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Determining the relationship between shear wave velocity and physicomechanical properties of rocks

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ABSTRACT

Thorough knowledge of physicomechanical properties of rocks is crucial during the primary and secondary stages of designing a rock engineering project. Laboratory examination of these properties requires high-quality rock specimens. However, preparing such high accuracy samples is a difficult, expensive, and time-consuming task, especially in weak and fractured rocks. Hence, indirect approaches seem an attractive research area for determining these properties. The main object of this study is to develop some empirical relations to determine different physical and mechanical properties of sedimentary and metamorphic rocks based on the shear wave velocity index. To do that, several schist, phyllite, and sandstone core samples were collected from the drilled boreholes in the Marivan Azad dam in western Iran. Then, the shear wave velocity and some physical and mechanical properties of rocks were measured in dry and saturated conditions. Subsequently, statistical analyses were conducted to develop shear wave velocity-based equations to determine different rock properties, including uniaxial compressive strength, modulus of elasticity, porosity, Poisson's ratio, slake durability index, density, and water absorption. An equation with the maximum correlation coefficient was proposed as the optimum equation to determine each of the above rock properties. Finally, the results of the proposed empirical equations were compared with those of laboratory measurements. This comparison proved the proposed equations to have high accuracy for determining the physicomechanical properties of rocks and can be used in practical projects with similar geological conditions to save time and money.

Keywords : *Shear wave velocity; Rock properties; Statistical analysis; Empirical equation; Azad dam*

1. Introduction

Determining the physicomechanical properties of rocks is an essential task in mining, tunneling, civil, petroleum, and gas engineering related projects. Generally, there are direct and indirect methods to determine rock properties. Direct methods, i.e., laboratory measurements, have very high accuracy, but they are time-consuming and expensive to perform. On the other hand, laboratory direct measurements need high quality and precise core samples, which can be difficult to prepare from weak, weathered, and fractured rocks. As an alternative, the application of indirect methods, i.e., common index tests and nondestructive seismic techniques, are useful in most cases. Therefore, indirect approaches, such as wave velocity index, have been utilized for determining the rock properties by many researchers.

The application of seismic techniques has increased recently in mining, geotechnical, petroleum, and gas engineering to determine rock properties for designing and analyzing the long-term stability of rock structures. The dynamic behavior of rocks is mostly described and estimated by these techniques. Furthermore, seismic techniques are used to evaluate rock bolt enforcement, measure rock blasting effectiveness, estimate disturbed zones around underground excavations, determine the weathering degree of rocks, characterize fractured rock mass parameters, identify damage formations, estimate tectonic stress of wells drilled in different reservoirs, and so forth. [1-4]. Moreover, the combination of shear wave velocity and compressional wave velocity can provide precise data to study a reservoir from a geophysical perspective. Besides, the application of wave velocities in rock engineering, especially in determining rock properties, and rock-related stress and deformations, has increased in recent years [5, 6]. This is because the physicomechanical properties of rocks such as rock type, grain size and shape, rock fabric, density, strength characteristics, hardness, and porosity can affect wave velocities [7-9]. It should be noted that utilizing the shear wave velocity for the above applications has been very limited until now, and most of the existing seismic-based relations are based on the compressional wave velocity. Also, the available shear wave velocity-based equations for determining the rock properties suffer from a lack of generalization and validation. Thus, these equations may not be applicable in practice because they are developed based on a limited number of rock characteristics. As a result, further investigation in this field is required.

Shear wave velocity is one of the most significant parameters for seismic exploration and rock characterization, i.e., determining the elastic properties of rocks, including young modulus and poison's ratio. In addition, this parameter has been used along with the compressional wave velocity in calculating the mechanical properties of rocks [10, 11]. Furthermore, several investigations have been conducted to develop empirical equations for the relationship between shear wave velocity and physical properties of rocks [12-16]. As an indirect method, Domnico [17] studied the relationship between shear wave velocity and the porosity of rocks. Vasconcelos et al. utilized the longitudinal ultrasonic pulse velocity to determine the properties of a granite rock and asses its weathering state [18]. They proved that ultrasonic pulse velocity is a simple and inexpensive tool for the estimation of granitic rocks' properties and their variations caused by weathering. Also, Wang et al. [19] investigated the correlations of compressional (V_P) and shear

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(V_s) wave velocities with Poisson's ratio of the rock. Their research proved that this parameter has a linear inverse relationship with V_p and V_s. Moreover, Liu et al. [20] presented the inherent relationships between shear wave velocity, rock porosity, and compressional wave velocity.

