AN EXPERIMENTAL IDENTIFICATION OF SHEAR WAVE VELOCITY OF BANGKOK CLAY USING BENDER ELEMENT

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Abstract

This paper serves to identify shear wave velocity, which can be continuously measured using bender element techniques under various stress paths on triaxial loading tests. However, the influence of mean effective confining stress can be applied to correlate the shear wave velocity as well. Very few studies can identify the vertical and horizontal stress effect of the shear wave velocity of clayed soil. The estimation of shear wave velocity paths under isotropic stress conditions is reasonably presented by three series of triaxial tests such as triaxial undrained compression test (CIU), triaxial drained compression test (CID), and triaxial stress control test (CIDS). The results indicated that the vertical stress and horizontal stress were found to be more favourable in both drained and undrained conditions, especially when shear wave velocity is properly normalized by void ratio function. The shear wave velocity during drained and undrained mode shearing at small strain to large strain levels was practically linear. Changes in the stress levels during drained and undrained shearing in clay were very small. As a result, the shear wave velocity along paths on CIU, CID, and CIDS on a logarithmic curve can be identified by the exponents for both vertical and horizontal stress direction. These component values have been employed to developed empirical functions for optimal predicting of the shear wave velocity in clayed soil. In conclusion, a simplified function is proposed that will help determine the shear wave velocity, which also helps to solve geotechnical problems.

Keywords: Bender element, Clayed soil, Shear wave velocity, Triaxial drained compression test, Triaxial undrained compression test.
1. Introduction

Shear wave velocity is known as a significant tool in estimating the stiffness of clay. It is especially useful for geomechanics designs or to assess the path of an elastic shear modulus due to vibration events, which can come from various sources, such as earthquakes, moving vehicles, and vibrations from wind turbines. Several studies related to the assessment, the stiffness of soils using bender element techniques together with triaxial tests have been reposted in the past [1-4]. It is conventionally and practically applied to measure the shear wave velocity of soils.

In general, the shear wave velocity of clay is classified into two categories: induced undrained and induced drained, following the concepts adopted by many researchers [5, 6]. The estimation of undrained shear strength for clayey soil is determined by using shear wave velocity. The undrained shear strength, void ratio, and shear wave velocity are entirely related. In addition, Ratananikom et al. [7] also investigated anisotropic stiffness of clayey soil from elastic wave propagation. They implied that the power functions of isotropic confining stress are main factor for determining the soil stiffness. As presented in previous literature, researchers developed an empirical expression model under a variation of mean effective stress, \( p' \), and void ratio, which was presented in [1, 8, 9]. The empirical equation of elastic shear modulus, \( G_{\text{max}} \), is as below:

\[
G_{\text{max}} = A \cdot F(e) \cdot \left( \frac{p'}{P_a} \right)^n
\]

where \( A \) is the coefficient of uniformity of a specimen, \( F(e) \) is the function of void ratio, \( P_a \) is the reference pressure for normalization and \( n \) is the best-fit parameter.

Very recently, Escribano and Nash [10] proposed that both stresses in the particle motion \( (\sigma_1') \) and wave propagation directions \( (\sigma_3') \) are the main components. The elastic shear modulus function as stress acts orthogonally to the wave motion plane. Eq. (1) has been extended for elastic shear modulus as:

\[
G = K_1 \cdot F(e) \cdot \sigma_1' \cdot \sigma_3' \]

where \( K_1 = \frac{\sigma_1'}{\sigma} \) (\( K_1 = 1 \) for isotropic condition), \( F(e) \) is the function of void ratio, and \( m \) and \( n \) are the coefficients corresponding to the direction of vertical effective stress, \( \sigma_1' \), and horizontal effective stress, \( \sigma_3' \). Based on Eq. (2), a new \( G_{\text{max}} \) model is directly related to developing a new empirical equation for the determined shear wave velocity of soil.

Notable previous research has studied the characteristics of shear wave velocity of sand soil behaviors under drained triaxial compression [11]. This work focused only on the shear wave velocity empirical expression correlation function for sand. However, while an empirical expression function is also appropriate for determined shear wave velocity paths, it is not adequate for clayed soil.

