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RECOVERY OF ELASTIC PARAMETERS FOR CROSS-ANISOTROPIC SANDY SOIL VIA ELASTIC WAVE MEASUREMENTS

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ABSTRACT

In this study, the elastic properties of loose to medium dense (Dr=50%) sandy soil were obtained from elastic wave propagation techniques in the laboratory. The soil specimens were assumed cross anisotropic medium. Two bender elements are embedded in the top cap and the pedestal of the triaxial device as receivers and transmitters in the vertical direction for P- and S-waves. In addition, two bender elements are attached to the membrane surrounding the soil specimen to measure horizontal P-wave velocities. After the preparation of the specimens, vertical and horizontal P-wave velocities and a vertical shear wave velocity were measured under different effective confining pressures. Numerically 5 independent elastic parameters of cross anisotropic soil samples were recovered. In terms of the anisotropy parameter (α), modified Young's modulus (E^*) and Poisson ratio (ν^*).

INTRODUCTION

The speeds of elastic (body)-waves passing through soils are affected by the characteristics of soils. Wave speed measurements are also low-strain tests. An approximate magnitude of strain falls into the range between 10^{-6} and 10^{-5}, the range is acceptable to determine elastic characteristics of soils from these wave speed measurements.

Many applications of wave speed measurements have been developed in the field and laboratory. Elastic constants, such as Elastic modulus and shear modulus (G_{max}), have been determined from wave speed measurements in different directions. These measurements and recovered elastic constants have been used to quantitatively identify soil anisotropy. Therefore, the pulse transmission has become a very popular method to measure elastic waves (P and S waves) propagating in soils in the laboratory.

The elastic behavior of many soils can be described by an elastic cross-anisotropic model with a vertical axis of symmetry. Based on this assumption, the five independent elastic constants must be determined independently for the elastic cross-anisotropic soil. Many researchers have evaluated the five independent constants of the model by means of elastic waves propagated through the soil at least along the two principal stress directions. However, mostly used triaxial dynamic test systems require cylindrical soil specimens and it is hard to do five independent elastic wave measurements in different directions. Graham and Houlsby (1983) proposed an anisotropic index parameter (α), Elastic Modulus (E^*) and Poisson ratio (ν^*) to assess elastic cross-anisotropic soil parameters.

In this study, medium dense (Dr=50%) soil specimens were created. After the preparation, vertical and horizontal P-wave velocities and a vertical shear wave velocity were measured under different effective confining pressures. α, E^* and μ^* values of the specimens were recovered to obtain five independent elastic cross anisotropic soil parameters.

ELASTIC CONSTANTS AND THEIR MEASUREMENTS

There is a proportional relation between the components of stress(σ_i) and the strain(ε_j) in a generally anisotropic elastic medium. This assumption can be identified by a set of well-known constitutive equations (Hooke's law). Due to the symmetries of the stress and strain tensors or the symmetry properties of the body, such as monoclinic, orthotropic, cross anisotropic and isotropic materials, constitutive Eq. 1 can be conveniently written in a matrix form containing six independent equations by

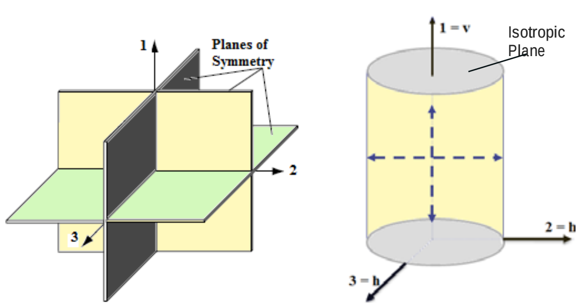
$$\sigma_i = C_{ij}\varepsilon_j \qquad \text{i,j = 1,2,3,4,5,6} \tag{1}$$

$$\varepsilon_i = S_{ij}\ \sigma_j \tag{2}$$

where C_{ij} and S_{ij} are the elastic stiffness and compliance tensors, respectively and there are only 21 independent elastic stiffness constants or elastic compliance coefficients.

$$C_{ij} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ & & C_{33} & C_{34} & C_{35} & C_{36} \\ & SYM & & C_{44} & C_{45} & C_{46} \\ & & & & C_{55} & C_{56} \\ & & & & & C_{66} \end{bmatrix} \tag{3}$$

If an elastic material has plane symmetry especially three mutually perpendicular planes of symmetry (Fig. 1.a), there is no interaction not only between normal stresses (σ) and shearing strains (γ) but also between shearing stresses (τ) and normal strains (ε).Such materials require 9 independent elastic constants in the stiffness matrix as given in Eq. 4. The material is also defined as an orthotropic material.



