SHEAR WAVE VELOCITY MODELING BASED ON WELL LOGGING DATA; A CASE STUDY FOR ONE RESERVOIR IN ONE OF THE SOUTHWEST IRANIAN OIL FIELDS

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***ABSTRACT**: Waves velocity are important parameters for determinate the dynamic modules magnitude in geomechanical studies. But, due to practices and cost limitations, shear wave velocity is not available in all wells. In this paper, it is trying to predict the shear wave velocity for one reservoir in one of the southwest Iranian oil fields from well log data, such as, compressional wave velocity, neutron porosity and density. Several methods were used to estimate the shear wave velocity. Then, based on obtained coefficient of determination and average absolute percent relative error between real and predicted values of shear wave velocity, final results compared together. The results of this work demonstrated that the obtained model from multiple linear regression method able to estimate the shear wave velocity better than other used methods.*

Keywords: wave velocity, well log data, dynamic modules, multiple regression, geomechanic, oil reservoir

1. INTRODUCTION

Geo-mechanical studies form an important section of oil and gas reservoirs analysis. So that, in main steps of reservoir analysis from exploration and drilling to development of reservoir these studies play a vital role. Identify the mechanical properties of reservoir rocks are the main principles during this studies. Direct and indirect methods used to determine the mechanical properties of rocks. Direct methods such rock mechanic tests result in exact values of mechanical properties than indirect methods. But, due to several limitations such as cost, practical constraints and lack of appropriate and adequate cores it is try to use of indirect methods for measuring the mechanical properties of rocks. By consider of continues obtained data from well logging, it is suitable, use of well log data as geomechanical studies to measure the mechanical properties. Although, recommended that use of direct method results for calibrating the indirect methods results to achieve the more accuracy [1].

Knowledge of the dynamic properties of reservoir rocks is indispensable to geomechanical studies of reservoirs. Young's modulus, Poisson ratio and Shear modulus are important dynamic properties of reservoir rocks that affect the different stages of geomechanical studies such as, well bore stability analysis, hydraulic fracturing design, perforation operation, bit selection, wellbore trajectory design, reservoir subsidence analysis, geo-mechanical modeling etc. based on Eq 1 to Eq 5 it is illustrated that wave velocity are very important and vital for calculate the dynamic modulus. Compressional wave velocity available in all wells, often. But shear wave velocity not available in all wells due to cost limitation and practical restrictions. Therefore, shear wave velocity determine in several wells, then by use of real values of shear wave velocity in these wells estimate the shear wave velocity in other wells [2-4].

$$E = 1.34 \times 10^{10}\rho V_s^2\left(\frac{3V_p^2 - 4V_s^2}{V_p^2 - V_s^2}\right) \qquad (1)$$

$$K = 1.34 \times 10^{10} \times \rho\,\frac{3V_p^2 - 4V_s^2}{3} \qquad (2)$$

$$G = 1.34 \times 10^{10} \times \rho V_s^2 \qquad (3)$$

$$C = \frac{1}{K} \qquad (4)$$

$$\vartheta = \frac{V_p^2 - 2V_s^2}{2V_p^2 - 2V_s^2} \qquad (5)$$

Where, E is Young's modulus in Psi, K is bulk modulus in Psi, G in shear module in Psi, C is compressibility module in Psi, ϑ is Poisson ratio, V_p is compressional wave velocity in ${ft}/{\mu s}$, V_s is shear wave velocity in ${ft}/{\mu s}$ and ρ is density in ${gr}/{cm^3}$.

In this paper it is try to predict the shear wave velocity for one reservoir in one of the southwest Iranian oil fields from well log data. So that, by use of obtained model from final results, predicting the shear wave velocity in other wells of the interest reservoir of the case study field which lacks of shear wave velocity data.

1.1 Literature of study

Wave velocity in rock depends on compressive and tensile strengths of rock or rock quality. Therefore, direct relation established between mechanical properties of rock and wave velocity in rock. So that, it is stated that elastic wave velocity in rock affected from intrinsic properties of rock such as, porosity, density, hardness and rock type. Range of compressional and shear wave velocity for different rocks presented in Figure 1 After propagation of wave, compressional and shear wave are produced. So that compressional wave produced along wave propagation and shear wave perpendicular of the wave propagation (see Figure 2). Therefore, shear wave velocity less than compressional wave velocity [5].

