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Cone Penetrometer Equipped with Piezoelectric Sensors for Measurement of Soil Properties in Highway Pavement

Final Report for Highway IDEA Project 112

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Cone Penetrometer Equipped with Piezoelectric Sensors for Measurement of Soil Properties in Highway Pavement

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ABSTRACT

Measurement of in-situ soil properties is imperative for pavement design. The stiffness and Poisson's ratio of base and sublayers are essential parameters in the design and quality control of compaction during construction of highway pavements. It is critical to have a portable, non destructive, and mechanized system to measure these parameters in-situ. Currently used techniques including California Bearing Ratio, Resilient Modulus, Dynamic Cone Penetrometer, and Falling Weight Deflectometer have limitations preventing compliance with requirements for the design of highway pavements. A new device implementing a cone penetrometer equipped with piezoelectric sensors to measure the soil properties underlying highway pavements has been developed. The system is mobile, versatile, reliable, and economical. The techniques for measuring soil stiffness are developed, utilizing bender and extender element techniques. Data acquired from the new device are compared with results of an empirical formula developed by Hardin and Richart (1963). Representative test results demonstrating the device performance are presented. This study shows that the device has great potential in improving the design and construction of new pavement and existing pavement. It can be used to assist quality control during construction of new pavement, evaluate the performance of existing pavement, and help forensic investigation in the event of a pavement failure. Plan for further development and commercialization of the device is proposed.

***Key Words**:* Bender element; cone penetrometer; constrained modulus; extender element; Poisson's ratio; shear modulus

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EXECUTIVE SUMMARY

The stiffness (elastic modulus and shear modulus) and Poisson's ratio of the base and sublayers are important parameters in the design and quality assurance during construction of highway pavements. During the construction of new pavement, it is very important and cost-effective to have a mobile and automated system that can measure the stiffness and Poisson's ratio of in-situ compacted soils accurately and quickly. For existing pavement before re-surfacing, it is essential to know the condition of the base and sublayers that have been subject to traffic loading and volatile environmental conditions for a number of years. When a failure of pavement occurs, a quick and accurate measurement of the properties of the foundation soil would be most valuable for the forensic investigation. The new highway construction guide proposed by AASHTO (American Association for State Highway and Transportation Officials) requires such measurements be conducted. The final report for NCHRP 1-37A considers such measurements as crucial. The currently used techniques such as CBR (California Bearing Ratio), resilient modulus, DCP (Dynamic Cone Penerometer) and FWD (Falling Weight Deflectometer) tests have limitations that can not satisfy all the requirements for design and quality assurance of highway pavements.

A new field-testing technique has been developed in the geotechnical laboratory of Case Western Reserve University to measure the stiffness and Poisson's ratio of soils using cone penetrometers equipped with piezoelectric sensors. The device using this technique includes a pair of cone penetrometers, each fitted with two piezoelectric sensors, which can be pushed into foundation soils. One set of the sensors is used as wave transmitters while the other set as wave receivers. An electrical pulse produced by a function generator is used to activate the transmitters. Vibration of the transmitters produces primary and shear waves that propagate through the soil and are captured by the receivers. Then from the measured velocities of shear and primary waves, soil stiffness and Poisson's ratio can be determined. The technique has been proven to produce reliable results in the laboratory. A number of papers have been published on this technique, Zeng et al. (2003 and 2004).

In this project, we worked jointly with the Ohio Department of Transportation and engineers at Pile Dynamics Inc., a civil engineering technology company, to further develop this technique into a low cost, automated and mobile unit that can be widely used during highway construction for monitoring and controlling construction quality of highway pavements, evaluating performance of existing pavements, and helping forensic investigation in case of a pavement failure. The system is mobile, versatile, user friendly, and applicable to all types of soils and field conditions. It is a low cost, mobile and automated system for rapidly measuring stiffness and Poisson's ratio of base and sublayers in the field, which has the potential to make significant contributions to improving the quality of pavement design and construction. Plans for field validation and commercialization of the device are proposed.

I BACKGROUND AND OBJECTIVES

In recent years, several testing methods have been developed to measure the mechanical properties (including elastic modulus, shear modulus, and Poisson's ratio) of soils. These measurements are utilized in the design of highway pavements and in quality control/quality assurance (QC/QA) processes. Consequently, organizations such as the American Association for State Highway and Transportation Officials (AASHTO), the Ohio Department of Transportation (ODOT), and the National Cooperative Highway Research Program (NCHRP) have dedicated research funding toward the investigation of these properties. As the NCHRP (2002) states: "Throughout the highway community the major pavement design emphasis is now on rehabilitation for which empirical design approaches have become inadequate." One recommendation for improvement to empirical approaches is the adoption of mechanistic methods supported by historic empirical methods. With this recommendation comes the exploration and development of new testing devices and data interpretation algorithms.

Mechanistic-empirical (M-E) approaches more sensibly characterize working pavements and enhance the dependability of designs. In the near future, design approaches will be based solely on mechanistic principles. However, because of the breach present in today's knowledge base, mechanistic design methods must be supported by empirical relationships. It has been concluded by AASHTO that the mechanistic-empirical design approach needs to be better defined before practical and realistic design procedures can be developed and implemented. Hence the development of a *Guide for the Design of New and Rehabilitated Pavement Structures,* based on M-E principles for adoption and distribution by AASHTO, has begun (NCHRP 2002).

At present, the most popular technique to determine the stiffness of underlying highway pavement soils is to conduct a California Bearing Ratio (CBR) test. This test is specifically used on soil samples prepared in the laboratory. The resulting value (or CBR) is then applied to calculate the resilient modulus of the soil, M_R, using compatible empirical expressions. One expression recommended by AASHTO is:

$$M_R = 10{,}340 * \text{CBR (kPa)} \qquad (1)$$

The use of the resilient modulus was proposed by the Strategic Highway Research Program in 1987. Several other methods had been previously used, but failed according to the Federal Highway Administration's (FHWA) standards. In 1996, the FHWA issued a new standard protocol for M_R testing called the *Long Term Pavement Performance Protocol P46*. This LTPP program protocol describes "the laboratory preparation and testing procedures for the determination of the Resilient Modulus of unbound granular base and subbase materials and subgrade soils under specified conditions representing stress states beneath flexible and rigid pavements subjected to moving wheel loads" (LTPP 1996). This protocol became very popular in the late 1990's and was recently improved upon with the new 2002 NCHRP 1-28A protocol. The advantages of the new protocol include clearer definitions of material classification. In addition, the applied stress and time duration are more representative to the field conditions.

However, there are problems and shortcomings with this and other testing methods. First, the majority of the testing methods use samples of the base, subbase, and subgrade layers that have been prepared and compacted in the laboratory using procedures

that are different from what the soils are subjected to in-situ. The laboratory compacted specimens may have stiffness different from the soils compacted in the field. The quality of laboratory tests in their ability to provide accurate measurements of soil properties depends greatly on the ability to recreate the conditions found in the field. Secondly, most of these tests require soil sampling which may be difficult to obtain due to the location of the project site with respect to both structural and personal safety. Even if it is possible to obtain a sample, it is highly likely that the sample will be disturbed through the sampling process itself, which ultimately provides inaccurate testing results. Thirdly, these tests do not offer the specific pieces of information needed by engineers and pavement designers to establish whether the stiffness of pavement materials and soils under construction meet design requirements. In addition, for an existing pavement where the subgrade, subbase, and the base soils have experienced years of weathering and traffic loading applications, the current testing methods are not capable of determining the stiffness of these in-situ soils. Finally, the value of Poisson's ratio is an important consideration in pavement design calculations. Currently, the value of Poisson's ratio is being estimated rather than measured in most cases (Zeng *et al*. 2003). This presents a great need to develop a non-destructive, accurate, and economical field test for the measurement of stiffness (elastic and shear moduli) and Poisson's ratio for the underlying soils of pavements. The new highway construction guide proposed by AASHTO and supported by the final report for the NCHRP (2002), 1-37A, recommends such key testing methods.