Vasanelli et al. [21] applied the ultrasonic pulse velocity (UPV) to evaluate the density and unconfined compressive strength of a building limestone sample. According to this research, a reliable linear correlation was found between UPV and compressive strength, whereas a low correlation was achieved for UPV with density. Özkan and Yayla [22] studied the correlation between UPV and physical properties of clay samples dried at high temperatures. Their findings proved the acceptable application of UPV to determine the physical properties of rock samples. Lin et al. [23] used the ratio of compressional wave velocity to shear wave velocity (Vp/Vs) index for determining the crack density and saturation degree at different depths. According to this research, the average crack density and saturation degree at depths 7 and 11 km were achieved equal to 25% and 91%, respectively. Hanm [24] proposed a dual-porosity model to investigate the differential pressure-dependent to the rock velocities and showed that this characteristic has a nonlinear direct relation with V_p and V_s. Based on laboratory measurements, Saito et al. [25] revealed that as the porosity in crustal rocks increases, their compressional and shear wave velocities decrease.

Reviewing the literature shows that most of the previous investigators tried to establish the empirical equations between compressional wave velocity and static rock properties. However, the relationships between shear wave velocity and most of the rock properties have not been established until now. Moreover, there are a few studies on correlating the wave velocities with rock properties in wet/saturated conditions. In other words, the previous studies are somewhat limited and incomplete. To overcome the existing limitations in laboratory measurements and to complete the previous studies, this paper attempts to determine the rock properties using shear wave velocity in dry and saturated conditions. To do that, empirical relations between shear wave velocity (V_s) and rock properties, including density (ρ), water adsorption (W_a), porosity (n), slake durability index (SDI), uniaxial compressive strength (UCS), Poisson ratio (PR), and modulus of elasticity (E), were statistically determined based on laboratory-measured data.

2. Database preparation

In order to conduct the statistical analyses, it is necessary to have sufficient data. In the current study, a sufficient amount of core samples were collected from a core drilling operation in the Azad dam site, Iran. These samples were prepared in the laboratory to measure the physicomechanical properties and the shear wave velocity of the rocks.

2.1. Case study

The case study of this paper is the Azad Dam, whose rock samples were prepared to provide suitable data for statistical analysis. This dam is located 40 km west of Sanandaj in the Kurdistan province, Northwest Iran between 46° 32′ 57″ eastern longitude and 35º 19′ 59″ northern latitude. The location of the dam on Iran's map is shown in Fig. 1. Form the geological viewpoint, this area is situated in the Sanandaj-Sirjan metamorphic zone, and its bedrocks composed of low-grade metamorphic sandstone, schist, and phyllite. Furthermore, some limestone outcrops can be found in highland regions of the study area. From the stratigraphical standpoint, the area is covered by upper Cretaceous to quaternary units [26]. Fig. 2 presents a schematic geologic map that shows the lithological units and faults in the area as well as the location of the drilled boreholes.

2.2. Samples preparation

The core samples were collected from the drilled boreholes at different exploration sites of the Azad dam, as shown in Fig. 2. The samples were collected from boreholes BH1, BH2, BH4, and BH4 that contain bedded sandstone, schist, and phyllite. The core samples were prepared with specific characteristics according to the ASTM standard (2001) [27], which necessitates having a cylindrical shape with 54 mm of diameter (NX-size), 110-115 mm of length, and a length to diameter ratio of 2.5. The ends and rib-sides of the cylindrical core samples were perfectly polished to provide the highest possible accuracy in which the elevation difference of any two points on either side should not be more than 0.001 mm. The image of some prepared core samples is shown in Fig. 3.

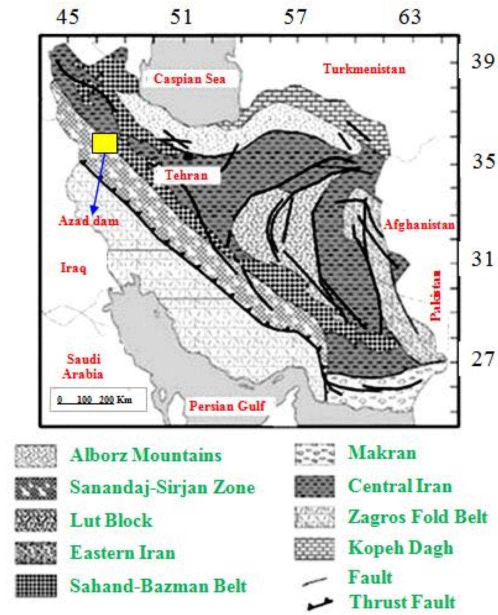

Fig. 1. The location of the Azad dam on the geologic map of Iran (after [26]).

