Geophysical and Geotechnical Evaluation of Tanjero Sandstone Layers at Dokan Area Using Ultrasonic Wave Method

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Abstract

The aim of this paper is to determine the capability of the ultrasonic technique to predicate and evaluate some elastic and geotechnical properties within sand stone layers. For this purpose, 15 rock samples were collected from Tanjero Formation that is exposed in Dokan area, northeastern Iraq. Elastic wave velocities (Vp and Vs) and density (*P*) values for rock samples were determined by applying laboratory testing. From Vp, Vs, and density values, the porosity, elastic modulus, and some geotechnical parameters were calculated. The relationship between P wave velocity and elastic properties of samples was derived. Empirical equations were obtained by applying the regression analyses between Vp and the measured elastic properties. Good correlations were found, which may supply a good estimation of elastic properties from velocity information related to the geological setting of the area. This work confirmed the capability of the ultrasonic technique for predicating the elastic properties of rocks.

Keywords: Tanjero Formation**,** Ultrasonic waves, Elastic properties, Geotechnical Evaluation.

التقييم الجيوفيزيائي والجيوتكنيكي لطبقات الحجر الرملي لتكوين تانجرو في منطقة دوكان باستخدام الموجات فوق الصوتية

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الخلاصه

تهدف الدراسة الحالية الى تحديد قابلية تقنية الموجات الفوق صوتية في تقدير وتقييم بعض الخصائص المرنة والجيوتكنيكية ضمن طبقات الحجر الرملي. لهذا الغرض تم جمع 15 عينة صخرية من تكوين تانجيرو المنكشف في منطقة دوكان شمال شرق العراق. تم تحديد سرعة الموجات الطولية والمستعرضة للعينات الصخرية بالإضافة الى كثافتها مختبرياً. من خلال دراسة سرع الموجات نوع Vp و Vs والكثافة، تم حساب المسامية وبعض معاملات المرونة والمعاملات الجيوتكنيكية لنماذج الصخور ثم رسمت العلاقة بين سرعة هذه الموجات والخصائص المرنة للعينات الصخرية. تم إنشاء المعادلات التجريبية باستخدام تحليلات الانحدار وقد اظهرت ترابطاً جيداً بين Vp والخصائص المرنة المقاسة، بحيث يمكن ان تساعد هذه العلاقات في تخمين الخصائص المرنة للصخور من معلومات السرعات في المناطق ذات الوضع الجيولوجي المشابه

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لمنطقة الدراسة. اكدت نتائج الدراسة الحالية قدرة تقنية الموجات فوق الصوتية على تخمين خصائص المرونة

للصخور .

Introduction

Seismic method, that can be conducted both in the field and laboratory, is a common non-destructive method used in civil engineering and mining projects [1, 2]. Ultrasonic method is one of the seismic methods that are used to establish the velocity of S and P waves in laboratory rock samples. Knowledge of Vs and Vp information, in addition to density values, enables the estimation of many geotechnical and elastic constants directly by using different recognized equations. There are various factors that affect the seismic velocities of rocks , among which are density, lithology, mineralogy , porosity , weathering , grain size, stress levels, joints and fractures, pore water, anisotropy, and temperature , which are used for confining pressure and rock mass properties, because waves velocity depends mainly on elasticity modulus of any materials [3]. The relation between wave velocities and rock properties has been studied by various researches outside and inside Iraq. Inside Iraq, different correlations between mechanical and geotechnical parameters of materials with ultrasonic velocities were set [4-10]. The obtained correlations were not stable and can be varied with rock conditions and types. The current study attempts to evaluate the characteristics of Tanjero sandstone formation which is exposed at Dokan area, northeastern Iraq, and to investigate the empirical relation between wave velocities (Vp and Vs) and rock properties, including some dynamic and geotechnical parameters. Such studies aided the engineers to obtain information about the properties of rocks in the preliminary stages of construction, by using cheap, fast, and non-destructive methods.