(a) (b)

Fig. 1 Plane symmetry for (a) orthotropic material (b) Cross anisotropic material (Sadd et al. 2005, Capar 2000).

$$C_{ij} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \tag{4}$$

If there is an axis of symmetry at any point such that the elastic properties in any direction within a plane perpendicular to the axis are all the same (Fig. 1.b), the plane is called an isotropic plane so the components of the stiffness matrix become five independent elastic constants. The material is called a cross anisotropic material. Its stiffness matrix can be given as:

$$C_{ij} = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{12} & C_{23} & C_{22} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \left(C_{11} - C_{12}\right)/2 \end{bmatrix} \tag{5}$$

Horizontally stratified soil deposits can be considered as cross anisotropic materials because many researches on soil microstructure show that soil particles arrangement (soil structure) in the vertical direction is easily affected by the influence of gravity. However soil particles are arranged randomly in the horizontal directions.

In the cross anisotropic cases, obtaining five elastic constants of soil must be determined independently as seen Eq. 6 and it is a formidable task. Many researchers have evaluated the five independent constants of the model by means of elastic waves propagated through the soil at least along the two principal stress directions.

$$[S] = \begin{bmatrix} 1/E_v & -\upsilon_{vh}/E_v & -\upsilon_{vh}/E_v & 0 & 0 & 0 \\ -\upsilon_{vh}/E_v & 1/E_h & -\upsilon_{hh}/E_h & 0 & 0 & 0 \\ -\upsilon_{vh}/E_v & -\upsilon_{hh}/E_h & 1/E_h & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{vh} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{vh} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{hh} \end{bmatrix} \tag{6}$$

$$\frac{\upsilon_{vh}}{E_v} = \frac{\upsilon_{hv}}{E_h} \tag{7}$$

Where,

$E_{v,}$ = Young's modulus for vertical direction

E_h = Young's modulus for horizontal direction

ν_{vh}= Poisson's ratio, strain in the <u>h</u> direction over the strain in the <u>v</u> direction due to stress applied in the <u>v</u> direction

ν_{hh}= Poisson's ratio for isotropic plane

G_{vh}= Elastic shear modulus in a vertical shear plane

G_{hh}= $E_h/2(1+\nu_{hh})$, Elastic shear modulus in a horizontal shear plane.

However, mostly used the triaxial dynamic test systems require cylindrical soil specimens and it is hard to do five independent elastic wave measurements in different directions. Graham and Houlsby (1983) proposed an anisotropic index parameter (α), Young's Modulus (E*) and Poisson's ratio (ν*) to assess elastic cross-anisotropic soil parameters (Ling at al. 2000)

$$\left\{\begin{aligned} E_v &= E^* \\ \nu_{hh} &= \upsilon^* \\ E_h &= \alpha^2 E^* \\ \upsilon_{vh} &= \frac{\nu^*}{\alpha} \\ G_{vh} &= \frac{\alpha E^*}{2\left(1+\upsilon^*\right)} \\ G_{hh} &= \frac{\alpha^2 E^*}{2\left(1+\upsilon^*\right)} \end{aligned}\right\} \tag{8}$$

$$[S]=\begin{bmatrix} 1/E^* & -\upsilon^*/\alpha E^* & -\upsilon^*/\alpha E^* & 0 & 0 & 0 \\ -\upsilon^*/\alpha E^* & 1/\alpha^2 E^* & -\upsilon^*/\alpha^2 E^* & 0 & 0 & 0 \\ -\upsilon^*/\alpha E^* & -\upsilon^*/\alpha^2 E^* & 1/\alpha^* E^* & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{2\left(1+\nu^*\right)}{\alpha E^*} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{2\left(1+\nu^*\right)}{\alpha E^*} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{2\left(1+\nu^*\right)}{\alpha^2 E^*} \end{bmatrix} \tag{9}$$

