Determination of Shear Wave Velocity in Offshore Terengganu for Ground Response Analysis

M Mazlina 1,2, M S Liew 1, A Adnan 3, I S H Harahap 1, N A Hamid 2
1 Civil and Environmental Department, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia
2 Faculty of Civil Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
3 Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia
E-mail: maz_3116@yahoo.com

Abstract. Amount of vibration received in any location can be analysed by conducting ground response analysis. Even though there are three different methods available in this analysis, One Dimensional ground response analysis method has been widely used. Shear wave velocity is one of the key parameters in this analysis. A lot of correlations have been formulated to determine shear wave velocity with cone penetration test. In this study, correlations developed for Quaternary geological age have been selected. Six equations have been adopted comprise of all soil and soil type dependent correlations. Two platforms sites consist of clay and combination of clay and sand have been analysed. Shear velocity to be used in ground response analysis has been obtained. Results have been illustrated in graphs where shear velocity for each case has been plotted. In avoiding under or over predicting of shear wave velocity, the average of all soil and soil type dependent results will be used as final Vs value.

1. Introduction
In structural design, the importance of ground response analysis (GRA) is very pronounced. GRA allows vibration in soil strata at any location being measured. From this analysis, requirement of structural resistance against horizontal load from seismic can be predicted. Amongst all, 1 Dimensional nonlinear method is widely used in ground response analysis. In order to conduct this analysis, one of the key parameters is shear wave velocity. Shear wave velocity (Vs) can be defined as the propagation velocity of shear wave through any medium (except for liquid and gasses) in all directions. The velocity will vary depending on the variation of density and elasticity of the medium along the direction of movement [1]–[6]. Shear wave velocity will be higher in rock as it will have low amplification factor. In softer soil, shear velocity will be lower where higher amplification factor will be produced. Therefore, to obtain Vs, site soil investigation will be conducted.

Shear wave velocity can be directly obtained from in-situ test or from available empirical correlations as proposed by previous researchers [7]–[10]. The usage of cone penetration test (CPT) in the investigation of offshore area is common and already being developed for four decades [11]. Same method with a little advancement on CPT has been applied in investigating soil in offshore Terengganu. The geotechnical investigations have been conducted by using Piezo Cone penetration test (CPTu), where only cone resistance (qc), penetration pore water pressure (u2) and sleeve friction (fs) can be obtained from in-situ test. In addition, direct measurement of shear wave velocity is not
available. Therefore, another option has to be chosen where shear wave velocity will be determined using correlation equations. However, due to lots of correlation available, selection of appropriate equations to replicate the shear wave velocity is required. Thus, this study is focusing on determining shear wave velocity based on CPT-Vs correlations which have been developed for Quaternary age, implemented for general and soil type dependent group.

Six developed correlation equations have been used in calculating shear wave velocity. It can be divided into two groups which are general (all soil) and soil type dependent groups (for clay and sand). These equations were developed based on \( q_c \) and \( f_s \) parameters. Two sites have been chosen where Site A has combination of clay and sand while Site B comprises of clay only. Data such as soil profile, cone tip resistance and sleeve friction has been extracted from soil investigation report. Calculations of shear wave velocity have been performed using selected correlation equations for Site A and B and comparisons have been made. Then, the final shear wave velocity to be adopted in ground response analysis will be determined.

Avoiding under and over design is among the main objectives in structural design. In under designed circumstances, the structure might fail due to excess load while overdesigned will cause waste of valuable resources. Therefore, it is essential to get the reasonable value for shear wave velocity in avoiding under and over design structure. Furthermore, these Vs will be used in conducting GRA which will produce results that will be used in structural design especially under seismic event.

2. Literature Review

This section has been divided into two subsections which are ground response analysis and CPT-Vs correlations. Summary of literature reviewed has been presented in each subsection.

2.1. Ground Response Analysis

Ground Response Analysis (GRA) method can be classified in three groups, which are 1-Dimensional (1D), 2-Dimensional (2D) and 3-Dimensional (3D) shear wave propagation methods. 2D and 3D methods will only be implemented under special request as more input data will be required [12]. In contrast with 2D and 3D, 1D method has been practically used worldwide as well as in the engineering structure’s code of practice when related to seismic. Equivalent linear or nonlinear methods will be used to replicate nonlinearity of stratigraphy in soil. In comparison with 2D and 3D, this method has been simplified where only thickness is measured while length of soil will be excluded and soil boundaries will be considered horizontal [13]. Therefore, in analysing seismic effect, this 1D ground response analysis will be conducted on platforms in Terengganu.

