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Development of large size Disk Transducer to evaluate elastic properties of coarse granular materials

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ABSTRACT: A new type of Disk transducer with the size of 80 mm diameter has been developed by assembling p-type piezo ceramic elements and s-type piezo ceramic elements, in order to carry out the elastic wave study of small to large grain size geomaterials. It has been proved that by using multiple numbers of piezo ceramic elements, development of required size of wave measurement device (i.e. disk transducer) is possible. To clarify the workability and applicability of such disk transducer, elastic properties of Toyoura sand (D50 = 0.20mm), Silica sand (D50 = 1.7 mm) and Ooiso gravel (D50 = 12mm were evaluated by three sorts of method (i.e. static method, disk transducer method and Trigger accelerometer method) by using the large triaxial apparatus with the rectangular prismatic specimen of 50cm*23cm*23cm. All the tested sample were in completely dry condition. Applying 11 number of very small strain (i.e. strain less than 0.001%) cyclic loading young's modulus and Poisson's ratios were derived and shear modulus were calculated. Both the axial and radial strain was locally measured by local deformation transducers. Newly developed large size disk transducer has been used to evaluate the elastic properties by wave measurement method. Trigger Accelerometer method was also used to compare the elastic wave properties obtained by elastic wave propagation method. To prove the reliability, consistency and further application on the geotechnical engineering study elastic properties measured by newly developed disk transducer method were compared with previous research and the stiffness found to be fallen in similar range within allowable scatters.

The stiffness of Silica sand and Ooiso gravel shows lowest and highest stiffness value respectively by all three methods in this study. Whereas the Static and accelerometer gives lowest and highest stiffness respectively. Overall trend of Poisson's ratio has been slightly decreasing with increasing the stress states.

The comparison of the static and dynamic method results shows the difference between the statically and dynamically measured properties of geomaterials may be because of grain size of geomaterials, input wavelength and inherent anisotropy of the specimen.

Key Words: Large size Disk Transducer, Small strain stiffness, laboratory test method, shear wave velocity

INTRODUCTION

After reorganizing static and dynamic properties are no more different from each other at very small strain level (woods, 1991), dynamic methods of evaluation also popular among the researchers for their rapid, non-destructive, and low-cost evaluation methods. By knowing the elastic wave velocities as measured with the wave-based techniques and density of the geomaterials, the stiffness of the geomaterials can be determined. Elastic wave measurement based on the cross-hole and down-hole methods have been used for long time in real construction sites(Stokoe and Hoar, 1978). In parallel to these many researchers have introduced various wave measurement systems particularly a shear or S-wave velocity for the calculation of shear modulus of geomaterials. Such as shear wave measurement by shear plates (Lawrence 1963, 1965), resonant column tests (Hardin and Drnevich 1972), and bender elements (Shirley and Hampton 1978). Because of the large size and need for the high excitation voltage (Ismail et al. 2005) use of the shear plates is limited. And the resonant

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column test has disadvantages like complexities and high cost of test equipment's. In contrast, a bender element is the most popular means of wave measurement in research on geotechnical engineering field because of not only their smaller size, and lower voltage required and easier operation but also cost-effectiveness and provides the realistic design parameter. By using bender element many researcher carried out the dynamic methods of investigations of clayey and sandy soils.

After the (woods, 1991), Dynamic and static properties are no more different from each other except for the strain levels, from the field and laboratory test of rocks and soils (Tatsuoka and Shibuya, 1992) reported that the precise measurement of the small strain can merge the gap of dynamic and static behavior of soils. The compared results from bender element, resonant column, static torsional and Triaxial tests on ham river sand, confirmed that static and dynamic stiffness were similar to each other at very small strains (Porovic and Jardine, 1994). With the introduction of new method so called Trigger and accelerometer method (TA method) of wave measurement on the laboratory it is reported that the difference between the dynamic and static properties of geomaterials is not only associated with the strain level but also affected by the grain size of geomaterials and input wavelength (AnhDan and Koseki, 2002). Disputable issue emerges in decades to the definitions of static and dynamic properties. The dynamic modulus obtained from wave velocity depend on the density of specimens(Tsutsumi 2006). The difference between statically and dynamically measured stiffness is due to possibly to the effects of heterogeneity of the specimen (Qureshi 2006). With the increment of input frequency the increasing trend of stiffness was investigated on Toyoura sand and Hime gravel (Wicaksono, 2007).

However, the application of wave measurement to coarse grained material is not easy, because of the tested material does not behave as continuous media. Besides this, to study the coarse grain geomaterials, large size testing apparatus is necessary. And some researcher pointed that to avoid the bedding error the size of piezo ceramic element should be at least 10 times more than the mean diameter of material. So, none of the successful elastic wave study has been carried out on the large grain size material yet, because of the limited availability of large triaxial cell and unavailability of appropriate elastic wave measurement device in laboratory. Considering these facts, this study focused to the development of large size wave measuring device which must be applicable to study the elastic wave properties of geomaterials having small to large grain on single apparatus. But the problem was about the size and capacity of laboratory wave study device. Recently developed DT method (Suwal and Kuwano, 2010)) gave better result than bender element in laboratory soil testing because of its completely flat surface. In addition, undisturbed and cemented material can also be tested easily. In this method compression wave, shear wave and both compression and shear waves together are excited at transmitter and responses on receiver (transducer) is possible. However it is not useful for large triaxial apparatus with the specimen size of 50cm*23cm*23cm triaxial cell available in IIS, The University in Tokyo because of the limitation of size and working capacity. In addition the amplitude of Received signal decrease with the increase in specimen length and more than 20mm size Piezo ceramic disk is not available in market. Hence to facilitate the study of elastic wave of large size granular material in large triaxial cell large size disk transducer needs to be developed.

Transducer for Wave measurement

Piezo-ceramic elements

The direction of the deformation of piezo-ceramic depends on the shape and composition of ceramic disk, direction of poling axis and applied electric field. A flat shaped P-type piezo-ceramic element is polarized in the direction perpendicular to the electrodes whereas S-type element is polarized in the direction parallel to the electrodes. As shown in figure 1 upon the application of electric voltage the direction of polarization is the direction of thickness of the element, so it generates compression wave. Flat disk having the properties as shown in table 1 were used in this study.

Development of large size disk transducer

As shown in figure 2, a large size i.e. 80mm dia. Disk had been developed as a single unit having the properties to the piezo ceramic disk. Total eight numbers (4 p-types and 4 s-types) of piezo elements were used in this study.