Therefore, the measurements of the directional elastic waves through a granular media have been one of experimental tools to recover elastic characteristics of soils. Based on the theory of plane wave propagation within an elastic body, compression wave (P-wave) and shear wave (S-wave) can be identified as function of ρ ,mass of the material, the components of elastic stiffness matrix, and d_1 ,d_2 ,d_3 direction cosines of the wave normal with respect to axes 1, 2, 3.

$$\left\{\begin{aligned} P-wave \Rightarrow V_P &= f_p(\rho, C_{ij}, d_1, d_2, d_3) \\ S-wave \Rightarrow V_S &= f_s(\rho, C_{ij}, d_1, d_2, d_3) \end{aligned}\right\} \tag{10}$$

In this study, the direction of wave measurements was chosen perpendicular or parallel to the principle axes 1, 2, 3. Therefore equation 10 can be simplified as follows:

P-wave velocity in the direction 1:

$$V_{p_V} = \sqrt{\frac{C_{11}}{\rho}} \tag{11}$$

P -wave velocity in the direction 2 or 3:

$$V_{ph} = \sqrt{\frac{C_{22}}{\rho}} \tag{12}$$

S wave velocity in the 1-2 plane:

$$V_{svh} = \sqrt{\frac{C_{44}}{\rho}} \quad \text{or} \tag{13}$$

LABORATORY EXPERIMENT

The focus of laboratory experiment is to quantitatively determine transversely anisotropic elastic constants of granular materials. Virginia Beach (VB) sand was used in this study. First index properties of the sand were determined. VB sand is uniformly graded, sub-angular sand. According to Unified Soil Classification System (USCS), it is poorly graded clean sand (SP). The specific gravity (Gs) of the sand was determined as 2.685± 0.012. The minimum and maximum dry densities are γ_{dmin}=14.48±0.017 kN/m^3 and γ_{dmax}= 16.56±0.016 kN/m^3 respectively.

In this study, the relative density of the reconstituted specimens was chosen to be 50% which represents a loose to medium-dense material. The relative densities of each specimen had to be between 48% and 52% to be accepted. Otherwise, specimen was rejected. The reason for choosing that kind of relative density was that the most liquefiable soils are saturated loose to medium uniform graded sand containing less than 5% fines.

Specimen Preparation Technique

Virginia Beach sand was poured into a flask. The flask was closed by a rubber stopper with a 6.35 mm diameter nozzle. The flask was placed upside-down above the mold. By rotating the flask, sand was poured into the mold from a controlled height (15.24 cm). The speed of rotation is important. A higher speed of motion could create a sample with a higher density. After some practice, the necessary rotational rate was experimentally established. To have 50% relative density for the VB sand specimen, the rotation speed was approximately 40-50 circles to have a one-inch soil layer in the mold

Measurements of Elastic Wave Velocities

The bender elements (10.41x10.41x6.1 mm), model number PZT-5B, were purchased from Morgan Matroc Inc. There are two different wiring connection possibilities for bender elements; serial and parallel connections. Two bender elements are embedded in the top cap and the pedestal of the triaxial device as receivers and transmitters in the vertical direction for P and S-waves. In addition, two bender elements are attached to the membrane surrounding the soil specimen to measure horizontal P-wave velocities as seen in Fig. 2.

