

The Humboldt Stiffness Gauge

A Field Instrument for Measuring Lift Stiffness & Soil Modulus

Small, Fast, Light-Weight & Reliable

DESCRIPTION

The Humboldt Stiffness Gauge (HSG) is a man-portable instrument that provides a simple, rapid and precise means of directly measuring lift stiffness and soil modulus (Fig. 1). It also provides an alternative means of measuring soil density.



The HSG is intended to meet a need that has existed since quality has been important to earthworks construction. This is the control of the construction process via the same

physical parameters that earthworks are designed with. For Example in highways:

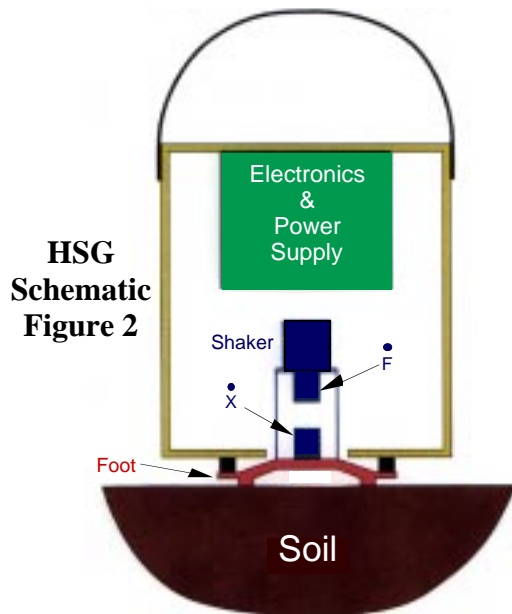
- Lift Stiffness is used to assure the uniform & effective transfer of loads from the pavement to the base & subgrade below and
- Soil Modulus is used to assure that each soil component allows the highway system to perform as needed.

The HSG measures the impedance at the surface of the soil. In other words, it measures the stress imparted to the surface and the resulting surface velocity as a function of time. Stiffness, force over deflection, follows directly from the impedance. The HSG imparts very small displacements to the soil ($< 1.27 \times 10^{-6}$ m or $< .00005$ "") at 25 steady state frequencies between 100 and 196 Hz. The stiffness is determined at each frequency and the average is displayed. The entire process takes about one minute. At these low frequencies, the impedance at the surface is stiffness controlled and is proportional to the shear modulus of the soil. If a Poisson's ratio is assumed and knowing the HSG's physical dimensions, shear and Young's modulus can be derived.

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The HSG weighs about 10 kg (~ 22 lb), is 28 cm (~ 11”) in diameter, 25.4 cm (~ 10”) tall and rests on the soil surface via a ring-shaped foot (Fig. 2). The foot bears directly on the soil and supports the weight of the HSG via several rubber isolators.

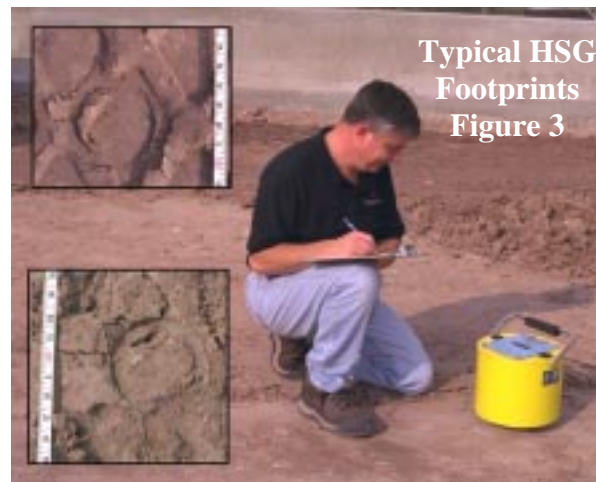


Also attached to the foot are the shaker that drives the foot and sensors that measure the force and displacement-time history of the foot. The connection between the shaker and force sensor is made via a rigid column.

The HSG is placed on the soil to make a measurement with little or no preparation of the soil surface. Typically, a slight push on or rotation of the HSG is needed obtain the required 60% minimum contact area between foot and soil (Fig. 3). On particularly hard or rough surfaces, seating of the foot can be assisted by the use of less than 1/4" of moist sand or local fines. Common field practice is as applicable to the HSG as it is to most current field measurement of soil performance. The

detailed procedure for using the HSG and preparing the soil is described in the HSG User Guide. The Guide is available from Humboldt (see Appendix).

