test the computed regression coefficient value evaluated and showed that these obtained empirical relations can be applied for the West of Iran. To verify and validate our results a detailed comparison between results of this study by other researchers were conducted by plotting graphs. The result of comparison shows good compatibility with each other.

Keywords: Rock mechanical parameters; P-wave velocity, predictive models, Zagors fault zone.

Introduction

In different condition and purposes, there are several developed approach and different modelling techniques for design of engineering structures using intact and rock mass index properties. In this case, application of ultrasonic techniques because of simplicity and non destructivity in field and laboratories[1,2] are increasingly being used in various fields of mining, geotechnical, civil and underground engineering. Rock type, density, grain size and shape, porosity, anisotropy, porewater pressure, clay content, confining pressure and temperature are effective factors on p-wave velocity but weathering, alteration, bedding planes and joint properties consisting of roughness, filling material, water, dip and strike have an important influence on the seismic velocity[3].

For site characterization, mining and civil engineering applications, having a strong laboratory database of rock mechanical and engineering properties will be very useful. In practice, such a database is not available and moreover, discontinuity and variable nature of rock masses increases difficulties of directly obtain the specific design parameters of interest. Application of these proposed correlations is of interest, mainly due to the fact that rock index tests have the advantages of being relatively fast and economical. However, obtained correlations are not constant and can be varied with rock types. Hence, several researchers have been established and propose empirical equations between the V_P, petrophysical and mechanical parameters of the rocks[4-29].

In this paper, we aim to establish predictive models for rock mechanical parameters as a function of V_P from collected and tests rock samples from the various boreholes of the Khorram rud earth dam site in Hamedan province in west of Iran. V_P, UCS, Schmidt hammer rebound test (N), density (dry, saturated), porosity and elastic modulus were the determined properties of samples in this study. Validation of obtained models in this study was investigated by conducting detailed comparison with available literature reviews for application of rock engineering. The samples were picked from various depths in each borehole and all samples were calibrated to be in standards format of ISRM[30].

Material and Methods

By considering the figure-1, Zagros Mountains follow a NW to SE pattern. A common way to divide this large area is considering two parts including Northern and Southern Zagros. Northern Zagros includes Iranian provinces of West Azerbayejan, Kurdistan, Hamedan, Kermanshahan, Ilam, Lorestan, Khuzestan and Chaharmahal va Bakhtiari. Southern Zagros covers provinces of Kohgiluye va Buyerahmad, Fars, Bushehr and Hormozgan. Geologically, Zagros Mountains consist of high and folded Zagros as two major parts. High Zagros forms the north eastern mountains and folded Zagros stands in the south and west of the high Zagros. Heading east, high Zagros faces inner highlands of the Zagros Mountains also known as Sanandej - Sirjan Zone. Folded Zagros instead ends in the Persian Gulf in south Khuzestan plain in south west and Mesopotamia in west.