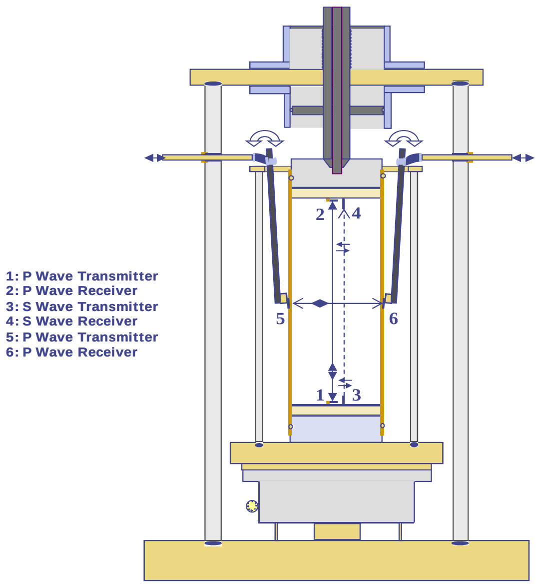


Fig. 2 Experimental setup

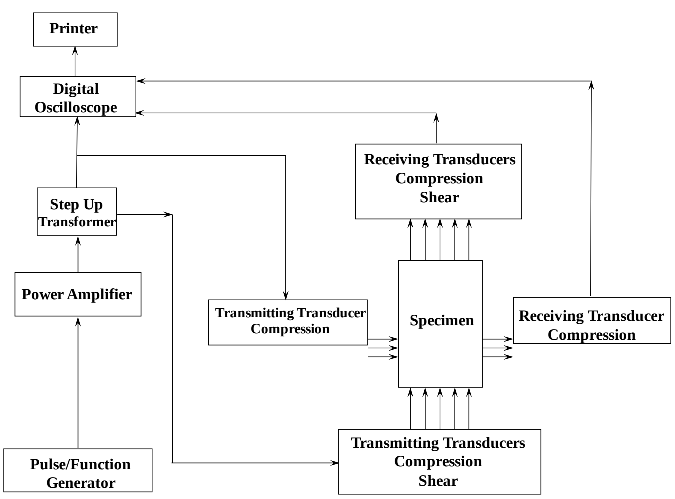


Figure 3 Electrical Connections Scheme

Electrical Connections

The pulse transmission system developed at Old Dominion University by Agarwal and Ishibashi (1992). The electrical source wave was generated by using a Hewlett Packard HP811A pulse/function generator capable of generating different shaped pulses such as sinusoidal, square, half square and triangle wave forms. In this study sinusoidal waveforms were used as input signals since all waveforms, except sinusoidal contain more than one frequency. In addition, after amplifying the input signals, the shapes of these waveforms are deformed easily, and interpreting the time difference between input and output signals becomes difficult.

The output range of the generator is between 0.15 and 15 volts and the frequency band can be adjusted from 0.1 Hz to 20 MHz. The amplitude of input wave signals generated was up to 10 volts. Since loose sandy materials have large damping characteristics, much higher than 15 volt magnitude of input signal is needed. Because a special amplifier and step up transformer were developed at Old Dominion University. The output voltage of the function generator could be amplified up to 1000 peak to peak volts. The output voltage of the function generator was changed from 1.5 to 11.0 volts to identify the effect on the received signals. When the soil specimens were dry, any output voltage of transmitted signal gave measurable data. It was found experimentally that l0 magnitude of input signal generate measurable elastic waves by the receivers. It should be noted that 10 volts of input signal were amplified to 160 volts by means of the power amplifier and further amplified through a transformer to step up the voltage up to 960 volts AC. This is very high amplitude. However, to pass noise levels and to transmit the wave on a loose sand specimen, this high amplitude was necessary. The magnitude of this reference wave signal that was directly sent to the oscilloscope was gradually reduced by a 1 megaohm resistor to protect the oscilloscope from the high voltage input. A correlation showing a reduction on the magnitude of the reference wave signal is illustrated in Fig. 3. The amplifier can produce a minimal change on the shape of the output signals. The reference signal must be taken just before a transmitter generates a pulse in the step-up transformer as seen in Fig. 3. The pulse transmission system has 5 μs delay-time.

