The Ohio Department of Transportation
Office of Research & Development
Executive Summary Report

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

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Problem

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 and after the construction of a 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. The new highway construction guide proposed by AASHTO (American Association for State Highway and Transportation Officials) recommends 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.

In this project, we developed the 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 and for evaluating performance of existing pavements. The system is mobile, versatile, user friendly, and applicable to all types of soils and field conditions. Preliminary tests in the laboratory show that the design objectives of this device have been achieved.

Objectives

The objectives of the proposed study are:

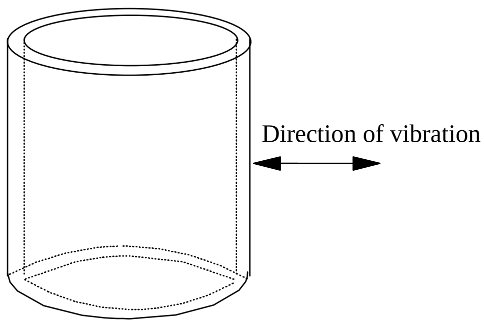
1) To improve the mechanical system of the device to make it applicable to complex and challenging field conditions. It will be mobile, robust, water proof, and applicable to all types of conditions possible in the field.

2) To improve the data acquisition system and the software for automated data analysis. We developed a user-friendly program to calculate the elastic modulus, shear modulus, and Poisson's ratio based on the reading from the wave tests and the results will be shown on the screen in a few minutes.

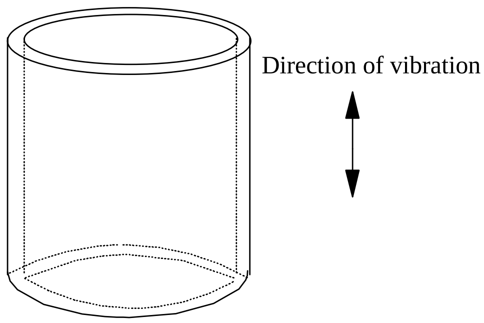
3) To conduct laboratory tests on a wide range of soils to check the system and to validate the results.

Description

Early in the project, we tried to modify the original design so as to protect the sensors in the penetrometer from being damaged by the surrounding soils when pushing in and pulling out of foundation soils. With the help of the sensor manufacturer, Piezo Systems, Inc. of Cambridge Massachusetts, we have purchased cylinder-shaped extender sensors (for measuring the velocity of P waves) and shear sensors (for measuring the velocity of S waves). The sensors have diameters of 1.9 cm (0.75 inch) and are illustrated in Fig.1. The sensors can be coated with waterproof materials to use in wet soils.



a) Extender elements



b) Shear elements

Fig.1 Cylinder-shaped sensors for measuring velocity of P and S waves

We purchased four pairs of each type of sensors and tested them individually. When buried in soils, the sensors can produce clear signals of P and S waves. We installed the sensors onto a penetrometer made from a hard plastic rod. By using the plastic rod, we can reduce the possibility of short circuit and the influence of static charge. The ultimate goal was to make the sensors part of the penetrometer (with the same diameter) so that when pushing in and pulling out of foundation soils, the sensors would not be damaged. However, when we tested this new design in the compacted soil layers, the signals received were weak when the distance between the two penetrometers was more than 5 cm (2 inch). In the field, one would expect the distance between the penetrometers be more than 5 cm (2 inch) and up to 10 cm (4 inch) to reduce the influence of soil disturbance as the penetrometers are pushed into the foundation soil. In addition, the system requires a power supply with a voltage higher than 100 volts, a condition difficult to satisfy in the field. Therefore, even though this design concept has shown some promises, it is abandoned at this moment. Future improvements in the sensor technology may make it possible in a few years.

We decided to go back to the original design concept to build the system with better protection of the sensors. We have fabricated the cone penetrometers in our laboratory and tested the system on two types of soil, a fine-grained Nevada sand and a coarse-grained sand. Compare with the earlier design, the new system has the piezoelectric sensors mostly within the penetrometer and the sensors have good contact with surrounding soils. There are small wedges made of steel placed just above and below the bender elements. They can protect the sensors when it is pushed into or pulled out of the foundation soil. For the extender elements, they stay inside the penetrometers and just touch the outside soils. The penetrometer with the sensors is shown in Fig.2. The details about the sensors and the protection are shown in Fig.3. The system was tested in the laboratory settings and worked very well. The laboratory test setup is shown in Fig.4. A graduate student, Miss Heather Halsko, has finished her M.S. degree based on this study.

