DEPARTMENT OF CIVIL AND COASTAL ENGINEERING
UNIVERSITY OF FLORIDA

DEVELOPMENT OF COMPACTION QUALITY CONTROL GUIDELINES THAT ACCOUNT FOR VARIABILITY IN PAVEMENT EMBANKMENTS IN FLORIDA

FINAL REPORT

Contract Number BC-287

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16. Abstract		
This report summarizes the results of research directed at developing improved procedures for determining the acceptability of highway pavement base and subgrade materials. Measured nuclear density values are compared with stiffness modulus obtained with the Soil Stiffness Gage in both laboratory and field testing. A variety of procedural and equipment modifications are discussed with the objective of improving the precision of the Soil Stiffness Gage test results. Test results and conclusions are reported.		
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

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CHAPTER 1
Background

INTRODUCTION

The Florida Department of Transportation (FDOT) is currently engaged in the implementation of a major quality management initiative, denoted as QC 2000. Much of this program is focused on re-engineering of the roles and responsibilities of construction project participants with regards to quality control and quality assurance. Additionally, however, the FDOT has undertaken revisions to its construction sampling and testing specifications. The new acceptance sampling and testing formats vary somewhat depending on the particular material area, but most have included a transition to a statistical acceptance method (SAM) procedure. Recognizing the distribution of quality values in all populations, the statistical acceptance methods, are considered one of the most efficient ways of managing quality.

Given the above general policy direction of the FDOT, the objective of this project was to begin the development of an improved testing and sampling methodology for the compaction of highway embankments. Currently, soil density is measured primarily by the nuclear density gauge and is the quality metric used to judge compaction acceptability. While density, at first inspection would seem to provide a positive correlation to a well performing, i.e. stiff or rigid material, this premise is now subject to further assessment. The previous statement can be taken to the extreme using mercury as an example. While mercury is 13.6 times **denser** than water (or 6.5 times denser than a dense soil), its' stiffness is virtually zero. The desired engineering property that will insure acceptable roadway performance is the soil stiffness (or soil modulus). In addition, several accidents have been reported involving the nuclear density gauge, and hence a non- nuclear method that would provide this critical measure is warranted.

A new device termed the Soil Stiffness Gauge or SSG, has recently been developed that propones to measure rigidity of the soil rather than density to predict performance. This new technology may provide a very powerful tool for highway designers and constructors. In fact, the FDOT currently has several units in the field and lab attempting to demarcate the variability of the device, the operator and material type effects. In addition, the University of Florida is statistically evaluating their test results and looking at new design enhancements.

RESEARCH PROCEDURES OVERVIEW

Initial Tasks

TASK 1-1 The objective of the research project was to begin the assessment of the Soil Stress Gauge (SSG) under controlled conditions. Since another, unrelated FDOT project was investigating the capillary rise phenomena in A-2-4 material by varying the fines content, we proposed to also conduct SSG tests in FDOT's 8 ft. by 8 ft. test pit. The six 6-inch lift sections (total depth of 3 ft.) provided ample depth to preclude lower boundary effects. A series of SSG tests were performed for various moisture conditions, and the effect of surface preparation (e.g., sand layer versus scarified condition), plumbness of the unit and test repeatability were evaluated. It is evident that moisture content plays a significant role in the SSG interpretation. In fact, the FDOT has confirmed that the manufacturers intend to include some type of moisture content sensor with future SSG units to increase their accuracy. Since this enhancement was not available at the time, we proposed to, and did purchase a sensor that would rapidly determine the soil moisture with depth. The details of the device are attached for your perusal. (Appendix A)

TASK 1-2 Concurrent with the above; the data was analyzed – specifically in terms of correlations between SSG and nuclear density. For all data, variability within each test protocol was examined, to confirm or refute its statistical viability.

TASK 1-3 Design of a surface preparation tool that will assure consistent SSG test conditions. Conceptually, the SSG handle would be modified so that no additional downward force could be applied to the ring foot other than weight from the device itself. Rotation of the device would prep the soil surface as well.

TASK 1-4 Once the above tests were completed (or near completion), a tentative SOP would be produced for the SSG operations. These suggestions would incorporate the Humboldt instructions and more standardized surface preparation procedures.

Phase II Tasks Overview

Based on the preliminary results of the above testing program, further directed research was performed. During this phase, the draft SOP developed from the prior work was continually examined and minor adjustments made. Specifically, the following tasks were attempted.

TASK 2-1 Using the test pit, uniform soil layers (in 6" lifts) were placed and SSG and nuclear density (ND) tests were conducted. The goal of this task was to confirm the effects of surface preparation and to evaluate spatial variability. The lifts were placed at or near optimum moisture content – thereby simulating actual field practice. Concurrently, at least 2 – 4 (depending on available staffing) plate load tests were conducted. The rationale for these tests was to investigate the existence of a correlation between SSG and soil moduli.

TASK 2-2 Subsequent mutual properties were varied in terms of soil classification and percent fines content (A-3, A-2-4, etc.) - however, horizontal homogeneity was preserved. For each material, the tests outlined in TASK 2-1 were conducted. By repeating the above tests for each material, the effects of soil type were evaluated.

TASK 2-3 After TASK 2-2 was completed, additional tests were performed to measure the effect water had on the accuracy of the SSG results by varying the water table location in the test pit. While it is implicit that moisture content will affect the SSG results, if a reliable trend can be determined, then it would be plausible to provide the FDOT with a reduction factor (or factors) for the above conditions (i.e., soaked conditions).

TASK 2-4 The final task was to present recommendations to the FDOT so that a decision can be made regarding a rationale management practice for contractor conducted testing. (i.e., QC 2000 criteria).

CURRENT PRACTICE

FDOT Testing and Acceptance Standards

Generally, embankments must be constructed in lifts of not more than 12 inches unless the contractor demonstrates the ability to achieve satisfactory results with lifts of greater thicknesses. Each lift must be compacted to 100% of the maximum density obtained by the AASHTO T99 Method C. Density is typically measured by a nuclear density device. The standard testing procedure calls for one density to be taken for each 500 feet of embankment lane per lift. Passing densities are recorded in a project density logbook. Those tests that fail are re-rolled until they pass. Hence, acceptance is a pass or fail criteria.

Representative Quality Values

Density test values from representative FDOT projects were reviewed in order to obtain an understanding of the quality levels currently being obtained. A summary of the density statistics for four projects is presented in Table 1. In general, the embankment test values have a standard deviation in the range of 1% to 2% of the target proctor density. Note that, while each of the reported projects produced passing test values, there is considerable difference in variability. In addition, it should be noted that even with the passing test values, a significant portion of the population is expected to fall below the target criteria.

Table 1. Summary of Embankment Test Densities for Representative FDOT Projects

Project	**A**	**B**	**C**	**D**
Number of Tests	29	29	50	351
Mean Value	100.4	100.4	100.4	101
Standard Deviation	0.42	0.42	3.99	1.83
Percentage < 100% Target	18%	18%	46%	31%

Note: Densities as a Percentage of Proctor Density

CHAPTER 2
Initial Trials

INITIAL TRIALS WITH THE HUMBOLDT GEOGAUGE

Introduction

Conceptually, introducing a statistical acceptance method procedure for the embankment compaction process would require an increase in the amount of test values taken. Therefore, testing efficiency is an important consideration. The Humboldt GeoGauge, also known as the Soil Stiffness Gauge (SSG) was considered as a possible alternative to the standard nuclear density test. The SSG weighs 11.4 kilograms (kg), is 28 centimeters (cm) in diameter, 25.4 cm tall, and rests on the soil surface via a ring–shaped foot. It is placed on the soil surface and activated by pressing a button. The GeoGauge imparts very small displacements to the soil at 25 steady-state frequencies between 100 and 196 Hz. Stiffness is determined for each frequency and the average from the 25 frequency sweep is displayed in approximately two minutes. A photograph of the Soil Stiffness Gauge is shown below in Figure 1.

Figure 1. Soil Stiffness Gauge

Initial Field Test Results

Initial field-testing of the SSG focused on observing the relationship between measured densities and stiffness values produced by the SSG. Soil densities were obtained with a nuclear density device and stiffness values using the SSG. Figure 2 presents an example of tests obtained from a FDOT project. These results are representative of the field test results from several different site locations. From the analysis of the data, it is apparent that the SSG values and densities were very poorly correlated. That is to say, that the SSG did not provide an acceptable estimate of the soil density.

Since the variability of the nuclear density measurements was reasonably well established from a substantial accumulation of field-testing, the precision of the SSG test results was assumed to contribute to the poor correlation. Therefore, a testing plan was developed to test the SSG under controlled conditions to determine the precision of the device.

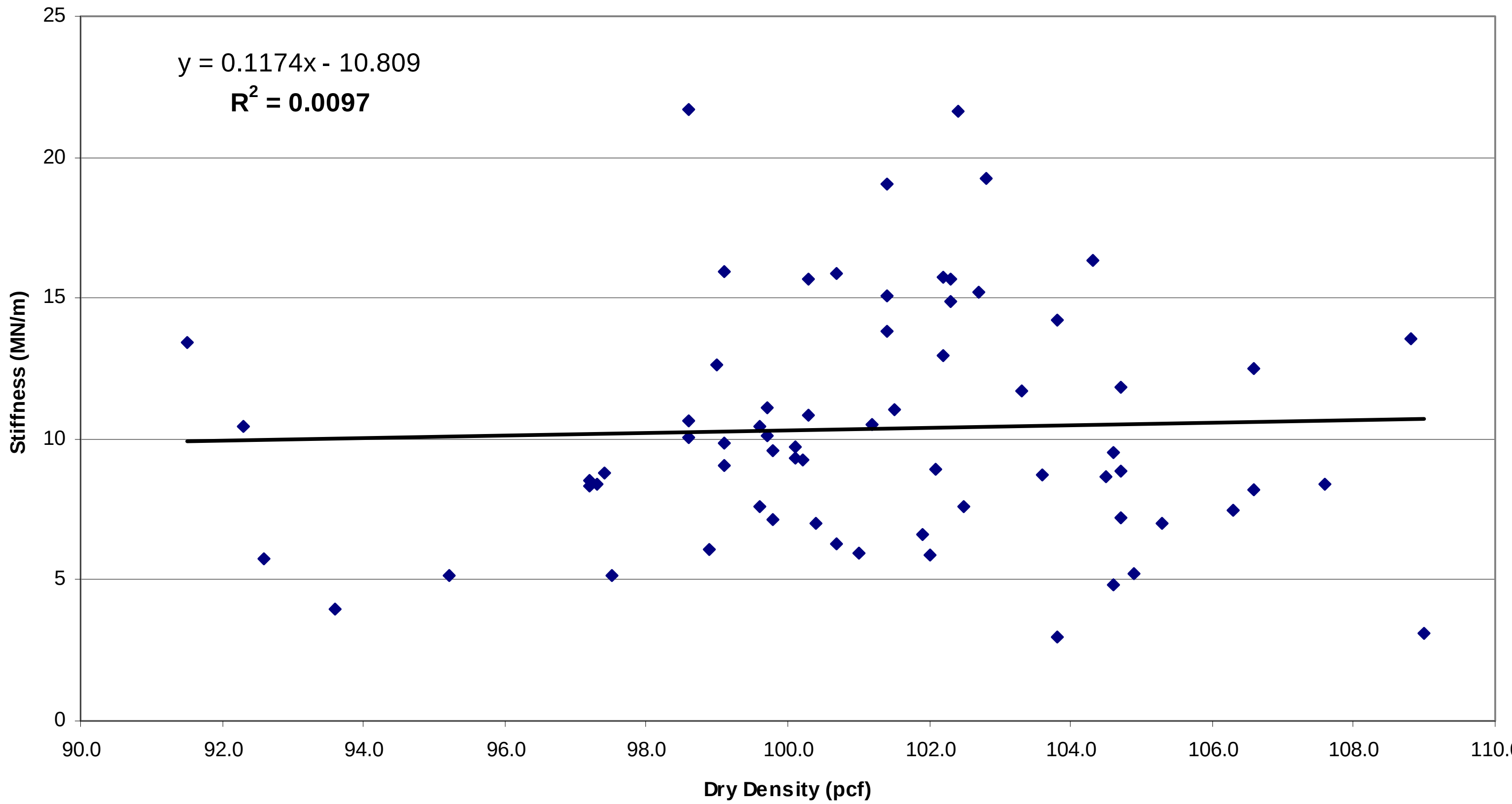


Figure 2. Typical Comparison of Field Dry Densities to SSG Stiffness Values

FDOT TEST PIT RESULTS

Stationary Multiple SSG Tests

During this time frame, it was decided that UF would purchase an SSG in order to conduct its own tests. Once delivered, a series of repetitive tests were conducted in the FDOT testing facility located on Waldo Road to determine the variability of the SSG readings.

The test pit was previously filled with homogenous material (A-2-4) compacted under controlled conditions. The SSG was placed on the soil, and checked to verify that the contact area between the foot ring and soil was greater than the minimum 60% suggested by the manufacturer. Eleven tests were conducted, one after the other, without lifting the device from the test location. The only human contact with the SSG was the operator pressing the start button. The results are presented in Table 2 and Figure 3.

The measured stiffness for the first three measurements increases 0.34 MN/m and 0.38 MN/m respectively and then remains approximately constant after that. There is a difference of 1.020 MN/m between the first (14.800 MN/m) and the last (15.820 MN/m) measured value. Compared to the average value (15.564) of the 11 recorded measurements, this represents a 6.5% variation**.** The coefficient of variation of 2.05% is close to the value of 2% specified by Humboldt for fine-grained soils.
Based on the results observed in Figure 3, if this trend continues through later experiments, two seating tests prior to the actual recorded test value will be recommended since the SSG device two tests to properly seat itself and provide consistent results. The peculiarities of this trend will be studied in greater detail in future research.

Table 2. Results of SSG Testing Without Moving the SSG at FDOT Waldo Test Pit

Test No.	Stiffness (MN/m)
1	14.800
2	15.140
3	15.520
4	15.610
5	15.620
6	15.650
7	15.650
8	15.810
9	15.770
10	15.810
11	15.820
Average	15.564
S. D.	0.319
Coefficient of Variation	2.05%

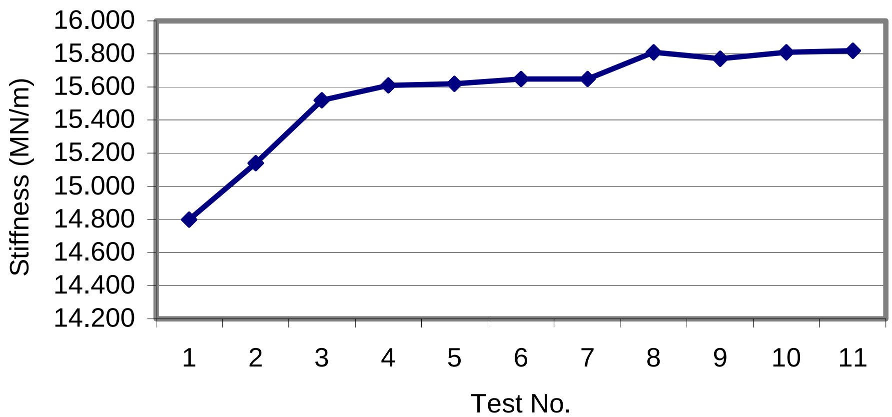


Figure 3. SSG Repeated Test Values Without Moving Device

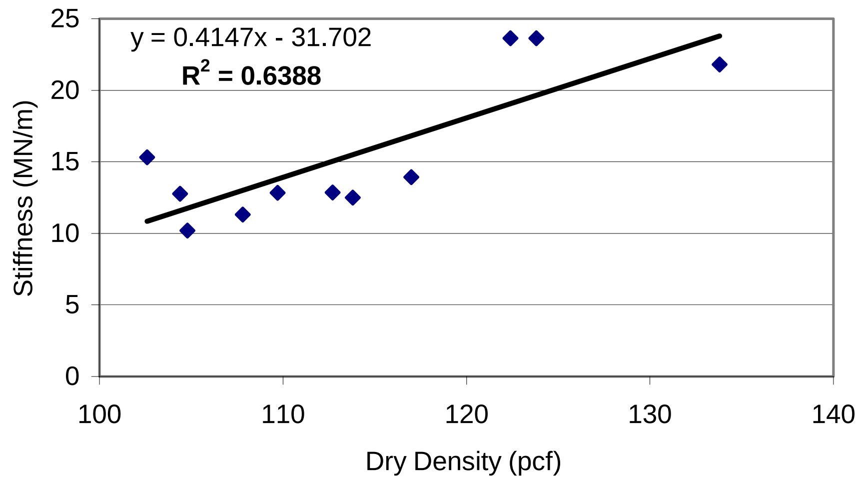


Figure 4. Comparison of SSG Stiffness and Density Values Obtained at the FDOT Test Pit

Additional Field Testing

Along with numerous tests performed in the test pit, SSG and nuclear density tests were also performed at several field sites. One such site was a shoulder-widening project on Highway 441 north of Gainesville in Alachua, Fl.

SSG and nuclear density tests were conducted on a four-inch limerock base over a 100-foot test section. The SSG tests were performed on ten-foot intervals while the nuclear density tests were performed at arbitrary locations between the ten-foot intervals after each pass of the vibratory roller compactor.

Two different series of tests were performed since rain had fallen, thereby noticeably affecting the SSG values. The second series of tests were performed 8 days after initial compaction. Figure 5 presents the results of all 68 tests. The results suggest little significant correlation between the SSG and density values.