The PS type element having the property to transmit and receive both the compression and shear wave

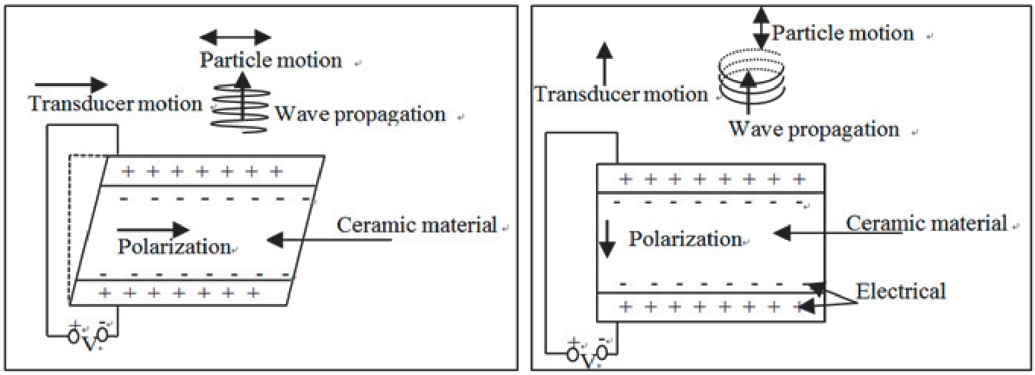


Figure 1. Schematic figure of piezo ceramic element: S-type element (left) and P- type element (right)

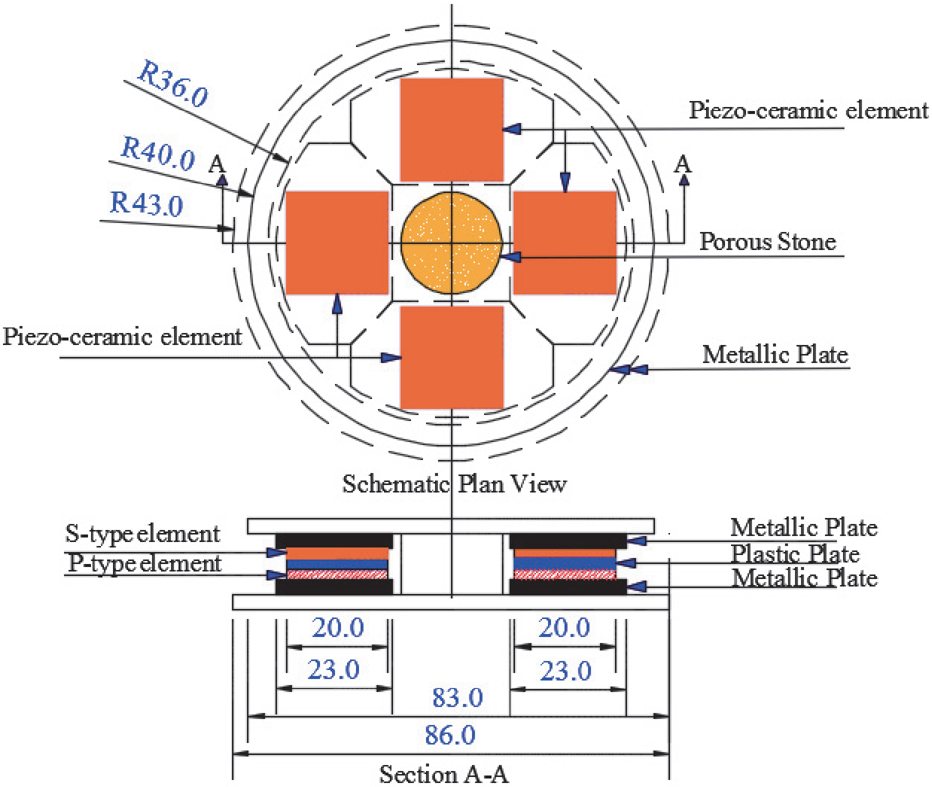


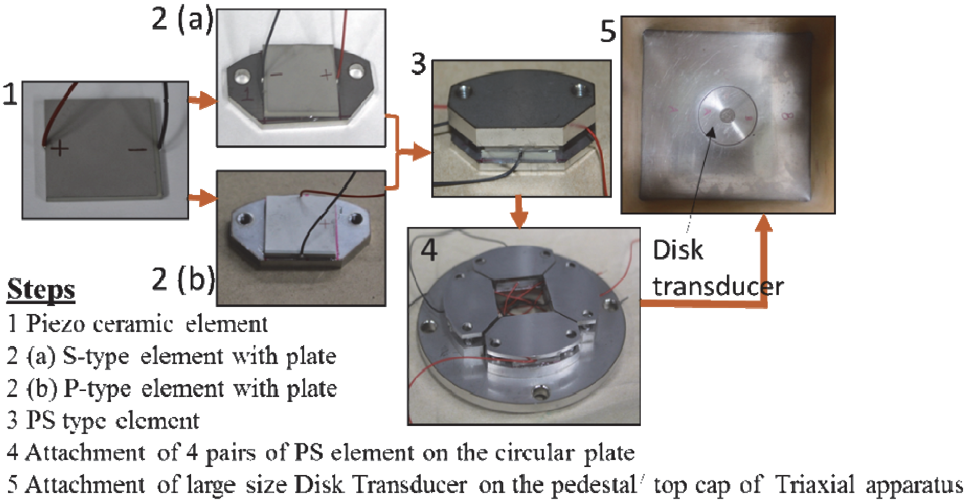
Figure 2. Schematic figure of large size Disk transducer

was made by merging the P-type and S-type element by applying the rapid araldite and to protect from being cross connection a small plastic plate having a thickness of 2mm was placed between them before merged together. Other two metallic plates were glued on the both side of such PS type element for the same. A circular metallic plate of diameter 80mm was screwed with 4 sets of PS element on the P side. S side of PS element was glued with another metallic plate to ensure the free movement of S element in the horizontal direction. Figure 3 explains the steps followed during the development procedure. During this procedure the polarization direction of s-type element should be same orientation to protect from being independent movement of piezo element on the application of electric field.

Items		k15*	C**	Mean Length	Mean Width	Mean Thickness
Unit		(%)	pF	mm	mm	mm
P-type, Z2T20×20S-LLYXN(C-6)	Maximum value	54.7	4310	19.99	19.99	2.012
	Minimum value	53.1	4060	19.87	19.87	2.005
	Average	54.32	4147.5	19.957	19.94	2.0101
	Standard deviation	0.677	67.27	0.0341	0.0247	0.00186
S-type, SZ2T20×20S-LLYX (C-6)	Maximum value	69.7	4540	20.07	19.99	2.007
	Minimum value	69.1	4450	19.96	19.89	1.995
	Average	69.39	4502.5	20.036	19.944	2.0001
	Standard deviation	0.118	26.93	0.0349	0.0313	0.00352

*coupling factor, ** electro static capacity

Table 1. Properties of used Piezo element



Steps

1 Piezo ceramic element
2 (a) S-type element with plate
2 (b) P-type element with plate
3 PS type element
4 Attachment of 4 pairs of PS element on the circular plate
5 Attachment of large size Disk Transducer on the pedestal/ top cap of Triaxial apparatus

Figure 3. Development steps of large size Disk Transducer

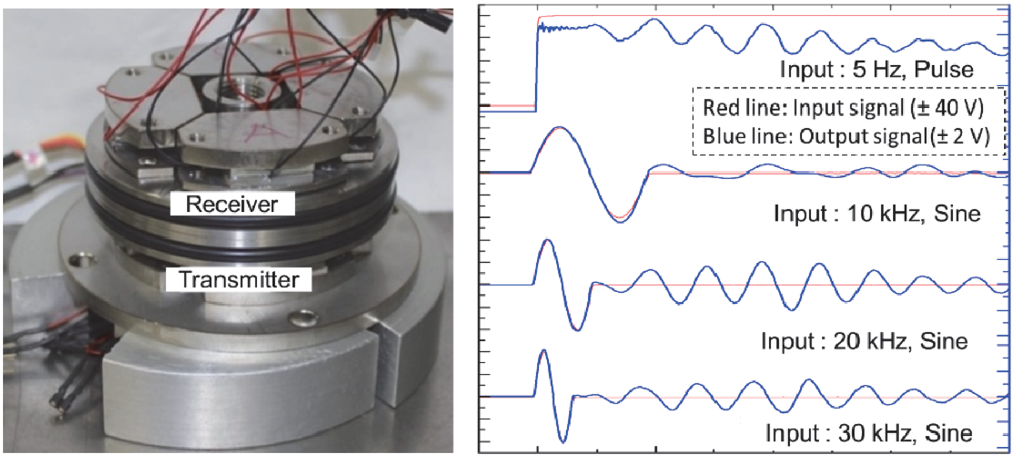
After the assembling procedure, proper connection of plates and ceramic element must be ensured. The connection between the piezo elements and plastic element, piezo elements to metallic plates should be checked carefully to make the noise free disk transducer. The wire connection in the transmitter was parallel because to give same voltage input from the entire transmitting piezo-ceramic element. On the other hand, for the receiver wire connection was made in series to gain the voltage as much as possible.