The current version of the HSG displays and logs the data in memory with sufficient capacity for a full day of data gathering (100s of measurements). The data may be downloaded to a PC for archiving and further analysis. It is powered by 6 disposable D-cell batteries. Measurements can be performed as close to operating construction equipment as safety will allow.



Many current methods of measuring soil modulus or stiffness in the field require large forces to produce a measurable deflection. The HSG uses technology borrowed from the military to measure very small deflections, allowing much smaller loads. The HSG does not measure the deflection resulting from the HSG weight. Rather, the HSG vibrates, producing small changes in force that produce small deflections. The soil deflects an amount δ , which is proportional to the outside radius of the ring foot (R), the Young’s modulus (E), the shear modulus (G) and Poisson’s ratio

(ν) of the soil.¹ The stiffness is the ratio of the force to displacement: $K=P/\delta$. The HSG produces soil stress and strain levels common for pavement, bedding and foundation applications (192 Pa or ~ 4 psi). As shown below, Young's and shear modulus can be determined from HSG measurements if a Poisson's ratio is assumed.

$$P \sim \frac{1.77RE}{(1-\nu^2)} \delta \sim \frac{354RG}{(1-\nu)}$$

$$K = \frac{P}{\delta} \sim \frac{1.77RE}{(1-\nu^2)}$$

The HSG is calibrated via the force-to-displacement produced by moving a known mass.

$$\frac{F}{\delta} = M(j\omega)^2$$

The value of the mass is precisely known and is less susceptible to change than a reference elastomeric pad or soil sample would be. A mass is used of sufficient size to represent a typical range of soil stiffness (e.g. 10 kg (~ 22 lb) represents ~ 4 MN/m at 100 Hz and 16 MN/m at 200 Hz). The mass is rigidly bolted to the foot during calibration. The HSG, with the mass attached, is supported on a rigid structure by a very compliant fixture. The fixture is sufficiently compliant so that the mass is effectively unrestrained in the measurement frequency band. The bias of a HSG measurement, relative to the value of the moving mass, is less than 1% coefficient of variation.

¹ Poulos, H.G., and Davis, E.H., *Elastic Solutions For Soil & Rock Mechanics*, 1974, page 167-168.

The precision of a HSG measurement on fine-grained soils is less than ~ 2% coefficient of variation. On coarse-grained soils, the coefficient of variation is typically less than ~ 5 %. On crushed aggregate, the coefficient of variation can get as large as ~ 10 %.

APPLICATIONS

The HSG can be applied to any nature of earthworks construction in the following ways.

- *Mechanistic Design Validation:* Current cost cutting trends are motivating the development of analytical models for earthworks. Earthworks are typically designed with engineering and material properties such as stiffness and modulus. The HSG enables the rapid acquisition of a large volume of this data, sufficient to validate these models.
- *Performance Specification Development:* Performance specifications are intended to reduce such things as the conservative over compaction associated with current specified methods. The problem is insufficient field data to develop the specifications that are directly relevant to performance (e.g., stiffness & modulus). Again, the HSG enables the rapid acquisition of the needed data.
- *Construction Process Control:* How are contractors going to control performance variability to comply with specified performance and warranties? The HSG enables rapid, comprehensive and direct measurement of performance in real-time. It allows a contractor to monitor the uniformity of the product as it is being constructed and adjust the construction process before a problem occurs.
- *Alternative Density Measurement:* The current inspection of materials and structures usually involves the measurement of density. Conventional

methods are generally time consuming or require special licensing and training. The HSG provides a precise, rapid and license free alternative. In conjunction with a moisture measurement, density can be typically predicted from stiffness within 5% of a laboratory measurement.

- ***Forensic and Diagnostic Investigation:*** The settling of earthworks can cause significant problems. Likewise, non-uniform compaction can cause premature failures. A characteristic of these effects is non-uniform structural stiffness. The HSG can easily detect these non-uniformities, revealing significant voids, discontinuities or inclusions behind pipes, tunnels, roadways, slabs and foundations without disturbing the structure.
- ***Non-Destructive Testing:*** Virtually every current soil field measurement disturbs the soil in some way. This is a problem for the application of a growing number of soil additives or substitutes. Controlled Low Strength Materials, for example, require repeated measurements of performance at the same locations as the material cures. Since the HSG does not disturb the soil, it makes possible the fast repeated measurements at a single location.