The experimental technique used in this study to measure the stiffness and Poisson's ratio of underlying soils in highway pavements takes advantage of piezoelectric sensors developed in recent years. These sensors are made of piezoceramic materials. When an electrical excitation is applied to a transmitter element, it leads to mechanical vibrations, which generate shear (s) or primary (p) waves in a soil. Similarly for a wave receiver, a mechanical vibration of the element leads to an electrical output. Thus, the velocity of the s- or p-wave can be determined by measuring the travel time and the distance between the wave transmitter and receiver. There are two types of piezoelectric sensors, which are both incorporated in this experimental technique. The first type is used to generate and receive s-waves and is called a bender element while the other type is used to generate and receive p-waves and is called an extender element. Since the maximum strain generated by a piezoelectric sensor in the surrounding soil is on the order of 10^{-3} % as reported by Dyvik and Madshus (1985), the stress-strain relationship is well within the elastic range of soils. This technique has been used by a number of researchers such as Dyvik and Madshus (1985), Thomann and Hryciw (1990), Jovicic (1996), Viggiani and Atkinson (1995), Hryciw and Thomann (1993), Jovicic and Coop (1998), and Zeng and Ni (1998) to measure stiffness of sand and clay in the laboratory in recent years.

At the present time, there is no such testing device on the market, which can dependably measure the stiffness of in-situ base and subgrade layers during and after pavement construction. However, a new field-testing device has recently been developed at Case Western Reserve University to measure small-strain elastic and shear moduli and Poisson's ratio of soils (Zeng *et al*. 2003). This new device employs the bender and extender element technique described in the preceding paragraph. The device includes a pair of cone penetrometers, which are each fitted with two piezoelectric sensors for a total of four sensors (or two pairs of sensors). This device can be pressed into foundation soils through the simple application of a vibratory hammer. One set of the piezoelectric sensors

located on one penetrometer is used as wave transmitters while the other set on the other penetrometer is used as wave receivers. An electrical pulse produced by a function generator is used to stimulate the transmitters. Vibration of the transmitters produces primary and shear waves (p- and s-waves) that disseminate through the soil sample and are captured by the receivers. From the measured velocities of the s- and p-waves, the stiffness and Poisson's ratio of the soil can be determined. Thus far, this cone penetrometer/piezoelectric sensor technique has been proven to yield reliable results in the laboratory. A number of papers have been published on the use of this technique (Zeng *et al*. 2003, 2004). In this project, a significantly improved version of this device is developed and presented along with results of laboratory tests.

II IDEA PRODUCT

The piezo-cone penetrometer is shown in Figure 1. It consists of one set of bender elements, one set of extender elements (for a total of four piezoelectric sensors), two rectangular push rods, two solid removable cones, two rectangular caps, and two adjustable connection rods. The push rods themselves each consist of two pieces of .635 cm x 5.08 cm x 152.4 cm (¼" x 2" x 60") flat stock aluminum. This material is lightweight, durable, and rustproof, making it suitable for field conditions. Metal rulers are engraved on the penetrometers so that the depth of the sensors below ground is known during the test. Two rectangular areas for the bender and extender elements are milled in the rod as well as an area to place and protect the lead wires. The cone tips are fabricated from stainless steel and are removable as they are simply screwed into the base of the rods (Figure 2). If the cones get dull or damaged they can easily be replaced or repaired. The penetrometers themselves are connected to each other with two horizontally adjustable connection rods made from fiberglass so as not to interfere with the electrical signals produced by the piezoelectric sensors (Figure 3). These rods are held in place by set screws which can be adjusted to provide various distances between the elements for optimum performance. The elements themselves can also be horizontally adjusted for maximum performance and protection (Figure 4). Two rectangular polypropylene caps were milled for the upper end of the push rods for easy placement of the ultrasonic vibratory hammer. As the penetrometers are pushed into the ground in steps, the distribution of elastic modulus and Poisson's ratio with depth is measured.

The piezoelectric sensors employed in this design were purchased from Piezo Systems Inc. of Cambridge Massachusetts (Figure 5). Bender element type Q220-A4-303Y (transmitter) and type Q220-A4-303X (receiver) were used in the cone penetrometer. Extender element Q220-A4-303YE (transmitter) and element Q220-A4-303XE (receiver) were used in the cone penetrometer as well. Each element has overall dimensions of 41.3 mm x 12.7 mm x 2.3 mm (1.63 in x 0.5 in x 0.09 in). Each sensor can be coated with an epoxy which creates a watertight seal and protects the sensors from any possible abrasions while pushing the rods into the foundation material. Any electrical connections (wires, etc.) can be sealed with a waterproof coating as well but are already well protected as they are fixed inside the cone penetrometers.

