STUDY OF COMPRESSIONAL AND SHEAR WAVE VELOCITY TESTS IN THE LABORATORY AND FIELD APPLIED TO SEDIMENTARY ROCKS OF RANTAU NANGKA DISTRICT, SOUTH KALIMANTAN

STUDI PENGUKURAN KECEPATAN RAMBAT GELOMBANG DAN GESER DI LABORATORIUM DAN LAPANGAN PADA BATUAN SEDIMEN DAERAH RANTAU NANGKA, KALIMANTAN SELATAN

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ABSTRACT

Compressional (Vp) and shear (Vs) wave velocities within rocks are often investigated by testing in the laboratory because it is easier and cheaper. However, it is more confidence with investigation results derived from the field due to the actual situation and conditions. In the laboratory, the wave velocities are commonly measured using ultrasonic pulse velocities test. But in the field, the velocities are commonly measured directly by several methods such as cross-hole seismic, down-hole seismic, suspension logging, seismic reflection, seismic refraction and spectral analysis of the surface wave. In the present study of field insitu tests, it has used down-hole seismic method. The field insitu test is more expensive than the laboratory test. Hence, this study would evaluate and compare data derived from both of laboratory and field insitu tests. Based on the measurements correlation, it is found that regression equation for each parameter are $V_{pL} = 0.0058e_{sF}^{0.0062V_{pF}}$ for compressional wave velocities, $V_{sL} = 0.0002V_{sF}^{2.1123}$ for shear wave velocities, $G_L = 0.2739G_F - 28718$ for shear modulus, $E_L = 0.3764E_F - 1x10^6$ for modulus of elasticity, $K_L = 1x10^{-6}K_F^2 - 9.1889K_F + 2x10^7$ for bulk modulus and $\lambda_L = 8x10^{-7}\lambda_F^2 - 2.232\lambda_F + 4x10^6$ for Lame constants. This equation can be applied to correct the laboratory test data in order to get close results between the laboratory and field insitu tests.

Keywords : compressional wave, shear wave, velocities, down-hole seismic test, ultrasonic pulse velocity test

SARI

Kecepatan rambat gelombang kompresi dan geser pada batuan sering diselidiki melalui pengujian di laboratorium karena lebih mudah dan murah, tetapi umumnya lebih dipercaya mempelajari sifat batuan secara langsung di lapangan karena dilakukan pada situasi dan kondisi yang sebenarnya. Di laboratorium, kecepatan rambat gelombang biasanya diukur menggunakan kecepatan denyut ultrasonik. Sedangkan di lapangan, kecepatan rambat tersebut biasanya diukur dengan beberapa metode seperti uji lintas lubang seismik, uji seismik lubang bor, suspensi logging, seismik refleksi, seismik refraksi, dan analisis spektral gelombang permukaan. Pada penelitian ini, pengukuran secara insitu di lapangan menggunakan uji sesimik lobang bor. Pengukuran secara insitu di lapangan lebih mahal dibandingkan dengan pengujian di laboratorium. Pada penelitian ini telah dilakukan evaluasi dan perbandingan data yang berasal dari laboratorium dan uji lapangan. Berdasarkan korelasi dari pengukuran tersebut telah ditemukan persamaan regresi untuk masing-masing parameter, yaitu $V_{pL} = 0.0058e_{sF}^{0.0062V_{pF}}$ *untuk cepat rambat gelombang kompresi,* $V_{sL} = 0.0002V_{sF}^{2.1123}$ *untuk cepat rambat gelombang geser,* $G_L = 0.2739G_F - 28718$ *untuk modulus geser,* $E_L = 0.3764E_F - 1x10^6$ *untuk modulus elastisitas,* $K_L = 1x10^{-6}K_F^2 - 9.1889K_F + 2x10^7$ *untuk modulus*

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ruah dan $\lambda_L = 8 \times 10^{-7} \lambda_F^2 - 2.232\lambda_F + 4 \times 10^6$ *untuk konstanta Lame. Persamaan ini dapat diaplikasikan untuk mengkoreksi hasil uji laboratorium agar dapat lebih mendekati hasil uji insitu.*

Kata kunci : *gelombang kompresi, gelombang geser, kecepatan, uji seismik lubang bor, uji kecepatan pulsa ultrasonik*

INTRODUCTION

Measurement of wave velocity as a dynamic property has often been used to provide information about rock structural properties. Magnitudes of dynamic constants are sensitive to mineralogical assemblages and are affected by shape, distribution and preferred crystallographic orientation of the components. Moreover, they are affected to an important degree by the presence of size and orientation of defects such as pores and cracks, in such a way that also depends on the presence of fluids.

In the laboratory, wave velocity is commonly measured using a method that based on the resonant modes of the specimens or the propagation of elastic waves in the specimens. International standard test to determine P and S-waves in the laboratory using ultrasonic pulse velocity (UPV) is found in the ASTM Standard Test Method D 2845-05. In Indonesia, the admitted standard test is the SNI 06-2485-1991. Both standard tests procedures are almost the same. Cylindrical rock sample is prepared by cutting and lapping the ends, then the length is measured. An ultrasonic digital indicator that consists of pulse generator unit, transmitter and receiver transducers are used for sonic pulse velocity measurement. The transmitter and receiver are positioned at the ends of specimen and the pulse wave travel time is measured. The velocity is calculated from dividing the length of rock sample by wave travel time. Both P and S-wave velocities can be measured.