ADVANTAGES & DISADVANTAGES

Reduced Construction Costs via Process Control

Compacted soil is an essential element of highway, airport, building, sewer and bridge construction. Soil density is used almost exclusively by the construction industry to specify, estimate, measure and control soil compaction. This practice was adopted many years ago because soil density can be determined via weight and volume measurements. In most soil compaction, however, soil density is not the desired

engineering property. Textbook authors Holtz and Kovacs state:

*"Since the objective of compaction is to stabilize soils and improve their engineering properties, it is important to keep in mind the desired engineering properties of the fill, not just its dry density and water content. This point is often lost in earthwork construction control."*²

When soil is compacted for pavements, pipe bedding and backfill, and foundations, the desired engineering properties are soil modulus and lift stiffness.

State DOTs and contractors acknowledge that the present methods for measuring density are slow, labor intensive or of uncertain accuracy. Hence, construction sites are often under-sampled, causing inadequate compaction to go undetected, or feedback provided too late for cost-effective correction of problems. This practice requires designers to over-specify in order to allow for the variability of the finished product. It also requires contractors to over-compact beyond what is specified to ensure acceptance and avoid rework. All of which means added cost to the owner.

By using the HSG to statistically control the quality of earthworks, over-specification and over-compaction can be virtually eliminated. The benefit of this is illustrated in Figure 4. The normal distribution curve labeled "Typical Soil Data" is for 140 measurements taken in sandy soil on the pipe bedding of an interceptor sewer project in Minnesota. The mean modulus is 67.7 MPa (9,830 psi), and the standard deviation is 12.9 MPa (1,872 psi), so the coefficient of variation is about 19 percent. Ninety five percent of the measurements are greater than the

² Holtz, Robert D., and Kovacs, William D., *An Introduction to Geotechnical Engineering*, 1981, page 141.

hypothetical “Design Modulus” of 46.5 MPa (6,750 psi). Assume that, by instituting a measurement and quality control program using the HSG, compaction could be stopped when the design modulus is reached instead of completing the specified compaction method (e.g., number of compactor passes at a defined weight, frequency & speed). Then it would be possible for the contractor to use less compactive effort (compactor passes), reducing the average soil modulus while maintaining the passing tests at ninety-five

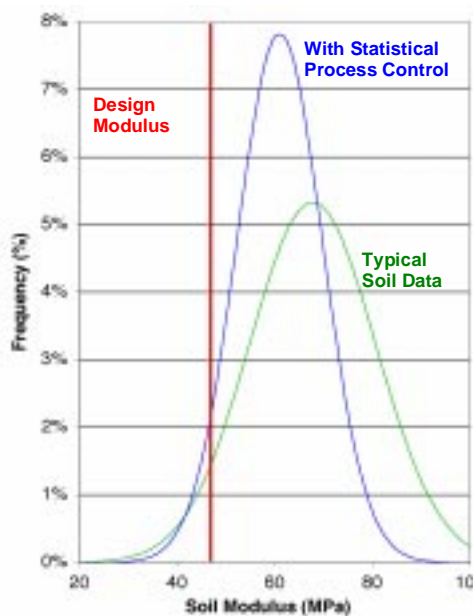


Figure 4

percent and saving cost. Field data suggests a 30% reduction in compactive effort is possible (the curve labeled "With Statistical Process Control" in Figure 4).

One Measure of Performance

From the start of organized construction, there has been the practical need to gauge performance of earthworks by one measure. By doing so, the relationship between design and construction is as precise and meaningful as construction materials and conditions will allow. The benefits to

earthworks reliability, maintainability and cost are obvious. The HSG offers the first simple, fast and direct way of enabling this. It makes the use of modulus or stiffness possible as a measure of performance from design to specification, construction process control, inspection and maintenance.

Engineering Limitations

All engineered embodiments of a technology have their limitations. The HSG is no different. Its current design was geared specifically to measuring a range of modulus and the stiffness of the top .10 to .20 m (4 to 8 inches) of a wide range of soils. Its mechanical impedance is "matched" for this function. The HSG's technology has the capability of measuring deeper (several feet), softer (very wet sand, mud, uncured concrete) and harder (asphalt, concrete and rock). The current HSG can not precisely measure these. By adaptations in weight, footprint, frequency and signal conditioning, future versions will. Development has been initiated towards that end.

What is Stiffness & What is It Good For?

Once you get beyond the design community, many construction engineers don't know what stiffness or modulus is, let alone what it means. The biggest obstacle in the HSG's path is the education of a conservative industry. Once the benefits of using the HSG are widely demonstrated and endorsed, it may well "sell itself". Until then, it will need to see as much field use as possible. The results obtained with it will have to be analyzed for and explained to the industry. It will need evaluations independent of the manufacturer and its partners. Bridges will have to be built between accepted methods and the HSG. This is true for any innovative product. Interest is high in the HSG and opinions are changing about soil stiffness.