o*Verification of workability*

Verification of workability

Since, newly developed disk transducer is assemblage of multiple number of piezo ceramic elements, First necessary thing to be checked is the time required to travel from the piezo element to the top surface of the Disk Transducer because the distance of s-type and p-type element from the top surface are 8mm and 12mm respectively. For this, a test (calibration) of disk was carried out by facing the transmitter and receiver of disk each other as shown in figure 4 [A]. This test was conducted without applying the load. The signals were transmitted through the transmitting disk and received by the receiver. Both input and output signal were recorded by the “HIOKI 8860-50 MEMORY HICORDER” Oscilloscope on various input frequencies. Figure 4[B] shows the typical S-wave form recorded on the pulse 5 Hz, Sine 10 kHz, Sine 20 kHz and Sine 30 kHz in time domain series at input voltage of 80 Volt. Considering the peak of the input and output signal as well as rising of the input and output signal, no time difference between the input and output signal was recorded in all frequencies. Similar phenomenon have been recorded on the p-waveform too.

Another things to be considered is to know the amplitude of the receiving signal with the increasing number transmitting and receiving piezo element, similar test were carried out as above condition. First the oscilloscope was connected with only one receiving piezo element. Then, transmitter was excited through one piezo element and signals were recorded on oscilloscope. By keeping one element



[A]

[B]

Figure 4. [A] Disk transducer, [B] S-waveform obtained at different frequency input

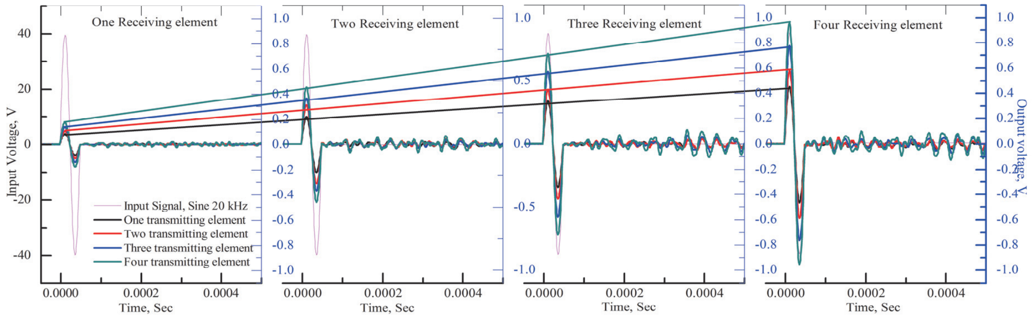


Figure 5. P- waveform obtained on sine 20 kHz input frequency at various combination of piezo element

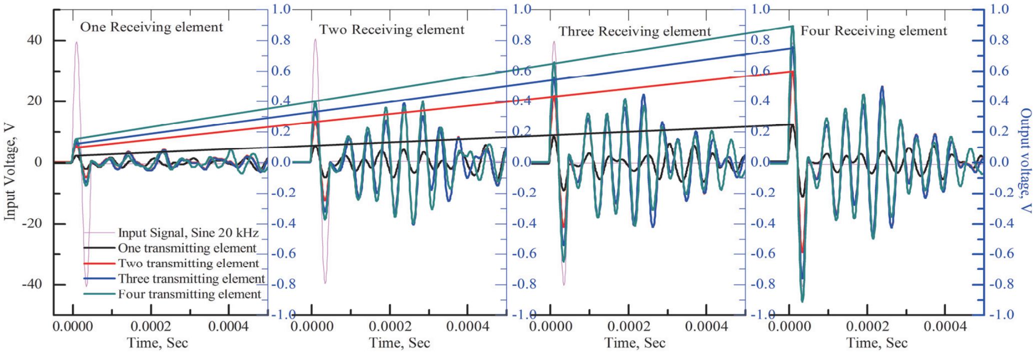


Figure 6. S- waveform obtained on sine 20 kHz input frequency at various combination of piezo element

connected on receiver and by increasing total number of transmitting element from one, two, three and four in transmitter, receiving signal were recorded. Similar, test were conducted for the total number of receiving element one , two, three and four at different frequencies such as pulse 5Hz, sine 10 kHz, sine 20 kHz and sine 30 kHz. Figure 5 shows the p-wave waveforms with varying transmitting and receiving element at different input frequency. First part of the graph represent for one receiving element and varying transmitting element. Similarly in second part two, third part three and fourth part represent the four receiving piezo element. All the waveforms at different frequency input shows that by increasing the number of transmitting element and receiving element the amplitude of receiving signal is increased. In case of s-wave waveforms similar result were obtained and shown in the figure 6.

MEASUREMENT ON GRANULAR MATERIALS

Material used:

In this study, three types of material were used Toyoura sand (D50 = 0.20mm) as a fine geomaterial, Silica sand (D50 = 1.7 mm) as a medium geomaterial and Ooiso gravel (D50 = 12mm) as a coarse geomaterial. Toyoura sand is fine grained, uniformly graded, and yellowish brown in color. It contains well rounded quartz particles because it derived from the siliceous rocks and shale. Silica sand consists of well-rounded particles and composed of almost pure quartz grains. This sand is one of the popular sand in the world. The grain size of silica sand can be varies from fine to coarse grain because it is produced by the degradation of quartz. Depending upon the grain size silica sand labeled with different number. In this study, Silica sand number 3 was used. Ooiso gravel is originally taken from the Ooiso, Kanagawa prefecture, Japan. This gravel is well rounded particle and looks like a pebbles. The photograph of the used materials is shown in Figure 7. Physical properties including specific gravity, maximum and minimum void ratio and mean diameter are shown in Table 2 and gradation curves is shown in Figure 8.

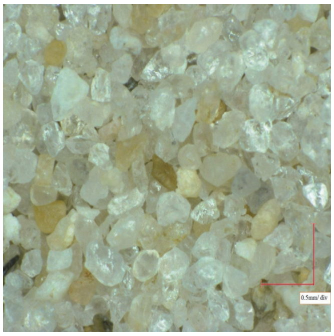


Figure 7. (a) Toyoura sand

Figure7. (b) Silica sand

Figure 7. (c) Ooiso gravel

Physical and mechanical Properties	Toyoura sand	Silica sand	Ooiso gravel
Specific gravity, G_s	2.62	2.63	2.57
Maximum void ratio, e_{max}	0.946	0.89	0.58
Minimum void ratio, e_{min}	0.637	0.70	0.480
Mean Diameter, D_{50} (mm)	0.19	1.7	12

Table 2. Properties of used materials

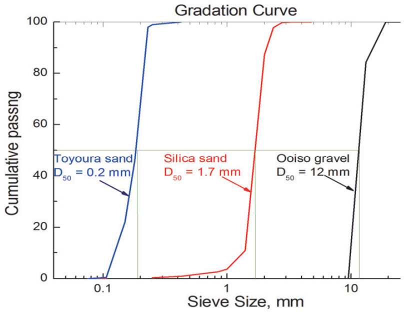


Figure 8. Gradation curve

Triaxial apparatus and wave measurement equipment
The large tri-axial apparatus available in the geotechnical laboratory at IIS, The University of Tokyo is used for this study. To install the elastic wave measurement device (i.e. Disk Transducer) in the top cap and pedestal necessary modification was done particularly for the present study. Although this is a true tri-axial cell, in this study it is used as a conventional tri-axial apparatus.

