Ohio Transportation Consortium Project Report

Developing an Economical and Reliable Test for Measuring the Resilient Modulus and Poisson's Ratio of Subgrade

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Abstract

The resilient modulus and Poisson's ratio of base and sub-layers in highway use are important parameters in design and quality control process. The currently used techniques include CBR (California Bearing Ratio) test, resilient modulus test, DCP (Dynamic Cone Penerometer) and FWD (Falling Weight Deflectometer) tests. Nevertheless, these techniques have certain limitations and sometimes fail to satisfy the requirement and accuracy for design purposes.

Meanwhile, piezoelectric sensors have been widely used for laboratory measurement of wave velocities in soil and rock specimens in recent years. For shear wave velocity determination, bender elements have been applied to the tests. On the other hand, extender elements have been used for the measurement of compression wave velocity.

Therefore, this new laboratory testing technique is developed to measure the two important parameters, the resilient modulus and Poisson's Ratio in a more advanced approach. The results of using this technique on a soil sample is presented and compared with that obtained from CBR tests. It is concluded that this new technique is simple, accurate and has potential to be widely used in engineering practice.

***Key words*: resilient modulus, Poisson's ratio, CBR test, piezoelectric sensor, wave velocity**

Introduction

The currently used techniques include CBR (California Bearing Ratio) test, resilient modulus test, DCP (Dynamic Cone Penerometer) and FWD (Falling Weight Deflectometer) tests. Nevertheless, these techniques have certain limitations and sometimes fail to satisfy the requirement and accuracy for design purposes, as discussed by Zeng (2008).

The California bearing-ratio test was developed by the California Division of Highways in 1929 as a means of classifying the suitability of a soil for use as a subgrade or base course material in highway construction. During World War II, the U.S Army Corps of Engineers adopted the test for use in airfield construction. The CBR test is currently used in pavement design for both road and airfields. Some state Departments of Transportation use the CBR directly. Others convert the CBR value to either the modulus of subgrade reaction k_s or to the Resilient Modulus M_R using empirical relationships. For example AASHTO converts CBR to M_R using

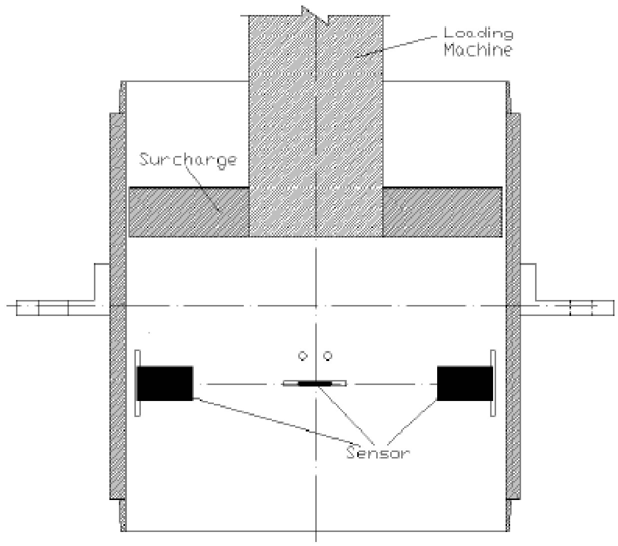
$$M_R=10340\times\text{CBR (kPa)}$$

$$\text{Or}\quad M_R=1500\times\text{CBR (lbs/in}^2\text{)}$$

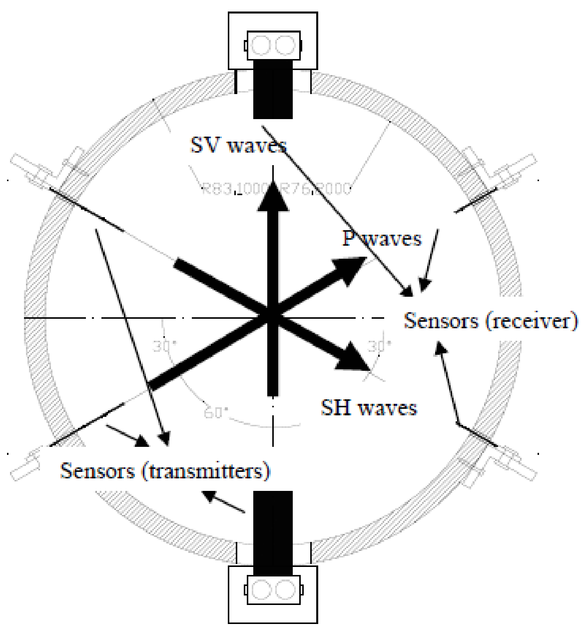
For the new method we are developing, the general device consists of a compaction mold used in CBR test, with three pairs of piezoelectric sensors fitted in. Three of the sensors on the one side are used as wave transmitters and the other three on the opposite side are used as wave receivers. The technology of using piezoelectric sensors to measure wave velocities in soil has been widely used in geotechnical engineering in recent years. The application of the technology is discussed by Leung at al. (2009).

In order to activate the transmitters, electrical pulses are produced by a function generator. The waves of vibration go through the compacted soil and are captured by the receivers. From the time difference between the wave generation and wave receiving, it is reasonable to get the travel speed of the primary wave (P wave) and shear wave (S wave).