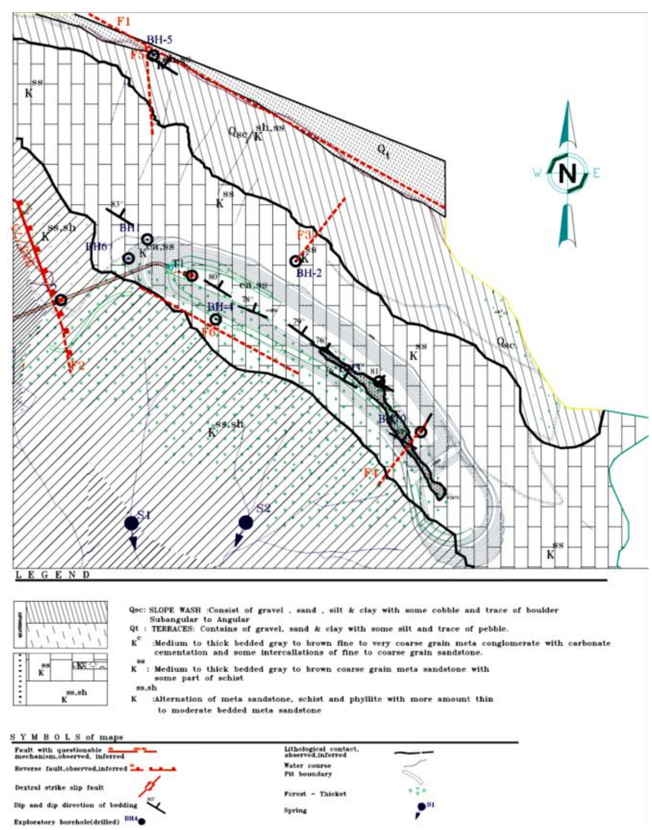

Fig. 2. The geologic map of the area, showing the location of faults and drilled boreholes in the Azad dam [26].

In order to remove the possible moisture in the cores, the specimens were dried at 105°C for 24 h. In addition, the saturation and floating approaches suggested by the ISRM [28] were used to determine some of the rock parameters, including density, unconfined compressive strength, modulus of elasticity, Poisson's ratio, and shear wave velocity in the saturated condition. The core specimens were saturated in a vacuum condition for more than 1 hour under less than 800 Pa pressure.

Fig. 3. The prepared core samples for conducting the laboratory tests.

2.3. Data measurement

In order to prepare a robust database, 54 datasets were provided based on valid laboratory tests in which the main properties of core specimens, i.e., UCS, E, n, PR, I_d, ρ, W_a, and V_S were calculated. For this purpose, all of the above-related tests were first conducted for all of the core specimens in a dry condition. Then, the same number of specimens were saturated to calculate the related parameters in the saturated condition. The mechanical properties of rock specimens, including UCS, E, and PR in dry and saturation conditions, were measured according to the standards suggested by the ISRM [28]. A servo-controlled uniaxial compression testing machine was used to measure the UCS, E, and PR parameters of core specimens. In this test, the stress value at the failure point was considered as the UCS of dry and saturated specimens. A stress rate of 0.5-1 MPa/s was used until rock failure occurred. Also, two vertical and horizontal gauges were installed on the specimens during the loading process. Strain measurements were conducted by using the linear variable differential transducer (LVDT) to calculate the parameters E and PR using the commonly available relations. E is the ratio of obtained UCS to the normal/axial strain, and PR is the negative ratio of recorded lateral strain to the axial strain.

In addition to the above parameters, water absorption, porosity, slake durability index, and density were determined based on the suggested methods by the ISRM [29]. Moreover, the bulk volume of cylindrical core specimens was measured using the caliper. The saturated-mass was determined after floating the specimens in water for 48 hours, whereas the dry-mass was measured after drying them in the oven at 105°C for 48 hours and cooling for 30 minutes. Finally, density (in dry and saturated conditions), water absorption, and porosity were calculated for all specimens according to the commonly available relations. The slake durability index (SDI) of the samples was also measured by using the slake durability testing machine. This parameter was used for evaluating the resistance of specimens to water based on the disintegration process resulted from the standard cycles of saturating and drying according to the suggested method by the ISRM [29].

The shear wave velocity (V_S) of prepared core specimens was determined using a portable ultrasonic non-destructive digital indicating tester (PUNDIT) based on the pulse-transmission technique suggested by Kern et al. [30]. The PUNDIT (Fig. 4) is composed of a pulse producer, a pair of transducers installed at each end of the sample (one transmitter with 1 MHz frequency for V_s measurement and one receiver), and an electronic calculator to measure the time intervals with a precision of 0.1 µS. Also, a pair of shear wave transducers are installed to measure the shear wave velocity. It should be noted that one-MHz-frequency-transmitters were used based on the technique suggested by Kern et al. [30]. They proved that a frequency of 1 MHz is an optimum value for utilizing the transducers for Vs measurement, and thus, they were applied in the current study.