HISTORY & USAGE³

'94 & '95 CONSTRUCTION SEASONS

Here the technology was transitioned from its origins in detecting non-metallic land mines for the U.S. Army. This was accomplished by a partnership between BBN Systems & Technologies of Cambridge, MA and CNA Consulting Engineers of Minneapolis, MN. Sponsored in part by the FHWA, a functional prototype was designed and constructed.

The HSG in "proof-of-principle" form was used widely in Minnesota in conjunction with the MnDOT's ongoing effort to improve construction processes for buried structures. The primary purpose of the field tests were to validate the HSG's technology, but a lot was learned about the non-uniformity of compaction under current methods and the corresponding implications to the structures life. The results prompted the MnDOT to request further use of the HSG when future prototypes were available.

'96 & '97 CONSTRUCTION SEASONS

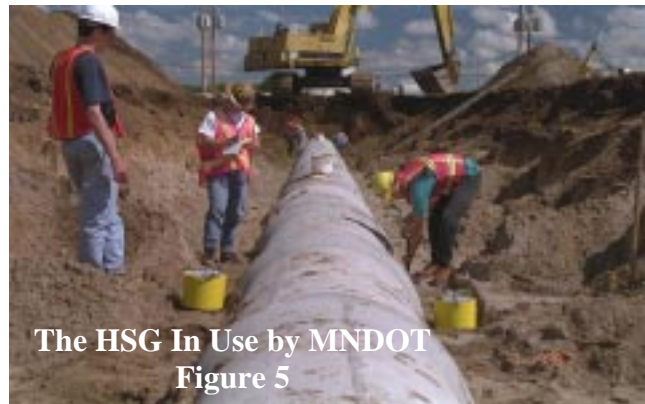
The HSG in pre-production form was extensively evaluated by Humboldt and the MnDOT as well as on a limited basis by the NYSDOT, TXDOT and University of Massachusetts. The primary purpose of the field tests was to validate and characterize the production form and function of the HSG.

The use of the HSG by the MnDOT revealed that soil stiffness/modulus played a more

³ The use of the HSG by any organization mentioned in this document does not necessarily constitute an endorsement of the HSG. The data analysis and corresponding conclusions in this document are to date those of Humboldt and not the users. Humboldt encourages the reader to contact the users directly for their impressions of the HSG.

significant role in the performance of buried structures than density (Fig.5). A corresponding reevaluation of how buried structures are installed is currently underway by the MnDOT. More details are available in a CNA Consulting Engineers report "MnDOT Overload Field Tests of Standard & SIDD RCP Installations" (see Appendix).

The use of the HSG by the University of Massachusetts showed promise and some problems. UMass was involved in the development of recommendations for Large Span Culvert Specifications. Specifically, they wanted to define the effects of current construction methods and live loads on the structure's performance. The results showed the promise of confirming that a meaningful relationship could be confirmed between dry



density and stiffness (see pg. 25 of UMass Report "Soil Compaction Modulus (Stiffness) Gauge Measurements Compared to Nuclear Moisture and Density Gauge Field Test Report", (see Appendix)). This is important if the use of stiffness for compaction control is to be accepted. The results also revealed a problem caused by the noise from construction equipment interfering with HSG measurements. This problem was linked to filtering, signal conditioning and the selected frequencies of operation. A design modification corrected the problem. The production version of the

gauge operates successfully within typical safe distances from operating construction equipment.

The use of the HSG by the NYSDOT and the TXDOT was limited to about a week each. Both are motivated to find better ways to control soil compaction. The TXDOT is leaning towards Young's or resilient modulus for that purpose. Their results showed that the HSG has promise and that other methods of measuring modulus in the field left much to be desired.

'98 & '99 CONSTRUCTION SEASONS

1998 brought the HSG to production and full independent field evaluation. This evaluation includes the participation of:

- **Univ. of Missouri:** Characterizing & Specifying Fly Ash Stabilized Subgrades
- **NCDOT:** Characterizing Base & Subgrade Stiffness and relating stiffness to other means of measuring compaction
- **H. C. Nutting Co., OH:** Non-Nuclear Measurement of Density
- **LADOT:** Improving Soil/Cement Base Quality
- **The City of San Jose, CA:** Non-Nuclear Measurement of Density
- **Ohio Univ.:** Improved Installation of Buried Plastic & Corrugated Steel Pipe
- **TXDOT:** Controlling Soil Compaction via Resilient Modulus
- **MODOT:** Non-Nuclear Measurement of Density
- **FHWA:** Soil Compaction Process Control
- **MnDOT:** Improved Installation of Buried Concrete Pipe
- **Rutgers Univ., NJ:** Control of Concrete/Silt Fills
- **FDOT:** Non-Nuclear Measurement of Density, Soil Compaction Process Control & Replacement of the LBR (Fig. 6)