The large scale tri-axial apparatus used in this study is shown in Figure 9. It has a stainless-steel cell, having the capacity of 2.94MPa for the cell pressure and 490 kN for the axial loading. The axial loading is controlled by the load cell attached just above the top cap of the pedestal. The cell pressure controlled device pneumatic pressure of about 1 MPa is amplified by an air-driven pump up to 3MPa. This is regulated by an electro-pneumatic servo valve. A personal computer is connected with the tri-axial apparatus to control, measure the data and feed back to the system. The personal computer is capable of various operations like setting the test conditions, control of machines, recording of data and processing of data.

Specimen preparation and testing procedure
Considering the properties of testing material, air pluviation technique was adopted to prepare the specimen for the Toyoura sand and Silica sand. In this method approximately homogenous density was maintain by controlling the pluviation height and changing the pouring direction from clockwise to anticlockwise of vice versa. But for the Ooiso gravel Tamping method was adopted because of large grain size. To control the density, The height of specimen was divided into 10 layers(i.e. 5 cm each) and tamping number were used equally in all the layers. All the tested specimen were prepared in completely dry condition with dimension of approximately 23cm*23cm*50cm at 40 kPa negative stress state.

Transducers for strain measurement:
Axial (vertical) and lateral (radial) strains are monitored by Local Deformation Transducer (LDT). LDT is the strain gauge based transducer developed in laboratory following to Goto et al., 1991, which can measure local strain in higher accuracy and free from bedding errors. In this study, LDT were used to measure both the axial and radial strain. To measure the axial strain, 6 numbers of LDT were fixed vertically at different location of specimen. Similary to measure the radial strain, 6 numbers of LDT were fixed horizontally at different position of specimen. Each LDT was attached on the specimen with the help of hinges glued on the membrane.

Wave measurement equipment:
There was a separate wave measurement unit for transmit the signal in to the specimen and receive the signal from the specimen. In order to generate the transmitted signal function generator was used. In this study function generator manufactured by "Textronix Co. Ltd., Model: AFG3021" was employed. It is capable of producing peak to peak voltage of 10V and twelve kinds of different waveforms at frequency ranges from 0.001Hz to 25MHz. The trigger rate range of this function generator is from 1ms to 500seconds.


Figure 9. Large Triaxial cell

An amplifier is used to magnify the input signal before transmitting into the disk transducer. The signal produce from the function generator is not enough to produce stable and distinct signal waveforms. So, this device amplified the signal as required manner before transmit through disk transducer. In this study an amplifier manufactured by the "NF

Corporation, Japan, Model: Has4014", was used. An oscilloscope record and displays the waveform of transmitted and received signals. The oscilloscope used in this study is "HIOKI 8860-50 MEMORY HICORDER".

Loading Sequence: As schematically shown in figure 2.18, the specimen was prepared at isotropic stress state of 40 kPa. Then stress level was increased up to 50 kPa. The specimen was subjected to creep condition for the at least 10 minutes to dissipate the stress thoroughly in the specimen. Then 11 number of cyclic loading were applied ensuring that strain is in the range of 0.001%. Again creep stage was applied for the elastic wave measurement in the specimen. Elastic wave measurements were carried out by two methods, one is Disk Transducer method and another is Accelerometer method. In accelerometer method, disk transducer was worked as a source instead of conventional trigger. So, both Disk transducer and accelerometer methods were carried out simultaneously.

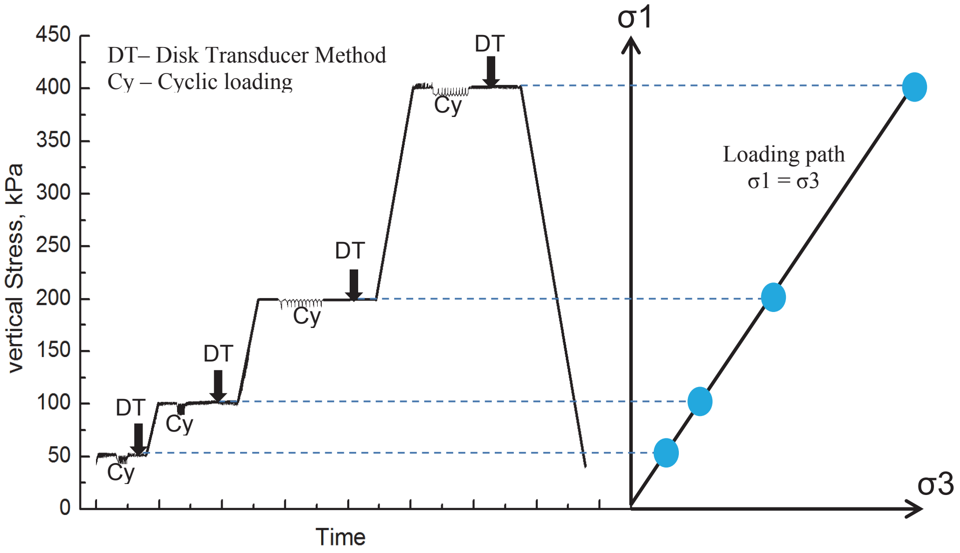


Figure10. loading sequence

Data acquisition and analysis:
In this study, static small strain stiffness was obtained by static triaxial cyclic loading tests with a single amplitude principal strain less than the threshold value of about 0.001% (Hoque, 1996; Jiang, 1996). The quasi-elastic properties evaluated within this small strain range are almost free from the influence of stress-strain histories that are small enough to maintain the initial fabric, type of loading (monotonic or cyclic), wave-form during cyclic loading and rate of shearing (dynamic or static) (Tatsuoka and Kohata, 1995). For small vertical cyclic tests at constant lateral stress (i.e., $\Delta\sigma h = 0$ and $\Delta\sigma v \neq 0$);

$$E_v = \Delta\sigma_v / \Delta\varepsilon_v \,, \qquad \text{And} \qquad \nu_{vh} = -\Delta\varepsilon_h / \Delta\varepsilon_v$$

Where, Evis the equivalent quasi-elastic Young's modulus in vertical. The parameters Ev and νvh could be evaluated from small vertical cyclic loadings. In this thesis, the elastic Young's modulus in vertical direction andpoison'sratio at the isotropic stress state at 50, 100, 200 and 400 kPa was evaluated. Shear modulus were calculated by using the young's modulus and poison's ratio. The typical example of the calculation of young's modulus and poison's ratio is shown in figure 4.2.

The velocity of waves were determined by,

Compressional wave velocity, VP = H/ Tp
Shear wave velocity, Vs = H / Ts
Where,
H = the height of specimen (distance between transmitter and receiver)
Tp = time period to propagate the compressional wave from transmitter to receiver
Ts = time period to propagate the shear wave from transmitter to receiver

Shear modulus (G), constrained modulus (M) and young’s modulus (E) can be calculated by using following formula.

