Shear Wave Velocity Estimation of Pilani Soil Using Ultrasonics

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Abstract- In order to evaluate dynamic response of soils, shear wave velocity of soils is widely used. This is small-strain parameter. These dynamic responses are seismic site response, machine foundation vibration and liquefaction potential of soil at site. Geologic aging of soil, its stress history, density, in-situ void ratio and effective confining stress are important parameters affecting shear wave velocity. Its correlation with SPT N value is available in literature. Involved technique of obtaining shear wave velocity of soil is complicated. There should be simple alternative of estimating it. In present study, ultrasonic P wave propagation at five different silty clay contents for Pilani region soil has been used for this purpose. SPT N value for these silty contents have been determined based on correlation equations available in literature. Based on these SPT N values, shear wave velocity for same silty clay contents have been determined for Pilani region soil. Variation of P wave velocity and shear wave velocity with silty clay content can be used as calibration curve. P wave velocity through 300micron sieved soil of same region can be determined. Its estimated value of shear wave velocity can be obtained from the calibration curve. For some sites in the region, additional sieving through 150micron sieve will also be required. This technique of estimating shear wave velocity is much simple for a specific region soil.

Keywords - Shear Wave Velocity, SPT N Value, Ultrasonic P Wave, Calibration Curve, Pilani Region

I. INTRODUCTION

Shear wave velocity of soil is an important dynamic property. Soil conditions beneath a structure have an impact on the propagation of ground motions from the bedrock to ground surface. Soil conditions at site amplify certain spectral accelerations and attenuate spectral accelerations at other periods. Spectral acceleration is used to estimate earthquake induced forces imparted to structure. Also, shear stresses imparted to soil due to earthquake are affected by soil properties. It has direct effect on liquefaction potential [1]. Shear wave velocity of soils is the soil property that has greatest effect on determination of adequate response spectra and estimation of shear stresses. Conventionally shear wave velocity is measured from in-situ field tests such as cross-hole or down-hole testing. Recently correlation equation is available in literature to obtain estimated value of shear wave velocity based on SPT N value of soil.

Important factors affecting shear wave velocity of soil are in-situ effective confining stress, in-situ void ratio, in-situ density, site stress history as well as geologic aging which create bonds between soil particles. Due to geologic aging, soil particles are relatively cemented. A relatively weak bond between soil particles due to geologic aging is not significant for large strain failure shear strength. On the other hand it will significantly increase small strain properties. Typical examples are shear wave velocity and liquefaction potential. Small amount of cementation in sand significantly increases its shear wave velocity [2]. Shear wave velocity is a primary parameter that can be used for seismic site classification.

Following equations available in literature are used to obtain estimated value of shear wave velocity V_s in m/s based on SPT N value of soil.

$$V_s = 130 + 7.5N \quad \text{(loose granular soil)} \quad \text{(SPT N range 0-20)} \quad (1)$$

$$V_s = 60 + 7N \quad \text{(dense granular soil)} \quad \text{(SPT N range 20-50)} \quad (2)$$

$$V_s = 40 + 8.333N \quad \text{(soft clay)} \quad \text{(SPT N range 0-6)} \quad (3)$$

$$V_s = 46.25 + 3.125N \quad \text{(stiff clay)} \quad \text{(SPT N range 6-30)} \quad (4)$$

SPT N value of soil can be obtained from following equations which are also available in the literature. Equation relating angle of internal friction, ϕ in deg. and SPT N value for cohesion-less soil is as follows.

$$\phi = 7N \text{ (for } \phi \leq 28) \quad (5)$$

$$\phi = 27.12 + 0.2857N \text{ (for } \phi > 28 \text{ till } \phi = 41.405) \quad (6)$$

Equation relating cohesion, c in kPa and SPT N value for intermediate soil is as follows.

$$c = -16.5 + 2.15N \quad (7)$$

Equation relating cohesion, c in kPa and SPT N value for cohesive soil is as follows.

$$c = -2.2049 + 6.484N \qquad (8)$$

Cohesion-less soil has nearly zero cohesion (less than 5kPa). Intermediate soil has more than 5kPa cohesion with 75micron finer less than 50%. Cohesive soil has more than 12kPa cohesion with 75micron finer more than 50% [3]. Cohesion-less and intermediate soil is freely draining. Angle of internal friction of cohesion-less soil and cohesion of intermediate soil can be determined in the laboratory from drained direct shear testing. Testing technique is quick, inexpensive and simple as compared to triaxial testing. Ease of sample preparation is another advantage in this regard. Cohesion for cohesive soil to be used in equation 8 is to be determined from unconfined compression testing or undrained triaxial testing as per soil condition at site. Unconfined compression testing is relatively simple with respect to triaxial testing.