To improve the contact of sample-end with the transducers, Vaseline was used as the coupling fluid at the sample-transducers interface. During the testing process, the samples and the ultrasonic transducers were placed vertically to utilize their own gravitational force to form a fixed pressure for better coupling between sample and transducers. No other pressures were applied in order to avoid the artificial uncertainty of stress. During the shear wave velocity tests, the information of longitudinal waves can be automatically computed, recorded, and demonstrated by the PUNDIT for further analyses. Having the transmitted time from the specimen length distance (transmitted from one end of the core specimen and received at the other end), one can calculate the shear wave velocity using Eq. (1):

$$V_S = {}^{S}\!/_{t} \quad (1)$$

where S and t are specimen length and wave transmitted time, respectively.

Fig. 4. The PUNDIT device used for V_s measurement.

2.4. Datasets description

Based on the above-mentioned laboratory measurements, 54 datasets were prepared for conducting the statistical analyses. Also, 54 tests were conducted on each parameter in which some non-destructive tests were first performed separately on each specimen. In the last step, the specimens were used to conduct destructive tests such as the UCS test to measure the UCS, E, and PR parameters. About 50 series of datasets were used to develop the empirical equations between the shear wave velocity and rock properties. The rest four datasets were kept to evaluate and validate the proposed equations. The measured parameters, their corresponding symbols and units, as well as their statistical characteristics, including maximum, minimum, mean, and standard deviation of datasets, are presented in Table 1. Furthermore, the samples of datasets utilized for the development of equations between shear wave velocity and rock properties in dry and saturated conditions are given in Table 2. It should be noted that the whole datasets were also used for evaluating the effects of physical and mechanical properties of rock samples on the shear wave velocity, as outlined in the next section.

3. Statistical analyses

3.1. Effect of rock properties on shear wave velocity

Assessment of rock properties on shear wave velocity is an important task in rock engineering, as discussed here. Based on the measured datasets, the effect of the physical and mechanical properties of the rock samples on the shear wave velocity are investigated in the current research. The effects of ρ-Dry, ρ-Sat, W_a, n, SDI, E-Dry, E-Sat, UCS-Dry, UCS-Sat, PR-Dry, and PR-Sat on V_s are demonstrated in Figs. 5-11. As shown in Fig. 5, the dry and saturated densities have an approximately direct effect on the shear wave velocity with a very low gradient. As shown in Fig. 6, water absorption has a relatively inverse influence on the shear wave velocity. This result is in agreement with the results of previous studies presented by Wang et al. [31] and Kassab and Weller [32]. However, this effect is not considerable and can be neglected. It can be concluded from Fig. 7 that the shear wave velocity decreases with increasing the porosity of the rock. Fig. 8 indicates that the higher the value of the slake durability index, the greater the amount of shear wave velocity.

Table 1. Description of the measured datasets.

Parameter	Symbol	Mean	Max	Min	Std dev.
Dry density (g/cm^3)	ρ-Dry	2.68	2.74	2.52	0.052
Saturated density (g/cm^3)	ρ-Sat	2.7	2.75	2.58	0.038
Water absorption (%)	W_a	0.89	1.98	0.22	0.488
Porosity (%)	n	2.54	5.81	0.38	1.375
Slake durability index (%)	SDI	98.78	99.6	97.6	0.414
Dry unconfined compressive strength (MPa)	UCS-Dry	61.11	151.5	12.1	39.71
Saturated unconfined compressive strength (MPa)	UCS-Sat	37.11	169.5	1.70	32.16
Dry modulus of elasticity (GPa)	E-Dry	18.93	42.8	3	8.013
Saturated modulus of elasticity (GPa)	E-Sat	14.35	26.2	2.6	6.28
Dry Poisson ratio (-)	PR-Dry	0.22	0.34	0.14	0.042
Saturated Poisson ratio (-)	PR-Sat	0.27	0.37	0.15	0.047
Dry shear wave velocity (m/s)	V_S-Dry	2863.31	3500	2392	268.51
Saturated shear wave velocity (m/s)	V_S-Sat	2858.5	3648	2280	337.77

Table 2. Samples of datasets in dry and saturated conditions.

ρ-Dry	ρ-Sat	W_a	n	SDI	UCS-Dry	UCS-Sat	E-Dry	E-Sat	PR-Dry	PR-Sat	V_S-Dry	V_S-Sat
2.52	2.58	0.22	0.38	97.6	12.1	1.7	3	2.6	0.14	0.15	2392	2324
2.60	2.65	0.38	1.12	98.3	18.3	5.47	8.57	6.4	0.17	0.21	2734	3491
2.70	2.72	0.94	2.69	98.9	68	32.1	21.1	17.16	0.24	0.29	2517	2967
2.74	2.75	1.98	5.81	99.6	151.5	169.5	42.8	26.2	0.34	0.37	2736	3150

According to Fig. 9, both the dry and saturated moduli of elasticity directly affect the shear wave velocity. On the other hand, Fig. 10 shows the direct effects of dry and saturated unconfined compressive strengths on the shear wave velocity. Nevertheless, the influence of the saturated unconfined compressive strength on the shear wave velocity is very low, and it almost has no influence on the shear wave velocity. Finally, Fig. 11 indicates that the dry Poisson's ratio has an inverse correlation with the shear wave velocity. On the other hand, the saturated Poisson's ratio has a negligible influence on V_s.

