Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-517

Cross anisotropic stiffness properties of soils via crosshole seismic wave measurements

Propriétés transversales anisotropes de rigidité des sols par la mesure de vagues sismiques sur une distance séparant deux trousitre de votre manuscrit

Dennis R. Hiltunen
Department of Civil and Coastal Engineering, University of Florida, Gainesville, Florida, USA
Yeonseok Choi
School of Civil Engineering, Purdue University, West Lafayette, Indiana, USA

ABSTRACT
Particulate materials such as soils are inherently anisotropic with respect to stiffness and strength properties. Anisotropic mechanical properties are not routinely assessed, yet differences in material properties can influence design-based calculations. The paper presents a methodology for assessing anisotropic shear properties of particulate materials. The method is based upon the measurement of seismic shear wave velocities via improved and extended crosshole testing techniques. Measurements completed at two test sites demonstrate ability of the methodology to assess anisotropic shear modulus of particulate materials.

RÉSUMÉ
Les matériaux à particules comme la terre sont par essence anisotropes en ce qui concerne leur rigidité et leur force. Les propriétés mécaniques anisotropes ne sont pas régulièrement mesurées et pourtant, les différences entre les propriétés des matériaux peuvent influencer les calculs destinés à l'élaboration d'un plan. Cet article présente une méthodologie qui permet d'évaluer les propriétés anisotropes frictionnelles des matériaux à particules. La méthode est basée sur la rapidité des vagues sismiques dont la mesure est rendue possible grâce à une technique élargie et approfondie; ces expériences sont menées sur la distance séparant deux trous. Les mesures qui ont été relevées sur deux zones-tests démontrent la capacité de cette méthodologie à évaluer la résistance frictionnelle anisotrope des matériaux à particules.

1 INTRODUCTION

Soils are inherently anisotropic with respect to stiffness properties. Depositional processes can clearly lead to material differences in vertical and horizontal planes, so-called structural anisotropy. Further, mechanical properties of these materials are governed by state of stress. It is widely recognized that stresses in particulate materials are anisotropic, thus differences in stiffness should be expected, i.e., stress-induced anisotropy. Anisotropic mechanical properties are not routinely assessed because methods are not well developed, yet there are several important problems in geotechnical engineering where characterization and influence of anisotropic behavior is particularly important.

Several studies have demonstrated that anisotropic stiffness properties of soil can be characterized accurately via a five-parameter, cross anisotropic model, including: 1) the landmark work of Stokoe, Lee, and Knox (1985) via tests in a large triaxial device, 2) calibration chamber tests in Italy (Bellotti, et al. [1996] and Fioravante, et al. [1998]), and 3) laboratory tests on smaller specimens (Zeng and Ni [1998]). Kim, Liao, and Roessett (1999) demonstrated analytically that a cross anisotropic model can be completely determined via appropriate propagation of seismic waves in a crosshole test. Using these ideas, the paper presents an in situ methodology for assessing anisotropic shear properties of particulate materials. The method is based upon measurement of seismic shear wave velocities via improved and extended crosshole testing techniques.

2 ANISOTROPY

2.1 *The Issue of Anisotropy*

Much of the early research on parameters affecting the moduli or seismic wave velocities of soil was conducted on laboratory specimens constituted under isotropic stress states, and the influence of stress state was captured via the mean effective stress (average of principal stresses). Later, the laboratory work of Roesler (1979), Yu and Richart (1984), and others began to reveal the importance of the relationship between wave velocities and individual principle stress components.

The landmark work of Stokoe and his collaborators (Stokoe, Lee, and Knox [1985] and Stokoe and Lee [1997]) employing large-scale cubical triaxial specimens, and studies conducted in Italy on large, cylindrical calibration chamber specimens (Bellotti, et al. [1996] and Fioravante, et al. [1998]) revealed more clearly and quantified the effect of stress state on wave propagation velocities, namely: 1) compression wave velocity (V_p) is a function solely of the stress in the direction of wave propagation (particle motion is in this same direction), 2) shear wave velocity (V_s) depends on two stresses, the normal stress in the direction of wave propagation, and the normal stress in the direction of particle motion, and 3) neither V_p or V_s are dependent on the out-of-plane stress component.