Thus it is easy to determine the resilient modulus and Poisson's ratio by equations. The test setup is shown in Figure 1.



a) Cross-sectional view of the compaction mold equipped with piezoelectric sensors



b) Top plan view of the compaction mold with three pairs of piezoelectric sensors

Fig.1 CBR compaction mold equipped with piezoelectric sensors

A current widely used technique to determine the stiffness of compacted soils is to conduct CBR test so as to determine the resilient modulus of soils, M_R. For example by using the empirical expression recommended by AASHTO:

$$M_R=10340\ CBR$$

By this means, we will be able to compare the results by using piezoelectric sensors.

While we measure the wave velocities by sensors, different ranges of pressure loading by CBR machine is attempted applying on the sample. Since the diameter of the piston is relatively larger than the tip-to-tip distance of the sensors, the wave velocities under the pressure are just average quantities. Thus we are trying to look at the tendency of the changes in soil modulus under different pressure of load system.

Materials and Facilities

The clay we used for testing is light brown silty clay: This kind of clay is commonly seen in the region of Ohio. The optimum moisture content test and CBR test followed the ASTM standard procedures described by Bowles (1992).

For compaction test, equipment involved include: compaction mold with base plate and collar, moisture cans, steel straightedge to smooth sample and soil mixer.

For standard CBR Test Equipments, a 152-mm diameter × 178-mm height CBR compaction mold with collar and spacer disk 151-mm diameter × 61.4-mm height has been used. Compaction rammer, expansion-measuring apparatus with dial gauge reading to 0.01mm and compression machine required with CBR penetration rate of 1.3mm/min were also needed.

For bender element test, the facilities that have been used except for CBR test equipments included: piezoelectric sensors (A220-A4-303YB and A220-A4-303XB), Agilent 54621A Oscilloscope and Agilent 33120A function generator.

Procedures and Results

Compaction Test

Objective

To determine the optimum moisture content (OMC) of the soil sample

Procedure

1. Each group should take 3-4 kg of air-dry soil, pulverize sufficiently to run through the No.4 sieve, and then mix with an initial amount of water.
2. Weigh the compaction mold.
3. Measure the volume of compaction mold.
4. Use 26 blows per layer to produce the same compaction energy.
5. Strike both the top and the base of the compacted cylinder of soil with the steel straightedge. If the smoothing process pulls out pieces of gravel, backfill the holes using both smaller pebbles and soil.
6. Weigh the mold and cylinder of soil and record its mass.
7. Extrude the cylinder of soil from the mold, split it, and take two water-content samples –one near the top and the other near the bottom- to test the water contents.

Result

From the test the OMC is determined. The result is shown in Figure 2.

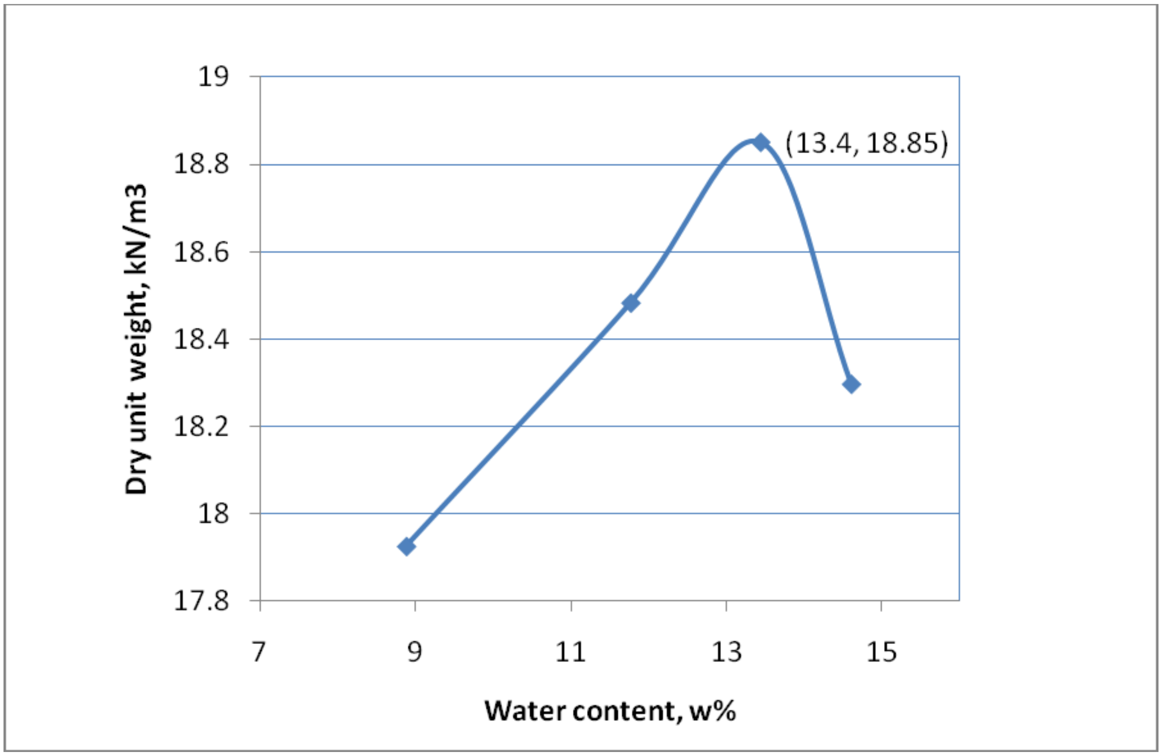


Figure 2 Result of OMC test

From the test, it was found that optimum moisture *w*= 13.4% and the maximum dry unit weight γ_{dry}=19.85 kN/m^3.