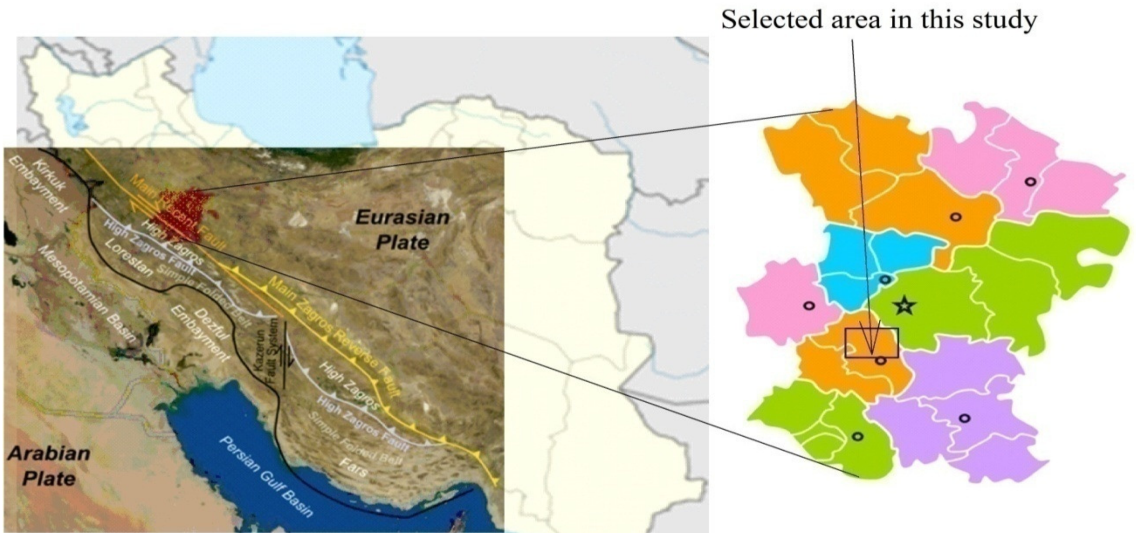

Figure1
Zagros fault characteristics and location of the studied area

Hamedan Province which located in the west of Iran is mostly mountainous in part of the Zagros range, especially high folded Zagros[31].

The site of Khorramrud embankment dam is located in 48º 18´ E and 34º 38´ N geographical coordinates, in 30 Km of southwest of Hamedan and near the Oshtoran village in west of Iran as shown in figure1. This clay core earth dam has a crest length of 755m, 55m height from the river base and 11.53Mm^3 reservoir capacity. A total of 13 boreholes up to depth of 80m with maximum depth of ground water table of 18.7m in the various location of site were drilled but the information of 10 boreholes because of better quality core samples were selected for analysis as shown in table-1. According to executed exploratory drilling, field investigations, surveying and acquisition of discontinuities information and prepared petrological thin sections, two types of lithology including sandstone and schist were recognized and structure properties of rock mass have been performed and analyzed. The sandstones of this area can separate into red sandstone (slightly weathered) and gray sandstone.

Table-1
Drilled exploratory boreholes in the studied area

Borehole	Depth and GWT (m)	Sample properties		
		Depth	**Sample No.**	**Rock type**
KB2: dam axis	55 (18.7)	24.28-25.00	51912	schist
		52.50-53.00	51914	schist
KB3:dam axis	35 (10.5)	28.00-28.50	51921	schist
BH2: dam axis	65 (9.70)	41.20-41.70	51924	schist
BH2(A): dam axis	60 (8.20)	54.00-54.30	42992	schist
		47.53-47.93	42991	sandstone
		32.50-32.80	42989	sandstone
KB1: right support	30 (---)	18.20-18.75	42944	sandstone
		24.68-25.00	42943	sandstone
BH1: right support	75 (---)	43.10-43.70	42950	sandstone
BH3: dam axis	75 (8.30)	42.20-42.75	42933	sandstone
		48.68-49.00	42934	sandstone
BH3(A): dam axis	80 (---)	24.72-25.00	42946	sandstone
		23.00-23.33	42945	sandstone
BH4: left support	30 (---)	11.20-11.50	42949	sandstone
		14.40-14.70	42950	sandstone
BH5: left support	65 (---)	15.30-15-60	42938	schist
		30.40-30.80	42942	schist
		32.40-32.95	42940	schist
		42.60-43.00	42941	sandstone
		60.57-60.95	42939	sandstone

Table-2
Obtained results of the tested samples in the studied area

Rock type (number of samples)	UCS (MPa)		N		E (GPa)		Vp (Km/s)		n (%)		γ_{sat} (gr/cm^3)		γ_d (gr/cm^3)	
	max	min	max	min	max	min	max	min	max	min	max	min	max	min
sandstone (21)	95	20	22.56	10.18	3.75	3.10	95	20	22.56	10.18	3.75	3.10	95	20
schist (9)	45.2	37.5	9.6	9.13	3.43	3.35	45.2	37.5	9.6	9.13	3.43	3.35	45.2	37.5

Table-3
Statistical analyses of the measured parameters

Rock Type	UCS (Mpa)	E(Gpa)	Vp(Km/s)	N	n(%)	γ_{sat} (gr/cm^3)	γ_d (gr/cm^3)
Sandstone	50.65±25.41	13.62±5.8	3.44±0.19	13.71±2.8	1.27±0.11	2.66±0.03	1.82±0.05
Schist	42.33±3.2	9.34±0.15	3.39±0.02	11.6±1.4	1.54±0.4	2.68±0.01	1.81±0.02

From this area, 30 picked samples were inspected to ensure that it would provide standard testing specimens without macroscopic defects, alteration zones and fractures according ISRM suggested methods and then tested for UCS, V_P, porosity, elasticity modulus, Schmidt hammer test and density. Obtained results of the measured samples and statistical analyses of them are given in tables-2 and 3 respectively. By considering the distribution of tested data, there is a probable relation between the UCS and other mechanical parameters in this area. Therefore as presented in figures-2 and 3, we plotted the contour line of the tested parameters for the selected area which shows same stretch in contour trends. This can improve the existence of probable relations between the mechanical parameters.