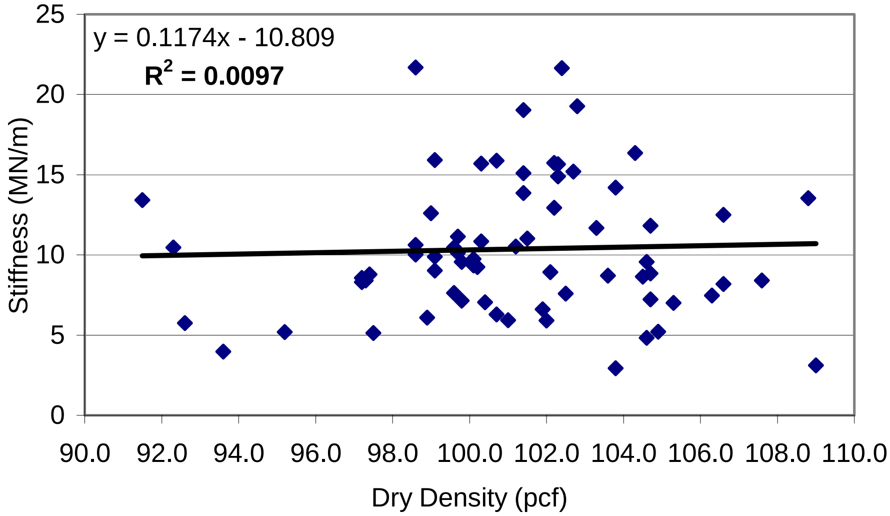


Figure 5. Results of SSG and Density Tests Performed on Highway 441, Alachua, Florida

SSG Test Variability

Since there was substantial scatter in the field data cited above, the conjecture was that the placement of the unit could be a major contributor to the output variability. Hence 18 additional tests were performed in the test pit to quantify this effect. Table 3 presents the results.

Table 3. Results of SSG Testing With Lifting and Replacing the SSG on A-2-4 (30% Fines)

Test	Test Average
1	10.185
2	9.121
3	12.699
4	13.264
5	12.880
6	12.558
7	14.681
8	11.232
9	12.246
10	14.267
11	10.122
12	10.042
13	9.658
14	11.560
15	12.714
16	19.655
17	15.867
18	13.620
Average	12.576
S.D.	2.561
C.O.V.	20.36%

A 20.36% coefficient of variation for 18 SSG tests performed in the test pit appears large when taking into account the fact that the tests were performed on the same material (A-2-4, 30% fines) and that the material was compacted under the same controlled conditions. The device was lifted and replaced between each test, therefore operator inconsistency might have played a major role in output variability.

Comparing SSG Values to Density Values

The test pit was set up such that there were two main areas with each area divided into sections containing various types of soils. The first main pit had three sections containing an A-2-4 material with varying amount of fines (12%, 20%, and 24%).

The second pit was divided into two sections. The first section contained an A-2-4 material (with 30% fines) and the other section an A-1-b material (Miami Oolite).

Plate load tests were conducted on the Miami Oolite and A-2-4 material (30% fines). A series of SSG tests were then performed before and after the loading was completed. Nuclear density tests were also performed after the loading approximately one foot away from the location of the loading site. The results for the A-2-4 material are presented in Table 4 and Figure 4. Under the controlled conditions at the test pit the correlation between the SSG values and density improved significantly over those previously obtained from field results.

Table 4. Results of SSG and Density Tests at FDOT Test Pit

Test No.	Dry Density (pcf)	Stiffness (MN/m)
1	109.7	12.838
2	113.8	12.501
3	112.7	12.866
4	117.0	13.929
5	133.8	21.807
6	122.4	23.647
7	123.8	23.646
8	107.8	11.304
9	104.8	10.202
10	104.4	12.766
11	102.6	15.328

SSG Stiffness-Nuclear Density Correlation on FDOT Hwy Project 441

The R^2 value of 0.0097 (Figure 5) between the SSG stiffness values and the nuclear density test values on project 441 shows no correlation between SSG stiffness and

Nuclear Density. This low R^2 value could be caused by different test locations for the SSG and nuclear density tests as well as different surface preparation conditions for the SSG. Another possible explanation for the low R^2 value is the effect of natural soil below the limerock base. A 4" layer of limerock base was used in the study, while the device measures the stiffness as deep as 6 to 8 inches.

The SSG value increased with the number of roller passes. Four passes seemed to be the optimal number in order to achieve the maximum SSG. For more information regarding this subject, please refer to the Texas DOT website listed under References.

Under controlled testing conditions (surface preparation and the same test location for both SSG and nuclear density) there seems to be a correlation between nuclear density and SSG. However, because the SSG is more sensitive to the quality of base and subgrade than the nuclear density gauge (Evaluation of In-Situ Resilient Modulus Testing Techniques by the Texas DOT, website provided in references) the correlation is more difficult to verify in the field. If a better correlation is needed between the SSG and nuclear density, it is recommended that future nuclear density tests should be conducted at the same point where the SSG tests are performed and not between two adjacent SSG tests.

Analysis of SSG-Nuclear Density Correlation in the FDOT Test Pit

An R^2 value of 0.64 shows a reasonable correlation between the 11 SSG measurements in the Test Pit and the corresponding nuclear density measurements. In this case, the SSG measurements and the nuclear density measurements were performed approximately one foot apart. This fact might explain why the R^2 values for these particular tests were greater than the other previously calculated R^2 values for the field results, where the nuclear density tests were performed 5 ft. away and adjacent to the SSG tests positions.

In addition, another series of tests on the same A-2-4 (30% fines) were conducted at the FDOT test pit to analyze the correlation between SSG and nuclear density readings. Nine SSG measurements were taken for each of the 27 nuclear density tests performed in the test pit. An average of each test's 9 SSG measurements was compared with the corresponding 27 nuclear density tests (Figure 6). A computed R^2 value of 0.25 shows a weak correlation between SSG Stiffness and the corresponding nuclear densities. The decrease in the R^2 value compared to the previous case could be partially explained by the different SSG and nuclear density test locations.

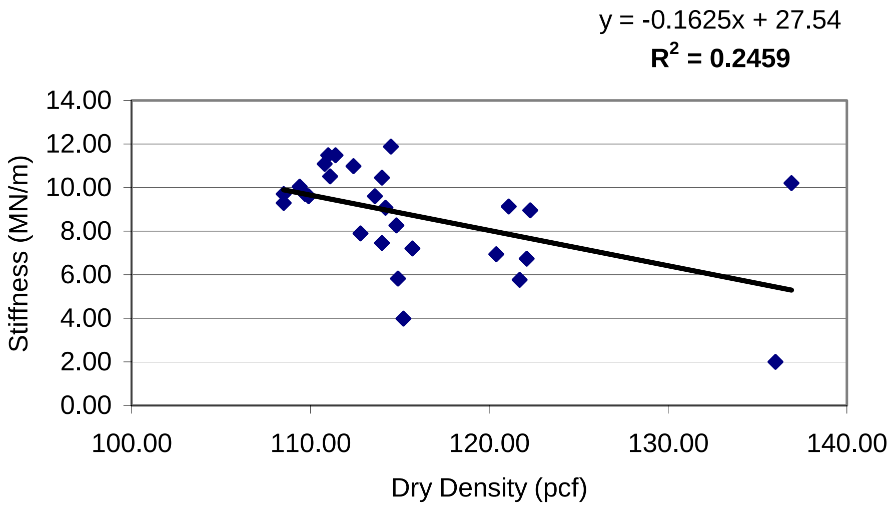


Figure 6. Comparison of SSG and Density Values Obtained at the FDOT Test Pit

Microwave moisture contents were performed for each of the 27 nuclear density tests mentioned above. An R^2 value of 0.06 shows no correlation between the measured SSG stiffness values and the existing moisture conditions (Figure 7).

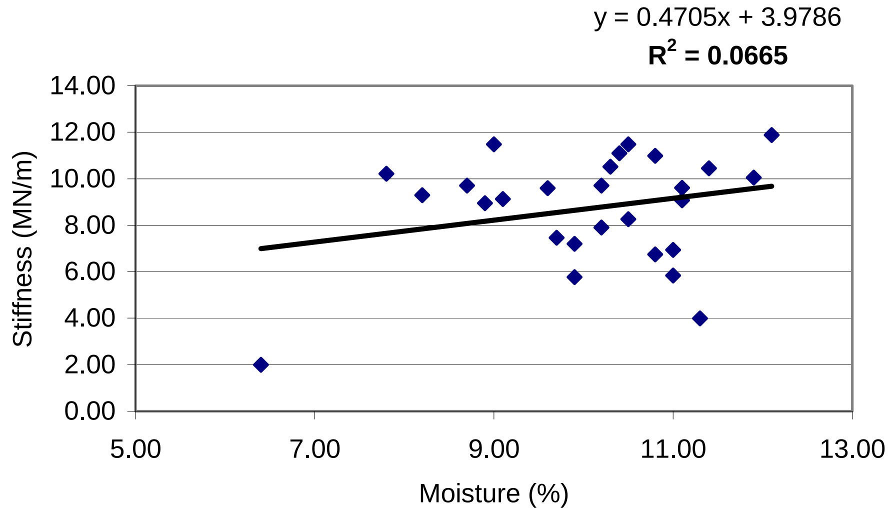


Figure 7. Correlation Between SSG Values and Moisture Content

Analysis of Plate Load Test Data Provided by the FDOT

The Florida Department of Transportation requested a comparison between results of Plate Load Tests (PLT) conducted in their Test Pit facility with corresponding SSG stiffness values.

The data contained results of eight Plate Load Tests performed on five different soil types (A-2-4·12%, 20%, 24%, 30%, Miami Oolite). In addition, the stiffness was measured with the SSG, before (three values) and after (three values) performing each Plate Load test. The water table during testing was located 24 inches below the surface. The SSG stiffness values were also included in the supplied data. The data supplied by the FDOT can be found in Appendix B.

The following correlations were attempted:

- Average resilient modulus versus average SSG stiffness (before and after performing the Plate Load Test).
- Percent fines versus SSG stiffness (before and after the Plate Load Test).
- Average resilient modulus versus average dry density.
- Average resilient modulus versus percent fines.
- Average resilient modulus versus average moisture content.

The results of all tests are summarized in Table 5.

Table 5. PLT Resilient Modulus, Dry Density, Moisture Content and SSG Stiffness Averages for the Various Test Pit Materials

Material	Avg. static modulus	Avg. resilient modulus	Avg. dry density	Avg. moisture content	Avg. SSG stiffness (MN/m)		
	psi	psi	pcf	(%)	Before PLT	After PLT	% Change
A-2-4 12% fines	14363.2	19793.7	111.6	3.05	10.54	9.81	-6.93
A-2-4 20% fines	20909.5	23769.7	114.9	4.3	10.8	11.71	8.42
A-2-4 24% fines	23526.5	20178.3	112.4	6.2	13.47	14.3	6.16
A-2-4 30% fines	16328.2	22989.2	118.9	8	12.34	13.53	9.64
A-1-b Miami Oolite	49400.5	50028	134	4.1	27.12	26.72	-1.47

Note: The average resilient modulus and the average SSG stiffness value for the Miami Oolite are not included in the subsequent analysis, since the modulus and stiffness values are extremely high compared to the other values. The static modulus represents the average of the first three cycles of the plate load test, while the resilient modulus represents cycles 4 thru 10,000. The average stiffness values in the shadowed areas of the above table indicate decrement in the values after performing a Plate Load Test (PLT). The Plate Load Test reflects materials tested under drained conditions (water table raised to the surface and then lowered to allow water to drainage from the strata).

Summary of Results

Based on the results of the tests, the following statements can be made:

- The average SSG stiffness values increased 6-10%, after performing the Plate Load Tests, in three out of five tests. In two of the tests, the average SSG stiffness decreased by 1-7%.

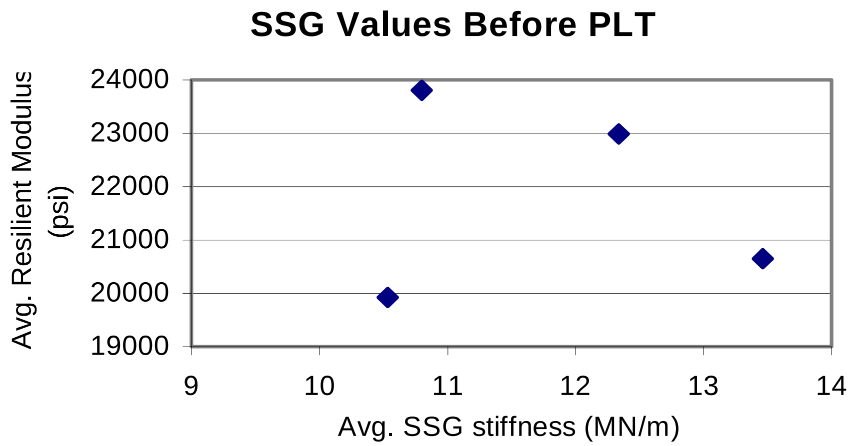
- The maximum increase (9.64%) was observed for the 30% fines material. The maximum decrease (6.93%) was observed for the material with 12% fines.

- The highest average SSG stiffness value (13.47 MN/m before and 14.30 MN/m after PLT) was recorded for the material with 24% fines. The average moisture content at the time of tests was 6.20% and the average dry density of the material was 112.4 pcf. The highest average resilient modulus (23,800 psi) was recorded for the material with 20% fines (moisture content - 4.3% and dry density - 114.9 pcf).

- The lowest average SSG stiffness value (10.54 MN/m before and 9.81 MN/m after PLT) and the lowest average resilient modulus (19,800 psi) were recorded for the material with 12% fines. The average moisture content was 3.05% and the average dry density, 111.6 pcf. The disturbance caused by removal of the plate after the PLT tests appears to be the reason for the lower SSG value after the tests.

- Based on the limited data, no definitive correlation between the various factors (i.e. percentage fines, dry density, average SSG stiffness, moisture content and average resilient modulus) can be concluded to date. However, this information will be added to future test data with the expectations that positive correlations may result.

Plots of the supporting data are shown on the following pages.



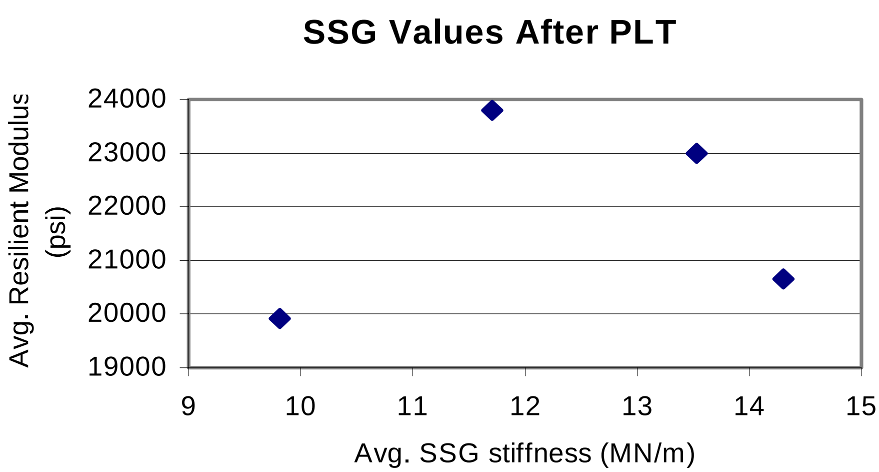
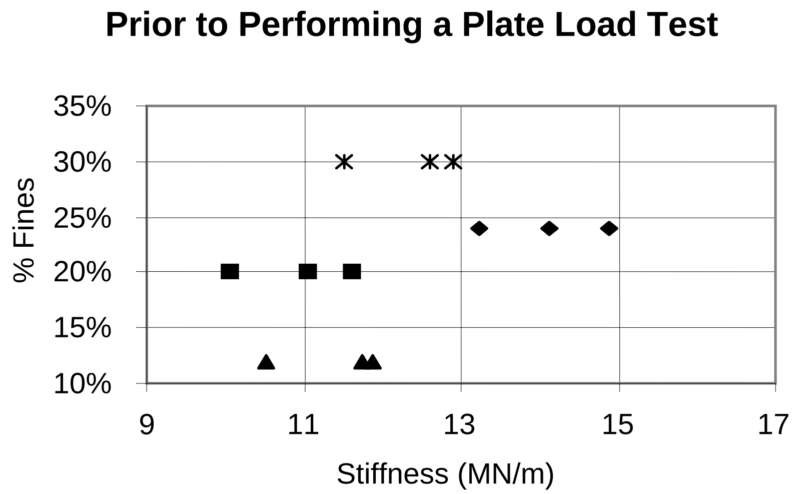


Figure 8. Average Resilient Modulus vs. Average SSG Stiffness (Before and After Performing Plate Load Tests) for All Samples.