Currently, 1D GRA can be conducted using developed programs. NERA (Nonlinear Earthquake Site Response Analyses of Layered Soil Deposits) is one of the available programs developed for nonlinear site response analysis. It is the upgraded version of EERA (Equivalent-linear Earthquake site Response Analyses of Layered Soil Deposits) which is an equivalent linear program that has been developed earlier. NERA has been selected due to the advantages that have been elaborated in previous researches [14], [13], [15] and NERA has been used in analysing ground response for onshore area in Malaysia and Indonesia. In this study, this program will be adopted to analyse ground response for Terengganu offshore area. Soil type, depth, total unit weight and shear wave velocity are among the key parameters in using NERA. All of these can be extracted from the soil investigation report except for shear wave velocity since resulting from the usage of CPTu in these offshore site investigations. In fact, CPTu are normally used in investigating the soil for offshore area. In solving this problem, determination of shear wave velocity through correlation equations is required. The in-situ results will be used to calculate shear wave velocity based on CPT-Vs correlation. Further discussions on CPT-Vs correlation have been provided in next subsection.

2.2. CPT-VS Correlations

In determining shear velocity, two main correlations have been developed based on Standard Penetration Test (SPT)-Vs and CPT-Vs correlations. These correlations will depend on geological age
and type of soil. However, only CPT-Vs correlation will be covered in this study since the available data are from CPTu. Part of the geological age is depicted in Figure 1.

| E O N | PERIOD       | EPOCH       |
|------|--------------|-------------|
|      | QUATERNARY   | HOLOCENE    |
|      | TERTIARY     | PLEISTOCENE |
|      | NEOGENE      | PLIOCENE    |
|      | PALEOGENE    | MIOCENE     |
| Mesozoic |          | OLIGOCENE   |
|        |              | EOCENE      |
|        |              | PALEogene   |
|        | CRETACEOUS   | 23.7M       |
|        | JURASSIC     | 36.6M       |
|        | TRIASSIC     | 57.8M       |
|        |              | 66.4M       |
|        |              | 144M        |
|        |              | 208M        |
|        |              | 245M        |

**Figure 1.** Geologic time scale [16]

Two methods have been suggested by Wair et al. [12] in determining Vs from CPT-Vs correlation, where selected correlation can be general (for all soil) or soil type dependent. Soil type dependent hereby is referring to clay soil and sand. In avoiding under or over estimates of Vs value, both methods have been considered.

Six developed correlations of CPT-Vs based on Quaternary age where two of each for all soil, sand and clay soil types have been selected [7]–[9]. These Vs has been determined according to overall soil type and the type of soil based on existing soil layers. Detail of the chosen correlation has been depicted in Table 1. The selected correlations are based on $q_c$ and $f_s$ which can be obtained from CPTu.

Hegazy and Mayne [7] have produced correlation for both all soil and soil type dependent which have been adapted in determining Vs in this study. The correlations were based on 61 sites (worldwide) where the data comprise of mine tailings, intermediate soils, sands and clays. Three correlations based on multiple regression analyses have been produced for all soil, clay and sand which dependent on $q_c$ and $f_s$ values. Friction ration also has been taken into consideration in all soil correlation. In the same year, Mayne and Rix [8] have produced a correlation for clay soil. This correlation is developed by analysing data from 31 sites (worldwide) that have been compiled in 1993. Only $q_c$ parameter is considered in obtaining Vs value.

