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Correlation of Dynamic and Static Young's Modulus for Limestone

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Abstract. The application of rock mechanics in the area of geotechnical engineering is important especially, in describing the strength of rock material for essessing the stability of excavations, foundations and slopes in rock. In this study, the characterization of the rock material was investigated through the Young's modulus parameter, which describes the relationship between the stress applied to the rock material and the resulting strain. For an elastic and homogeneous solid, the measurement of Young's modulus can be determined either from the static or dynamic measurements. Numerous studies outline the differences between the Young's modulus obtained from static and dynamic measurement in the laboratory. Comparatively, the measurement using static methods are more direct and realistic, as it describes the behaviour of rock deformation until failure occurs. The dynamic methods are more versatile and continuous, as they rely solely on the measurement of elastic wave velocities. However, one of the most notable disadvantages of rock material characterization by means of dynamic methods is that it overestimates the failure of rock material when compared to its actual value. With this in mind, the aim of this study is to obtain the measurements of Young's modulus using both the static and dynamic methods. Based on the comparison made, an empirical equation of $E_{st} = 0.9264 (E_{dy}) + 0.4976$ with coefficient of determination, R^2 of 0.8 is obtained for estimating the static Young's modulus for limestone. The equation is applicable in situation where static measurement could not be carried out, and also serves as reliable estimation of Young's modulus from dynamic measurement.

1. Introduction

Information on the mechanical properties of rock is of paramount importance in the study of rock mechanics, and it has been applied in several aspects of the geotechnical filed which includes rock slope stability and strength of foundations [1-5]. The Young's modulus describes the deformation stiffness of rock material under applied load. Two methods can be used to measure Young's modulus; i.e. static and dynamic methods. The static method involves direct measurement on the deformation of rock material under monotonically increasing axial load at confining pressures ranging from 1MPa and 15MPa.

[6] recommends three methods (Figure 1) to calculate the Young's modulus which are the tangent, average and secant method. The tangent Young's modulus, E_t is measured at stress level at some fixed percentage of the ultimate strength, generally taken at a stress level equal to 50% of the ultimate uniaxial compressive strength. Average Young's modulus, E_{av} is determined from the average slopes of the approximately straight line portion of the axial stress-axial strain curve, while secant Young's modulus E_s is usually measured from zero stress to some fixed percentage of the ultimate strength, generally at 50%. The selection of which calculation method to use, depends on design conditions. For example when design of rock engineering structure is associated with earthquake, secant Young's modulus (at 100 % ultimate stress) is normally used.

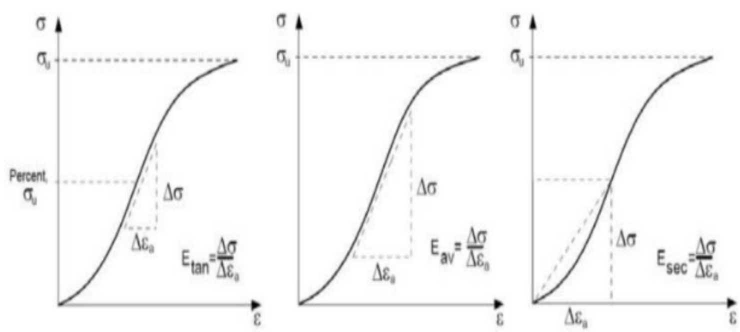

Figure 1. Three methods for calculating Young's modulus; tangent, average and secant method (after [7])

The dynamic measurement is an empirical method which involves measurement of the velocity of propagating elastic waves through rock sample (time taken for the elastic waves to travel from one end to the other end of the sample). [6] recommends three approach; high frequency, low frequency ultrasonic pulse, and resonant method. Selection of dynamic measurement depends on several factors such as length, shape and average grain size of the sample. To calculate the Young's modulus, 1- or 3-dimensional equations of wave propagations are used, as shown in the following equations:

$V_p = d.\ t_p^{-1}$ Equation (1)
$V_s = d.\ t_s^{-1}$ Equation (2)

where, V_p is the P-wave velocity, V_s is the S-wave velocity, t_p and t_s are the time taken by P- and S-wave to travel through a distance d (length of sample), respectively.