Figure 1. Piezo-Cone Penetrometers

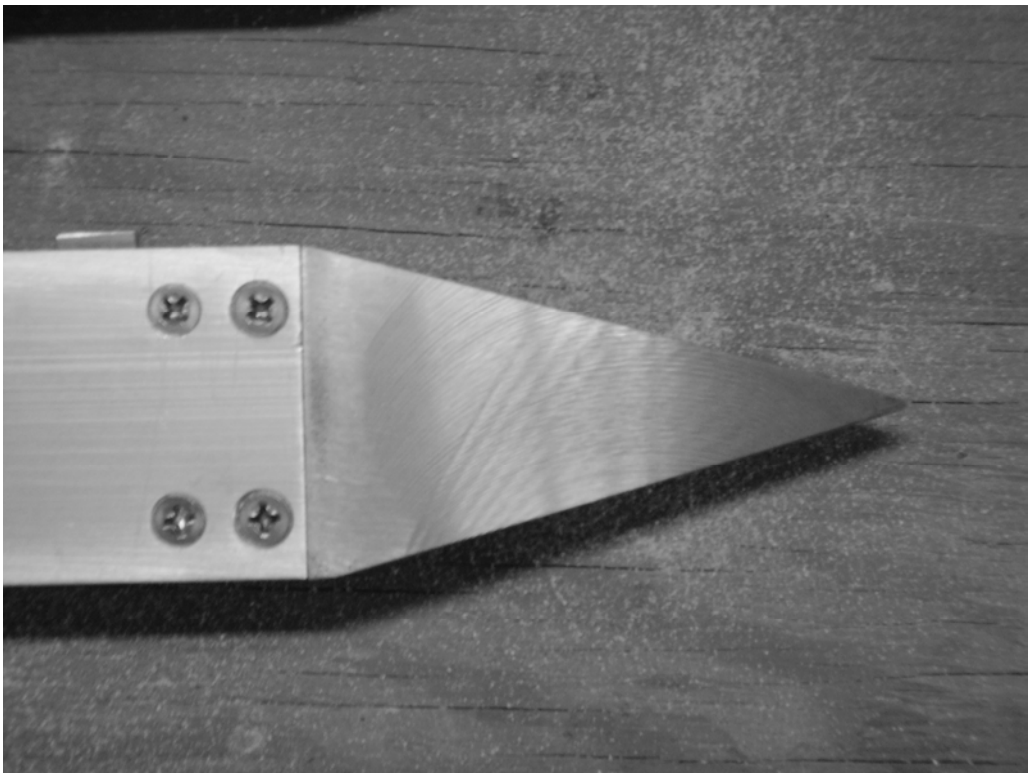


Figure 2. Steel Cone Tip

Figure 3. Connection Rod

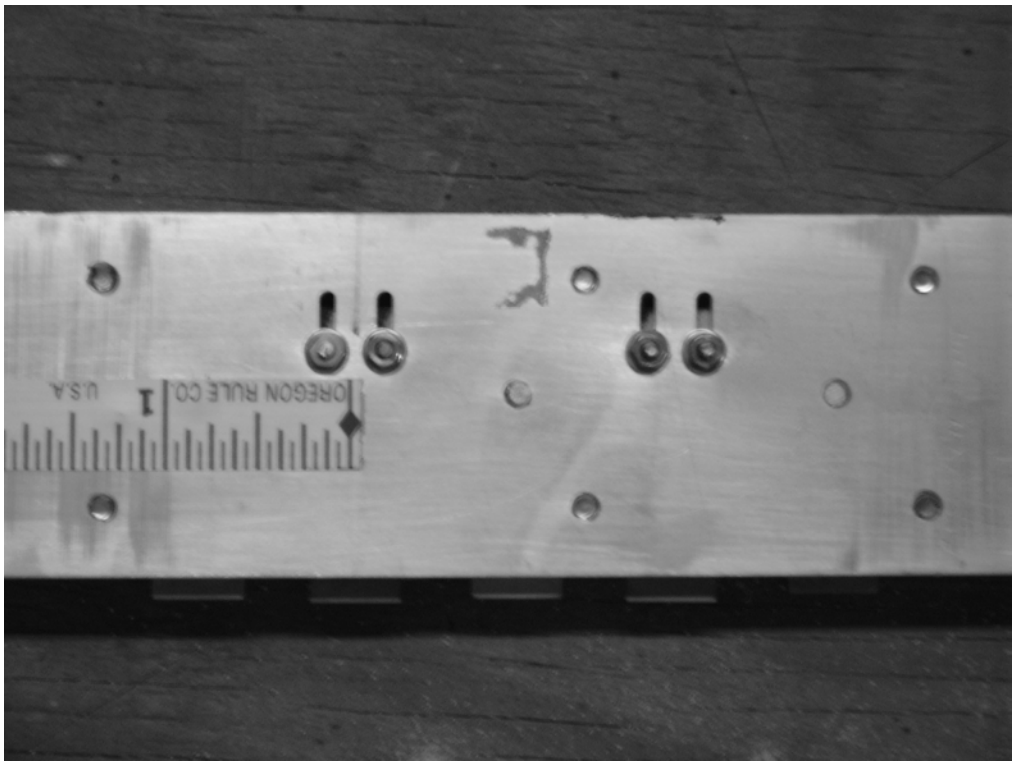
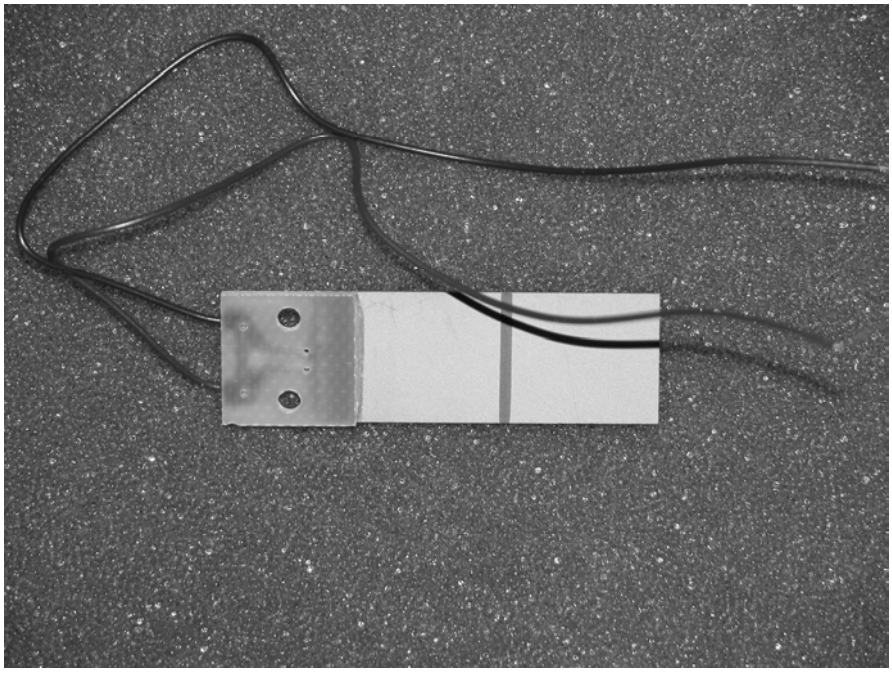
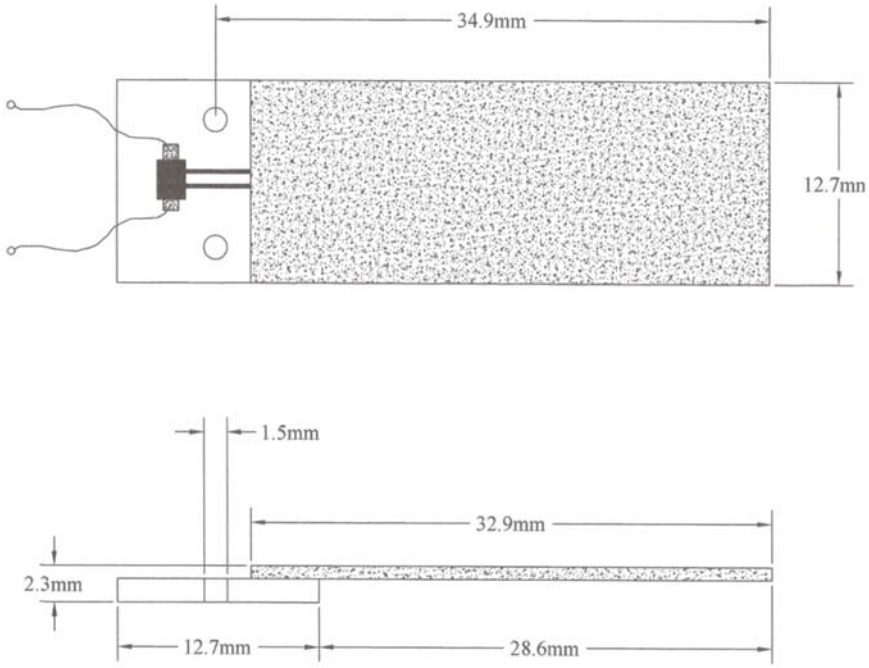


Figure 4. Adjustable slats for piezoelectric sensors



(a) Typical bender element



(b) Typical element dimensions

Figure 5. Piezoceramic elements

III CONCEPT AND INNOVATION

Base and sublayer stiffness and Poisson's ratio are important parameters for material characterization in highway construction. During and after pavement construction, it is very important and cost-effective to have a low cost, mobile, and automated system that can measure the stiffness and Poisson's ratio of in-situ base and sublayers accurately and quickly. The new highway design guide proposed by AASHTO requires such measurements be conducted. The upcoming release of the final report for NCHRP 1-37A also recommends such systems be used in highway construction. However, in the construction of highway pavements at present, engineers often have to rely on field observations and empirical relationships which are prone to errors. The results of such estimation depend on the experience of field inspectors and the time and place of the inspection. Other testing techniques such as DCP and FWD do not measure these parameters directly and have to rely on empirical relationship or inverse analyses to derive these parameters. Consequently, it can lead to over-conservative design in some cases, while in some other cases, inadequacy of base and sublayer soil stiffness has lead to damage and even failure of the pavements. Therefore, there is the urgent need to develop an economical and automated system that can measure the stiffness and Poisson's ratio of soils in the foundation of pavements directly.