Besides Hegazy and Mayne [7] and Mayne [9] has produced a correlation for all soil type which depends on $f_s$. Equation in Table I is as presented in Mayne [10] where the correlation developed in 2006 has been presented in log. Correlation by Sykora and Stokoe cited in Wair et al. [12] is developed by analysing data from 9 sites in United State. The linear equation correlated Vs with $q_c$ where the correlation can be used in predicting Vs for sand[12].
Table 1. Correlation of CPT-Vs

| Soil Type | Model | Equation for Vs | $r^2$ | Paired Data |
|-----------|-------|----------------|-------|-------------|
| All Soil  | Hegazy & Mayne (1995) | $(101 \log(q_c) - 11.4)^{1.47} (100 f_s/q_c)^{0.3}$ | 0.70 | 323 |
|           | Mayne (2007) | $118.8 \log(f_s) + 18.5$ | 0.82 | 161 |
| Sand      | Sykora & Stokoe (1983) | $134.1 + 0.0052 q_c$ | 0.61 | 256 |
|           | Hegazy & Mayne (1995) | $12.02 q_c^{0.319} f_s^{0.0466}$ | 0.57 | 92 |
| Clay      | Hegazy & Mayne (1995) | $3.18 q_c^{0.549} f_s^{0.025}$ | 0.78 | 229 |
|           | Mayne & Rix (1995) | $1.75 q_c^{0.627}$ | 0.74 | 481 |

In solving limitation of resources such as time, cost and also access to site, correlations such as CPT-Vs and SPT-Vs will be used in determining Vs. Besides the developed correlations, new correlations have been produced and normally, the developed equations along with the in-situ Vs results will be used for verification [17].

In summary, the shear wave velocity is one of the key parameter in determining peak surface acceleration in ground response analysis. Amongst all available programs, NERA has been chosen as the appropriate program to be used in analysing peak surface acceleration. Lots of correlations have been developed to determine Vs through SPT and CPT. Since only CPTu method was used in site investigation for offshore sites where direct Vs measurement is not available, calculating Vs by using correlation is a necessity. Thus, correlation between CPT-Vs has been adopted in this study.

3. Methodology

This section is focusing on the adopted methodology in determining shear wave velocity. Six correlations of CPT-Vs have been selected as discussed in literature review. Two sites will be discussed in this paper. Site A has a combination of clays and sand while Site B is totally clay as presented in Table 2 and Table 3 respectively. In order to simplify the results presentation, labelling has been used and further description is available in Table 4.

Table 2. Soil layers in Site A

| Stratum | Soil Description               | Penetration (m) |
|---------|--------------------------------|-----------------|
|         |                                | From | To   |
| 1       | Firm to stiff CLAY             | 0.0   | 1.7  |
| 2       | Very stiff CLAY                | 1.7   | 2.7  |
| 3       | Hard CLAY                      | 2.7   | 5.7  |
| 4       | Very stiff silty CLAY          | 5.7   | 8.8  |
| 5       | Stiff CLAY                     | 8.8   | 13.9 |
| 6       | Very stiff CLAY                | 13.9  | 19.0 |
| 7       | Stiff to very stiff CLAY       | 19.0  | 66.0 |
| 8       | Stiff to very stiff CLAY       | 66.0  | 81.0 |
| 9       | Very stiff to hard CLAY        | 81.0  | 101.0|
| 10      | Medium dense to dense SAND     | 101.0 | 127.3|
| 11      | Very stiff to hard CLAY        | 127.3 | 150.0|
Table 3. Soil layers in Site B

| Stratum | Soil Description          | Penetration (m) |
|---------|---------------------------|----------------|
|         |                           | From | To  |
| 1       | Very soft to soft CLAY    | 0.0  | 6.0 |
| 2       | Soft to firm CLAY         | 6.0  | 18.0|
| 3       | Firm to stiff CLAY        | 18.0 | 33.0|
| 4       | Stiff CLAY                | 33.0 | 42.0|
| 5       | Stiff CLAY                | 42.0 | 58.0|
| 6       | Stiff to very stiff CLAY  | 58.0 | 67.2|
| 7       | Very stiff CLAY           | 67.2 | 72.8|
| 8       | Very stiff CLAY           | 72.8 | 80.1|
| 9       | Very stiff CLAY           | 80.1 | 89.1|
| 10      | Very stiff CLAY           | 89.1 | 95.8|
| 11      | Hard CLAY                 | 95.8 | 115.9|
| 12      | Hard CLAY                 | 115.9| 122.3|
| 13      | Hard CLAY                 | 122.3| 127.8|
| 14      | Hard CLAY                 | 127.8| 150.0|