CBR Test

Objective

To determine the Bearing Ratio of the clay under the OMC from the test

Equipment

CBR equipment consisting of 152-mm diameter×178-mm height CBR compaction mold with collar and spacer disk 151-mm diameter×61.4-mm height

Compaction machine equipped with CBR penetration piston (43.63-mm diameter with cross-sectional area of 19.35 cm^2) and capable of a penetration rate of 1.3mm/min

Procedure

1. Prepare 12kg of fine-grained soil at the optimum moisture content of the soil (13.4%).
2. Weigh the two molds less base plates and collars.
3. Compact the soil according to 56 blows/3 layers.
4. Remove the collar, and trim the sample smooth and flush with the mold.
5. Remove the spacer disk and base plate, weigh the mold plus compacted soil, and compute the wet mass, density and unit weight and record on the Data Sheet.
6. Repeat Step 1-5 for the 2nd sample which will be soaked**.**

For Unsoaked samples of soil, do Steps 7-9; for soaked samples, proceed to Step 10.

7. Place slotted weights on the sample to simulate the required overburden pressure.
8. Place the specimen in the compression machine and seat the piston. Set the load dial to zero.
9. Record the data on Data sheet 2b. Extrude the sample, split and take two moisture samples each within the top, bottom and center of the sample to determine the water content.

For soaked samples

10. Place a piece of filter paper on top of the compacted sample and then cover with the perforated plate with adjustable stem. Add sufficient additional slotted weights to obtain the desired surcharge.
11. Immerse the mold and weights in a container of water so the water covers the top of the sample. Attach the dial gauge.
12. Set the gauge to zero and record the time of the start. Take readings at 0, 1, 2, 4, 8, 12, 24, 36, 48, 72, and 96h of elapsed time.
13. At the end of the soaking period, leave it drain for 15 minutes. Weigh the soaked sample and record on Data Sheet.

14. Repeat steps 7-10.

Result

The results of CBR tests are shown in Figure 3.