The research is mainly intended to demonstrate the results of various stress paths of the shear wave velocity in clayey soil subjected to isotropic conditions in both drained and undrained conditions for shearing specimens. An identification of the shear wave velocity paths under three series of triaxial compression tests - triaxial undrained (CIU), triaxial drained (CID), and triaxial stress control (CIDS) was carried out. An empirical model to correlate and identify the shear wave velocity paths of different stress paths is proposed for clayey soil.
2. Materials and Research Methodology

2.1. Clay soil

Undisturbed specimens of Bangkok clay were collected from the center of Thailand. Each specimen was taken from a depth of 11.5 to 12.0 m. The basic physical and particle shapes are concluded in Table 1. The grain particle size of the clayey soil specimen was illustrated in Fig. 1(a). The entire specimens were dark silty clay. All specimens were prepared to cylinder sharp with approximately 5 cm outer diameter and approximately 10 cm high. In this study, three series of CIU, CID, and CIDS triaxial compression test samples were fully saturated with a back pressure of 100 kPa with mean effective stress 300 kPa. After B value reached greater than 0.99, the consolidation confining pressure used for these specimens was isotopically consolidated under 150, 225 and 300 kPa, respectively. Once this was done, the specimens were sheared together to measure the travel time. The flow diagram of testing and produce is given in Fig. 2.

<table>
<thead>
<tr>
<th>Soil data</th>
<th>Standard Test</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
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<td>55-65</td>
</tr>
<tr>
<td>Total Unit Weight, ( \gamma_t ), kN/m(^3)</td>
<td>ASTM D 4253-16</td>
<td>15.20</td>
</tr>
<tr>
<td>Liquid limit, LL, (%)</td>
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<tr>
<td>Plastic limit, PL, (%)</td>
<td>ASTM D 4318-17e1</td>
<td>29</td>
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<tr>
<td>Plasticity index, PI, (%)</td>
<td>ASTM D 4318-17e1</td>
<td>56</td>
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<tr>
<td>Specific gravity, ( G_s )</td>
<td>ASTM D 854 – 14</td>
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</tr>
<tr>
<td>Initial void ratio, ( e )</td>
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</tr>
<tr>
<td>Over consolidation ratio, OCR</td>
<td>ASTM D 2435</td>
<td>0.6-1.2</td>
</tr>
<tr>
<td>Shape of grain particle</td>
<td>Dark clay</td>
<td></td>
</tr>
</tbody>
</table>

*Initial void ratio, \( e \) calculated by this equation, \( e = G_s / \rho_d - 1 \).

Fig. 1. (a) Grain particle size of the specimen, (b) Size of soil specimens.
2.2. Research methodology

Both CIU and CID triaxial loading tests of clay specimens were conducted on a shear specimen under a strain-controlled manner, whereas the triaxial CIDS was a sheared specimen under stress control via use a pneumatic air cylinder. This series of triaxial compression tests were evaluated by adopting the bender element technique system. The schematic view of the triaxial equipment used in the research is displayed in Figs. 3 and 4, respectively.

2.2.1. Undrained triaxial test with load-unloading control (CIU)

After the consolidation stage for CIU was completed, the drainage valve was closed immediately and then the soil specimen was sheared until the axial strain was approximately 10%. The axial strain rate to machine control followed the ASTM Standard ASTM D4767-11 Standard Test Method for Consolidated Undrained
Triaxial Compression Test for Cohesive Soils (Strain rate = 0.02 mm/min). Multiple stages of triaxial loading and unloading compression tests are controlled in this study. As approximately 0.2% axial strain unloading was carried out at every cyclic circle, the axial strain loading increased up to 1%. For the next load compression tests, the axial strain approached 2.5%, 3.8%, 6%, to a maximum of 10%. During the loading and unloading control period, the travel time was continually measured by a pair of bender elements. This bender element was sketched in Figs. 5(a) and (b). The cell-back pressure data and the axial force from the transducer data were automatically recorded by the ELE data logger.

2.2.2. Monotonic drain triaxial compression test (CID)

The monotonic drain triaxial compression test (CID) was conducted under fully isotropic consolidation tests after excess pore water pressure was attained. The specimen was sheared by strain control at an axial strain rate of approximately 0.004 mm/min. Underline the fact that the strain rate machine control followed the Standard ASTM D7181 – 11 Standard Test Method for Consolidated Drained Triaxial Compression Test for soils. At all times for shear specimens, pore pressure data, cell-back pressure data, axial force data, axial displacement, and volume-change data were automatically recorded by an ELE data logger. Meanwhile, the travel time to compute the shear wave velocity was recorded until axial strain displacement was attained.