A more detailed listing of current users is available from Humboldt (see Appendix). It describes who they are, where they are, why they are using the HSG and how they intend to use it. Their usage is widely varied, but they have one thing in common. They are looking for safer, more practical, faster, more accurate and more meaningful ways of controlling the compaction of soils and new materials.



The HSG
in Use on Florida I-4
Figure 6

The testing by current users is in general very thorough. Testing typically includes large spatial sites with many conventional measurements in companion with the HSG. The test planning for most of the users is available from Humboldt (see Appendix).

Stiffness & Density

Most of the early data has focused on confirming the relationship between density and stiffness. We began with the following relationship that was developed some 3 years ago from the work of Hryciw &

Thomann⁴ and made minor modifications to fit the data.

$$\rho_D = \frac{\rho_0}{1 + 1.2 \left[\frac{Cm}{K} - .3 \right]^{.5}}$$

where

$$C = \frac{(C_1 \sigma_1^P)4a}{(1-\nu)}$$

C_1 = is a function of moisture and soil type

σ_1 = is the overburden stress

P = is typically between 1/2 and 1/4

a = is the foot radius

ν = is Poisson's ratio

ρ_D = is the dry density

ρ_0 = is the ideal, void free density

m = (% moisture content by weight)/100

K = is stiffness

The basic approach is to first define C for a geographical region, independent of everything but moisture, from companion stiffness, moisture content and density measurements. Then use C , measured stiffness and measured moisture content to predict dry density. This approach allows for moisture content to be included in each prediction of dry density. It also allows the

values of C determined from the companion measurements to be fitted to a linear equation with our two independent variables, K and m .

$$C = n(K/m) + b$$

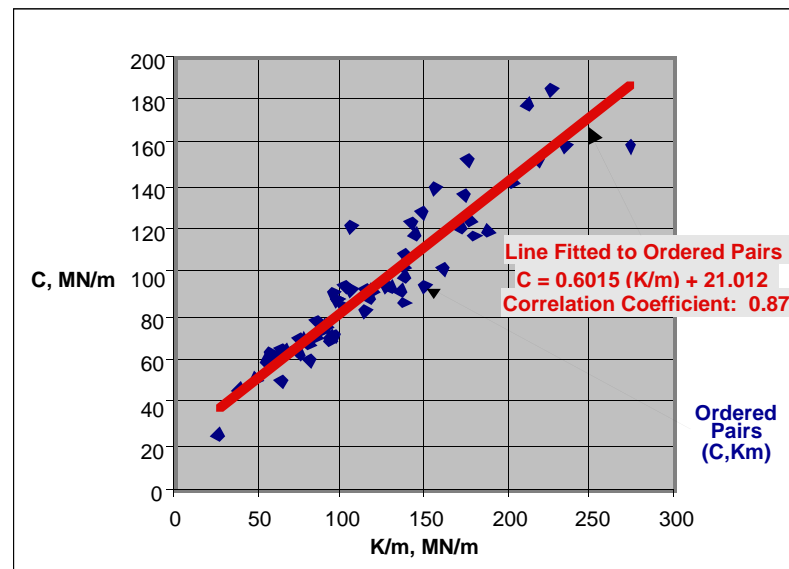
where

n is the slope

and

b is the intercept.