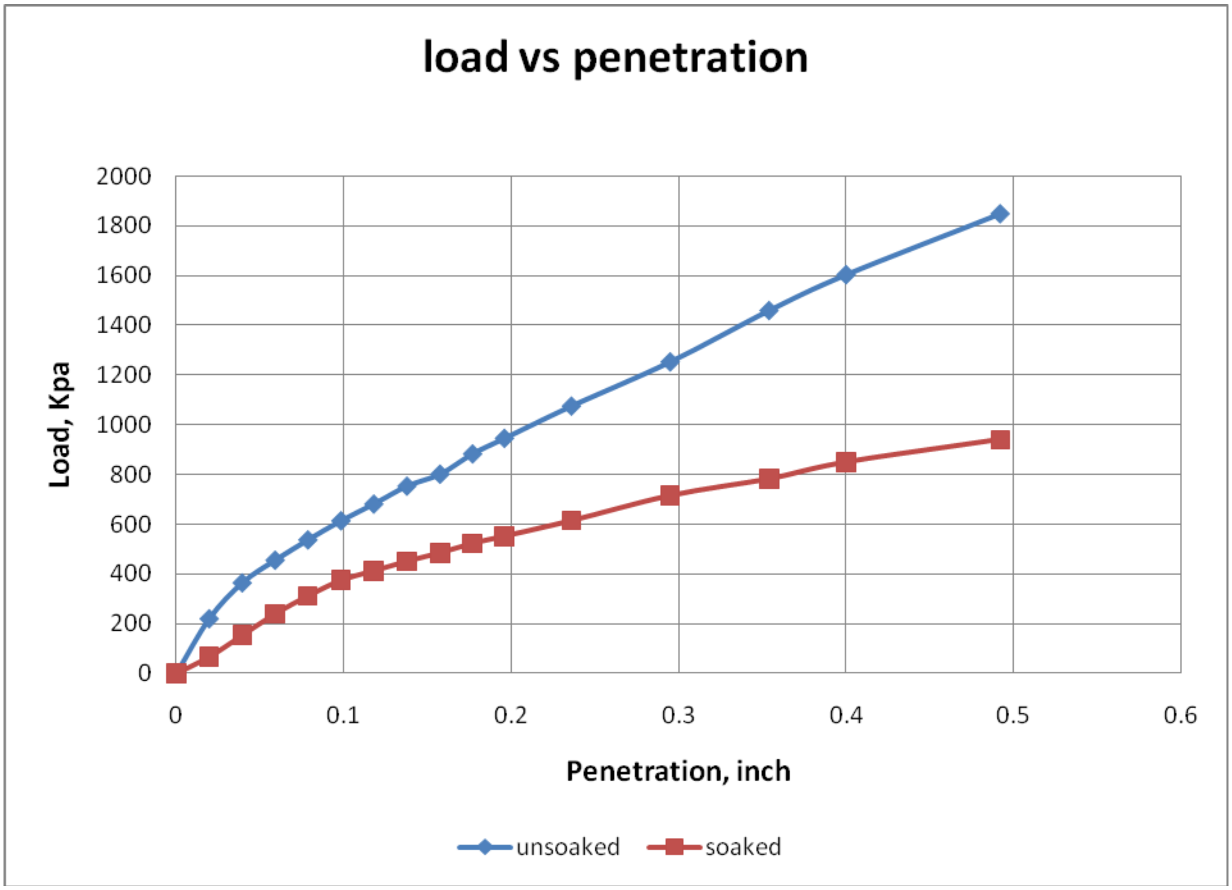


Figure 3 Results of CBR tests on the clay

From the CBR tests, we can derive:

Soaked resistance= 375 Kpa

Standard resistance =6900 Kpa

Unsoaked CBR=614(100)/6900=8.9(%)

Soaked CBR =375(100)/6900=5.43(%)

% Reduction = 1.0-5.43/8.9=0.39

The estimated resilient modules of soils are:

Soaked soil: M_{RS}=10340×5.43=56146.2 kPa=56.15 MPa

Unsoaked soil: M_{RU}=10340×8.9=92026 kPa=92.03 MPa

Bender Element Test

Objective

To determine the shear modulus and resilient modulus of the soil

Soil Samples

To investigate the performance of the bender and extender elements by comparing the results from CBR tests, the same two types of soil samples as CBR tests were made: the clay under the optimum moisture content of 13.4% and the saturated clay.

Test Set-up

A picture of the bender-extender element test set-up used in the study is shown in Fig.4. One pair is used to generate the P wave while the other two pairs are used for S wave in different directions.

Fig.4 Bender and Extender Element Test Set-up

The bender–extender elements were positioned through the slots in the mold with the protrusion length of approximately 25mm and fixed in position using silicone adhesive sealant. The sensors are fragile and non-waterproof so they are coated with an even layer of epoxy resin. Fig.5 shows a single sensor with resin coated during the experiment. Typical results of extender element tests are shown in Fig.6 and 8 for soaked and unsoaked samples, respectively. Typical results of bender element tests are shown in Fig.7 and Fig.9, respectively.

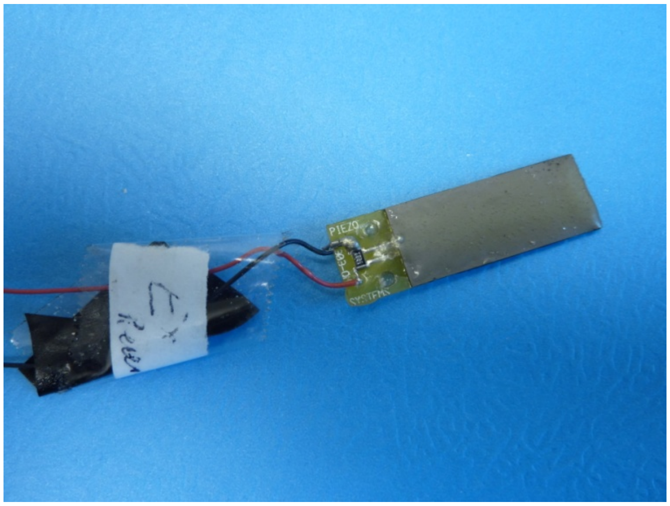


Fig.5 Bender element with epoxy resin that are later pushed into the slot

For Soaked Soil Sample

Table 1 Travel Time of the Waves in Three Directions (μs)

Piston Load ,kPa	**S vertical**	**S horizontal**	**P**
0	910	740	260
250(0.05 inch)	870	660	250
360(0.1 inch)	832	620	241
550(0.2 inch)	823	614	234