2.2.3. Drained triaxial test with stress control (CIDS)

In this paper, the drained triaxial stress-control test was performed under isotropic consolidation conditions. The loading control specimen was achieved via a pneumatic air cylinder (double action) mounted on the top beam of the triaxial apparatus. The stress-control triaxial test setup and bender element setup are shown in Fig 4. Three specimens with 150 kPa, 225 kPa and 300 kPa mean effective stress constant (\( p' \)) were used. After excess pore water pressure was terminated, the pneumatic air cylinder was applied to the shear specimen and the travel time was measured. Note that at this stage the vertical stress, \( \sigma_1' \) was increased, whereas the horizontal stress remained constant.

For the next step, an axial load was maintained until the dispersal of the excess pore water pressure ended appeared together with a measurement of the travel time. Then back pressure was kept, and the cell pressure was released. The specimen was consolidated until the dispersal of the excess pore water pressure stopped. Then the travel time was measured. Repeat step by step until an axial strain more than 10% strain axial strain.

As for the mean effective stress constant, \( p' \), the function to control mean effective stress is given by the following function as:

\[
p = \frac{\sigma_1' + 2\sigma_2'}{3} \tag{3}
\]

or

\[
\frac{p}{A} = 3p' - 2(CP - BP) \tag{4}
\]

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\[ q' = \frac{P}{A} = \sigma_1' - \sigma_3' \tag{5} \]

where \( p' \) is the vertical effective stress (kPa), \( \sigma_1' \) is the vertical effective stress (kPa), \( \sigma_3' \) is the confining effective stress (kPa), \( q' \) is the deviator stress (kPa), \( CP \) is cell pressure (kPa), and \( BP \) is back pressure (kPa).

**Fig. 3.** General arrangement of equipment used for the triaxial strain control test (CIU and CID).

**Fig. 4.** General arrangement of equipment used for the triaxial stress control test (CIDS).
2.2.4. Bender element technique

Commercial bender elements from PIEZO SYSTEMS, INC. were employed to assess shear wave velocity. A couple of bender elements, type T 226-A4-303Y (Transmitter) and T 226-A4-303X (Receiver) with dimensions of $31.7 \times 12.7 \times 0.66$ mm (length $\times$ width $\times$ thickness) were equipped in the top cap and pedestals of the triaxial gadget. Fig. 5(a) shows the main components of the bender measurement system and interpretation of the travel time is responsible for computing the shear wave velocity. The main components of the bender measurement system were a digital oscilloscope, function generator, amplified voltage, and data logger. The 50 Hz with an amplitude of $+10$ V and $-10$ V (20 V peak to peak) square wave used in this study is recommended by Viggiani and Atkinson [12]. The FDS 100 function generator was employed to provide excitation voltage to the amplifier voltage, which was applied to the transmitter bender element in the bottom pedestal of the triaxial apparatus. Consequently, when excitation voltage from the function generator was applied to the transmitter bender element, it caused vibrations that generated the shear wave which propagated straight the soil specimen.

This wave was received by the receiver bender element in the top cap. The applied voltage, receiver signal, and square wave were recorded by the digital oscilloscope and transferred to the computer. Finally, gauging the travel time, $t$ of the wave, the wave velocity, $V_s$ is defined as follows:

$$V_s = \frac{L_{tt}}{t} \tag{6}$$

where $L_{tt}$ is the edge-to-edge distance from the transmitter to the receiver bender elements, and $t$ is the wave’s travel time from the transmitter, $t_0$, and the receiver, $t_1$, which were measured by first arrival of output wave under time domain method. This method is widely employed and is not complicated for interpretation the wave’s travel time [13, 14].

![Diagram of the bender element system and interpretation](image)

**Fig. 5.** (a) Chart of the bender element system, and (b) Schematic view of the bender element interpretation.
3. Results and Discussion

3.1. Determination of correlation parameters function

According to past research, Taiebat and Dafalias [9] state that the shear wave velocity is governed by mean effective stress. The correlation function under isotropic loading conditions is proposed as below:

$$V_s = K \left( \frac{\sigma_1' + 2\sigma_3'}{2} \right)^R$$  \hspace{1cm} (7)

where $K$ is a parameter containing the influence of the void ratio, $\sigma_1'$ and $\sigma_3'$ are the vertical and confining stresses, and $R$ is a constant. That behaviour can be found in various literatures [2, 3]. However, the correlation function is practical for determining the path for shear wave velocity. Escribano and Nash [10] proposed that the elastic shear modulus, Eq. (2), on stress has been well recognized to be dependent on the particle motion directions, both $\sigma_1'$ and $\sigma_3'$, as vertical and horizontal planes respectively. In contrast, the shear wave velocity on stress acting on the wave motion included in the direction plane is displayed as the elastic shear modulus. Since the range of initial void ratio of the study is about 1.83-1.90 which is quite similar to the range of initial void ratio of Pisa clay, the function of void ratio $F(e) = e^{-1.43}$ presented by Jamiolkowski et al. [15] is used to normalize the shear wave propagation.