The Study Area

The study area lies in the northern part of Iraq, Iraqi Kurdistan Region, within Dokan area, Sulaimaniyah Governorate (Figure-1). The rock samples for this study were collected from Tanjero Formation exposed in Dokan area.
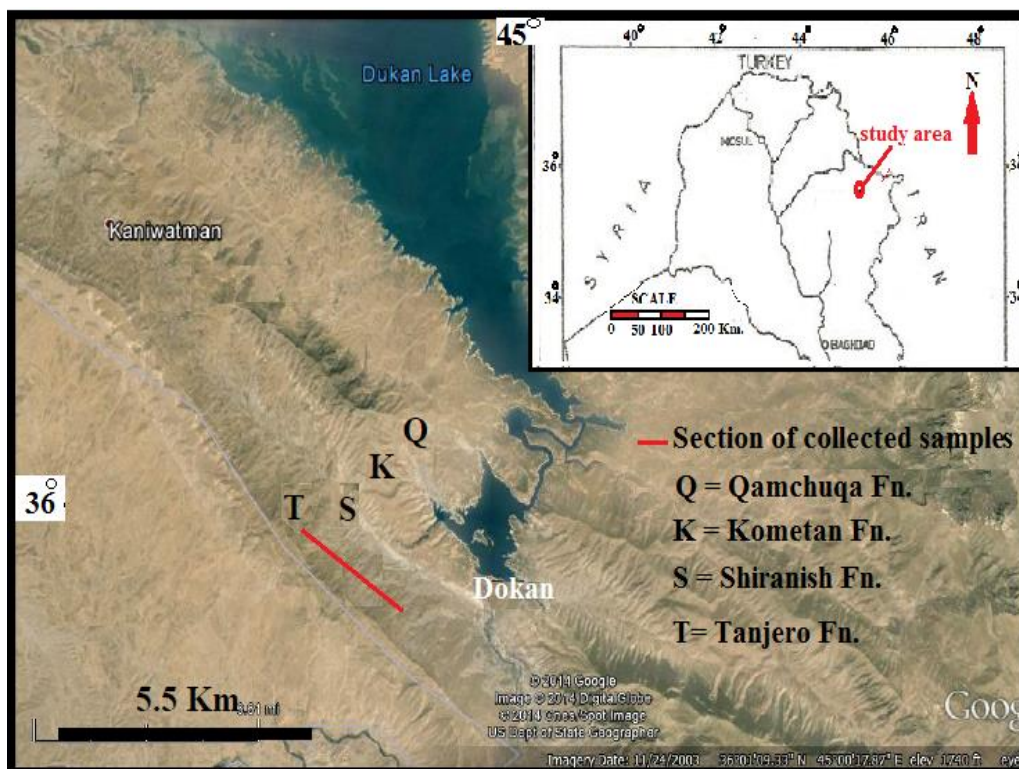

Figure 1-Location map of the study area

In the study area, the upper part of the formation comprises sandstone layers with silty marl, conglomerates, and silty organic detrital limestone. The sandstones are composed predominantly of grains of chert and green igneous and metamorphic rocks. The Tanjero Formation becomes finer

grained and more thinly bedded towards the SW. This formation is composed of flysch sediments near Dokan area (Lesser Zab Valley) [11]. These flysch sediments are rapidly subsiding at the fore deep basin directly in front of the thrust plates of the obducted margin of the Southern Neo-Tethys. The age of the coarse sandstone layer in the study area is of the Maastrichtian [11].

Field Work

Fifteen samples were collected manually from the layers of sandstone from randomly distributed sites of Tanjero Formation at Dokan area.

Laboratory Works

The first step was cutting and smoothening the samples in cubic shape with a side length of 10 cm in order to ensure accurate transit time measurements for both Vp and Vs times. In order to evaluate the elastic and geotechnical properties of sandstone rocks in the area, laboratory measurements were performed for both longitudinal and transverse wave velocities for all samples. These measurements were conducted by using the New Sonic viewer (Model-5217A) which is available in the Department of Geology, University of Baghdad. The arrival times of the propagated waves (T) were measured, and the Vp and Vs waves were determined by using the following equations:

$Vp = L / TP$

$Vs = L / Ts$

where L is the sample length in cm and Tp and Ts are arrival times in micro second. The range of Vp was 4476-6393 m/sec and the average was 5432.53 m/sec. However, Vs was found to be range 2341-3190 m/sec and its average was 2821.53 m/sec.

Density Measurements

1-   The method which was used for density determination of the geometrical shaped samples was based on sample volume in m³ and weight in Kg, by using the following equation:

Density $(Kgm/m^3) =$ Weight-W (Kgs) / Volume-V (m³)

The maximum density value was found to be 2829 kg/m³, and the minimum value was 2597 kg/m³, whereas the average value was 2746.93 kg/m³.