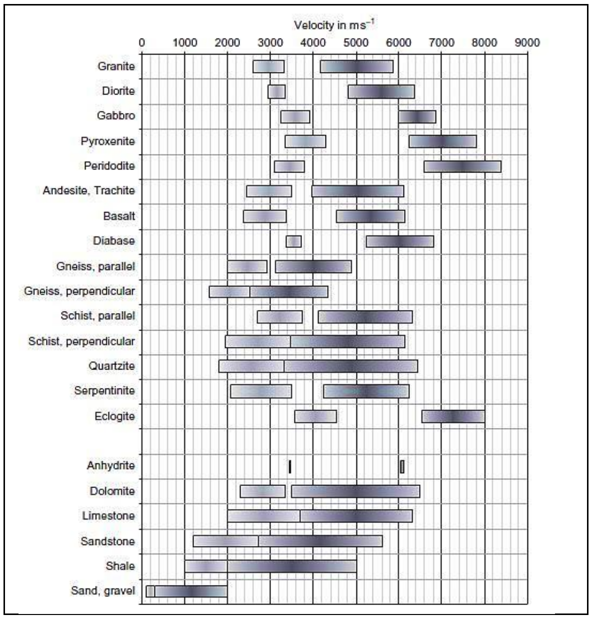

Figure. 1: Range of wave velocity in different rocks. [5].

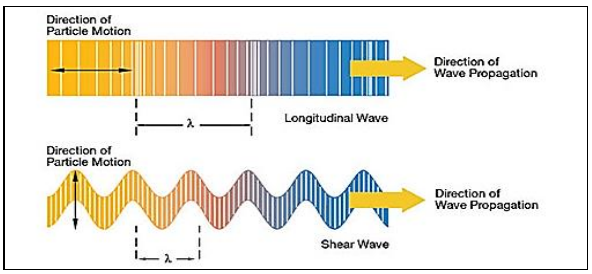

Figure. 2: Schematic of shear wave and compressional wave propagation direction. [6]

Nowadays used of dynamic methods to estimate the elastic parameters in rock engineering accepted and are popular due to these methods are nondestructive methods. Methodology in this methods involved send the waves in to the rock and measure the wave velocity. This methods performed in laboratory based on ASTM D2845 as ultrasonic test [7].

In well logging operation, compressional and shear wave transit time measured in $^{\mu s}/_{ft}$. If it is concerned measuring the wave velocity in rock with length L after Time t, then, wave velocity measured as follow in $^{m}/_{s}$ [8].

$$V(^{m}/_{s}) = \frac{304800}{DT(^{\mu s}/_{ft})} \tag{6}$$

Where, V signifies wave velocity.

Wave transit time measured in $^{\mu s}/_{ft}$ in well logging operation as mentioned previous. For convert the $^{\mu s}/_{ft}$ to $^{m}/_{s}$ below equation used.

$$V(^{m}/_{s}) = \frac{L(mm)}{t(s)} \times 1000 \tag{7}$$

Where, DT is wave transit time in $^{\mu s}/_{ft}$.

And, also:

$$V(^{km}/_{s}) = \frac{V(^{m}/_{s})}{1000} \tag{8}$$

Many authors worked many studies for measuring the shear wave velocity in previous decades. Several important of these works mentioned in follow.

Picket (1963) expressed that it is possible detect the lithology from V_p/V_s ratio. So that, it is equal to 1.9 for limestone, 1.8 for dolomite and 1.6 for sandstone [9].

Dominico (1984) by use of Picket experimental data conclude that porosity effect on wave velocity. So that, porosity effect on carbonates less than porosity effect on sandstones. And, porosity effect on shear wave velocity is more than porosity effect on compressional wave velocity in carbonate rocks. Dominico correlation for wave velocity and porosity presented as follow in different effective pressure [10].

$$^{1}/_{V} = A + B\emptyset \tag{9}$$

Where, $\emptyset$ is porosity in %, V is wave velocity in $^{\mu s}/_{ft}$, A and B are Dominico equation coefficients which presented in Table 1. A is related to rock matrix and B is related to pore geometry and formation effective pressure.

Castagna et al (1993) present the below equations to shear and compressional wave velocity in limestone and dolomite [9, 11].

$$V_s = -0.055V_p^2 + 1.01V_p - 1.031 \tag{10}$$

And for dolomite:

$$V_s = 0.583V_p - 0.078 \tag{11}$$

Where, V_s is shear wave velocity in km/s and V_p is compressional wave velocity in km/s.