Table 4. Results Labelling

| Label | Description                                |
|-------|--------------------------------------------|
| A     | Hegazy & Mayne (1995)                      |
| B     | Mayne (2007)                               |
| C     | Sykora & Stokoe (1983)                     |
| D     | Hegazy & Mayne (1995)                      |
| E     | Hegazy & Mayne (1995)                      |
| F     | Mayne & Rix (1995)                         |
| All Soil | Average for Soil Type = All Soil       |
| Combination | Average for combination of Sand and Clay soil types |

The main parameters in selected correlation equations (as in Table 1) are \( q_c \) and also \( f_s \), which can be directly recorded during CPTu event. Data for Site A and B have been extracted from soil investigation report for platforms located in Terengganu offshore area. Details such as depth, types of soil, \( f_s \) and \( q_c \) are available. \( V_s \) values have been calculated for both sites. In both sites, CPTu has been conducted up to 150m in depth. For Site A, all six correlations were used since there is a layer of sand among the clay layers. In Site B, only correlation A, B, E and F were used due to the absence of sand layer. There are 11 soil layers which dominated by clay in Site A while Site B has 14 layers of clay.

In phase one, \( V_s \) were calculated for model A and B, for all soil type. Then, Model B, C, D and E were used to calculate \( V_s \) based on soil type in each layer for phase two and results have been plotted. Results from phase one and two have been depicted in figure to ease the comparison. The averages of results from phase one and phase two has been determined in phase three where the final \( V_s \) values have been obtained. The average and final \( V_s \) values have been presented in figure. Results and discussion is available in the next subsection.

4. Results and Discussion
This section presented results of \( V_s \) for phases one, two and three as mentioned in methodology. Figure 2 and Figure 3 have shown plotted results of \( V_s \) (phase one and two) for Site A and B respectively. Site A is a combination of clay layers and a sand layer (second last layer). Therefore, all
selected correlations have been used in determining Vs values. Different with Site B, all layers comprise of clay. Thus, correlations C and D have not been used to determine Vs. However, at both sites, clay soils are the dominant.

It can be seen that Vs values from correlations developed for all soil produced lower values compared to soil dependent type for clay soil at both sites. However, different scenario was obviously seen by sand layer where values of Vs from all soil correlation are higher compared to correlation for sand. Increment of Vs values can be seen as the depth increased. The same trend can be observed in the difference between all soil and soil type dependent results. Vs values for the last layer for correlations E and F are almost double Vs from correlations A and B in Site B. The existence of sand layer has reduced the difference between Vs values for all soil and soil type dependent in Site A.

![Figure 2. Vs values from phase one and two for site A](image1)

![Figure 3. Vs values from phase one and two for site B](image2)

Figure 4 and Figure 5 presented results from phase three for Site A (11 soil layers) and Site B which consists of 14 clay layers. The average of all soil and combination (for Site A) and all soil and clay (for Site B) have been plotted. Due to the absence of in-situ Vs values, final Vs values were calculated based on average off all soil and combination. This will help in reducing over or under prediction of Vs values which will affect analysis on local site effect.

![Figure 4. Vs values from phase three for Site A](image3)

![Figure 5. Vs values from phase three for Site](image4)

Prediction of local site effect is very important in seismic event as the potential of raised in amplification factor can be detected. Amplification factor will be very significance in the case of thick soft soil layering the earth surface as in Taipei basin [18]–[20]. It will allow proper mitigation to be taken prior to seismic event [15]. Correlations A and B used in this study also being used by Ahmad et al. [17] in verifying new correlation for stiff soil where the predictive capability of the correlations were found to be good. It has the same soil type as in this study area.
In predicting the local site effect, ground response analysis must be conducted where shear velocity is among the important parameters. Challenges occur when correlation equations need to be used instead of direct Vs measurement due to factors such as cost, limited resources and expertise. Soil stratigraphy normally comprises of layers of soil which can be from the same type or combination of different types of layers. Lots of correlations between CPT-Vs have been developed but, how it can be used to determine Vs for offshore Terengganu is among the raised questions. Thus, the average results from all soil and soil type dependent correlation is found to be reasonable to be used in determining shear wave velocity for offshore Terengganu.

