GeoGauge™

A Practical Field Gauge for Compaction Process Control Via Mechanistic Parameters – In-Place Stiffness & Modulus

Hand-Portable, Fast & Reliable

A white paper by Humboldt Mfg. Co., Norridge, Illinois, U.S.A.

Description

The GeoGauge, formerly Soil Stiffness Gauge, is a hand-portable gauge that provides a simple, rapid and precise means of directly measuring lift stiffness and soil modulus for compaction process control (Fig. 1). Patent Pending.

The GeoGauge, manufactured by Humboldt Mfg. Co., Norridge, Illinois, U.S.A., is intended to meet two needs that existed since quality has been important to earthwork construction.

One; to control the compaction process via the same engineering or mechanistic parameters that earthworks are designed with. For example in highways:

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

Two; Process control measurements at earthwork production speeds. Efficient process control without delays from third party or laboratory input assures greater soil uniformity as the process control remains with the contractor.

Modulus and stiffness are two different mechanistic properties. Modulus refers to a property of a material and has no physical boundaries. A given material will have the same modulus whether it is 0.1 meter thick or 1.0 meter thick. Stiffness refers to a property of a structure, and is influenced by its physical dimensions, modulus of the material and its boundary conditions such as how it is held, supported or constrained. A structure's stiffness will be different if you change its thickness.

Soil compacted for a useful purpose is then a structure and since it is designed and constructed as a structure it is thus more meaningful and practical to be measured as a structure. There is no need to "convert" the designers engineering parameters into density parameters.

The GeoGauge 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 GeoGauge imparts very small displacements to the soil (< 1.27 x 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 of the 25 is displayed. The entire process takes about one minute. At these

Technical Contact:
Scott Fiedler, Product Manager, Humboldt Mfg. Co., 7300 W. Agatite Ave., Norridge, Illinois 60706, U.S.A.
Tel: +708-456-6300 (Ext. 231), 800-544-7220 (Ext 231), Fax: +708-456-5412, Email: fiedler_hmc@msn.com

low frequencies, the impedance at the surface is stiffness controlled and is proportional to the shear modulus of the soil. With user's input of Poisson's ratio, Young's and shear modulus can be derived.

Work done by CNA Consulting Engineers, Minneapolis, MN. confirm GeoGauge measuring the soil's response to the unloading of stress to arrive at accurate stiffness and modulus values. CNA also confirm that the GeoGauge's combination of small stress and sensitive sensors make it as accurate as CNA's quasi-static plate load apparatus with much higher loads. This means that relationships and correlations are possible with other modulus and strength measurements. Early results show good agreement with different devices.

The GeoGauge weighs 10 kg (22 lbs), is 280 mm (11") in diameter, 270 mm (10") tall and rests on the soil surface via a ring–shaped foot (Fig. 1). The foot bears directly on the soil and supports the weight of the GeoGauge via isolators. Attached to the foot are the shaker that drives the foot and sensors that measure the force and displacement-time history of the foot.

Operation

The GeoGauge is placed on the soil to make a measurement with little or no preparation of the soil surface. Typically, a slight press and rotation of the GeoGauge is needed obtain the required 60% minimum contact area between foot and soil. On particularly hard or rough surfaces or where significant aggregates are present, seating of the foot is assisted by the use of less than 6 mm (1/4") of moist or wet sand or local fines. Common field practice and soil preparation is as applicable to the GeoGauge as it is to most current field measurement. The detailed procedure for using the GeoGauge and preparing the soil is described in the GeoGauge User Guide. (see Appendix)

The current version of the GeoGauge displays and logs the data in memory with sufficient capacity for a full day of data gathering (500 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-place require large forces to produce a measurable deflection. The GeoGauge uses technology borrowed from the military to measure very small deflections, allowing much smaller loads. The GeoGauge does not measure the deflection resulting from the GeoGauge weight. Rather, the GeoGauge 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 (υ) of the soil.[1] The stiffness is the ratio of the force to displacement: $K=P/\delta$. The GeoGauge produces soil stress and strain levels common for pavement, bedding and foundation applications (27.58 kPa or ~ 4 psi). As shown below, Young's and shear modulus can be determined from GeoGauge measurements if a Poisson's ratio is assumed.

$$P \sim \frac{1.77\,RE}{(1-\upsilon^2)}\delta \sim \frac{3.54\,RG}{(1-\upsilon)}\delta$$

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

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

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

A mass is used as a reference since its value is precisely known and is not susceptible to change than a reference elastomeric pad or soil sample. A mass of sufficient size is used 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 attached to the foot during calibration. The

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

GeoGauge, with the mass, is supported on a rigid structure by a very compliant fixture that the mass is effectively unrestrained in the measurement frequency band. The bias of a GeoGauge measurement, relative to the value of the moving mass, is less than 1% coefficient of variation. The precision of a GeoGauge measurement on fine-grained soils is less than ~2% coefficient of variation. On course-grained soils and crushed aggregate the coefficient of variation is typically less that ~5%.