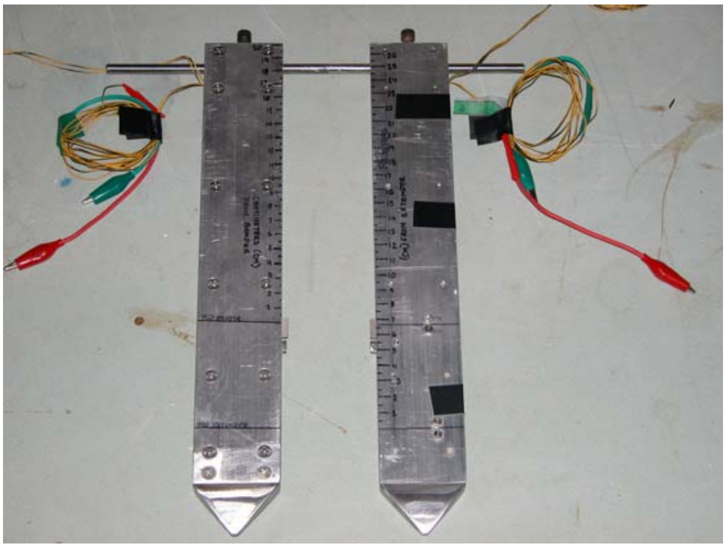


Fig.2 Cone penetrometer equipped with piezoelectric sensors

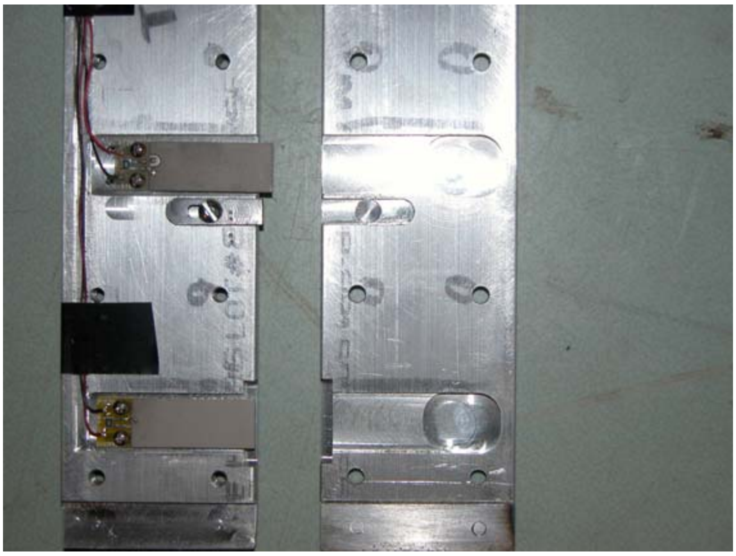


Fig.3 Piezoelectric sensors mounted in the penetrometer

Fig.4 Laboratory test setup for the cone penetrometer

Tests were carried out on two types of soils using the test setup shown in Fig.4. The first soil is Nevada sand - a fine-grained soil, while the second one is a coarse-grained sand. For each type of the soil, one dense sample and one loose sample each was prepared for testing. In addition, each test was repeated at least once and very good repeatability was achieved, suggesting the performance of the system is reliable. Example results are shown in Fig.5. As shown in the figure, the stiffness of sand increase gradually with depth as confining pressure increases. Based on the measured constrained modulus and shear modulus, it is possible to calculate the Poisson's ratio of the soil. In the test, the Poisson's ratio measured varied between 0.3 to 0.4, which is typical for sand. Also shown in the figure is the value of shear modulus calculated by a widely used empirical equation, the Hardin and Richards equation, which estimate shear modulus of soil based on in-situ stress and density of soil. As can be seen from the figure, the tests results agree very well with that of the empirical equation. For all the soil samples tested, such good agreement was achieved. In comparison with results on the same soil using other devices (CBR test and the old design penetrometer), the agreement is very good, proving that the new device is accurate in determining the stiffness and Poisson's ratio of soils.