Previous studies showed that if series connected bender element is used to generate P and S waves, it generate higher voltage than parallel connected bender elements but it creates lower motion than the parallel connected one does (Thomann and Hryciw 1990). However, the wiring of parallel bender elements is a very difficult. It is possible to damage bender elements during the process. In addition, bender elements need to be re-cut and this could reduce the efficiency of the bender elements. If an input signal was highly amplified, it can be easily detected by the serial connected bender elements. Therefore, serial connected bender elements were used for this research (Capar 2000).

Frequency of Elastic Waves

According to Nakagawa et al. (1996), P-wave and S-wave are not affected by the frequency of the waves. However, a certain frequency, close to the natural frequency of bender elements, can provide high output signals. In this study, experimental trials showed that the best readings occurred between 17 to 22 kHz for vertical P-wave bender elements (Fig. 4) and between 20 to 30 kHz for horizontal P-waves.

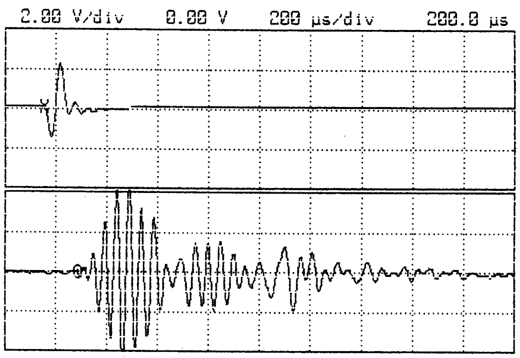


Figure 4 P wave(V_{pv}) speed measurements in the vertical direction at (f)=17 kHz. (Capar 2000).

Another observation was that when the input frequency of S-wave bender element was higher than 9 kHz, P-wave or unknown waves were generated by S-wave bender dements, and those were overlapped on the first arrivals of S-waves. As given in Fig. 5.

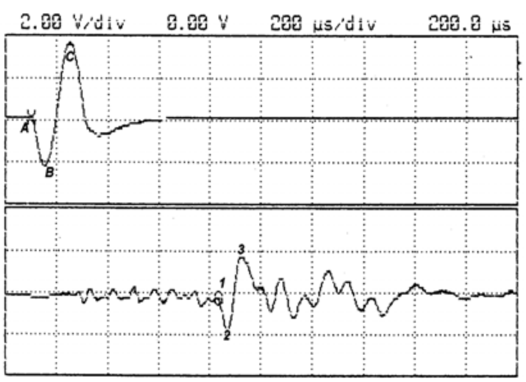


Figure 5. Typical S wave(V_{svh}) speed measurements in the vertical direction at (f)=9 kHz. (Capar 2000).

Additional consideration regarding to frequency of input signal is needed. Previous studies emphasized that the first arrival disturbance of a received wave may not represent the arrival of shear wave (Viggianni et al 1995, Jovicic et al 1996, Brignoli et al. 1996, Arroyo et al. 2003, Arulnathan et al. 2003, and Wang et al 2007). Some other waves could overlap shear wave signals. The first arrival wave was called a near-field component propagating in the specimen with the velocity of a compressional wave. Viggianni et al. (1995) suggested that because of a near-field effect, corresponding peaks of input-output signals can be more accurate to measure the travel time instead of using time difference between the first arrival time of input and output signals. Therefore, the near-field effects can be neglected.

RESULTS

After the preparation of the soil specimen was completed under 5 psi, vertical and horizontal P-wave velocities and vertical shear wave velocity were measured. Elastic wave velocities were also measured at the different effective confining pressures. During the tests, soil samples were dry because P-wave velocities cannot be measured correctly when the samples were fully saturated. Since loose density of the samples, the magnitude of P-wave velocities were almost same as the speed of P wave in the water.

It was found that P and S wave propagation are highly affected by effective confining pressure ($\sigma_3^/$). By using curve fitting techniques, following equations were obtained with high correlations (Capar 2000, Ishibashi et al. 2003).

$$V_{pv} = 203.43\left(\sigma_3^/\right)^{0.154} \tag{14}$$

$$V_{ph} = 148.99\left(\sigma_3^/\right)^{0.21} \tag{15}$$

$$V_{Svh} = 75.069\left(\sigma_3^/\right)^{0.2489} \tag{16}$$

where V_{pv}, V_{ph} and V_{Svh} are in m/sec, and ($\sigma_3^/$) is in kN/m^2.