Table 1 Values of A and B for Domenico correlation.

Pressure (Psi)	Carbonate rocks			
	Compressional wave		Shear wave	
	A	B	A	B
500	171.3	370.8	333.4	649
1000	168.7	283.1	323.3	451.8
2000	167.3	241.3	318.5	374.8
3000	166.1	215.4	341.1	335.5
4000	165.1	197.9	311.5	304.7
5000	164.2	186.9	309.1	286.9
6000	163.5	178.8	307.3	273.3

Bastos et al present the below equation for limestone of Brazilian reservoirs [12].

$$V_s = 0.55V_p + 41.6 \tag{12}$$

Where, v is wave velocities in m/s.

Intelligent networks were used by several authors in previous years as an appropriate tool to predict the shear wave velocity in oil fields. In this method, construct the network by use of available data in several wells, then, predict the shear wave velocity in other wells by used of constructed network. Figure 3, Figure 4 and Figure 5 shows the presented final results by previous authors for predict the shear wave velocity from intelligent networks [9, 11, 12].

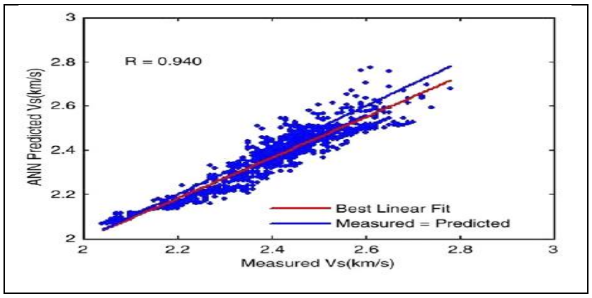

Figure. 3: Shear wave velocity prediction by use of ANN (Artificial Neural Network) [12].

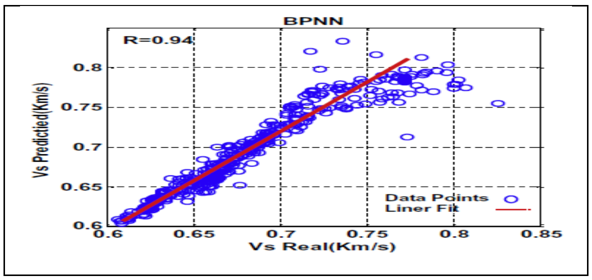

Figure. 4: Shear wave velocity prediction by use of BPNN (Back Propagation Neural Network) [11].

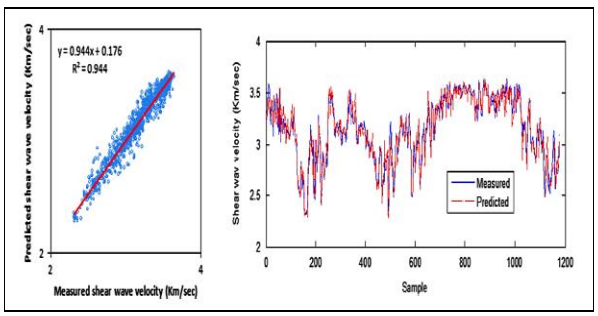

Figure. 5: Shear wave velocity prediction by use of SVR (Support Vector Regression) [9].

2. METHODOLOGY

In this work it is try to predict the shear wave velocity based on well log data in two wells of one reservoir in one of the southwest Iranian oil fields. So that, after comparison between several methods, selecting the best method which more accuracy for predics the shear wave velocity in other wells. In any method, after obtain the shear wave velocity values calculate the Coefficient of determination (R^2) and average absolute percent relative error ($AAPRE$) between real and predicted values of shear wave velocity. Then, based on mentioned parameters for used methods, recommend the best method.

R^2 indicates how good the equation matches the data and illustrate a value of the utility of the model or equation. If R^2 is closer to 1, therefore good fitting established between real and predicted values. And $AAPRE$ define as the relative absolute deviation from the real values. These parameters determined as follow [13, 14]:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{\sum_{i=1}^{n}(x_i - m_x)^2} \tag{13}$$

$$AAPRE = \frac{\sum_{i=1}^{n} \frac{|(x_i - \hat{x}_i)|}{x_i} \times 100}{n} \tag{14}$$

Where, x_i is real value, $\hat{x}_i$ is predicted value, m_x is average of real values and n is number of data.