Linear regression analysis is a statistical process for estimating the relationships among variables and aims to describe the output variable y through a linear combination of one or more input variables. Due to several advantages such as simplicity, providing adequate and interpretable description of how the inputs affect the outputs, linear models were largely developed and are still good reasons to study and use them since they are the foundation of more advanced methods. Moreover, for prediction purposes they can often outperform fancier nonlinear models, especially in situations with small numbers of training data or a low signal-to-noise ratio. Finally, linear models can be applied to transformations of the inputs and therefore be used to model nonlinear relations.

In this study, as presented in table-3, at the first of all, the results of the executed tests were determined and after statistical analysis, the range, the mean and the standard deviation values for each measured properties were calculated. By application of the least square regression analysis method and using Matlab curve fitting tool and curve expert mathematical software the linear and power regression among the UCS, density, porosity and elastic modulus of samples as a function of V_P and mainly to derive reliable, empirical approaches for the determination of UCS were expressed. To determine whether there is any relation between UCS and other parameters or not the Student t-test is performed and a relation is observed.

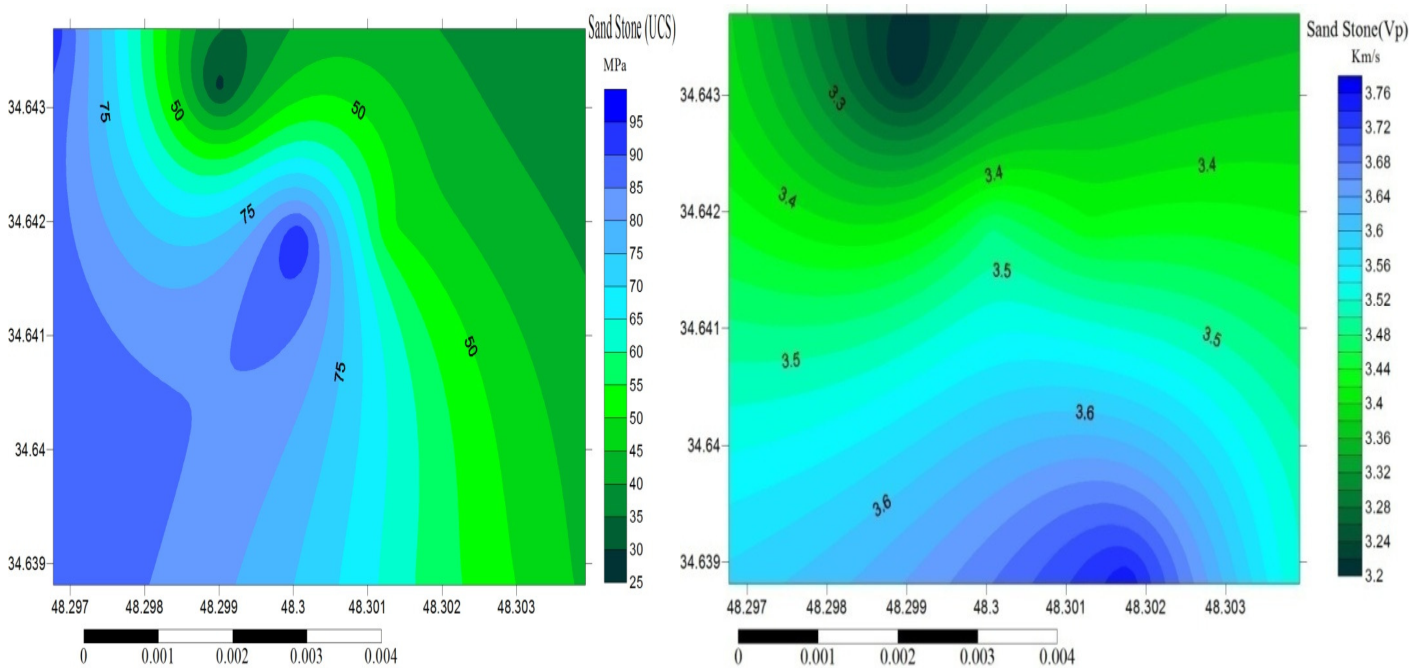

Figure-2

Variation of V_P and UCS in the selected area on base of the tested sandstone samples

