Characterizing P-Wave Velocity and Elastic Properties of Sedimentary Rocks for Foundation of Building

Nurul Huda Abdullah and Nur Nabila Sazaly
Faculty of Civil Engineering,
Universiti Teknologi MARA,
40450 Shah Alam, Selangor

Haryati Awang & N.H. Hamid
Institute for Infrastructure Engineering and Sustainable Management, Faculty of Civil Engineering,
Universiti Teknologi MARA,
40450 Shah Alam, Selangor

ABSTRACT

The aim of this paper is to develop empirical models based on laboratory experimental works using a number of rock samples using seismic velocity parameters and deformation properties. Furthermore, it is very important to express the relationship between elastic properties and seismic velocity of tropical sedimentary rocks which can be used for construction of foundation building. Ultrasonic pulse velocity test (UPV) is used worldwide to measure ultrasonic wave velocity which able to penetrate through intact rock and the wave travel time is depending on the particle arrangement of rock microstructure. Elastic properties of rock such as Young modulus, shear modulus and bulk modulus can be determined by conducting uniaxial compressive strength test (UCS) with deformation measurement. The results between the P-wave velocity were correlated and regression equations were established to present the correlation between them. Regression analysis (R^2) shows that the correlation values of P-wave and Young modulus, shear modulus and bulk modulus at 0.63, 0.61 and 0.60, respectively. It can be concluded that from the relationship of P-wave and elastic properties parameters, the result of allowable soil bearing pressure can be used for design foundation building and the laboratory analysis of samples is used to predict P-wave velocity.

Keywords: *P-wave Velocity, Elastic Properties, Sandstones, Allowable Bearing Pressure, Shear Modulus, Bulk Modulus*

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Introduction

Recently, Malaysia experiences drastic development in the construction of medium and high rise buildings especially the city centre due to increases in population, employment, educations and business. The office buildings, commercial buildings and residential apartments have highly demand to fulfil the purpose of migration from rural areas to Kuala Lumpur as the capital city of Malaysia. The medium and high rise RC buildings must be designed to cater for vertical loads including dead load and imposed load and safely transfer to the foundation of the building. The ability of the structure to sustain the applied loads from superstructures of the building depends on the soil condition and types of foundation buildings.

Foundation building on the rock is part of engineered systems for any buildings to transmit the load from superstructures to substructures including the foundation buildings which underlying rock. The thickness of the pile cap of the foundation using either precast concrete piles or Bakau piles needs to carefully design to cater for high vertical load. Despite of physical properties of rock are strong and stable behaviour but a jointed rock mass under unconfined condition with very low bearing capacity can cause the rock mass collapse under its self-weight. Without a proper detailing design and poor construction of the foundation, the building will encounter some structural problems such as cracking of floor slab and wall, settlement foundation of the building and to some extent, the whole building can collapse within its design life. The collapsed of building might be to natural disasters such as earthquake, landslide, tsunami and typhoons. Therefore, the determination of mechanical and physical rock properties is essential before any construction of building take place as well as to maintain the safety starting from construction until life span of the buildings.

Advanced characterization techniques by applying non-destructive techniques (NDT) such as ultrasonic wave velocity is one of the available method to determine the characteristics of a rock at any particular site. Ultrasonic wave velocity is the measurement of the acoustic wave propagation concerning time depends on the particle arrangement of rock microstructure. The use of P-wave technology to measure the P-wave velocity of rock is a relatively simple task because the portable equipment can be used in the laboratory or in the field without tedious preparation of rock cores and it is non-destructive test. This test method is reliable to establish a correlation between P-wave velocity and rock engineering properties [10].

Many researchers found out that the P-wave velocity in the rock has a very closely relationship of rock properties [1,4,9,10,15]. Further studies on the various velocities and elastic parameters of sandstones as a function of allowable bearing capacity were also carried out [8]. The uniaxial compressive strength of the joint mass rock has always been considered as a more reliable index for strength estimation of rocks and commonly used in establishing the bearing capacity of the rock mass [12].