Shear modulus (G) = ρ*Vs2
Constrained modulus (M) = ρ*Vp2

Young’s modulus

$$(E) = \frac{M(1-2\nu)(1+\nu)}{(1-\nu)}$$

Based on an anisotropic elasticity modeling proposed by Tatsuoka et al. (1999) considering both the inherent and stress induced anisotropy, shear and young’s modulus is related as,

$$G = \frac{E\ 2(1-\nu)}{2(1+\nu)1 + aR^{n} - 2\sqrt{a}..R^{n/2}\cdot\nu}$$

Where,
a = the coefficient on the degree of inherent anisotropy
R= the stress ratio (R= σv/σh)
n = the stress state dependency coefficient

When isotropic stress condition is considered (R=1) and inherent anisotropy is neglected (a=1), the above equation becomes,

Both shear modulus and young’s modulus are function of velocity of wave. So Poisson’s ratio in

$$G = \frac{E}{2(1+\nu)}$$

isotropic stress states can be computed in terms of velocity.

INTERPRETATION OF SIGNALS IN THIS STUDY

To study the elastic properties of geomaterials elastic wave velocity measurement is necessary. Wave velocity measurement requires the travel distance of wave i.e. distance between the transmitter and receiver of the disk transducer and time required to propagate the signal from transmitter to receiver. Compressional wave arrival time is relatively easier than shear wave arrival time. Near field effect, reflection and refraction of waves makes difficulty to detect the accurate arrival point.

There are a lot of methods to estimate the arrival time of wave such as cross correlation method (Viggiani and Atkinson 1995, Moshin et al. 2004 and Want et al. 2007), time domain analysis (Viggiani and Atkinson 1995, Arulnathan et al. 1998, Clayton et al. 2004), frequency domain approach (Viggiani and Atkinson 1995, Brocanelli and Rinaldi 1998, Greening et al 2003), multiple reflections (Arulnathan et al. 1998), wavelet analysis (Brandenberg et al. 2008) and variable path method (Boonyatee T. et al. 2009). However in this study time estimation by measuring the first major deflection of the received signal also known as the rise to rise method (Kawaguchi et al, 2001) was employed for the Accelerometer method. In case of disk transducer method travel times were obtained by considering the difference of time between the peak of the input signal and peak of the received signal i.e. peak to peak method (Viggiani and Atkinson 1995). Both the method are presented in the figure 11 and 12.

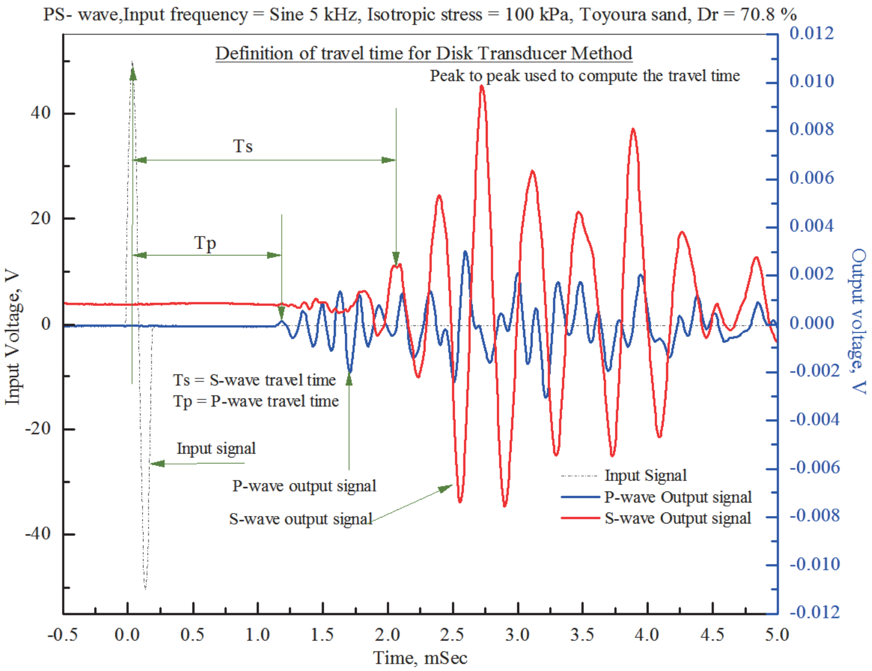


Figure 11. Definition of arrival time period for Disk Transducer method

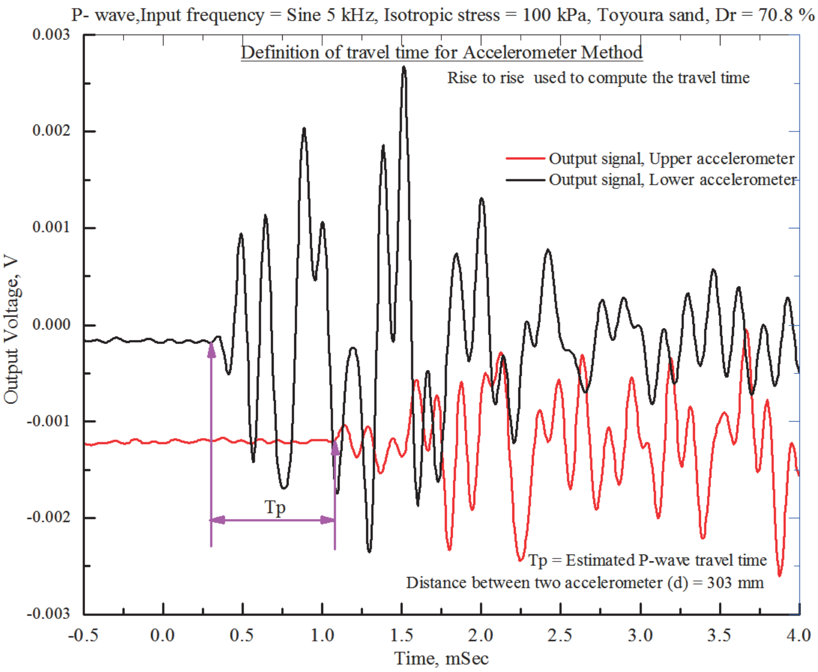


Figure 12. Definition of arrival time period for Accelerometer method

TEST RESULTS AND DISCUSSIONS

Test cases

In this study, elastic properties of three types of materials (Toyoura sand, Silica sand and Ooiso gravel) were evaluated. For each material two test has been carried out. The specimen size in all test cases is about 50cm*23cm*23cm. The elastic properties (Young's modulus, shear modulus and Poisson's ratio) were evaluated at isotropic stress state of 50 kPa, 100 kPa, 200 kPa and 400 kPa. All the tests were carried out in dry condition. Because dynamic and static measurements were done at almost same conditions (i.e. specimen and stress level), the possible change in void ratio, temperature etc. were ignored in this study. In case of Toyoura sand, test 1 (T-1) has the relative density 73% and test 2 (T-2) has 70.8%. For the silica sand test one and test two has 89.2% and 79.01% relative density respectively. For the Ooiso gravel, because of difficultly to compaction density becomes almost similar test one is 91.36% while test two is 91.66% relative density.