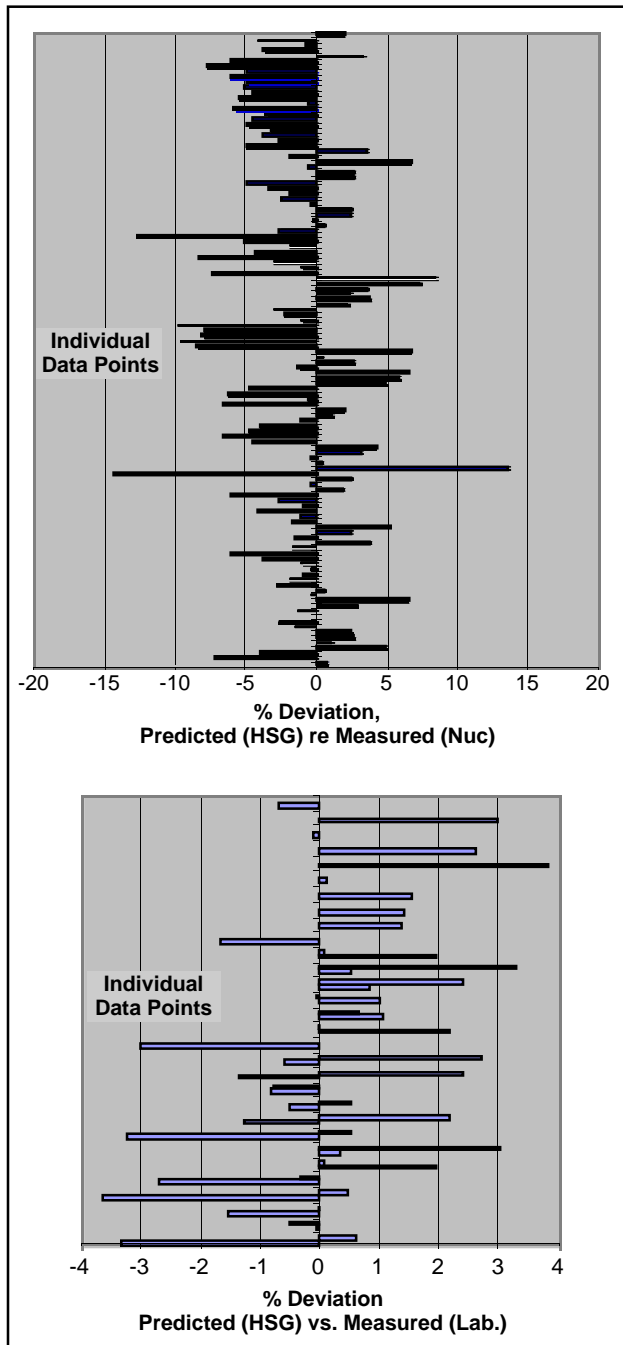
This linear relationship between C , K and m allows a more appropriate C to be used in the prediction of each dry density as opposed to selecting a limited number of C s to be used over several moisture ranges. Figure 7 is typical of the linear relationship achieved with field data.



**Typical Linear Relationship
C vs. K/m
Figure 7**

This approach has worked well to date with a significant volume of data (100s of measurements) from 6 sites located on the east coast, on the west coast and in the mid-west of the United States.

⁴ Roman D. Hryciw & Thomas G. Thomann, "Stress-History-Based Model for Cohesionless Soils", *Journal of Geotechnical Engineering*, Vol. 119, No. 7, July, 1993



Typical Results
Predicted vs. Measured Density
Figure 8

Humboldt has issued a preliminary report that describes the results to date (see Appendix). It shows that when companion

measurements are made with a nuclear density gauge,

- ~ 70% of the predicted densities were within 5% of the measured values
 - ~ 25% of the predicted densities were within 5% to 10% of the measured values
- and
- ~ 5% of the predicted densities differ more than 10% from the measured values.

When the companion density measurements were made in the laboratory,

- ~ 100% of the predicted densities were within 4% of the measured values

Figure 8 illustrates these results.

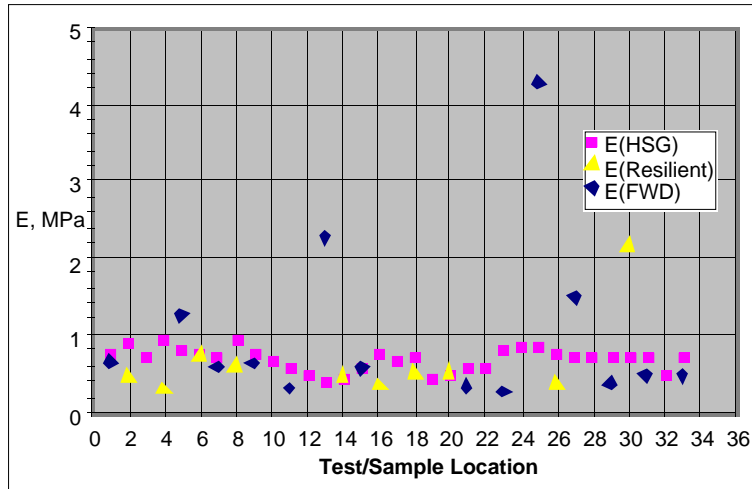
The degree of agreement between the predicted and measured density is consistent with the measurement accuracy of most of the current field and laboratory measurements of soil performance. This is very significant. It means the HSG could be used, along with a companion measurement of moisture content, to predict dry density. For many reasons, engineers, DOT's and contractors are looking for an alternative to the nuclear gauge. The HSG now appears to be such an alternative.