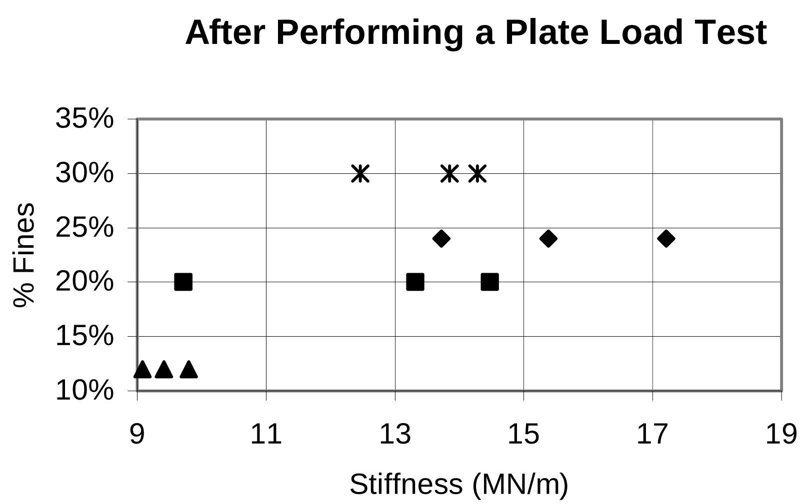
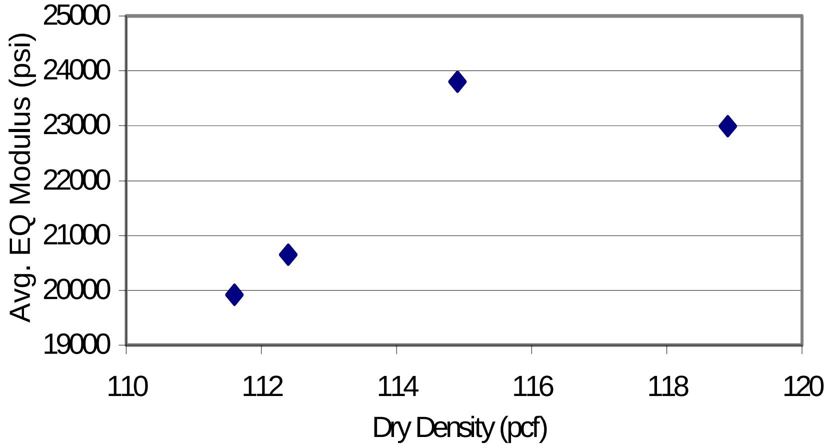


Figure 9. Percent Fines vs. SSG Stiffness Values Before and After a Plate Load Test



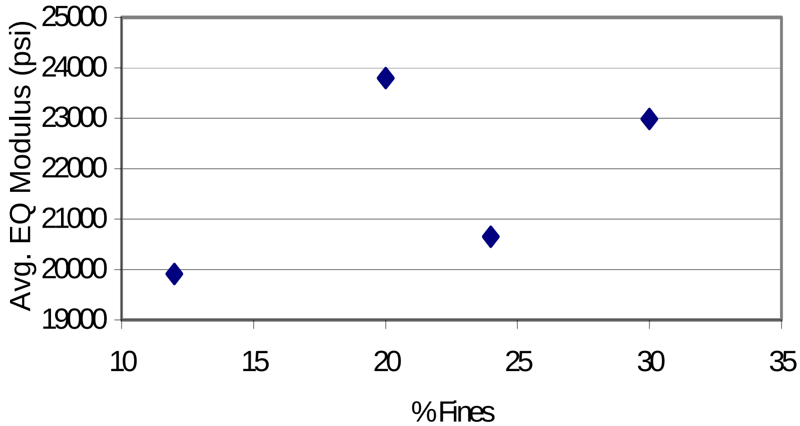


Figure 10. Average Resilient Modulus vs. Dry Density and Percent Fines

Preliminary Conclusions

Repeatability and precision of the SSG device appears to be largely dependent on the conditions existing at the machine/soil interface such as moisture content and actual placement of the device. It bears mentioning that Humboldt also has remarked that operator influences on SSG results can be a major contributor to variability.

Acting on the hypothesis that the precision of the SSG device could be enhanced with improved consistency of the above factors, the research team initiated a series of tests to develop a better SSG testing procedure. The SSG device's positive attributes, such as its ease of use and its ability to perform tests in less time, may lead to an attractive alternative or complement to nuclear density testing. Hence, the reliability of the generated data is vital to the successful implementation of this device.

CHAPTER 3
ENHANCEMENTS TO THE SSG TESTING PROCEDURE

SPRING CALIBRATOR DEVICE

Concept

Since the FDOT envisions using numerous devices in the field, it was felt that some type of calibrator could be designed to periodically check their operational status. Hence, a very stiff spring with a 5.5” outer diameter and a spring stiffness (*k)* of 4000 lb/in was used to develop the prototype system. The spring was compressed between two steel plates (10”x 10” and 0.5” thick) using four bolts at the corners of the plates. A groove was cut in the top plate to fasten the SSG foot ring during the tests. A photograph of the device is shown in Figure 11. The concept was to compress the spring to various stiffness values and note the resulting SSG output.

Figure 11. Spring Calibrator

Initial Tests

A series of tests were conducted using 1000, 4000 and 8000 lb. spring preload force to simulate three different stiffness values.

Initially, the spring was preloaded to 1000 lb. The SSG's foot ring was then locked in the groove on the top plate using a friction bolt and four SSG tests were performed. Next, a series of tests were conducted using four SSG devices (FDOT's three and UF's one), with the spring preloaded to 4000 lb. For the 8000 lb. preload tests, two SSG devices were used for comparison.

Test Results – 1000 lb. Preload Results Using University of Florida's SSG Device

For the four repetitive tests, the SSG stiffness values (average) ranged from 13.9-14.2 MN/m with the corresponding standard deviations, for the entire frequency range (100-196 Hz), ranging from 15.05-15.45 MN/m. A possible explanation for the extremely large S.D. ranges is provided in the Conclusions section.

However, if the high S.D. input frequencies are truncated (outliers removed), the S.D. values for the four tests ranged from 0.06-1.57 MN/m (using 23 frequencies out of 25). A very interesting point was observed in the data - the mean of the lowest and highest stiffness values was very close to the SSG recorded stiffness value. Table 6 and Figure 12 present the test results.

Table 6. SSG Results with 1000 lb. Preload Spring Calibrator

		Test # 1	Test # 2	Test # 3	Test # 4
1	Highest SSG value @ 152 Hz.	51.83	51.46	50.9	50.6
2	Lowest SSG value @ 116 Hz.	-23.52	-23.68	-23.4	-22.7
3	Average of (1 & 2)	14.15	13.89	13.76	13.98
4	SSG value – readout from unit	14.20	14.20	14.0	13.9

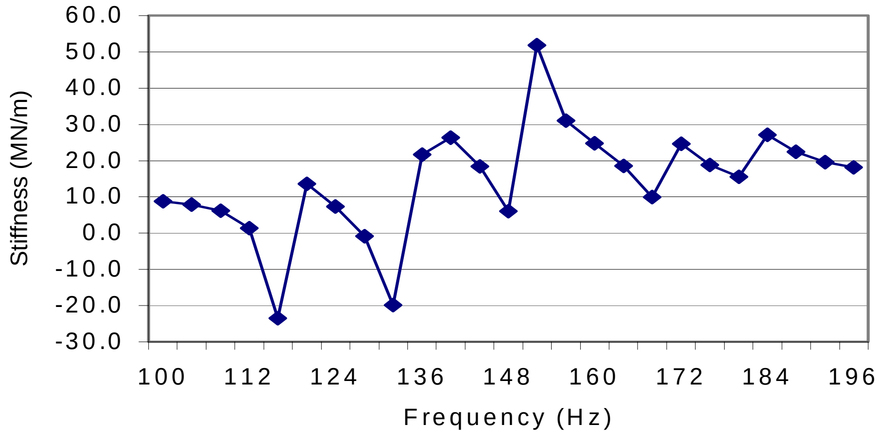


Figure 12. Typical Stiffness vs. Frequency Preloaded to 1000 lb

Test Results - 4000 lb. Preload Results for the Four Different SSG Devices

The average SSG stiffness values of each test for the four devices were very close to one another; therefore, Test # 2 values were used for the frequency analysis in Tables 8 and 9. Test # 2 values obtained for the four devices were 23.1, 22.6, 22.7 and 22.5 MN/m respectively (Table 7). (Note: three tests were conducted per device to obtain the average values in Table 7). Figure 13 shows a typical stiffness versus frequency plot.

For the three tests conducted with each device:

1. The highest SSG stiffness value (23.1 MN/m) was recorded for FDOT's device (B-14).
2. The lowest stiffness value (22.5 MN/m) was recorded with UF's device (B-76).
3. The highest stiffness value, using the entire 25 frequencies (100-196 Hz), was found at 132 Hz input frequency with the FDOT's device (B-14) and at 164 Hz with the other three devices.
4. For the input frequency range 100-196 Hz, the highest S.D. (14.81 MN/m) was found with the FDOT's device (B- 61).
5. The lowest S.D was 7.56 MN/m with UF's device (B-76).

The stiffness values were then separated into three ranges depending on the regularity of the values. The difference between the highest and the lowest stiffness value in each range was arbitrarily limited to 6.0 MN/m for devices B- 61 and B-76. The values for the other two devices fluctuated too much for any discrete ranges to be identified. Therefore, the results of only two devices were classified into the ranges shown below. The corresponding stiffness and S.D. values for these three ranges are presented in Tables 8 and 9.

Table 7. Summary of SSG Test Results with 4000 lb. Preload Spring Calibrator

Device		Test 1	Test 2	Test 3
B-14	Average	22.90	23.10	22.40
	S.D.	9.36	9.46	10.18
B19	Average	22.30	22.60	22.40
	S.D.	12.94	13.86	13.69
B-61	Average	22.30	22.70	22.80
	S.D.	14.66	14.81	14.41
B-76	Average	22.40	22.50	22.40
	S.D.	7.50	7.56	7.64

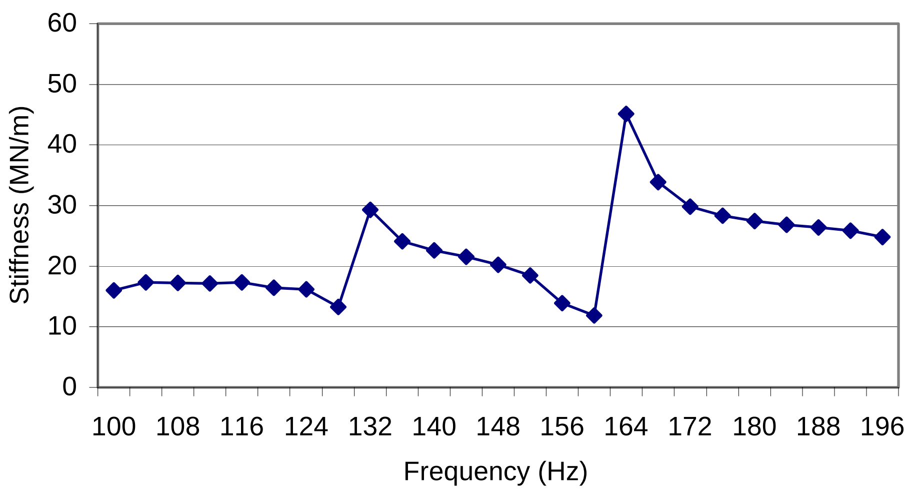


Figure 13. Stiffness vs. Frequency Plot with the Spring Calibrator Preloaded to 4000 lb

Table 8. SSG Results with 4000 lb. Preload Spring Calibrator

	Frequency (Hz)	Test # 2 Avg. (MN/m)		Difference	
		B- 61	B-76	MN/m	Percent
1	100 – 124	16.8	15.2	-1.6	10%
2	136 – 152	21.4	21.2	-0.2	1%
3	172 – 196	27.1	27.5	0.4	1%
Average (1-3)		21.8	21.3	-0.5	1%
Stiffness Reading (100-196)		22.7	22.5	-0.2	1%

Table 9. SSG Standard Deviations with 4000 lb. Preload Spring Calibrator

	Frequency (Hz)	Test #2 S.D. (MN/m)		Difference
		B- 61	B- 76	MN/m
1	100 – 124	1.3	0.6	0.7
2	136 - 152	2.4	2.2	0.2
3	172 - 196	1.5	1.6	0.1
S.D. Reading		14.8	7.6	7.2

Test Results - 8000 lb. Preload Results for the Two Different SSG Devices

The average SSG values for four tests run on each device were very close. Therefore, Test #1 values were used for the frequency analysis in Tables 10 and 11.

For the four tests conducted with each device:

1. UF's device, the average SSG stiffness value was 24.3 MN/m and the standard deviation for 100-196 Hz was 9.1 MN/m.
2. For the FDOT's device, the average SSG stiffness value was 25.4 MN/m with a S.D. of 14.3 MN/m (100-196 Hz).
3. For UF's device, the S.D. using all 25 input frequencies ranged from 0.01 - 0.59 MN/m.
4. For the FDOT's device, the S.D. using all 25 input frequencies ranged from 0.02-1.91 MN/m.

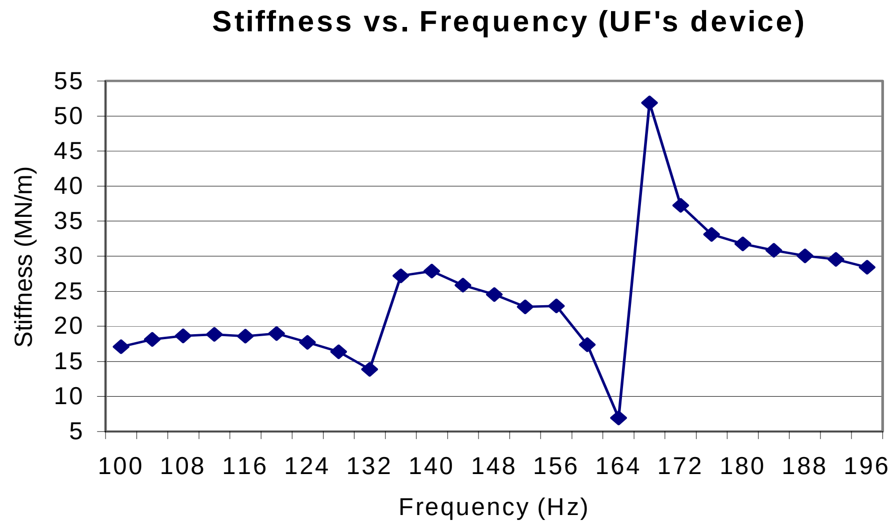
The stiffness values were again classified into three ranges depending on the consistency of the stiffness values. The corresponding stiffness and S.D. values for these three ranges are shown in Tables 10 and 11. Figure 14 presents typical stiffness – frequency plots for the UF and FDOT devices.

Table 10. SSG Results with 8000 lb. Preload Spring Calibrator

	Frequency (Hz)	**Test # 1 Average stiffness (MN/m)**		**Difference**	
		B-76	B-61	MN/m	Percent
1	100 – 128	18.0	20.5	2.4	13%
2	140 – 156	24.8	27.3	2.5	10%
3	176 – 196	30.6	35.8	5.1	17%
4	Average (1-3)	24.5	27.8	3.4	14%
5	Stiffness Readout	24.3	25.4	1.1	5%

Table 11. SSG Standard Deviations with 8000 lb. Preload Spring Calibrator

	Frequency (Hz)	**Test # 1 S.D. (MN/m)**		**Difference**
		B-76	B-61	MN/m
1	100 – 128	0.9	1.2	0.3
2	140 – 156	2.2	2.8	0.6
3	176 – 196	1.7	1.9	0.2
4	S.D. Readout	9.1	14.3	5.2



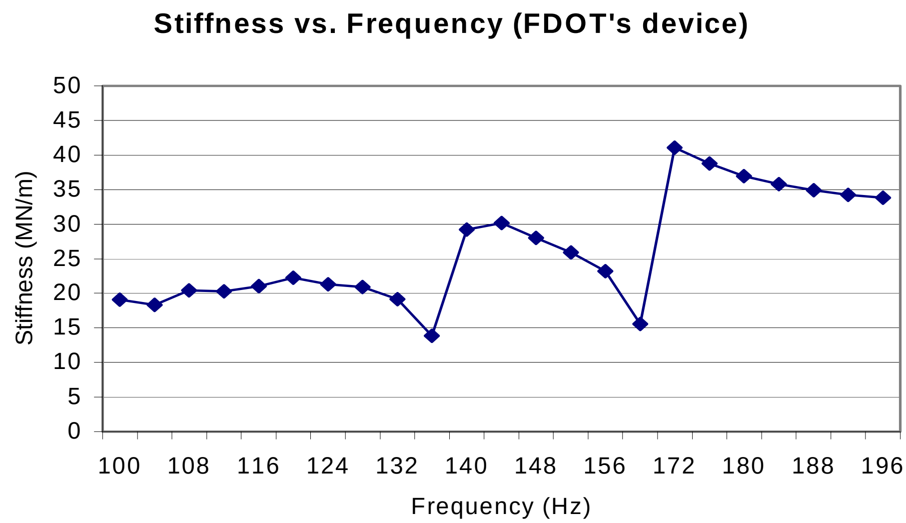


Figure 14. Typical Stiffness vs. Frequency Plots with Spring Calibrator Preloaded to 8000 lb

Conclusions

1. The purpose of developing the spring calibrator was to calibrate various SSGs by comparing the stiffness value of the spring with the SSG value measured for that particular spring preload. The stiffness value of the spring (0.70 MN/m or 4000 lb/in) was known. However, the SSG value for the tests performed with the spring calibrator (14.0 – 25.0 MN/m) was higher than the spring's original stiffness value. This deviation from the original value was most probably caused by the calibrator's assembly. The SSG was placed on the top horizontal steel plate that in turn was supported on the spring using four threaded rods. Thus, the SSG stiffness value also depended on the stiffness value of the top plate and the friction between the rods and the plate in addition to the stiffness value of the spring. Hence, it was impossible to ascertain the actual stiffness of the calibrator due to the interaction of the various components. A new calibrator incorporating cables to preload the spring is envisioned and will be constructed.
2. For the tests performed, the SSG values with each device were similar. These stiffness values indicated the repeatability of the SSG device. Hence the calibrator can be a valuable tool in verifying the variability among units.

A summary of the test results is presented in Table 12.

