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Evaluation of the Humboldt Stiffness Gauge

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Submitted by

Dr. Ali Maher*
Professor and Head

Mr. Thomas Bennert*
Research Engineer

Dr. Nenad Gucunski,* Professor

** Dept. of Civil & Environmental Engineering
Center for Advanced Infrastructure & Transportation (CAIT)
Rutgers, The State University
Piscataway, NJ 08854-8014

NJDOT Research Project Manager
Mr. Anthony Chmiel

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16. Abstract

This report pertains to the evaluation of a non-nuclear means of determining the dry density of soils. The device is called the Humboldt Stiffness Gauge (HSG). The device is essentially a small-scale plate load test and takes approximately 1 minute. The test parameter from the test is a stiffness value that is average over approximately 6 to 14 inches beneath the HSG. The manufacturer of the HSG then uses a method to determine a regression equation to use the stiffness parameter to determine the dry density of the soil. However, to establish the regression equation, prior knowledge of the soil's moisture content and dry density is needed.

Research was conducted both in the laboratory and in the field to evaluate the HSG. The laboratory testing was used to establish the depth extent of the measurement of the device, as well a repeatability of the device. This was done by conducting controlled tests within constructed "soil bins". Laboratory testing was also conducted to evaluate how certain objects located beneath the device affected the measurements, as well as to determine if the device may be used as a locator for buried objects. Both a steel pipe and a PVC pipe were selected as objects that the device may encounter under field conditions. The objects were buried at various depths below the device with HSG testing conducted directly over the object, as well as in the immediate vicinity of the object. All "soil bin" tests were accompanied by density balloon testing to verify the soil's dry density. Results of the laboratory testing program show that the device is very repeatable and that it typical has a measurement depth of approximately 6 to 10 inches beneath the device. The laboratory testing also indicated that the device does not have a potential for future use locating buried objects in a homogeneous soil, meanwhile, measurements do not seem to be affected due to small objects located below the device.

The field-testing consisted of utilizing the device on a full-scale research project involving the beneficial reuse of Portland cement amended dredge material as an embankment. Over 400 hundred tests were conducted during the placement of the embankment material, with nuclear density gauge and Clegg Impact Hammer (CIG) tests. Results indicate that the device can be used as an alternative means of estimating the dry density of the soil, as long as there is a way of determining the moisture content of the soil.

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Humboldt Stiffness Gauge, dry density, nuclear density gauge, compaction control

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ABSTRACT

This report pertains to the evaluation of a non-nuclear means of determining the dry density of soils. The device is called the Humboldt Stiffness Gauge (HSG). The device is essentially a small-scale plate load test and takes approximately 1 minute to conduct. The test parameter from the test is a stiffness value that is averaged over approximately 6 to 12 inches beneath the HSG. The manufacturer of the HSG then uses a method to determine a regression equation to use the stiffness parameter to determine the dry density of the soil. However, to establish the regression equation, prior knowledge of the soil's moisture content and dry density is needed.

A laboratory program was initiated to evaluate the HSG as a method to determine the dry density of the soil. "Soil bins" were constructed to provide a quality control method of compacting soil to a known dry density and then use the HSG to test the soil. Rubber balloon (T205) tests were conducted to verify the dry density of the compacted soil. The HSG was evaluated for both repeatability and also its ability to determine the dry density, and possibly the resilient modulus of the soil. Larger "soil bin" tests were also conducted to determine if the HSG could be used to "locate" buried objects beneath the HSG. Since the device measures an average stiffness beneath it, objects would either increase or decrease the stiffness in a homogeneous soil. Both a steel pipe and a PVC pipe were used in the study.

Field testing of the device was done by its use in a full-scale study on the beneficial re-use of Portland cement amended dredge sediments as an embankment material. Over four hundred tests were conducted during the placement and compaction of the embankment material. The HSG tests were also accompanied by both nuclear gauge and Clegg Impact Hammer (ASTM D5874) tests. The calibration of the HSG was conducted in the field prior to the testing by using the nuclear density gauge.

Based on the results of this study, it is recommended that device be used with soils that have been amended with a lime-based additive. Nuclear testing of these amended soils is difficult due to the hydroxide ions that are produced during hydration. Since it may take a minimum of twelve hours to actually determine the dry density by using nuclear density testing due to the necessity of oven drying the soil, the HSG can be a viable alternative if properly calibrated. The study also showed that the device has a typical depth range of six to ten inches and is repeatable. Further testing concluded that the device could not be used as a locating device for buried drainage pipes in homogeneous soils. Continued tested should be conducted to evaluate the device's use as a means of determining the resilient modulus in-situ.

INTRODUCTION

The Humboldt Stiffness Gauge (HSG) (Figure 1) acts as a miniature plate load test (Figure 2). The HSG imparts very small displacements to the soil ($< 1.3 \times 10^{-6}$ m or 0.00005 inches) at 25 steady state frequencies between 100 and 196 Hz. The stiffness is determined at each frequency (displacement) and is then averaged. The stiffness is determined by the ratio of the force to displacement ($K=P/\delta$). The displacement (δ) is proportional to the outside radius of the HSG, and the Young's Modulus (E) and Poisson's ratio (μ) of the soil.

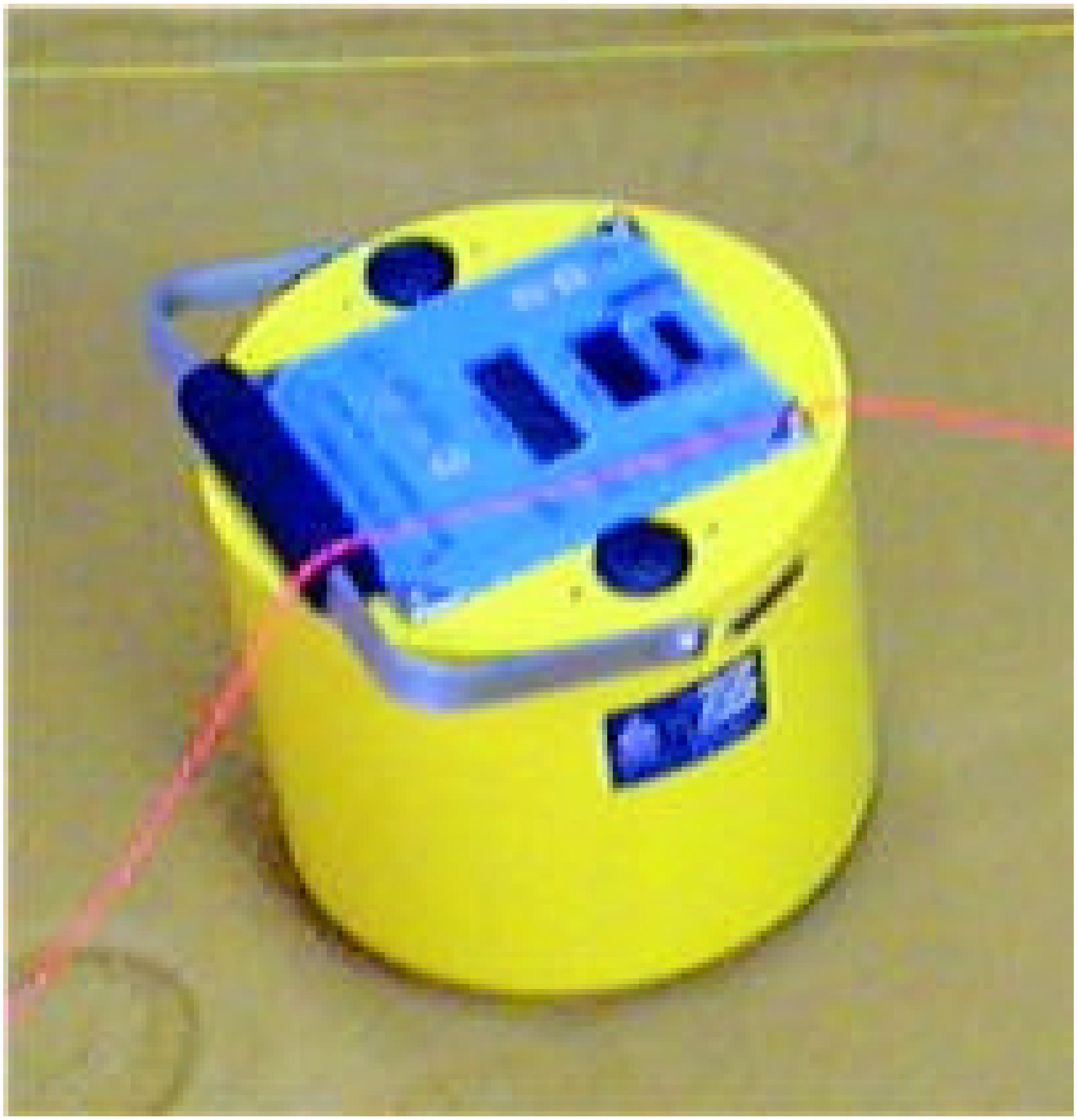
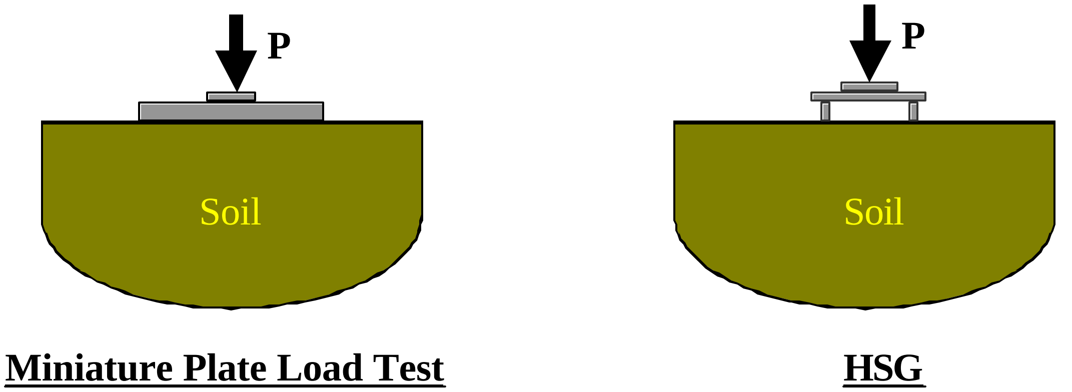


Figure 1 – The Humboldt Stiffness Gauge



Miniature Plate Load Test

$K = P/d = (2rE)/(1-n)^2$

HSG

$K = P/d \approx (1.77rE)/(1-n)^2$

Figure 2 – Humboldt Stiffness Gauge Test and Theoretical Plate Load Test

The soil stiffness, as measured by the HSG, is related to the density of the soil. The basic relationships are shown with equations (1) through (3) (Hyrciw and Thomann, 1993).

$$G = \frac{K(1-\mu)}{4a} \qquad (1)$$

$$G = \frac{(C_1 s_{11}{}^{P})}{(0.3+0.7e^2)} \qquad (2)$$

$$r_D = \frac{r_O}{(1+e)} \qquad (3)$$

where,

K – stiffness
μ – Poisson's ratio
a – the device's foot radius
C_1 – function of moisture and soil type
σ_1 – overburden stress
P – typically 0.25 to 0.5
ρ_D – actual density
ρ_O –density with no voids
e – void ratio

Although the relationship between the soil stiffness and the density has a theoretical basis, as of this date, the developed relationships have been mostly empirical. Because of this, the stiffness measured from the HSG must be transformed into a dry density. This is typically accomplished by conducting nuclear density gauge tests along side of HSG tests, developing a calibration curve from the results, and then using the measuring stiffness directly into a regression equation relating dry density to stiffness. This calibration is recommended for each soil tested.

RESEARCH OBJECTIVES

The main goal of the research reported here was to provide the NJDOT a small-scale demonstration on the suitability of using the Humboldt Stiffness Gauge (HSG) for the use of compaction control of soils.

The research presented here is divided into two distinct sections outlined in the following:

1. Laboratory Investigation of the HSG
2. Field Trial of the HSG

The laboratory investigation of the HSG was centered on its use. In particular, how deep does the device typically measure, how repeatable is the device, and how do objects located under the device in a homogeneous soil effect the measurements? Another important question that was investigated was; do you have to develop a calibration curve for each soil tested or can one use a general equation for a particular soil type? The HSG stiffness was also compared to laboratory determined resilient modulus values for three New Jersey subgrade soils and for a typically used granular subbase material.

The field trial of the research was conducted using the device in conjunction with a nuclear density gauge for compaction control during the construction of two test embankments. The embankments were constructed of Portland cement amended dredge material (organic clayey silt with sand). This provided an excellent opportunity to directly compare the two devices, especially since it was known that the nuclear gauge was having difficulties determining the moisture content in the field. The use of the HSG as an alternative means of compaction control was very attractive.

LITERATURE SEARCH

A search of literature was conducted to determine how other users are using the Humboldt Stiffness Gauge (HSG), problems or successes they have had with the device, and to determine if general regression equations could be developed from the literature. The literature search was divided into HSG for compaction control and HSG used for design purposes for mechanistic pavement design.

HSG for Compaction Control

The HSG has been proposed as a non-nuclear means of determining the dry density of the compacted soils. The HSG could then be used as a rapid means of QA/QC during construction. The initial methodology of the determination of dry density via HSG was centered around the work of Hryciw and Thomann (1993) and is illustrated in the following equation:

$$r_D = \frac{r_O}{1+1.2\left[\frac{Cm}{K}-0.3\right]^{0.5}} \tag{4}$$

where,

$$C = \frac{\left(C_1 s_1^{\,P}\right)4a}{\left(1-u\right)}$$

C_1 = a function of moisture and soil type
σ_1 = the overburden stress
P = typically between 0.5 and 0.25
υ = poisson's ratio
ρ_D = the dry density of the soil
ρ_O = the ideal, void free density
K = stiffness
a = the HSG's foot radius
m = (% moisture content by weight)/100

As described and recommended in the Soil Stiffness Gauge User Guide provided by the manufacturer, to utilize the equation (4), C must first be defined for the soil type, independent of everything except moisture content and density. Therefore, C is to be solved as the following:

$$C = \left(\frac{K}{m}\right)\left\{\left[\frac{\left(\frac{r_O}{r_D}-1\right)}{1.2}\right]^2 + 0.3\right\} \tag{5}$$

where,

m = moisture content
K = stiffness
All other variables the same as for equation (3)

This allows the determination of C to be fitted to a linear equation (6), as recommended by the manufacturer, with two independent variables, K and m. However, to accomplish the determination of C, the HSG must first be used in conjunction with a means of determining the dry density of the material. This is typically done by conducting HSG tests in the immediate vicinity of either nuclear density gauge tests or for the HSG to be conducted on material of a known dry density and moisture content. This initial calibration of the device will have a large impact on the determined values.

$$C = n\left(\frac{K}{m^{0.25}}\right) + b \qquad (6)$$

Table 1 shows a list of current researchers/organizations evaluating the device and as to how they are doing so.