2. Material and Methods

Limestone samples were collected from Gua Kandu, and Gunung Rapat in Ipoh, Perak (Figure 2). Core samples with height to diameter of 2 : 1 were cored with both end surfaces lapped to the required conditions. The static measurements were conducted by using the multistage triaxial compressive strength test which were carried out in the Rock Mechanics and Rock Physics Laboratory, Universiti Teknologi PETRONAS (UTP). The multistage triaxial compression test provides a measure of the compressive strength and stress-strain characteristics by simulating *in-situ* confining pressures, and measuring the corresponding deformation characteristics of the samples. The test was performed over a range of confining pressures between 1 MPa and 15 MPa to define the limestone material strength envelope according to the recommendation of [8]. The apparatus used for the triaxial test is IPC Global RT-1000 (Figure 3). During the test, the confining pressures were set constant while the axial stress were increased gradually until the sample approached its maximum peak strength and failed.

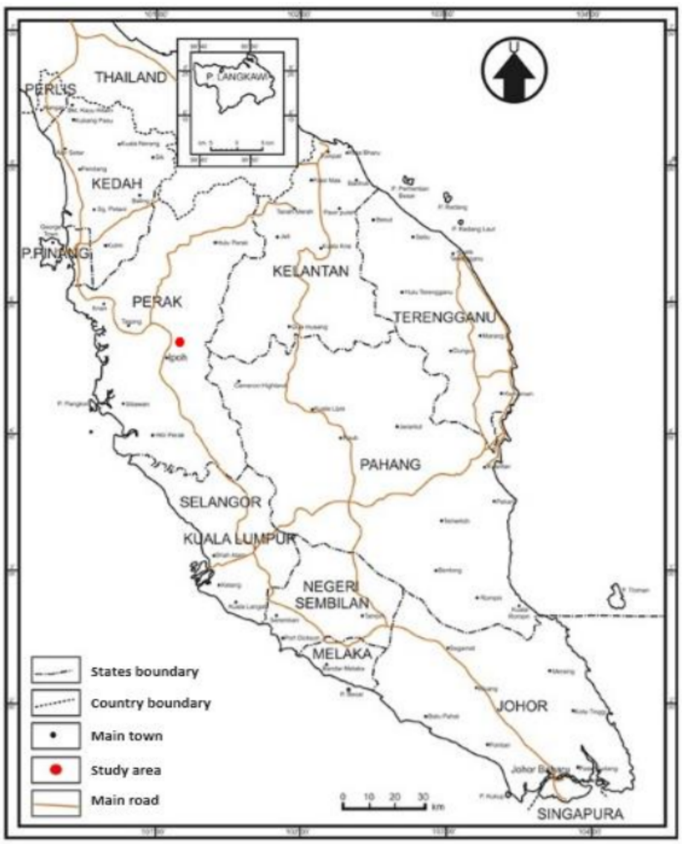

Figure 2.Location of study area is in Ipoh, Perak

The dynamic measurement was conducted by using the Autolab 500 manufactured by Coretest Systems, Inc. (Figure 4) which were carried out at Rock Mechanics and Rock Physics Laboratory, Universiti Teknologi PETRONAS (UTP). The Autolab 500 is an automated triaxial compression test intended to measure P-wave velocity and S-wave velocities of rock samples under simulated pressure. The core sample dimensions were measured at 2 inch x 1 inch (height: diameter). The ends of core samples were trimmed to smooth and flat surfaces to permit maximum transmission of wavelength from the transducers. Samples were placed inside two pressure vessels that was separated by a moveable piston. The pressure in each chamber was controlled with high pressure, servo hydraulic intensifiers. Overburden pressures on the rock were developed in the lower chamber. A differential stress was exerted on the sample when pressure in the top chamber is greater. Data was displayed in waveform, and propagation time were read out from the waveform with a high degree of accuracy.

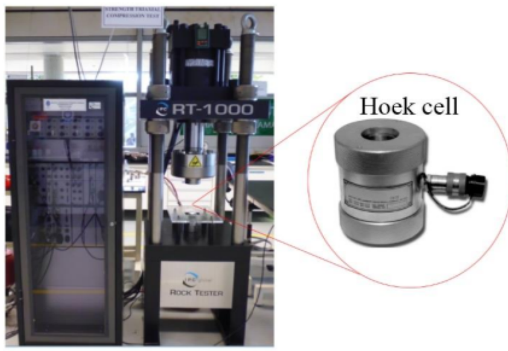

Figure 3.RT-1000 to conduct the triaxial compression test.