Pilani region soil at five different tested silty clay contents was found to be either cohesion-less or intermediate type. SPT N value was found to range from 11.6 to 27.58. Based on these values, these silty clay contents can be classified as loose or dense granular soil. Furthermore, their shear wave velocities can be determined from equation 1 or equation 2. Shear wave velocity determination based on this approach is quite lengthy and complicated. It requires complicated experimental set-up as well. Simple alternative to it is always desirable. In the present study, it has been achieved knowing ultrasonic P wave velocity through these same silty clay contents. Calibration curve has been developed to get estimated value of shear wave velocity knowing ultrasonic P wave velocity at these silty contents. As ultrasonic P wave velocity determination requires very simple experimental set-up, suggested technique has lot of advantages.

Wave based nondestructive tests are special class of nondestructive testing technique. When elastic waves travel through the soil medium, characteristics of primary and secondary elastic wave changes with soil properties. Such important properties are elastic moduli, density, moisture content, void ratio, porosity, degree of saturation and particle size composition under in-situ conditions. Elastic waves could be primary or secondary. Primary waves are also called longitudinal P waves. Secondary waves are also called transverse shear waves.

Ultrasonic testing is long established nondestructive testing method. It involves longitudinal P wave velocity determination through the sample. This velocity measurement is then correlated with sample properties. Longitudinal P wave velocity measurement through sample can be achieved by measuring time taken by a longitudinal pulse to travel a measured distance in the sample. Through transmission is the simplest technique of transit time measurement. Low frequency transducer at 150kHz frequency was used in the present study. Transmitting and receiving transducers were placed in contact with sample aligned with each other with grease as coupling agent. Least count of transit time measurement was 0.1microsecond. Pulse echo and impact echo techniques are also available for transit time measurement.

Ultrasonics deals with vibratory waves having frequency above 20kHz. Since ultrasonic waves are stress waves, they can exist only within mass media. For their transmission, there should be direct and intimate contact between masses. Medium elastic property is responsible for sustained vibrations required for ultrasonic wave propagation. Consequently, ultrasonic waves can also be called elastic waves. In low intensity application, propagation characteristics of ultrasonic wave is used to learn about media through which the wave is propagating. Nondestructive testing is low intensity application. In high intensity application, effect is produced on the medium due to ultrasonic wave propagation. Medical therapy, atomization of liquids, machining of brittle materials are some typical examples of high intensity application.

In order to assess quality of materials from ultrasonic velocity measurement, path length and transit time should each be measured to an accuracy of about $\pm 1\%$. Time taken for earliest part of pulse to reach receiving transducer from the time it leaves transmitting transducer is measured. Depending on relative placement of transducers on the surface of sample, transmission could be direct, indirect or semi-direct. Direct transmission or through transmission is the most adequate. In this technique longitudinal pulses leaving the transmitting transducer are propagated mainly in direction normal to the transducer face. In through transmission technique, P wave velocity is determined using equation.

$$\text{P wave velocity} = \text{path length/transit time} \qquad (9)$$

Restriction in using equation 9 is that the least lateral dimension (dimension measured perpendicular to the path of pulses) should not be less than pulse amplitude. In absence of attenuation, amplitude of P wave is $\frac{1}{4}^{th}$ of its wavelength. If frequency of ultrasonic P wave is chosen such that the corresponding wavelength of incoming ultrasonic pulse is at least 10 times more than average soil grain size, effect of attenuation won't be felt [4].