In the field, wave velocities are commonly measured by several methods such as cross-hole seismic, down-hole seismic (DHS), suspension logging, seismic reflection, seismic refraction and spectral analysis of surface waves (SASW). In this study, the measurement of wave velocities used DHS test. The test requires only one borehole to provide shear and compressional velocity wave profiles. The method uses a hammer source at the surface to impact a wood plank and generate shear and compressional waves. This is typically accomplished by coupling a plank to the ground near the borehole and then impacting the plank in the vertical and horizontal directions. The energy from these impacts is then received by a pair of matching three component geophone receivers, which have been lowered down hole and are spaced 1.5 to 3 m apart. The Standard Test Methods for DHST is ASTM D7400 – 08.

The P and S-wave velocities are directly related to the important geotechnical elastic constants of poisson's ratio, shear modulus, bulk modulus and Young's modulus (modulus of elasticity). The study of P and S-wave propagation in the rocks has been made to find the poisson's ratio, shear and elasticity modulus, fractures and discontinuities in the rock mass (Tamunobereton et al., 2010). These parameters are used in analyzing rock behavior under both static and dynamic loads, where the elastic constants are input variables to the models that define the different states of deformations such as elastic, elasto-plastic and failure (Rao, 2003; Zhang, 2005). The current basic challenges do not just technical capability but also economic feasibility of any project (Singh and Shrivastva, 2009). P and S-wave velocities have proved to be immensely useful in gathering geotechnical information about the area.

The fundamental question refers to whether the laboratory tests are precise and accurate enough to understand the wave velocities or it should use costly measurements in the field to get data accurately. In determining the differences from the measurement results of wave velocities obtained in the field and laboratory, thus the present study would compared both laboratory and field measurements data. Therefore, the purpose of this study is to search correlation of the wave velocities (V_p and V_s) and its derivatives between field insitu and laboratory tests.

METHODOLOGY

The field study area was located in Rantau Nangka, Sungai Pinang District, Banjar County, South Kalimantan. Data retrieved from geotechnical core drilling at a depth of between 20-40 meters were done within claystone layer. The main geological formation of the area is shown in Figure 1. The area consists of claystone, sandstone, coal, limestone and marl overlaying semi-consolidated pleistocenic sediments with cemented sand (Sikumbang and Heriyanto, 1994). Field insitu tests (DHS tests) used five boreholes and laboratory tests (UPV tests) employed 50 drill cores as shown in Figure 1. Each borehole had been applied four times for seismic down hole tests at 20, 24, 28 and 32 meters respectively. The borehole was 4.5 inches in diameter with PVC cased to ensure good transmission of the wave energy. The hole must be cased and grouted to prevent rock caving during the tests. The source and receiver were placed at the depth of 20 – 40 meters within the claystone layers.

the P-wave velocity (V_P) and S-wave velocity (V_S) can be expressed by the following equation of Biot-Gassmann:

$$V_p = \sqrt{\frac{K + \frac{4}{3}G}{\rho}} \text{ .... (eq. 1)}$$

$$V_s = \sqrt{\frac{G}{\rho}} \text{ .... (eq. 2)}$$

Where K is the bulk modulus of the rock, G is the shear modulus of the rock and ρ is the bulk density of rock. The equations (1) and (2) apply to the elastic condition.