Table 1 – Current Users and Applications of the Humboldt Stiffness Gauge (HSG)

HSG User/Organization	Project	Results
NCDOT	Used for Compaction Control Modulus Based Specs for Roads	Good Still Pending
Cal. Polytech.	Used for Compaction Control	Fair
H.C. Nutting	Used for Compaction Control	Good
City of San Jose	Used for Compaction Control	Poor
FDOT	Used for Compaction Control	Poor
MODOT	Used for Compaction Control Modulus Based Specs for Roads	Fair Still Pending
NYSDOT	Used for Compaction Control	Poor
FHWA Lab	Used for Compaction Control	Good

As can be seen from the literature search, there were mixed results when it came to using the HSG for compaction control (i.e. determining the dry density).

Data from Table 1 also allows for the evaluation of using calibration curves developed by other researchers on other soils to be used for the soils tested in this project. Therefore, if this can be done, perhaps a universal equation for sand can be established for future use.

HSG for Mechanistic Design

Work has also shown that the HSG may be used to directly determine stiffness characteristics of subgrade soils and granular base materials for mechanistic design. The input parameters for mechanistic pavement design are shown in figure 3 As can be seen, the need for “stiffness parameters”, shown in the figure as resilient modulus, is a necessity for design. Therefore, a fast and inexpensive means of determining these values in-situ makes the HSG even more attractive.

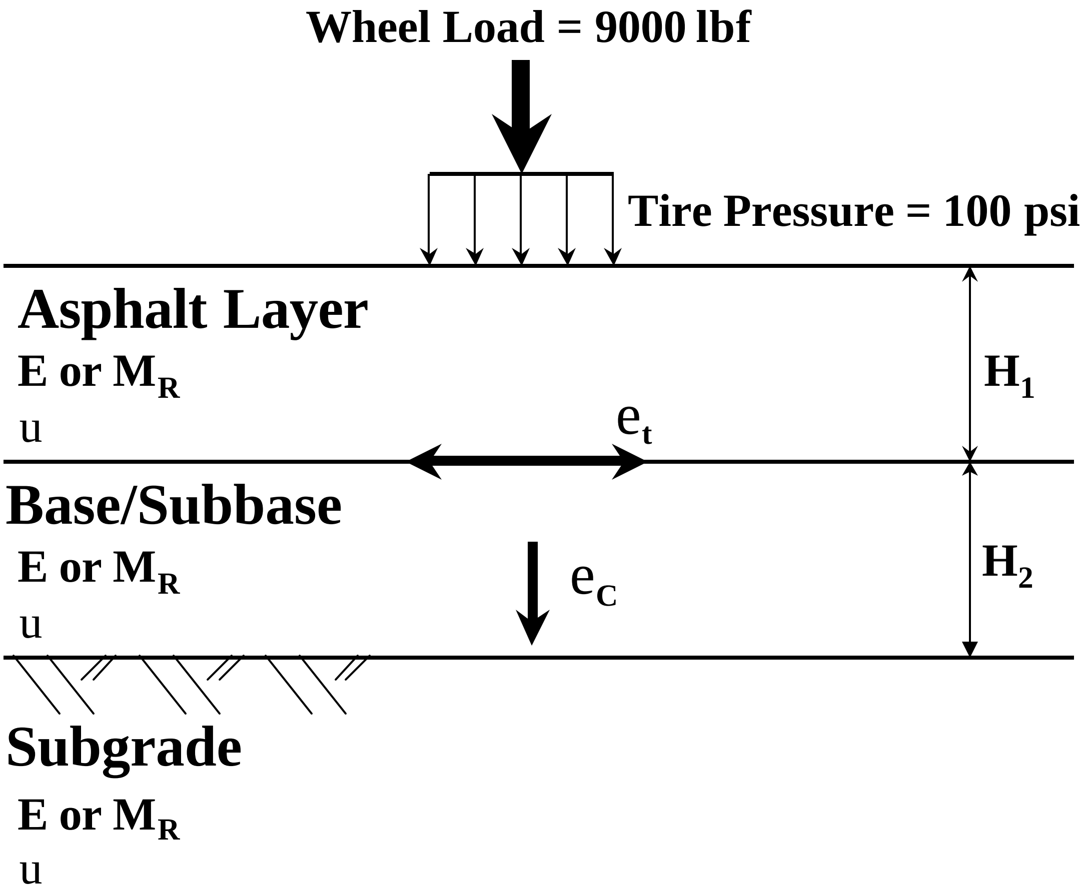


Figure 3 – Typical Mechanistic Pavement Design Characterization

where,

E or M_R - “Stiffness Parameters” or Resilient Modulus
μ - Poisson’s Ratio
ε_t - tensile strain
ε_C - compressive strain
H_1 – height of asphalt layer
H_2 – height of base/subbase layer

Most of the researchers/investigators are utilizing the HSG as an alternative means of controlling compaction during the construction of pavement sections utilizing the methodology described earlier. However, a few researchers/investigators have looked at utilizing the device for stiffness determination in mechanistic pavement design (Chen et al., 1999; Siekmeier et al., 1999).

Siekmeier et al. (1999) compared the HSG to the dynamic cone penetrometer, as well as other tests (Falling Weight Deflectometer – FWD and a portable FWD – PFWD), to characterize subgrade soils and granular bases in Minnesota. Laboratory resilient modulus tests were also conducted on reconstituted soil samples compacted to dry densities within 1% of that determined in the field. Results showed that when the HSG was compared to FWD and the PFWD, the modulus results were consistent, although lower. This trend was explained by concluding that the subgrade soil and granular base material are both stress dependent. The stress imposed on the soil is less for the HSG (0.02 to 0.03 MPa) then the FWD and PFWD (0.7 to 0.9 MPa), and therefore, the determined modulus was less. When the HSG modulus was compared to the laboratory samples, the HSG was approximately 50% of the laboratory samples. Illustrating that perhaps the stresses imposed during laboratory testing may be too high for direct comparisons.

Chen et al. (1999) conducted a very similar test scheme using the HSG, FWD, Dirt Seismic Pavement Analyzer (D-SPA), and Olson Spectral Analysis of Surface Waves (SASW). Based on the work conducted, Chen et al. (1999) developed a relationship between the back-calculated resilient modulus from the FWD and stiffness determined by the HSG. Equation (7) shows the regression equation developed.

$$M_R = 37.654(K) - 261.96 \quad (n = 8,\ r^2 = 0.82) \qquad (7)$$

where,

M_R – resilient modulus determined from the FWD (MPa)
K – stiffness determined by the HSG (MN/m)

Although the data only consisted of eight locations, a relatively good relationship can be observed. Based on work conducted, the authors also developed a simple table to be used to evaluate the base material's quality (Table 2).

Note: The HSG manufacturer recommends that the device only be used up to 23 MN/m. Results higher may lose accuracy.

Table 2 – Evaluation of Base Material Quality from HSG Results (adapted from Chen et al., 1999)

Base Quality	HSG Stiffness (MN/m)	FWD Modulus (MPa)
Poor	<10	< 140
Good	18 – 24	310 – 450
Excellent	>30	> 700

Based on the previous work for the use of the HSG for mechanistic pavement design, it seems that the device has a strong potential for future use, as long as correlations/calibration of the device can be conducted. This can either be conducted utilizing field techniques (SASW, FWD, DSPA) or from laboratory evaluation (resilient modulus testing).

EXPERIMENTAL PROGRAM

The experimental program comprised of two distinct phases: (1) Laboratory evaluation of the Humboldt Stiffness Gauge (HSG) using soil bins; (2) Full scale field study utilizing the HSG in conjunction with a nuclear density gauge.

Phase (1a) – Laboratory Evaluation - Part A

A laboratory investigation was developed to evaluate the potential of using the Humboldt Stiffness Gauge (HSG) as a compaction control method, as well as a device to evaluate the resilient modulus of subbase and subgrade soils. The laboratory investigation was conducted utilizing small "soil bins" for controlled testing (Figure 4). The "soil bin" consisted of a steel 55-gallon drum that was cut to provide a maximum height of 24 inches. The "soil bin" was lined with a fiberglass insulation to help minimize side-wall stresses that would develop during interface friction of the soil and the steel drum. The soil was compacted in three inch layers using a hand tamp device. The soils used for the evaluation are shown in Table 3.

Table 3 – Properties of Soils Tested in "Soil Bin"

Soil Number	Classification (AASHTO)	γd_{max} (pcf)	$W\%_{opt}$ (%)	% Fines (%)	LL	PI
Soil #1	A-2-4	130	7.3	31	15	N.P.
Soil #2	A-4	128.5	7.7	41	21	1.5
Soil #3	A-4	126.7	8.5	30	21	4
CJ I-3	A-1	112.5	4	3.5	0	N.P.

The soils used were of particular interest since the materials were in the field currently. Soil #1 is a subgrade soil under Rt. 46; Soil #2 is a subgrade soil under Rt. 80; and Soil #3 is a subgrade soil under Rt. 206. The CJ I-3 soil is a granular subbase material from a supplier in Central New Jersey. The gradations of the soils are shown in Figure 5 and the compaction curves are shown in Figure 6. Also, resilient modulus testing has been

Figure 4 – Small “Soil Bin” Used for Laboratory Evaluation of the HSG

conducted on all four materials. The resilient modulus curves are shown in Figures 7 through 10. Regression results for the M_R are shown as a dotted line and open symbols. Actual measured results of the resilient modulus testing is shown as the solid lines and solid symbols.

The laboratory evaluation procedure proceeded as follows. A HSG test was conducted after every lift (three inches) was compacted. After every other lift (every six inches), a compaction control test was conducted. The HSG test was conducted every layer to provide a method of determining the measurement depth of the device. The first compaction control test conducted was a Rubber Balloon Density Test (ASTM D2167 – Density and Unit Weight of Soil In-Place by the Rubber Balloon Method) – Figure 11. This test provided compaction control and a reference of the unit weight for the HSG comparison. Compaction was also controlled by the mass-volume relationship of the compacted soil bin. Since the wet density was constant, and the volume of the soil bin was constant, it provided an easy calculation for the amount of soil needed to be compacted three inches.