Young's & Resilient Modulus

Another area of interest to current users is finding a simple reliable way of controlling soil compaction via soil modulus. For example, the TXDOT has been evaluating the HSG with other methods for this purpose. The assumption is that because of the low measurement frequencies and small deflections, the modulus measured by the HSG should be about the same as that measured by AASHTO method T292. The TXDOT has indicated a reasonable degree of success in this regard and is planning to publish its data later in '99. Data taken by The NCDOT also shows promise (Fig. 9).

The differences between Young's modulus (HSG) and resilient modulus (AASHTO

then can therefore be related to yield strength (force/area at yield) and subsequently modulus (stress/strain). Since the HSG also provides a measure of modulus, the stiffness and CIV should be related via modulus. Data from several states is currently being analyzed to that end. Figure 10 further defines the differences between the HSG and Clegg Impact Tester.



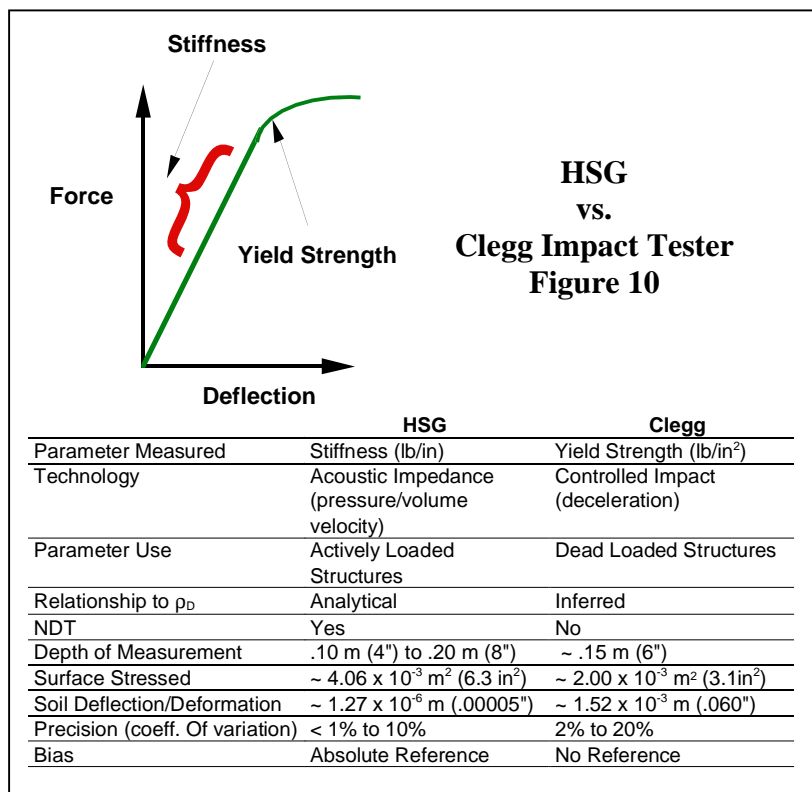
NCDOT Modulus Data, 9/98
Figure 9

T292) vary from less than 10% to a factor of 2. The differences are believed to be due to the non-uniformity of compaction around each test location. More testing is on-going to understand these differences.

Stiffness & Clegg Impact Value

Stiffness and Clegg Impact Value (CIV) are two different yet related things. The HSG measures soil stiffness, force/deflection, over the soil's resilient region (where it recovers from deformation). CIV, as measured with a Clegg Impact Tester, is a measure of the deceleration of a known mass dropped from a known height as it deforms the soil surface over a known area. The fact that successive drops eventually produce the same CIV indicates that the soil is yielding, not failing, under the stress. The CIV

Stiffness & Process Control
Since the HSG enables rapid and direct measurements of performance in real-time, users are thinking that process control may be a practical reality. Users are asking themselves what stiffness, what strength, what durability and what life earthworks should have. The HSG has provoked discussions between design, materials and