Table 1 tabulates the S-wave velocity, factor of safety and allowable bearing pressure for hard rock and soft weak rock. If the S-wave velocity is bigger than 4000 m/s, the rock can be classified as 'hard' rock and if S-wave velocity is between 750 to 4000 m/s, the rock is categorized as 'soft' weak rock. Other researcher determined the factors of safety based on the allowable bearing pressures for various rock types [13]. They also discovered that there is a direct relationship between the P-wave velocity, v_p and the average unit weight, γ of the rock material as defined in Equation 1:

$$\gamma = \gamma_o + 0.002v_p \tag{1}$$

where γ = the unit weight in kN/m^3 based on P-wave velocity; v_p= P-wave velocity in m/s; γ_o=18kN/m^3 for limestone, mudstone conglomerate, claystone; γ_o=20kN/m^3 for greywacke, schist, tuff and cracked sandstone; γ_o= 24 kN/m^3 for hard rocks.

Table 1: Factor of safety and allowable bearing pressure based on types of rocks [8]

Rock type	S-wave velocity, v_s(m/s)	Factor of safety, n	Allowable bearing pressure, q_a(kN/m^2)
'Hard' rock	$v_s \geq 4000$	n = 1.4	$q_a = 0.071\ \gamma\ v_s\ /n$
'Soft' weak rock	$750 \leq v_s \leq 4000$	n = 4.6-0.008v_s	$q_a = 0.1\ \gamma\ v_s\ /n$

Therefore, the primary objective of this study is to determine the relationship between seismic velocity and elastic properties which are Young's modulus, shear modulus and bulk modulus of sedimentary rocks. Additionally, the correlation between them can be extended to determine the allowable bearing pressure in foundation design perspective, especially for sandstones using empirical methods.

Materials and Methods

General Geology

The proposed study site to determine the P-wave velocity of the rock is located at Puncak Perdana, Shah Alam, Selangor, Malaysia as shown in Figure 1. Based on the geological map, the study area underlain by Kenny Hill Formation which was estimated in the range of 1200 m to 1500 m thick that covered in several places, notably towards the south of Kuala Lumpur, starting from Petaling Jaya and Puchong to Kajang and Putrajaya [11]. One of the common Kenny Hill formations were sedimentary structures rocks. The sedimentary rocks consist predominately of limestone, sandstone, soft-sediment deformation, graded bedding and some organic tubes. For most sandstone beds, cross-bedding is conspicuously absent. Flattened and stretch clay pebbles also observed in some sandstone beds. The thickly bedded fine to medium-grained quartzose sandstone is of a light yellowish colour [6].

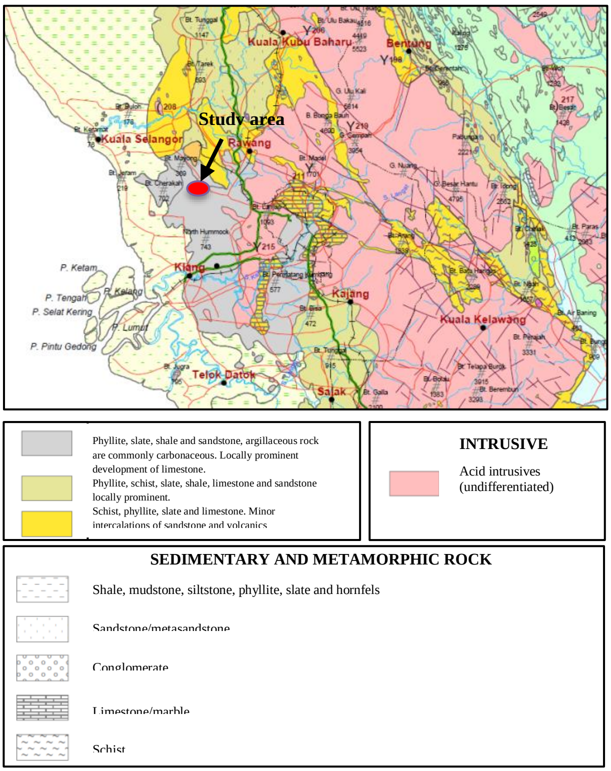

Figure 1: Geological map of the study area [11].