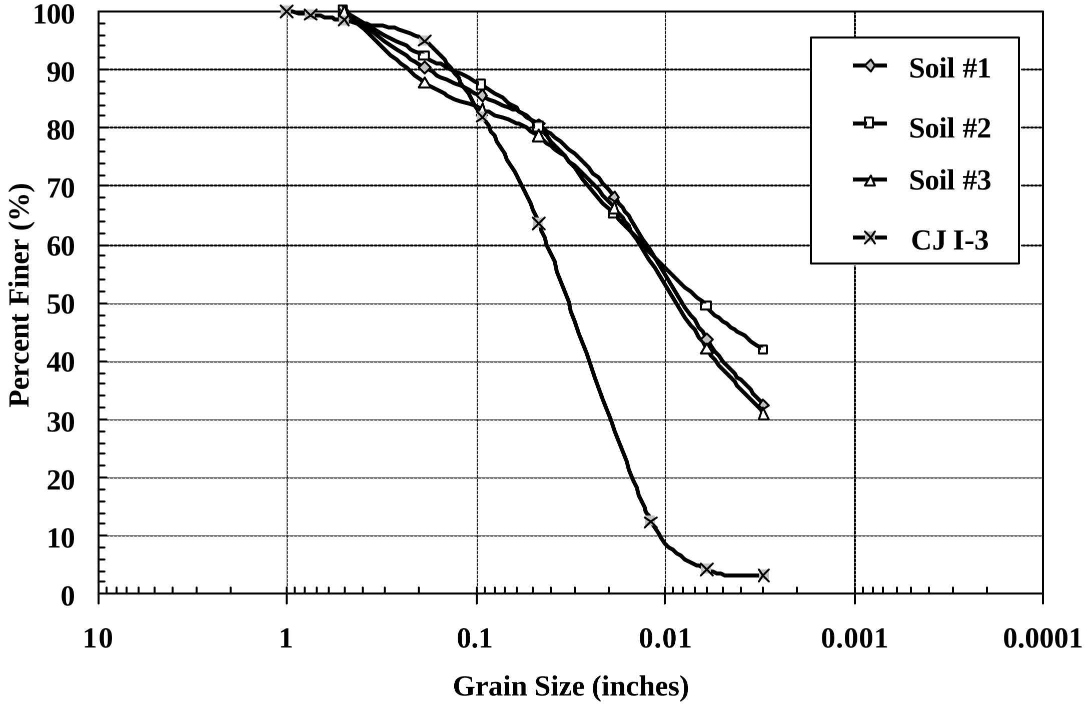


Figure 5 – Gradations of Soil Used in Small “Soil Bin” Evaluation

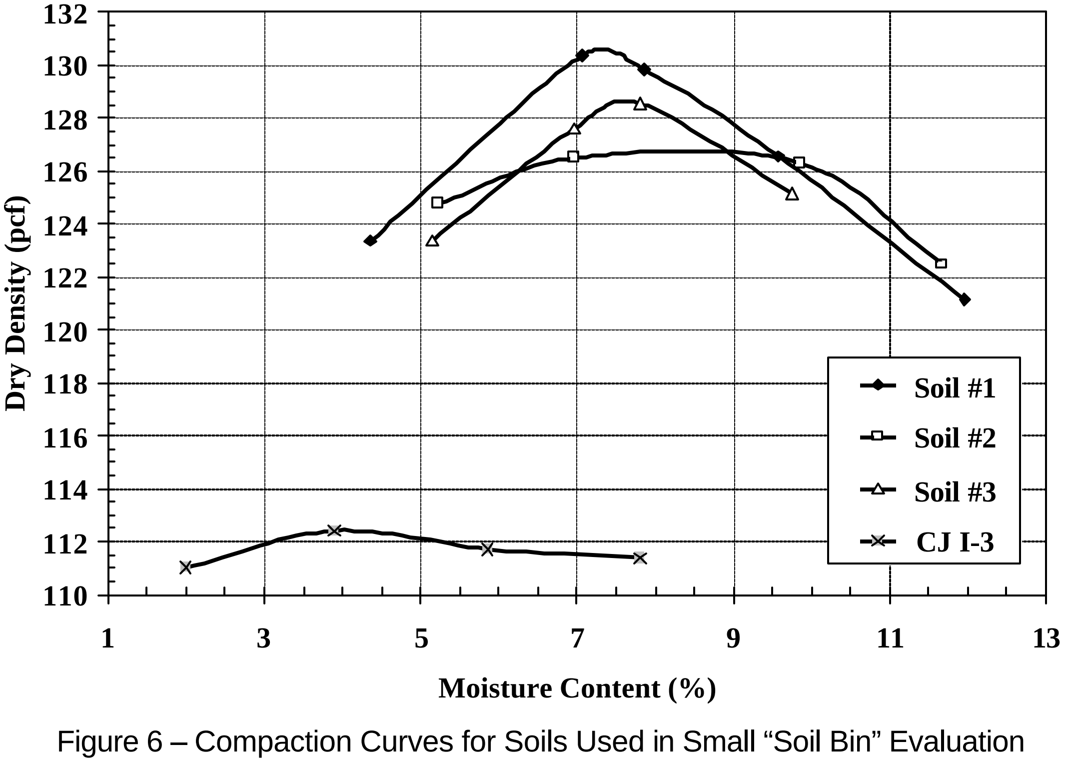


Figure 6 – Compaction Curves for Soils Used in Small “Soil Bin” Evaluation

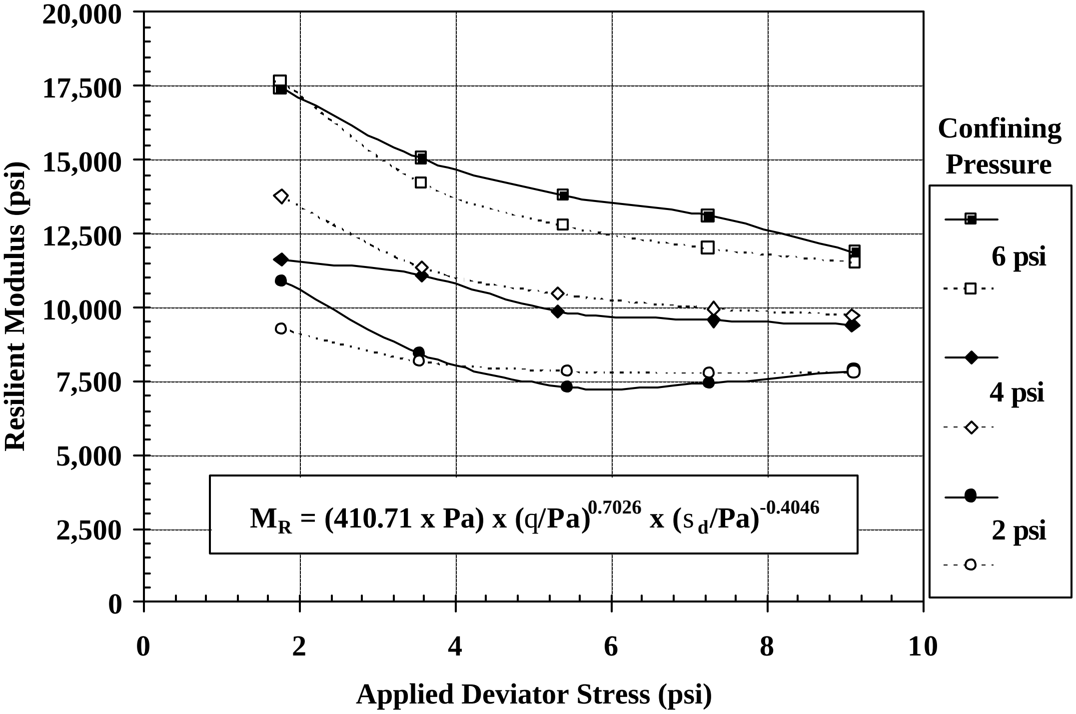


Figure 7 – Resilient Modulus Results of Soil #1

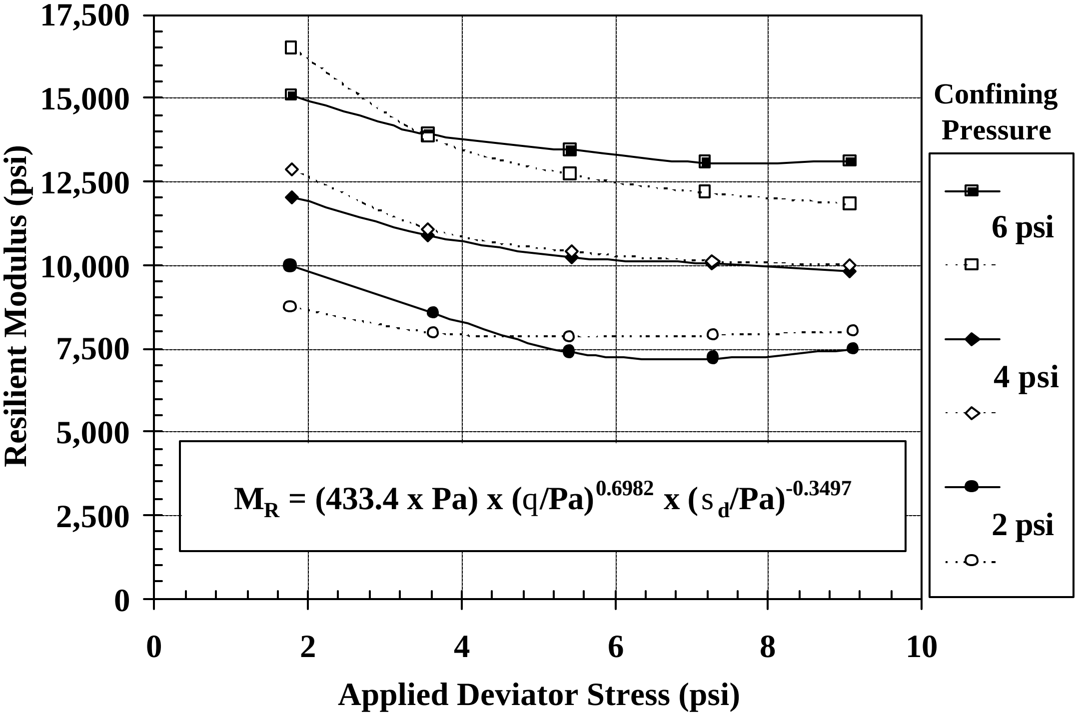


Figure 8 – Resilient Modulus Results of Soil #2

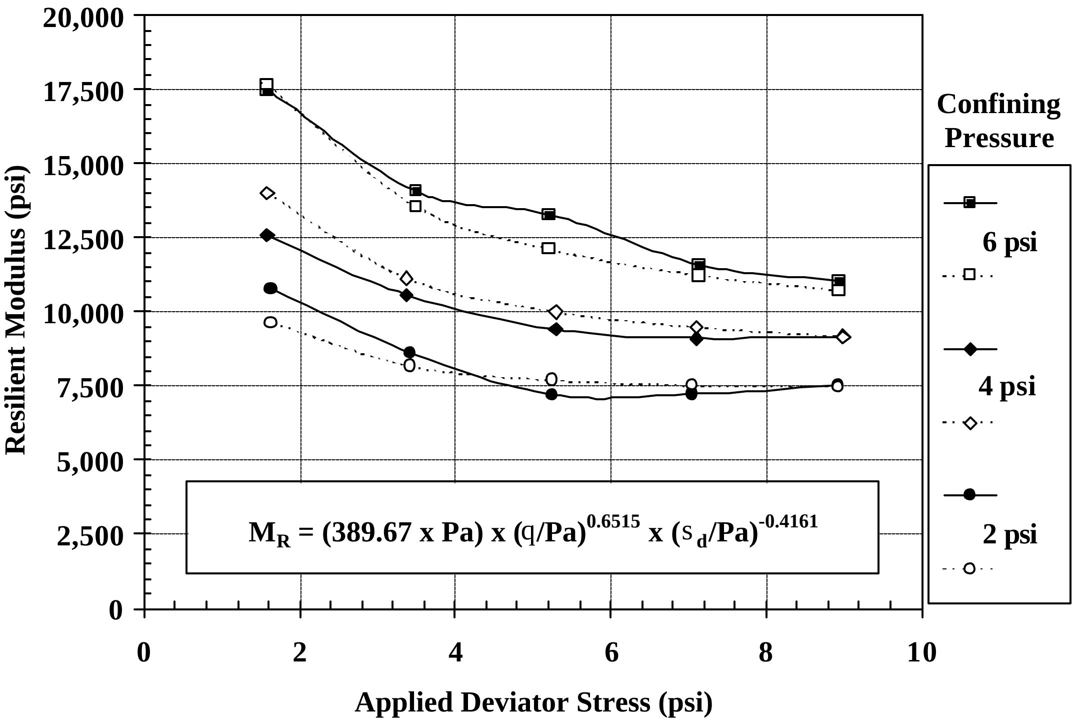


Figure 9 – Resilient Modulus Results of Soil #3

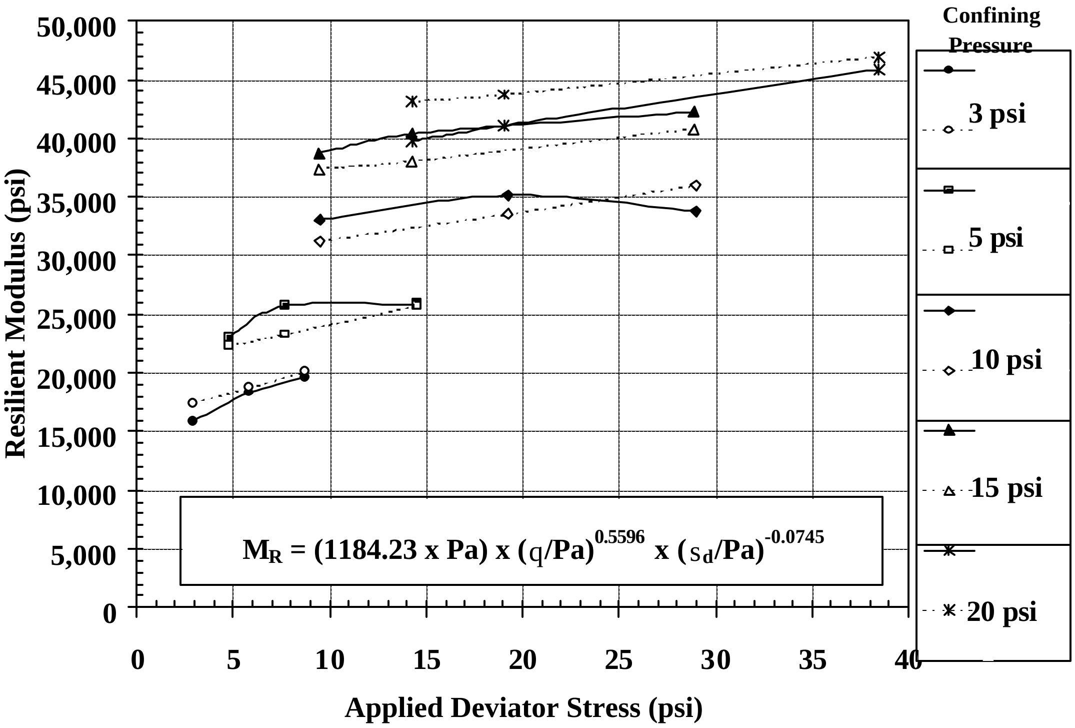


Figure 10 – Resilient Modulus Results of CJ I-3

Figure 11 – Rubber Balloon Density Test Apparatus

<u>Phase (1b) – Laboratory Evaluation - Part B</u>

A large soil bin was utilized to evaluate the effects on the Humboldt Stiffnes Gauge that obstructions would have in a homogeneous soil. Two different pipes were used in the evaluation; a 3 inch diameter, hollow PVC pipe and a 2.5 inch diameter, hollow steel pipe. The pipes were chosen as obstructions since a future possible use of the device would be to use the HSG for compaction control around buried objects, such as underground pipelines. Figure 12 shows the bin and test configuration used.