Porosity Measurement

Laboratory measurements of porosity were achieved for 6 samples out of 15. The water saturation method was applied, which is important in deducing pore volume (Vv), as follows:

Weight of fluid in space = weight of saturated sample – weight of dry sample

From the equation above, porosity was determined depending to the equation below:

$(\Phi)\% = (Vv/V) \times 100$

where Vv is pore volume, which is the weight of fluid and V is the total volume of the sample.

The average porosity determined by this method was found to be 2.43%.

This value of porosity was used to determine the constants A and B for the equation below, that was used to calculate the porosities of the collected 15 samples.

$1/V = A + B \ \Phi$

A and B are constants and can be determined using statistical expressions, as follows:

$B = [\Sigma XiYi – \{\Sigma (Xi) \ \overline{\Sigma (Yi)}\}/n] / \sqrt{\Sigma (Xi)^2 - \{\Sigma (Xi) \}^2/n}$

Mean $X = \Sigma Xi / n$ and Mean $Y = \Sigma Yi / n$

$A = \Sigma Yi / n – B \times \Sigma Xi / n$

where Xi is the porosity values measured in laboratory, Yi refers to 1/Vs values, because using 1/Vp for calculating porosity is useless since Vp is not sensitive to porosity, and n is the total number of measured samples [12].

The values of constants A and (B) that were calculated from the 6 selected samples were 291.967 and 54.602, respectively. These values were used then to predicate the porosity values of all other dry samples [12]. The values of porosity ranged 1.7-3.6% and the average was 2.41%. It is clear that there are no significant differences between the average value of the 15 samples, which was 2.41% and that of the 6 samples used to determine the constants A and B, which was 2.43%.

Determination the Elastic and Geotechnical Parameters

After laboratory determination of Vp , Vs, and density for the rock samples , several parameters of elasticity, such as Young modulus (E) , Bulk modulus (K), shear modulus (μ) , Poisson's ratio (σ), and Lame's constant (λ), as well as other geotechnical parameter , such as material index (Im),

concentration index (Ic), and ultimate bearing capacity (Qu), were obtained from the equations shown in Table-1.

Table 1- Equations used to calculate elastic and geotechnical parameters of rock samples collected from Tanjero Formation, northern Iraq.

Rocks parameter	Equation	Reference
Young's Modulus *(E)*	$E = \dfrac{\rho\, v_S^2\left(3v_P^2 - 4v_S^2\right)}{v_P^2 - v_S^2}.$	[13-14]
Shear Modulus (μ)	$\mu = Vs^2\rho$	[13-14]
Poisson's Ratio (σ)	$\sigma = \dfrac{v_P^2 - 2v_S^2}{2\left(v_P^2 - v_S^2\right)}$	[13-14]
Bulk Modulus (K)	$K = \rho\left(v_P^2 - \frac{4}{3}\, v_S^2\right)$	[13-14]
Lame's Constant (λ)	$\lambda = \rho(V_P^2 - 2V_S^2)$	[13-14]
Material Index (Im)	$Im = \dfrac{3 - \left(V_p/V_s\right)^2}{\left(V_p/V_s\right)^2 - 1}$	[15-16-17]
Concentration Index (Ic)	$Ic = \left(1 + \sigma\right)/\sigma$	[15-16-17]
Ultimate bearing capacity (Qu)	$Qu = \dfrac{1}{3}\left(\dfrac{Vp}{240}\right)^{2.38}$	[15-16-17]

Results and Discussion

The main properties obtained from laboratory work and from the velocity measurement of rock samples are listed in Table-2. The range values of wave velocity were 4476- 6393 and 2341-3190 m/sec for P and S waves, respectively. Density value ranged from   2597 to 2829 kg/m³ and porosity values ranged from 1.7 to 3.6%. The obtained elastic and geotechnical properties showed different values depending on the factors affecting seismic wave velocity and density. The Young modules values ranged from 3.87E+10 to 7.30 E+10 Pa. The shear modulus values ranged from 1.42 E+10 to 2.75 E+10 Pa. The differentiation of shear wave velocities has an important role in producing variation in this parameter, because of its sensitivity to changes in porosity within sandstone rocks. The increasing value of this parameter is a good indicator of increasing rock hardness. Poisson's ratio values ranged from 0.18 - 0.38 , which indicates that the sandstone samples in the study area possess moderate to hard rocks [16]. The Bulk modulus values ranged from 4.76E+10 to 1.194 E+11 Pa .The decreasing value of this parameter means high porosity of those samples [17]. Lame's constant values ranged from 1. 97E+10 to 6.18 E+10 Pa. This parameter is the same as shear modulus and it is valid for isotropic media [18, 19]. The material index, concentration index, and ultimate bearing capacity (Qu) were estimated alongside the results provided by the elastic moduli. The range of the material index values in the study area varied from -0.01 to -0.44, which reflects fairly to moderately competent of rocks [20, 21]. The calculated concentration index values for the rock samples ranged between 3.64 and 4.97, which reflects fairly competent of rocks [17, 20, 22]. The ultimate bearing capacity (Qu) values ranged from 352 to 823Kg/cm². The variation in values of elastic   and geotechnical properties is due to the textural, structural, and compositional variations that occurred in the rocks of   Tanjero Formation.