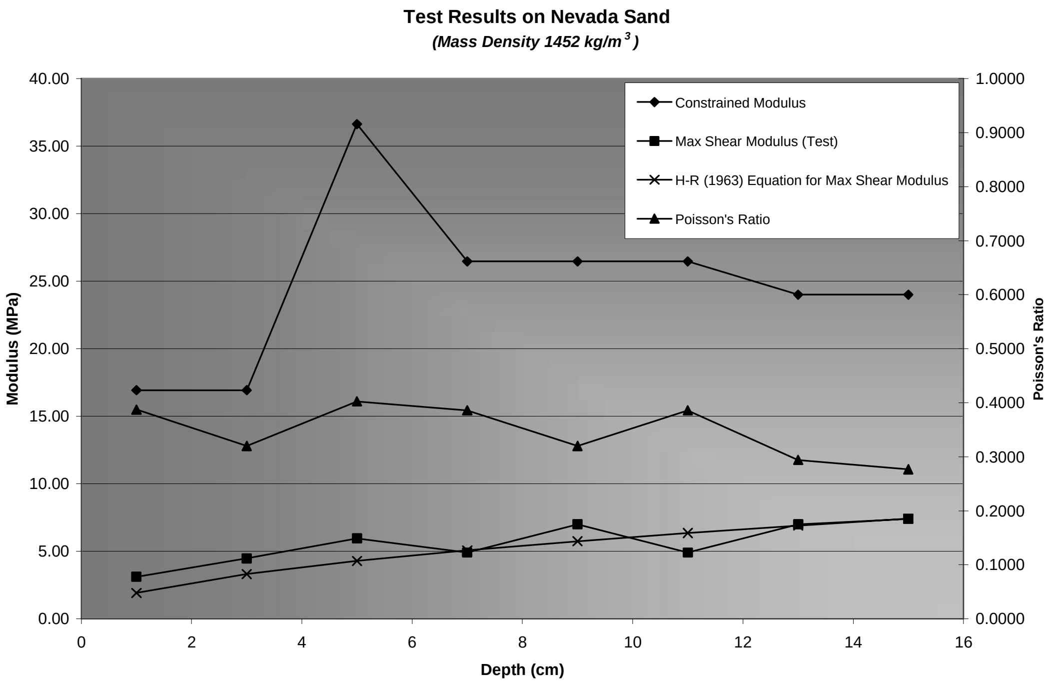


Fig.5 Test results of stiffness and Poisson's ratio of dense Nevada sand

Conclusions & Recommendations

In summary, the objectives of the project have been successfully accomplished. A graduate student finished her M.S. degree using this project. The design concept has been proven in the laboratory and the device is ready for field verification. For the next stage of the project, we will improve the design of the system by making it light weight, waterproofing the sensors so they can work for wet soils, and developing a vibration system to drive the penetrometer into ground smoothly. We will also carry out tests on different types of soils, both dry and wet, and improve the data acquisition system.

Currently, we are improving the design and operation of the device. We hope to finish the latest round of improvement in three months. Then we will test the device in the field at sites managed by the Ohio Department of Transportation.

Implementation Potential

When the new device is fully developed, we need to conduct pilot study at sites managed by ODOT. We need to conduct tests at one site of pavement under construction to check the quality of compaction and to determine mechanical properties of subbase and subgrade in situ. We also need to conduct tests on a section of existing pavement to measure the property of subbase and subgrade that have been in operation for a number of years. To use the device, two holes need to be cored through the pavement. If the field tests are successful, we can start using this device in selective projects in the state to build up experience and database. Then the results will be critically reviewed and the final implementation plan will be recommended.

The plan for implementation includes the following steps: 1) we will work with Pile Dynamics to further improve the design of the device and the data acquisition system for field use; 2) we will cooperate with ODOT to select two sites for field testing; 3) based on the results of field testing and feedbacks from engineers, we will improve our design; and 4) we will conduct field demonstration of the device, develop users' manual, and train engineers for state-wide application of the device.