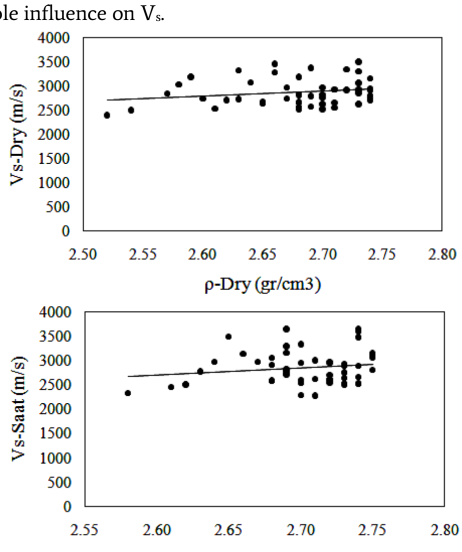

Fig. 5. The relationship between shear wave velocity and density in dry and saturated conditions.

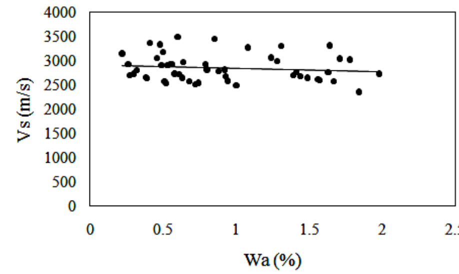

Fig. 6. The relationship between shear wave velocity and water absorption.

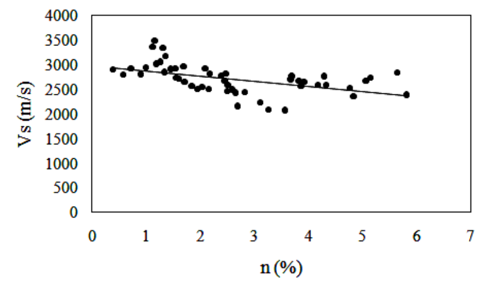

Fig. 7. The relationship between shear wave velocity and porosity.

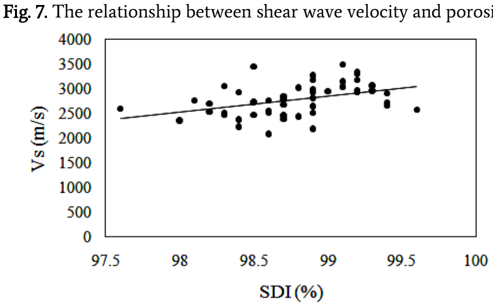

Fig. 8. The relationship between shear wave velocity and slake durability index.

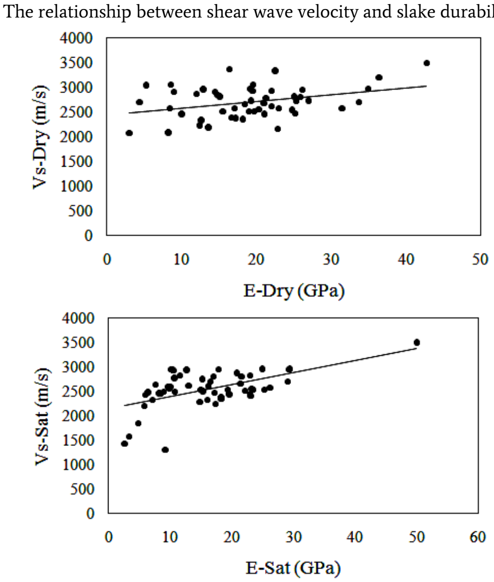

Fig. 9. The relationship between shear wave velocity and modulus of elasticity in dry and saturated conditions.

3.2. Development of empirical relations

In this section, we have developed the optimum empirical relations between the rock properties in dry and saturated conditions and the shear wave velocity based on statistical analyses. For this purpose, five relations, including linear, logarithmic, polynomial, power, and exponential equations have been developed between each of the described rock properties in Table 1 and the shear wave velocity. The obtained relations between V_s and rock properties, including ρ-Dry, ρ-Sat, W_a, n, SDI, E-Dry, E-Sat, UCS-Dry, UCS-Sat, PR-Dry, and PR-Sat, are demonstrated in Tables 3 to 13, respectively.