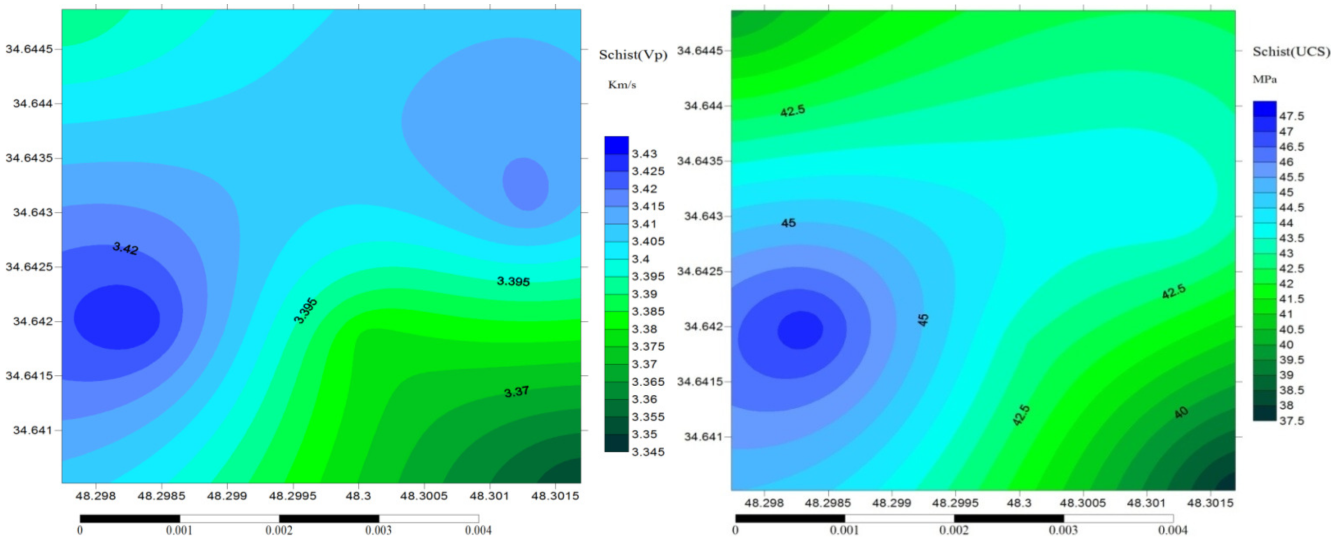

Figure-3

Variation of V_P and UCS in the selected area on base of the tested schist samples

The t-test compares the computed values with tabulated values using null hypothesis[32]. According to the t-test, when computed t-value is greater than tabulated t-value, the null hypothesis is rejected and obtained correlation coefficient (r) is acceptable. Also, observed level of significance is often used in hypothesis test[33]. In this case, as p-value is smaller than level of significance ($\alpha = 0.05$), the null hypothesis is rejected. Therefore, it means that there is a relation between the correlated parameters and this shows that r-value is significant.

The equation of the best fit line, the 95% confidence limits, and the correlation coefficient (r) which indicates of how well the model fits the data, were determined for each regression as shown in figures 4 to 7. The high value obtained r-value in the introduced relationships in these figures can be a reasonable evidence for the correctness of these empirical relationships.