These results led to a more detailed understanding of the effects of state of stress on stiffness properties of soil, including the issue of anisotropy in stiffness. Structural or fabric anisotropy was clearly demonstrated: for specimens tested under isotropic states of stress, notable differences in wave velocities were determined for propagation in the vertical and horizontal directions for both P- and S-waves. Stress anisotropy (or mechanical heterogeneity) was also clearly revealed, as this was not unexpected due to our everyday acceptance of the fact that the in situ stress state in soils is typically anisotropic, and the effects of individual components of stress on wave velocities.

2.2 *The Importance and Significance of Anisotropy*

For a more fundamental, accurate understanding and characterization of soil behavior, the anisotropy of soil should be taken into account. Anisotropic behavior is important for structural response analysis of soils above cavities, e.g., tunnels. Lee and Rowe (1989) discussed that anisotropy has a significant effect on the shape of the settlement trough, and that reasonable agreement between observation and theory is obtained for G_{vh} / E_v of between 0.2 and 0.25, which is smaller than the isotropic value of G_{vh}/E_v=0.33. Elastoplastic finite element analyses were performed to determine the effects of elastic anisotropy on surface settlement caused by a uniform surface loading and by tunnelling. The results suggest that when attempting to predict settlement induced by tunnelling, attention should be given to the effect of elastic anisotropy and, in particular, to the ratio of the shear modulus in the vertical plane due to vertical loading (G_{vh}) to Young's modulus in the vertical direction (E_v).

2.3 *Cross Anisotropic Model*

The detailed studies of wave propagation in triaxial and calibration chamber tests described above revealed two significant findings for level-ground conditions where the horizontal and vertical directions are also the principal axes: 1) velocities of waves with a stress contained in a vertical plane are not equal to velocities with stresses contained solely in a horizontal plane, and 2) for velocities whose stress-dependent components are contained solely in a horizontal plane, velocities are independent of direction. Thus, the horizontal plane is an isotropic plane with the vertical axis an axis of symmetry. This behavior can be modeled with the cross anisotropic model of elasticity that consists of five independent elastic parameters. The model is presented in detail by Kim, Liao, and Roessett (1999).

2.4 *Determining the Cross Anisotropic Model*

The cross anisotropic model for a soil can be determined via laboratory tests, including: 1) small-scale specimens in resonant column, torsional shear, and others, but these methods suffer from the many inherent problems of constructing representative samples, etc., and 2) large-scale triaxial or calibration chamber tests that are well suited for fundamental research studies but not for practice.

It would be most desirable to characterize the cross anisotropic model via in situ tests. Kim, Liao, and Roessett (1999) have investigated the issue analytically and proposed some possibilities. Anisotropic behavior influences data collected in a seismic downhole test, but data collected in downhole testing are not sufficient to determine all five parameters of the cross anisotropic model. However, an appropriately designed set of crosshole measurements can determine all five parameters. Equations for the methodology are provided in detail in the paper, and because of space limitations are not repeated herein. Measurements are required of P-, SV-, and SH-wave velocities along a horizontal ray path, and similarly along one ray path at a known angle from horizontal. With additions and modifications to typical test equipment, crosshole seismic wave methodologies can be employed in situ to determine these important characteristics of an anisotropic particulate material.

3 CROSSHOLE TESTING SYSTEM

The crosshole test has been well documented (Hoar and Stokoe [1978], Stokoe and Woods [1972], and Woods [1986]). Testing can be conducted with a minimum of two boreholes advanced to equal depths a known distance apart. However, the crosshole test method is optimized with use of three boreholes. The source is an impulse hammer that is advanced down one of the boreholes. Receivers are then placed in the remaining boreholes. These receivers are usually some type of transducer depending on the material being tested. Receivers then transfer body wave arrivals to the time recorder.

3.1 *Vertical Shear Waves (SV)*

Typically, crosshole testing is conducted in soil to obtain shear wave velocity with depth from vertical shear (SV) waves, i.e., waves that propagate perpendicular to particle motion and confined to the vertical plane. The test has been standardized, and specifications can be found in ASTM Testing Standard D 4428 Standard Test Methods for Crosshole Seismic Testing.