2.1 Characteristics of interest reservoir and field

This work done in one reservoir in one of the southwest Iranian oil field, where, shear wave velocity available in two wells of field wells. Dipole Sonic Imagers (DSI) run in wells A and B for measuring the shear wave velocity. By use of below methods shear wave velocity predicted by available data from two mentioned wells.

2.2 Use of empirical equation

The main lithology in interest reservoir is carbonate rocks (Dolomite and Limestone), therefore, ability of available equation for predict the shear wave velocity in carbonate rocks check in interest reservoir.

2.3 Use of relation between shear and compressional wave velocity in interest reservoir

By use of presented model from Castagna and Grinberg, in below equation obtained values of A_0 and A_1. So that, obtain the liner model for calculate the shear wave velocity [15].

$$V_s = A_0 + A_1.V_p \tag{15}$$

2.4 Multiple regression method

Regression is a statistics method to estimate a mathematical correlation for determinate the unknown variable based on known variable or variables [16]. In this work, shear wave velocity predicted from well logs data, such as, NPHI (neutron porosity), RHOB (bulk density) and compressional wave velocity by use of multiple regression method in SPSS software. So that, first, investigate the relation between shear wave velocity and input parameters (RHOB, NPHI and V_p). Then, find the coefficients equation ($a, b, c\ and\ d$) in follow equation.

$$V_s = a + bV_p + cNPHI + dRHOB \tag{16}$$

Where, NPHI is neutron porosity in %, RHOB is bulk density in $^{gr}/_{cm^3}$, V_p is compressional wave velocity in m/s and V_s is shear wave velocity in m/s. It should be noted that, in multiple regression model, it is use of available data in all wells as input parameters, so that, final model useable in all wells.

2.5 Artificial Neural Network (ANN) method

Artificial Neural Networks are models based on neural structure of the brain. ANN is a useful network with a widely application in science and engineering such as, classification and approximation functions. Generally, designing a neural network consists of seven steps which show in Figure 6. Neural networks don't follow of constant algorithms. These networks respond to whatever learned from experience. Therefore, it is essential available the adequate examples to learning the network. So that, the network able to learn the relationship between inputs and output or outputs. Generally, 80 percent of data are used as learning the network and 20 percent are used to test the network [17].

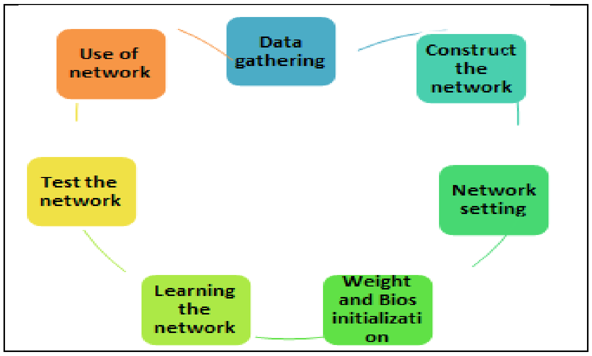

Figure. 6: Design steps of neural networks.

In this work, according to obtained continues well log data and available the adequate data it is used of ANN tool from MATLAB software. So that, first, construct the network in one well and then check the constructed networks in other well. Finally, comparison the ability of ANN tool with other used methods.

It shout be noted that, in different run by use of ANN, obtain the different result. Therefore, the final result for ANN ability to predict the shear wave velocity, reported after ten run by use of ANN tool for any wells from averaging the ten previous run results.

3. RESULTS

Shear wave velocity predicted in two wells A and B for interest reservoir of case study field. Empirical equations (Eq 10, Eq 11 and Eq 12) and mentioned previous methods were used to shear wave velocity prediction in these two wells. So that, first, presented results in well B based on obtained models from well A and Empirical equations, then presented result in well A from similar steps for well B. Finally, recommended the best method to predict the shear wave velocity according to the obtained R^2 and AAPRE between real and predicted values from each method.

3.1 Predict the shear wave velocity in well B based on obtained model from well A

3.1.1 Shear wave velocity based on compressional wave velocity

By use of Eq 15 Shear wave velocity obtained from compressional wave velocity in well A. So that, coefficients A_0 and A_1 obtained from the linear regression method. Then, predicted the shear wave velocity in well B. Figure 7 shows the relation between shear wave velocity and compressional wave velocity in well A. Eq 17 established between V_s and V_p in well A.

$$V_s = 0.458V_p + 518.69 \qquad (17)$$

Where, v is wave velocities in m/s.