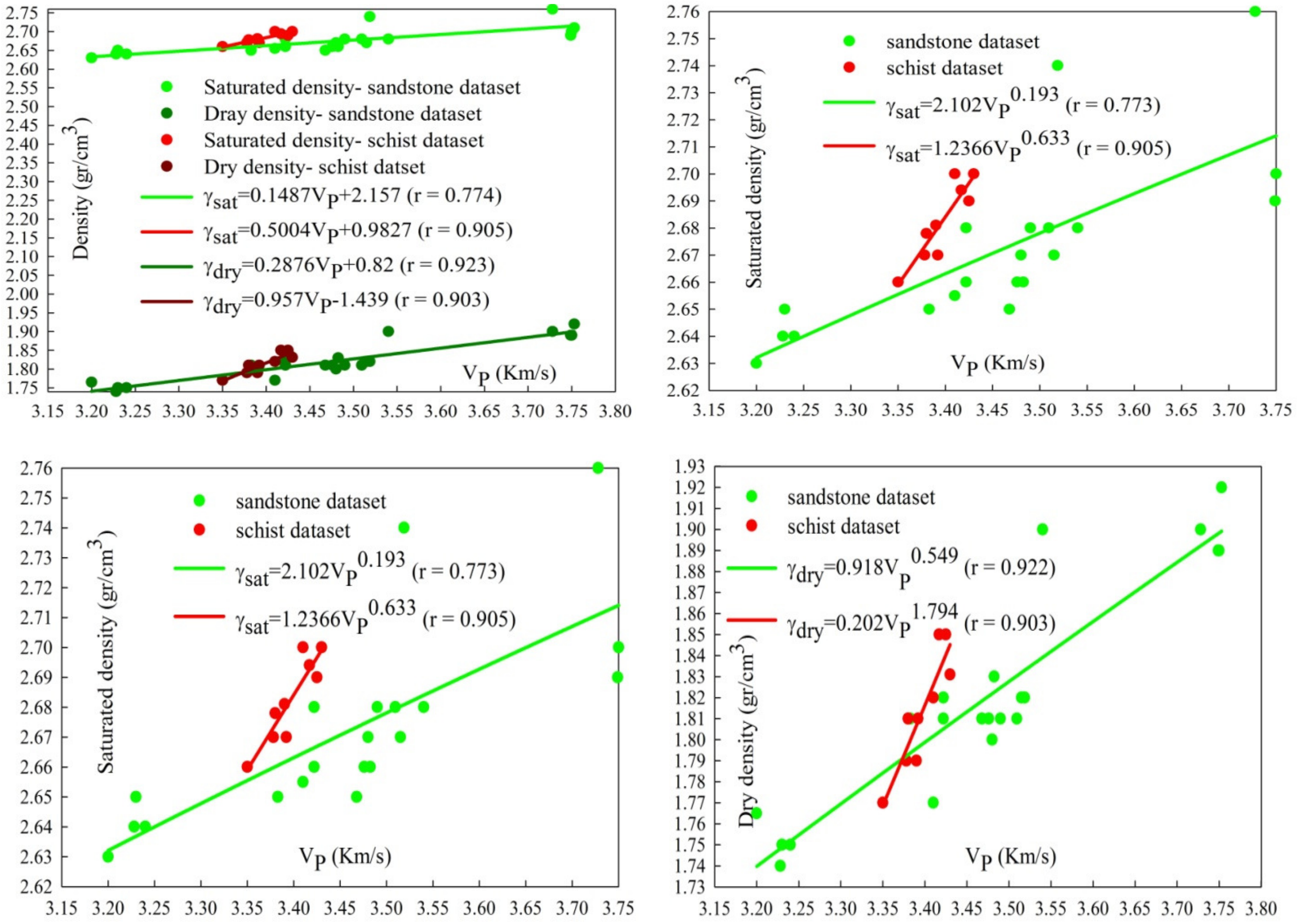

Figure-4

Obtained linear and power correlation for dry and saturated density as function of V_P