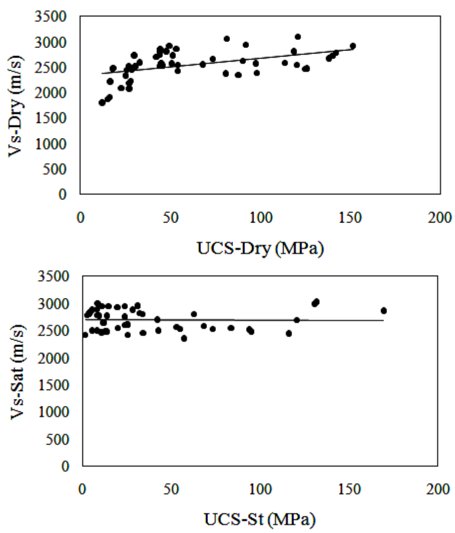

Fig. 10. The relationship between shear wave velocity and unconfined compressive strength in dry and saturated conditions.

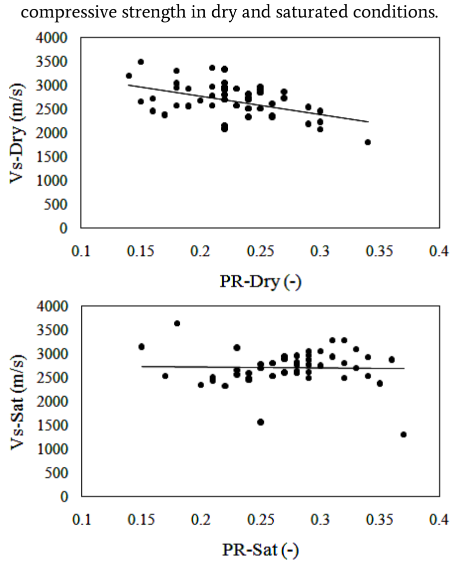

Fig. 11. The relationship between shear wave velocity and Poisson's ratio in dry and saturated conditions.

These relations have been evaluated using the correlation coefficient (R^2) index in which the equations with the highest R^2 values were considered as the proposed optimum relation to estimate the corresponding parameter. On this basis, the proposed optimum relations to determine the above-mentioned parameters are presented in Table 14. As seen, the correlation between the shear wave velocity and the physical parameters, i.e., density in the saturated condition, is greater than that of the dry condition. On the other hand, for the mechanical parameters, including UCS, E, and PR, the correlations with shear wave velocity are greater in the dry condition.

Table 3. Developed relations between ρ-Dry and V_S in different states.

Relation	Type	R^2
ρ-Dry $=0.0001V_S+2.27$	Linear	0.9289
ρ-Dry$=0.4076\ln V_S-0.5535$	Logarithmic	0.8948
ρ-Dry$=-7E\text{-}08V_S^2+0.0005V_S+1.7498$	Polynomial	0.9602
ρ-Dry$=0.7971V_S^{0.1528}$	Power	0.9449
ρ-Dry$=2.298e^{5E\text{-}05Vs}$	Exponential	0.9247

Table 4. Developed relations between ρ-Sat and V_S in different states.

Relation	Type	R^2
ρ-Sat$=0.0001V_S+2.4048$	Linear	0.8903
ρ-Sat$=0.3048\ln V_S+0.2829$	Logarithmic	0.9265
ρ-Sat$=-8E\text{-}08V_S^2+0.0005V_S+1.7925$	Polynomial	0.9760
ρ-Sat$=1.1007V_S^{0.1132}$	Power	0.9245
ρ-Sat$=2.4197e^{4E\text{-}05Vs}$	Exponential	0.8875

Table 5. Developed relations between W_a and V_S in different states.

Relation	Type	R^2
$W_a=0.0017V_S-3.7414$	Linear	0.9535
$W_a=4.5895\ln V_S-35.415$	Logarithmic	0.9246
$W_a=6E\text{-}07V_S^2-0.0018V_S+1.0223$	Polynomial	0.9748
$W_a=1E\text{-}19V_S^{5.4815}$	Power	0.9618
$W_a=0.0033e^{0.002Vs}$	Exponential	0.9494

Table 6. Developed relations between n and V_S in different states.

Relation	Type	R^2
$n=0.0043V_S-9.5855$	Linear	0.948
$n=11.749\ln V_S-90.624$	Logarithmic	0.9166
$n=2E\text{-}06V_S^2-0.0053V_S+3.6662$	Polynomial	0.9738
$n=8E\text{-}19V_S^{5.3446}$	Power	0.9668
$n=0.0097e^{0.0019Vs}$	Exponential	0.9576

Table 7. Developed relations between SDI and V_S in different states.

Relation	Type	R^2
$SDI=0.0012V_S+95.531$	Linear	0.8755
$SDI=3.4755\ln V_S+71.406$	Logarithmic	0.9035
$SDI=-1E\text{-}06V_S^2+0.0079V_S+86.231$	Polynomial	0.9589
$SDI=74.886V_S^{0.0352}$	Power	0.9028
$SDI=95.586e^{1E\text{-}05Vs}$	Exponential	0.8746

Table 8. Developed relations between E-Dry and V_S in different states.