From Eq 17 shear wave velocity predicted in well B. Figure 8 shows the real and predicted values of shear wave velocity in well B.

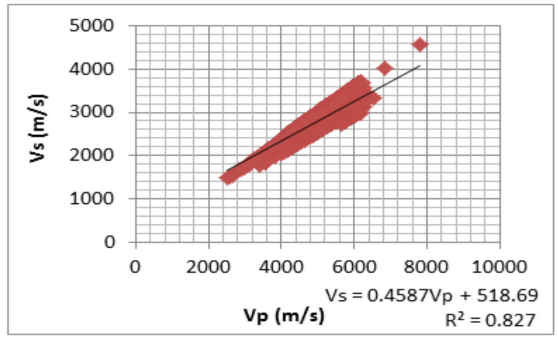

Figure. 7: V_p versus V_s in well A.

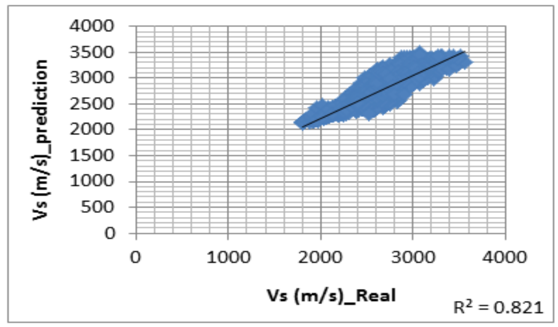

Figure. 8: Comparison of real versus predicted shear wave velocity from Eq 17 values in well B.

3.1.2 Multiple linear regression method to shear wave velocity prediction in well B from well A data

Shear wave velocity predicted from well logs data, such as, NPHI, RHOB and compressional wave velocity by use of multiple linear regression method in SPSS software. First, investigate the relation between shear wave velocity and input parameters (RHOB, NPHI and V_p). Then, coefficients of equation (a, b, c and d) found in Eq 16.

V_p and V_s relation in well A presented in Figure 7. Figure 9 and Figure 10 shows the relation between shear wave velocity with RHOB and NPHI in well A.

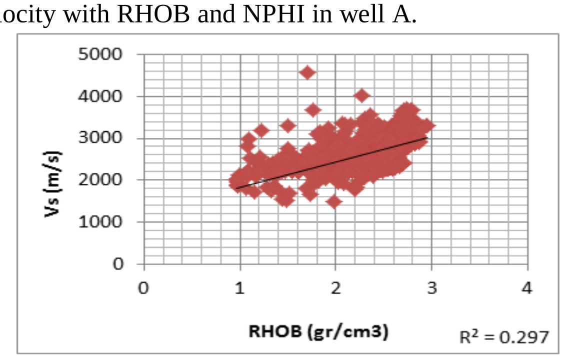

Figure. 9: V_s versus RHOB in well A.

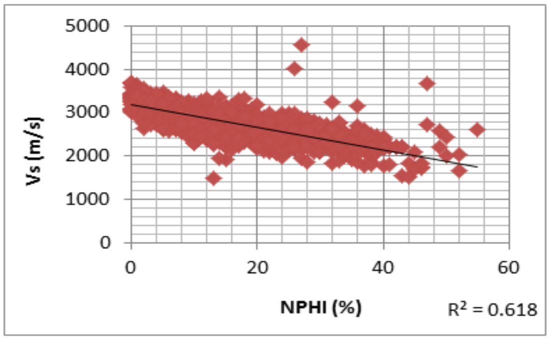

Figure. 10: V_s versus NPHI in well A.

After checking the relation between output parameter (V_s) and input parameters (RHOB, NPHI and V_p), by use of the analysis module in SPSS software performed multiple regression between output and input parameters. So that, obtained the constants in Eq 16. Eq 18 shows the final result to shear wave velocity modeling from multiple regression method.

$$V_s = 1019.964 + 0.386V_p - 6.451NPHI - 14.911RHOB \qquad R^2 = 0.850 \tag{18}$$

Shear wave velocity predicted in well B from Eq 18.
Figure 11 shows the relation between real and predicted shear wave velocity values in well B.