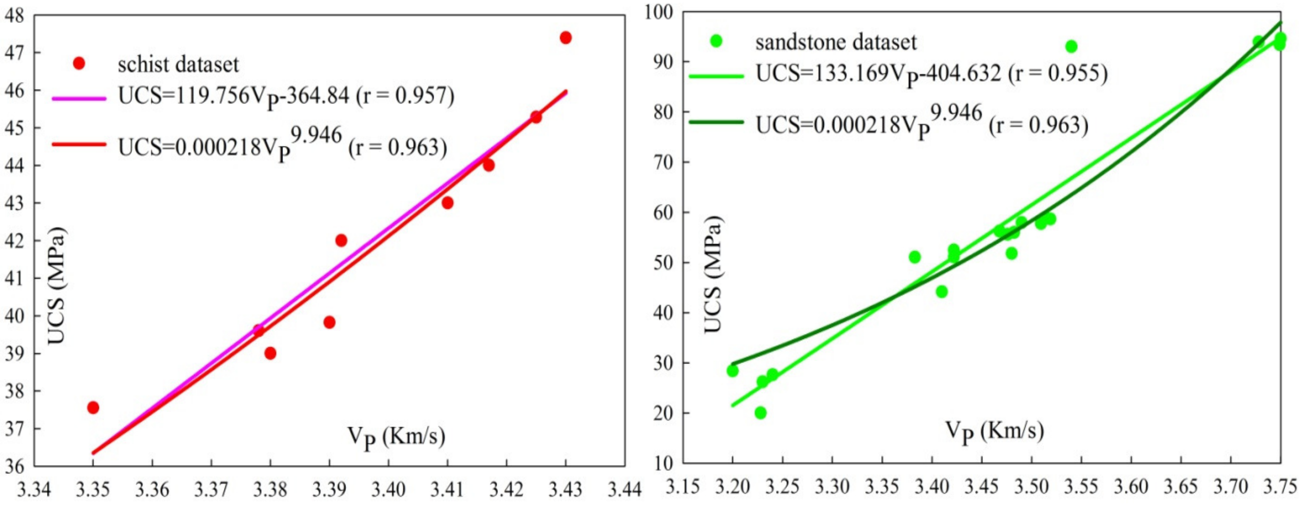

Figure-5

Calculated linear and power correlation for UCS as function of V_P

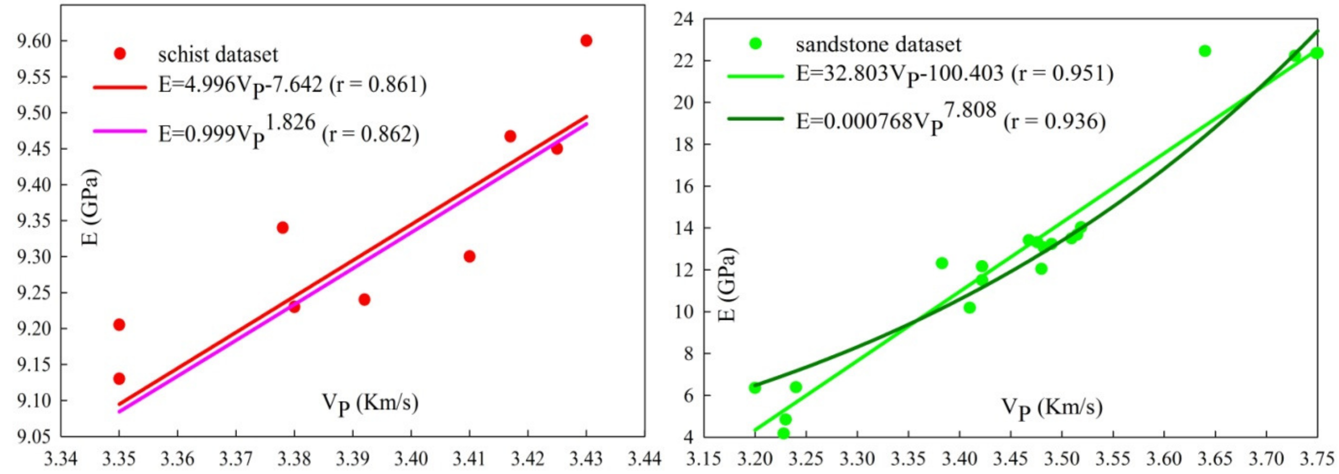

Figure-6

Obtained linear and power correlation for elasticity modulus as function of V_P

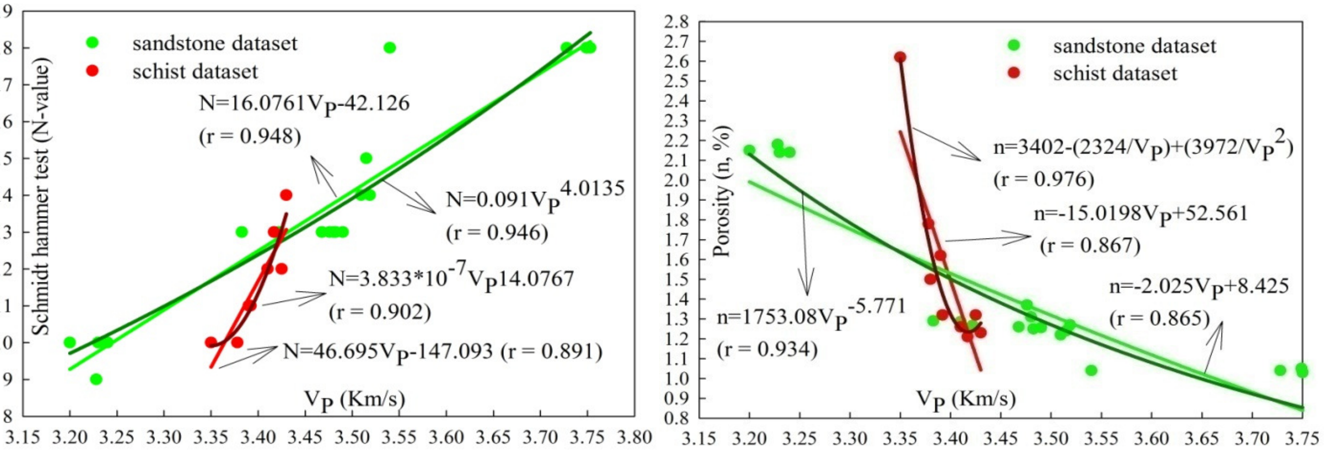

Figure-7

Results of linear and power correlation of porosity and Schmidt hammer test with V_P

Results and Discussion

Application of the linear and nonlinear regression techniques including simple or multiple analyses for predicting the unknown from known variables are commonly used in rock engineering[3,6,7,26,33]. To evaluate the validity of the generated equations between the V_P and other rock properties and according to available relation forms, we conducted power and linear relationship between UCS-N and substitute our data in the proposed relations by Shorey et al.