Table 2- Elastic Modulus and Geotechnical Parameters of sandstone at the study area

| porpsity	Im	Qu	Ic	Young's M.	Bulk M.	λ	μ	σ	Vp	Vs	Density	Sample
%		Kg/cm²		Pascal	Pascal	Pascal	Pascal		m/sec	m/sec	Kg/m³	Number
2.5	-0.30	551	4.07	5.50E+10	7.878E+10	3.87E+10	2.08E+10	0.33	5400	2747	2750	1
1.7	-0.20	697	4.34	7.11E+10	8.848E+10	4.08E+10	2.73E+10	0.30	5960	3190	2687	2
2.1	-0.19	588	4.35	6.22E+10	7.717E+10	3.55E+10	2.4E+10	0.30	5549	2974	2708	3
2.3	-0.14	507	4.49	5.80E+10	6.781E+10	3.02E+10	2.26E+10	0.29	5216	2855	2767	4
2.9	-0.51	655	3.64	5.11E+10	1.052E+11	5.78E+10	1.85E+10	0.38	5808	2567	2812	5
1.8	-0.26	688	4.19	7.07E+10	9.492E+10	4.53E+10	2.69E+10	0.31	5929	3088	2820	6
2.8	-0.25	465	4.21	4.83E+10	6.427E+10	3.06E+10	1.84E+10	0.31	5031	2630	2663	7
3.2	-0.14	352	4.51	4.11E+10	4.767E+10	2.11E+10	1.6E+10	0.28	4476	2456	2650	8
1.9	-0.40	823	3.87	7.22E+10	1.194E+11	6.18E+10	2.68E+10	0.35	6393	3080	2821	9
2.8	-0.01	366	4.97	4.85E+10	4.884E+10	1.97E+10	1.94E+10	0.25	4548	2619	2822	10
2.5	-0.17	473	4.42	5.50E+10	6.638E+10	3.01E+10	2.13E+10	0.29	5067	2743	2829	11
2.4	-0.14	483	4.51	5.61E+10	6.513E+10	2.89E+10	2.18E+10	0.28	5110	2803	2777	12
1.8	-0.21	657	4.30	6.74E+10	8.577E+10	3.99E+10	2.59E+10	0.30	5815	3089	2711	13
1.8	-0.31	761	4.06	7.30E+10	1.051E+11	5.17E+10	2.75E+10	0.33	6186	3141	2790	14
3.6	-0.44	459	3.78	3.87E+10	6.892E+10	3.65E+10	1.42E+10	0.36	5000	2341	2597	15

In order to describe the relation between wave velocities and elastic moduli of core samples, a regression analysis was achieved .The equations of the best fit line and the regression coefficients (R^2) were established for each relation. The following sections aim to discuss correlations that allow the estimation of properties of rocks from seismic velocities.

The relations between density and velocities of Vp and Vs

The relationships between density and the velocities of Vp and Vs were drawn for the 15 samples. Figures-(2 and 3) show proportional linear relationships, along with the equations used