In this experimental study, P-wave velocities in vertical and horizontal direction and S-wave velocity in vertical direction were measured individually by changing effective confining pressure starting from 34.35 to 344.74 kN/m^2 (in increment of 10 psi).

Recovery of Elastic Parameters

During the experiments, all elastic wave velocities were obtained in the 1-2 plane. From Eqs. 11, 12 and 13, the following 3 non-linear equations are derived.

$$V_{Pv}^2\rho - C_{11} = 0 \tag{17}$$

$$V_{Ph}^2\rho - C_{22} = 0 \tag{18}$$

$$V_{Svh}^2\rho - C_{44} = 0 \tag{19}$$

Also by using inverse of the compliance matrix [S] for cross anisotropic materials defined by Graham and Houlsby (1983), the components of the stiffness matrix such as C_{11}, C_{22}, C_{44} can be obtained as follows:

$$C_{11} = \frac{E^*(1-\nu^*)}{(1+\nu^*)(1-2\nu^*)} \quad (20)$$

$$C_{22} = \frac{E^*\alpha^2(1-\nu^*)}{(1+\nu^*)(1-2\nu^*)} \quad (21)$$

$$C_{44} = \frac{E^*(1-2\nu^*)}{2(1+\nu^*)(1-2\nu^*)} \quad (22)$$

Finally, combining Eqs. 17, 18 and 19 with 20, 21 and 22, three non-linear equations are made to obtain modified elastic parameters such as E^*, α and ν^*. Since the equations need to be solved numerical techniques, numerical analysis software was coded in Mathematica 7. This program uses Modified Newton-Raphson method for solving a system of nonlinear equations. For initial inputs, $E^* = 10000$, $\alpha=1$, $\nu^*=0.1$ and elastic wave velocities obtained from Eqs. 15, 16 and 17 at different effective confining pressure given in Table 1 were used to run the program.

Table 1 Initial Input Values of Elastic Wave Velocities

$\sigma_3^/$	Vp_v	Vp_h	Vs_{vh}
kPa	m/sec	m/sec	m/sec
50	371.58	338.80	198.76
100	413.44	391.88	236.19
150	440.08	426.71	261.27
200	460.02	453.29	280.66
250	476.10	475.03	296.69
300	489.66	493.57	310.47

Table 2 Calculated Modified Elastic Parameters at Different Effective Confining Pressures.

$\sigma_3^/$	E*	ν*	α
kPa	Mpa		
50	173.41	0.2713	0.9118
100	229.27	0.2374	0.9479
150	269.15	0.2144	0.9696
200	301.09	0.1964	0.9854
250	328.11	0.1814	0.9978
300	351.69	0.1683	1.0080

The results are given in Table 2 and plotted in Figs. 6, 7 and 8. As is known, anisotropic index parameter (α) shows the magnitude of fabric anisotropy for the material. If α is less than unity, the material shows more rigidity in vertical direction compare to the other directions. As seen in Table 2, α is less than 1 for low confining pressures. After confining pressure values pass 200 kPa, practically the soil samples show isotropic elastic behavior. It assumed that sand particles are orientated by increasing effective confining pressure.

Modified Young's modulus E^* values increase with increasing effective confining pressure. That means the sand samples are exhibiting a higher rigidity. However, Poisson's ratio (ν^*) values decrease with increasing the confining pressure. Consequently, lower Poisson's ratio was obtained when using the dynamic test method due to its higher stiffness. The dynamic test method can be conducted at the range of strain values falling in to between 10^{-6} and 10^{-5}. It is important results to consider the strain level affecting of determining the elastic properties of materials.