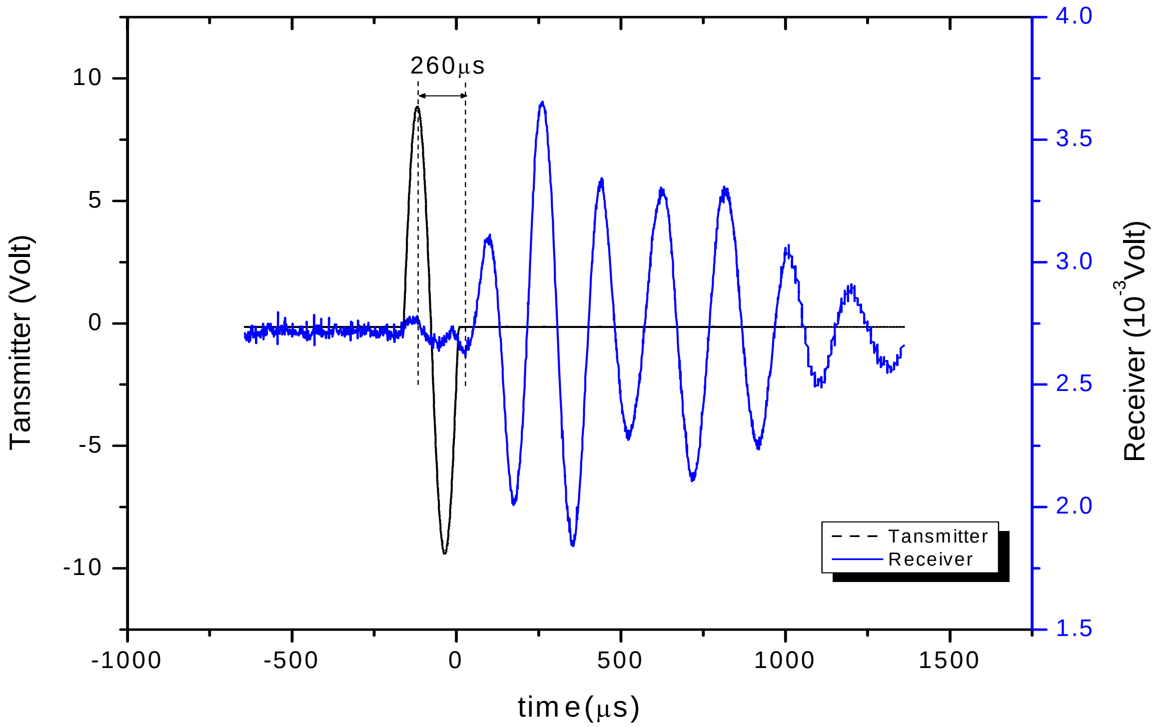


Fig.6 Typical P wave signals recorded on oscilloscope for soaked sample

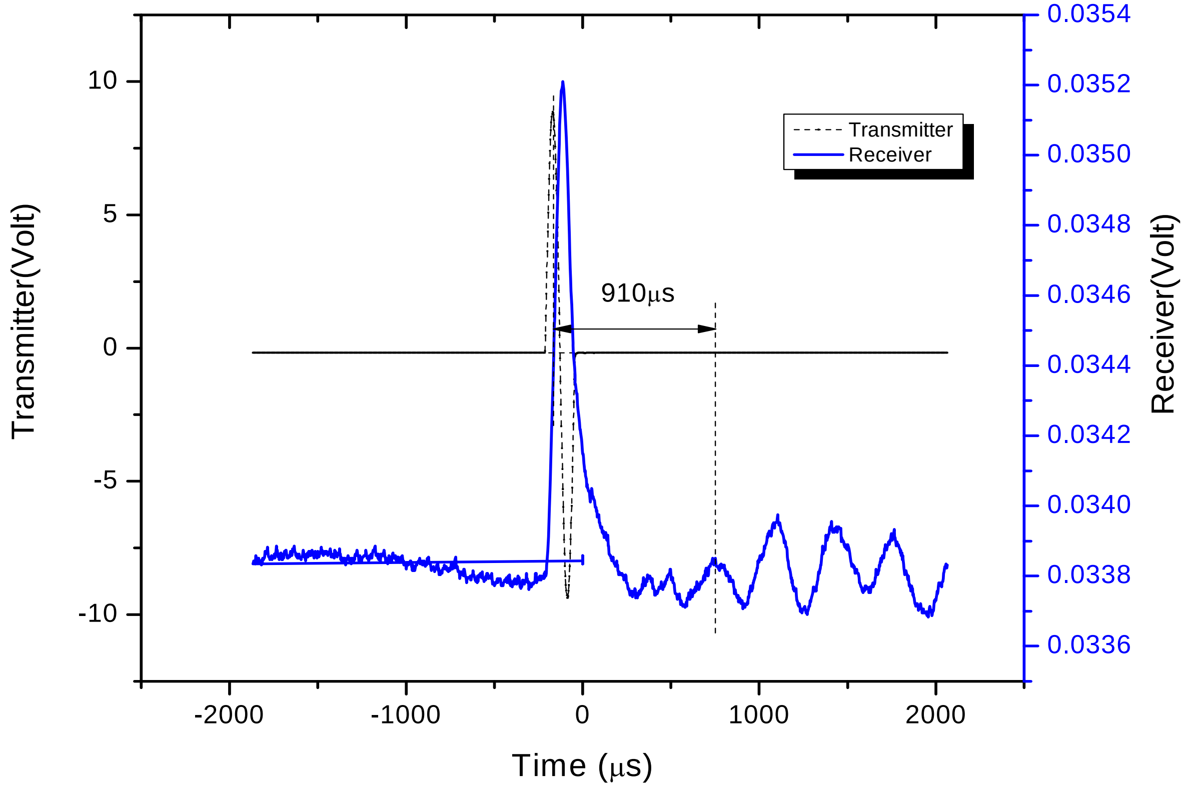


Fig.7 Typical S wave signals recorded on oscilloscope for soaked sample

Suppose the distance between the S vertical wave transmitter and receiver is L_s. The average shear wave velocity is

$$V_{sv} = L_{sv}/t_{sv} = 10\text{cm}/910\ \mu\text{s} = 109.9\text{m/s}$$

The shear modulus in the vertical plane $G_{max,v}$ would be:

$$G_{max,v} = \rho_d V_{sv}^2 = 2.06\times10^3\times109.9^2 = 2.49\times10^7\ \text{Pa}$$