Vp = 2.560*P* - 1601.
R² = 0.107
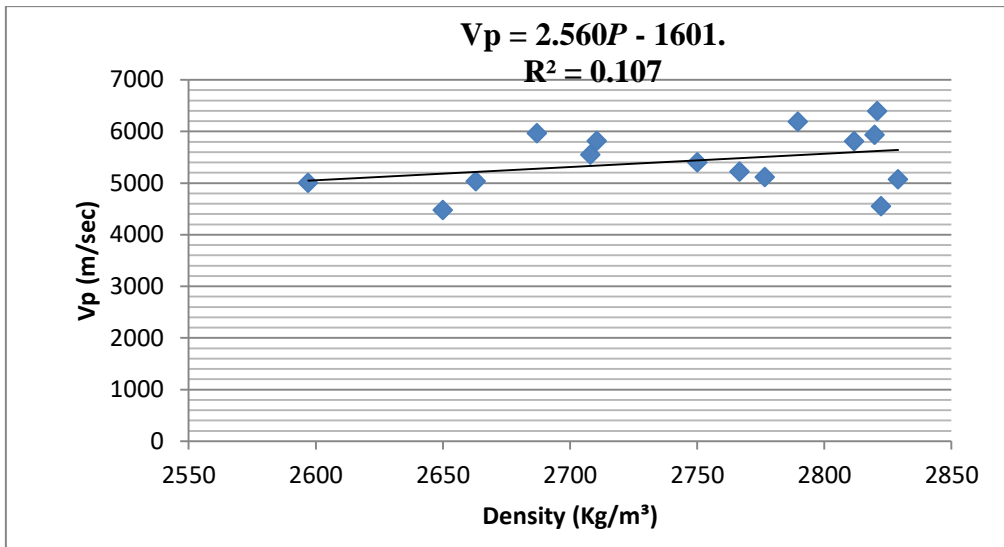
Figure 2- The relation between density and Vp of the samples considered in the area

Vs = 1.312*p* - 784.3
R² = 0.131
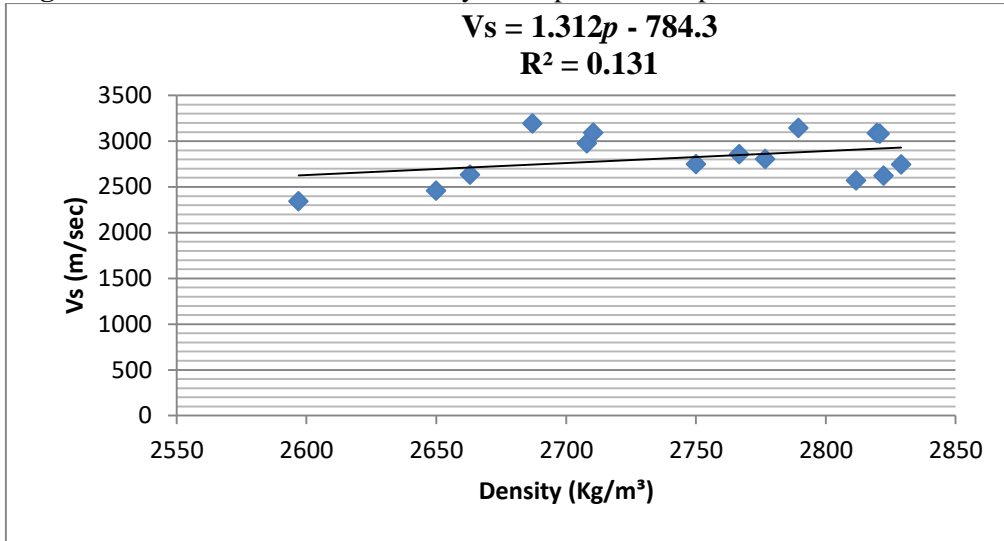
Figure 3- The relation between density and Vs of the samples considered in the area
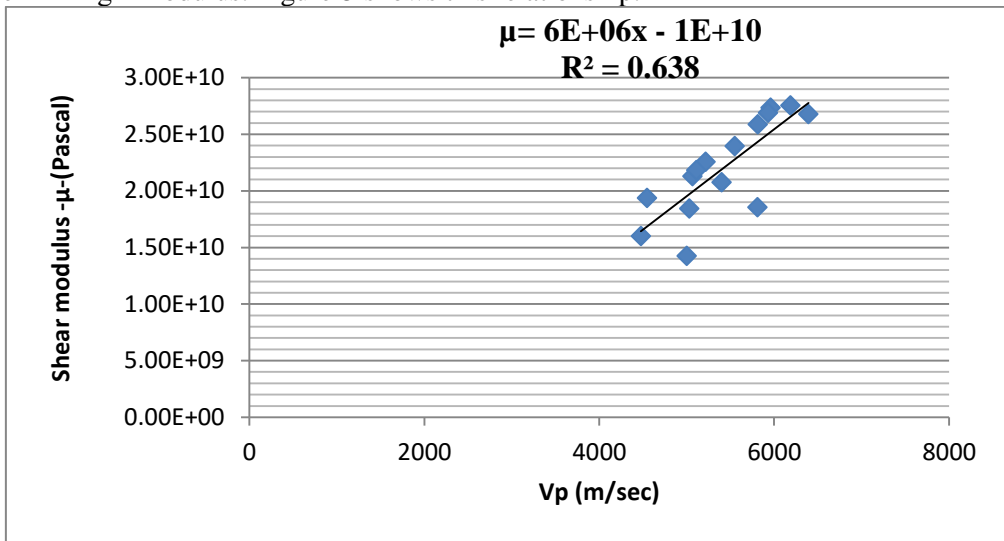
The relation between Vp and Vs