Relation	Type	R^2
E-Dry$=0.0396V_S-46.207$	Linear	0.9841
E-Dry$=95.848\ln V_S-695.49$	Logarithmic	0.9552
E-Dry$=7E\text{-}08V_S^2+0.0392V_S-45.723$	Polynomial	0.9841
E-Dry$=4E\text{-}06V_S^{2.081}$	Power	0.9719
E-Dry$=6.389e^{0.0008Vs}$	Exponential	0.9068

Table 9. Developed relations between E-Sat and V_S in different states.

Relation	Type	R^2
E-Sat$=0.0202V_S-40.745$	Linear	0.9862
E-Sat$=56.547\ln V_S-432.49$	Logarithmic	0.9878
E E-Sat$=-3E\text{-}06V_S^2+0.0352V_S-61.603$	Polynomial	0.9890
E-Sat$=4E\text{-}14V_S^{4.226}$	Power	0.9270
E-Sat$=0.2261e^{0.0015Vs}$	Exponential	0.8887

Table 10. Developed relations between UCS-Dry and V_S in different states.

Relation	Type	R^2
UCS-Dry$=0.1049V_S-219.91$	Linear	0.8105
UCS-Dry$=252.96\ln V_S-1934.4$	Logarithmic	0.7543
UCS-Dry$=0.0001V_S^2-0.5315V_S+576.13$	Polynomial	0.9642
UCS-Dry$=3E\text{-}17V_S^{5.3161}$	Power	0.9337
UCS-Dry$=0.1573e^{0.0022Vs}$	Exponential	0.9615

Table 11. Developed relations between UCS-Sat and V_S in different states.

Relation	Type	R^2
UCS-Sat$=0.0759V_S-171.17$	Linear	0.7426
UCS-Sat$=169.97\ln V_S-1307$	Logarithmic	0.5971
UCS-Sat$=5E\text{-}05V_S^2-0.21V_S+198.46$	Polynomial	0.9635
UCS-Sat$=5E\text{-}19V_S^{5.7309}$	Power	0.8833
UCS-Sat$=0.036e^{0.0024Vs}$	Exponential	0.9399

Table 12. Developed relations between PR-Dry and V_S in different states.

Relation	Type	R^2
PR-Dry=0.0001V_s-0.1242	Linear	0.9465
PR-Dry=0.3243lnV_s-2.3299	Logarithmic	0.9195
PR-Dry=5E-08V_s^2-0.0001V_s+0.2121	Polynomial	0.967
PR-Dry=1E-06$V_s^{1.5466}$	Power	0.9541
PR-Dry=0.0424$e^{0.0006Vs}$	Exponential	0.9673

Table 13. Developed relations between PR-Sat and V_S in different states.

Relation	Type	R^2
PR-Sat=0.0001V_S-0.0429	Linear	0.9320
PR-Sat=0.3378lnV_S-2.3924	Logarithmic	0.9551
PR-Sat=-6E-08V_S^2+0.0005V_S-0.5254	Polynomial	0.9703
PR-Sat=2E-05$V_S^{1.2141}$	Power	0.9147
PR-Sat=0.0874$e^{0.0004Vs}$	Exponential	0.8811

Table 14. Proposed optimum relations for the estimation of rock properties based on shear wave velocity.

Relation	R^2
ρ-Dry=-7E-08V_S^2+0.0005V_S+1.7498	0.9602
ρ-Sat=-8E-08V_S^2+0.0005V_S+1.7925	0.9760
W_a=6E-07V_S^2-0.0018V_S+1.0223	0.9748
n=2E-06V_S^2-0.0053V_S+3.6662	0.9738
SDI=-1E-06V_S^2+0.0079V_S+86.231	0.9589
UCS-Dry=0.0001V_S^2-0.5315V_S+576.13	0.9642
UCS-Sat=0.036$e^{0.0024\ Vs}$	0.9635
E-Dry=7E-08V_S^2+0.0392V_S-45.723	0.9841
E-Sat=-3E-06V_S^2+0.0352V_S-61.603	0.9815
PR-Dry=1E-06$V_S^{1.5466}$	0.9703
PR-Sat=-6E-08V_S^2+0.0005V_S-0.5254	0.9673

4. Validation of the proposed equations

In order to validate the proposed equations, the obtained results were compared with the actual values that were not incorporated in the development of relations based on the correlation coefficient (R^2), and the root mean square error (RMSE) criterion. For this purpose, four datasets were used, and the correlation between the measured and predicted values was measured. Comparing the measured and predicted values from the proposed relations for ρ-Dry, ρ-Sat, W_a, n, SDI, E-Dry, E-Sat, UCS-Dry, UCS-Sat, PR-Dry, and PR-Sat are shown in Figs. 12 to 18, respectively.