[9], Haramy and Demarco[34], Singh et al[35], Gokceoglu[36] and Kilic and Tymen[19]. As presented in figure-8, after the plotting and comparison of the obtained graphs, our introduced relation in case of linear regression for schist has a good agreement by Haramy and Demarco[34] and Singh et al[35] but in case of sandstone, despite of the same trend with them a sharper slope can be observed. In the power correlation, the sandstone data set showed better compatibility with Kilic and Tymen[19] and also approximate agreement with Gokceoglu[36]. The main reason of differences in this comparison can be referred to the rock type. Some of the researcher developed their relation on base of several different rock types but and in our study the rock types are not very different.

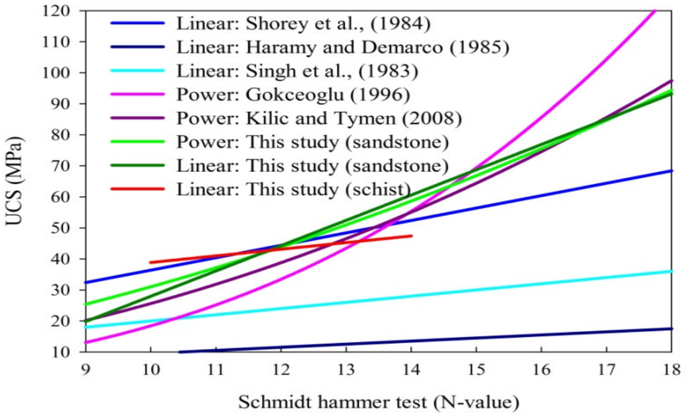

Figure-8

Comparison between results of this study with other researchers

Moreover, as indicated in figure-9, by overlapping of our data with reported UCS-E and UCS-porosity curves, the location of data showed reasonable and logic fitting by these proposed curves, which can certify the results of this study.