This relation is useful for determining of the velocity of Vs from the velocity of Vp, because the generation of Vp is easier than the generation of Vs. The relationship is shown in Figure- 4 with its equation.

Vs = 0.362V*p* + 853.4
R² = 0.615
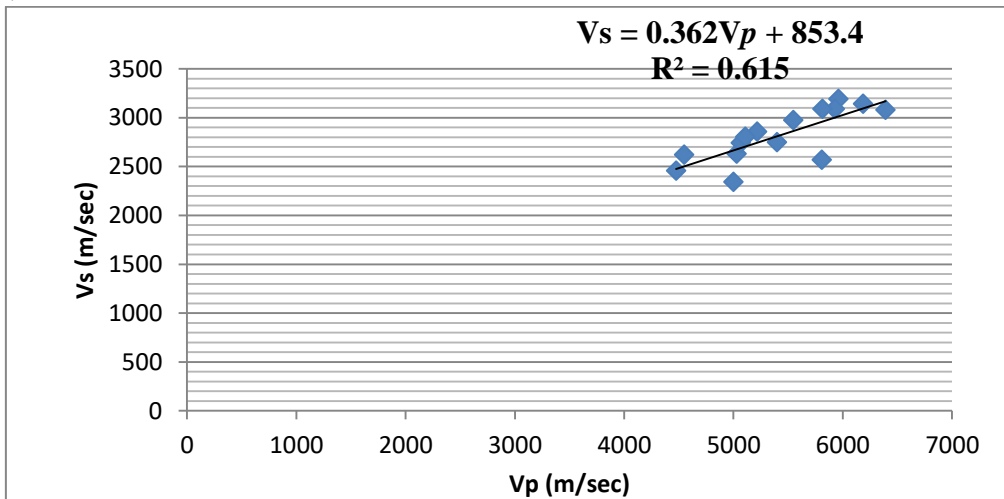
Figure 4- The relation between Vp and Vs of the samples considered in the area.

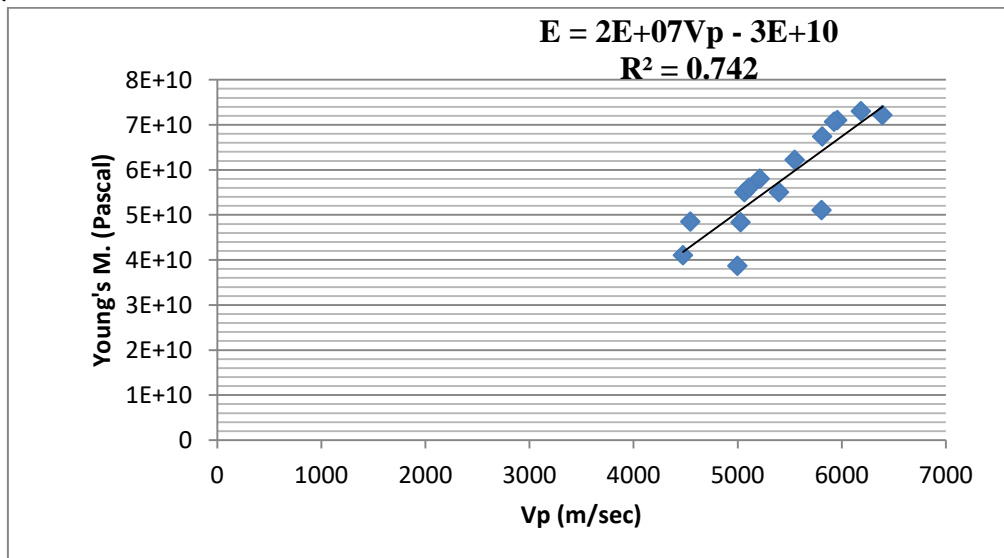**The relation between Vp and shear modulus**

Shear modulus is considered as a function of Vp. These two parameters have a direct proportion with each other, which was considered as a good indicator to the quality factor of sandstone rocks of Dokan. This indicator is based on the number of cracks per meter and considered as similar to the parameter Young's modulus. Figure-5 shows this relationship.

$$\mu = 6E+06x - 1E+10$$
$$R^2 = 0.638$$

Figure 5- The relation between Vp and μ of the samples considered in the area.