Similarly, the shear modulus in the horizontal plane $G_{max,h}$ is referred to as:

$$G_{max,h} = \rho V_{sh}^2 = 2.06\times10^3\times135.14^2 = 3.76\times10^7 \text{ Pa}$$

For P waves

$$V_p = L_p/t_p = 10\text{cm}/260\ \mu\text{s} = 384.6 \text{ m/s}$$

The constrained modulus of the soil in the horizontal plane would be

$$M = \rho V_p^2 = 2.06\times10^3\times384.6^2 = 3.05\times10^8 \text{ Pa}$$

The poison ratio μ in the vertical plane would be

$$\mu_{,v} = [(M/G_{max,v}-2)/(2\ M/G_{max,v}-2)] = 0.45$$

The poison ratio μ in the horizontal plane would be

$$\mu_{,h} = [(M/G_{max,h}-2)/(2\ M/G_{max,h}-2)] = 0.43$$

The resilient modulus in the horizontal and vertical plane can be determined as:

$$E_{,h} = 2\ G_{max,h}\ (1+\mu_{,h}) = 2\times3.76\times10^7\times(1+0.43) = 107.5 \text{ Mpa}$$

$$E_{,v} = 2\ G_{max,v}\ (1+\mu_{,v}) = 2\times2.49\times10^7\times(1+0.45) = 72.2 \text{ Mpa}$$

For Unsoaked Soil Sample

Table 2 Travel Time of the waves (μs)

Piston Load, kPa	**S vertical**	**S horizontal**	**P**
0	880	630	220
250(0.05 inch)	856	587	210
360(0.1 inch)	820	555	205
550(0.2 inch)	818	550	200