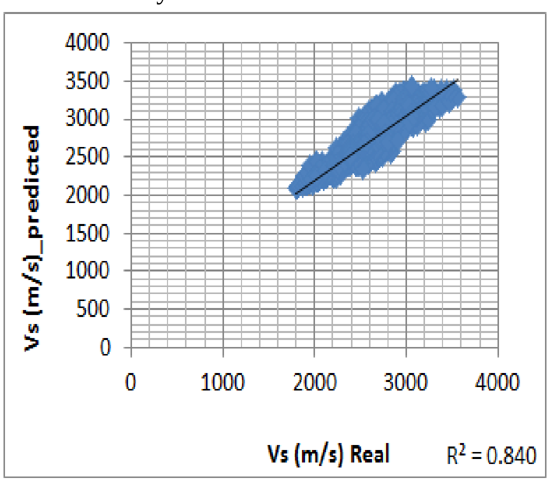

Figure. 11: Comparison of real versus predicted shear wave velocity from Eq 18 values in well B.

3.1.3 Use of ANN tool to shear wave velocity prediction in well B based on well A data

Shear wave velocity predicted by use of ANN tools in MATLAB software. First, constructed the network in well A with input parameters (NPHI, RHOB and V_p) and output parameter (V_s). Then, shear wave velocity predicted in well B by use of constructed network. Figure 12 shows the schematic of constructed network. %70 of data for training the network, %10 for validation and %20 for testing the network were used.

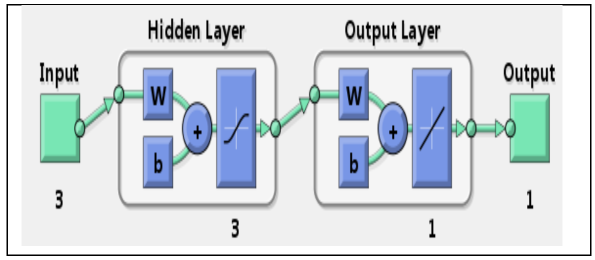

Figure. 12: Schematic of constructed network to shear wave velocity prediction.

Ten runs were performed to predict the shear wave velocity in each wells. Then, reported average of results as the final result.
Figure 13 shows the results for constructed steps during building the network.
After constructing the network, shear wave velocity predicted in well B by use of constructed network in well A. Figure 14 shows the relation between real value and predicted value of shear wave velocity in well B.

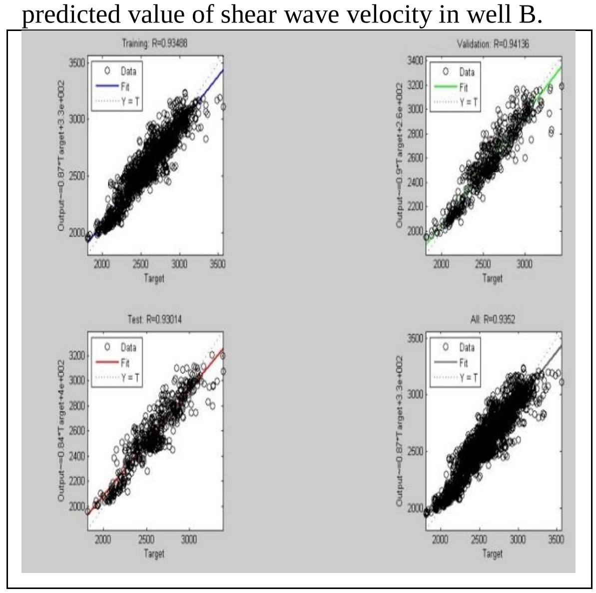

Figure. 13: Steps results during building the network in well A.

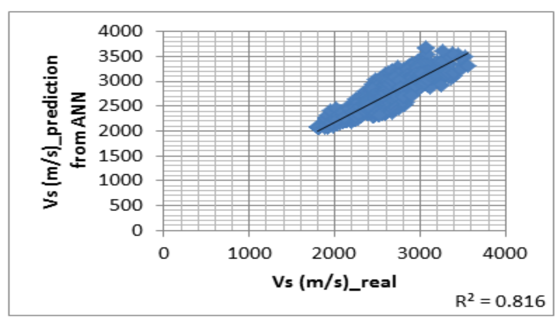

Figure. 14: Comparison of real versus predicted shear wave velocity from ANN tool values in well B.

3.1.4 Empirical correlations to shear wave velocity prediction in well B

By use of empirical correlations proposed from authors (Eq 10, Eq 11 and Eq 12) shear wave velocity predicted in well B. Then, checked the relation between real and predicted values of shear wave velocity.