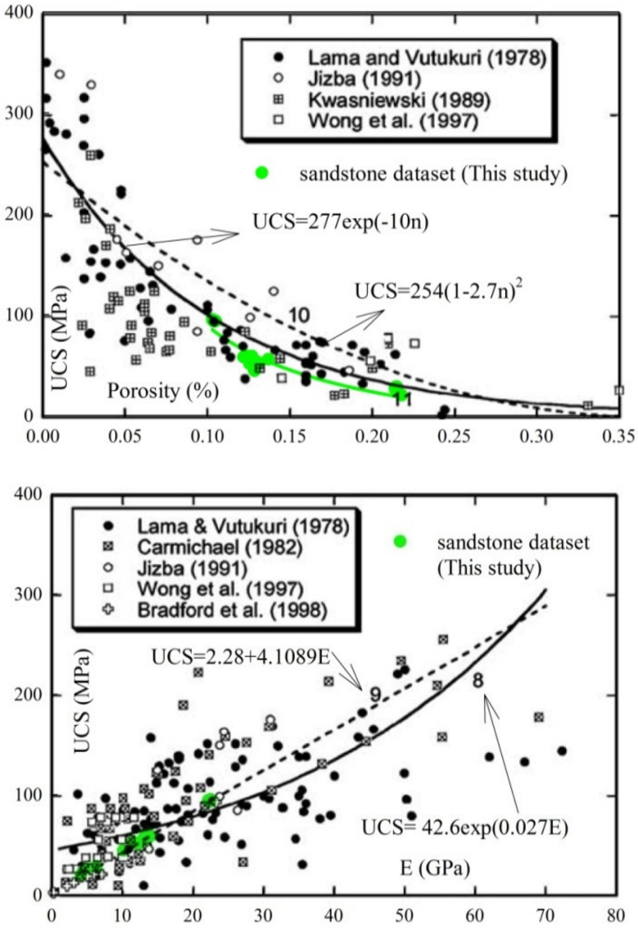

Figure-9

Overlap of obtained data with UCS-E and UCS-porosity relations reported by Chang et al,[16] for different rock types

Conclusion

This study proposed multiple regression empirical relationship to estimate the rock mechanical parameters of two different rocks as a function V_P which is easy to measure, non destructive faster and a relatively economic method for rock characterization. The test was performed on 30 collected samples from various depth of drilled boreholes in the area related to Khorram rud earth dam in west of Iran consisting of schist and sandstones. The picked samples were tested according to standard testing methods and the results examined to generate empirical relationship between UCS, modulus of elasticity, Schmidt hammer test, porosity and density (dry and saturated) as a function of V_P. By application of the linear and nonlinear correlations, student t-test and statistical analysis of the obtained data, the best fit line with highest regression coefficient were determined and the result showed that these rock mechanical parameters can be predicted with high r-value and acceptable safety by conducting V_P test.

By attention to this point that using the specific rock type is the main limitation of these developed relations, it should be mentioned that they are not applicable for general rock types and purposes. In this case to validate and modify our results, the obtained UCS in this study were put into the other proposed linear and nonlinear empirical formulas of UCS-N and the results were compared to this study. According to rock type and proposed relations, the obtained results of this study in nonlinear regression conditions showed good adaptability with Kilic and Tymen[19] and also approximate agreement with Gokceoglu[36], but in linear conditions our results showed better compatibility with Haramy and Demarco[34] and Singh et al[35]. The obtained results in linear condition presented fairly agreement by Shorey et al.[9], but it is less than the others. Moreover, to verify the method, a comparison between obtained data in this study by original published graphs by other researchers have executed, which showed that the range of our obtained data have acceptable distributions and good validities.

In the obtained relationships for UCS-V_P, for both rock types, the power correlation gives higher r-value and these power forms are suggested for application. In case of E-V_P, for sandstone the linear regression gives better r-value but for schist, due to not significant differences between r-value both power and linear can be applied.

In case of n-V_P, the power form with high r-value is applicable and suggested for this area. For N-V_P, both linear and power correlations are applicable in sandstone but in case of schist, the power regression gives better r-value. For determined relationships between γ-VP in dry and saturated density conditions, both linear and power correlations for sandstone and schist can be employed.

In totally, on the basis of obtained results of regression coefficients in this study, in some cases both linear and nonlinear regressions have the same or no significant differences r-value and both of them are applicable but due to simplicity the linear relation is suggested.

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