A new testing technique has been developed in the geotechnical laboratory of Case Western Reserve University to measure the stiffness and Poisson's ratio of soils using piezoelectric sensors mounted on cone penetrometers, Zeng et al (2003 and 2004), whereby these piezoelectric sensors are made from piezoelectric materials. The basic component of the sensors is an advanced material primarily used by the defense industry to fabricate sensors that can measure air resistance to missiles during their flight and ultimately to give feedback to the guidance system. Only recently, the technology was de-classified for civilian use. The device used in this method includes a pair of cone penetrometers, each fitted with two piezoelectric sensors (one set used as wave transmitters while the other set as wave receivers), which can be pushed into the foundation of existing highways or highways under construction. For existing pavements, two pilot holes can be cored through the pavement. Then the device can measure the stiffness and Poisson's ratio of the underlying soil that has been subjected to traffic loading and weather changes for a long period of time. This is very useful before pavement re-surfacing is done to determine the required overlay thickness. When a failure of pavement occurs, engineers can use this device to determine the mechanical properties of the base and sublayers quickly, thus helping to identify the cause of failure. When using this device, a pulse generated by a function generator is used to activate the transmitters. Vibration of the transmitters produces shear (S) and primary (P) waves that propagate through the soil and are captured by the wave receivers. Then from the measured velocities of shear and primary waves, soil stiffness parameters (elastic modulus, shear modulus, and Poisson's ratio) can be determined. The results have been compared with current practice of soil stiffness determination based on the CBR (California Bearing Ratio) test and resonant column test in laboratory with very good agreement. This technique has received strong support from academia, state transportation departments such as the Ohio Department of Transportation, and private industries. Case Western Reserve University has obtained a US patent (#7,082,831) for this technique.

Based on the successful testing of the technique in the laboratory, we see a great potential for such device to be used in monitoring and controlling construction quality of base and sublayers of pavements, evaluating the performance of existing pavement, and helping forensic investigation in the field. However, in order to make this technique as an industry wide standard test, it is necessary to improve the device design such that it can be applied to complex and rugged field conditions. It also needs to demonstrate capability of this technique through pilot study cases, compare the results with that of existing techniques, and establish "target" values for different type of soils for the earthwork technicians to base their acceptance criteria.

IV INVETIGATION THROUGH LABORATORY TESTING

4.1 Soil description

Two types of sand were tested to simulate soil materials underlying highway pavements. One was Nevada sand, purchased from the Gordon Sand Company of Compton, California, which has a grain size distribution shown in Figure 6. The other sand used was a mixture of various sands. The grain size distribution of this sand is also shown in Figure 6. This sand is coarse-grained sand and is classified as well-graded whereas the Nevada sand is classified as a poorly-graded sand.

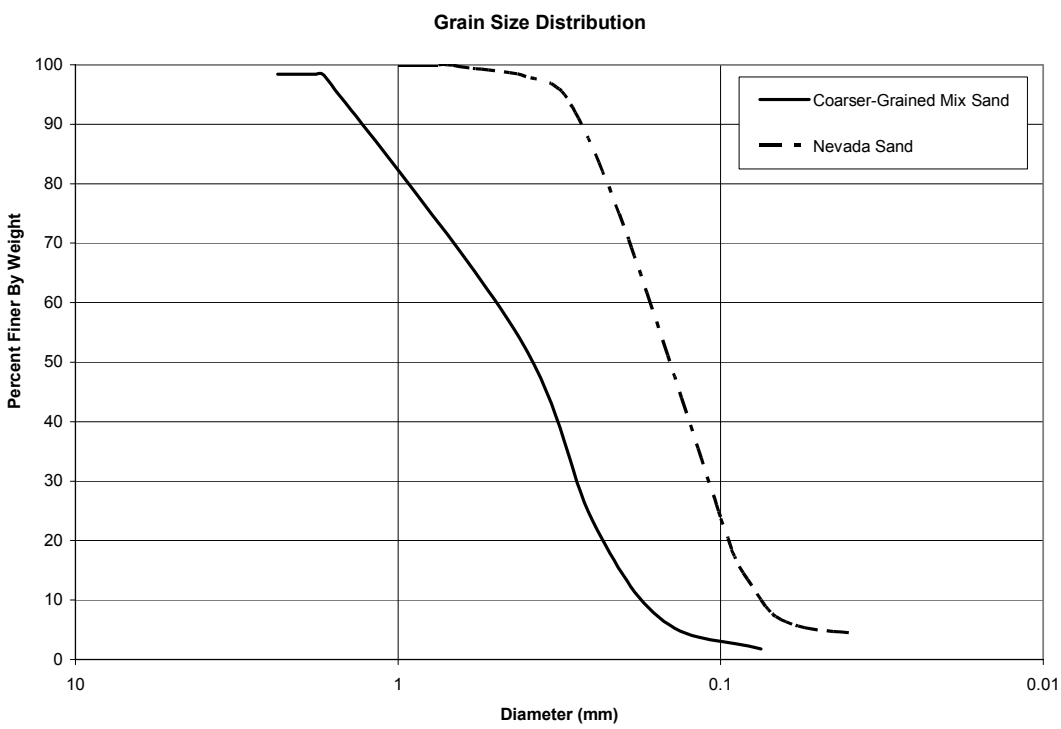


Figure 6. Grain size distribution

4.2 Experimental setup

The experimental setup in the laboratory is shown in Figure 7. A 33120A Agilent Waveform Generator was used to produce the triggering source signals. A square impulse wave was adopted as the source signal, which has been known to produce clearer and

more reliable results. A 54624A Agilent Oscilloscope was used to capture and display the received signals that were amplified by a 467A Hewlett Packard Power Amplifier.