Consequently, in terms of $G_{\text{max}} = \rho V_s^2$, where $\rho$ is the total density of the soil specimen and $V_s$ is shear wave velocity of the soil mass, the $V_s$ function $\rho = \rho d = G_s/(1+e)$ can be used. Subsequently, Eq. (7) can be re-written in terms of $V_s$ as.

$$V_s = e^{0.715} \cdot \sigma_1' \cdot \sigma_3'^n \cdot \left( \frac{1+e}{G_s \rho_w} \right)^{0.5}$$  \hspace{1cm} (8)

or

$$\log \frac{V_s}{e^{0.715}} = m \cdot \log \sigma_1' + n \cdot \log \sigma_3' + 0.5 \log \left( \frac{1+e}{G_s \rho_w} \right)$$  \hspace{1cm} (9)

where $m$ and $n$ are the constant coefficients of the vertical and horizontal effective stress respectively, $\rho_d$ = dry density of the soil specimen, $\rho_w$ = density of water, and $G_s$ = specific gravity of clayed soil.

3.2. Determination of correlation parameters function for CID

In the case of drained triaxial tests (CID), the monotonic axial strain loading to shear specimen is approximately 10% of an axial strain deformation. Throughout the process of specimen shearing, the peak deviator stress from relationships between the deviator stress, $q = \sigma_1' - \sigma_3'$, and vertical strain, $\varepsilon$, during drained compression tests in Fig. 6(a) does not appear. It is noted that the deviator stress, $q'$ is increased along a path during a drained compression test.

As for the relationship between normalized shear wave velocity, $V_s / F(e)$ and vertical stress, $\sigma_1'$ throughout drained shearing, it can be plotted in Fig. 7, shows that the shear wave velocity, $V_s$, of CID can, therefore, give one of the best examples of shear wave velocity in normalized paths in drained triaxial compression tests. Since the curve between normalized shear wave velocity and
vertical stress, $\sigma_1'$, on a logarithmic plot, should be linear as very confining effective stress 150, 225 and 300 kPa. Based on Eq. (9), the values of $n_1$, $n_2$, and $n_3$ from the vertical gap between liner lines at different confining stress points are computed whereas the $m$ coefficient is used to determine the slope of the best-fitted line. Consequently, it is seen that those stress parameters, as well as the direction of the $m$ and $n$ coefficient, could reasonably be presented for the drained triaxial compression test of clay.

![Image](cid_1.png)

**Fig. 6.** (a) Axial strain and deviator stress of CID and (b) Mean effective stress changed with shear wave velocity of CID.

![Image](cid_2.png)

**Fig. 7.** The relationship between vertical stress and $V_s/F(e)$ for clay.

### 3.3. Determination of correlation parameters function for CIU and CIDS

The correlations between the deviator stress, $q' = \sigma_1' - \sigma_3'$, and vertical strain, $\varepsilon_z$, during undrained compression (CIU) are illustrated in Fig. 7(a). The load and un-load stage are presented at an axial strain deformation of about 2%, with a strain rate to sheared specimen of 0.02 mm/min. As seen in the illustration, the peak of the deviator confining stress at 150 kPa, 225 kPa, and 300 kPa occur if the strain reaches 5.2%, 4.7%, and 5.4% respectively. The paths of shear wave velocity with mean effective stress, $p'$, are presented in Fig. 8(c). The results indicate that the shear wave velocity of undrained shearing is governed by the mean effective stress. The variation of shear wave velocity during load-unload tests to shear specimens are very small. Taking into account the impact of the
vertical effective stress, $\sigma_1'$; horizontal stress, $\sigma_3'$ and void ratio, the results from the CIU experiments show that the vertical effective stress, $\sigma_1'$; and horizontal stress, $\sigma_3'$, are affected by the magnitude of shear wave velocity. Note that in the case of undrained triaxial compression tests, the void ratio during shearing is constant.