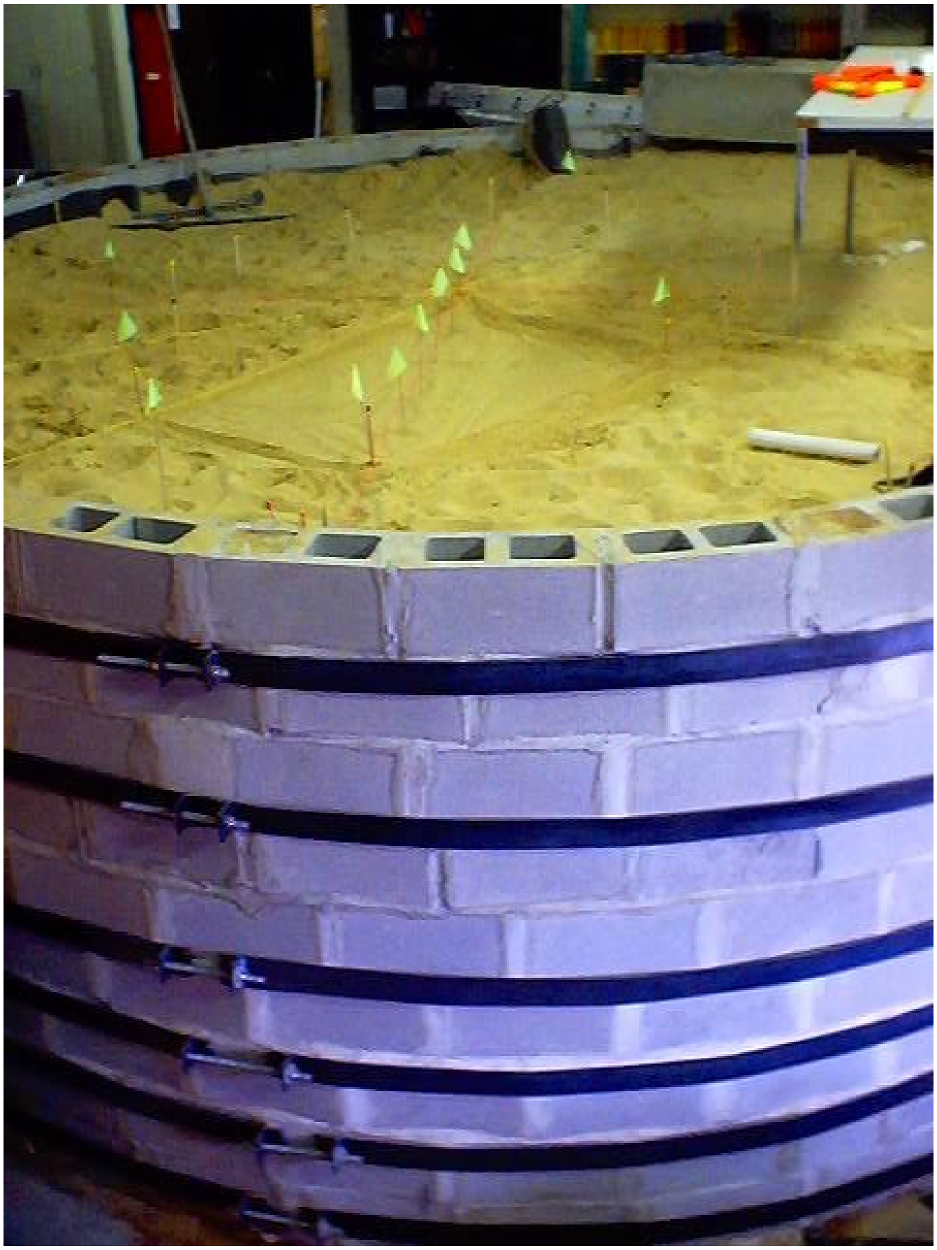


Figure 12 – Large Test Bin Used for HSG Evaluation

The large soil bin is approximately eight feet deep and fifteen feet in diameter. It is filled with a soil that is predominantly a sand with silt. Soil properties of the soil were not important for this portion of the evaluation. The only importance was that the material was homogeneous without obstructions or impurities.

The excavation area was approximately 2 feet wide, 3 feet long, and two feet deep (Figure 13). This allowed the object to be placed at varying depths within the soil area.

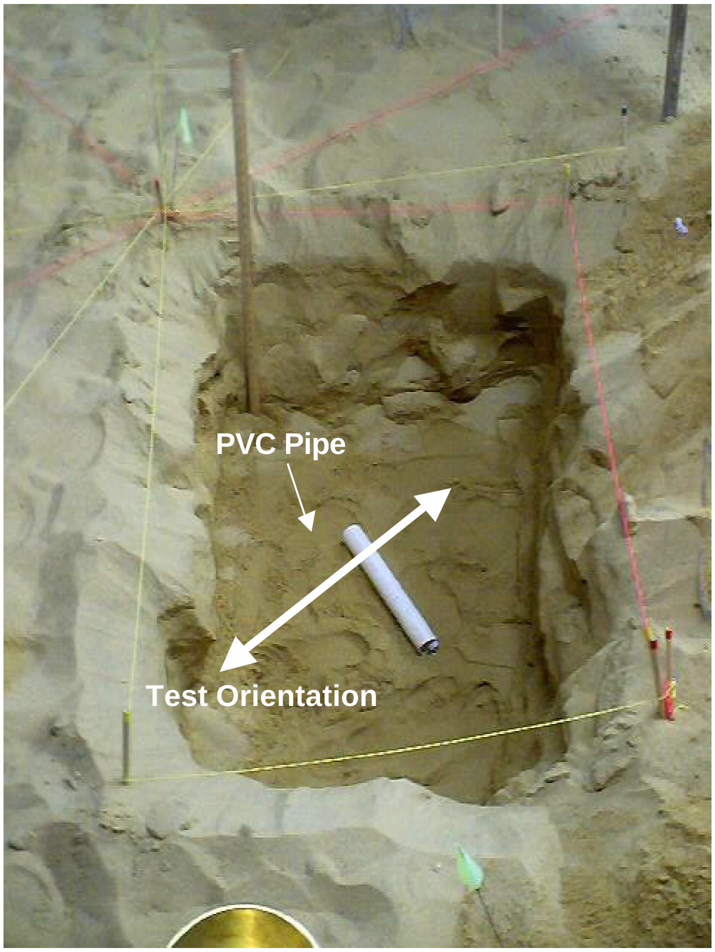


Figure 13 – Excavation Area and PVC Location

HSG tests were conducted perpendicular to the placement angle of the buried pipe. Five tests were conducted equally spaced from one another in the test orientation shown in Figure 13. This would allow for the soil to be tested outside of the buried area and directly over the buried pipe. Sand cone tests were also conducted within the excavated area for compaction control purposes. Figure 14 shows a final tested section. The rings and green flags are indications of the foot of the HSG after a test and the holes are from Rubber Balloon Density tests.

Phase (1a) – Laboratory Evaluation - Part A - Results

The small soil bins were utilized to evaluate the following characteristics of the Humboldt Stiffness Gauge: (1) The repeatability of the device; (2) The depth at which the device can measure; (3) The devices ability to predict the dry density of the soil using previously determined calibration equations; and (4) The devices ability to predict the resilient modulus of the soil when compared to laboratory determined resilient modulus values for which samples were compacted at the same dry density.

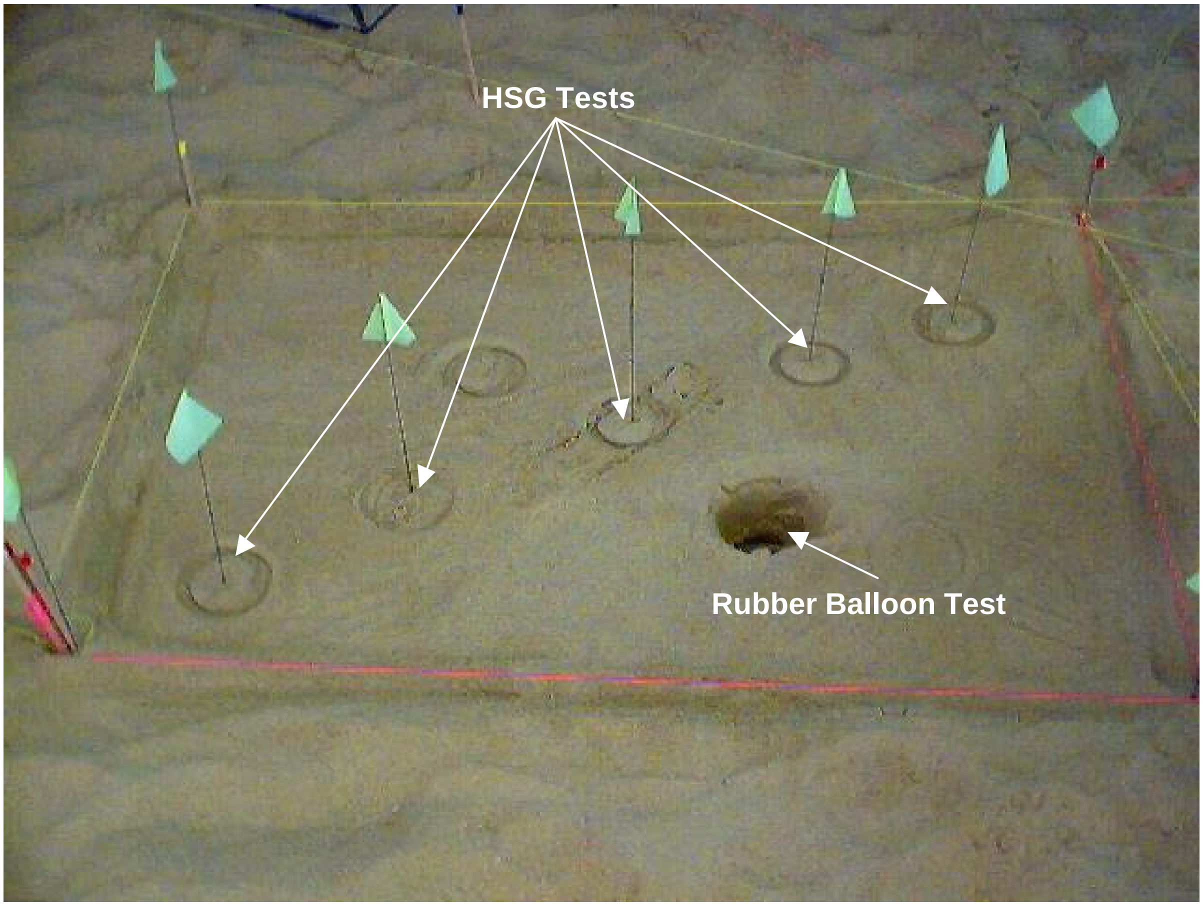


Figure 14 – Final Test Layout from Large Soil Bin Evaluation

Measurement Repeatability - Results

The repeatability of the device was evaluated by testing the same location (depth) 3 times in a row, as well as repeating the entire procedure for a total of 6 measurements. The results for the four soils tested are in Table 4. As shown in the Table, the standard deviation for the three measurements that were taken at a particular section are extremely low, illustrating the devices repeatability. It can also be shown that the measurements from Test #1 to Test #2 are consistently close. There are small discrepancies between some of the results; however, this is due to the small changes in density from one test to the other.

From the results, it can be concluded that the HSG provides an excellent repeatability when conducting consecutive measurements. However, results may vary, as shown in Table 4, for identical soils compacted at slightly different densities. Table 5 shows the results from the Rubber Balloon Density test illustrating the slight difference in compacted densities.

Table 4 - Repeatability of Test Results from the HSG (from 3 Consecutive Measurements)

Soil Sample	Distance from Bottom (inches)	Average Stiffness* Test #1	Average Stiffness* Test #2	Standard Deviation Test #1	Standard Deviation Test #2
Soil CJ I-3	3	1.046	0.057	0.0231	0.0186
	6	7.833	8.145	0.0451	0.0529
	9	8.794	8.947	0.0451	0.0264
	12	8.44	8.897	0.0266	0.0416
	15	7.8	7.9	0.0361	0.0173
	18	7.323	7.303	0.0929	0.0289
	21	7.548	N.A.	0.0252	N.A.
Soil #1	3	0.497	0.943	0.0666	0.0186
	6	8.567	8.387	0.2111	0.0529
	9	10.683	9.673	0.0451	0.0264
	12	9.793	8.883	0.0266	0.0416
	15	10.18	9.6	0.0361	0.0173
	18	12.053	10.747	0.0929	0.0289
Soil #2	3	-0.4	-0.613	0.0231	0.0186
	6	4.313	4.726	0.0451	0.0529
	9	13.777	13.567	0.0451	0.0264
	12	13.57	13.997	0.0266	0.0416
	15	14.113	13.76	0.0361	0.0173
	16.6	13.03	12.973	0.0929	0.0289
Soil #3	2	-1.25	-1.303	0.0	0.0231
	5	1.97	1.247	0.255	0.0379
	8	4.727	4.78	0.202	0.0458
	11	11.75	10.273	0.344	0.27
	14	11.39	10.65	0.104	0.11

* Stiffness Units are MN/m (1 MN/m = 5.67 lb/in)

Depth of Measurement - Results

The depth of the measurement from the HSG was evaluated by inspecting the plot of stiffness versus distance from the bottom of the soil bin (Figures 15 through 18). Since the soil was compacted to a relatively constant dry density throughout the soil bin, the stiffness of the soil should be somewhat constant. Therefore, by determining the distance from the bottom of the bin at which the stiffness measurements become relatively constant would provide indication of the extent of depth measurement.

Table 5 – Compacted Density Results from Small Soil Bin Testing

Soil Sample	Distance from Bottom (inches)	Dry Density (pcf) Actual Test #1	Actual Test #2	Target
CJ Soil	6	112.5	113.9	113
	12	113.9	113.2	113
	18	114.2	114.3	113
Soil #1	6	128.5	127.6	130.5
	12	127.7	129	130.5
	18	129.2	127	130.5
Soil #2	6	126.3	127.9	126.8
	12	125.5	123.4	126.8
	18	124.7	122.7	126.8
Soil #3	5	125.3	126.1	128.3
	11	124.5	124.3	128.3

Figure 15, which contained the Central Jersey I-3 soil, shows that the device typically measured to depths of approximately six inches. Figure 16, which contained the Rt. 46 subgrade soil, showed depths of approximately 9 inches. This depth of nine inches is also consistent in Figures 17 and 18, which included the Rt. 80 and Rt. 206 subgrade soil, respectively. The Rt. 46, Rt. 80, and Rt. 206 were similar soils with similar dry densities; therefore, the stiffness' and depth measurements should all be similar.

Another indication that the trend indicated above is correct is that the I-3 soil was compacted to a looser density than the other three soils, as indicated in Table 5. Therefore, the I-3 soil would have a smaller range of measurement than the other three soils. This is based on the fact that a denser medium will transmit vibrations more efficiently than a looser medium.

Based on stiffness versus height above the bottom of the soil bin analysis and the soils tested, it can be concluded that the device can measure depths of approximately 6 to 9 inches. However, as can be seen from the data, the depths will ultimately be dependent on the compacted/in-situ density of the soil (i.e. – Looser soil, shallower depth; Denser soil, deeper depth).