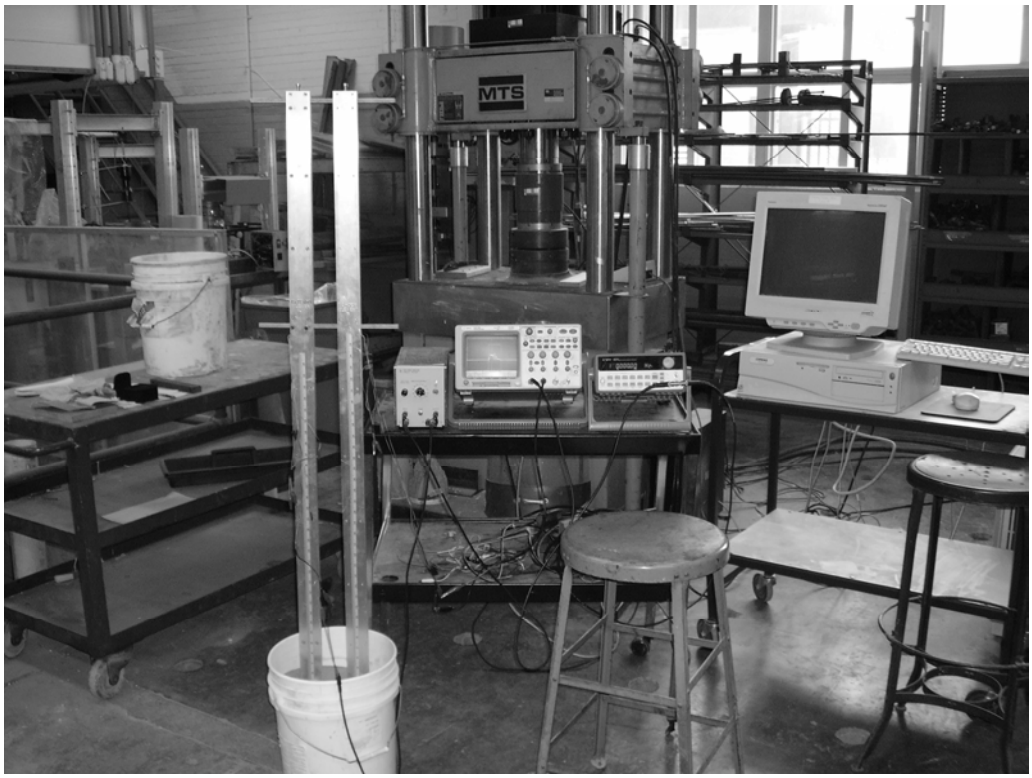


Figure 7. Experimental setup for laboratory tests.

4.3 Theory behind the testing

The shear wave velocity can be calculated from the travel time of the shear waves produced and received by the pair of bender elements. Assuming that the distance between an s-wave transmitter and an s-wave receiver is L_s and that the time for the wave to travel this set distance is t_s, the average shear wave velocity can be calculated as:

$$V_s = L_s / t_s \tag{2}$$

In a similar fashion the primary wave velocity can be calculated from the travel time of the primary waves produced and received. In this case, the following equation is employed:

$$V_p = L_p / t_p \tag{3}$$

where L_p is the distance between the extender element transmitter and receiver and t_p is the travel time of the p-wave.

The shear modulus, $G_{\max}$, and the constrained modulus, M, of the soil can be calculated as:

$$G_{\max} = \rho * V_s^2 \tag{4}$$

$$M = \rho * V_p^2 \quad (5)$$

where ρ is the mass density of the soil. Using the calculated values for the shear modulus and the constrained modulus taken at the same depth, the Poisson's ratio of the soil can be calculated. The Poisson's ratio (μ) is given by:

$$\mu = [(M / G_{max} - 2) / (2M / G_{max} - 2)] \quad (6)$$

Finally, the elastic modulus (E) can be determined using the calculated values for the shear modulus and Poisson's ratio:

$$E = 2G_{max} * (1 + \mu) \quad (7)$$

4.4 Testing procedures

The two sand samples were prepared in a steel container with a diameter of 30.48 cm (12 in) and an overall height of 91.44 cm (3 ft). The steel container had enough lateral stiffness to simulate a K_o condition that is characteristic of conditions found in the field. Too often many analyses assume that soils have isotropic properties which lead to significant errors in the calculation of soil properties. Imposing a K_o condition in the laboratory creates anisotropic soil properties which are representative of those usually existent in the field. Soil samples were created by pouring the sands into the container using a hopper. In the creation of each sample, the height and rate of pouring were kept constant so as to achieve uniformity throughout the soil sample. Four different samples were prepared, two Nevada sand samples and two coarse-grained mix sand samples. Samples of different densities were created by varying the height of the hopper: the greater the distance between the hopper and the container, the denser the sample, and vice versa. After each sample was prepared, the penetrometer was gently pushed into the soil until the piezoelectric sensors reached a specified depth. Bender and extender element tests were then conducted to measure the shear and primary wave velocities. After recording these measurements, the cone penetrometer was pushed to deeper positions in the soil to obtain other measurements. Upon the final depth of testing, the s-wave velocities, p-wave velocities, shear modulus, and constrained modulus were calculated. In addition, measurements of s- and p-wave velocities were taken at the same locations in order to calculate the Poisson's ratio and the elastic modulus at the corresponding depth.

Field tests can be performed in a similar fashion. The piezo-cone penetrometer can be pushed directly into the sublayers of a pavement under construction. A vibratory hammer will be used in cases where stiffer soils do not allow the penetrometer to be easily pushed into the ground. For an existing pavement, two holes can be cored through the upper layers of asphalt or concrete, and the penetrometers again can be gently pushed into the underlying soils. The testing procedure and calculations described above can then be implemented at different depths to obtain and check the mechanical properties of the soil sublayers. Since this test is considered a non-destructive test, little disturbance to the under-layers of new or existing pavements is created. Thus, results are likely to be reliable and accurate.

4.5 Experimental results

The experimental results are primarily based on the arrival time of the s-and p-waves produced by the bender and extender elements, respectively. The main challenge in these experiments is the ability to positively determine the arrival of these waves. Typical outputs as recorded by the oscilloscope are shown in Figures 8 and 9. Note that the polarity of the s-wave can be reversed thus reversing the signal produced on the seismograph trace and positively identifying the shear wave arrival (Figure 10).