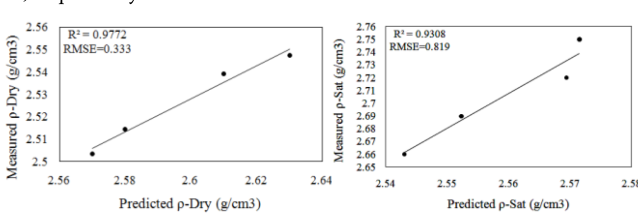

Fig. 12. Comparison of the measured and predicted density values in dry and saturated conditions.

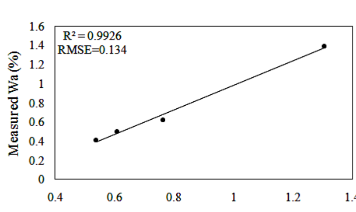

Fig. 13. Comparison of the measured and predicted water absorption values.

As seen, the obtained correlation coefficient varies from 0.8353 to 0.9989, which are the highest correlation values and can be acceptable for the statistical models. Moreover, the resulted RMSE values range from 0.106 to 0.819, which are the acceptable values of RMSE in the evaluation of these models. This shows that the proposed equations have a considerable capability in predicting the physical and mechanical properties of rocks and can be used in this field reliably.

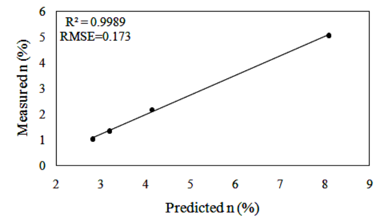

Fig. 14. Comparison of the measured and predicted porosity values.

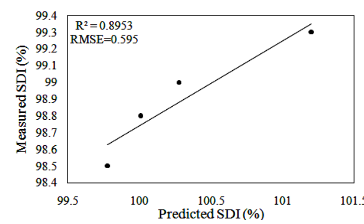

Fig. 15. Comparison of the measured and predicted slake durability index values.

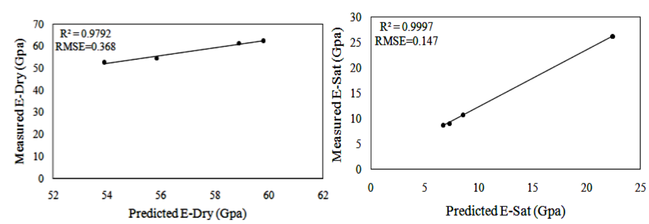

Fig. 16. Comparison of the measured and predicted moduli of elasticity in dry and saturated conditions.

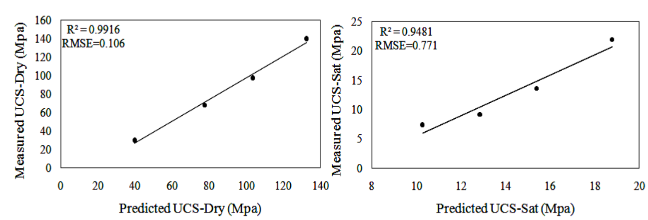

Fig. 17. Comparison of the measured and predicted unconfined compressive strengths in dry and saturated conditions.

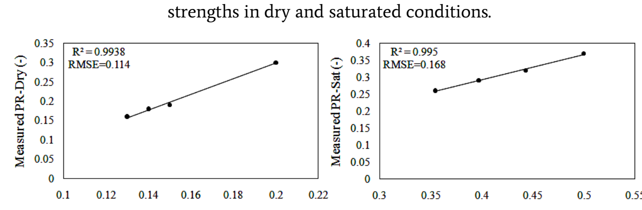

Fig. 18. Comparison of the measured and predicted dry Poisson's ratios.

5. Conclusion

In this research, rock properties, including uniaxial compressive strength, modulus of elasticity, density, Poisson's ratio, porosity, slake durability index, and water absorption, were determined based on the shear wave velocity. The study was conducted based on the datasets provided from laboratory tests on rock core samples gathered from the core drilling operation in the Azad dam. In the first stage, the effects of rock properties on the shear wave velocity were discussed. Then, the statistical analyses performed on the datasets, which lead to the development of five empirical relations, i.e., linear, logarithmic, polynomial, exponential, and power types between shear wave velocity and each of the above-mentioned rock properties. Then, the relations with a higher correlation coefficient (R^2) index were selected as the optimum proposed empirical equations in this study. To validate the accuracy of the proposed equations in the current research, we used four series of the measured data that were not incorporated in the development of the equations. Based on this evaluation, the correlation coefficient values ranged from 0.8353 to 0.9989, and RMSE values varied from 0.106 to 0.819. The results of this validation demonstrated that the proposed equations have a high level of accuracy, and their predicted results have very good conformity with the measured values. Accordingly, it can be concluded that the proposed empirical equations have good capability in the assessment of rock properties and can be successfully applied in practical projects with similar geological conditions.

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