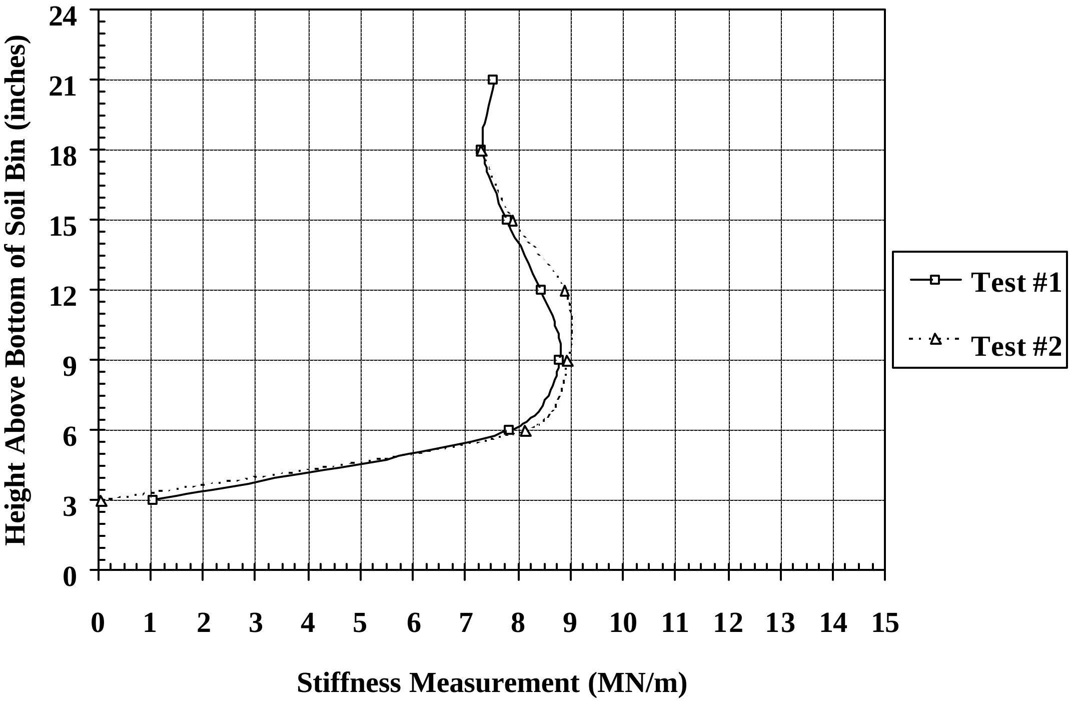


Figure 15 – Stiffness versus Height Above Bottom of Soil Bin for CJ I-3 Soil

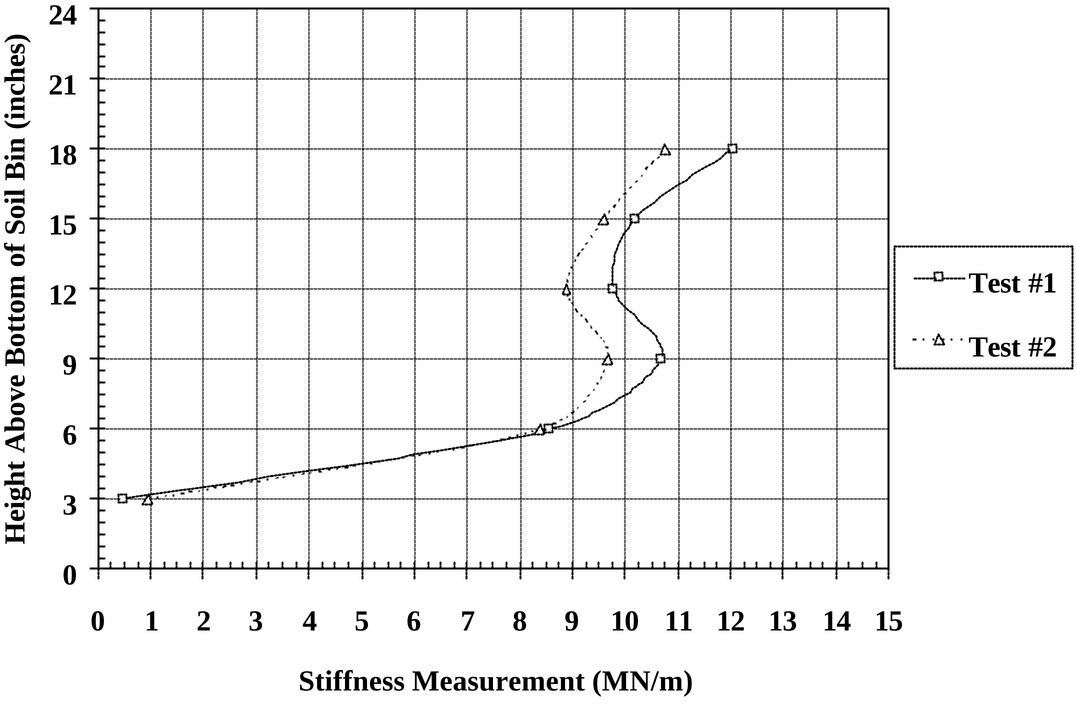


Figure 16 – Stiffness versus Height Above Bottom of Soil Bin for Soil #1

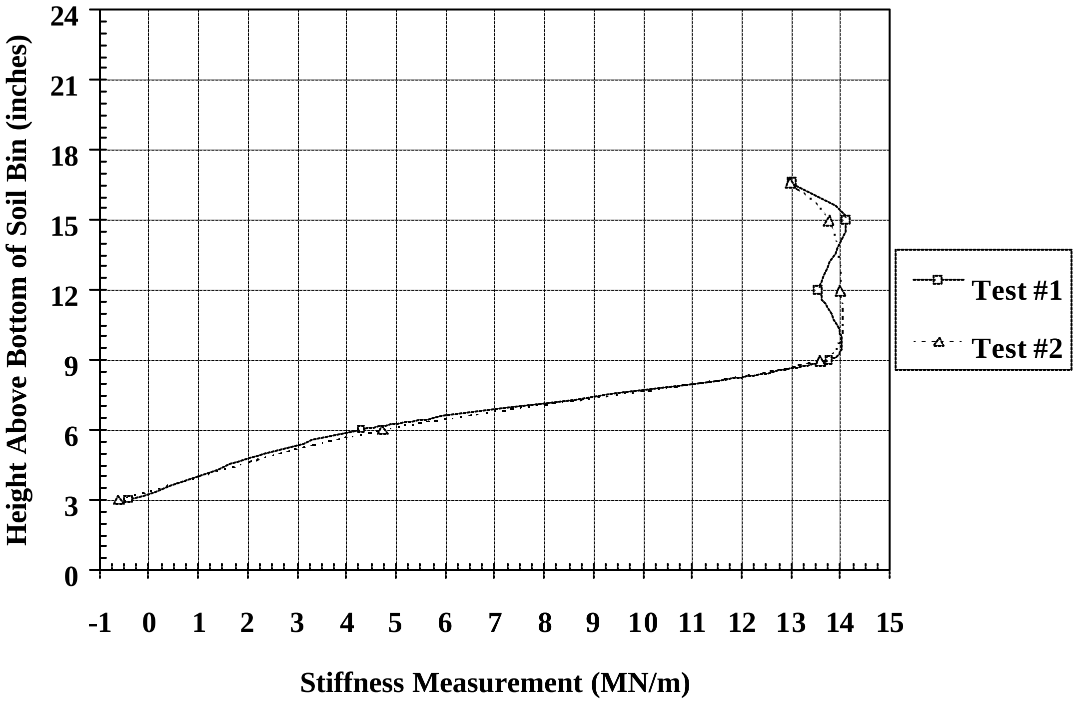


Figure 17 - Stiffness versus Height Above Bottom of Soil Bin for Soil #2

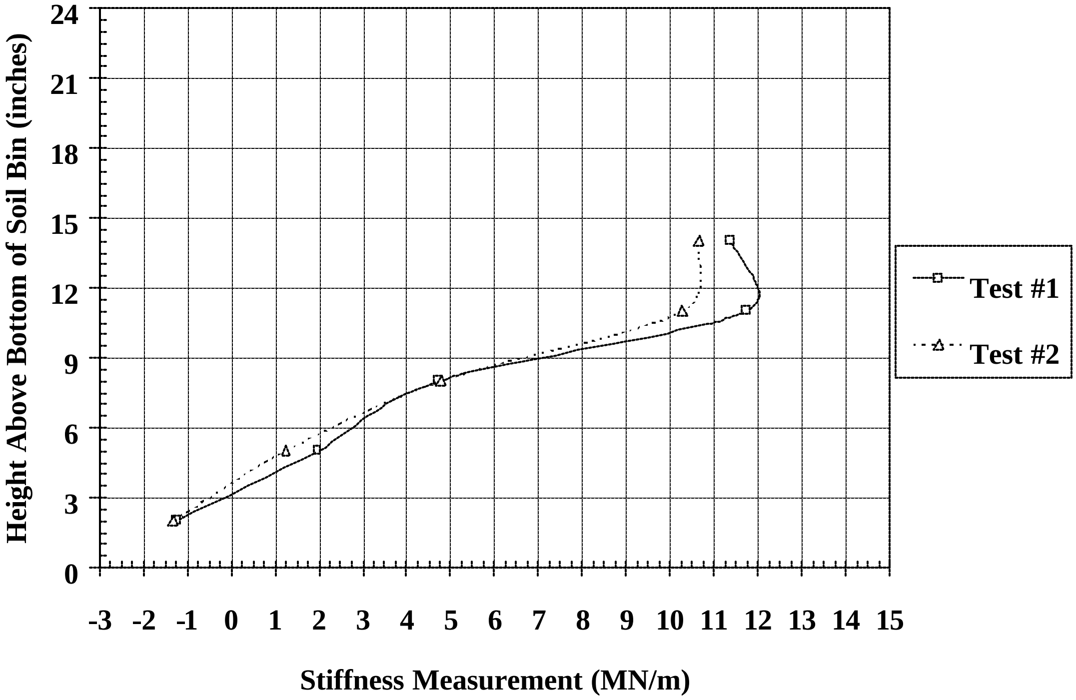


Figure 18 – Stiffness versus Height Above Bottom of Soil Bin for Soil #3

Dry Density Predictions – Results

To utilize the Humboldt Stiffness Gauge (HSG) as a compaction control device, a calibration must be made to convert measured stiffness to dry density. The methodology of this calibration was described earlier. This procedure can be time consuming, not to mention, a means of accurately measuring the dry density must be present for the calibration. Therefore, if a general calibration equation can be utilized to specific soils, (i.e. sand, silt, clay) then the device would be much more attractive. The HSG would also be able to be utilized upon request, without needing to schedule time for calibration. Although the manufacturer does not recommend this procedure, a full-scale pilot study, detailed later in the report, was conducted using the manufacturer's recommended procedure.

Based on a literature search, regression equations for the determination of dry density were used in the evaluation. The regression equations utilized from the analysis are shown in Table 6. The equations were only used if the researchers/institutions showed fair to excellent performance from Table 1. NCDOT was not used in the evaluation due to their limited number of data points used in their calibration.

Table 6 – Regression Equations Used in Analysis

Researcher/Institution	Soil Type	Regression Equation
Cal. Polytechnic Institute	Sandy Soil	$C = 4.4561(K/m^{0.25}) + 12.704$
	Clayey Soil	$C = 2.9946(K/m^{0.25}) + 23.61$
FHWA	Aggregate Soil	$C = 5.8177(K/m^{0.25}) - 25.173$
	Sandy Soil	$C = 3.1862(K/m^{0.25}) + 2.5947$
	Clayey Soil	$C = 33.626(K/m^{0.25}) - 69.423$
H.C. Nutting Co.	Sandy Soil	$C = 3.1484(K/m^{0.25}) + 2.6727$
	Clayey Soil	$C = 2.8146(K/m^{0.25}) + 10.44$

It should be emphasized that the moisture content must be included as an input parameter in the analysis. "This linear relationship between C, K, and m allows a more appropriate value of C to be used in the estimate of each dry density as opposed to selecting a limited number of C's to be used over several moisture ranges." (Humboldt Mfg. Co., 1999)

The Central Jersey I-3 soil was analyzed using: (1) California Polytechnic Institute's Sandy Soil Equation, (2) FHWA's Aggregate Soil and Sandy Soil equations, and (3) H.C. Nutting Co.'s Sandy Soil equation.

Resilient Modulus Estimation - Results

As mentioned earlier, there is a definite need for the field evaluation of modulus parameters for base, subbase, and subgrade soils. By having a means of determining modulus values in the field, a field engineer would have verification of mechanistic design parameters to ensure the pavement system was constructed properly.

Laboratory resilient modulus tests were conducted on the soil samples to determine their respective modulus properties. The regression equations were illustrated in Figures 6 through 9. All samples were compacted to their maximum dry density and optimum moisture content, which corresponds to the target dry densities for the small soil bins.

Egorov (1965) developed a theoretical equation to convert stiffness to elastic modulus from a loaded ring (Equation 8). Equation 7, developed from FWD back-calculations by Chen et al. (1999), is also restated since it was also used for comparisons.

$$M_R = 37.654(K) - 261.96 \qquad (n = 8,\ r^2 = 0.82) \tag{7}$$

$$M_R = \frac{P \cdot b \cdot \left(1 - m^2\right)}{d \cdot R} \tag{8}$$

where,

M_R – resilient modulus determined from the FWD (MPa)
K – stiffness determined by the HSG (MN/m)
K = P/d for Equation (8)
P - dynamic load (kN)
d - deflection due to loading (mm)
b - ring shape and rigidity factor = 0.566 for HSG
m – Poisson's ratio (assumed to be 0.35)
R – radius of HSG ring

Solving for M_R in Equation (8) based on the factors and assumptions used reduces the equation to Equation (9)

$$M_R = 8.7K \tag{9}$$

To determine the resilient modulus from the laboratory tests, two variables need to be known to input into the regression equation. The first is the applied deviatoric stress. The HSG manufacturer states that, "The GeoGauge produces soil stress and strain levels common for pavement, bedding, and foundation applications, approximately 4 psi." Siekmeier et al (1999) suggests that the HSG applies a vertical stress of about 2.9 to 3.6 psi. Therefore, it was assumed for the analysis that the deviatoric stress is 3.8 psi. The next variable is the bulk stress. The bulk stress encompasses the applied deviatoric stress and the confining stresses in the soil. Therefore, the value for the bulk stress can be computed using Equation (10).

$$q = 2k_O s_V + s_V + s_d \qquad (10)$$

where,

θ – bulk stress
k_O – coefficient of lateral earth pressure = μ/(1-μ) = 0.54
σ_V – average overburden pressure
σ_d – applied deviatoric pressure

The average overburden pressure was computed by using one half of the maximum depth measurement, as determined earlier, and the compacted unit weight of the soil. The computed input values and resilient modulus values from the laboratory regression equations and the HSG correlations are shown in Table 7. The subbase material, CJ soil shows extremely close agreement to the theoretical value of Egorov (1963), however, it is three times as high as the FWD back-calculated equation of Chen et al. (1999). The results for the other three soils have poor comparisons to both of the estimation methods.