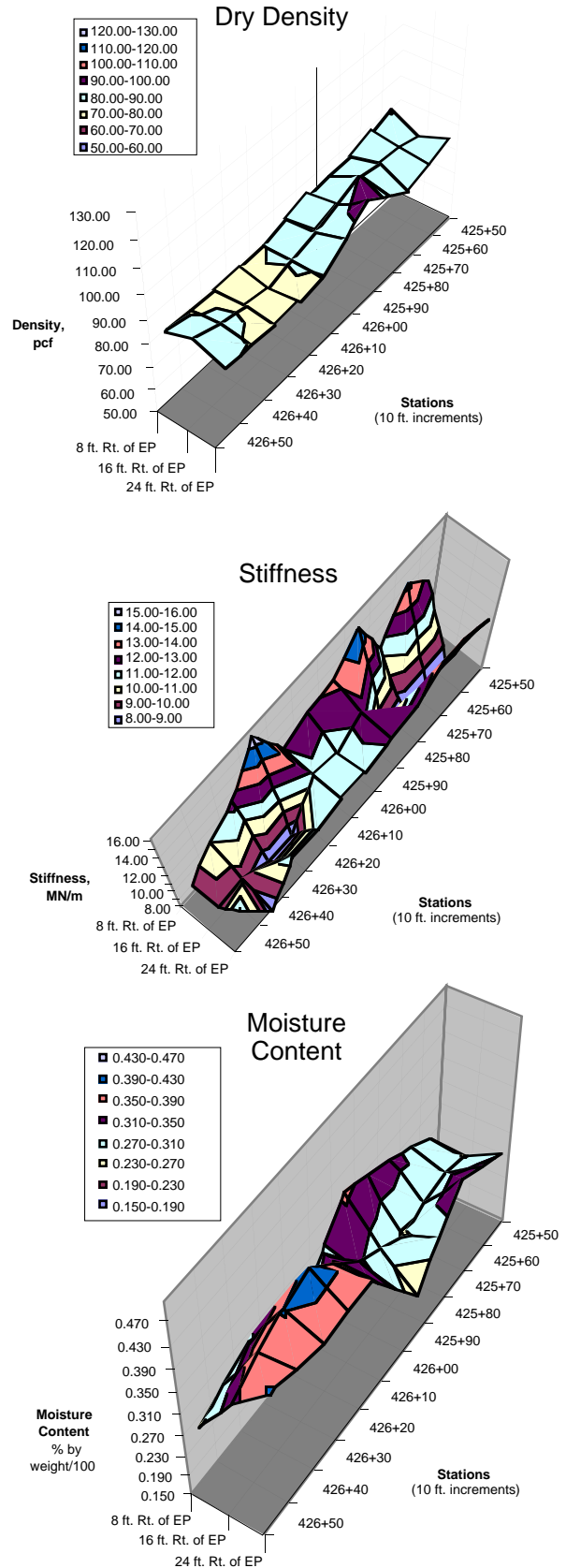


construction operations in order to define what is required for beneficial process control. The TXDOT is one of the first state DOTs to analytically and empirically begin this definition. Included is determining how variable local soil stiffness is and how it relates to desired performance tolerances. Figure 11 shows the spatial variations in dry density, moisture content and stiffness for a random site. Each quantity is shown in a surface plot corresponding to the soil surface where the data was taken. Each of these quantities is plotted on the same relative scale. This means that the "Z" axis range of each surface plot is $\sim \pm 50\%$ of mean value for all the data. The plots show that stiffness is a more sensitive measure of soil performance than density. Even when the variability in moisture content is accounted for, the variability in stiffness relative to dry density is amazing!

Standardization

During January, '99, a presentation was made to ASTM Subcommittee D18.08 regarding the development status of the HSG. The Subcommittee thought that there was sufficient basis and need to warrant the development of a standard method covering the HSG. Such a standard is under development.

Soil Variability
NCDOT: Project 8.T521103
(US 64 at Chatham County), 10/98
Figure 11



APPENDIX

ADDITIONAL DOCUMENTS AVAILABLE FROM HUMBOLDT

The following are available from the individual noted on the first page. They are available in either hardcopy or pdf format.

- HSG User Guide
- "MnDOT Overload Field Tests of Standard & SIDD RCP Installations", 1/99, J. Hill (MnDOT), J. Kurdziel (North Star Concrete), C. Nelson (CNA Consulting Engineers), J. Nystrom (The Cretex Companies) & M. Sondag (CNA Consulting Engineers), Annual TRB Meeting
- "Soil Compaction Modulus (Stiffness) Gauge Measurements Compared to Nuclear Moisture and Density Gauge Field Test Report", 10/97, J. Sussmann, M. Webb & E. T. Selig, University of Massachusetts, Amherst, MA
- Detailed Listing of Current HSG Users
- Test Planning for Typical HSG Users
- Preliminary Report: "Predicting Dry Density from Soil Stiffness & Moisture Content", 11/6/98, Humboldt Mfg. Co.