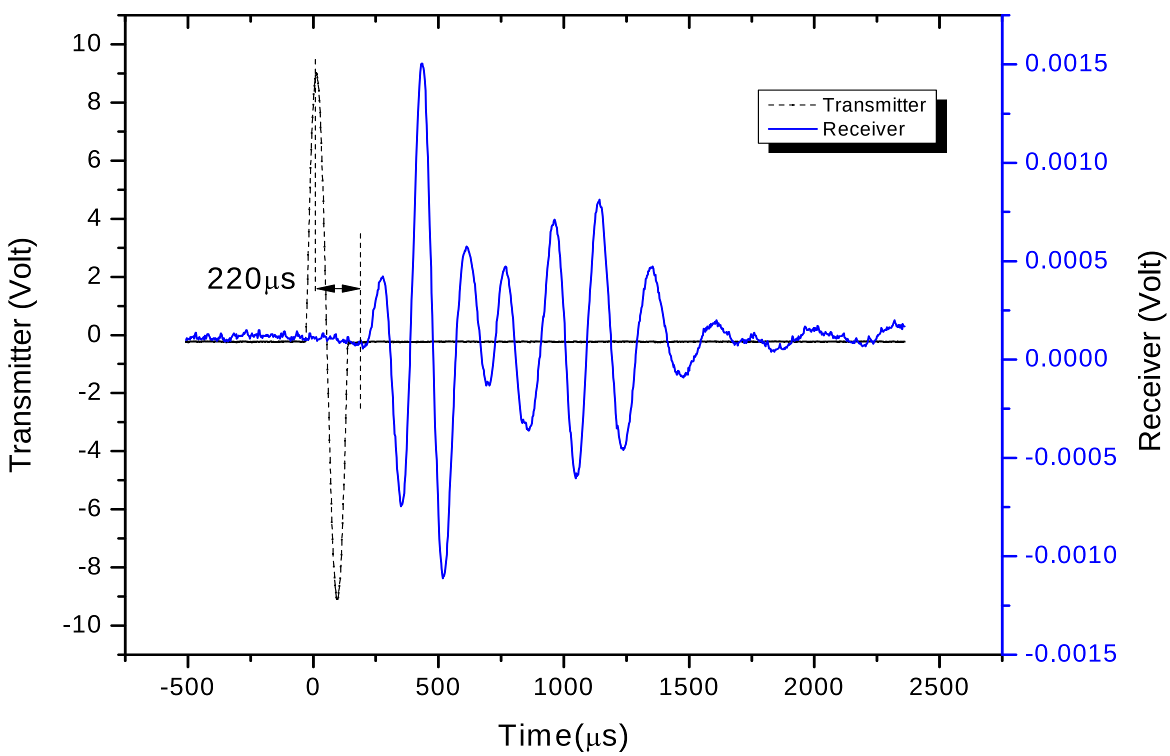


Fig.8 Typical P wave signals recorded on oscilloscope for unsoaked sample

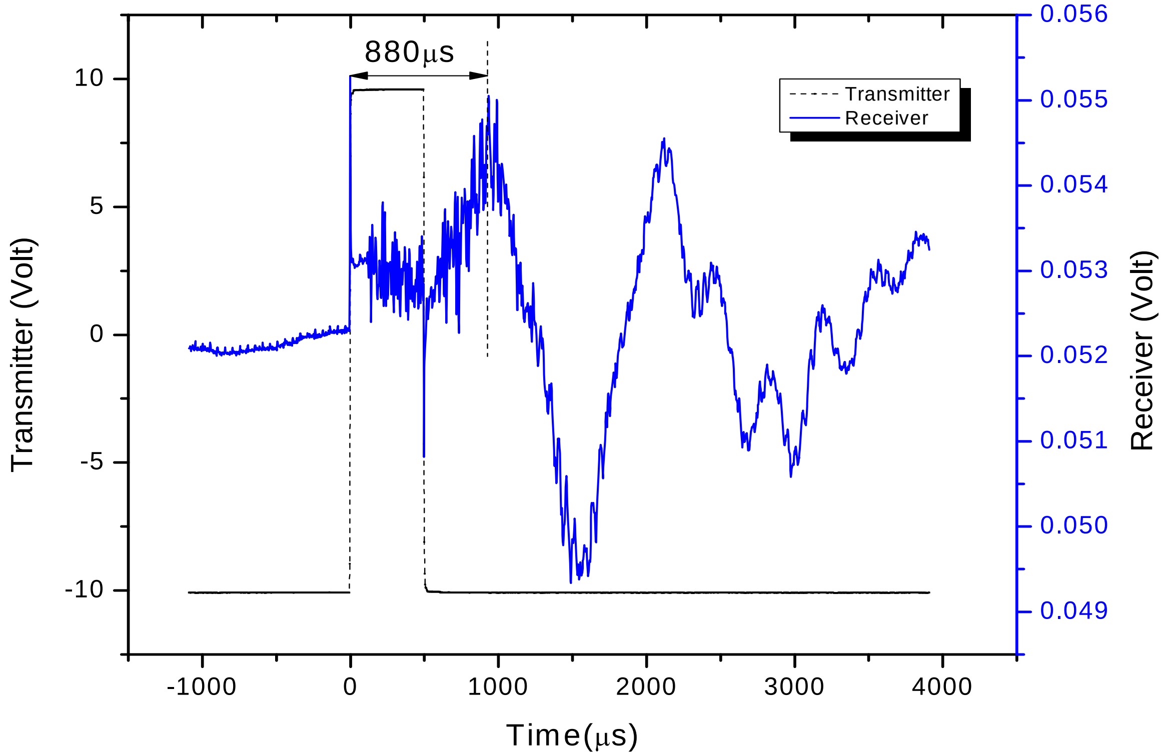


Fig.9 Typical S wave signals recorded on oscilloscope for unsoaked sample

Suppose the distance between the S vertical wave transmitter and receiver is L_s. The average shear wave velocity is

$$V_{sv} = L_{sv}/t_{sv}=10cm/880\ \mu s=113.6m/s$$

The shear modulus in the vertical plane $G_{max,v}$ would be:

$$G_{max,v} = \rho_d\ V_{sv}^2=2.1\times10^3\times113.6^2=2.71\times10^7\ Pa$$

Similarly, the shear modulus in the horizontal plane $G_{max,h}$ is referred to as:

$$G_{max,h} = \rho V_{sh}^2 = 2.1\times10^3\times158.7^2 = 5.29\times10^7 \text{ Pa}$$

For P waves

$$V_p = L_p/t_p = 10\text{cm}/220\ \mu\text{s} = 454.55 \text{ m/s}$$

The constrained modulus of the soil in the horizontal plane would be

$$M = \rho V_p^2 = 2.1\times10^3\times454.55^2 = 4.34\times10^8 \text{ Pa}$$

The poison ratio μ in the vertical plane would be

$$\mu_{,v} = [(M/G_{max,v}-2)/(2\ M/G_{max,v}-2)] = 0.47$$

The poison ratio μ in the horizontal plane would be

$$\mu_{,h} = [(M/G_{max,h}-2)/(2\ M/G_{max,h}-2)] = 0.43$$

The resilient modulus in the horizontal and vertical plane can be determined as:

$$E_{,h} = 2\ G_{max,h}\ (1+\mu_{,h}) = 2\times5.29\times10^7\times(1+0.43) = 151.3\text{Mpa}$$

$$E_{,v} = 2\ G_{max,v}\ (1+\mu_{,v}) = 2\times2.71\times10^7\times(1+0.47) = 79.7 \text{ Mpa}$$

Table 3 Average Resilient Modulus Changes under Different

Load Pressures for Soaked and Unsoaked Sample of Soil

Load(kPa)	**$E_{,h(soak)}$**	**$E_{,v(soak)}$**	**$E_{,h(unsoak)}$**	**$E_{,v(unsoak)}$**
0	107.5	72.2	151.3	79.7
250	135.3	78.9	174.2	84.1
360	153.3	86.13	195	91.5
550	156.3	88.16	198.5	92.3

The results are also shown in Fig. 10.