A reason for such discrepancies between methods can be somewhat explained due to the varying differences in stresses applied to the soil for each particular test method. The laboratory testing consists of much higher confining pressures when compared to the FWD work. And in return, the FWD impacts a much larger stress on the soil then the HSG. Therefore, for legitimate correlations to be established, a much more thorough testing program should be considered. However, since both the FWD and HSG are theoretically based on the same soil properties and principles, a correlation does seem possible. For correlations to be developed between the laboratory testing and the HSG, modifications within the laboratory testing protocol would be needed to evaluate confining pressures that the HSG would encounter.

Table 7 – Computed Resilient Modulus Values

Soil Sample	θ (psi)	σ_d (psi)	Resilient Modulus (psi)		
			Laboratory	Chen et al. (1999)	Egorov (1963)
CJ Soil	4.2	3.8	9541.3	2965.8	9431.3
Soil #1	4.5	3.8	4536.7	13,888.4	11,946.3
Soil #2	4.45	3.8	5161.6	36,825.8	17,227.8
Soil #3	4.5	3.8	4468.3	23,172.6	14,084

Phase (1b) – Laboratory Evaluation - Part B - Results

The large soil bins were used with the Humboldt Stiffness Gauge to determine how the stiffness measurements were affected by objects placed below the device. The soil bin was filled with a homogeneous sand to ensure that the measurements could only be affected by objects that were buried. The objects buried were a PVC pipe and a steel pipe. These objects were selected due to their potential to be located on site due to preexisting pipelines/drainage systems.

For evaluation purposes, the pipes were buried at varying depths below the surface; six inches, nine inches, twelve inches and eighteen inches. Measurements were conducted on the outside of the pipe, both sides, and also directly over the pipe. Figure 19 shows the typical layout of test measurements. The flags with the circles below correspond to HSG measurements and the pipe is buried perpendicular to the direction of measurements.

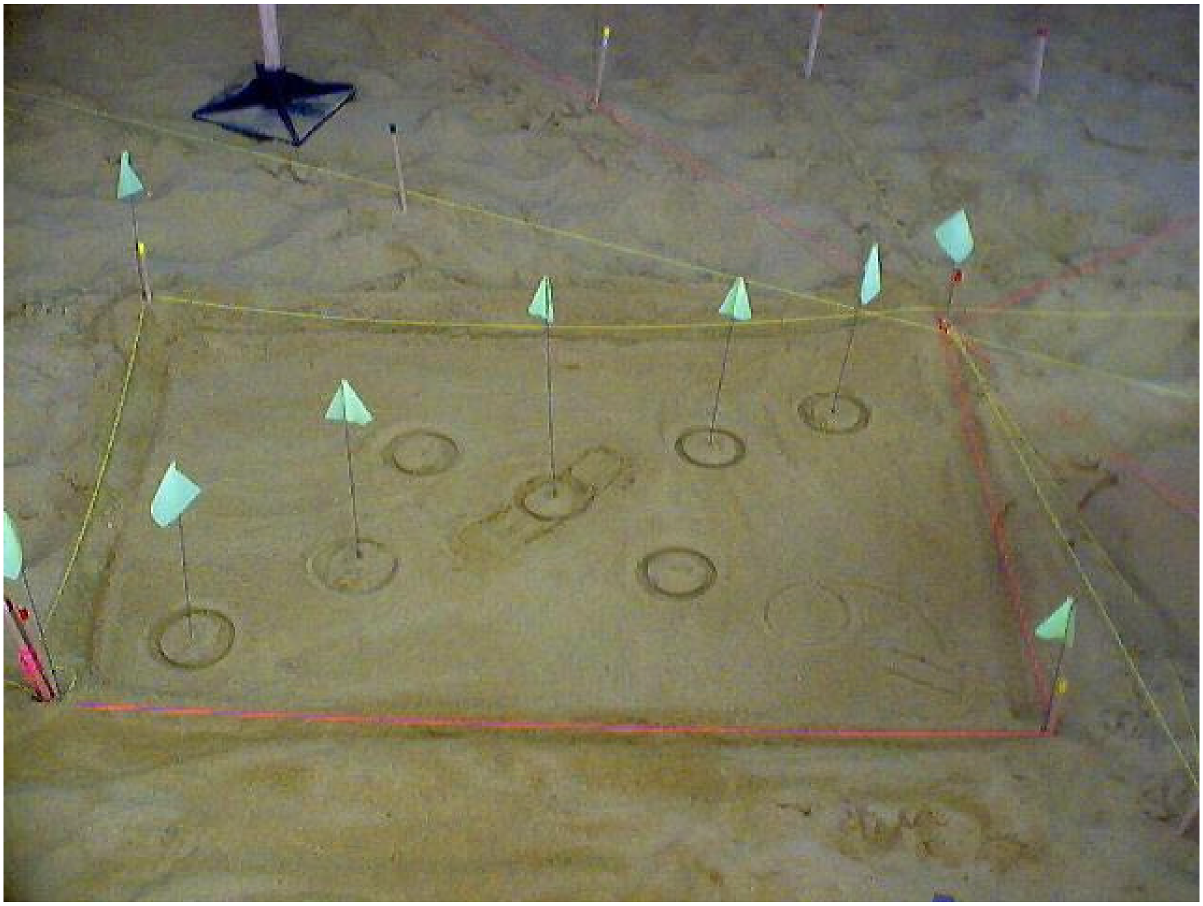


Figure 19 – HSG Test Layout for the Large Soil Bin Analysis

Results for the testing are shown as figures 20 through 23. The results generally show that the HSG measurements are not particularly affected by the pipes located under the device. It seems that the HSG measures the average "all-around" stiffness from the imposed stress bulb. These results are both promising and disappointing. They are promising with respect that small obstructions do not influence the measurements as much as previously thought. Therefore, natural objects like stones and tree roots should not compromise the stiffness measurements of the surrounding soil. However, these results do show that the HSG device is not sensitive enough to possibly locate small objects/voids below the device. This would negate the device's future possible use as a means of locating utility pipes/line or voids left due to improper compaction.

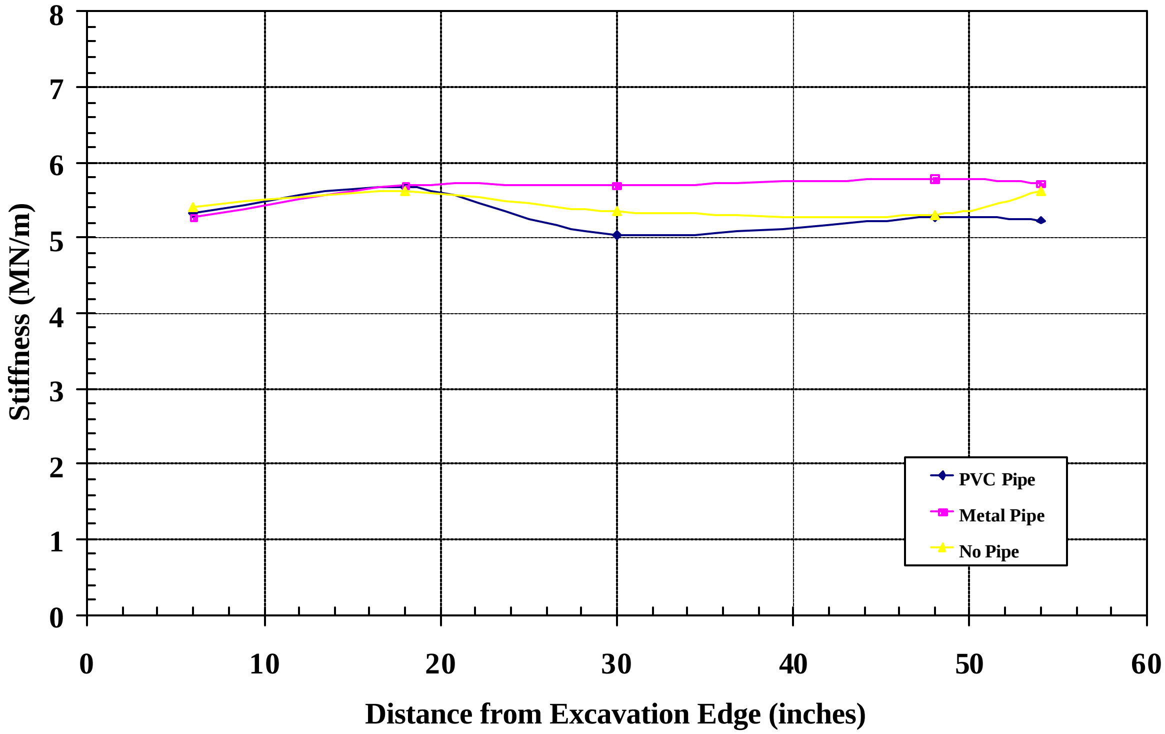


Figure 20 - Large Bin Measurements with Pipes Buried Six Inches Below Surface

Phase (2) – Full-Scale Field Study

A full-scale field study was conducted as part of a compaction control effort on two constructed test embankments in Elizabeth, NJ. The test embankments were constructed entirely of Portland cement stabilized dredge material. The material proved to be extremely difficult to determine dry density by means of a nuclear density gauge due to the device's inability to accurately determine moisture content. It seems that due to the hydroxide ions that are present during the hydration of the Portland cement, accurate readings of moisture content cannot be obtained. Figure 24 shows the comparison between the nuclear gauge's measured moisture content and the moisture content obtained from oven drying. As shown in the figure, the nuclear gauge measurements are nearly one half of those determined from conventional oven drying. Therefore, it seems that compaction control of cement stabilized soils would provide excellent field for HSG use.