Table 12. Summary of Spring Calibrator Test Results

SSG ID#		Test 1	Test 2	Test 3	Test 4	Mean	S.D.	COV
1000 lb Preload								
B – 76	Average	14.20	14.20	14.00	13.90	14.08	0.15	1.1%
	S.D.1	15.41	15.05	15.15	15.45			
4000 lb Preload								
B – 14	Average	22.90	23.10	22.40	-	22.80	0.36	1.6%
	S.D.1	9.40	9.50	10.20	-			
B – 19	Average	22.30	22.60	22.40	-	22.43	0.15	0.7%
	S.D.1	12.90	13.90	13.70	-			
B – 61	Average	22.30	22.70	22.80	-	22.60	0.26	1.2%
	S.D.1	14.70	14.80	14.40	-			
B – 76	Average	22.40	22.40	22.40	-	22.40	0.00	0.0%
	S.D.1	7.50	7.60	7.60	-			
Overall average		22.48	22.7	22.5		22.56	0.12	0.5%
8000 lb Preload								
B – 61	Average	25.40	25.40	25.30	25.20	25.33	0.10	0.4%
	S.D.1	14.30	14.40	14.70	14.80			
B - 76	Average	24.30	24.30	24.40	24.40	24.35	0.06	0.2%
	S.D.1	9.10	9.00	8.90	8.80			
Overall average		24.85	24.85	24.85	24.80	24.84	0.02	0.1%

Note: S.D. - Standard Deviation of stiffness values for different tests with the same device.
S.D.1 – Standard Deviation of stiffness values between 100-196 Hz for a single test.

LIGHTWEIGHT CALIBRATOR DEVICE

Concept

As mentioned, the current calibrator could not measure the spring's true stiffness value required for an absolute stiffness calibration. Moreover, it is very heavy. Therefore, a different type of calibrator was envisioned that could remedy the two drawbacks. Aluminum was selected because of its lightweight property. A 0.19" thick aluminum plate was fixed between two circular pipes. A photograph of the device is shown in Figure 15.

Figure 15. Lightweight Aluminum Calibrator

The assembly of the unit resembled fixed end beam conditions. The equation of stiffness of the plate is:

$$k = \frac{P}{\delta}$$

Where:
k = Stiffness, lbs/in
P = Load, lbs
δ = Deflection, inches

The force required to deflect the plate by one inch was calculated using plate bending theory. The solution of the formulas provided the plate stiffness value. The results of the calculations are shown in Table 13.

Formulas used for the stiffness value calculation:

$$k = \frac{400 * \pi * E * T^3}{273 * A}$$

$$A = R^2 - R_1^{\,2} - B$$

$$B = 2 * R_1^{\,2} * \log \frac{R}{R_1}$$

Where:
k = Stiffness (lbs/in)
E = Modulus of Elasticity
T = Thickness (in inches) of the plate
A, B = Variables
R = Outer radius of the ring (in.)
R_1 = Inner radius of the ring (in.)

Table 13. Aluminum Plate's Theoretical Stiffness Values for Different Plate Thickness and Radii

R (in)	R^2 (in^2)	R_1 (in)	$R_1^{\,2}$	$2R_1^{\,2}$	$\frac{R}{R_1}$	$\log\frac{R}{R_1}$	B (in^2)	A (in^2)	T (in)	T^3 (in^3)	Defl.	k (lb/in)	k (MN/m)
2.59	6.7	2	4	8	1.30	0.26	2.07	0.64	0.25	0.02	1	112,320.04	19.67
2.59	6.7	2	4	8	1.30	0.26	2.07	0.64	0.19	0.01	1	47,385.02	8.30

SSG Tests Performed with the Aluminum Calibrator Placed on a Concrete Floor

1. Four tests were conducted. The results are summarized as follows:
   - For the 0.19" (3/16") thick plate, the average of two SSG test values was 13.2 MN/m.
   - For the 0.25" thick plate, the average of two SSG test values was 12.0 MN/m.

The average stiffness values and their standard deviations are summarized in Table 14.

2. The stiffness values were separated into two ranges depending on the regularity of the values. The difference between the highest and the lowest stiffness value in each range was arbitrarily limited to 1.0 MN/m. The corresponding stiffness and S.D. values for these two ranges are shown in Table 15 and Table 16. In Table 16, the stiffness values for the 100-144 range did not meet the difference limitation of 1 MN/m, therefore, the range of 108-144 was used.

Typical Stiffness vs. frequency values and plots of the lightweight calibrator tests are shown in Table 17 and Figure 16 respectively.

Table 14. Test Results with Lightweight Calibrator

		Stiffness (MN/m)	
		0.19" Plate	**0.25" Plate**
Test # 1	Average	13.1	11.9
	S.D.	1.9	1.5
Test # 2	Average	13.3	12.0
	S.D.	2.0	1.6

Table 15. Tests Performed with the 0.19” Plate

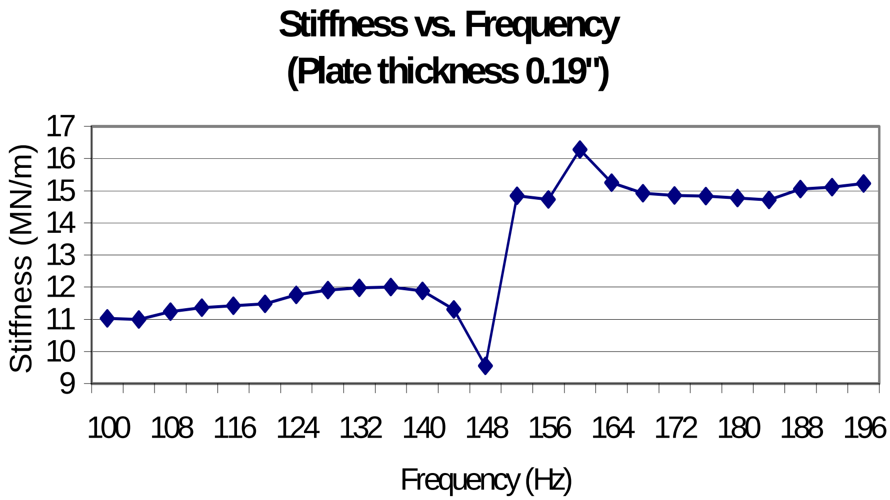
No.	**Frequency (Hz)**	**Stiffness MN/m**	**S.D. MN/m**
1	100 – 144	11.53	0.37
2	152 – 196	15.05	0.43
3	Average of 1 & 2	13.29	0.40
4	Average (100-196)	13.10	1.95

Table 16. Tests Performed with the 0.25” Plate

No.	**Frequency (Hz)**	**Stiffness MN/m**	**S.D. MN/m**
1	108 – 144	11.12	0.31
2	152 – 196	13.13	0.19
3	Average of 1 & 2	12.12	0.25
4	Average (100-196)	11.90	1.49

Table 17. Stiffness Values for Tests Performed with Different Plate Thicknesses

No.	**Frequency (Hz)**	**Stiffness (MN/m)**	
		0.19" Plate	**0.25" Plate**
1	100	11.0	7.0
2	104	11.0	10.1
3	108	11.2	10.6
4	112	11.4	10.9
5	116	11.4	11.0
6	120	11.5	11.0
7	124	11.8	11.1
8	128	11.9	11.1
9	132	12.0	11.2
10	136	12.0	11.2
11	140	11.9	11.2
12	144	11.3	11.9
13	148	9.6	11.4
14	152	14.8	13.4
15	156	14.7	13.1
16	160	16.3	12.9
17	164	15.3	13.0
18	168	14.9	13.0
19	172	14.8	13.0
20	176	14.8	13.0
21	180	14.8	13.1
22	184	14.7	13.2
23	188	15.1	13.2
24	192	15.1	13.4
25	196	15.2	13.5
Average		**13.1**	**11.9**
S.D.		1.9	1.5



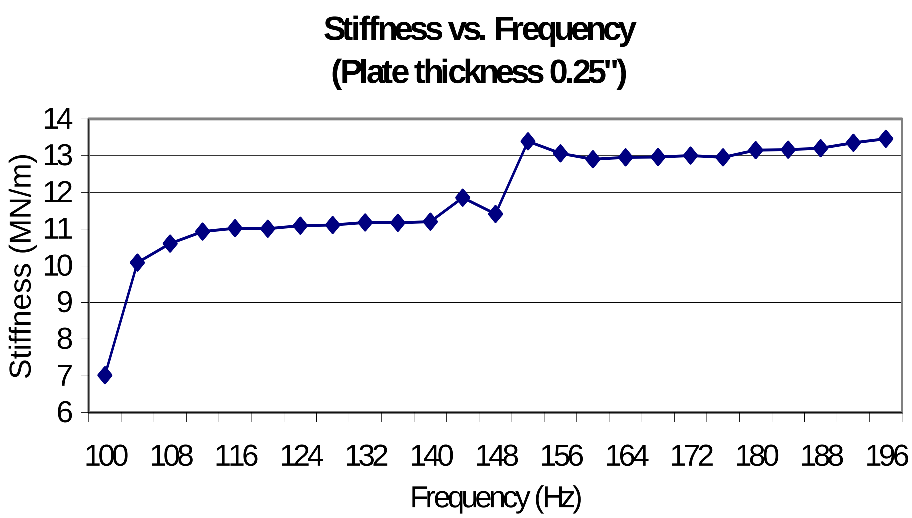


Figure 16. Typical Stiffness vs. Frequency Plots with the Aluminum Calibrator and Different Plate Thicknesses

SSG Test Results With the Lightweight Calibrator Placed on a Concrete Pad

Since simply placing the calibrator on a concrete surface did not appear to provide the proper coupling, a series of tests were performed to quantify this effect. A total of three SSG tests were performed on a large concrete pad, two with the calibrator, and one without. The 19” plate was used in the calibrator. Initially, the calibrator was placed on the concrete pad and a SSG test was performed. Then the calibrator was attached to the concrete pad using epoxy and the test repeated. The final test was performed by setting the SSG directly on the concrete pad. A photograph of the calibrator attached to the concrete pad using epoxy is shown in Figure 17.

Figure 17. Lightweight Calibrator Attached to a Solid Concrete Pad Using Epoxy

Test Results (Summarized in Table 18):

- When the calibrator was not attached to the concrete, the SSG stiffness value was 13.9 MN/m and the standard deviation of stiffness values for the 100-196 Hz range was 0.7 MN/m.
- When the calibrator was attached using the epoxy, the SSG stiffness value was 25.0 MN/m and the standard deviation of stiffness values for 100-196 Hz was 2.95 MN/m.

- Without the calibrator, the SSG stiffness value was 27.7 MN/m and the standard deviation of stiffness values for 100-196 Hz was 3.05 MN/m.

Note: These results are referenced in Table 19 and Figure 18.

Table 18. SSG Stiffness and S.D. Values for Tests Performed with the Lightweight Calibrator

Description of tests	Stiffness (MN/m)	S.D. (MN/m)
SSG placed on calibrator, setting on concrete pad	13.90	0.75
SSG placed on calibrator attached to concrete pad using epoxy	25.00	2.95
SSG placed on concrete pad (calibrator not used)	27.70	3.05

Table 19. Stiffness Values for the SSG Input Frequency Range

Frequency (Hz)	Stiffness (MN/m)		
	With calibrator (Epoxy not used)	With calibrator (Epoxy used)	Without calibrator
100	13.23	20.82	22.70
104	13.23	21.21	23.12
108	12.98	21.40	23.28
112	12.78	21.21	23.99
116	13.00	22.07	24.24
120	13.25	22.19	24.54
124	13.15	22.64	25.31
128	13.29	22.96	25.71
132	13.47	23.24	26.23
136	13.62	23.53	26.91
140	13.80	24.30	27.32
144	13.96	23.53	27.92
148	14.08	22.67	28.36
152	14.06	24.94	28.70
156	13.28	27.55	31.31
160	15.81	27.32	27.04
164	14.89	27.33	28.38
168	14.76	27.46	29.36
172	14.69	28.23	29.95
176	14.67	28.41	30.59
180	14.62	28.67	31.53
184	14.32	29.20	31.89
188	14.28	27.70	32.08
192	13.85	28.47	30.88
196	13.49	28.83	31.71
Average	13.90	25.00	27.70
S.D.	0.75	2.95	3.05

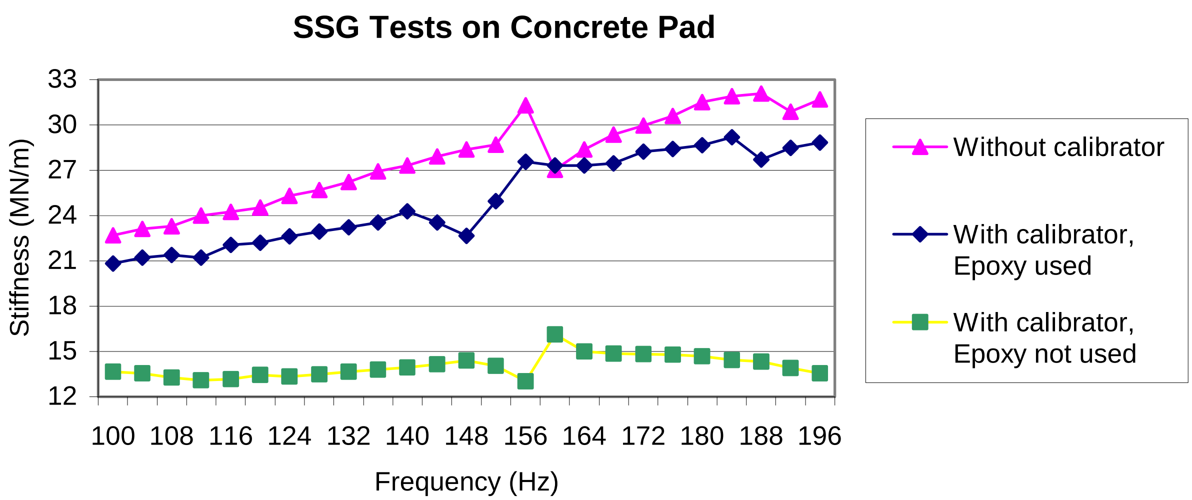


Figure 18. Stiffness vs. Frequency Plots for the Tests Performed on the Lightweight Calibrator on Concrete Pad

Conclusions

The purpose of developing the aluminum calibrator was to calibrate the SSG via a lightweight calibrator by comparing the stiffness value of the assembly with the SSG measured stiffness value. The stiffness value of the assembly was calculated as 8.3 and 19.67 MN/m for 0.19” and 0.25” plate thickness respectively. However, the SSG stiffness values (11.0 – 25.0 MN/m) for the tests performed with the lightweight calibrator did not resemble the assembly’s calculated stiffness value. It seems that the SSG stiffness value depended on the base material below the calibrator. The results suggested that the SSG input frequencies transferred to the base material below the assembly and the SSG stiffness value more closely resembled the stiffness value of the material below the assembly. As seen in Figure 18, tests run with the calibrator, using epoxy, closely resembled the direct test results on the concrete pad. Therefore, this confirms the fact that the transfer of energy from the SSG’s foot ring to the soil is critical if accurate and consistent values are to be achieved.

Evaluation of Sand as a Medium to Improve the SSG-Soil Interface and the Effect of SSG Inclination

Wet Sand

Test Description and Program

A series of tests were conducted at the FDOT test pit facility to determine the effect of wet sand as a coupling material and SSG inclination under controlled conditions. The test pit was filled with homogenous, compacted material (A-2-4, 24% fines).

The SSG was placed directly on the soil at the first test location. Seating of the SSG was achieved by applying two 90-degree rotations. The 10° inclination from vertical was achieved by applying vertical downward force after rotating the device. Six measurements were taken at this location, one after the other, without lifting the device for either the 0° or 10° inclinations. The SSG was only contacted to press the measurement button. This procedure was repeated at five other locations in the test pit. The SSG was inclined at 10° for two test locations and at 0° for four additional test locations.

After conducting these tests, a layer of 0.25” wet sand was placed at each of the six locations and the testing procedure was repeated.

Test Results

The following results represent measurements taken at one test location. These results (Table 20 and Figure 19) were randomly selected only to show an example of the effect of wet sand and inclination on the stiffness values.

Table 20. Results of SSG Test Using Wet Sand as an Interface with a 0° and 10° Inclination

Test #	Stiffness (MN/m)			
	No Sand		Wet Sand	
	0° Inclination	10° Inclination	0° Inclination	10° Inclination
1	7.13	6.97	7.5_	7.58
2	7.16	7.16	7.81	7.72
3	7.18	7.16	7.66	7.70
4	7.16	7.16	7.72	7.67
5	7.17	7.22	7.84	7.79
6	7.15	7.15	7.81	7.43
Average	7.16	7.12	7.78	7.65
S.D.	0.07	0.08	0.14	0.13
C.O.V	0.48%	1.16%	0.77%	1.57%

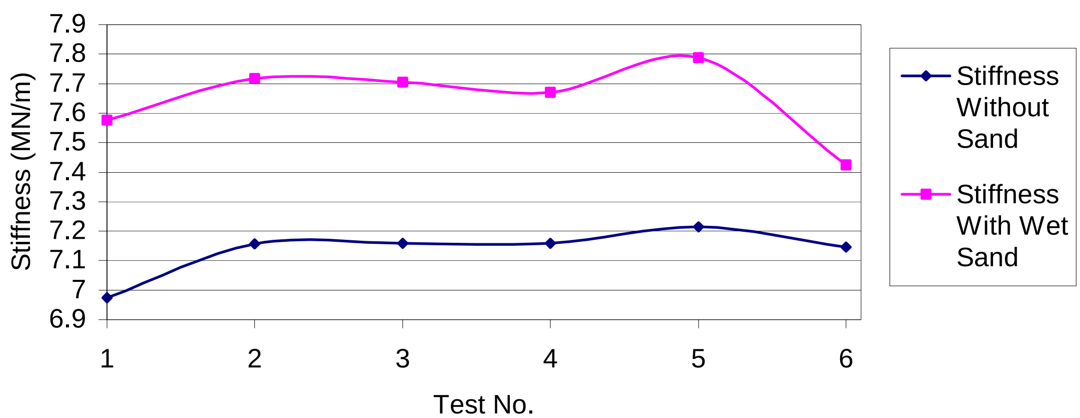


Figure 19. Plot of SSG Stiffness With and Without Wet Sand Interface (10° Inclination)

Dry Sand

Test Description and Program

A series of tests were conducted on 09.22.00 at the FDOT testing facility to determine the effect of dry sand as a coupling material under controlled conditions. Tests were performed in two test pits filled with homogenous, compacted material. One test pit was filled with A-2-4, 12% fines and the other with A-2-4, 30% fines.