The relation between and Young Modulus

Figure-6 shows a linear relationship with a high regression coefficient value (R^2=0.74) between E and Vp .

$$E = 2E+07Vp - 3E+10$$
$$R^2 = 0.742$$

Figure 6- The relation between Vp and E of the samples considered in the area.
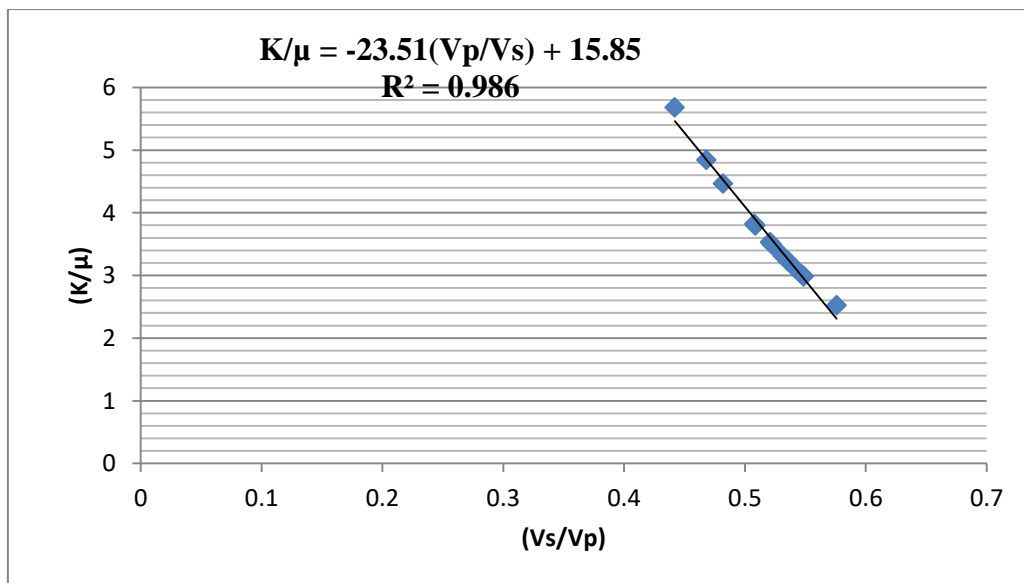
The relationship between Vp and Bulk Modulus

Bulk modulus is used to inspect the resistance of rocks to compression. A high value of this modulus can be noted in the compacted cemented rocks than in the porous rocks .The relation between K and Vp was plotted in Figure-7. The high regression coefficient (R^2 = 0.92) reveals a strong linear positive correlation between K and Vp in the studied samples.
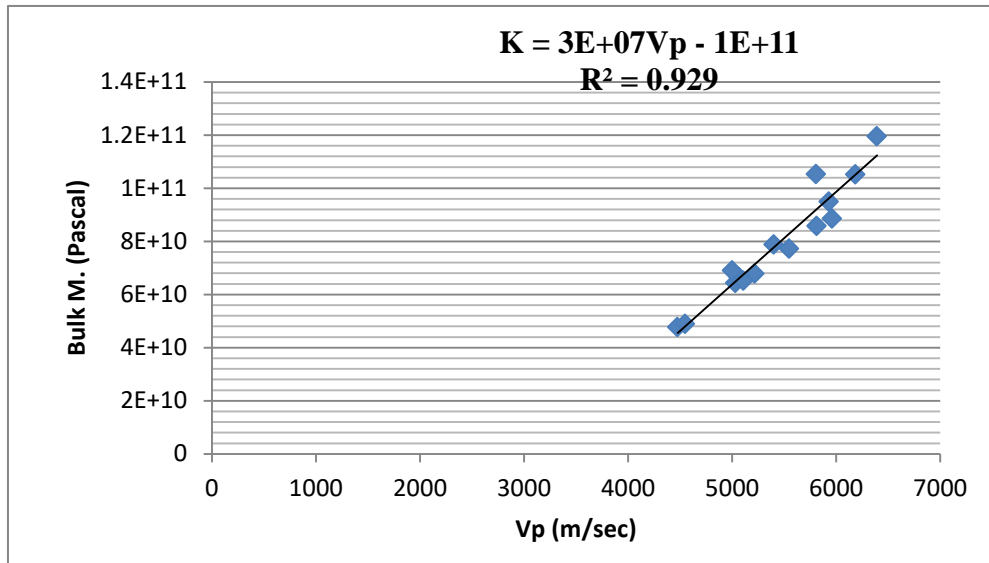
Figure 7- The relation between Vp and K of the samples considered in the area.