Field testing was conducted for this study according to these specifications. Boreholes were drilled to a specified depth and cased with 4-inch diameter PVC pipe grouted in place. As suggested by ASTM, the source used in the investigation was a Bison hammer. The Bison hammer is an in-hole source, hydraulically coupled to the borehole, and produces SV-waves by creating a vertical traction in the source hole. Geophone packers were used as three-dimensional receivers. Packers are comprised of three velocity transducers oriented along the x, y, and z planes. The orientation of the transducers used is dependent on the direction of the polarized wave. For SV-waves confined to the vertical plane, the geophone aligned parallel to the z-axis was used to collect vertical shear wave data. In addition to velocity transducers, geophone packers also contain a rubber inner tube and airline. With the receiver at the desired depth, the tube is inflated with air against the borehole. Thus, the pneumatic tube enables coupling between soil, cased borehole, and transducer at a known depth. The recorder used in this study was a Data Physics SignalCalc 620 Dynamic Signal Analyzer, which is capable of recording wave arrivals in the time domain.

The essential measurement of the crosshole test is interval travel time. Interval travel time is the time required for the shear wave to travel between two receivers and therefore eliminates need for precise triggering of the source and recording equipment. It is obtained by selecting the first arrival of the SV-wave at each receiver and is equal to the difference in arrival times. Vertical shear wave velocity is then computed as the distance between receivers divided by interval travel time.

3.2 *Horizontal Shear Waves (SH)*

Although crosshole testing is typically conducted to obtain profiles of vertical shear wave velocity with depth, these profiles do not present a complete assessment of a site's condition, as this standard test method only typifies the soil parameters pertaining to the vertical plane. To develop a comprehensive evaluation of site conditions, properties in the horizontal plane must also be characterized. In fact, parameters derived from in situ measurement of horizontal shear (SH) waves may be more appropriate for assessing certain soil dynamic problems, such as liquefaction potential. It is possible to obtain shear wave velocity profiles with depth from horizontal shear waves, i.e., waves that propagate perpendicular to particle motion and are confined to the horizontal plane, with improved crosshole testing.

In an attempt to ascertain the shear wave velocity in the horizontal plane, standard crosshole methods were used to conduct field testing using an energy source to produce horizontal shear (SH) waves. It is desirable for the source to be rich in horizontal shear waves while simultaneously generating little compression wave energy. ASTM specifications state that in order to produce identifiable shear waves, the source must transmit energy to the ground primarily by directionalized distortion. Thus, a pure traction must be created by the source in the borehole to produce energy that propagates perpendicular to particle motion in the horizontal plane.

The horizontal force required to create the SH wave is produced by a series of four pneumatically-coupled solenoids (figure 1). The source is connected to a high-pressure air cylinder that provides a supply of air required to fire the solenoids. The high-pressure air cylinder is connected to a double hose reel with both low- and high-pressure lines. The high-pressure line supplies air pressure directly to the source. The low-pressure line is coupled to a triggering valve, which allows the source to be fired by the operator by merely pushing a button. Use of the low-pressure line and trigger helps to conserve the air supply and provides a simple manner in which to fire the source. Upon triggering, the solenoids fire simultaneously horizontally producing the necessary propulsion to generate horizontal shear wave energy. Again, geophone packers are used as receivers. For SH-waves confined to the horizontal plane, the velocity transducer aligned parallel to the x-axis was used to collect horizontal shear wave data. Orientation rods were connected to the solenoid hammer and receivers to ensure that alignment of polarized wave and receivers was maintained during testing at subsequent depths in the borehole. Horizontal shear wave arrivals were recorded in the time domain using a Data Physics SignalCalc 620 Dynamic Signal Analyzer.


Figure 1. SH-Wave Crosshole Source

The essential measurement of the crosshole test is interval travel time. ASTM specifications state that for defendable shear waves, energy sources should be repeatable and, although not mandatory, reversible. It is well documented that shear waves typically show a reversal in wave arrival when the source is rotated 180 degrees. Travel time records collected for horizontal shear waves produced from the solenoid source have repeatedly demonstrated reversibility of the source and thus suggest the validity of the solenoid hammer for producing SH-wave energy.