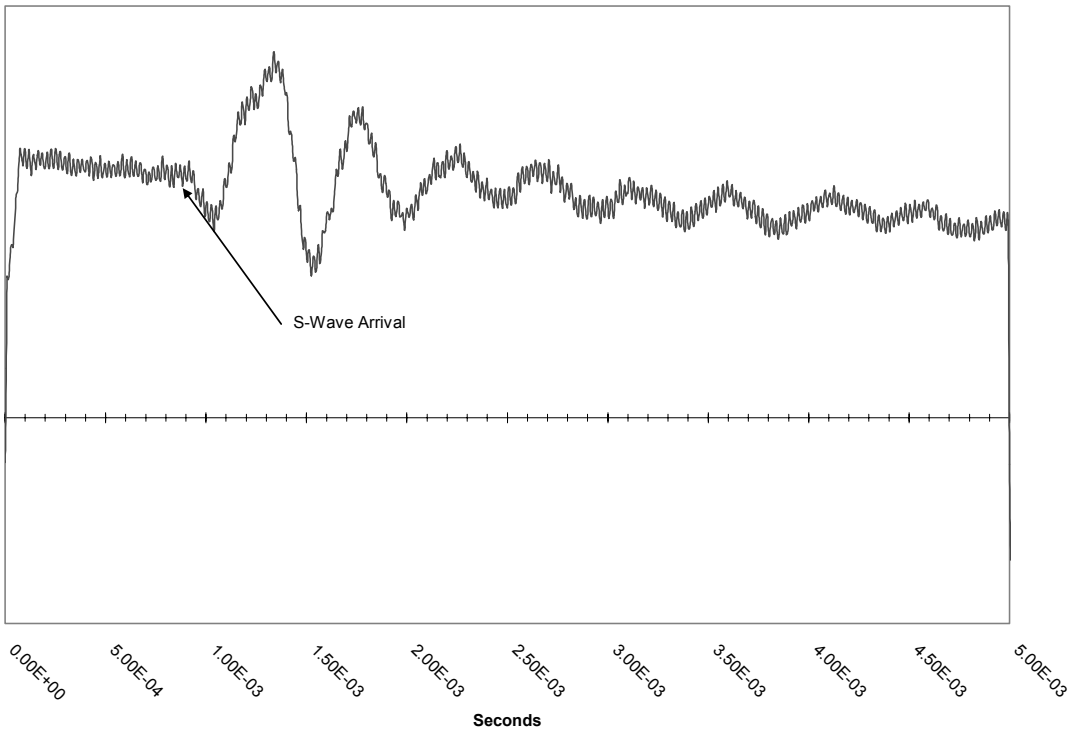


Figure 8. S-wave arrival time

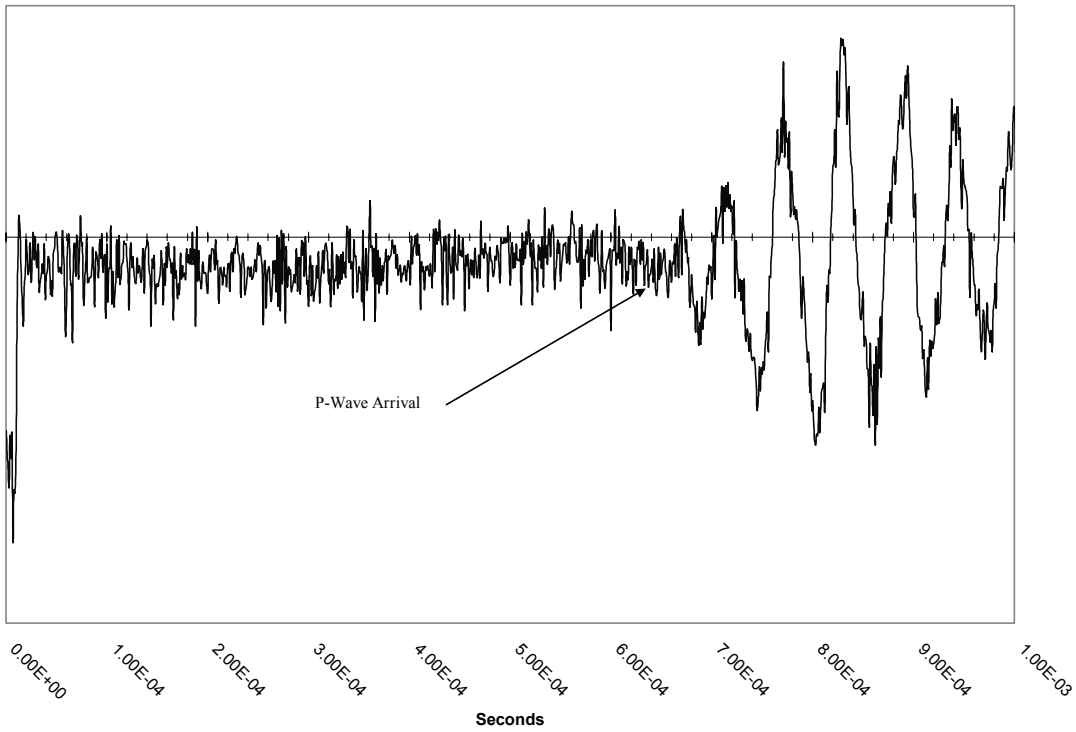


Figure 9. P-wave arrival time

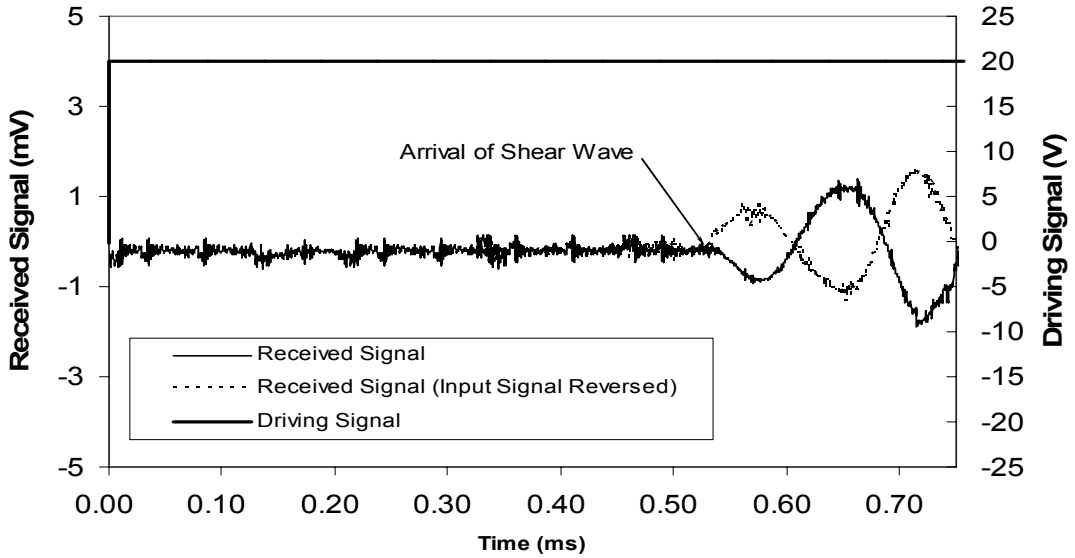


Figure 10. S-wave with reverse polarity

The results for the four different tests (on Nevada sand and coarser-grained mix sand) conducted in the laboratory are shown in Figures 11 through 14.

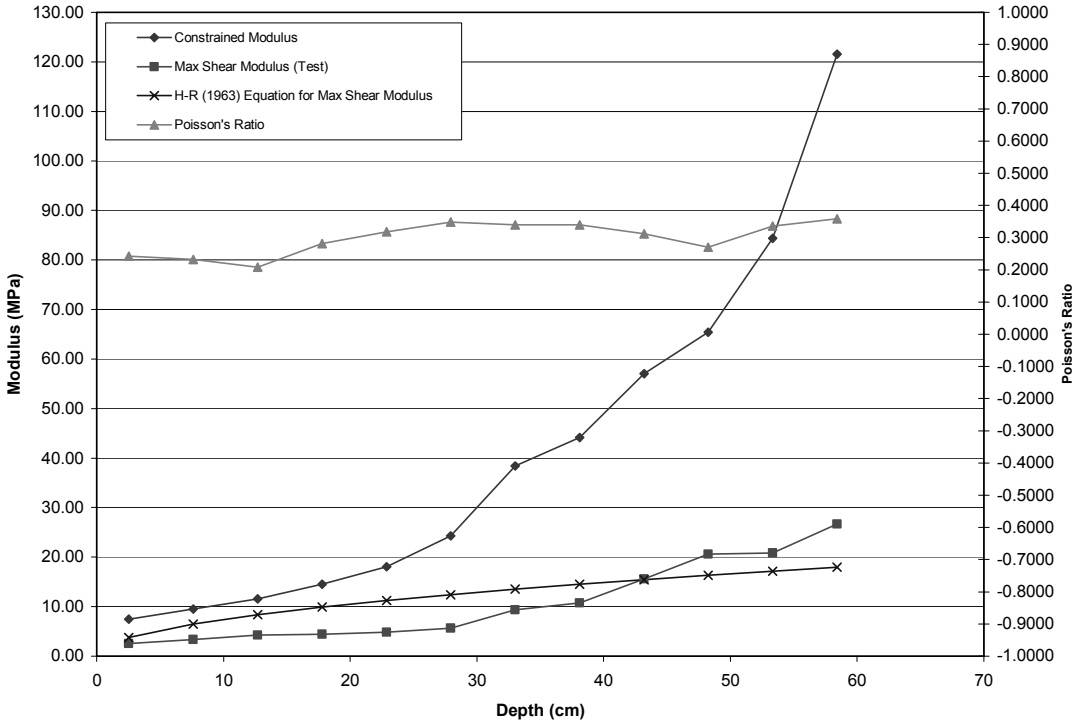


Figure 11. Test results on Nevada sand (mass density 1,525.54 kg/m^3)