II. EXPERIMENTAL DETAILS

Soil mixture used in the experiments was sand and silty clay. Sand passing 300micron sieve and retained on 150micron sieve was obtained from close to ground surface at a location close to Birla Institute of Technology & Science, Pilani campus after conducting the sieve analysis. Soil was predominantly sand. Similarly silty clay passing 150micron sieve and retained on 75micron sieve as well as passing 75micron sieve and retained on pan was obtained from a depth of 12 to 15meters from a ditch close to Institute campus after conducting sieve analysis. Soil was predominantly silty clay at this depth. Classification of aforementioned soil as sand or silty clay is as per dispersion test results. Water content in all the five soil samples was taken as 10%, which is worst in-situ. As soil mixtures were freely draining type, drained direct shear testing was done to find out cohesion and angle of internal friction. As per the values obtained, these soil mixtures were classified as cohesion-less or intermediate type. Accordingly equation 5, equation 6 or equation 7 was used to obtain SPT N value for these soil mixtures. Based on thus obtained SPT N values, aforementioned soil mixtures can be classified as loose granular soil or dense granular soil as per equation 1 and equation 2. Shear wave velocity, V_s in m/s given in Table 1 has been obtained from equation 1 or equation 2 depending upon the obtained SPT N value. 150micron passing and 75micron retaining as well as 75micron passing and pan retaining silty clay was half each in each soil mixture. Even if 75micron retaining or pan retaining silty clay was other than half each in each mixture, obtained cohesion and angle of internal friction values were found to be about the same.

Ultrasonic testing was carried out using ultrasonic materials tester (Model: Emefco type UCT3). This was low ultrasonic frequency (150kHz) tester for civil engineering applications. Coarse grained samples like soils can conveniently be tested with this ultrasonic materials tester. Through transmission technique was used. The velocity of ultrasonic P wave was determined using equation (9). For the all five soil mixtures tested at 10% water content, the mixture was statically compacted in a wooden frame of 6cm x 6cm inner plan area. Bulk density of compacted soil for each mixture in the wooden frame was 1.45 gm/cm^3. Thickness of wooden frame or sample thickness was 1.7cm. Transmitting and receiving transducers having 3.6cm diameter each were centrally placed on the opposite faces of soil sample, such that their axes were collinear. Grease was used as coupling agent between the transducer face and the soil sample. Ultrasonic P wave transmits through soil mixture sample from transmitting to receiving transducer. This transit time of ultrasonic P wave was determined using aforementioned ultrasonic materials tester for all five soil mixtures. Consequently, based on this ultrasonic P wave velocity was determined for all five soil mixtures. These values for all five soil mixtures have also been listed in table 1 in m/s. 150micron passing and 75micron retaining as well as 75micron passing and pan retaining silty clay was half each in each soil mixture. Even if 75micron retaining or pan retaining silty clay was other than half each in each mixture, obtained ultrasonic P wave velocity values were found to be about the same.

Table 1 Shear wave velocity and P wave velocity variation with silty clay content for Pilani region soil

Silty clay content (%)	Cohesion (kPa)	Angle of internal friction (deg)	Soil type	SPT N value	V_s (shear wave velocity, m/s)	V_p (P wave velocity, m/s)
10	2.687	35	Cohesion-less	27.58	253.06	340
30	8.453	22.5	Intermediate	11.6	217	376.1
50	11.336	13	Intermediate	12.94	227.05	448.5
70	14.121	9	Intermediate	14.24	236.8	510.5
90	11.052	29	Intermediate	12.81	226.075	459.4

III. CALIBRATION CURVE DEVELOPMENT

Variation of ultrasonic P wave velocity with silty clay content has been shown in Figure 1 for Pilani region soil based on present study. Similarly variation of shear wave velocity with silty clay content has also been shown in the same Figure for Pilani region soil. This Figure thus can be used as calibration curve. From Figure 1 it is clear that as long as ultrasonic P wave velocity is less than 459.4m/s, there is unique silty clay content for this P wave velocity. However, if ultrasonic P wave velocity is in between 459.4m/s and 510.5m/s, there are two possible silty clay contents for that P wave velocity.

From ground surface till about 5meters depth, soil profile is about the same in Pilani region. Furthermore, this soil is mixture of soil from ground surface and soil from 12 to 15meters depth. As most of geotechnical construction is in this depth zone in the region, its shear wave velocity information is always required when it comes to safe geotechnical design under dynamic loading. One can take soil sample from required depth of aforementioned region (up to 5meters depth), oven dry it and sieve it through 300micron sieve. Through transmission ultrasonic testing can be done on this soil sample at 10% water content to obtain P wave velocity using technique described in present study. Technique of P wave velocity determination using through transmission technique is very simple. Knowing P wave velocity through the soil sample, its estimated shear wave velocity value in m/s can be directly obtained from Figure 1 as long as obtained P wave velocity is less than 459.4m/s. For P wave velocity more than 459.4m/s, additional sieving through 150micron sieve will have to be done to get exact silty clay content. For the obtained silty clay content, estimated shear wave velocity value in m/s can still be obtained from Figure 1.