4 TEST RESULTS

Crosshole testing was conducted at two soils sites to collect measurements of travel time for both SV- and SH-waves and characterize each site with detailed velocity profiles. The two sites were located along the Interstate I-99 corridor between Bald Eagle and State College, Pennsylvania. Structure 203 will be an integral abutment bridge that carries the northbound lanes of I-99 across route US 322 north of Port Matilda, PA. It is one of four integral abutment bridges to be instrumented as part of I-99 research. 319 Annex is located near Structure 319 which will be a two-lane bridge that carries the southbound lanes of I-99 over route US 322. Each crosshole array consisted of three boreholes with a 10-ft distance between source and first receiver, and a 10-ft distance between first and second receivers. Measurements were collected at multiple depths at each site, and velocity profiles are shown in figures 2 and 3 in conjunction with material log information for all three holes. The shear wave velocity profiles appear consistent with materials encountered during the borings. Note, the horizontal shear wave measurements were collected at the same depths as vertical shear wave measurements. In comparing the velocity profiles from the two different shear waves, the SH-wave velocity is typically less than the SV-wave velocity, illustrating the presence of anisotropy in elastic shear stiffness parameters.

5 CONCLUSIONS

Based upon data presented herein, the following conclusions are appropriate:

- Particulate materials such as soils are anisotropic with respect to shear modulus.
- Improved seismic crosshole testing techniques can assess anisotropic shear modulus of particulate materials.

REFERENCES

Bellotti, R., Jamiolkowski, M., Lo Presti, D.C.F., and O'Neill, D.A. (1996), "Anisotropy of Small Strain Stiffness in Ticino Sand," *Geotechnique,* Vol. 46, No. 1, pp. 115-131.

Fioravante, V., Jamiolkowski, M., Lo Presti, D.C.F., Manfredini, G., and Pedroni, S. (1998), "Assessment of the Coefficient of the Earth Pressure at Rest from Shear Wave Velocity Measurements," *Geotechnique*, Vol. 48, No. 5, pp. 657-666.

Hardin, B.O. and Black, W.L. (1966), "Sand Stiffness Under Various Triaxial Stresses," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 92, No. 2, March, pp. 27-42.

Hoar, R.J. and Stokoe, K.H., II (1978), "Generation and Measurement of Shear Waves In Situ," *Dynamic Geotechnical Testing, ASTM STP 654*, American Society for Testing and Materials, pp. 3-29.

Kim, S.M., Liao, S.T., and Roesset, J. M. (1999), "Simulation of the Crosshole Method in Isotropic and Anisotropic Media," *International Journal for Numerical and Analytical Methods in Geomechanics,* Vol. 23, No. 11, pp. 1101-1119.

Lee, K.M. and Rowe, R.K. (1989), "Deformations Caused by Surface Loading and Tunnelling," *Geotechnique,* Vol. 39, No.1, pp. 125-140.

Pennington, D.S, Nash, D.F.T., and Lings, M.L. (1997), "Anisotropy of G_0 Shear Stiffness in Gault Clay," *Geotechnique*, Vol. 47, No. 3, pp. 391-398.

Roesler, S.K. (1979), "Anisotropic Shear Modulus Due to Stress Anisotropy," *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 105, No. 7, July, pp. 871-880.

Stokoe, K.H., II and Lee, S.H.H. (1997), "Effects of Stress State and Soil Fabric on Body Wave Velocities Measured by Borehole Methods," *Technical Report GL-97-21*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, September.

Stokoe, K.H., II, Lee, S.H.H., and Knox, D.P. (1985), "Shear Moduli Measurements Under True Triaxial Stress," *Advances in the Art of Testing Soils Under Cyclic Conditions*, Proceedings of an ASCE Geotechnical Engineering Division Session, Detroit, Michigan, October, pp. 166-185.

Stokoe, K. H., II, and Woods, R. D. (1972), "In Situ Shear Wave Velocity By Cross-Hole Method," *Journal of the Soil Mechanics and Foundations Division,* ASCE, Vol. 98, No. 5, May, pp. 443-460.

Sully, J.P. and Campanella, R.G. (1995), "Evaluation of in situ Anisotropy from Crosshole and Downhole Shear Wave Velocity Measurement," *Geotechnique,* Vol. 45, No. 2, pp. 267-282.