In tests of CIDS, the stress with a mean effective constant, $p'$, of 150, 225 and 300 kPa was performed. The stair-step of both axial strains loading and the deviator stress, $q'$ are illustrated in Fig. 8(b). The strain loading of each specimen approached an axial strain of approximately 8% to 14%. Both the results of vertical stress and horizontal stress with shear wave velocity are illustrated in Fig. 8(d).

The results indicate that the normalized shear wave velocity of each sample while increasing the vertical stress, $\sigma_1'$; and decreasing the horizontal stress, $\sigma_3'$, are almost constant. Moreover, the effective void ratio from the path of the normalized shear wave velocity, $V_s/F(e)$ with vertical stress, $\sigma_1'$; and horizontal stress, $\sigma_3'$, in a logarithmic curve, are illustrated in Figs. 9 (c) and (d). The results indicate that the normalized shear wave velocity, $V_s/F(e)$, extremely increased when increasing vertical stress, $\sigma_1'$, whereas with the horizontal stress, $\sigma_3'$, a decrease was observed.

Also, when considering the paths of normalized shear wave velocity, $V_s/F(e)$, for undrained triaxial tests (CIU) and triaxial stress control tests (CIDS), both CIU and CIDS show similar developments of vertical effective stress, $\sigma_1'$; whereas the horizontal effective stress, $\sigma_3'$, along tested paths, have changes.

Based on Eq. (9), the correlating shear wave velocity path is linked to the CIU and CIDS case. The dependency paths between normalized shear wave velocity, $V_s/F(e)$, and vertical effective stress, $\sigma_1'$; in CIU is plotted in Fig. 9(a). The best-fitted lines from the logarithm at each effective confining pressure path on the results were significantly linear.

The coefficient $m$ can also be calculated from the slope between vertical effective stress, $\sigma_1'$; and normalized shear wave velocity $V_s/F(e)$. Since horizontal stress, $\sigma_3'$; on both CIU and CIDS was changed along paths during shearing the specimens, the horizontal effective stress, $\sigma_3'$; and normalized shear wave velocity, $V_s/F(e)$, almost have a linear relationship.

To sum up, the method to explore coefficient $n$ as CID is not adequate. The coefficient $n$ can be estimated by using Eq. (10). It can be rewritten from Eq. (9) as.

$$n = \frac{\log \left( \frac{V_s}{e^{0.15}} - m \log \sigma_1' - 0.5 \log \left( 1 + e \frac{1 + e}{G_0' \rho_v} \right) \right)}{\log \sigma_3'}$$

Note that according to the test results from CIU and CIDS, the $n$ coefficient for their condition is computed by using Eq. (10). The $n$ coefficient at about 0-10% strain displacement is computed by averaging the $n$ coefficient along a path of horizontal effective stress, $\sigma_3'$. 
3.4. Stress parameter for clay

In this research, the characteristics of shear wave velocity were categorized into two groups. Herein, both drained and undrained conditions were explored to optimize the correlation function responsible for estimating the shear wave velocity under various stress paths of clay.

As the results show, the main empirical equation (Eq. 9) is adopted to find out the stress parameter as acting on vertical effective stress, $\sigma_1'$ and horizontal effective stress, $\sigma_3'$. whereas the function of void ratio proposed in [10] was randomly selected by an initial void ratio value of clayed soil specimen. A different relationship between stress parameter, $\sigma_1'^m$, $\sigma_3'^n$ and normalized shear wave velocity obtained from CIU, CID, and CIDS are summarized in Table 2.

<table>
<thead>
<tr>
<th>Test type</th>
<th>Effective confining Pressure (kPa)</th>
<th>Constant, $p'$ (kPa)</th>
<th>Coefficient, $m$</th>
<th>Coefficient, $n$</th>
<th>$n_{avg}$</th>
<th>$n_{sd}$</th>
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</thead>
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<td>CID</td>
<td>150</td>
<td>-</td>
<td>0.7652</td>
<td>-</td>
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<tr>
<td></td>
<td>225</td>
<td>-</td>
<td>0.1040</td>
<td>0.8002</td>
<td>0.7886</td>
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<td></td>
<td>300</td>
<td>-</td>
<td>0.6753</td>
<td>0.8006</td>
<td>-</td>
<td>-</td>
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<tr>
<td>CIU</td>
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<td>-</td>
<td>0.1964</td>
<td>0.6466</td>
<td>0.6668</td>
<td>0.01753</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>-</td>
<td>0.6784</td>
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<td>0.05325</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>-</td>
<td>0.6241</td>
<td>0.6754</td>
<td>0.6754</td>
<td>0.05325</td>
</tr>
<tr>
<td>CIDS</td>
<td>-</td>
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<td>0.7304</td>
<td>-</td>
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<td></td>
<td>-</td>
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</table>
The coefficient $m$ and $n$ for clay in the table above were proposed. The criteria for using coefficient $m$ and $n$ shall be as follows:

(a) before substitute $m$ and $n_{avg}$ exponent in terms of vertical effective stress, $\sigma_1'$ and horizontal effective stress, $\sigma_3'$, the concerning for shear wave velocity function under drained state, undrained state, and stress control state shall be required.

(b) in determining the paths of shear wave velocity with $m$ and $n_{avg}$ proposed only for the isotropic consolidation state shall be used.

The normalized shear wave velocity and stress parameter, $\sigma_1'^m \cdot \sigma_3'^n$ is plotted in Fig. 9. After comparisons of the $m$ coefficient as vertical effective stress, and the $\sigma_1'$ plan for CID and CIU tests, the findings demonstrated that the shear wave velocity of CIU rapidly goes up when compared with CID, whereas the stress path remained constant.

It was found in CIDS the highest $m$ coefficient was observed. If you consider the stress effect on horizontal effective stress, $\sigma_3'$ on shear wave velocity, the $n$ coefficient of CIU less than coefficient $n$ of CID is illustrated whereas coefficient $n$ of CIDS was 0.6753. These results concluded that a new empirical model is applicable for predicting the path of shear wave velocity. This is done separately for CID, CIU, and CIDS for clay.

![Fig. 9. (a and b) The relationship between vertical stress, $\sigma_1'$, and $V_s$ normalized CIU and CIDS (c and d), the relationship between horizontal stress, $\sigma_3'$, and $V_s$ normalized CIU and CIDS.](image-url)
4. Conclusions

Based on historical tests results from CIU, CID, and CIDS subjected to triaxial loading, the shear wave velocity paths have been described. The results indicate that the wave propagation on vertical stress direction, and particle motion on horizontal stress direction – as well as each state’s void ratio on triaxial loading – are mainly influenced by affecting the wave shear, of which the drained and undrained condition tests are not the same. Interpreted data is summarized as follows:

- According to the CIU test, the results indicated that the shear wave velocity is governed by the vertical effective stress, $\sigma_1'$, and horizontal effective stress, $\sigma_3'$. When the normalized shear wave velocity along paths is reduced, it is because the void ratio does not change.

- As evidenced by the test outcomes of CID in the research, with increased vertical effective stress, $\sigma_1'$, normalized shear wave velocity, $V_s / F(e)$, increased. The void ratio is dominant.

- In CIDS tests, the shear wave velocity along paths is almost constant at 0 - 10% during strain displacement. After the 10% strain, the shear wave velocity will decrease. The $m$ coefficient will be developed by increasing vertical effective stress whereas $n$ coefficient will govern by horizontal effective stress.

- As seen in the test results of CIU, CID, and CIDS, a new empirical equation model, (Eq. 8) is appropriate for predicting the characteristics of shear wave velocity of clay.

### Nomenclatures

- $e$: Void ratio of soil
- $F(e)$: Function of void ratio
- $G_{max}$: Elastic shear modulus, MPa
- $G_s$: Specific gravity of clayed soil
- $K$: Coefficient of Earth pressure at rest
- $L$: Distance (cm) between transmitter and receiver bender element
- $m$: Coefficient of vertical effective stress
- $n$: Coefficient of horizontal effective stress
$t$ Travel time ($\mu$s) in of the wave from the transmitter and the receiver

$V_s$ Shear wave velocity, m/s

**Greek Symbols**

\( \rho \) Total density of the soil specimen, kN/m$^3$

\( \rho_d \) Dry density of the soil specimen, kN/m$^3$

\( \rho_w \) Density of water, kN/m$^3$

\( \sigma_1 \) Vertical effective stress, kPa

\( \sigma_3 \) Horizontal effective stress, kPa

**Abbreviations**

CID Drained triaxial compression test

CIDS Triaxial stress control test

CIU Undrained triaxial compression test

**References**