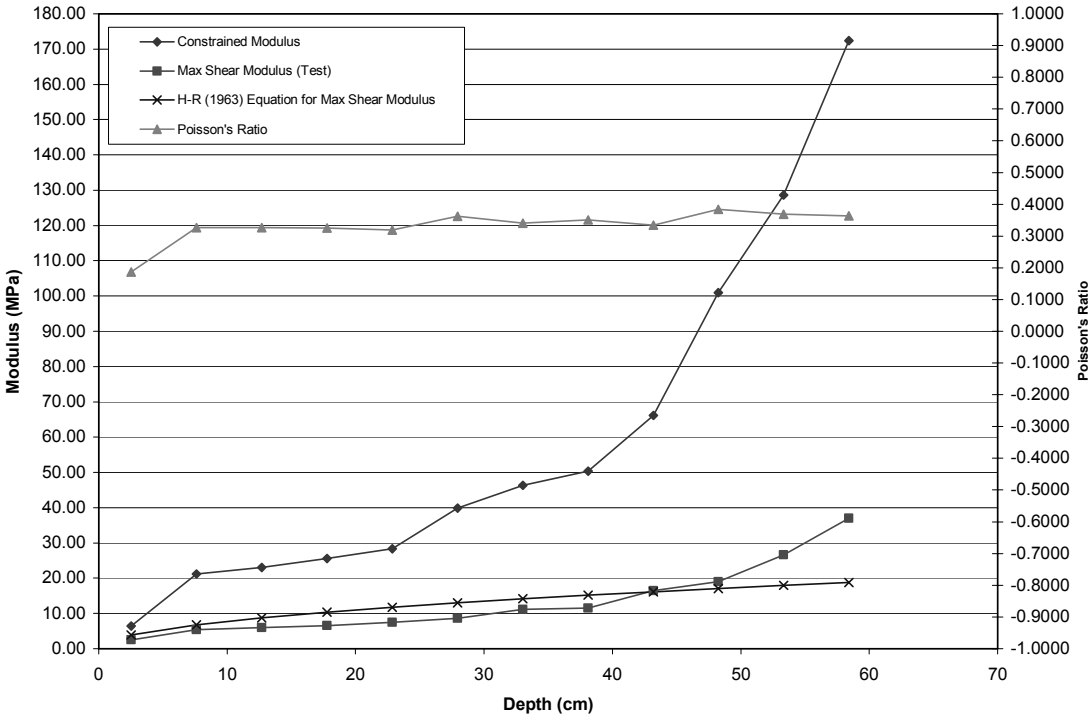


Figure 12. Test results on Nevada sand (mass density 1,543.74 kg/m^3)

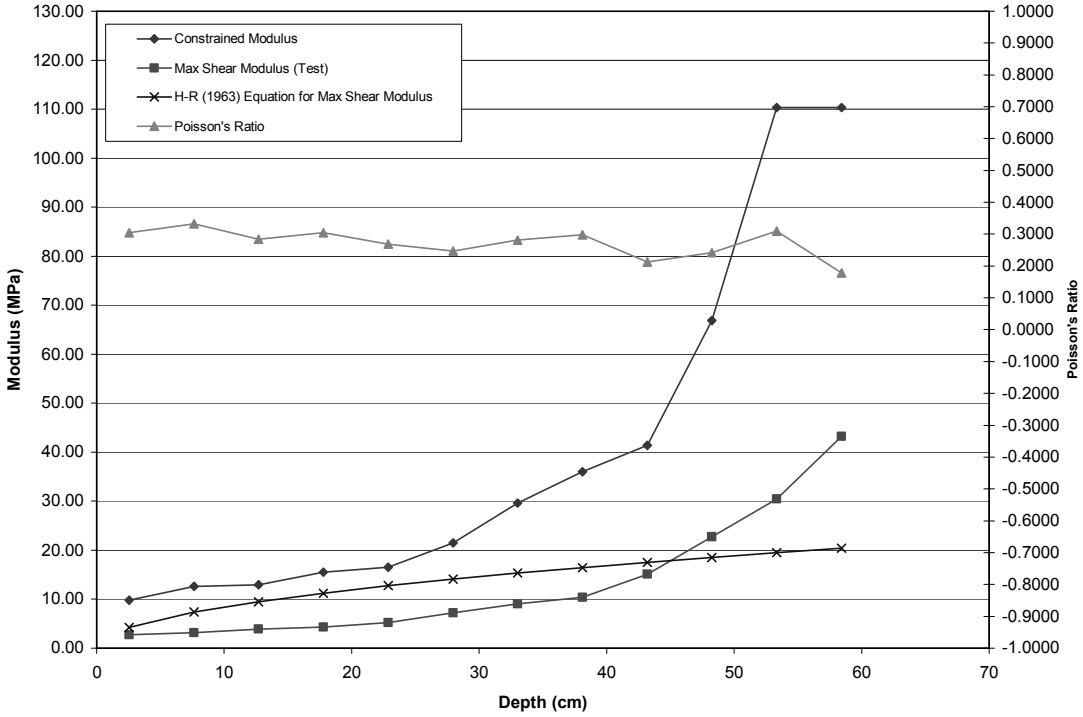


Figure 13. Test results on mix sand (mass density 1,575.86 kg/m^3)

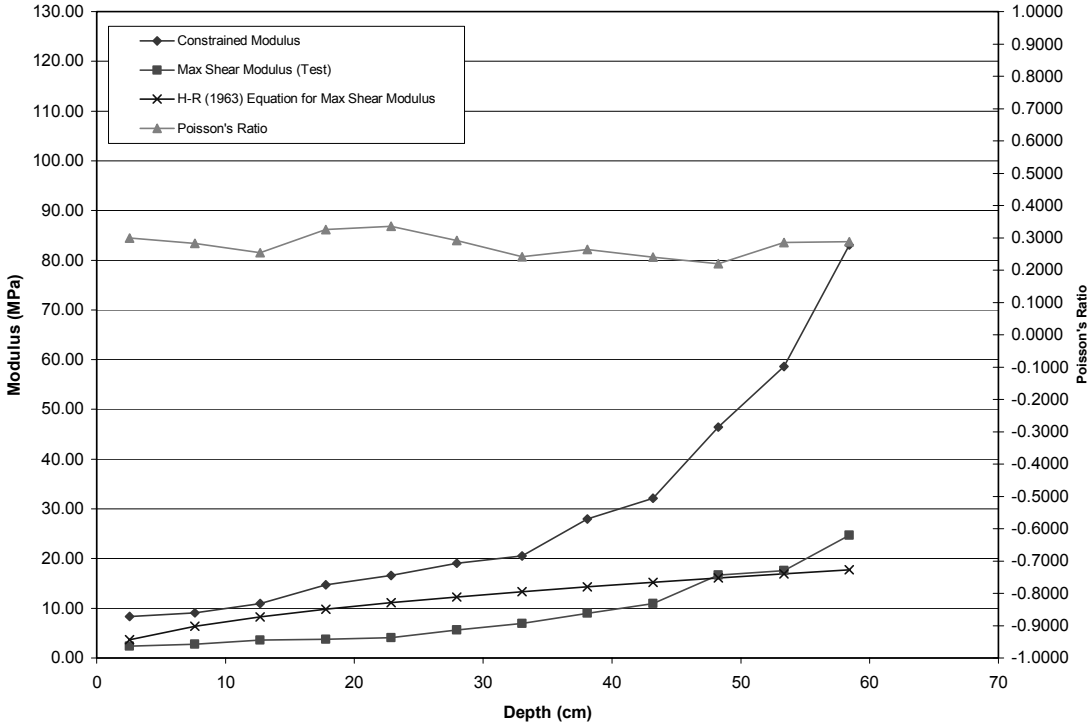


Figure 14. Test results on mix sand (mass density 1,520.29 kg/m^3)