Figure 15 shows the relation between real and predicted shear wave velocity from Eq 10 presented by Castagna for limestone.

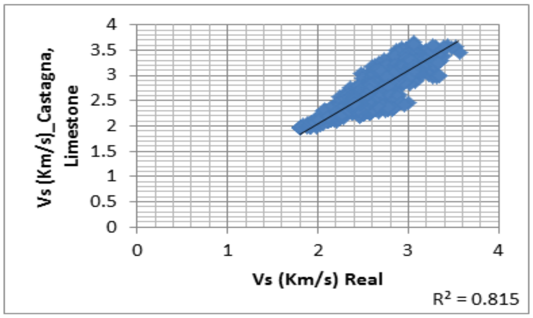

Figure. 15: Comparison of real versus predicted shear wave velocity from Eq 10 values in well B.

Figure 16 shows the relation between real and predicted shear wave velocity from Eq 11 presented by Castagna for dolomite.

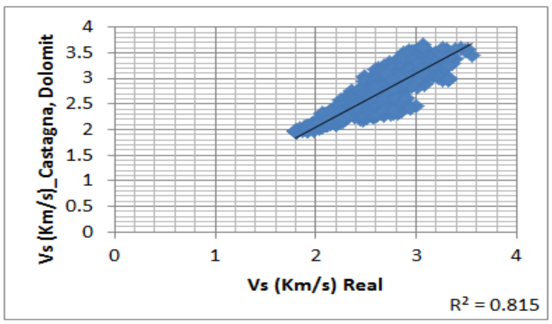

Figure. 16: Comparison of real versus predicted shear wave velocity from Eq 11 values in well B.

Figure 17 shows the relation between real and predicted shear wave velocity from Eq 12 presented by Bastos for the limestone of Brazilian reservoirs.

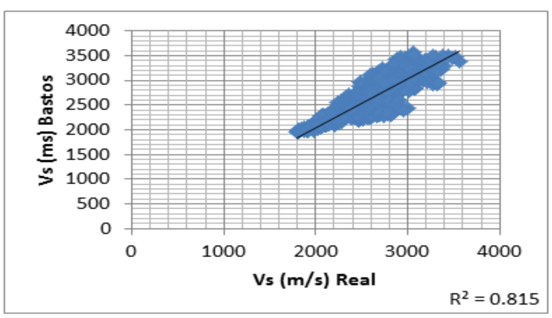

Figure. 17: Comparison of real and predicted shear wave velocity from Eq 12 values in well B.

3.1.5 Overall results for shear wave velocity prediction in well B

AAPRE calculated for above presented six cases to shear wave velocity prediction in well B from Eq 14. Overall results for shear wave velocity prediction in well B presented in Table 2.

Figure 18 shows the real and predicted values of shear wave velocity in well B. In this figure, red line refers to real values of shear wave velocity and blue line refer to predicted values of shear wave velocity from used methods to shear wave velocity prediction during this work.

Table 2 Shear wave velocity prediction results in well B

Case No	Model description	R^2 @ well B	AAPRE @ well B
1	$V_s = 0.4587V_p + 518.69$ $R^2 = 0.827$	0.821	5.16
2	$V_s = 1019.964 + 0.386V_p - 6.451NPHI - 14.911RHOB$ $R^2 = 0.850$	0.840	5.05
3	Constructed network in well B	0.816	5.47
4	$V_s = -0.055V_p^2 + 1.01V_p - 1.031$	0.815	5.10
5	$V_s = 0.583V_p - 0.078$	0.815	5.00
6	$V_s = 0.55V_p + 41.6$	0.815	5.00