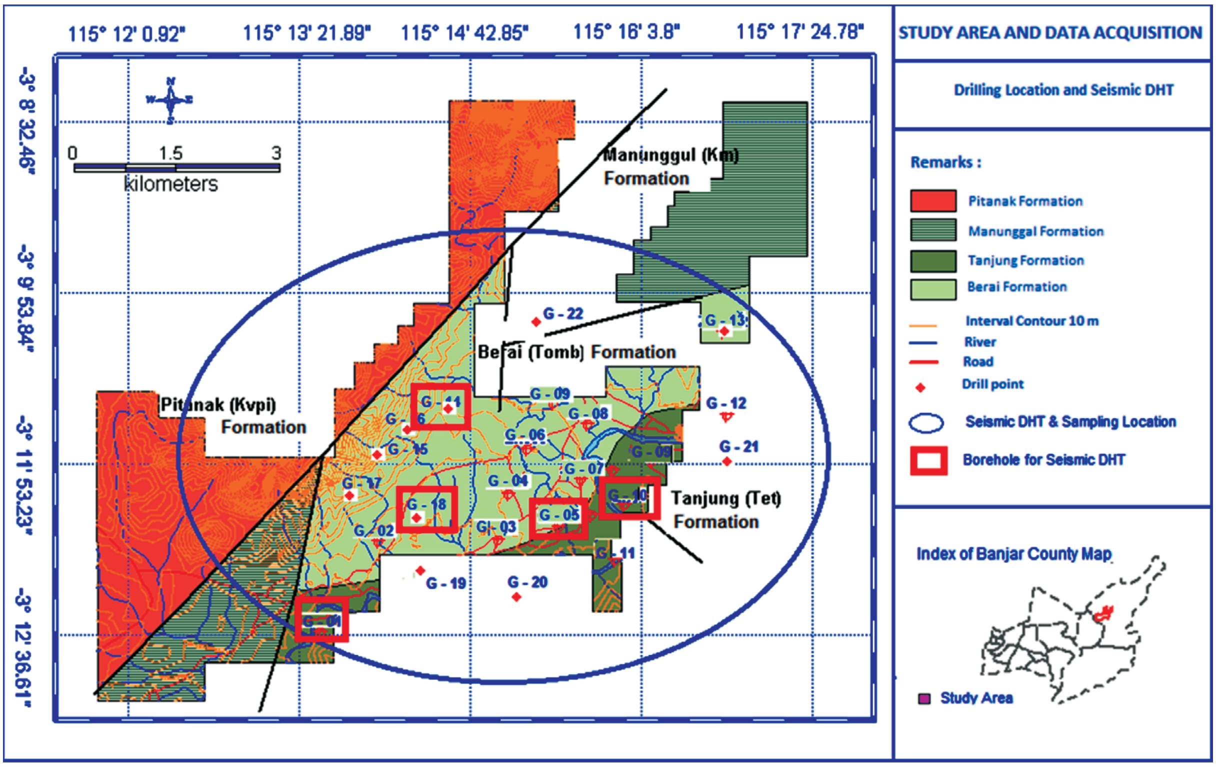

Figure 1. Location of DHS tests and geotechnical sampling

The main concept of this study is to search and compare the velocities of wave propagation between field insitu and laboratory tests. The former was performed in the field and the later was performed at the Laboratory of Rock Mechanics, R & D Center for Mineral and Coal Technology (*tek*MIRA). Cheng and Leong, 2011 stated that

Field Insitu Tests

The DHS test is an accurate measurement method to determine the seismic wave velocities of the rocks. The P and S-wave velocities are directly related to the important geotechnical elastic constants of poisson's ratio, shear modulus, bulk modulus, and Young's modulus (Soupios, et.al., 2005). A fundamental assumption inherent in the test methods is that a laterally homogeneous medium is being characterized. In a laterally homogeneous medium the source wave train trajectories adhere to Snell's law of refraction (Cheng and Leong, 2011).

Another assumption inherent in the test methods is that the stratigraphic medium to be characterized can have transverse isotropy. Transverse isotropy is a particularly simple form of anisotropy because velocities only vary with vertical incidence angle and do not with azimuth. By placing and actuating the seismic source at offsets rotated 90° in plain view, it may be possible to evaluate the transverse anisotropy of the medium (Vilhelm, et.al., 2008).

The test method was to determine interval velocities from arrival times and relative arrival times of compression either vertically or horizontally as well as polarized shear seismic waves generated near the surface and travel down to an array of vertically installed seismic sensors. A preferred method was intended to obtain data to be used in critical projects by which the required highest quality data were included.

Laboratory Tests

In this study, samples were tested by ultrasonic pulse velocity (UPV). The samples were selected at a regular interval throughout the core drill. The specimens for testing were prepared by cutting the ends of the core using a rock saw to produce flat end surfaces that satisfies to the ASTM standard. After cutting process, the samples were preserved in a vacuum sealed polyethylene bag or plastic freezer bag to maintain insitu moisture conditions. The UPV measurements were completed using a low-frequency portable ultrasonic nondestructive digital indicating tester (PUNDIT) equipped with two 1-MHz transducers to determine the transit time of a sound wave through the length of the rock core.

For testing purposes, a coupling medium was used between transducers and the rock specimen in term of minimizing signal loss from the transducers through to the rock. The system equipped by Fujitsu Notebook was used to record sample dimensions as well as P and S-wave transit times and a software was is applied to calculate the ultrasonic wave velocities and dynamic properties. The P and S-wave velocities were determined by dividing sample length over ultrasonic wave

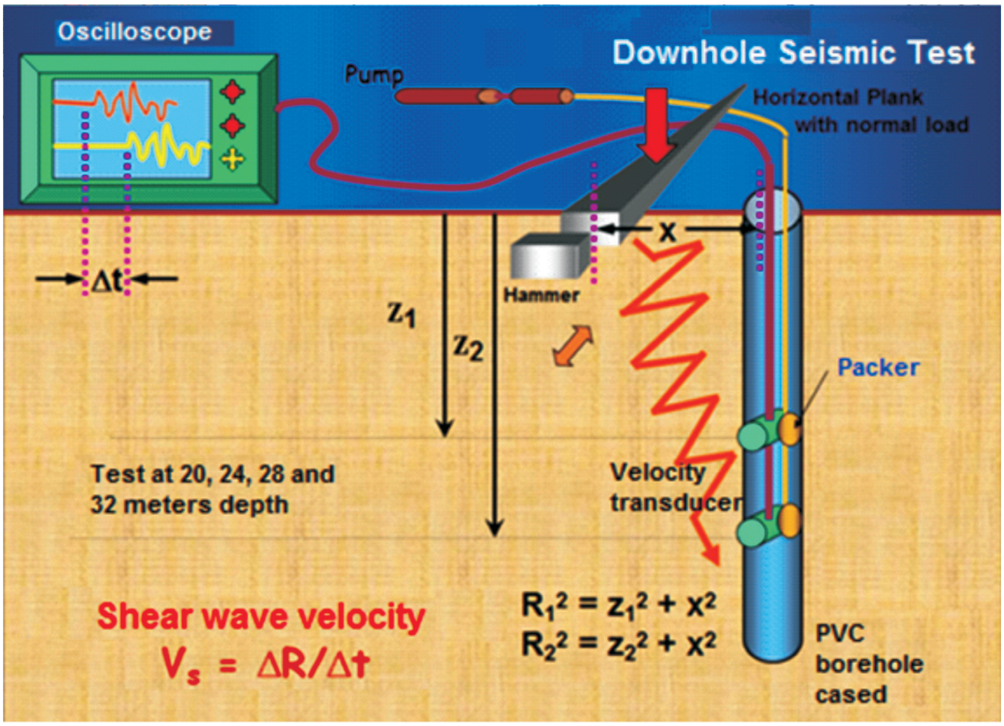

Figure 2. Schematic of DHS test

travel time throughout the sample. The velocity was then computed using the following formula (Chary, et al., 2006):