The SSG was placed directly on the soil at the first test location in the test pit filled with the 12% fine material. Seating of the SSG was achieved by applying a 90-degree rotation twice (similar to the wet sand tests). Six measurements were taken at this location, one after the other, without lifting the device. This procedure was repeated at four other locations in the same test pit and at one location in the other test pit (30% fines). The device remained vertical during testing.

After conducting these tests, a 0.25” thick layer of dry sand was placed at each of the six locations and the testing procedure repeated.

Test Results

The following results represent measurements taken at one test location. These results were randomly selected only to illustrate the effect of dry sand on stiffness values. Table 21 and Figure 20 present representative values for the tests results.

Table 21. Results of SSG Tests With and Without Dry Sand as Coupling Material

Test #	**Stiffness (MN/m)**	
	Without Sand	With Sand
1	9.361	8.373
2	9.425	8.441
3	9.431	8.479
4	9.423	8.488
5	9.428	8.504
6	9.451	8.538
Average	9.420	8.471
S.D.	0.031	0.057
C.O.V.	0.32%	0.68%

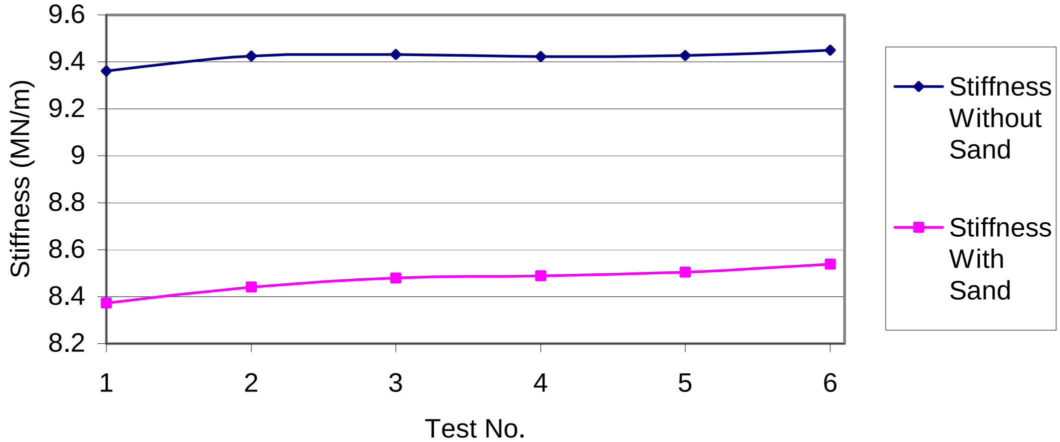


Figure 20. Plot of SSG Stiffness With and Without the Dry Sand Coupling Material

Lifting and Replacing the SSG on a layer of Dry Sand

Test Description and Program

A series of tests were conducted at the FDOT testing facility to determine the effect of lifting and replacing the SSG under controlled conditions. The tests were performed with and without the use of dry sand as a coupling material. Tests were performed in two test pits filled with compacted material (A-2-4, 12% fines and A-2-4, 30% fines).

The SSG was placed directly on the 12% fines soil. Seating of the SSG was achieved by applying a 90-degree rotation twice. Six measurements were taken at this location, one after the other, lifting and replacing the device after each test. This procedure was then repeated on the 30% fines material.

After conducting these tests, a 0.25" thick layer of dry sand was placed at each of the two locations and the procedure repeated.

Test Results

The following results (Table 22 and Figure 21) represent measurements taken at one test location in the test pit filled with A-2-4, 12% fines. These results were randomly selected only to show an example of the effect of lifting and replacing the device on stiffness values.

Table 22. Results of SSG Tests with and without Dry Sand as a Coupling Material

Test	**Stiffness (MN/m)**	
	Without Sand	With Sand
1	8.65	9.73
2	8.78	10.28
3	8.43	10.39
4	8.92	10.37
5	8.84	10.20
6	8.81	10.27
Avg.	8.74	10.21
S.D.	0.18	0.24
C.O.V.	2.01%	2.40%

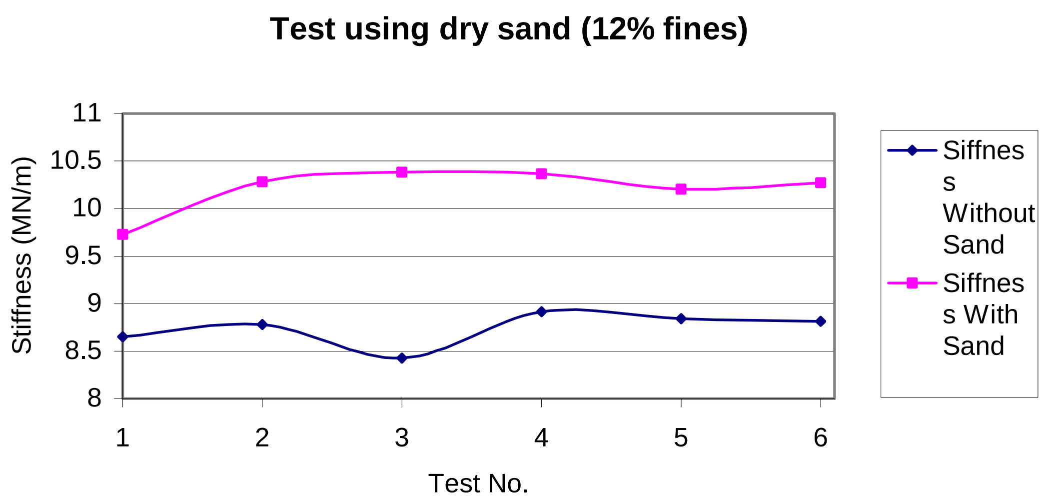


Figure 21. Plot of SSG Stiffness With and Without the Dry Sand Coupling Material

Results and Summary

The inclination effects on the coefficient of variation were slightly larger when tests were performed with instrument inclination (10 degrees) compared to tests with the instrument in a vertical position. The test results for the A-2-4, 24% fines material are: 1.57 % (inclined) versus 0.77 % (vertical) for the wet sand tests, and 1.16 % (inclined) versus 0.48 % (vertical) without sand.

SSG inclinations increased the average stiffness value for the wet sand tests compared to the stiffness values without sand. This was found in 4 out of the 6 tests performed. In addition, the inclination of the instrument increases the variability of the stiffness values. In the vertical position, the average stiffness value was higher without sand compared to those performed with sand. (5 out of the 6 tests performed). In addition, the sand affected the variability of the stiffness values. The coefficient of variation was higher in 11 out of the 14 sand tests compared to tests performed without sand. The C.O.V. increased approximately 5.52 % with the addition of sand.

When the tests were performed at the same location by lifting the instrument and placing it back in the same location each time, the C.O. V. increased from 0.48 % without lifting to 6.11% for the lift and replace tests.

A summary of the test results is presented in Table 23 below.

Table 23. Summary of SSG Tests Using Sand as a Coupling Material

Test No.	C.O.V.		Average Stiffness			Test description
	Without Sand	With Sand	Without Sand	With Sand	Difference	
A-2-4, 24% fines						
1	1.06%	1.68%	7.14	7.65	6.70%	SSG inclination 10
2	0.76%	1.96%	10.10	11.38	11.24%	SSG lift and replace
3	1.15%	0.87%	12.22	14.96	18.33%	SSG lift and replace
4	2.01%	2.07%	12.95	9.37	27.67%	SSG inclination 10
5	1.28%	2.02%	14.54	11.14	23.39%	SSG lift and replace
6	0.70%	0.79%	9.97	12.54	20.51%	SSG lift and replace
A-2-4, 12% fines						
7	0.32%	0.68%	9.42	8.47	10.07%	SSG not lifted
8	0.18%	0.49%	9.82	10.26	4.30%	SSG not lifted
9	0.52%	0.72%	10.81	10.27	5.01%	SSG not lifted
10	0.66%	0.61%	9.67	9.52	1.54%	SSG not lifted
11	0.73%	1.35%	12.85	12.00	6.67%	SSG not lifted
12	2.01%	2.40%	8.74	10.21	14.38%	SSG lift and replace
A-2-4, 30% fines						
13	2.05%	0.66%	12.24	9.99	18.35%	SSG not lifted
14	6.04%	9.82%	9.97	10.66	6.47%	SSG lift and replace

Note: Tests 1-6: Wet sand. Tests 7-14: Dry sand.

Use of Sandpaper as a Medium to Improve the SSG – Soil Interface

As the SSG test results using sand as a coupling material did not indicate any clear, positive effect on the results, the research team initiated a study with another material to improve the contact area at the SSG-soil interface. The idea of using sand as a coupling material is to fill the inconsistencies between the soil and the foot ring. In this study, however, sandpaper was used to increase the surface roughness and hence contact area between the foot ring and soil.

Tests were performed in the FDOT test pits. Two types of sandpaper were used (fine and coarse). These tests were performed without moving (i.e., lift and replace) the device after each test. Due to time constraints and availability, we were unable to perform these tests directly on A-2-4 material, therefore, all the tests were performed over a 5" layer of limerock base.

Test Pit Procedure for the SSG Tests Performed Without Sandpaper

A series of tests were conducted at a single location in the test pit filled with compacted A-2-4, 20% fines material. A 5" thick layer of limerock was then placed and compacted on the A-2-4 material. The SSG was placed on the limerock base and five tests were conducted without lifting the device. Typical stiffness values for the input frequency range 100-196 Hz are given in Table 24 while a more detailed summary is presented in Table 26.

Test Pit Procedure Using Sandpaper (Fine and Coarse)

A series of tests were conducted at a single location (on limerock base) in the 20 % fines test pit to determine the effect of sandpaper on the stiffness results. A 6", circular piece of adhesive backed fine sandpaper was placed on the limerock base and 5 tests were conducted without moving the device (i.e. lifting and replacing).

Five more tests were then performed in the same manner at the same location using coarse sandpaper. Typical stiffness values for the input frequency range 100-196 Hz are given in the Table 25, with a more detailed summary provided in Table 27.

A typical stiffness vs. frequency graph for the tests with coarse sandpaper on the limerock base is shown in Figure 23. Figure 22 shows the graph for the test without sandpaper.

Table 24. Stiffness Values Without Sandpaper (Limerock Base)

Frequency (Hz)	**Stiffness (MN/m)**
100	11.6
104	11.9
108	11.9
112	12.1
116	12.0
120	12.3
124	12.9
128	13.1
132	13.3
136	13.7
140	13.8
144	14.0
148	14.0
152	14.3
156	14.5
160	14.7
164	14.6
168	14.4
172	14.7
176	14.7
180	14.7
184	14.6
188	14.4
192	14.5
196	14.4
Average	13.6

Note: Shaded areas are frequencies of interest.

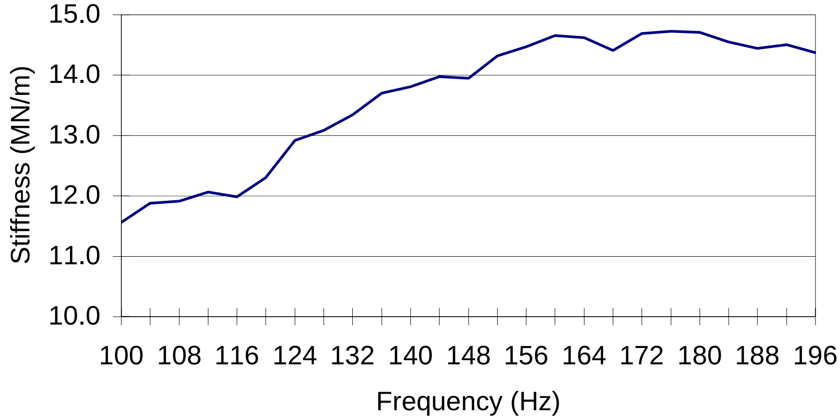


Figure 22. Typical Stiffness vs. Frequency Plot for Tests Without Sandpaper

Table 25. Typical Stiffness Values Using Coarse Sandpaper (Limerock Base)

Frequency (Hz)	Stiffness (MN/m)
100	4.8
104	5.2
108	5.2
112	5.3
116	5.4
120	5.6
124	5.8
128	5.8
132	5.9
136	6.1
140	6.2
144	6.1
148	6.2
152	6.2
156	6.2
160	6.2
164	6.3
168	6.2
172	6.3
176	6.3
180	6.4
184	6.4
188	6.4
192	6.5
196	6.5
Average	6.0

Note: Shaded areas are frequencies of interest.

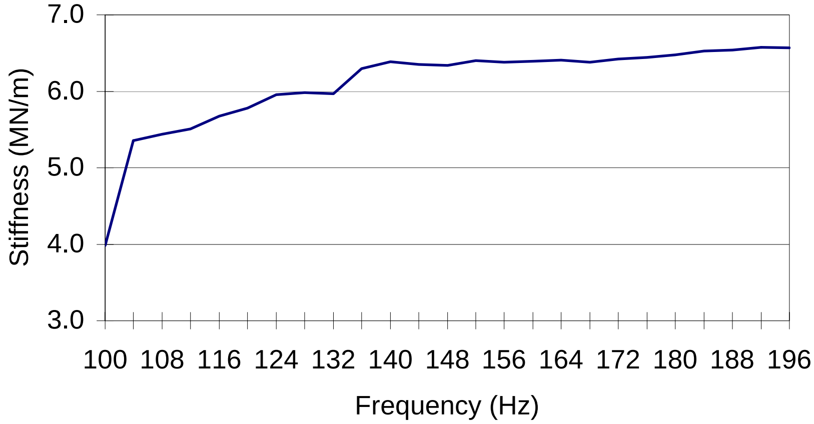


Figure 23. Typical Stiffness vs. Frequency Plot Using Coarse Sandpaper

Table 26. Tests Without Sandpaper

Test No.		**Limerock base on A-2-4 20% fines**		
		100-140 Hz	144-196 Hz	Readout
1	Stiffness	12.6	14.50	13.64
	S.D.	0.80	0.25	1.09
2	Stiffness	12.6	14.50	13.67
	S.D.	0.83	0.20	1.07
3	Stiffness	12.7	14.40	13.66
	S.D.	0.90	0.26	1.09
4	Stiffness	12.7	14.50	13.68
	S.D.	0.75	0.24	1.06
5	Stiffness	12.80	14.50	13.74
	S.D.	0.77	0.25	1.03
Average	Stiffness	12.67	14.47	13.68
	S.D.	0.08	0.02	0.04

Table 27. Tests With Sandpaper (Limerock base on A-2-4 20% fines)

Test No.		Fine sandpaper			Coarse sandpaper		
		100-132 Hz	138-196 Hz	Readout	100-132 Hz	138-196 Hz	Readout
1	Stiffness	5.88	7.24	6.75	5.44	6.28	5.97
	S.D.	1.32	0.06	1.01	0.36	0.11	0.47
2	Stiffness	5.94	7.58	6.99	5.52	6.43	6.10
	S.D.	1.59	0.03	1.22	0.62	0.08	0.58
3	Stiffness	5.98	7.84	7.17	5.54	6.48	6.14
	S.D.	1.70	0.05	1.34	0.67	0.08	0.60
4	Stiffness	6.11	8.00	7.32	5.53	6.56	6.19
	S.D.	1.69	0.06	1.35	0.86	0.06	0.71
5	Stiffness	6.20	8.13	7.44	5.51	6.62	6.22
	S.D.	1.65	0.06	1.34	0.99	0.06	0.79
Average	Stiffness	6.02	7.76	7.13	5.51	6.47	6.12
	S.D.	0.13	0.36	0.27	0.04	0.13	0.10

Summary of the SSG Tests Performed with Sandpaper

For all the tests performed on the limerock base, the average stiffness value was 6-8 MN/m higher without the sandpaper compared with sandpaper (both coarse and fine).

In addition, the standard deviation with sandpaper was 0.36-1.70 MN/m in the frequency range of 100-132 Hz and an average stiffness of 5.4-6.2 MN/m.

However, the standard deviation decreased to 0.03-0.11 MN/m for the 136-196 Hz range, with an increased average stiffness of 6.3-8.1 MN/m.

Hence, if the stiffness values for the 100-132 Hz test range are not used in the average stiffness calculation, then the stiffness values for all other remaining frequencies is very consistent for an individual test.

As all these tests were performed on a thin limerock base overlaying the A-2-4 subbase material, a recommendation on frequency data truncation cannot yet be made at this time, as additional research is still required. In addition, a question arises as to what soil is actually being tested, since the bulb of influence extends into the subbase material

USE OF PINS ON SSG FOOT RING TO IMPROVE THE SSG – SOIL INTERFACE

Analysis of the sandpaper tests suggested a decrease in standard deviation of the SSG values when coarse sandpaper was used. It was assumed that the increase in the soil-foot ring contact area produced this improvement. However, it was felt that a better alternative to sandpaper as a coupling device be researched. Four 4.5 mm long, pointed pins were attached to the foot ring to provide a better coupling with the soil and increase the total amount of contact area. A sketch of the foot ring with four pins attached is shown in Figure 24.