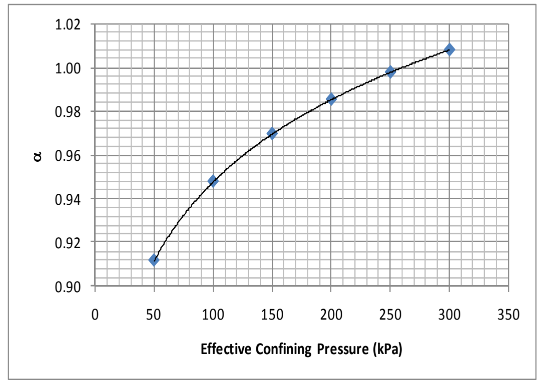


Figure 6 Index Parameters of Sand Specimens

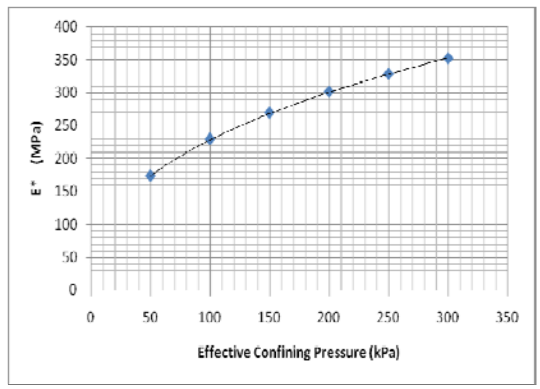


Figure 7 Modified Young's Modulus of Sand Specimens

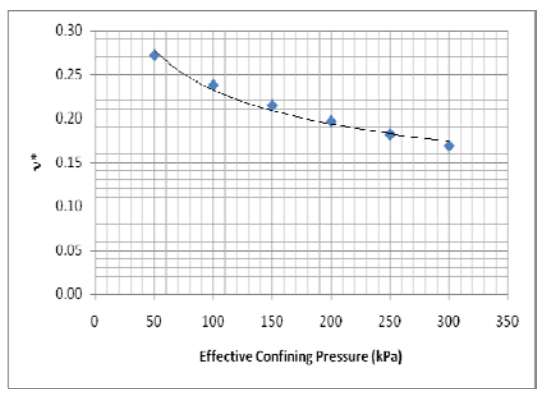


Figure 8 Modified Poisson's Ratio of Sand Specimens

After calculation of modified elastic parameters, Cross anisotropic elastic constants given in Table 3 were recovered from E^*, α and ν^*. Recovered cross anisotropic elastic constants of the sand specimens were also plotted in Figs. 10, 11 and 12.

Table 3 Values of Recovered Cross Anisotropic Elastic Constants for Sand Specimens

σ_3'	E_v	E_h	ν_{vh}	ν_{hh}	G_{vh}	G_{hh}
kPa	Mpa	Mpa			Mpa	Mpa
50	173.412	144.162	0.298	0.271	62.183	56.697
100	229.266	205.980	0.251	0.237	87.807	83.228
150	269.147	253.044	0.221	0.214	107.444	104.181
200	301.092	292.346	0.199	0.196	123.988	122.174
250	328.105	326.637	0.182	0.181	138.555	138.244
300	351.687	357.336	0.167	0.168	151.718	152.932