Evaluation of small strain stiffness

As already explained in the static method of testing, eleven number of cyclic loading were carried out in 50 kPa, 100 kPa, 200 kPa and 400 kPa stress state in each test. Strain level in each cycle of loading should be around 0.001%. Figure 13 shows the typical axial and radial strain during small cyclic loading of Toyoura sand at 400 kPa stress state. The axial strain is about 0.001% and the radial strain is less than 0.0002%. Both the strain measurements were compute by averaging 6 numbers of LDTs in both the direction. The axial strain is plotted in square symbol indicating scale in left side of graph, while radial strain is plotted in circular symbol indicating scale in right side of the graph. Using the axial strain computed and respective vertical stress state Young's modulus of Toyoura sand is evaluated. Typical measurement of Young's modulus of Toyoura sand at isotropic stress state of 200 kPa is shown in figure 14.

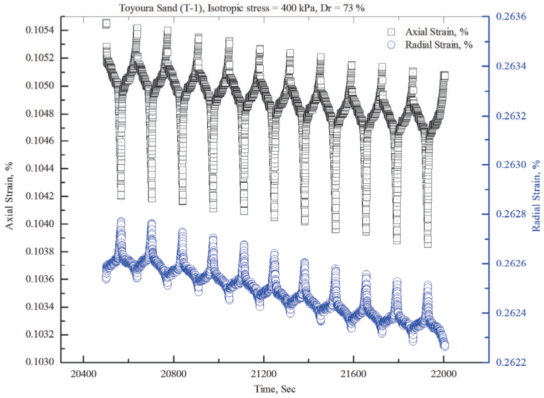


Figure 13. Axial and Radial strain during cyclic loading on Toyoura sand

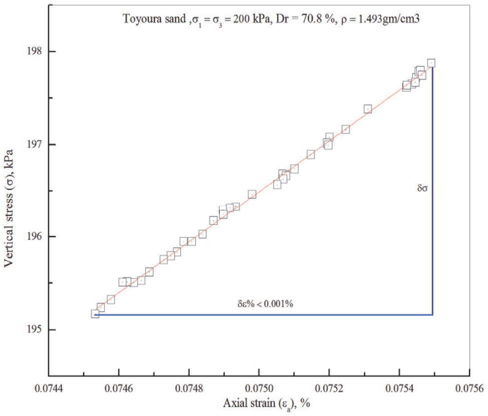


Figure 14. Typical stress-strain relationship on Toyoura sand

Disk transducer and Accelerometer method of elastic wave propagation method are used to evaluate the elastic properties of Toyoura sand. As explained in the loading sequence elastic wave study at 50 kPa, 100 kPa, 200 kPa and 400 kPa is done. The typical compressional and shear waveforms at 5 kHz input frequency in different isotropic stress state by Disk transducer method are shown in figure 15. In the waveform plot input signal is presented in volt at left side and received signal in millivolt at right side. The compressional and shear waveform by Accelerometer method at 5 kHz input frequency in different isotropic stress state level is plotted in figure 16.

Using such kind of waveform and applying the before mentioned analysis method and formulae stiffness had been calculated. In this calculated stiffness void ration have been nullify by using the void ratio function f(e). By such a way calculated normalized shear modulus from all the methods on Toyoura sand are plotted in figure17. Both the normalized shear modulus and isotropic stress are in logarithmic scale. The newly developed disk transducer gives the acceptable closeness (i.e. less than 10%) to the static method. While accelerometer method gives higher stiffness than both methods.

Further, to prove the reliability of newly developed flat shaped large size disk transducer, the result obtained in 50cm length specimen (i.e. specimen adopted on this study) by static as well as large size disk transducer method are compared with the previous research (Suwal 2013). The previous research was conducted in same batch of Toyoura sand at author's laboratory just one year before by using the 20 mm size disk transducer. This research experimental methodology is completely matched with the previous research so author took the 5 experimental data of Toyoura sand which is conducted in small triaxial cell having the specimen dimension 15cm height and 75 mm dia.

The normalized Shear modulus of Toyoura sand obtained in author's research (i.e. 50 cm length specimen) and previous research (i.e. 15cm length specimen) are compared and plotted in figure 18.The stiffness result shows the consistent result in both researches. The small strain stiffness measurement by applying the newly developed large size disk transducer performed well and applicable for further study. So, author decided to use such disk transducer to elastic wave study of coarser geomaterials than Toyoura sand (D50 = 0.20mm) and brought out the study on Silica sand (D50 = 1.7 mm) and Ooiso gravel (D50 = 12mm).

The normalized shear modulus calculated from all the methods on silica sand are plotted in figure 19. Figure 20 represents the stiffness of Ooiso gravel. Both the normalized shear modulus and isotropic stress are in logarithmic scale. In both materials the stiffness obtained on the disk transducer method has close relation than the stiffness by accelerometer with static method. Initially at 50 kPa stress state the difference of stiffness given by disk transducer and static method is large but with increasing the stress state the closeness is decreasing. Whereas the stiffness by accelerometer shows inconsistent and scattered and much higher than other two methods.