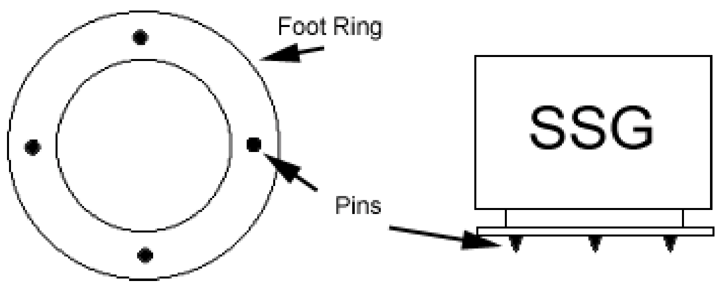


Figure 24. SSG Foot Ring With Four Pins Attached

A series of tests were conducted to determine the effect of the pins. Initially, four pins were attached and twelve tests conducted in the test pit. Four additional pins were then added and six tests performed. Fourteen non-pin tests were run to compare the results.

Pins Attached to the Foot Ring

Test pit 3 was filled with a compacted A-2-4, 12% fines material. A 5" layer of limerock was then added. Six tests were performed with the four pins attached. The initial three tests on the limerock base were performed without lifting the device. Three additional tests were then conducted at the same location, with the SSG lifted and reset after each test.

Test pit 4 contained the 30% fines material with the 5" thick layer of limerock. Six tests were conducted in the same manner as above. Three without lifting the device, while the other three, the device was lifted and replaced.

Four more pins were then attached to the foot ring, making eight pins total. Six tests were then repeated in test pit 3 using the same procedure as above.

Tests Method When No Pins Were Attached to the Foot Ring

To compare the "with" and "without" pins results, seven tests were conducted in test pit 3 (A-2-4, 12% fines). The SSG was placed on the limerock base and three non-lift tests were conducted. Four additional tests were then run at the same location, with the SSG lifted and reset after each test.

Seven tests were conducted in the same manner as above in test pit 4 (A-2-4, 30% fines). Results of tests performed with pins attached to the foot ring are summarized in Table 28 and 29. Table 30 shows the results of tests conducted without pins.

Table 28. Comparison Between SSG Test Results With Different Number of Pins Attached (A-2-4, 12% fines)

Test No.	**Stiffness (MN/m)**			
	4 pins		**8 pins**	
	Without Lifting	Lifting	Without Lifting	Lifting
1	9.73	9.34	10.48	10.79
2	10.34	9.07	11.18	11.55
3	10.41	9.70	11.41	9.98
Average	10.16	9.37	11.02	10.77

Table 29. Comparison Between Stiffness Values for the Tests in Different Materials With Four Pins

Test No.	**Stiffness (MN/m)**			
	12% fines		**30% fines**	
	Without Lifting	Lifting	Without Lifting	Lifting
1	9.73	9.34	8.65	9.03
2	10.34	9.07	9.14	9.65
3	10.41	9.70	9.39	8.01
Average	10.16	9.37	9.06	8.90

Table 30. Comparison of SSG Test Results in Different Test Materials Without Pins

Test No.	**Stiffness (MN/m)**			
	12% fines		**30% fines**	
	Without Lifting	Lifting	Without Lifting	Lifting
1	15.01	15.90	14.04	14.62
2	15.61	15.40	14.90	14.65
3	15.85	16.21	15.13	13.14
Average	15.49	15.86	14.69	13.99

Summary of Tests Conducted With and Without Pins

For the 18 tests performed with the pins attached to the foot ring, the average measured stiffness values was higher when the device was not disturbed compared to the tests when the device was lifted and reset in the same location. For these two conditions, the difference between averages was not significant (0.2-0.8 MN/m). The stiffness values were higher with 8 pins compared to 4 pins. (See Table 28)

The SSG averages were higher with no pins attached to the foot ring. There was an average difference of 4.5 MN/m for tests without pins compared to tests with pins. These tests suggest that the attachment of pins to the foot ring adversely affected the stiffness readings. The pins could not adequately penetrate the soil due to the limerock's hard surface, and hence the contact area of the foot ring and soil was probably less than the manufacturer's recommended 60% contact area. Therefore, the trend of stiffness values for different input frequencies was not considered. As expected, the average stiffness value was higher when the contact area of the foot ring with the soil was increased. Effective coupling is paramount if the device is to be used on aggregate base surfaces.

When tests were performed at the same location without lifting the device, the measured average stiffness value increased with successive tests. Nevertheless, when the device was lifted and reset at the same testing location, the measured stiffness value varied randomly for successive tests.

Again, as noted elsewhere, for the seven tests without pins, the individual test results' standard deviation was greater (0.77-2.43 MN/m) when lifting and replacing the device, compared to the non-lifting technique. This suggests that a S.O.P. might include "seating" multiple tests prior to recording the values.

The standard deviation for tests conducted in test pit 4 (30% fines) was 1.08-1.2 MN/m, and in test pit 3 (12% fines) was 2.04-2.12MN/m. These results represent the SSG tests without pins and non-lifting and replacing. It is possible that as the % fines increase, the soil/foot contact area may also increase. One explanation is the fact that since finer grained soils have increased surface area to volume ratios, the foot is thus in contact with a larger number of soil particles, creating increased energy transfer efficiency.

DEVELOPMENT OF THE "ROTATION HANDLE"

Concept

Initial test results suggested that test variability depended on the surface preparation and how the operator places the device on the soil. Acting on this hypothesis, an effort was made to develop an alternative handle for the SSG device to minimize preloading the soil. The SSG manufacturers have suggested that the SSG should be rotated 90 degrees back and forth using "minimal" to approximately 15 pounds force (depending on the soil type) to make the contact area between the foot ring and soil greater than 60% of the foot ring surface area. Generally, the SSG's self-weight is sufficient to act as the minimal force (since the weight of the device is 22 lbs) to provide adequate contact. However, the vertical force may not be consistent and may depend on each individual operator. This is easy to vary since the current handle allows for a substantial vertical force to be applied while seating the device. While working with the SSG, it was felt that the current handle might produce some of the variability due to inconsistent placement of the device among different operators. The current handle appears to be primarily designed to lift the device rather than to facilitate rotation. A handle was designed that can be lifted easily and rotated consistently as well. Thus, the purpose of designing a new handle was to provide a consistent process to seat the SSG onto the soil.

The initial handle was made from two separate pieces of aluminum, each made of approximately two-six inch pieces clamped together. Two pieces were clamped to add flexibility while operating. The handle was made so that it could be folded and unfolded when necessary. A photograph of the handle is shown in Figure 25.

Figure 25. Alternative Design of the SSG Handle

Field Tests

A series of tests were conducted on a 12 inch stabilized subgrade, minimum LBR of 30, at a construction site located at the University of Florida to observe the effect of the recently developed handle. It was a 1000-foot two-lane road construction site with each lane 16 feet wide. The material was compacted to 98% of AASHTO T-180. The site passed final acceptance at the time of the tests. On a single lane, three locations were chosen 10 feet apart lengthwise. At each location, three tests were conducted, each using a different method of testing (refer to Table 31 for testing procedures). Test number 2, at each location, was performed with the handle mentioned above, while the remaining tests were performed using the standard handle.

Table 31. Test Results With New Handle

No.	Description	Stiffness (MN/m)				S.D.	C.O.V.
		Location 1	Location 2	Location 3	Average	MN/m	
1	SSG not rotated before tests, Initial test (standard handle)	7.5	8.6	8.1	8.1	0.6	7%
2	SSG rotated 90 degrees back and forth with no vertical force (new handle)	10.8	10.3	10.7	10.6	0.3	3%
3	SSG rotated 90 degrees back and forth with vertical force before tests (standard handle)	11.3	7.3	9.5	9.4	2.0	21%
Average		9.8	8.5	9.1	9.1		

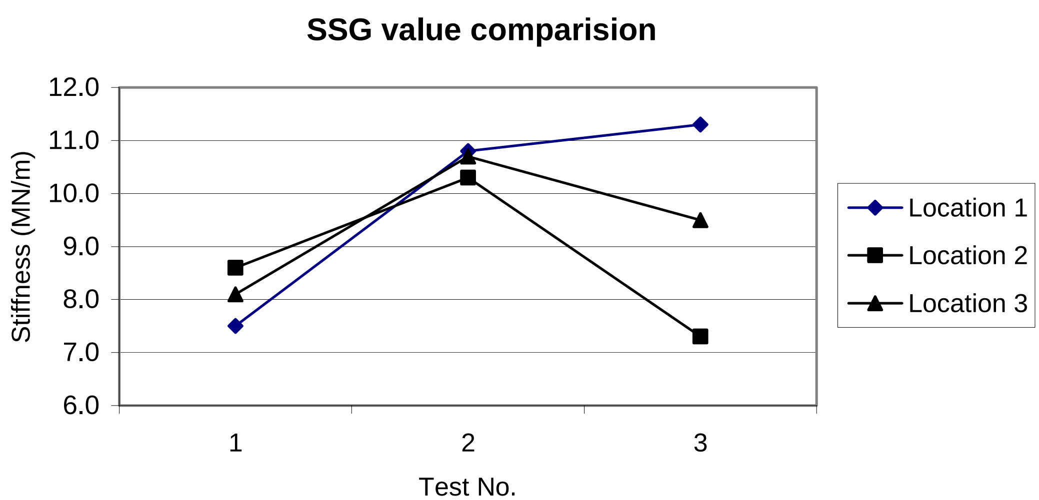


Figure 26. Field Test Results Using New Handle

Summary of Test Results

The standard deviation of the test results at three different locations was the lowest (0.3 MN/m) when the SSG was seated on the soil by rotating it with self-weight vertical force alone. The stiffness values varied significantly at the same location containing uniform compacted material when different seating procedures were used. Thus, the test results reinforce previous conclusions that the variability of SSG stiffness depends on testing procedure and operator influences.

Based on these tests, it was concluded that a handle, which prohibits vertical force, was an important addition to the device's operational efficiency. An improved version of the handle used in these tests has been developed that is more compact and user friendly. This handle will be used in future research efforts. An AutoCAD rendering of the improved handle is provided in Figure 27.

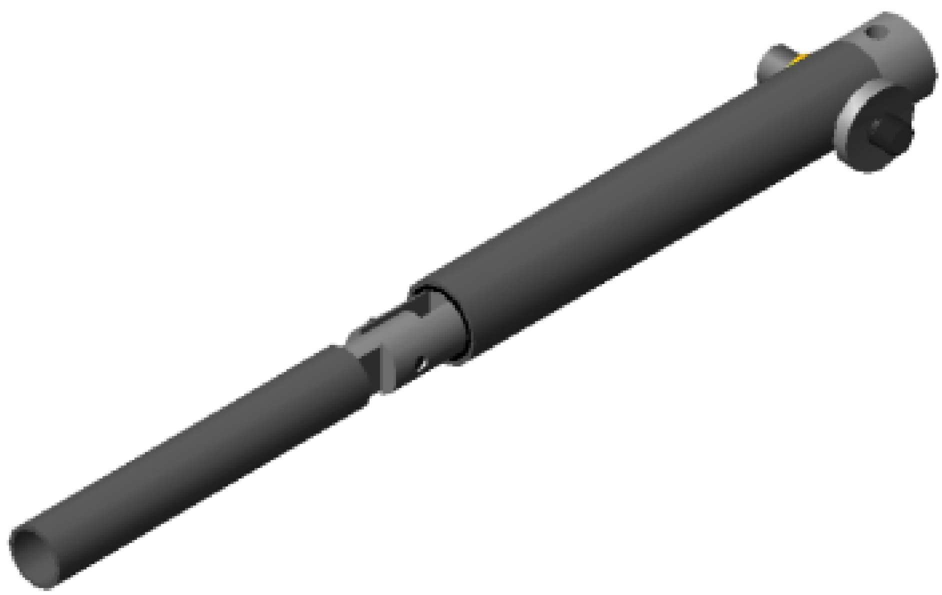


Figure 27. Improved SSG Handle

CHAPTER 4
STATISTICAL ACCEPTANCE METHOD FOR PAVEMENT EARTHWORK CONSTRUCTION

DEVELOPMENT OF A STATISTICAL ACCEPTANCE METHOD (SAM) FOR EARTHWORK COMPACTION

Introduction

Generally, the development process involves the following steps:

1. Determine the controlling quality property
2. Select the method of test
3. Define acceptable limits
4. Identify reasonable risk
5. Design a sampling plan
6. Determine procedures for rejected lots
7. Define contractor QC responsibility
8. Convert process to specification language
9. Review for practicality

Moving beyond the pass-fail test procedure to the use of a SAM procedure requires that more tests. Consequently, the efficiency of the test procedure becomes more critical. Therefore, much of the research effort in this initial project phase has been focused on developing the SSG as a potential testing method. However, a prerequisite to the use of any testing method is to fully understand the precision of the device.

Use of the SSG as a Test Method

With the SSG enhancements developed in this study, the precision of the SSG is now comparable to that of the nuclear density tests. The most recent tests indicate an average standard deviation of 0.3 MN/m (Table 31). Further testing is required, but the initial results have demonstrated the feasibility of using the SSG as a compaction-testing device.

The SSG’s features, such as ease of use and the ability to perform a large number of tests, suggest an attractive alternative or complement to nuclear density testing.

Since a mean and standard deviation of several SSG test results can be calculated, and the SSG itself provides an individual standard deviation value, based on the frequency sweeps, these values can be used to calculate the quality index. The quality index, in turn, can serve as a statistical acceptance measure. To implement a highway quality assurance program, the following definitions are used.

Quality Measures Definitions

Quality: (1) The degree or grade of a product or service. (2) The degree to which a product or service satisfies the needs of a specific customer. (3) The degree to which a product or service conforms to a given requirement.

Percent defective (PD): also called percent nonconforming. The percent of the lot falling outside specification limits. It may refer to either the application value or the sample estimate of the population value.

Percent within limits (PWL): also called percent conforming. The percentage of the lot falling above a lower specification limit, beneath an upper specification limit, or between upper and lower specification limits. It may refer to either the population value or the sample estimate of the population value. PWL = 100 – PD.

Acceptable quality level (AQL): that minimum level of actual quality that is considered fully acceptable as a process average for a single acceptance quality characteristic. For example, when quality is based on percent within limits (PWL), the AQL is that actual (not estimated) PWL at which the quality characteristic can just be considered fully acceptable.

Rejected quality levels (RQL): That maximum level of actual quality that is considered unacceptable (rejectable) as a process average for a single acceptance quality characteristic. For example, when quality is based on percent defective (PD), the RQL is that actual (not estimated) PD at which the quality characteristic can just be considered fully rejectable.

Acceptance number (c): In attributes acceptance plans, the maximum number of defective units in the sample that will permit acceptance of the inspected lot or branch.
Acceptance constant (k): The minimum allowable quality index (Q) for a variables acceptance procedure.
Quality index (Q): A statistic which, when used with appropriate tables, provides an estimate of either percent defective or percent within limits of a lot. It is typically computed from the mean and standard deviation of a set of test results.

Quality Assurance Elements

Quality assurance: All those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service. Quality assurance addresses the overall problem of obtaining the quality of a service, product or facility in the most efficient, economical, and satisfactory manner possible.
Quality control: Also called process control. These are quality assurance actions and considerations necessary to assess production and construction processes. The objective is to control the level of quality being produced in the end product. This concept of quality control includes sampling and testing to monitor the process but usually does not include acceptance sampling and testing.
Acceptance sampling and testing: Sampling, testing and the assessment of tests done to determine whether or not the quality of produced material or construction is acceptable in terms of the specifications.

Need for Additional Research

The most difficult and critical step in developing a quality acceptance method is in determining what quality levels will produce the desired long-term product performance. Generally, an acceptable quality level (AQL) and a rejection quality level (RQL) are established. Typical AQLs are in the range of 10 to 20 percent defective. In this application, defective means falling below the specified value.
The FDOT has a well-established testing history based upon nuclear densities. However, the SSG is providing stiffness, which is a different metric. The challenge is to confidently develop the relationship between the selected quality value (in this case

stiffness) and product performance. Additional directed testing is required to develop the performance – stiffness relationship so that acceptable and rejection limits can be set. The most efficient and timely method of developing the relationship between SSG values and embankment/pavement performance is with the FDOT's Heavy Vehicle Simulator. A research plan using the HVS has been proposed to provide the additional information needed to conclude development of the statistical acceptance procedure for embankment compaction.

CHAPTER 5
SUMMARY AND RECOMMENDATIONS

SUMMARY OF FINDINGS

The objective of this project was to begin the development of an improved testing and sampling methodology for the compaction of embankments. Currently soil density, primarily measured by the nuclear gauge, is the quality metric used to judge compaction acceptability. The desired engineering property is the soil stiffness (or soil modulus), when soil is compacted for pavements. The Soil Stiffness Gauge or SSG, which directly provides a stiffness value, may provide a more direct measure of soil acceptability. For this reason much of the research effort was focused on development of testing procedures using the SSG.