Sample Preparation

The rock samples were collected from the Puncak Perdana area, Shah Alam, Selangor as shown in Figure 1. A total number of eight samples of sandstones were bored and collected during site investigation works using the boreholes drilling method as shown in Figure 2. The preparation of samples carefully handled because it might break during cutting and trimming processes. The collected samples are representing the parent rock mass which the properties are to determine in this study. The particular shape and size of the sample performed by the ISRM standard [7]. Normally, the size of the specimen which is in between 54mm diameter and the height is two times of diameter. In foundation engineering practices, laboratory tests of rock cores can be obtained by rotary drilling usually limited to uniaxial compressive tests (UCS). The main objective of UCS analysis is to determine the uniaxial compressive strength and the deformability of rock samples. Subsequently, ultrasonic pulse velocity test (UPV) was used to obtain P-wave velocity.

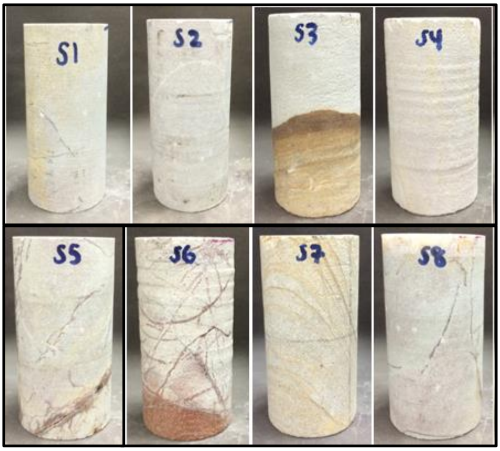

Figure 2: Cored samples of sedimentary rocks collected at Puncak Perdana.

Ultrasonic Pulse Velocity test (UPV)

Portable Ultrasonic Non-Destructive Digital Indicating Tester (PUNDIT) is a flexible instruments test which designed primarily to measure ultrasonic velocity and to determine several important elastic properties of rock. Furthermore, PUNDIT is easy to operate, lightweight and portable with high order of accuracy and stability. It also provides adequate measurements of acoustic wave propagation time. PUNDIT equipment consists of an ultrasonic instrument comprising an electronic timing device, pulser or transmitter, echo amplifier (receiver) as shown in Figure 3. The testing procedure can be conducted based on the ASTM standard [3].

The PUNDIT apparatus can generate an ultrasonic pulse with a frequency between 20 kHz to 150 kHz and it can measure the transit time for transmitting transducer through the sample to the receiving transducer by displaying it in form numerical indicator tubes. Coolant gel was applied at the rock specimen’s surface before any testing take place. However, the surface of the sample needs to be cleaned from debris and removed all the sharp and rough edges before testing it. The clean and smooth surfaces can ease the testing, and can lead to accurate and precise in results.

The mode of propagation of a P-wave velocity is always longitudinal in isotropic and homogeneous solids. Therefore, the particles in the solid have vibrations along or parallel to the travel direction of the wave energy. Equation 2 can be used to determine the P-wave velocity of the rock which is expresses in term of bulk modulus, shear modulus and density in a homogeneous isotropic medium:

$$v_p = \sqrt{\frac{K + \frac{4G}{3}}{\rho}} \tag{2}$$

where v_p= P-wave velocity (m/s); K = bulk modulus (kN/m^2); G = shear modulus (kN/m^2); ρ = density (kN/m^3)

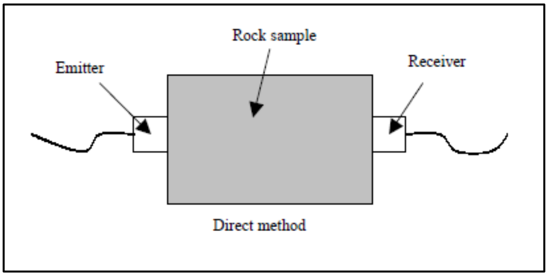

Figure 3: Schematic diagram of P-wave velocity measuring equipment (the PUNDIT).

Meanwhile, the velocity of S-wave velocity is determined by the elastic constant and mass density of the material which is given in Equation 2:

$$v_s = \sqrt{\frac{G}{\rho}} \tag{3}$$

where v_s= S-wave velocity (m/s); G = shear modulus (kN/m^2); ρ = density (kN/m^3)

Uniaxial Compressive Strength test (UCS)

UCS testing is used to determine the uniaxial compression strength and deformability characteristic of rock specimens. This test can determine the stress and strain value for the rock samples. The detailed procedure of UCS test referring to ASTM standard [2]. UCS has been conducted using Universal Testing Machine (UTM) of 100 tonnes capacity with incremental loading at a nearly constant rate. Test specimens shall be right from core not less than the NX core size approximately 54 mm having the 2:1 length to diameter ratio confirms with generally recommended for the compression test [2]. Load of the specimens were applied continuously at a constant rate until its failure whereby the sample is deformed. Figure 4 shows the axial and the radial deformation of the cylinder sample before and after testing. Strain gauges were glued to the cylinder sample to measure the strain when axial load was applied to the rock sample. Hairline cracks and crushing of sample was observed after the experimental work was completed.