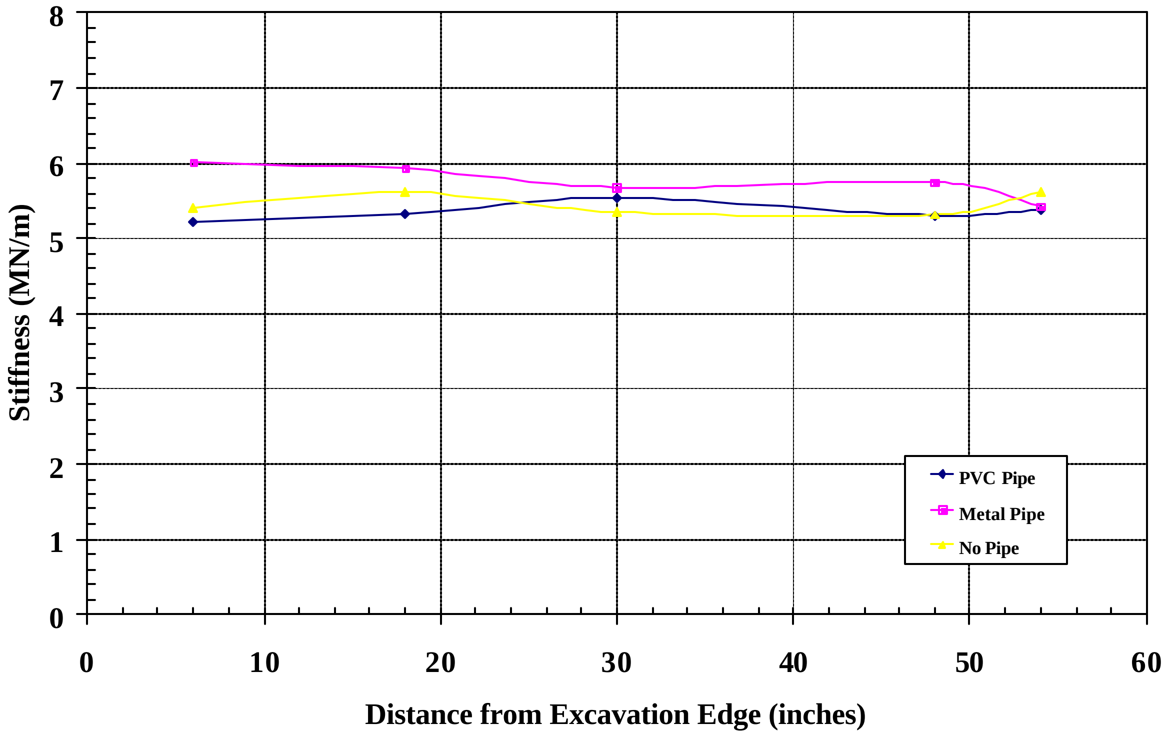


Figure 21 – Large Bin Measurements with Pipes Buried Nine Inches Below Surface

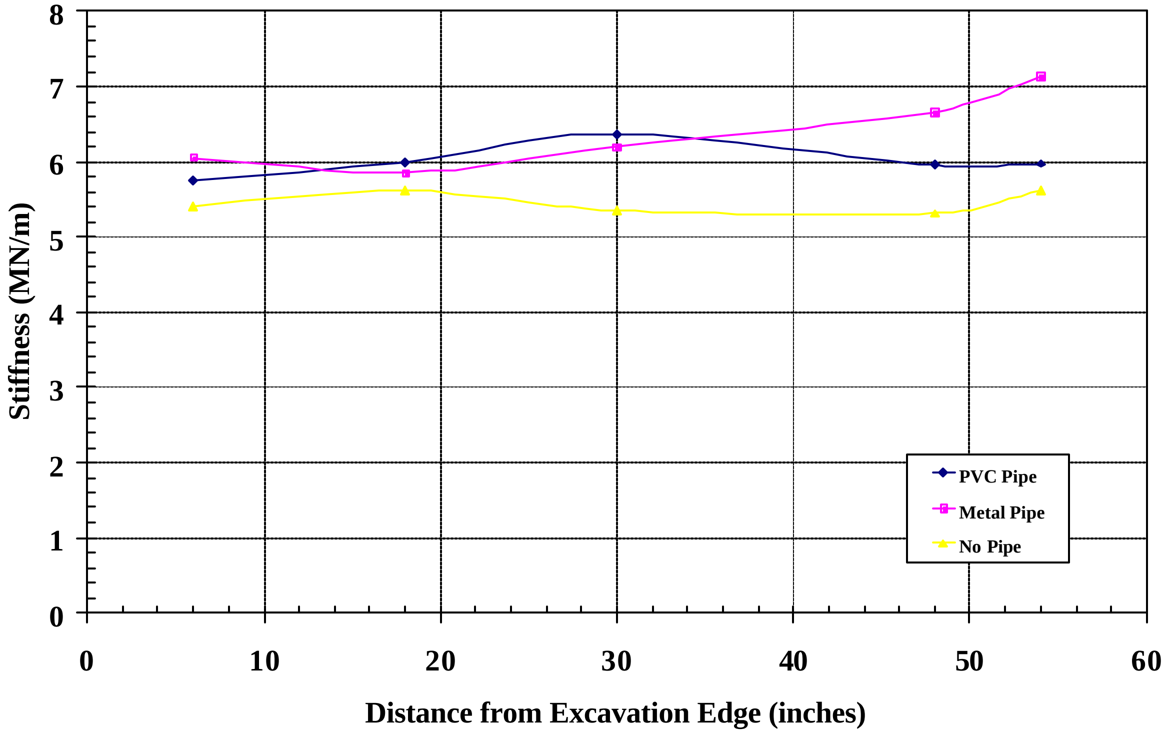


Figure 22 – Large Bin Measurements with Pipes Buried Twelve Inches Below Surface

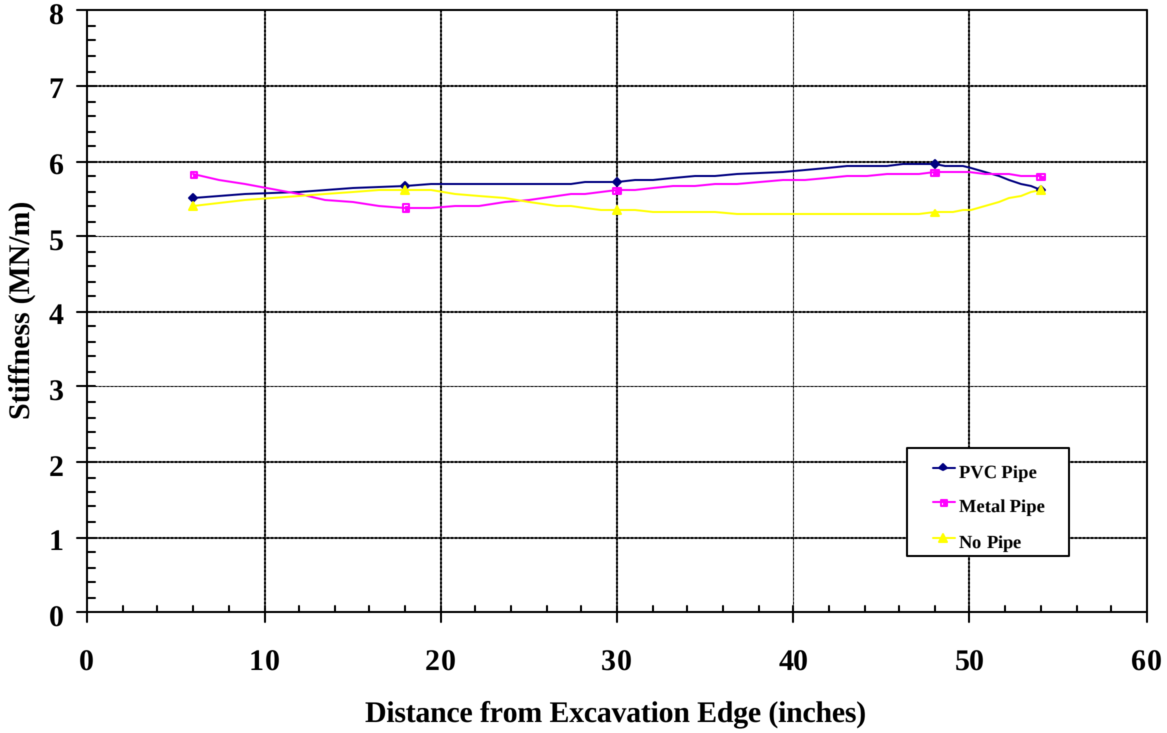


Figure 23 – Large Bin Measurements with Pipes Buried Eighteen Inches Below Surface

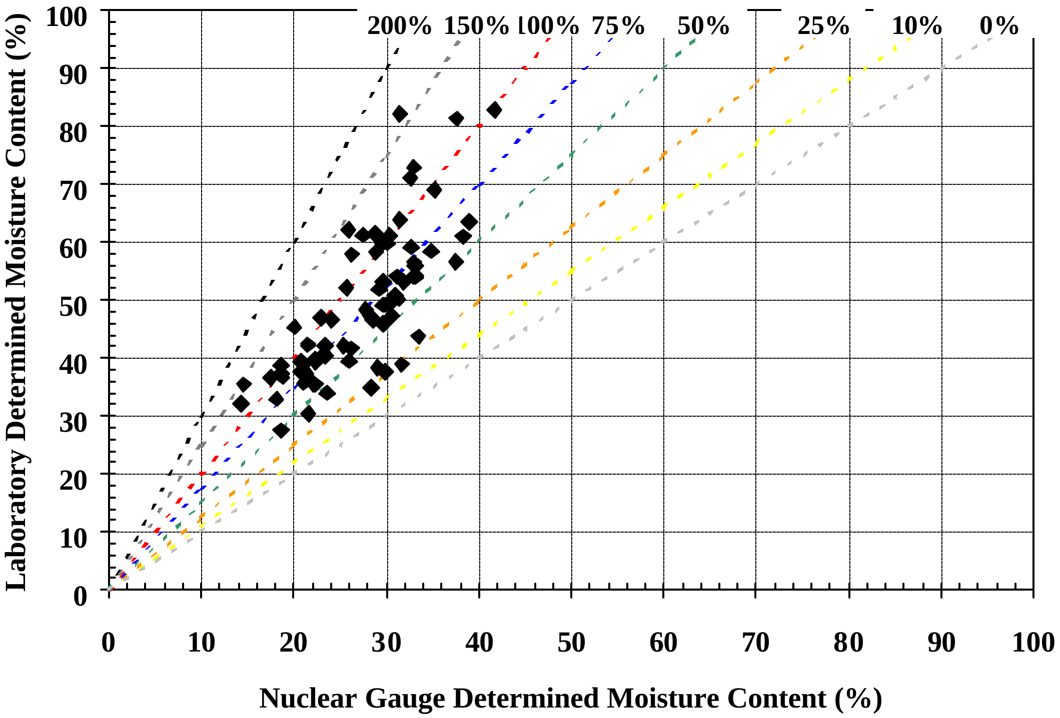


Figure 24 – Nuclear Gauge Determined Moisture Content versus Oven Dried

Field Study Testing Program

The measurements were conducted on both embankments during their construction, with the calibration measurements conducted during the first 2 lifts of embankment #1. An aerial schematic of the embankments is shown as Figure 25. Each lift of the embankment typically received twelve to twenty HSG measurements, with each measurement accompanied by a nuclear gauge measurement. There were approximately 150 total locations on embankment #1 and 200 on embankment #2. Approximately 50 points from embankment #1 were utilized for the calibration.

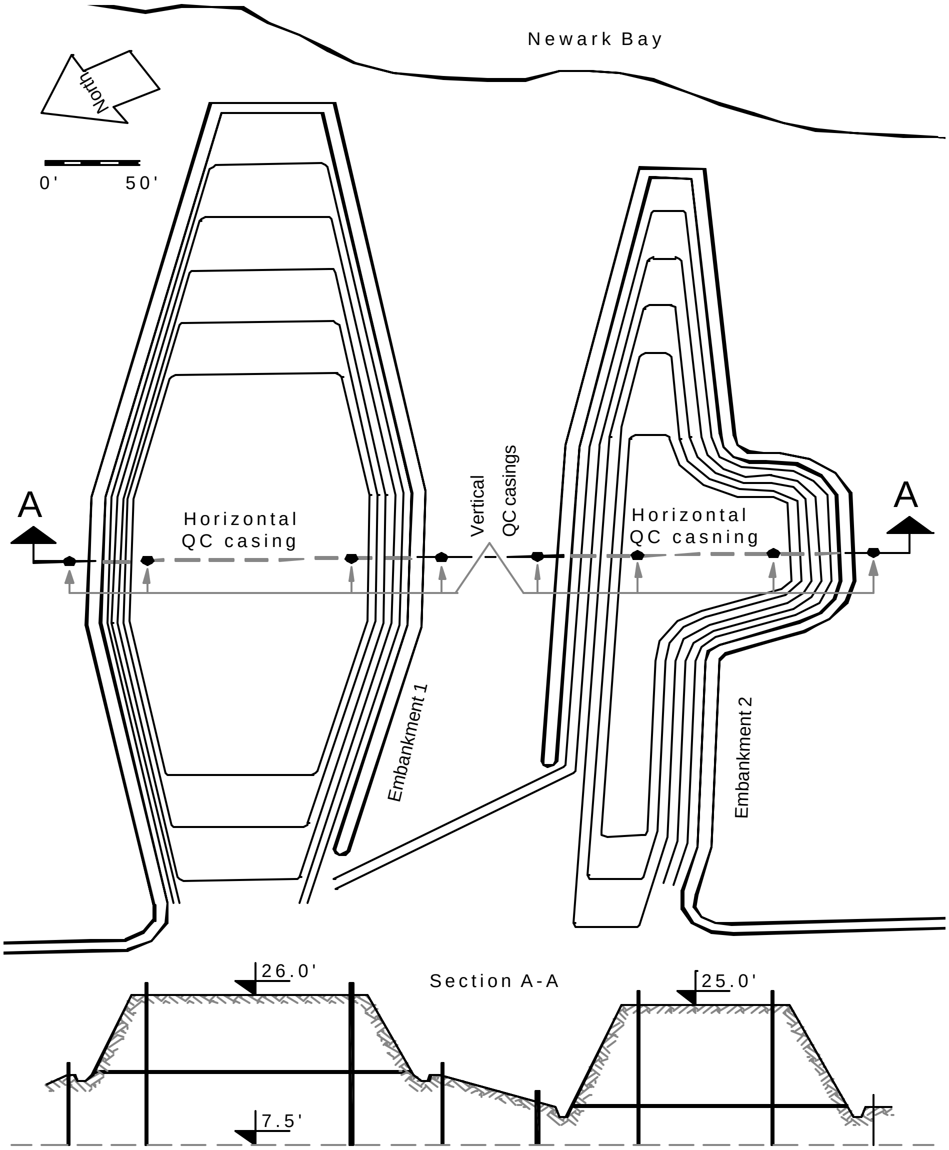


Figure 25 – Aerial View of Portland Cement Stabilized Dredge Material Embankments

The initial calibrations for the HSG were established by first conducting a HSG measurement and then use the nuclear gauge directly over the location of the HSG measurement. Soil samples were then and oven dried in a field laboratory oven overnight. Results from the HSG calibration for the cement stabilized dredge material are shown as Figure 26. The regression analysis shows a very good agreement with an R^2 value of 0.94.

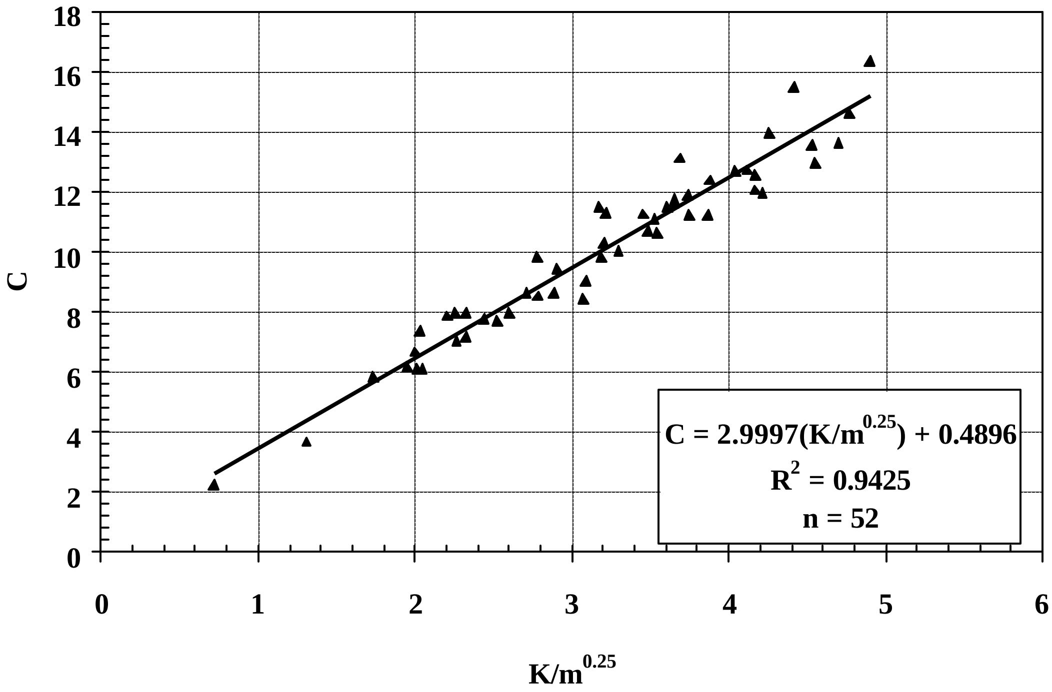


Figure 26 – Calibration of HSG for Cement Stabilized Dredge Material

Field Study Testing Program - Results

Utilizing the calibration equation, the predicted dry density from the HSG was compared to the actual dry density from nuclear density measurements and oven dried moisture contents for the remainder of the locations. Figures 27 and 28 show the results from embankment #1 and embankment #2, respectively. The solid line indicates 0% error, with the dashed line representing 5% error and the dotted line representing 10% error from the actual. For both embankments, a majority of the locations were within 5% error of the actual dry density, with almost all of the data falling with 10% error. Therefore, it can be concluded from the comparisons that the calibration was satisfactory and that the predictions were in good agreement with the actual dry density measurements.