$$V_p = \frac{L_s}{T_p} \quad \text{(eq. 3)}$$

$$V_s = \frac{L_s}{t_s} \quad \text{(eq. 4)}$$

Shear modulus (G), dynamic young modulus (E), Lame constant (λ), bulk modulus (K) and dynamic poisson ratio (υ) can be represented as follows (Rai, et al., 2011) :

$$G = \rho V_s^2 \quad \text{(eq. 5)}$$

$$E = 2(1+\upsilon)G \quad \text{(eq. 6)}$$

$$\lambda = \rho(V_p^2 - V_s^2) \quad \text{(eq. 7)}$$

$$K = (\rho/3)(3_p^2 - 4V_s^2) \quad \text{(eq. 8)}$$

$$\upsilon = \frac{\left\{1 - 2\left(\frac{V_s}{V_p}\right)^2\right\}}{2\left\{1 - \left(\frac{V_s}{V_p}\right)^2\right\}} \quad \text{(eq. 9)}$$

V_P is compressional wave velocity, L_S is length of the sample, λ is density, T_P is travel time of compressional wave and T_S is travel time of shear wave. Results of the study by Knackstedt et al., (2005) claimed that the computed values of bulk and shear modulus for the grain overlap and pore-lining models are similar. It indicates only a small dependence of the models on microstructure or the distribution of the second mineral phase.

RESULTS AND DISCUSSION

This study was conducted to determine scale effect in the measurement of the wave velocity. The scale effect has been studied by some researchers to know geomechanics behaviors of rocks. Thuro, et al (2001) divided the scale effect into two components that was represented by the shape scale, which take account the variation of the ratio D/L (diameter/length) and the size scale in which this ratio is constant and the size of the specimen growth. Hence, values obtained from the tests show that shape scale have significant effect in to the results, but no effect for size (Déthié et al, 2013). Scale effect also appears in some tests such as dynamic behaviors of rock and can be compared by statistical approach. Comparative study of compressional and shear wave velocities between field insitu tests and laboratory tests involved four separated surveys, that is at 20, 24, 28 and 32 meters depth. P and S-wave measurements for the five geotechnic boreholes were made in the range of 20 - 40 meters depths. Result of DHT is presented in Table 1 while result of laboratory test for drill core samples and result of UPV test in the laboratory are presented respectively in Table 2 and 3.

A correlation between compressional wave velocities from DHS (field insitu tests) and UPV (laboratory tests) is shown in Figure 4. High regression coefficient reveals a strong correlation between the two velocities test that enables estimating one velocity to another. The following equation defines this relationship:

$$V_{pL} = 0.0058e^{0.0062C_{pF}} \quad \text{(eq. 10)}$$

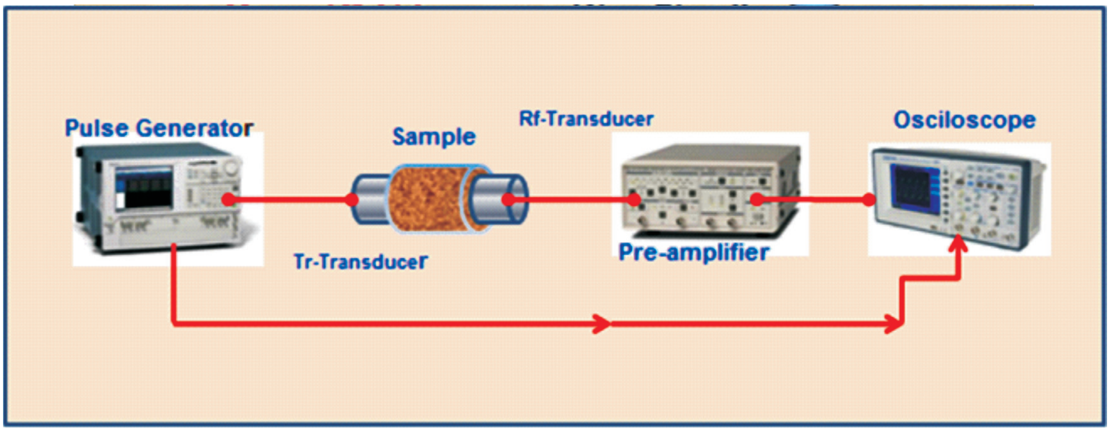

Figure 3. Schematic equipments of UPV test

Table 1. Result of DHS test for compressional and shear wave velocities

No	Test I (20 m)		Test II (24 m)		Test III (28 m)		Test IV (32 m)	
	Vp	Vs	Vp	Vs	Vp	Vs	Vp	Vs
G-1	2030	1217	1970	1183	2010	863.0	2222	1218
G-2	2000	1114	2020	1255	1860	777.8	1950	964
G-3	2000	1116	2030	1255	2100	950.5	2000	1017
G-4	2061	1263	1980	1185	1990	841.4	2010	1034
G-5	2020	1176	1990	1206	2040	890.2	1886	920
G-6	2030	1178	1960	1182	2010	847.6	2010	1039
G-7	2072	1343	1970	1184	2209	1167.2	2030	1047
G-8	2051	1228	1999	1222	2051	910.5	1990	1008
G-9	2061	1236	1990	1213	2030	872.5	2051	1053
G-10	2061	1239	1980	1185	2162	1062.6	2061	1057
G-11	2350	1488	2000	1236	2050	896.2	2061	1061
G-12	2061	1268	2010	1243	2051	910.5	2094	1061
G-13	2061	1325	2100	1280	2116	978.3	2100	1070
G-14	2100	1351	1990	1219	2100	925.5	2105	1071
G-15	2200	1402	2050	1269	1793	768.4	1851	898
G-16	2300	1437	1999	1224	2105	950.9	2116	1077
G-17	2400	1531	2150	1338	1877	811.3	2127	1106
G-18	1999	1072	1960	1135	2127	983.5	2150	1158
G-19	2000	1141	1970	1184	2150	1016.3	2173	1169
G-20	2100	1356	1999	1226	2162	1063.9	1793	886

Table 2. Density of Rantau Nangka claystones, tested from drill core samples

Spec. No.	Average		Weight	Density	Spec. No.	Average		Weight	Density	Spec. No.	Average		Weight	Density
	Diameter	Length				Diameter	Length				Diameter	Length		
	cm	cm	gr	Gr/cm^3		cm	cm	gr	Gr/cm^3		cm	cm	gr	Gr/cm^3
L-101	4.51	10.48	358.10	2.139	L-201	4.38	8.90	286.42	2.136	L-301	5.00	11.04	434.02	2.002
L-102	4.60	11.77	410.85	2.100	L-202	4.38	11.07	362.68	2.174	L-302	5.12	10.30	433.62	2.046
L-103	5.22	10.62	373.42	2.116	L-203	4.47	10.42	320.74	1.961	L-303	5.22	11.04	447.68	1.970
L-104	4.51	10.22	362.95	2.223	L-204	4.47	9.51	320.62	2.148	L-304	6.10	13.61	761.68	1.915
L-105	4.50	9.55	310.38	2.044	L-205	4.45	11.02	312.72	1.825	L-305	5.22	12.18	598.38	1.681
L-106	5.22	10.74	348.55	2.041	L-206	4.45	10.69	320.70	1.929	L-306	5.40	11.35	499.78	1.923
L-107	4.47	10.54	329.35	1.991	L-207	5.10	11.10	474.05	2.091	L-307	5.22	10.33	407.92	1.724
L-108	4.44	10.50	367.70	2.262	L-208	5.10	10.79	456.22	2.072	L-308	4.94	10.91	427.10	2.042
L-109	4.44	10.19	353.05	2.238	L-209	5.10	11.48	481.22	2.052	L-309	4.94	11.13	445.10	2.087
L-110	4.51	10.99	377.74	2.152	L-210	5.10	9.77	400.58	2.007	L-310	5.22	10.82	482.90	2.085
L-111	4.51	11.29	396.08	2.196	L-211	5.66	11.11	570.98	2.043	L-311	5.22	11.62	504.50	2.029
L-112	4.46	11.00	385.70	2.244	L-212	5.66	11.52	586.05	2.022	L-312	4.50	9.55	310.38	2.044
L-113	4.46	10.59	378.30	2.287	L-213	5.17	11.20	494.52	2.103	L-313	5.22	10.74	348.55	2.041
L-114	4.46	10.56	358.25	2.172	L-214	5.17	11.42	502.05	2.094	L-314	4.47	10.54	329.35	1.991

Table 2. Density of Rantau Nangka claystones, tested from drill core samples

Spec. No.	Average		Weight	Density	Spec. No.	Average		Weight	Density	Spec. No.	Average		Weight	Density
	Diameter	Length				Diameter	Length				Diameter	Length		
	cm	cm	gr	Gr/cm3		cm	cm	gr	Gr/cm3		cm	cm	gr	Gr/cm3
L-115	4.47	11.63	426.82	2.299	L-215	5.02	11.02	445.82	2.044	L-315	4.44	10.50	367.70	2.262
L-116	4.47	11.44	426.08	2.138	L-216	5.10	11.15	466.02	2.044	L-316	4.44	10.19	353.05	2.238
L-117	4.48	10.20	366.15	2.277	L-217	5.10	10.26	428.56	2.045	L-317	4.51	10.99	377.74	2.152
L-118	4.48	9.68	320.00	2.097	L-218	4.97	10.05	428.02	2.093	L-318	4.51	11.29	396.08	2.196
L-119	4.43	10.10	331.20	2.126	L-219	4.97	10.72	441.08	2.121	L-319	4.98	11.48	475.22	2.052
L-120	4.43	10.95	362.20	2.146	L-220	5.50	11.16	494.92	1.867	L-320	4.98	9.77	298.56	2.007