Figure 4: The samples tested before and after testing condition.

Analysis of Tests

The method of least squares regression was used to analyse the experimental results. Based on the results, the power relationship between Young's modulus, shear modulus and bulk modulus and P-wave velocity was established and formulated. The correlation for elastic properties and P-wave velocity of the tested rocks are using regression equation. Curve lines and the correlation coefficient (R^2) are determined for each regression. Best-fitted relations were considered to be straight lines for all cases.

The preliminary design of foundation building proceeds after the allowable bearing pressure obtained in that particular area. A corresponding empirical relationship, which used for soft weak rock is defined in Equation 4:

$$q_a = 0.1\,\gamma\,v_s\,/n \qquad (4)$$

Where q_a is the allowable bearing pressure, n is the safety factor, v_s = S-wave velocity and γ is the density of the soft weak rock.

Results and Discussions

Correlation between Elastic Properties and P-Wave Velocity

Table 2 shows the elastic properties of eight numbers of samples which collected at site. The elastic properties of the rocks were Young Modulus, Shear Modulus and Bulk Modulus. The P-wave velocity and uniaxial compression strength also measured for each specimen. Four samples were classified as hard rock and six samples were ‘soft’ weak rock. The hard rock samples have higher compressive strength as compare to ‘soft’ weak rock. A similar pattern and behaviour goes to Young Modulus, shear modulus and bulk modulus.

Table 2: Results of the P-wave velocity, UCS and other elastic properties of rock samples

Sample No	P-wave velocity, v_p (m/s)	UCS (MPa)	Young's modulus, E (GPa)	Shear modulus, G (GPa)	Bulk modulus, K (GPa)
1	5210.4	41.57	24.8	9.13	23.07
2	5210.4	44.56	24.54	10.89	10.95
3	779.8	11.05	38.09	0.91	2.74
4	3312.8	5.19	3.17	1.23	2.52
5	2924.2	9.13	6.91	2.76	4.70
6	4808.8	88.78	14.9	5.70	12.90
7	4679.2	76.04	8.98	3.30	10.85
8	1577.8	11.70	5.70	2.35	3.28

The method of least squares regression was used to analyse the experimental result. Based on the results, the power relationship between Young’s modulus, shear modulus, bulk modulus and P-wave velocity was found and illustrated in Figure 5 to Figure 7. The regression equation and correlation made between elastic properties and P-wave velocity of the tested rocks shown in Table 3. Also, the equation of the curve line and the correlation coefficient (R^2) determined for each regression. The best-fitted relations were considered to be straight lines for all cases.

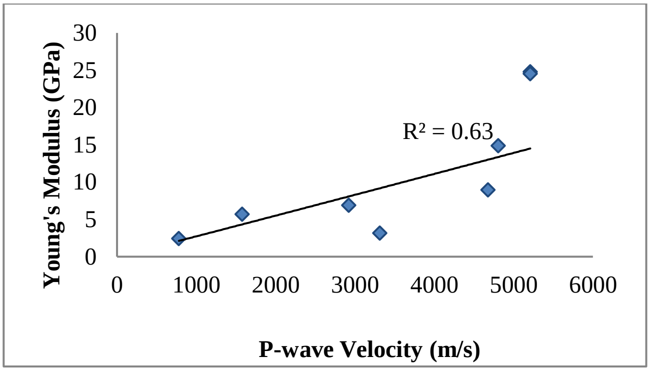

Figure 5: Correlation of Young's modulus and P-wave velocity.