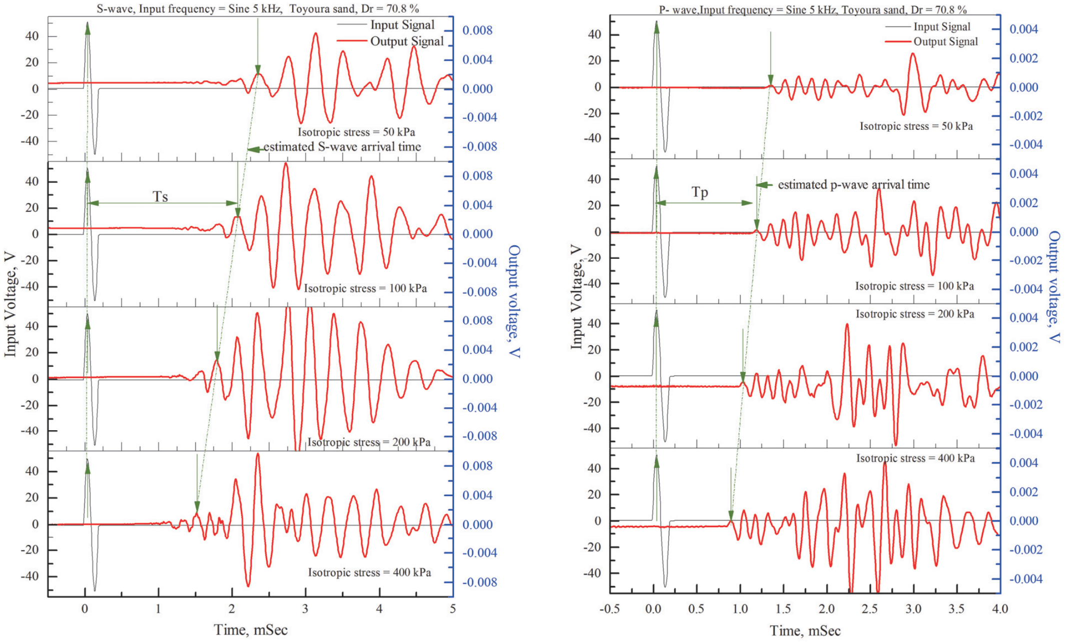


Figure 15. Waveforms obtained on Toyoura sand by disk Transducer method

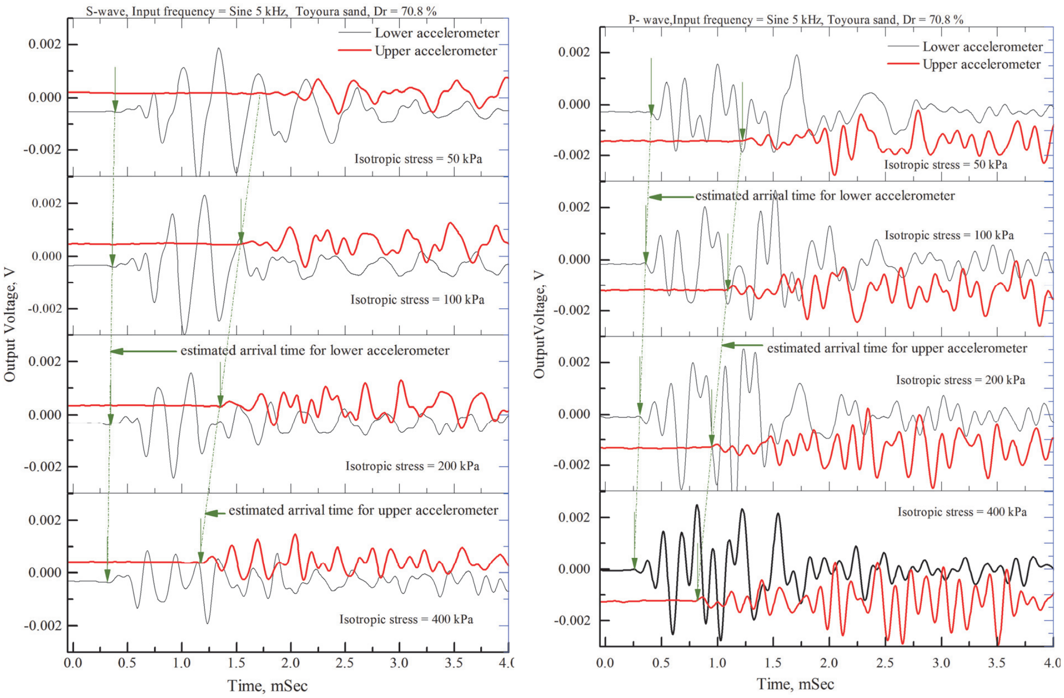


Figure 16. Waveforms obtained on Toyoura sand by Accelerometer method

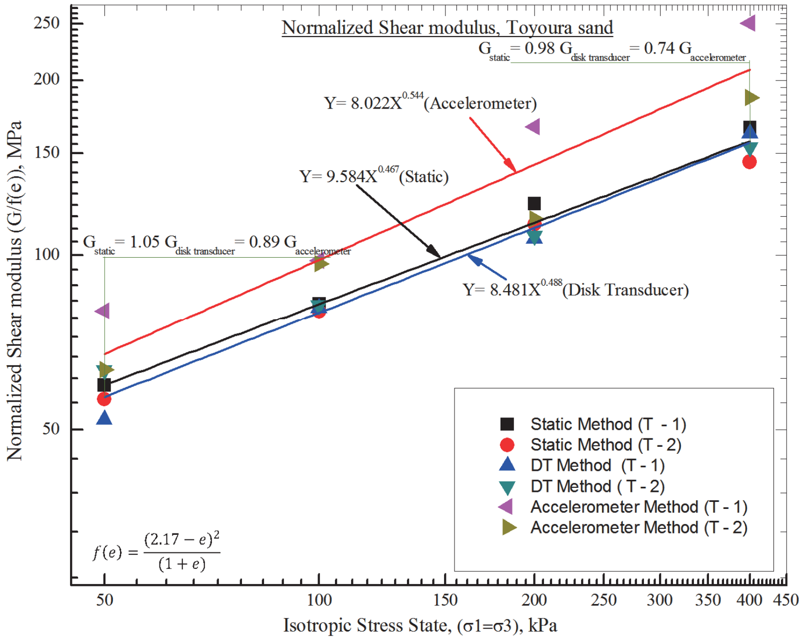


Figure 17. Normalized Shear modulus on Toyoura Sand

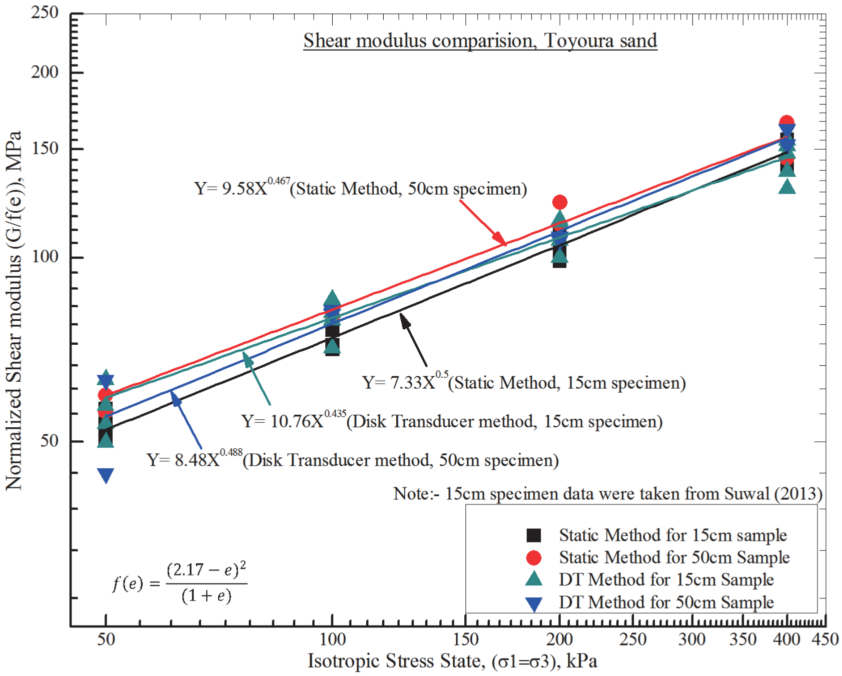


Figure 18. Comparison of Stiffness obtained on Toyoura sand

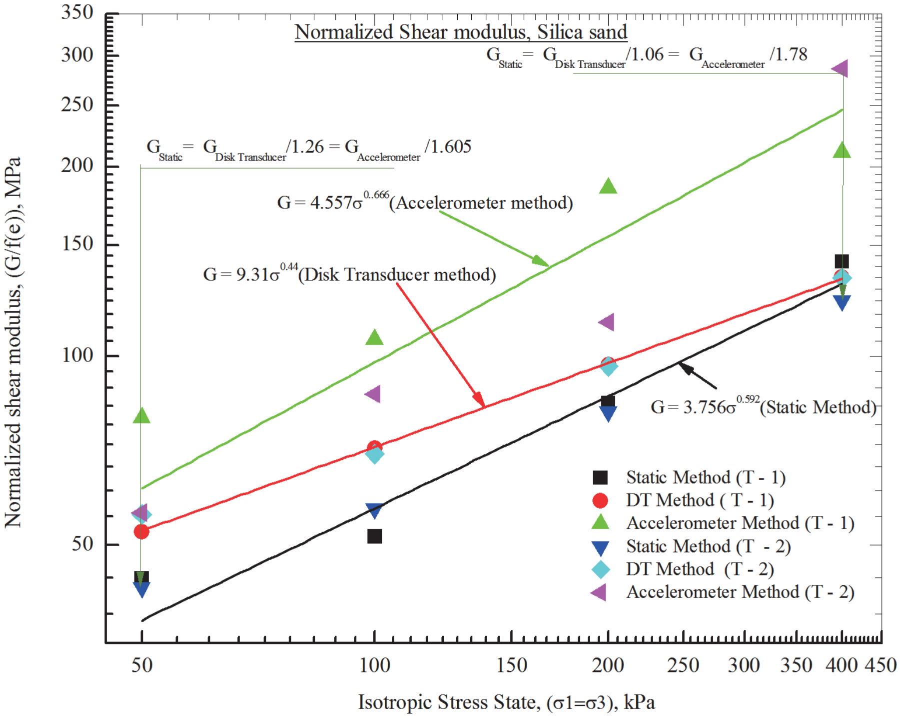


Figure 19. Stiffness obtained on Silica sand

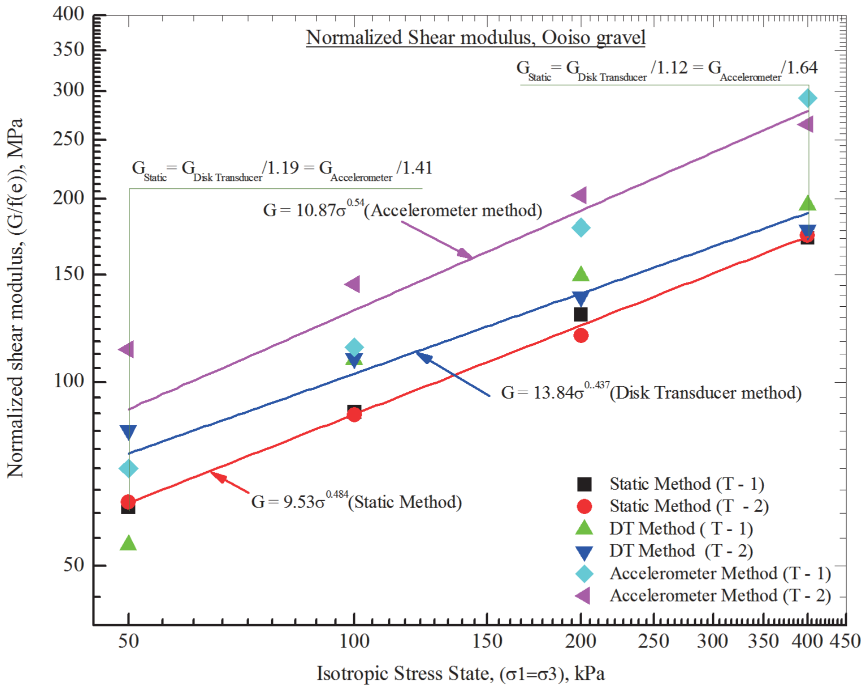


Figure 20. Stiffness obtained on Ooiso gravel

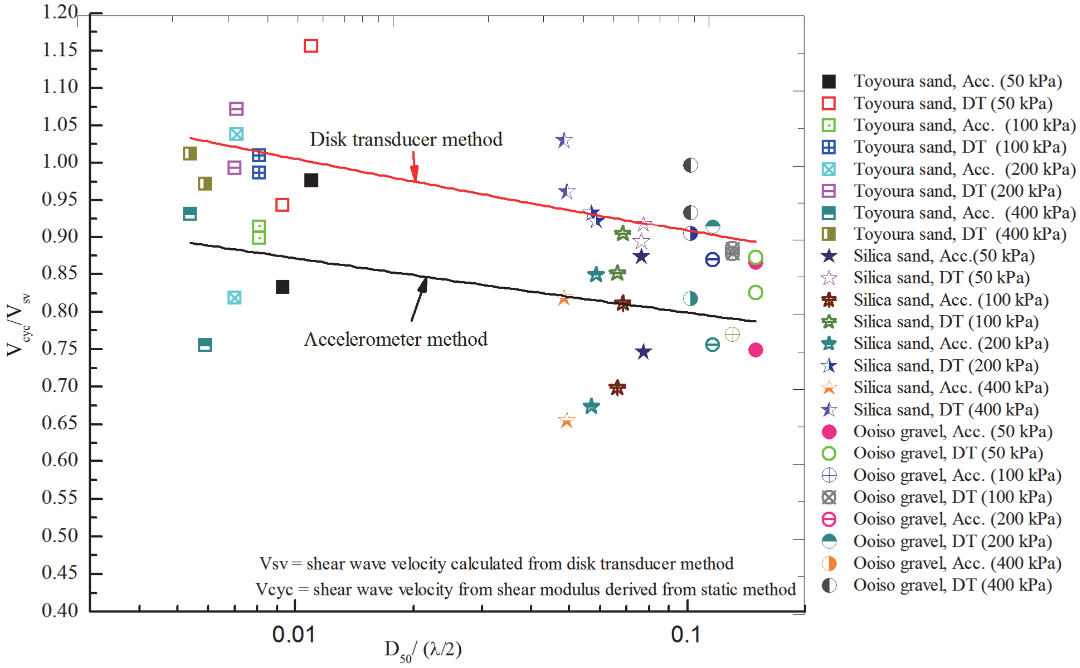


Figure 21. Relationship between Vcyc/Vsv and D50/ (λ/2) for Toyoura sand, Silica sand and Ooiso gravel

Possible affecting factors on the evaluated stiffness

The ratio of wave velocity (Vcyc/Vsv) against ratio of mean particle diameter to half of wavelength is plotted in figure 21. The shear wave velocity for static method (Vcyc) was back calculated by using the evaluated shear modulus. whereas Vsv is the shear wave velocity by Disk transducer method. The ratio of shear wave velocity obtained on all three materials at various isotropic stress states is plotted. The rectangular symbol represents the Toyoura sand, star symbol represents Silica sand and circular symbol represent the Ooiso gravel. The ratio of shear wave velocity (V_{cyc}/V_{sv}) given by static method and accelerometer method is varies from 0.90 to 0.75, with increasing the $D_{50}/(\lambda/2)$. While the ratio of shear wave velocity (V_{cyc}/V_{sv}) by static method and disk transducer method is varies from 1.03 to 0.85, with increasing the $D_{50}/(\lambda/2)$. For the particular material, the ratio of shear wave velocity in decreasing with decreasing