Table 3. Result of UPV tests for compressional and shear wave velocities

Spec. No	Vp	Vs	Spec. No	Vp	Vs	Spec. No	Vp	Vs
	m/sec			m/sec			m/sec	
L-101	2014.99	755.19	L-201	1998.54	630.32	L-301	1085.58	243.21
L-102	1857.05	663.64	L-202	426.62	202.53	L-302	1217.58	320.18
L-103	962.37	467.61	L-203	1862.71	434.53	L-303	1621.43	348.99
L-104	990.60	482.81	L-204	1046.14	320.18	L-304	1634.06	366.12
L-105	1073.68	482.91	L-205	1127.64	350.12	L-305	1696.54	370.47
L-106	1085.58	489.44	L-206	1879.19	448.19	L-306	3172.43	590.76
L-107	1093.75	489.59	L-107	1416.76	395.09	L-307	1798.57	412.63
L-108	2210.20	823.02	L-208	1968.17	561.10	L-308	1893.99	420.73
L-109	1144.94	499.02	L-209	1696.54	396.91	L-309	3280.42	655.62
L-110	1217.58	507.18	L-210	1763.44	425.48	L-310	1912.47	426.24
L-111	1812.29	611.11	L-211	1802.34	426.24	L-311	2730.16	428.81
L-112	1224.30	518.89	L-212	1843.41	432.16	L-312	2804.72	431.89
L-113	1344.71	519.84	L-213	1873.36	444.35	L-313	2898.44	456.99
L-114	1714.33	345.38	L-214	1357.02	371.73	L-314	955.02	232.96
L-115	884.86	527.81	L-215	1756.46	420.11	L-315	2983.78	477.21
L-116	1798.57	545.17	L-216	1912.47	477.21	L-316	3027.55	489.59
L-117	884.86	371.33	L-217	1917.19	506.74	L-317	1344.74	339.03
L-118	1798.57	590.76	L-218	1929.46	531.86	L-318	3050.89	495.38
L-119	866.61	352.18	L-219	376.66	183.21	L-319	3070.96	507.18
L-120	1835.88	655.62	L-220	1969.13	586.07	L-320	1763.44	371.11

V_{pL} is compressional wave velocity from laboratory tests and V_{pF} is compressional wave velocity from field insitu tests.

A correlation between shear wave from DHS (field insitu tests) and UPV test (laboratory tests) is established showing a power relationship as shown in Figure 5. The high regression coefficient reveals a strong correlation between the two velocities tests which enables estimation of one velocity having another one. The following equation defines this relationship:

$$V_{sL} = 0.0002V_{sF}^{2.1123} \quad \text{................................(eq. 11)}$$