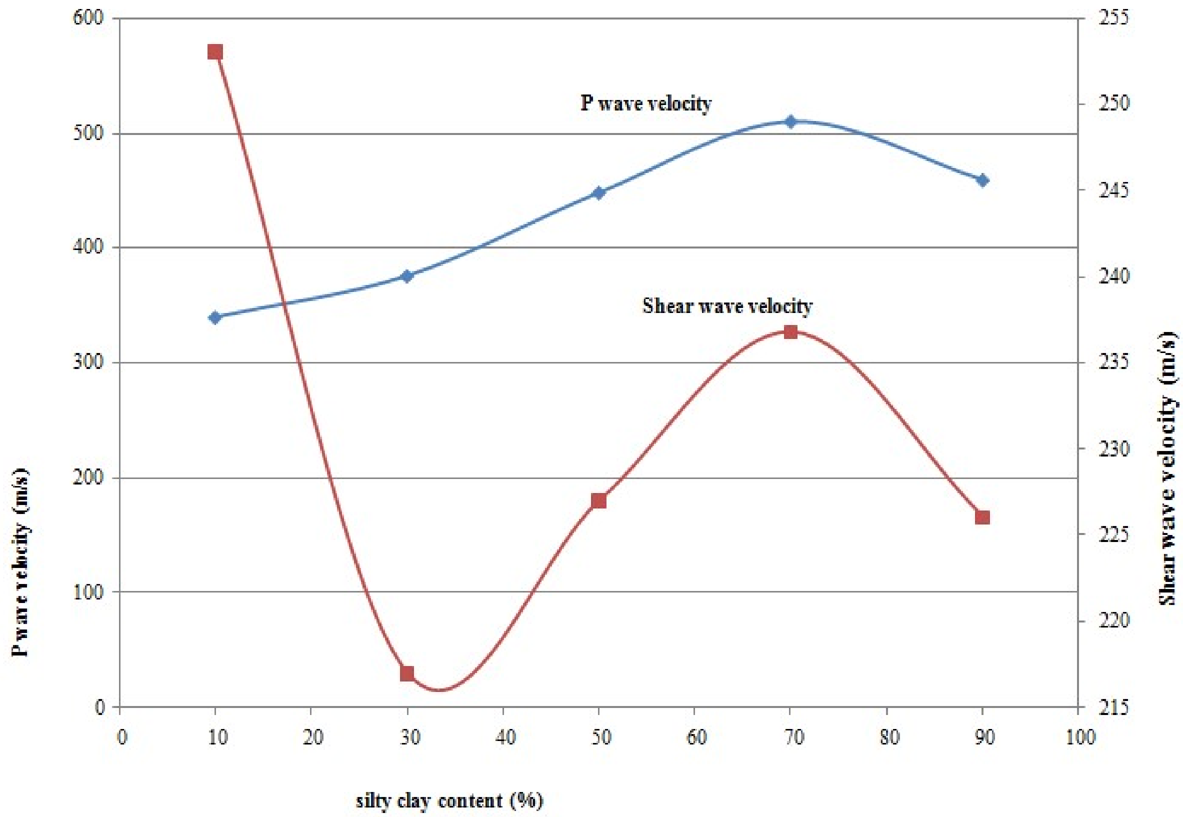

Figure 1. P wave velocity and shear wave velocity variation with silty clay content

IV. CONCLUSIONS

Conventionally, shear wave velocity is measured from in-situ field tests such as cross-hole or down-hole testing. Recently correlation equations are available in literature to obtain estimated value of shear wave velocity based on SPT N value of soil. However, these field based and laboratory based techniques are lengthy and complicated.

When it comes to dynamic loading onto geotechnical construction, shear wave velocity is an important soil dynamic property at small strain. It has immense use in study of dynamic behavior of foundations, substructures, soil retaining structures and other soil structures. These include earth and rockfill dam, during earthquakes as well as for their earthquake resistant design. Soil, in general is polyphase material consisting of solid soil particles, water and air. Shear wave velocity should be determined for this in-situ soil condition. At low strain level of less than 10^{-4}%, shear wave propagation indicates soil elastic properties also [5].

Accurate estimation of shear wave velocity is always required for dynamic loading analysis at site. Calibration curve developed in present study based on ultrasonic P wave propagation through soil to estimate it is much simple. It has been developed for Pilani region. Similar calibration curves can be developed for other regions also as long as soil mixture composition is about the same. This will result in improved geotechnical design for dynamic loading conditions at site.

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