Initial activities were directed at understanding the relationship between soil density and soil stiffness. Initial field-testing of the SSG focused on defining the relationship between measured densities and stiffness values produced by the SSG. Soil densities were measured by nuclear density and stiffness values were obtained using the SSG. The results of numerous tests (68) were representative of the field test results obtained from various field locations. From the analysis of the initial test data, it is obvious that the SSG values and the densities were poorly correlated. That is to say, the SSG did not provide a reliable estimate of the density on the initial tests. (Page 12-22)

Moisture content is a very important factor in the highway design. A correlation was attempted between stiffness and moisture content. Analysis of the SSG tests performed in test pit suggested no correlation between the measured SSG values and the existing moisture conditions with an R^2 value of 0.06. (Page 23)

A comparison between Plate Load Tests (PLT) conducted in FDOT's Test Pit facility with corresponding SSG stiffness values was performed. The data contained results of eight Plate Load Tests in five different soil types. The SSG stiffness values were also included in the supplied data. Correlations were attempted between static plate load moduli (Secant or Young's Modulus) and average dry density, static plate load moduli and percent fines, and static plate load moduli and average SSG stiffness. An effort was also attempted to determine if a correlation exists between percent fines and SSG stiffness (measure before and after the Plate Load Test). Based on the limited data, no definitive correlation between the various factors (i.e. percent fines, dry density, average SSG stiffness, moisture content and static plate load moduli) could be concluded. (Page 23-28, Appendix B)

Since, the variability of the nuclear density measurements was reasonably well established from a long history of field-testing, the precision of the SSG test results was suspected as a cause of weak correlation. Therefore, the research team made considerable effort in the design of testing enhancements.

The preliminary tests had indicated that repeatability and precision of the SSG device appeared to be largely dependent upon the condition existing at the soil – machine interface. Significant factors appeared to be:

- The condition of the soil surface.
- Placement and operation of the device by the operator.

Acting on the hypothesis that the precision of the SSG could be enhanced with improved consistency of the above factors, the research team initiated a series of tests to develop an improved SSG testing procedure. The SSG’s features such as, ease of use and the ability to perform a large number of tests (critical for statistical verification), might lead to an attractive alternative or complement to nuclear density testing. Hence, the reliability of the generated data was vital to the successful implementation of this device.

A series of tests were conducted to study the effect of soil surface condition and the placement of the device.

According to the SSG manufacturers, it is suggested that moist sand should be used to increase the contact area at soil-machine interface, depending on the soil type. The research team performed tests using sand between the soil-foot ring interface. In addition, the effect of SSG inclination was studied. The results suggested that the average stiffness coefficient of variation was slightly greater when tests were performed with instrument inclination at 10 degrees compared to tests performed with the instrument in a vertical position.

Thus, the inclination of the instrument did adversely affect the consistency of the stiffness value. The results suggested that plumb-ness of the unit should be verified prior to testing. A bubble level was purchased and should be attached to the unit to verify the inclination prior to testing. In addition, both wet and dry sand affected the variability of the stiffness values. The coefficient of variation of stiffness was higher in 11 out of the 14 runs performed with wet and dry sand compared to no sand. These results did not support manufacturer's recommendation (Table 23). (Page 48-54)

The effect of placement (setup) of the unit on output variability was examined by conducting tests where the device was lifted and replaced between each reading. Results were recorded before and after replacing the device. The variability of the stiffness value increased significantly from 0.48 % without lifting the device to 6.11% with lifting and replacing. These test results led to a series of tests, the results of which supported the primary results (Table 23). (Page 54)

As the SSG test results with sand did not indicate any clear positive effect on the results, the research team initiated a study to determine another option to improve the SSG-soil interface. Since the concept of using sand to fill the minute gaps between the soil and ring foot was proposed, sandpaper was tried to increase the surface roughness and hence contact area between the foot ring and soil. (Page 55-60)

Analysis of the sandpaper tests suggested a decrease in the standard deviation of the SSG values when coarse sandpaper was used. It seems that the increase in the soil-foot ring contact area caused this improvement. However, the test results were skewed when compared to SSG values without sandpaper. The dissimilarity between the two materials (sandpaper and the ring foot) might have caused the difference. Efforts were made to continue further tests using a material that would be consistent with that of the SSG's foot ring. Hence 4.5 mm long pointed pins were attached to the foot ring to provide a better grasp and contact area with the soil.

A series of tests were then conducted at the FDOT testing facility to determine the effect of these pins. Initially four pins were attached to the foot ring and four more pins were added later. Fourteen tests were also conducted when no pins were attached, to compare the results. (Page 61-65)

Averages of the measured stiffness values were higher when eight pins were attached compared to the tests with four pins. However, the average values were higher with no pins. It was concluded from these tests that the attachment of pins to the foot ring did not improve the test results. Specifically, in a limerock base, the pins could not penetrate into the material. For this scenario, the primary contact with the soil was on the pins rather than the foot ring.

Due to the sensitivity of the SSG instrument to various factors cited previously, it was necessary to ensure that the device itself did not have any inherent systematic errors. In addition, with multiple devices in use, calibration of them was desirable before drawing any conclusions on the variability of the results. The calibration procedure adopted by the manufacturer is a pseudo calibration technique since the device is suspended in air and allowed to vibrate with no foot ring contact. The research team felt a need for the development of a portable device that would simulate a known resistance (stiffness) as well as be simple to use. Two portable calibrator devices were developed and several tests were performed to identify the possibility of their implementation.

The first incarnation utilized a stiff spring for the required reaction. The availability of a wide range of springs with different stiffness values (k) was the main reason for its use. The purpose of developing the spring calibrator was to calibrate various SSGs by comparing the stiffness value of the spring with the SSG value for that particular spring preload. The system was developed in such a way that the SSG could be placed on the top of a spring (using a steel plate) and operated – thereby measuring the spring's stiffness. The stiffness values of the spring ranged from 1.40MN/m (8000 lb/in), 0.70 MN/m (4000 lb/in), to 0.18 MN/m (1000 lb/in). However, when tested, the SSG stiffness values (14.0 – 25.0 MN/m) were higher than the spring's original stiffness value. The calibrator's assembly most probably caused this deviation from the original value. The

SSG was placed on the top horizontal steel plate and in turn was supported on the spring using four bolts. Thus, the SSG stiffness value also depended on the stiffness value of the top plate and the friction between the bolts and the plate. While there was a stiffness discrepancy between the calibrator and the SSG due to the interaction of the various components, the differences between test results from the same unit were very repeatable and hence useful from a relative viewpoint.

A series of tests were conducted with the calibrator using four (DOT's three and UF's one) devices, with the spring preloaded to 4000 lb. For the tests performed with the calibrator, the SSG values for each device were very similar. The standard deviation for each device ranged from 0 to 0.36 MN/m. These stiffness values indicated the repeatability of the SSG devices and the usefulness of using a calibrator on a regular basis for comparative purposes. (Table 12) (Page 30-38)

The SSG did not measure the spring's stiffness value, which would be a requirement for an absolute calibration procedure. Moreover, the spring calibrator is quite heavy. Therefore, a second type of calibrator was designed using aluminum as the flexural component. A 0.19" thick aluminum plate was fixed between two circular sections. The assembly resembled a fixed end beam condition. The weight required to deflect the plate by one inch was then calculated. The stiffness value of the assembly was calculated as 8.3 and 19.67 MN/m for 0.19" and 0.25" plate thicknesses respectively. (Page 38-47)

The SSG value for the tests performed with this calibrator (11.0 and 25.0 MN/m for the 0.19" and 0.25" plate thickness respectively) also did not produce the assembly's calculated stiffness value. It appears that the SSG stiffness value depended, to a large extent, on what type of material the calibrator was set on. The results indicated that the SSG input frequencies were transferred to the base material below the assembly and hence the SSG value was affected by this stiffness.

The most important of the design enhancements attempted by the research team was the development of a new handle. The SSG user guide suggests that the SSG should be rotated 90 degrees back and forth using minimal to approximately 15 pounds of vertical force (depending on soil type). The objective is to produce a contact area between the foot ring and soil of at least 60% of the total foot ring area. Generally, the SSG's self-weight is sufficient to act as the minimal force required to insure the above requirement. However, when different personnel operate the device, the vertical force may not be consistent – especially if inadvertent force is applied to the device through the existing, rigid handle. During the SSG research, it was felt that the current design of the handle might increase variability due to inconsistent placement of the device. The original handle appears to be primarily designed to lift the device rather than to facilitate rotation. Efforts were thus made to design a handle that can still be used to lift the device, but to rotate it consistently as well. Thus, the purpose of designing a new handle was to provide uniform seating of the SSG on the soil.

The initial design of handle was made of two separate pieces of aluminum, each made of two six-inch pieces clamped together. Tests were performed in the field to observe its effect. The standard deviation of the test results at three different locations was the lowest (0.3 MN/m) when the SSG was seated on the soil by twisting it with the newly developed handle. On the other hand, with the original handle, the stiffness values varied significantly when different placement techniques were used. Thus, the test results reinforced the previous conclusions that the variability of the stiffness value depended largely on how the unit is seated on the soil. (Page 66-68)

Finally, the stiffness vs. SSG input frequency trend was studied for most of the above tests. The stiffness value tends to increase as the frequency increases on a limerock base. Additional tests directly on a subbase (in controlled conditions) are warranted to observe stiffness vs. SSG input frequencies. Pending further research, it may be recommended that certain input frequency ranges be identified and truncated to reduce the variability in SSG readings. Also, the SSG results tend to increase with successive tests, when the device is not lifted after each test. For example, results of eleven tests on an A-2-4 material revealed that the measured stiffness for the first three measurements increased at a rate of 0.34 MN/m and 0.38 MN/m respectively and then remained approximately constant after that. There was a difference of 1.020 MN/m between the first stiffness measurement of 14.800 MN/m and the last measured value of 15.820 MN/m. Compared to the average value (15.564 MN/m) of the 11 recorded measurements this represented a 6.5% variation**.** The coefficient of variation was 2.05%, close to the value of 2% specified by Humboldt for fine-grained soils. (Page 15-16, Table 2)

The increment in the stiffness value tends to vary according to the testing conditions, test material and many other factors. Since the standard deviation and average of stiffness results can be easily calculated, they can be used to calculate quality indices. Once determined, this quality index could ultimately be used as a statistical acceptance measure. However, additional directed testing is required to develop the performance – stiffness relationship so that acceptable and rejection limits can be set.

RECOMMENDATIONS

With the SSG enhancements developed in this study, the precision of the SSG is now comparable to that of the nuclear density tests. The most recent tests indicate an average standard deviation of 0.3 MN/m. Further testing is required, but the initial results have demonstrated the feasibility of using the SSG as a compaction control testing device.

Additional testing is needed to establish sufficient data to develop statistical confidence with the use of the SSG for determining the acceptability of compacted soils for highway construction. Furthermore, development of statistical acceptance procedures involving the SSG requires a basic understanding of the relationship between the Quality Index determined from stiffness measurements and pavement performance. This long-term performance information is not yet available.

Therefore, the research team recommends continued testing with the SSG. More specifically, a testing program using the Heavy Vehicle Simulator (HVS) now on site at the FDOT Material Testing Facility is recommended. Testing should be accomplished using the two outdoor test pits. The testing plan should be designed to investigate the relationship between measured soil stiffness in the sub-base and base materials, the effects of moisture content and ultimate pavement performance.

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APPENDIX A

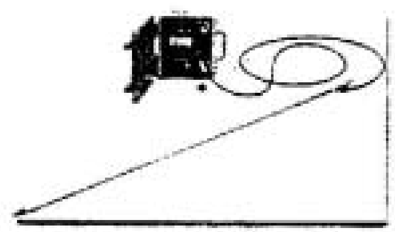
MOISTURE PROBE INFORMATION SHEETS

PLATE LOAD TEST AND SSG STIFFNESS DATA SUPPLIED BY THE FLORIDA DEPARTMENT OF TRANSPORTATION

MOISTURE·POINT

"Use the probes as stand-alone sensors, or incorporate them into multiplexed configurations for wide area monitoring networks."

Offering an unprecedented combination of portability, ease of operation, and high precision, Moisture·Point® is an award-winning, innovative system for measuring volumetric soil moisture.



With over four years of development and laboratory/field testing, Moisture·Point® is the ultimate moisture monitoring system offering its users the unique ability to monitor a vertical or horizontal soil moisture profile. Moisture·Point® is specifically designed with features for both general purpose and scientific use, and it provides an unparalleled degree of accuracy and resolution - with virtually no disturbance to existing soil horizons.

As a general purpose data gathering tool, Moisture·Point® is an effective, easy to use instrument. Installation is as simple as inserting a **profiling probe** into soil or other particulate substrates, connecting the probe to the data viewing/logging **instrument** (the MP-917, available from E.S.I. Environmental Sensors Inc.), and pressing the activation button.

Moisture·Point® can be used manually, as a stand alone monitoring tool,or incorporated into a large, wide area network for remote, unattended operation.

Through ESI's **MP-917 Instrument** and **View·Point** software, the Moisture·Point® system also enables direct or remote access to signal calibration and gain variables for scientific data gathering and analysis. In addition, users can directly monitor, capture and store both raw and processed waveforms using a personal computer.

Moisture·Point® Components and Software

System Components	Model #:
Single Diode Probe	SDP
Second Diode Assembly for SDP	SDA
Rugged Single Diode Probe	SDR
Rugged Single Diode Probe with Clip On 20cm Rods	SDR-CO20
Rugged Single Diode Probe with Clip On 30cm Rods	SDR-CO30
Additional 20cm Rods for SDR-CO20	SDR-RODCO20
Additional 30cm Rods for SDR-CO30	SDR-RODCO30
51cm Profiling Probe (1x30cm segment)	PRB-C
81.5cm Profiling Probe (4x15cm segments)	PRB-K
98.5cm Profiling Probe (5x15cm segments)	PRB-H
112cm Profiling Probe (1x30cm & 4x15cm segments)	PRB-F
142.5cm Profiling Probe (3x30cm & 2x15cm segments)	PRB-A
Display Instruments	
Display Instrument	MP-917
Software	
View·Point	MODEL

Please note that an equipment leasing option is available in the United States and Canada for ESI's instrumentation.

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MOISTURE·POINT TECHNOLOGY

Moisture·Point® offers accuracy within 3% in most soil conditions WITHOUT calibration.

Enhanced Time Domain Reflectometry

Originally developed to measure the dielectric constant of homogeneous materials, conventional Time Domain Reflectometry (TDR) techniques have been usefully applied to soil measurement by the agricultural and soil science community for many years.

TDR has many advantages over other methods of soil moisture measurement. It offers excellent spatial resolution and definition, the ability to measure close to the soil surface, and its signals can be multiplexed and directly post processed using computers. In addition, measurements of volumetric water content are substantially independent of soil type and salinity for most soil types.

Traditionally, there have also been some limitations that have affected the accuracy of TDR-based moisture measurement. However, through patented signal discrimination and processing techniques developed by E.S.I. Environmental Sensors Inc., Moisture·Point® instruments solve the signal-to-noise ratio, waveform detection and discrimination, signal quality validation and circuit stability problems inherent to TDR. The result is an advanced system, able to measure soil moisture with impressive accuracy across a broad spectrum of soils.

Competing Technologies

1. Frequency Domain Reflectometry (FDR)

FDR is based on a change in the frequency of an RF pulse due to changes in the dielectric constant (Capacitance) of a material. This technology works very well in homogeneous or bulk materials having a relatively constant granularity, or consistency (i.e., sand, wheat, and corn). The material itself can be calibrated to some standard, and in a well calibrated consistent medium the probe readings will be very accurate.

The main difficulty in using FDR systems for soil moisture is that the bulk material (naturally occurring soil) is not homogeneous. This condition requires the soil at the site to be carefully calibrated, for the specific location of interest, over the entire profile. This process involves gravimetric analysis of core samples from the probe insertion borehole, and several peripheral cores in the immediate area. In addition, the response of FDR is non-linear with changes in soil water content. This requires soil calibration at several different moisture contents to insure accuracy over the expected range of measurement. Such a process is both time consuming and expensive, and to insure accuracy it must be accomplished at every location.

The site calibration problem becomes even more complex for environmental remediation applications where the very process itself may significantly change site conductivity characteristic over time. It is possible that under some conditions, site recalibration may be required to maintain accuracy.

Additionally, FDR site calibrations are unique to the instrument and probe used. If a probe fails, or must be serviced during the course of a program, site recalibration will be required for the replacement probe to maintain accuracy.

2. Neutron Probe

A neutron probe is not measuring water content directly. It is measuring hydrogen atoms and these can be from any source, including bound water and hydrocarbons. The use of a neutron probe in environmental, or environmental remediation applications usually requires frequent site recalibration due to changes in the hydrogen provided by sources other than water. In addition, a neutron probe is not accurate within the top 15 cm. of the soil surface due to neutron loss from the region of influence into the atmosphere.

The user of a neutron probe usually requires special training, and a government license for transport, ownership and use of a radioactive source. The soil core from the probe borehole must be gravimetrically analyzed to establish a calibration reference curve to insure probe accuracy, and the site calibration curve is specific to a particular probe. Additionally, neutron probes "age" with use as the activity level of the source degrades. This "aging" of the probe requires periodic site recalibration to maintain accuracy.