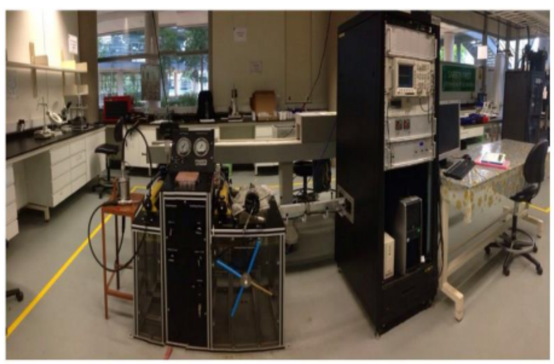

Figure 4. Autolab 500 to measure P-wave and S-wave velocity under simulated pressure

3. Results and Discussion

A total of 15 static and dynamic tests were conducted. The multistage triaxial compression test were conducted over the range of confining pressures of 1 MPa to 15 MPa. The axial stress-axial strain curve were plotted and Young's modulus were calculated by using all three methods. Table 1 summarizes the values of Young's modulus obtained from static and dynamic methods.

In overall, the minimum, maximum, median, standard deviation and average dynamic Young's modulus (E_{dy}) were 6.6 GPa, 9.9 GPa, 9.6 GPa, 0.9 GPa and 9.2 ± 0.5 GPa respectively. The minimum, maximum, median, standard deviation and average Young's modulus obtained using the tangent method were 6.6 GPa, 11.7 GPa, 10.1 GPa, 1.3 GPa and 9.9 ± 0.7 GPa respectively. The minimum, maximum, median, standard deviation and average Young's modulus obtained using the average method were 6.8 GPa, 10.4 GPa, 9.2 GPa, 0.9 GPa and 9.0 ± 0.6 GPa, while the minimum, maximum, median, standard deviation and average Young's modulus obtained using the secant method were 5.0 GPa, 10.2 GPa, 8.1 GPa, 1.4 GPa and 8.0 ± 0.8 GPa respectively. Table 2 summarized the statistical analysis results of dynamic Young's modulus (E_{dy}) and static Young's modulus using tangent, average and secant method.

Figure 5 shows the boxplots of dynamic Young's modulus and static Young's modulus based on the tangent, average and secant method. By looking at the boxplot, the skewness for all the modulus data is negative. This means that more data at the study area has a higher value of Young's modulus than the average value.

Table 1. Summary of Young's modulus values obtained from static and dynamic methods

Sample	Dynamic (GPa)	Static		
		Tangent (GPa)	Average (GPa)	Secant (GPa)
GK 5-5 (1)	8.8	10.1	8.5	7.2
GK 5-5 (2)	9.8	11.7	9.8	8.4
GL-K3 (1)	9.9	9.1	9.3	8.9
GL-K3 (2)	9.6	10.3	9.9	10.2
GL-K3 (3)	9.9	11.7	10.4	9.8
GL-K5 (1)	6.6	8.4	6.8	6.6
GL-K5 (2)	7.6	6.6	7.2	8.1
GL-K6 (4)	9.3	9.3	8.8	6.6
GL-K5 (4)	9.5	9.5	9.2	5.0
GL-K5 (6)	8.7	9.9	8.5	7.2
GL-K6 (1)	9.0	10.4	9.6	7.5
GL-K6 (2)	9.6	10.8	8.6	9.0
GL-K6 (3)	9.8	9.5	9.4	9.5
GR-K1 (1)	9.8	11.2	9.1	8.4
GR-K1 (2)	9.9	10.5	10.1	7.9

The differences between the static and the dynamic values were determined by analyzing the percentage difference between the two methods. It can be concluded that the percentage difference between dynamic Young's modulus and static Young's modulus calculated using tangent, average and secant method were 6.6%, 2.1% and 17.7%, respectively. The results show that the values of static Young's modulus calculated using the average method has higher similarities with dynamic Young's modulus values. Table 3 summarized the percentage difference between dynamic and static Young's modulus calculated using tangent, average and secant method.

Table 2. Summary of statistical analysis results of dynamic and static Young's modulus

Young's Modulus	No.	Min. (GPa)	Max. (GPa)	Median (GPa)	Standard Deviation (GPa)	Mode (GPa)	Average (GPa)
Dynamic	15	6.6	9.9	9.6	0.9	9.5 – 10.0	9.2 ± 0.5
Tangent	15	6.6	11.7	10.1	1.3	9.0 – 11.0	9.9 ± 0.7
Average	15	6.8	10.4	9.2	0.9	8.5 – 9.5	9.0 ± 0.6
Secant	15	5.0	10.2	8.1	1.4	7.0 – 9.0	8.0 ± 0.8

Based on the percentage difference, the value of the Young's modulus derived from the average method was chosen as the static modulus (E_{st}) value since the value does not deviates much from the dynamic modulus value (E_{dy}). A linear equation of $E_{st} = 0.9264 (E_{dy}) + 0.4976$ with the determination of coefficient, R^2 of 0.8 is proposed to estimate the value of static Young's modulus from dynamic measurement. Figure 6 shows the proposed correlation.