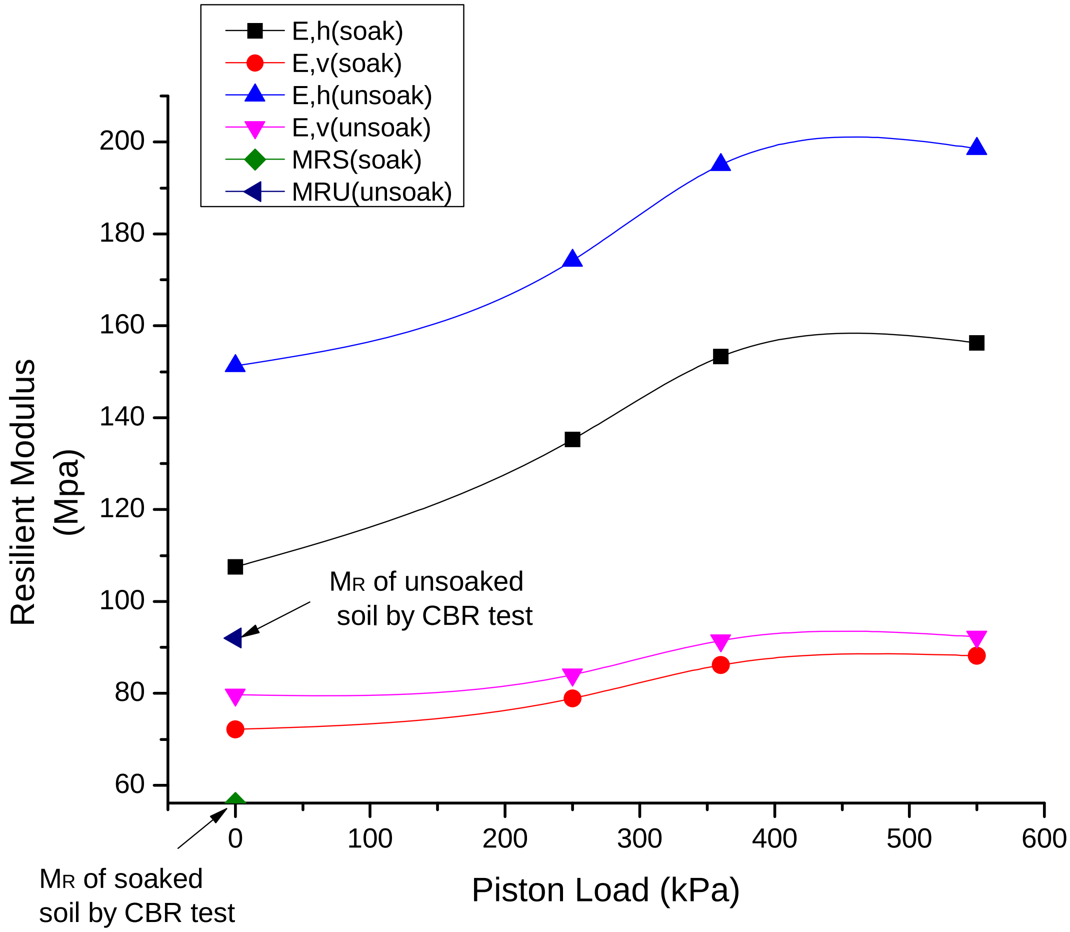


Fig.10 Relationship between measured resilient modulus and vertical pressure.

As shown in the figure, all the elastic moduli measured increases with vertical pressure, consistent with general principles in soil mechanics. The elastic modulus in the horizontal plane is consistently higher than that in the vertical plane. This can happen in heavily compacted clay, indicating the horizontal stress is higher than the vertical stress or K_0 larger than 1. For the unsoaked samples, the measured elastic modulus in the horizontal plane is higher than that measured by CBR method while the measured elastic modulus in the vertical plane is a little bit lower. For the soaked samples, the measured elastic modulus on both the horizontal and vertical planes are higher than that measured by CBR method.

Conclusions

There are a number of limitations for CBR method. Firstly, the reliability and repeatability of the experimental results are not satisfying-since it is difficult to achieve consistent results as well as the fact that it depends on empirical equations to get resilient modulus. Secondly, each specimen has to be disposed after the test because the samples are inclined to be damaged after a loading application. Whenever there is a new testing condition such as a different confining pressure or different water content, a new specimen needs to be prepared. As it is not possible to prepare identical samples, some discrepancies are introduced. What's more, Poisson's ratio, which is also an important parameter in the design calculation, cannot be measured. At present, Poisson's ratio is estimated rather than measured in most projects. At last, from the mechanic perspective, the loading conditions which made by CBR test is different compared with those of the actual sites. The common design of pavement thickness is larger than 50mm, so when the loads from tires transmit to the sub-layer, they are exerted on a wider area on the soil due to the stress dispersion, which proves the fact that it is unreasonable to simulate the load effect by a relatively small-area piston load on the sample during the CBR test. Because of the above mentioned reasons, CBR tests have certain drawbacks and are not commonly used nowadays.

The results from our test are based on the techniques of piezoelectric sensors. The technique of using piezoelectric sensors in soil property determination has been used successfully in the past. In comparison to CBR test, this method is much more accurate and reliable by applying the electric signals on a regular basis. It is non-destructive and non-intrusive, thus the resilient modulus tested are larger than those from the destructive CBR test. It measures resilient modulus as well as Poisson's ratio directly without using any empirical relationships.

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