From the data recorded by the sensors on the cone penetrometer it can be seen that both the constrained modulus and the shear modulus gradually increase with depth as the effective confining pressure increases. In addition, as the density of the samples increase, so do the values for the constrained and shear modulus. Also shown in the graphs are the results from the calculations of a well known empirical equation for the shear modulus of sands developed by Hardin and Richart (1963). The shear moduli collected from the tests generally show good agreement with the shear moduli from this equation. In addition, Poisson's ratio was calculated from the shear modulus and constrained modulus and is also included in the graphs. The graphs reveal that the Poisson's ratio is generally between 0.2 and 0.4 which is reasonable for dry sands.

V CONCLUSIONS

A newly improved piezo-cone penetrometer has been developed and constructed for the measurement of the soil stiffness of underlying soils of highway pavements. Bender and extender elements were implemented in the design to produce and receive s- and p-waves for the determination of the soil stiffness. Two different soils (Nevada sand and a coarser-grained mix sand) were tested to determine the accuracy and reliability of this new device. The conclusions of this study are as follows:

(1) The piezo-cone penetrometer can be used in the in-situ measurement of soil properties, such as the measurement of base and subgrade layer stiffness and Poisson's ratio during and after the construction of highway pavements.

(2) The piezo-cone offers reliable measurements of the shear modulus, constrained modulus, Poisson's ratio, and the elastic modulus of soils. These measurements can be taken simultaneously by this device and continuous profiles of these parameters can be obtained.

(3) The piezo-cone penetrometer test offers a new mechanistic approach for the quality control / quality assurance of pavement design and construction.

(4) Compared to empirical equations such as that of Hardin and Richart (1963) for the measurement of shear modulus, the results of piezo-cone penetrometer test are reasonable.

(5) The test is easy, quick, economical, reliable, and can be made mobile and automated for use in the field.

VI PLANS FOR IMPLEMENTATION

Following the successful completion of laboratory tests, it is clear that this technique has promising potential in the construction quality control of new pavement, evaluation of performance of existing pavement, and forensic investigation in the event of a pavement failure. The laboratory demonstration shows that this technique is mobile, versatile, user friendly, and applicable to all types of soils and field conditions. It is superior over the current available techniques. A US patent (#7,082,831) has been issued for this technology.

Before the technique can be adopted in the field and the device is produced commercially, one crucial step is to test the technique in the field and make real time measurement to verify the technique. The plan is to submit a proposal to the IDEA program for field tests in close collaboration with Ohio Department of Transportation. The field tests will be conducted using the facility of Advanced Pavement Research Center of

Ohio University and the ODOT Super-Pavement testing facility at Daleware County in Ohio. The measured properties of base and sublayers will be compared with the results using other testing device. After the field tests, Case Western Reserve University will discuss commercialization of the device with Pile Dynamic Inc. The project is expected to start in 2007.

INVESTIGATOR PROFILE

Prof. Zeng of the Department of Civil Engineering at Case Western Reserve University served as the principal investigator for the project. He obtained his B.S. degree in civil engineering at Tsinghua University in China and M.Phil. and Ph.D. degrees at Cambridge University in England. He has been working in the area of geotechnical engineering for the past 20 years. Prof. Zeng's research specialties are applications of piezoelectric sensors, geotechnical earthquake engineering, centrifuge modeling, numerical simulation, and vibration of foundations. His research work has been funded by the National Science Foundation, NASA, National Academy of Sciences, Department of Interior, Department of Labor, and Ohio Department of Transportation. He has over 100 refereed journal publications, conference papers, and research reports. He has given more than 50 seminars, invited lectures, and conference presentations.

Prof. Zeng started working on the research topic of application of piezoelectric sensors while working at University of Kentucky. The research was funded by NSF. Since then, his research on this topic has been funded by NASA, National Academy of Science, and Ohio Department of Transportation. He has published more than ten papers on this topic. Prof. Zeng directed and guided the research reported in this project.

One graduate student, Miss Heather Hlasko, carried out most of the research work reported here under the guidance of Prof. Zeng. She finished her M.S. degree in 2006 on this topic. Currently, she is pursuing her Ph.D. degree on the same topic. She is a recipient of the prestigious Research Fellowship of the Ohio Aerospace Institute and the Eisenhower Fellowship for Transportation Research. She has won numerous academic awards and wants to become a professor after finishing her Ph.D. degree.

REFERENCES

Dyvik, R., and Madshus, C., Lab measurement of G_{max} using bender elements. *Advances in the Art of Testing Soils Under Cyclic Conditions*, V. Koshla, pp. 186-196, 1985.

Hryciw, R.D., and Thomann, T.G., Stress-history-based model for G^e of cohesionless soils. *ASCE Journal of Geotechnical Engineering*, 1993, **119**(7), 1073-1093.

Jovicic, V., Coop, M.R., and Simic, M., Objective criteria for determining G_{max} from bender element tests. *Géotechnique*, London, 1996, **46**(2), 357-362.

Jovicic, V., Coop, M.R., and Simic, M., The measurement of stiffness of clays with bender element tests in triaxial apparatus. *Geotechnical Testing Journal*, ASTM, 1998, **21**(1), 3-10.

NCHRP Project 1-37A: Development of the 2002 guide for the design of new and rehabilitated pavement structures. Available online at: http://www.ence.umd.edu/~schwartz/abstracts/nchrp_1_37a.html (accessed 10 May 2005).

Thomann, T.G. and Hryciw, R.D., Laboratory measurement of small strain shear modulus under K_o conditions. *Geotechnical Testing Journal*, GTJODJ, 1990, **13**(2), 97-105.

U.S. Department of Transportation, *Long-Term Pavement Performance Protocol P46: Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils* (McLean, Virginia: 1996), P46-1.

Viggiani, G., and Atkinson, J.H., Interpretation of bender element tests. *Géotechnique*, London, 1995, **45**(1), 149-154.

Zeng, X., Figueroa, J.L. and L. Fu., Measurement of base and subgrade layer stiffness during and after construction using a cone penetrometer equipped with piezoelectric sensors. *Proceedings of the International Conference on Highway Pavement Data, Analysis and Mechanistic Design Applications*, 2003, Volume 2, September, Columbus, Ohio.

Zeng, X., Figueroa, J.L. and L. Fu., Measurement of base and subgrade layer stiffness using bender element technique. *Recent Advances in Materials Characterization and Modeling of Pavement Systems*, 2004, ASCE Geotechnical Special Publication 123, 35-45.

Zeng, X. and B. Ni, Application of bender elements in measuring G_{max} of sand under K_o condition. *Geotechnical Testing Journal*, ASTM, 1998, **21**(3), 251-263.