Table 3. Summary of percentage difference between dynamic and static Young's modulus

Sample	Percentage difference between dynamic and static Young's modulus		
	Tangent (%)	Average (%)	Secant (%)
GK-5-5 (1)	-13.0	3.2	22.4
GK-5-5 (2)	-16.5	-0.5	16.1
GL-K3 (1)	9.7	7.4	11.9
GL-K3 (2)	-7.5	-3.3	-5.8
GL-K3 (3)	-15.1	-4.3	2.0
GL-K5 (1)	-20.8	-2.8	0.0
GL-K5 (2)	15.3	5.4	-6.0
GL-K6 (4)	-0.1	5.9	40.5
GL-K5 (4)	0.8	3.7	90.6
GL-K5 (6)	-12.8	1.9	21.1
GL-K6 (1)	-13.4	-5.7	20.1
GL-K6 (2)	-11.5	11.4	6.6
GL-K6 (3)	3.8	4.0	3.5
GR-K1 (1)	-12.6	7.7	17.5
GR-K1 (2)	-5.4	-1.7	25.2
TOTAL	**-6.6**	**2.1**	**17.7**

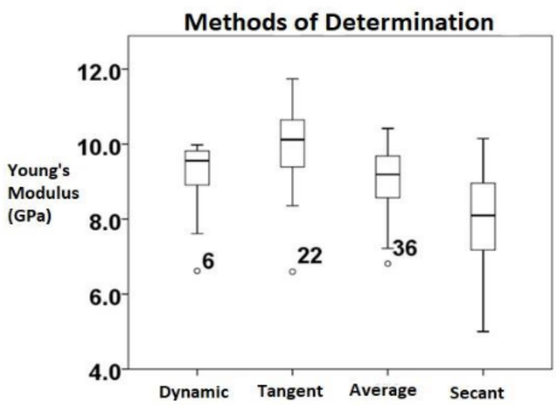

Figure 5. Boxplots of dynamic Young's modulus and static Young's modulus based on the tangent, average and secant method.

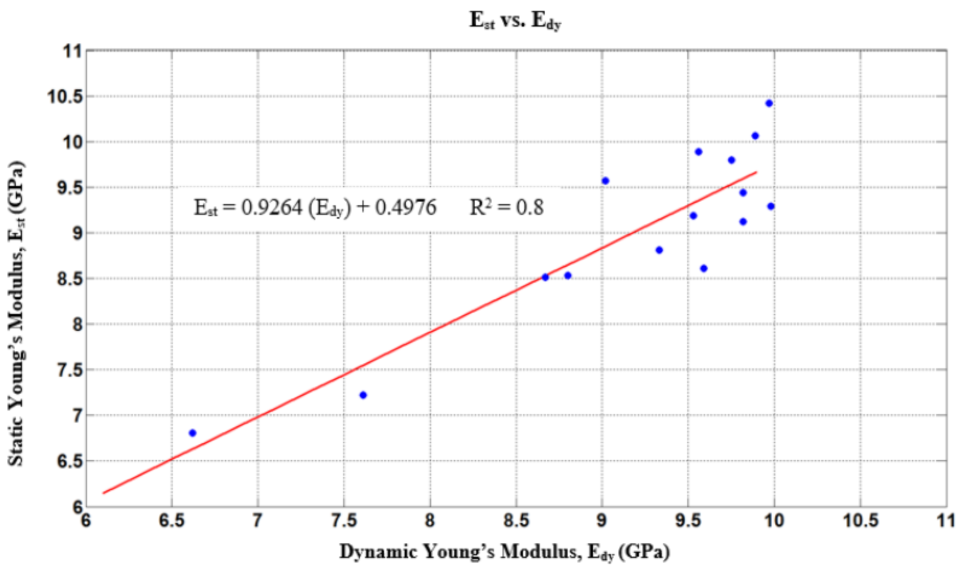

Figure 6. Proposed linear equation $E_{st} = 0.9264$ (E_{dy}) + 0.4976 (with $R^2 = 0.8$) for estimating static Young's modulus from dynamic measurement.

4. Conclusions

A total of 15 sets of multistage triaxial compression test and ultrasonic velocity test were conducted on limestone samples. From the analysis of the axial stress-axial strain curves, the static Young's modulus (calculated based on the average method) relates more reliably with the dynamic values as compared to the tangent and secant method. Correlation equation $E_{st} = 0.9264$ (E_{dy}) + 0.4976 has been proposed for estimating the value of static Young's modulus from dynamic measurement. This study presents a useful and reliable approach for estimating static Young's modulus without the need for carrying out static measurement in the lab.

5. Acknowledgements

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