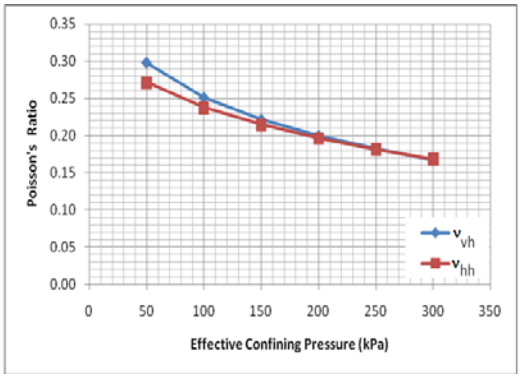


Figure 9 Cross Anisotropic Poisson's Ratio of Sand Specimens

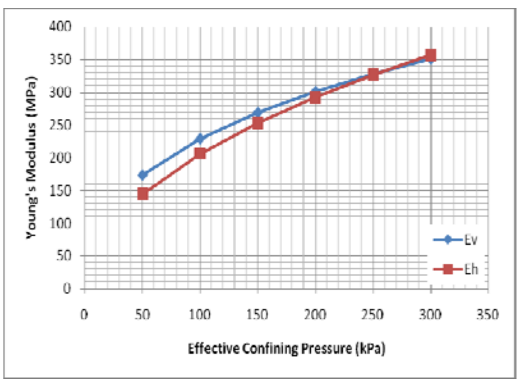


Figure 10 Cross Anisotropic Young's Modulus of Sand Specimens

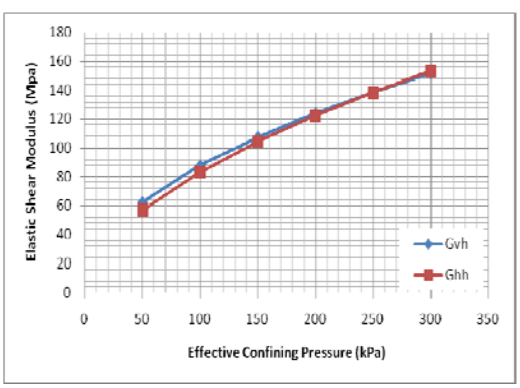


Figure 11 Cross Anisotropic Shear Modulus of Sand Specimens

Ling et al. 2000 indicated that although cross anisotropic elastic constants are independent, there are some constrains exist among the parameters due to positive strain energy or stored energy as follows:

$$\frac{E_v}{E_H}(1-\nu_{hh})-2\nu_{vh}^2 \ge 0 \tag{17}$$

$$G_{vh} \le \frac{E_v}{2\nu_{vh}(1+\nu_{hh})+2\sqrt{\left(\frac{E_v}{E_h}\right)(1-\nu_{hh}^2)\left[1-\left(\frac{E_h}{E_v}\right)\nu_{vh}^2\right]}} \tag{18}$$

Table 4 Control Values For Cross Anisotropic Elastic Constants

σ_3'	Eq. 17	Eq. 18
kPa		
50	0.699	62.183
100	0.723	87.807
150	0.738	107.444
200	0.748	123.988
250	0.756	138.555
300	0.763	151.718

Data given in Table 3 were used to check inequality Eqs. 17 and 18 and the results are listed in Table 4. According to calculations of the equations, anisotropic elastic constants meet the requirements.

CONCLUSIONS

In this study, medium dense (Dr=50%) soil specimens were created. After the preparation, vertical and horizontal P-wave velocities and a vertical shear wave velocity were measured under different effective confining pressures. α, E^* and μ^* values of the specimens were recovered to obtain five independent elastic cross anisotropic soil parameters. The following conclusions are made:

- Wave speed measurements without compromising the stress history of the soils to determine elastic constants of soils such as Young's modulus(E), Shear modulus (G) and Poisson's ratio(ν). Especially G and ν are difficult to obtained from standard soil mechanics laboratory equipment. The elastic wave measurement system is easy to install triaxial static and dynamic test apparatus. In this way, initial characteristics of soil specimens can be identified just before the destructive tests.

- Most soil deposits have fabric anisotropy due to gravity. Because many researches on soil microstructure show that soil particles arrangement (soil structure) in the vertical direction is easily affected by the influence of gravity. However soil particles are arranged randomly in the horizontal directions which means cross anisotropy. However, mostly used soil mechanics test systems require cylindrical soil specimens and it is hard to do five independent elastic constants of the soil sample. Graham and Houlsby (1983) model can reduce the number of the cross anisotropic material model to 3 independent elastic constants and By using the elastic wave measurement system installed triaxial dynamic test apparatus, the parameters of Graham and Houlsby model were determined.

- Cross anisotropic elastic constants, $E_{v,}$ E_h ν_{vh},ν_{hh} G_{vh}, and G_{hh} were recovered in terms of E^*,ν^*,α. The results show that evaluated values in concordance with constrain defined in Eq. 17 and 18.

- Numerically obtained values of the elastic constants show that soil specimens are stiffer in vertical direction at the low confining pressure; however, if the confining pressure passes 200 kPa, the soil specimens become stiffer in all directions not just in the vertical directions. In other words, the specimens exhibit isotropic behaviors.

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