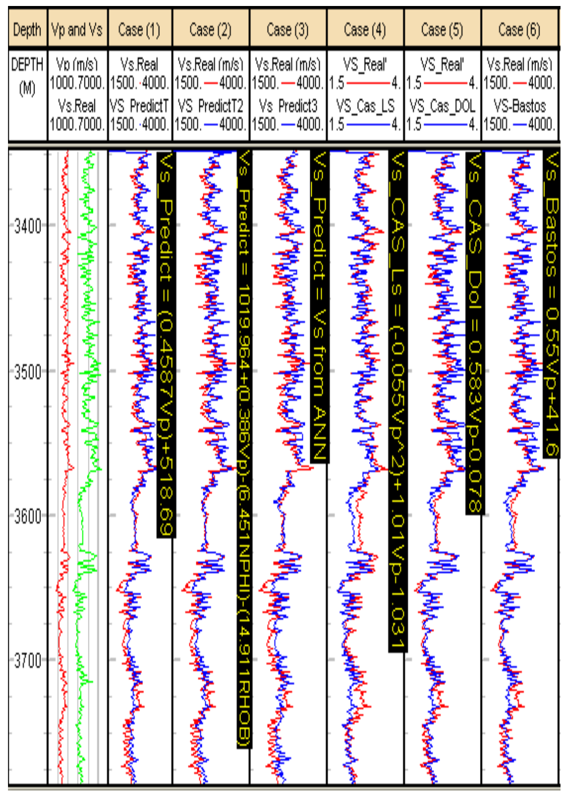

Figure. 18: Real and predicted values of shear wave velocity in well B (3348m-3787m). For cases 4 and 5 V in km/s.

3.2 Overall results for shear wave velocity prediction in well A

Above similar steps for shear wave velocity prediction in well B were performed in well A. Overall results for shear wave velocity prediction in well A presented in Table 3. Figure 19 shows the real and predicted values of shear wave velocity in well A.

Table 3 Shear wave velocity prediction results in well A

Case No	Model description	R^2 @ well A	AAPRE @ well A
1	$V_s = 0.4352V_p + 545.81$ $R^2 = 0.818$	0.827	4.95
2	$V_s = 1365.364 + 0.363V_p - 7.923NPHI - 139.83RHOB$ $R^2 = 0.831$	0.830	5.00
3	Constructed network in well B	0.730	5.7
4	$V_s = -0.055V_p^2 + 1.01V_p - 1.031$	0.830	7.72
5	$V_s = 0.583V_p - 0.078$	0.827	4.95
6	$V_s = 0.55V_p + 41.6$	0.827	5.00

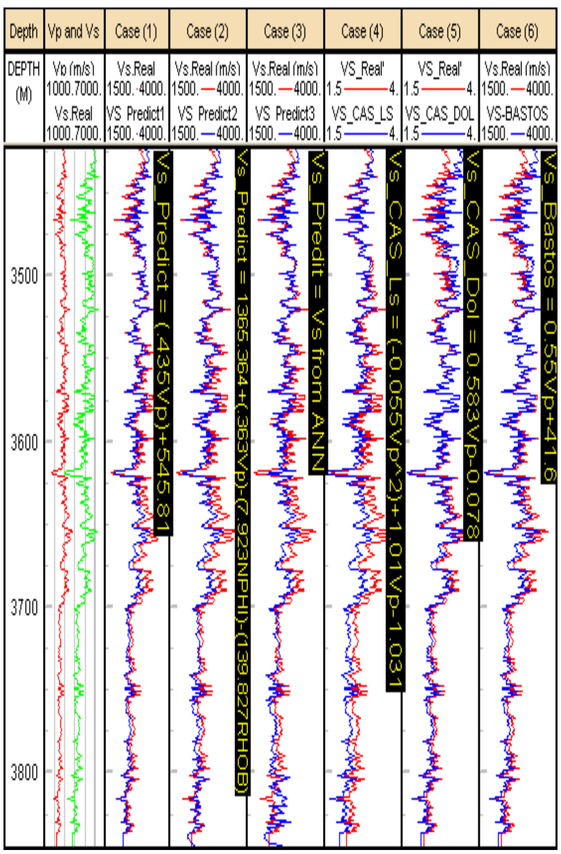

Figure. 19: Real and predicted values of shear wave velocity in well A (3420m-3844m).

4. CONCLUSION

In this paper, it is trying to predict the shear wave velocity in one reservoir of the one of the southwest Iranian oil fields based on available well log data from two wells of interest field wells. It is demonstrated that, well logging data are useable data to predict the shear wave velocity, due to continuous and actual values of these parameters. After comparison the several methods to predict the shear wave velocity, based on obtained R^2 and AAPRE for any used methods it is illustrated that obtained model from multiple regression method (Eq 18) is more acceptable method to predict the shear wave velocity in this reservoir. Since, Eq 18 involve intrinsic properties of rock such as porosity, density and compressional wave velocity, therefore it is illustrated that, other intrinsic parameters of rock can be effects on shear wave velocity such as GR. Therefore, recommended that, modeling the shear wave velocity based on more intrinsic parameters of rock to acquire the more accuracy.

5. ACKNOWLEDGEMENT

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