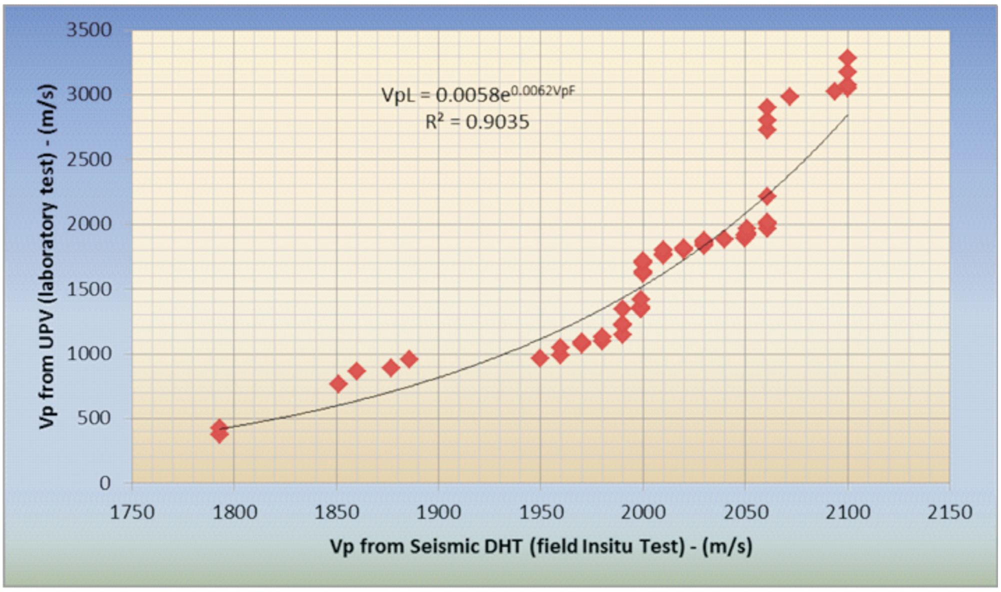

Figure 4. Correlation between V_p from seismic DHS and Vp from UPV tests

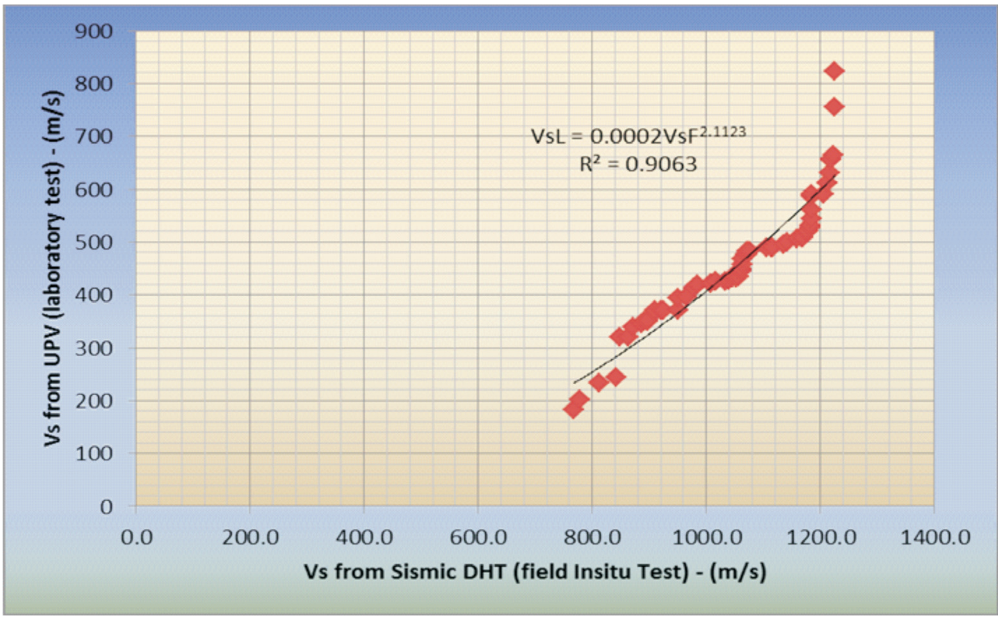

Figure 5. Correlation between V_s from DHS and Vs from UPV tests

V_{sL} is shear wave velocity from laboratory test and V_{sF} is shear wave velocity from field insitu test.

According to equation 1, 2, 5, 7 and 8, density of rock affects wave velocities (V_p and V_s), shear modulus (G), Lame constants and bulk modulus. Approximately, 60 tests results are used to determine claystone density, it is taken from drill core at 20-40 meters in depth. Based on equation 5, shear modulus from field insitu tests (G_F) and from laboratory tests (G_L) is shown in Figure 6.

From the correlation of G_F and G_L can be found the equation as follow :

$G_L = 0.2739G_F - 287185$........................ (eq. 12)

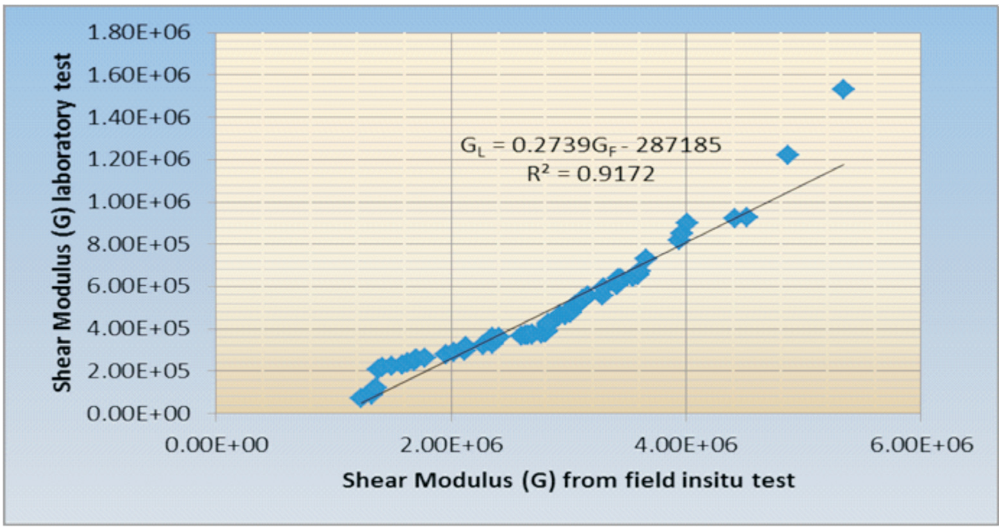

Figure 6. Correlation between shear modulus G_F and G_L

Using the same method to compare field insitu and laboratory tests for several parameters, i.e, the Elasticity Modulus (E_F and E_L), Bulk Modulus (K_F and K_L) and Lame Constants (λ_F and λ_L) are shown on Figure 7, 8 and 9.

Based on its correlations, it can be obtained the equation as follows:

E_L = 0.3764E_F - 1E + 06........................ (eq. 13)

$K_L = 1 \times 10^{-6} K_F^2 - 9.1889 K_F + 2 \times 10^7$ .... (eq. 14)

$\lambda L = 8 \times 10^{-7} \lambda_F^2 - 2.2325 \lambda_F + 4 \times 10^6$........ (eq. 15)