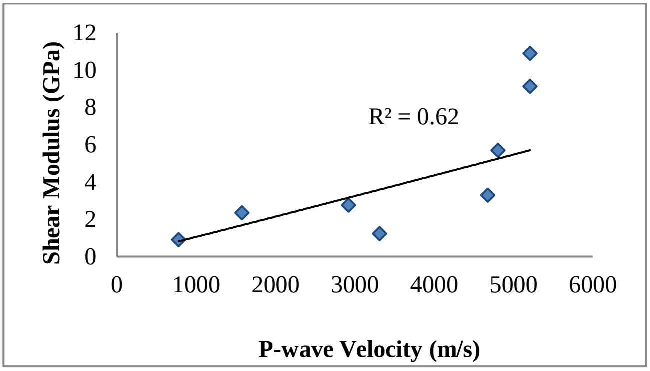

Figure 6: Correlation of Shear modulus and P-wave velocity.

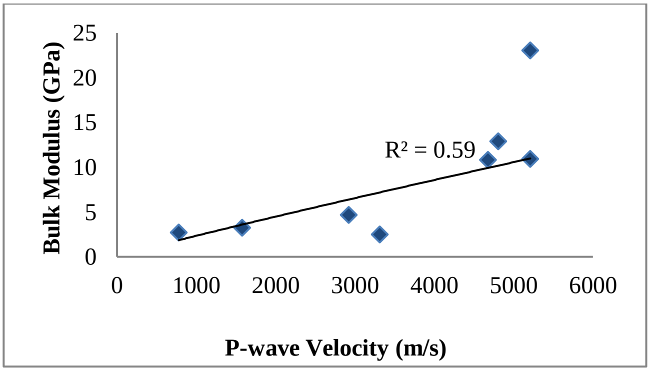

Figure 7: Correlation of Bulk modulus and P-wave velocity.

Table 3: Regression analysis results

Parameters to be related	Regression equation $y = cx^b$	R^2
Young's modulus and P-wave velocity	$y = 0.0025x^{1.0123}$	0.63
Shear modulus and P-wave velocity	$y = 0.0009x^{1.0222}$	0.61
Bulk modulus and P-wave velocity	$y = 0.0037x^{0.9348}$	0.60

In general, the elastic modulus increases with the increase in P-wave velocity. Relatively good correlation values obtained between P-wave velocity and Young's modulus, the shear modulus and bulk modulus of R^2 to be 0.63, 0.61 and 0.60, respectively. The results show there are power relations between P-wave velocity and the elastic properties tested of the rocks. Thence, the straight regression lines represent a relatively good correlation between elastic properties and P-wave velocity of the tested rocks. The test results agreed with Altindag [1] and the result approximate of the finding.

Relationship between P-wave Velocity and Allowable Bearing Pressure of Foundation Design

Since the P-wave and S-wave velocities are measured, it is no need to do the testing in the laboratory and including extensive borehole data. Based on a relatively simple empirical expression, the allowable bearing pressure and the approximate value of the unit weight were determined rapidly. Apart from that, S-wave velocity can be measured from the following relationship as stated in Equation 3. Table 4 shows the allowable bearing pressure value determined from P-wave velocity. The preliminary design of foundation proceeds after the allowable bearing pressure obtained in that particular area. A corresponding empirical relationship, which used Equation 4 stated above.

Table 4: Allowable bearing pressure based on P-wave velocity of sandstone

Sample No	P-wave velocity, v_p(m/s)	Density, ρ (N/m²)	S-wave velocity, v_s (m/s)	Unit weight, γ (kN/m³)	Allowable bearing pressure, q_a(kN/m²)
1	5210.4	1519.9	2451.49	30.42	3728.81
2	5210.4	942.60	3413.01	30.42	5191.32
3	779.8	6501.25	374.13	21.56	403.30
4	3312.8	379.06	1801.36	26.63	2398.12
5	2924.2	980.01	1678.18	25.85	2168.92
6	4808.8	886.50	2535.70	29.62	3755.06
7	4679.2	696.51	2176.68	29.36	3195.19
8	1577.8	2576.20	955.09	23.16	1105.78

Conclusions

The results indicate that a significant correlation between P-wave velocity values and Young's modulus; shear modulus and bulk modulus of sedimentary rocks which developed the following empirical equations agreed by other researchers [1,4,9,10,12,15]. Besides, the test results were significant linear relationships with R^2 of 0.63, 0.61 and 0.60 respectively. As a conclusion, the equation agreed with the previous study using the soft rock to estimate the allowable bearing pressure used in preliminary foundation design. The equations obtained in this study are practical and accurate enough to apply and recommended for use in practice.

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