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SSG's For Initial Plate Load Tests

Water Table at 24 inches below top of Embankment

24% -200

Test 1		112.5	6.30%
Stand.Dev.	Value	Stan.Dev	Value
Before		After	
1.23	14.89	1.25	17.21
1.14	13.24	1.69	13.72
1.31	14.11	1.33	15.38

Test 2		112.3	6.10%
Stan. Dev.	Value	Stan. Dev.	Value
Before		After	
1.35	11.62	1.17	11.46
1.28	12.74	1.2	13.36
1.47	14.19	1.34	14.68

20%-200

Test 1		115	4.50%
Stan. Dev.	Value	Stan.Dev.	Value
Before		After	
1.11	11.04	1.12	9.72
1.09	10.07	1.14	14.47
1.13	11.06	1.12	13.32

Test 2		114.8	4.10%
Stan. Dev.	Value	Stan. Dev.	Value
Before		After	
1.72	10.36	1.35	11.2
1.07	9.45	1.37	11.23
1.14	12.82	1.37	10.29

12% -200

Test 1		113.3	3.10%
Stan. Dev.	Value	Stan. Dev.	Value
Before		After	
1.72	11.75	1.27	9.08
1.67	10.52	1.43	9.41
1.68	11.88	1.92	9.8

Test 2		112	3.00%
Stan. Dev.	Value	Stan. Dev.	Value
Before		After	
1.19	9.3	1.24	10.14
1.14	8.54	1.54	11.53
1.24	11.22	1.22	8.91

30% -200

Test 1		116.9	8.00%
Stand.Dev.	Value	Stan.Dev	Value
Before		After	
1.7	12.61	1.32	14.28
1.16	11.51	2.48	13.85
1.57	12.89	1.08	12.46

Note: Only one plate test was ran

Miami Oolite (A-1-a)

Test 1		134	4.10%
Stand.Dev.	Value	Stan.Dev	Value
Before		After	
4.11	23.79	1.79	22.83
1.63	23.72	1.29	27.07
1.94	33.85	2.73	30.27

Note: Only one plate test was ran

Data 24%_1

Repeated Load Plate Test

Source :		Data tested : 7/27/2000	Dry Density : 112.5
Material : A-2-4 24% -200		Tested by : K. Hamm	Moisture : 6.30%
Pressure = 20 psi		Condition : WT 24" Below Top of Embankment	
Time Seq. = 1.0 sec cycles		Pit # : East	
Eer : 1.18 pr/(Resilient Deformation)		Location : 24%_1	

No. of Load Cycles	N. Tans Reading: Permanent (in)	N. Tans Reading: Total (in)	S. Trans Reading Permanent (in)	S. Trans Reading Total (in)	Average Deformation Permanent (in)	Average Deformation Total (in)	Resilient Deformation (in)	EQ Modulus Eer (psi)
1	0.0139	0.0238	0.0061	0.0138	0.0100	0.0188	0.0088	13620.3
50	0.0239	0.0316	0.0100	0.0179	0.1700	0.0248	0.0078	18140.2
100	0.0261	0.0338	0.0112	0.0191	0.0188	0.0265	0.0078	18140.2
200	0.0288	0.0365	0.0126	0.0205	0.0207	0.0286	0.0078	18140.2
500	0.0334	0.0410	0.0147	0.0226	0.0240	0.0318	0.0078	18140.2
1000	0.0369	0.0446	0.0161	0.0240	0.0265	0.0343	0.0078	18140.3
2000	0.0401	0.0473	0.0158	0.0237	0.0279	0.0355	0.0076	18676.3
5000	0.0425	0.0497	0.0164	0.0229	0.0294	0.0363	0.0069	20586.3
10000	0.0448	0.0502	0.0133	0.0211	0.0290	0.0357	0.0066	21400.0
15000	0.0457	0.0518	0.0139	0.0216	0.0298	0.0367	0.0069	20441.7
20000	0.0466	0.0526	0.0140	0.0214	0.0303	0.0370	0.0067	21179.3
25000	0.0474	0.0534	0.0140	0.0211	0.0307	0.0372	0.0065	21787.3
30000	0.0483	0.0542	0.0143	0.0207	0.0313	0.0375	0.0062	22890.1
								19330.9 Average

Note: cycles 4,5 10 & 25 were not used as problem with data acquisition occurred.

Data 24%_2

Repeated Load Plate Test

Source :		Date tested : 7/28/2009	Dry Density : 112.5
Material : A-2-4 24% -200		Tested by : K. Hamm	Moisture : 6.30%
Pressure = 20 psi		Condition : WT 24" Below Top of Embankment	
Time Seq. = 1.0 sec cycles		Pit # : East	
Eer : 1.18 psi(Resilient Deformation)		Location : 24%_2	

No. of Load Cycles	N. Tans Reading: Permanent (in)	N. Tans Reading: Total (in)	S. Trans Reading Permanent (in)	S. Trans Reading Total (in)	Average Deformation Permanent (in)	Average Deformation Total (in)	Resilient Deformation (in)	EQ Modulus Eer (psi)
1	0.0062	0.0072	0.0033	0.0096	0.0048	0.0084	0.0036	33432.7
4	0.0026	0.0084	0.0039	0.0094	0.0032	0.0089	0.0057	24962.3
5	0.0029	0.0085	0.0039	0.0099	0.0034	0.0089	0.0056	25520.3
10	0.0035	0.0093	0.0044	0.0116	0.0040	0.0096	0.0057	24960.5
25	0.0048	0.0124	0.0055	0.0124	0.0051	0.0120	0.0069	20492.6
50	0.0061	0.0137	0.0062	0.0133	0.0062	0.0131	0.0069	20492.6
100	0.0075	0.0152	0.0071	0.0142	0.0073	0.0142	0.0069	20465.2
200	0.0090	0.0164	0.0079	0.0156	0.0084	0.0153	0.0069	20595.3
500	0.0107	0.0185	0.0086	0.0157	0.0097	0.0170	0.0074	19155.1
1000	0.0118	0.0193	0.0088	0.0147	0.0103	0.0175	0.0072	19801.3
2000	0.0127	0.0202	0.0088	0.0151	0.0108	0.0177	0.0069	20441.8
5000	0.0143	0.0216	0.0078	0.0147	0.0111	0.0181	0.0071	20042.8
10000	0.0163	0.0236	0.0069	0.0136	0.0116	0.0186	0.0070	20290.2
15000	0.0179	0.0251	0.0061	0.0126	0.0120	0.0188	0.0069	20595.3
20000	0.0189	0.0259	0.0055	0.0120	0.0122	0.0190	0.0068	20909.8
25000	0.0199	0.0270	0.0054	0.0119	0.0127	0.0195	0.0068	20751.3
30000	0.0205	0.0281	0.0053	0.0117	0.0131	0.0198	0.0066	20699.0
							Average	21976.9
							Overall average	20653.9

Repeated Load Plate Test

Source :		Data tested : 8/1/2000	Dry Density 115
Material : A-2-4 24% -200		Tested by : R. Venick	Moisture 4.50%
Pressure = 20 psi		Condition : WT 24" Below Top of Embankment	
Time Seq = 1.0 sec cycles		Pit # : Middle	
Eer : 1.18 pr/(Resilient Deformation)		Location : 20%_1	

No. of Load Cycles	N. Tans Reading: Permanent (in)	Total (in)	S. Trans Reading Permanent (in)	Total (in)	Average Deformation Permanent (in)	Total (in)	Resilient Deformation (in)	EQ Modulus Eer (psi)
1	0.0076	0.0118	0.0031	0.0081	0.0053	0.01	0.0046	25874.9
4	0.0086	0.0132	0.0043	0.0096	0.0064	0.0114	0.0049	28632.7
5	0.0092	0.0137	0.0045	0.0099	0.0069	0.0118	0.0049	28632.7
10	0.0104	0.0149	0.0058	0.0112	0.0081	0.013	0.0049	28632.1
25	0.0123	0.0167	0.008	0.0138	0.0102	0.0153	0.0051	27762.1
50	0.0136	0.0182	0.0098	0.0153	0.0117	0.0168	0.0051	27950.9
100	0.0156	0.0212	0.0113	0.0179	0.0134	0.0195	0.0061	23148.1
200	0.0172	0.0226	0.0133	0.0192	0.0152	0.0209	0.0057	24677.3
500	0.0191	0.0249	0.0148	0.0208	0.017	0.0227	0.0057	24751.7
1000	0.0209	0.0261	0.0158	0.022	0.0183	0.024	0.0057	24751.7
2000	0.0224	0.0277	0.0173	0.0231	0.0198	0.0254	0.0056	25207.2
5000	0.0248	0.03	0.0199	0.0262	0.0224	0.0281	0.0057	24751.7
10000	0.0269	0.0319	0.0232	0.0293	0.025	0.0306	0.0056	25362.9
15000	0.0286	0.0337	0.0257	0.0318	0.0271	0.0327	0.0056	25362.9
20000	0.0302	0.0348	0.028	0.0337	0.0291	0.0342	0.0052	27483.5
25000	0.0317	0.0362	0.0297	0.0353	0.0307	0.0358	0.0051	27575.7
30000	0.0325	0.0371	0.0303	0.0358	0.0314	0.0365	0.0051	27575.8
								26386.7 Average

Data 20%_2

Repeated Load Plate Test

Source :		Date tested : 8/2/2000	Dry Density 115.3
Material : A-2-4 24% -200		Tested by : R. Venick	Moisture 4.20%
Pressure = 20 psi		Condition : WT 24" Below Top of Embankment	
Time Seq. = 1.0 sec cycles		Pit # : Middle	
Eer : 1.18 p/(Resilient Deformation)		Location : 20%_1	

No. of Load Cycles	N. Tans Reading Permanent (in)	N. Tans Reading Total (in)	S. Trans Reading Permanent (in)	S. Trans Reading Total (in)	Average Deformation Permanent (in)	Average Deformation Total (in)	Resilient Deformation (in)	EQ Modulus Eer (psi)
1	0.0052	0.0125	0.0071	0.0150	0.0062	0.0138	0.0076	15844.1
4	0.0074	0.0137	0.0097	0.0174	0.0085	0.0155	0.0070	20240.3
5	0.0079	0.0133	0.0101	0.0169	0.0090	0.0151	0.0061	23213.5
10	0.0095	0.0153	0.0114	0.0187	0.0104	0.0170	0.0066	21512.0
25	0.0121	0.0177	0.0138	0.0205	0.0128	0.0191	0.0063	22637.9
50	0.0145	0.0202	0.0149	0.0212	0.0147	0.0207	0.0060	23546.0
100	0.0172	0.0232	0.0164	0.0234	0.0168	0.0233	0.0065	21797.3
200	0.0199	0.0252	0.0182	0.0249	0.0191	0.0251	0.0060	23546.1
500	0.0229	0.0301	0.0204	0.0280	0.0217	0.0290	0.0074	19199.9
1000	0.0250	0.0319	0.0215	0.0289	0.0233	0.0304	0.0072	19753.7
2000	0.0270	0.0336	0.0227	0.0302	0.0249	0.0319	0.0071	20042.8
5000	0.0298	0.0360	0.0253	0.0327	0.0276	0.0343	0.0069	20596.4
10000	0.0326	0.0389	0.0282	0.0353	0.0304	0.0371	0.0067	21124.8
15000	0.0351	0.0414	0.0300	0.0369	0.0325	0.0391	0.0066	21399.9
20000	0.0372	0.0430	0.0314	0.0383	0.0343	0.0407	0.0063	22330.4
25000	0.0387	0.0448	0.0325	0.0363	0.0356	0.0420	0.0064	21972.1
30000	0.0402	0.0461	0.0336	0.0403	0.0368	0.0432	0.0064	22209.6
								21233.3 Average

23800.0 Overall average

Repeated Load Plate Test

Source	:	Date tested	8/4/2000	Dry Density:	112.0
Material	: A-2-4 12% -200	Tested by	: K. Hamm	Moisture :	3.0%
Pressure	= 20 psi	Condition	: WT 24' Below Top of Embankment		
Time Seq.	= 1.0 sec cycles	Pit #	: West		
Eer	: 1.18 pr/(Resilient Deformation)	Location	: 12%_2		

No. of Load Cycles	N. Trans Reading: Permanent (in)	N. Trans Reading: Total (in)	S. Trans Reading: Permanent (in)	S. Trans Reading: Total (in)	Average Deformation Permanent (in)	Average Deformation Total (in)	Resilient Deformation (in)	EQ Modulus Eer (psi)
1	0.0301	0.0393	0.0126	0.0226	0.0214	0.0309	0.0096	12589.6
25	0.0343	0.0418	0.0182	0.0277	0.0262	0.0348	0.0085	16834.8
50	0.0362	0.0435	0.0212	0.0308	0.0287	0.0372	0.0084	16770.6
100	0.0383	0.0457	0.0250	0.0342	0.0316	0.0399	0.0083	17013.6
200	0.0406	0.0480	0.0286	0.0375	0.0346	0.0427	0.0082	17373.3
500	0.0440	0.0513	0.0333	0.0415	0.0386	0.0464	0.0077	18301.9
1000	0.0467	0.0540	0.0370	0.0445	0.0419	0.0493	0.0074	19110.6
2000	0.0495	0.0569	0.0401	0.0476	0.0448	0.0522	0.0075	18978.2
5000	0.0535	0.0607	0.0447	0.0513	0.0491	0.0560	0.0069	20441.6
10000	0.0572	0.0642	0.0488	0.0554	0.0530	0.0598	0.0068	20751.3
15000	0.0596	0.0667	0.0518	0.0583	0.0557	0.0625	0.0068	20751.3
20000	0.0614	0.0686	0.0542	0.0603	0.0578	0.0644	0.0067	21288.9
25000	0.0629	0.0701	0.0561	0.0623	0.0595	0.0662	0.0067	21016.7
30000	0.0640	0.0712	0.0575	0.0634	0.0608	0.0673	0.0065	21882.1

Note: cycles 4,5, & 10 were not used as problem with data aquistion occurred

Repeated Load Plate Test

Source	:	Date tested:	7/6/2000	Dry Density:	134.0
Material	: Miami Oolite	Tested by :	K. Hamm	Moisture :	4.1%
Pressure	= 50psi	Condition :	WT 24" below Top of Embankment		
Time Seq.	= 1.0 sec cycles	Pit # :	North		
Eer	: 1.18 pr/(Resilient Deformation)	Location :	Oolite_1		

No. of Load Cycles	E. Trans Reading: Permanent (in)	E. Trans Reading: Total (in)	W. Trans Reading: Permanent (in)	W. Trans Reading: Total (in)	Average Deformation Permanent (in)	Average Deformation Total (in)	Resilient Deformation (in)	EQ Modulu Eer (psi)
1	0.0253	0.0335	0.0187	0.0231	0.0220	0.0283	0.0063	49400.5
4	0.0265	0.0346	0.0202	0.0240	0.0234	0.0293	0.0060	59385.7
5	0.0268	0.0359	0.0204	0.0248	0.0236	0.0304	0.0068	52416.9
10	0.0278	0.0376	0.0217	0.0266	0.0247	0.0321	0.0074	48120.5
25	0.0318	0.0416	0.0242	0.0300	0.0280	0.0358	0.0078	45358.5
50	0.0373	0.0468	0.0264	0.0300	0.0319	0.0384	0.0066	53930.4
100	0.0438	0.0540	0.0363	0.0395	0.0401	0.0468	0.0067	52685.9
200	0.0520	0.0620	0.0433	0.0469	0.0477	0.0545	0.0068	52018.9
500	0.0640	0.0730	0.0383	0.0473	0.0512	0.0601	0.0090	39438.3
1000	0.0722	0.0806	0.0435	0.0522	0.0579	0.0664	0.0085	41678.2
2000	0.0795	0.0865	0.0471	0.0553	0.0633	0.0709	0.0076	46487.1
5000	0.0869	0.0943	0.0495	0.0573	0.0682	0.0758	0.0076	46592.6
10000	0.0916	0.0991	0.0497	0.0573	0.0707	0.0782	0.0075	47344.1
15000	0.0949	0.1020	0.0491	0.0562	0.0720	0.0791	0.0071	49872.2
20000	0.0973	0.1037	0.0483	0.0551	0.0728	0.0794	0.0066	53508.7
25000	0.0992	0.1054	0.0477	0.0546	0.0735	0.0800	0.0065	54358.1
30000	0.1008	0.1064	0.0468	0.0535	0.0738	0.0799	0.0061	57879.8

Repeated Load Plate Test

Source :
Material : A-2-4 30% -200
Pressure = 20 psi
Time Seq. = 1.0 sec cycles
Eer : 1.18 pr/(Resilient Deformation)

Date tested: 7/5/2000
Tested by : K. Hamm
Condition : WT 24" Below Top of Embankment
Pit # : South
Location : 30%_1

Dry Density: 118.9
Moisture : 8.0%

No. of Load Cycles	N.. Trans Reading: Permanent (in)	N.. Trans Reading: Total (in)	S. Trans Reading: Permanent (in)	S. Trans Reading: Total (in)	Average Deformation Permanent (in)	Average Deformation Total (in)	Resilient Deformation (in)	EQ Modulus Eer (psi)
1	0.0216	0.0314	0.0148	0.0197	0.0182	0.0256	0.0074	16328.2
4	0.0257	0.0340	0.0168	0.0203	0.0213	0.0271	0.0059	24173.5
5	0.0261	0.0344	0.0171	0.0209	0.0216	0.0277	0.0060	23550.1
10	0.0275	0.0363	0.0182	0.0221	0.0229	0.0292	0.0063	22334.2
25	0.0307	0.0393	0.0208	0.0250	0.0258	0.0321	0.0064	22153.6
50	0.0334	0.0416	0.0237	0.0283	0.0285	0.0350	0.0064	21975.9
100	0.0357	0.0434	0.0277	0.0331	0.0317	0.0382	0.0065	21685.9
200	0.0379	0.0456	0.0325	0.0383	0.0352	0.0419	0.0067	21020.3
500	0.0406	0.0481	0.0381	0.0439	0.0394	0.0460	0.0066	21347.9
1000	0.0430	0.0501	0.0413	0.0473	0.0421	0.0487	0.0066	21403.5
2000	0.0448	0.0516	0.0439	0.0498	0.0443	0.0507	0.0063	22334.1
5000	0.0467	0.0534	0.0470	0.0526	0.0468	0.0530	0.0062	23022.3
10000	0.0474	0.0536	0.0493	0.0546	0.0483	0.0541	0.0058	24607.6
15000	0.0469	0.0530	0.0505	0.0558	0.0487	0.0544	0.0057	24905.9
20000	0.0458	0.0518	0.0522	0.0569	0.0490	0.0543	0.0053	26512.7
25000	0.0452	0.0512	0.0526	0.0574	0.0489	0.0543	0.0053	26512.7
30000	0.0452	0.0510	0.0534	0.0580	0.0493	0.0545	0.0053	26947.4