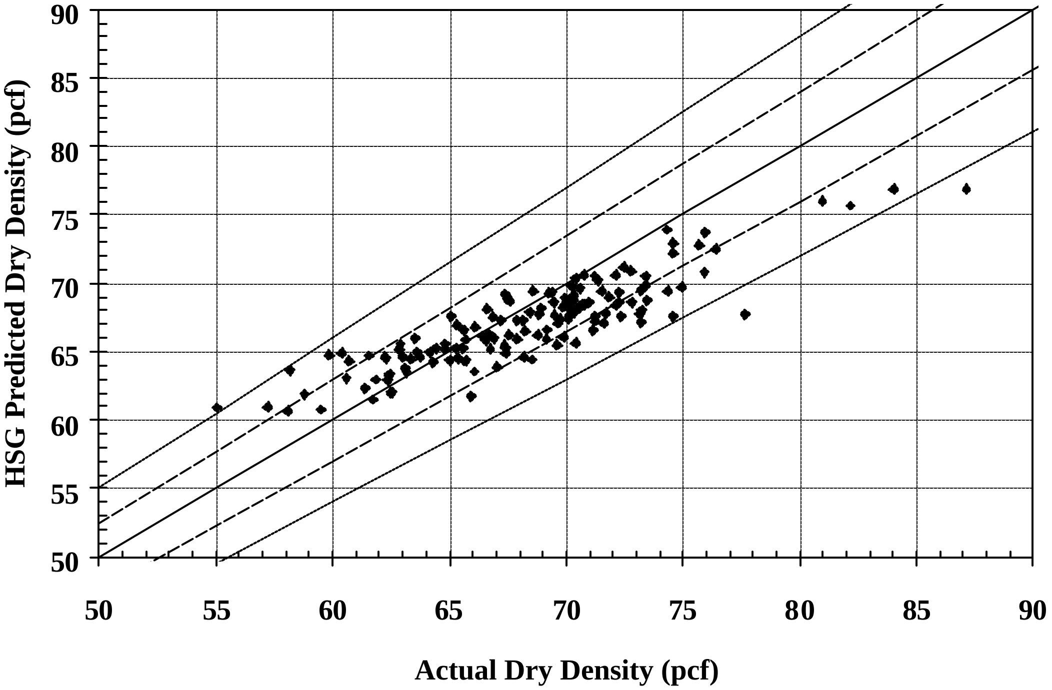


Figure 27 – Dry Density Comparison for Embankment #1

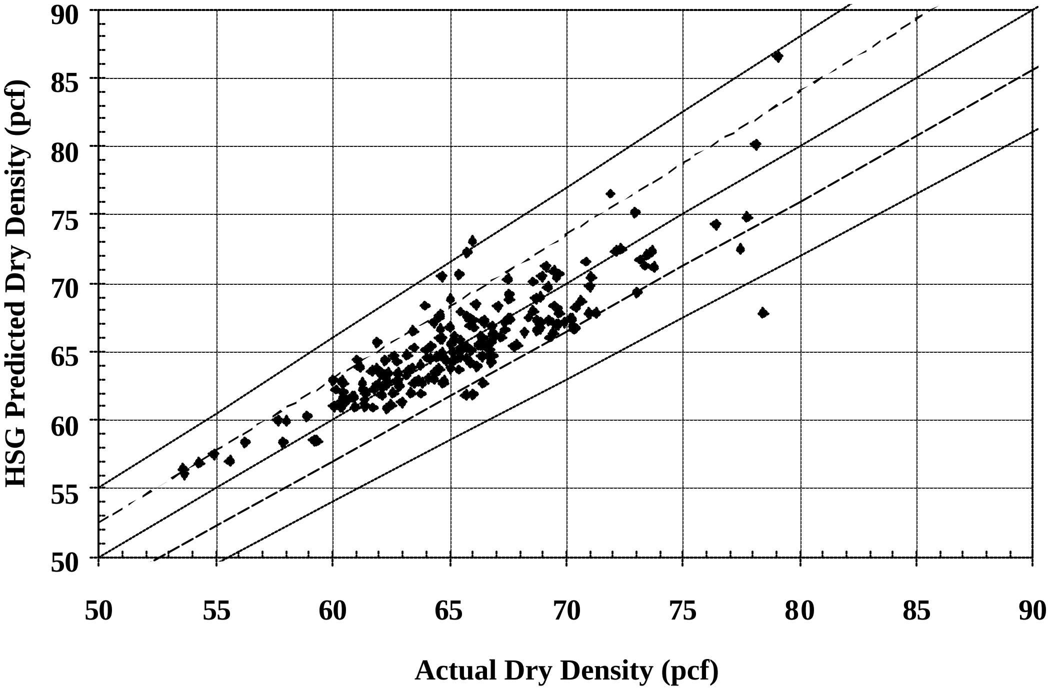


Figure 28 – Dry Density Comparison for Embankment #2

Figures that more closely illustrate the % difference between the actual dry density and the predicted are shown as figures 29 and 30. Embankment #1 had an average percent difference of 3.8%, while embankment #2 had an average percent difference of 2.5%.

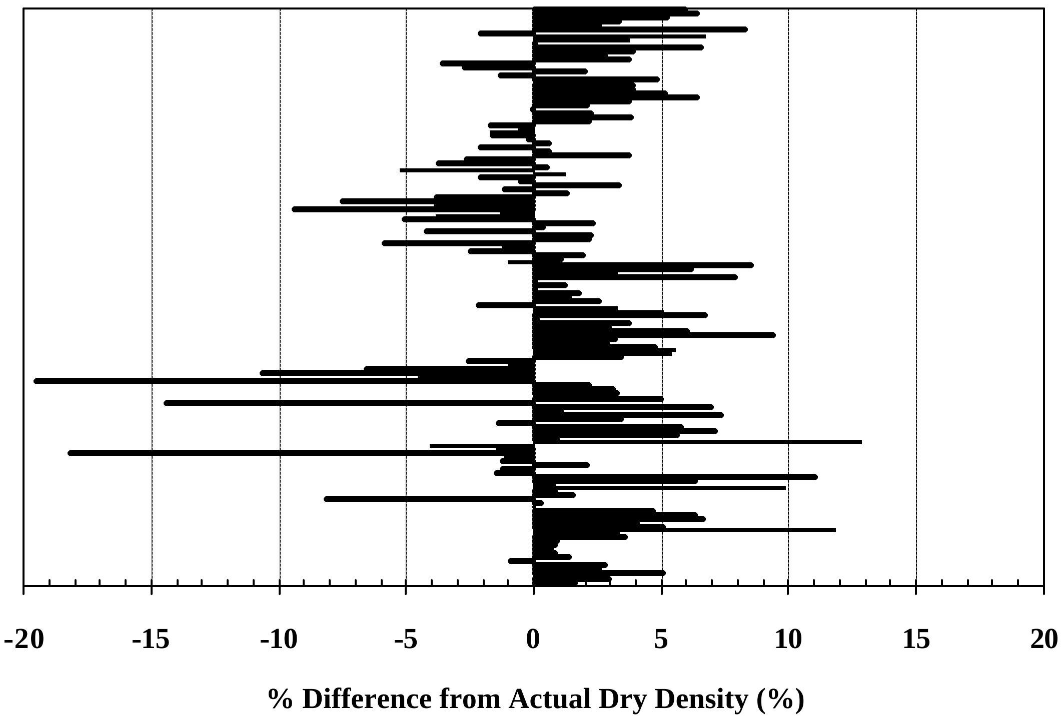


Figure 29 – Percent Difference Between Actual and Predicted Dry Density - Embankment #1

Field Study Testing Program – Compaction Control

During the compaction of the embankments, there was compaction criteria that had to be meet before the next lift of the embankment was to be placed. The field compaction criteria of the cement stabilized dredge material was a dry density greater than 60.6 pcf and a moisture content less than 50%. The criteria were based on compaction tests from the laboratory and also field experience. Each lift on the embankment needed to have at least 75% of the measurements taken to pass the compaction criteria. If this were not meet, the lift would be ripped up and allowed to dry and/or recompacted. Therefore, a true test of the HSG would be to see if the device could indicate a failed location on the embankment lifts.

Embankment #1 had a total of 11 locations fail the dry density compaction criteria. Of the 11 failed locations, the HSG was able to accurately predict 2 of the locations would fail. However, what needs to be indicated is that all 11 of the failed dry density locations failed due to excessive moisture content values and not compactive effort. This is important since even the nuclear gauge needed to have the moisture content separately

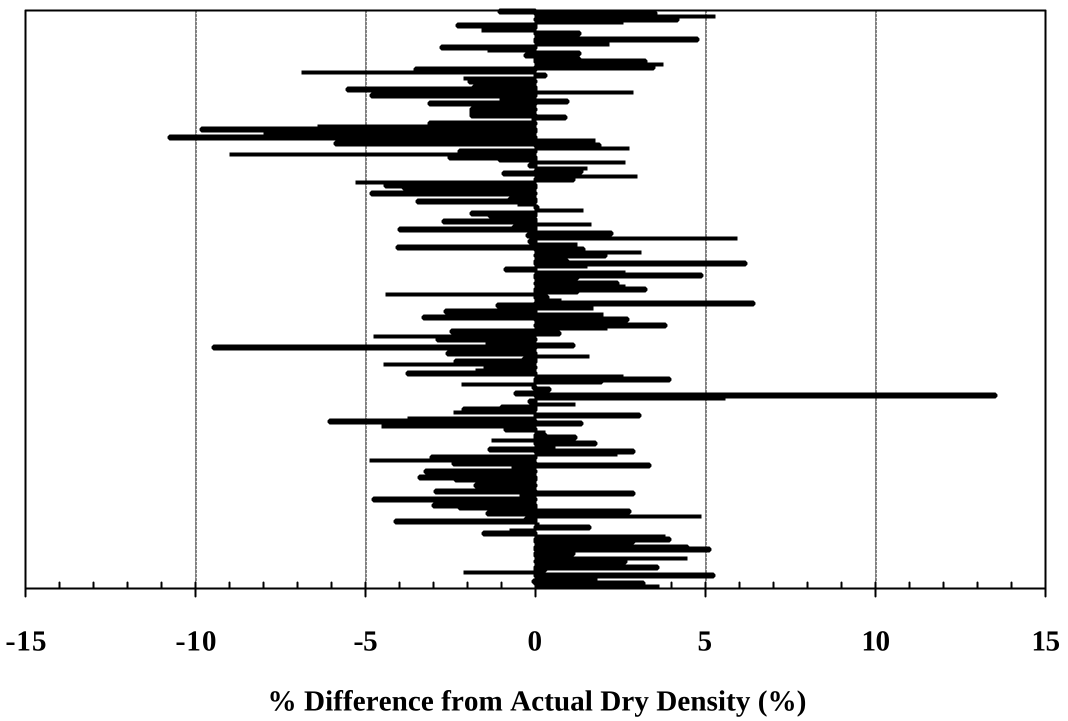


Figure 30 – Percent Difference Between Actual and Predicted Dry Density – Embankment #2

evaluated by oven drying. Therefore, the compaction control would have taken the same amount of time using the HSG, however, without the use of a nuclear device. Another important note is that the HSG did not inaccurately predict a failed location that had actually passed.

Embankment #2 had a total of 24 locations fail the dry density compaction criteria. Of the 24 failed locations, the HSG was able to accurately predict 12 of the locations would fail. However, the same scenario occurred with embankment #2 as had occurred in embankment #1; the 24 dry density locations failed due to moisture content and not due to compaction. Again, the HSG did not falsely predict any failed locations.

CONCLUSIONS

An evaluation of the Humboldt Stiffness Gauge was conducted to evaluate different aspects of the device. Primarily, the device is being proposed as a non-nuclear means of determining the dry density of soils compacted in the field. Possible future applications may be to utilize the device as a direct means of determining modulus parameters of soils compacted in the field for mechanistic pavement design.

For this particular research evaluation, the following aspects were evaluated under laboratory conditions: (1) The repeatability of the device; (2) The depth at which the device can measure; (3) The devices ability to predict the dry density of the soil using previously determined calibration equations; (4) The devices ability to predict the resilient modulus of the soil when compared to laboratory determined resilient modulus values for which samples were compacted at the same dry density; and (5) The possibility of the stiffness measurements being affected by objects located beneath the measuring device.

A full-scale field evaluation was also conducted as per the manufacturer's recommended procedure. The procedure was evaluated to determine how accurate the device can estimate the in-situ dry density when compared to nuclear density gauge measurements.

Based on the research conducted, the following conclusions can be drawn:

1. The Humboldt Stiffness Gauge provides repeatable measurements.
2. Typical measurement depths for the device range from six to ten inches for the soils measured in the study. The depths will be greater for stiffer soils and less for softer soils.
3. Soil specific calibrations should be developed for each soil tested. Based on calibration equations developed by a number of researchers, including the FHWA study, the calibration equations did not correspond to the soils tested from this research project.
4. There is potential for the HSG to be used to determine resilient modulus parameters of soils, however, calibration to the different applied stress conditions (either laboratory testing or FWD) is needed for validation.
5. The presence of small objects located beneath the HSG device seems to have little to no affect on the overall stiffness measurements for the depths evaluated.
6. When following the recommended calibration and testing procedure, the HSG can provide an alternative means of estimating the dry density of the soil. Unfortunately, a means of determining the moisture content of the soil is needed.

RECOMMENDATIONS

The following recommendations for future research or work are as follows:

1. The Humboldt Stiffness Gauge should be evaluated to determine if it can be used to estimate the resilient modulus properties of in-situ or compacted soils for mechanistic pavement design. The device can either be calibrated to laboratory results, or results for the FWD. However, special care should be taken for the evaluation to be conducted at similar applied stress levels.
2. The Humboldt Stiffness Gauge should be evaluated in conjunction with a portable means of determining the soil's moisture content. This would provide an almost instantaneous way of determining the in-situ dry density, without the current need of taking soil to an oven/drying process for moisture content determination.

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