5. Conclusion
In this study, determination of Vs which is one of the key parameters in GRA has been conducted. Six developed CPT-Vs correlations have been selected which comprise of correlations for general and soil type dependent. In clay soil, the general correlations have produced lower Vs values compared to soil type dependent correlations. However, different scenarios can be observed for sand type of soil. The differences in results between these correlations have been highlighted. Therefore, the average of all soil and soil dependent results will be used as final Vs. This method is adopted in order to avoid under or over prediction of Vs value which will affect peak surface acceleration in ground response analysis.

References
[1] S. L. Kramer, 1996, Geotechnical Earthquake Engineering. Prentice Hall.
[2] R. M. J. S. Wicander, 2006, The Changing Earth Exploring Geology and Evolution.
[3] C. K. Erdey, 2007, Earthquake Engineering Application to Design. John Wiley & Sons.
[4] L. D. Elnashai, A S, Sarno, 2008 Fundamentals of Earthquake Engineering. First. John Wiley & Sons.
[5] R. Villaverde, Villaverde, 2009, Fundamental Concepts of Earthquake Engineering.pdf. CRC Press- Taylor & Francis Group.
[6] T. K. Datta, 2010, Seismic Analysis of Structures. Singapore: John Wiley & Sons (Asia).
[7] Y. A. Hegazy and P. W. Mayne, 1995, Statistical Correlations Between Vs and CPT Data for Different Soil Types,” in Inter. Symp. on Cone Penetration Testing, CPT ’95. Vol. 2, pp. 173–178.
[8] G. J. Mayne, P W, Rix, 1995, Correlations Between Shear Wave Velocity and Cone Tip Resistance in Natural Clays, Soils Found., vol. 35, no. 2, pp. 107–110.
[9] P. W. Mayne, 2006, In-situ test calibrations for evaluating soil parameters,” in Characterization and Engineering Properties of Natural Soils II, Singapore, pp. 1601–1652.
[10] P. W. Mayne, 2007, Final Report * NCHRP Project 20-05 Topic 37-14 Cone Penetration Testing State-of-Practice.
[11] T. Lunne, 2012, The Fourth James K. Mitchell Lecture : The CPT in offshore soil investigations - a historic perspective The Fourth James K. Mitchell Lecture : The CPT in offshore soil investigations - a historic perspective,” Geomech. Geoengin., vol. 7, no. June 2012, pp. 75–101.
[12] B. R. Wair, J. T. Dejong, and T. Shantz, 2012. Guidelines for Estimation of Shear Wave Velocity Profiles.
[13] M. Irsyam, D. T. Dangkua, and D. Hoedajanto, 2008, Proposed seismic hazard maps of Sumatra and Java islands and microzonation study of Jakarta city , Indonesia,” J. Earth Syst. Sci., vol. 117, no. November, pp. 865–878.
[14] M. Marto, A., Adnan, A., Hendriyawan and Irsyam, 2011, Microzonation Maps for Kuala Lumpur and Putrajaya, Malaysian J. Civ. Eng., vol. 23, no. 1, pp. 63–85.
[15] A. Adnan, Hendriyawan, and A. Marto, 2008, Development of Microzonation Maps of Kuala Lumpur City Centre for Seismic Design of Buildings,” JURUTERA, no. March, pp. 12–15.
[16] USGS, 2006, USGS Geology and Geophysics.
[17] I. Ahmad, M. Waseem, M. Abbas, and U. Ayub, 2015, Evaluation of Shear Wave Velocity Correlations and Development of New Correlation Using Cross-hole Data, Geohazards Environ., vol. 1, pp. 42–51.
[18] C. Wang, Y. Lee, M. Ger, and Y. Chen, 2004, Investigating Subsurface Structures and P- and S-wave Velocities, vol. 15, no. 4, pp. 609–627.

[19] R. Iyisan and H. Khanbabazadeh, 2013, A numerical study on the basin edge effect on soil amplification,” Bull. Earthq. Eng., vol. 11, pp. 1305–1323.

[20] Y. Huang, B. Huang, K. Wen, Y. Lai, and Y. Chen, 2010, Investigation for Strong Ground Shaking across the Taipei Basin during the M W 7.0 Eastern Taiwan Offshore Earthquake of 31 March 2002, vol. 21, no. 3, pp. 485–493.