The relationship Between Vs/Vp and K/μ

From an engineering point of view, the relation between Vs/Vp and K/ μ is very important. It could be used for isolating weakest zones from strongest ones [23]. The relationship between Vs/Vp and K/μ is plotted in Figure-8. It shows a linear inverse relationship with high regression coefficient (R^2=0.986), which indicates that the ratio increases linearly with decreasing Vp/Vs value.


Figure 8- The relation between Vs/Vp and K/μ of the samples considered in the area

The relation between Poisson's ratios and velocity ratio

The relationship between σ and the ratios of Vs/Vp was found to be a linear inverse relationship with a high regression coefficient (R^2=0.99), as shown in Figure-9. This means that, when Poisson's ratio increases, the ratio of Vs / VP decreases, which reduces the brittleness and rigidity of rocks.
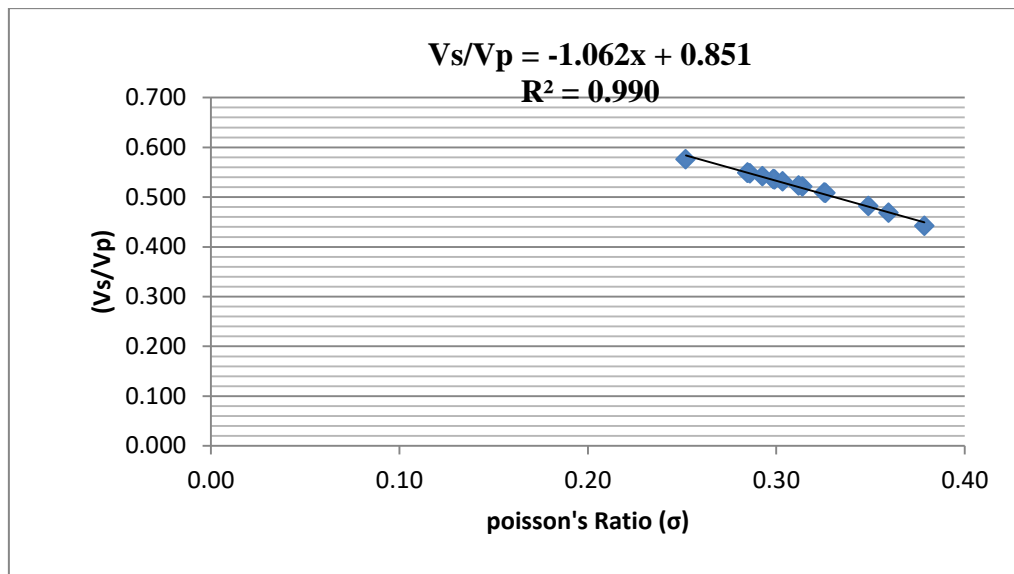
Figure 9- The relation between σ and Vs/Vp of the samples considered in the area

Conclusions

The current study aimed to estimate and evaluate some elastic and geotechnical parameters by using the ultrasonic test method. Laboratory measurements for 15 rock samples collected from sandstone layers of Tanjero Formation were conducted to calculate density, porosity, and elastic wave velocities. From the laboratory results, geotechnical and elastic parameters were estimated. According to the values of the calculated geotechnical parameters, including material index, concentration index, and ultimate Bering capacity, the studied samples were classified as fair to moderate competent rocks. Empirical equations were derived between Vp and the elastic parameters by using regression analyses. The results indicated some direct and other inverse linear relationships between Vp and elastic parameters. The relations between Vp and the parameters of Vs, μ, E, and K demonstrated good associations, as shown by the direct linear relations. But the relations between velocity ratio (Vs/Vp) and each of K/μ and σ showed strong linear inverse relationships with high regression coefficient values (R^2=0.986 and R^2=0.99, respectively). It could be concluded that the empirical equations obtained can be used to estimate and evaluate the elastic parameters of a site, if the information on Vp is available. This allows replacing complex and expensive test methods with a faster and cheaper method like the ultrasonic method.

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