Woods, R. D. (1986), "In Situ Tests for Foundation Vibrations," *Use of In Situ Test in Geotechnical Engineering, Geotechnical Special Publication No. 6*, Proceedings of an ASCE Geotechnical Engineering Division Specialty Conference, Blacksburg, Virginia, June, pp. 336-375.

Yu, P. and Richart, F.E., Jr. (1984), "Stress Ratio Effects on Shear Modulus of Dry Sands," *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 110, No. 3, March, pp. 331-344.

Zeng, X. and Ni, B. (1998), "Measurement of G_{max} Under Anisotropic Loading Condition Using Bender Elements," *Geotechnical Earthquake Engineering and Soil Dynamics III, Geotechnical Special Publication No. 75*, Proceedings of an ASCE Geo-Institute Specialty Conference, Seattle, Washington, August, pp. 189-200.

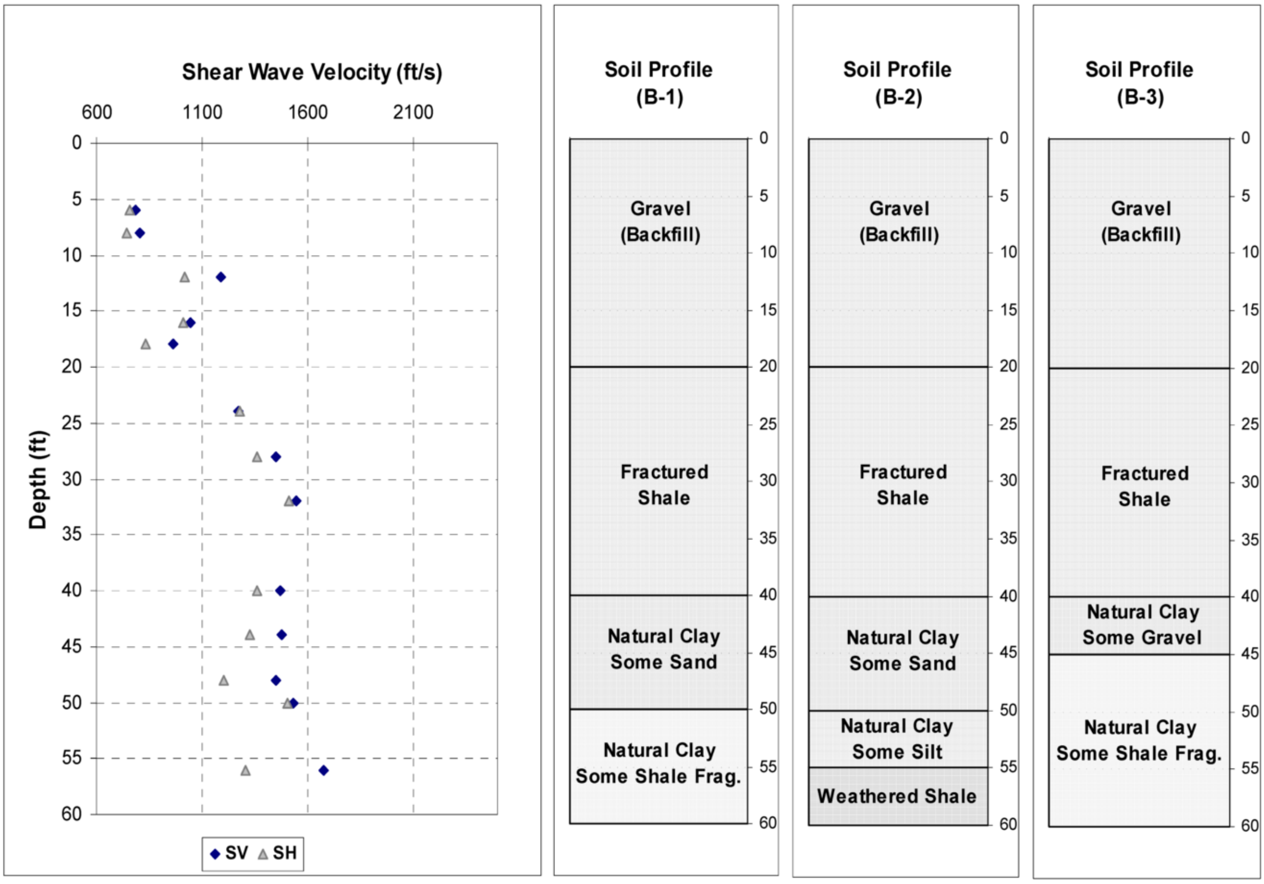

Figure 2. Composite Material Profile: Structure 203

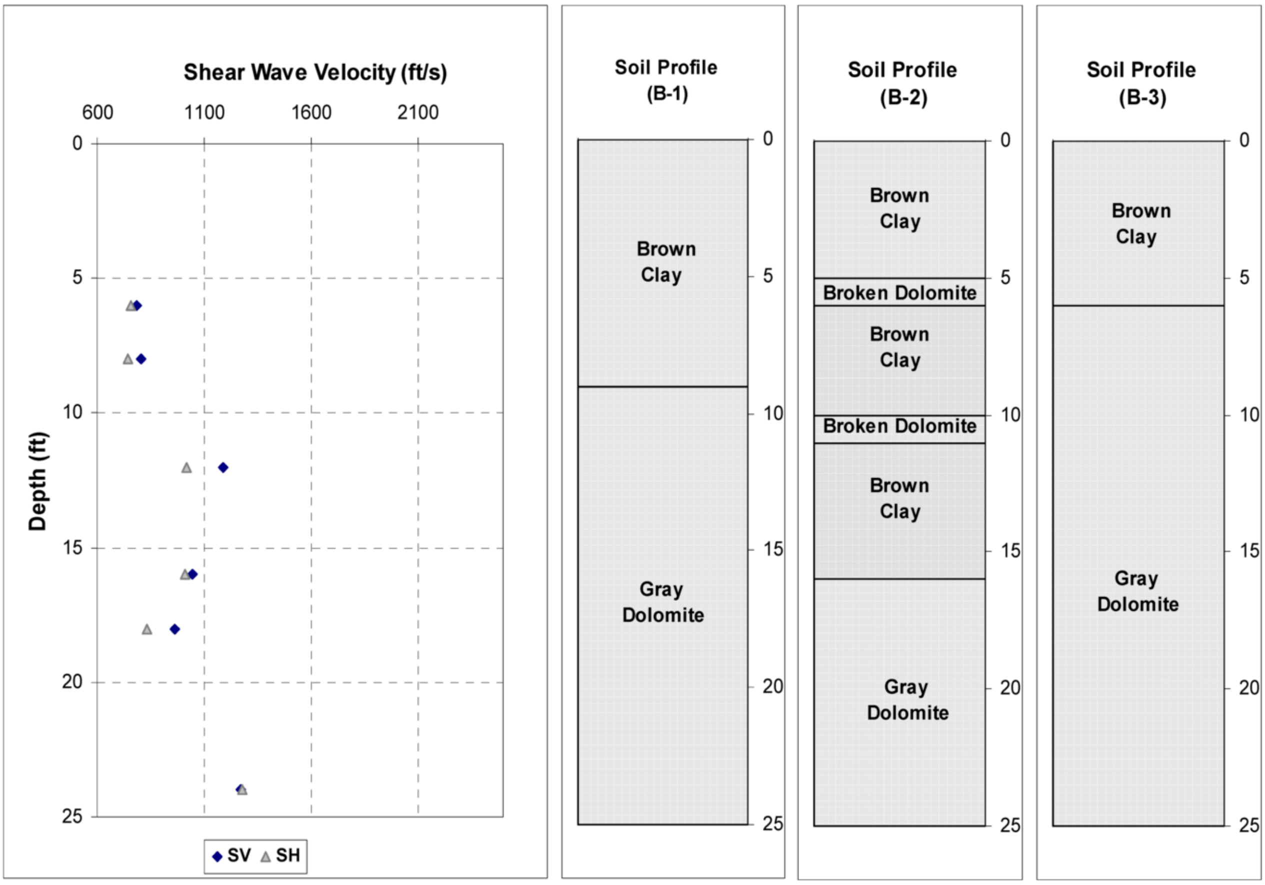

Figure 3. Composite Material Profile: Site 319 Annex