confining stress states. The trend of (V_{cyc}/V_{sv}) decreasing with increasing $D_{50}/(\lambda/2)$ makes the good agreement with past research(see also Tanaka et al 2000). But the ratio is much closer with unity on disk transducer method. Which also proves that newly developed disk transducer method might be the better technique of elastic wave study method on laboratory.

CONCLUSIONS

1. Disk transducer with the size of 80 mm diameter was developed successfully by assembling the 4 numbers of p-type piezo ceramic element and 4 numbers of s-type piezo ceramic element. By using multiple numbers of piezo ceramic elements, development of required size of wave measurement device (i.e. disk transducer) is possible. Therefore by increasing the size of testing device larger particle size geomaterials can be easily tested.
2. The compressional and shear waves were successfully investigated. The elastic properties on Toyoura sand measured by large size disk transducer were compared with the previous research result. The stiffness fell in similar range within allowable scatters. It proves the workability and reliability of newly developed Disk transducer.
3. The elastic properties of three types of materials, Toyoura sand, Silica sand and Ooiso gravel were evaluated by Static method, Disk transducer method and Accelerometer method. The result from the static method and disk transducer method were within allowable scatter range in all three types of material. While the accelerometer gives closer value in Toyoura sand but in other two materials the ranges varies from 40% - 78% higher than static method.
4. The differences of statically and dynamically calculated stiffness might be depends on grain size and wavelength.

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