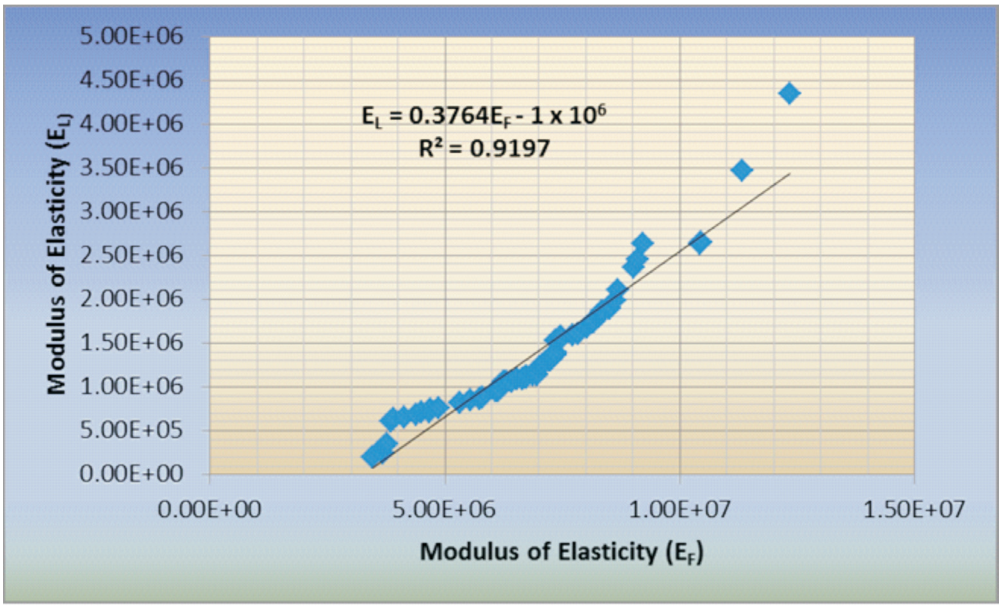

Figure 7. Correlation between elasticity modulus E_F and E_L

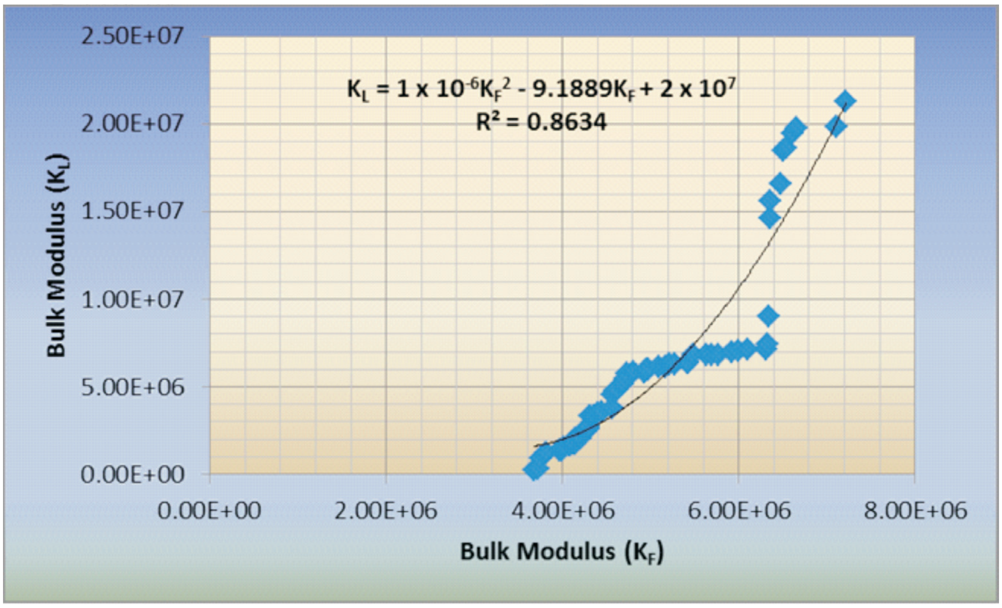

Figure 8 Correlation between Bulk Modulus K_F and K_L

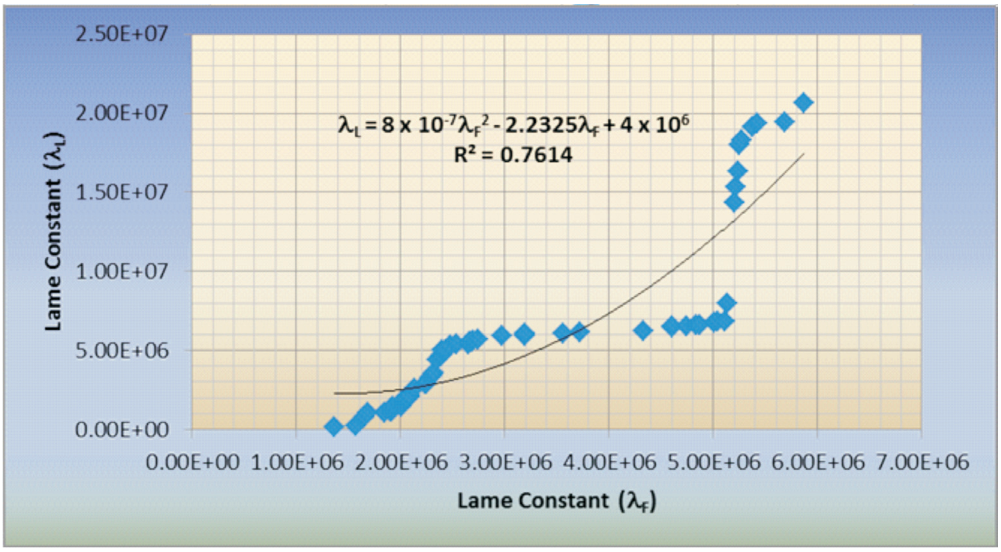

Figure 9. Correlation between Lame constant λ_F and λ_L

CONCLUSION

Compressional (Vp) and shear (Ps) wave velocities are important dynamic properties of rocks that can be measured both at field insitu and laboratory tests. The scale effect is significant to show whether the values decrease or increase that are obtained from the laboratory and field insitu tests. Decreasing or increasing of those values is a consequence of scale effect, which is caused by the heterogeneity of the materials. Vp and Vs determinations from field insitu tests are relatively more difficult and costly than that of laboratory tests. The high regression coefficient (R square more then 0.7) reveals a good correlation, which means that the high cost of field insitu measurements can be replaced by lower cost measurements in the laboratory. Direct measurement in the field insitu are considerably more accurate than measurement in the laboratory. The regression equation with high coefficient for each parameter that have been found in this study can be used as a corrected data of the laboratory tests results.

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