Applications

The GeoGauge can be applied to any nature of earthwork 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. Designers care most how the subgrade, base and pavement work together to cyclically deflect as a function of time and traffic loads. The mean stiffness of each layer and its uniformity is a primary factor in how the pavement fatigues, the span of its life and what maintenance it will require. The GeoGauge 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 GeoGauge 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 GeoGauge enables rapid, comprehensive and direct measurements in real-time without delaying or interfering with the compaction process. Process control allows the contractors themselves, to monitor the uniformity of the product as it is being constructed and to adjust the construction process toward the specifications and while potential problems can be dealt with.

Alternate Measurements: CBR, DCP, subgrade reaction, Clegg Impact Value, FWD and plate loads are some of measurements that the more practical GeoGauge can alternate for. Since these are all forms of strength parameters, relationships have already been determined or can easily be established.

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 GeoGauge provides a precise, rapid and license free alternative. In conjunction with a moisture measurement, density can be typically estimated 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 GeoGauge 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 stabilizers, additives or substitutes. Controlled Low Strength Materials and cement, fly-ash or polymer stabilized soil, for example, require repeated measurements at the same locations as the material cures. Since the GeoGauge does not disturb the soil, it makes possible the fast repeated measurements at a single location.

Specific applications by various users are listed in *Current Users of Humboldt GeoGauge (see Appendix).*

Reduce Construction Costs via Process Control

Compacted soil is an essential engineered element of highway, airport, railroad, 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 easily 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 beddings, trenches, backfills, foundations and other structures, the desired engineering properties are soil modulus and lift stiffness.

State DOTs, consultants and contractors acknowledge that the present methods for measuring density are slow, labor intensive, of uncertain accuracy and of no engineering relevance. Hence, construction sites are often under-sampled, causing inadequate and non-uniform compaction to go undetected. Most subsequent feedbacks are too late for cost-effective correction of problems. This practice requires designers to over-specify to allow for the variability of the finished product. Contractors, knowing the inherent variability of soils, then over-compact beyond what is specified to insure acceptance and avoid rework or penalties. All of which means added initial cost to the owner.

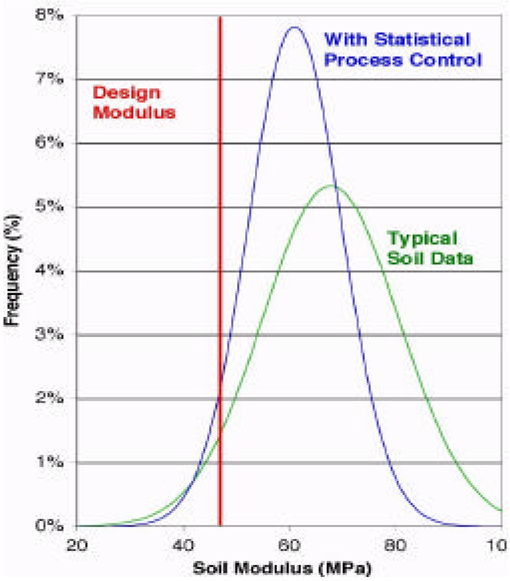

Figure 2

By using the GeoGauge to statistically control the quality of earthworks, over-specification and over-compaction can be virtually eliminated. The benefit of this is illustrated in Figure 2. 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 hypothetical "Design Modulus" of 46.5 MPa (6,750 psi). Assume that, by instituting a measurement and process control program using the GeoGauge, compaction could be stopped when design stiffness is reached instead of completing the specified compaction method (e.g., number of compactor passes at a defined weight, frequency & speed). It would then 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 percent and saving cost. Field data suggests a 30% reduction in compactive effort is possible (the curve labeled "With Statistical Process Control" in Figure 2). Leads to "optimum compaction with minimum effort" or minimum effort compaction.

In designing a new highway, future traffic load expectations needs to be established before the engineering can begin. Engineers need to know what performance and life the highway would have to be capable of. A typical design procedure, before construction, is to determine the modulus of the soil to be used via laboratory methods of soils taken from the field. When the modulus has been determined for each soil of each component, then the thickness of each component can be established for the desired stiffness. The designer's engineering specifications then gets conservatively converted to density specifications. Hence, at this density, or Proctor, with this thickness, should do the job. There are two major flaws in this conversion. No contractor can insure that the thickness has been reached or is able to construct uniformly throughout

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

the site. With soil being inherently variable, how can the designers be assured that the original engineering specification been reached and is uniform? With density measurements, it is empirically based and cannot be assured. With GeoGauge, measuring directly to original engineering specifications is now possible. The stiffness of each lift, layer and component can be controlled and easily be made uniform by the contractor doing the work. Ideally, the contractor controls the compaction process to performance specifications, not physical specifications.

If during the compaction process, the available or borrowed soil becomes lower in quality, and the expected stiffness would not be reached at the expected thickness or compactive effort, merely adding to the thickness or effort can achieve the specified stiffness. In this example, the contractor controlled the process towards the engineering specifications.

Reduce Life-Cycle Cost

FHWA has stated that if roadways were constructed more uniform, roadways could achieve double the life with reduced maintenance. It only takes a plus or minus 25 percent from the mean stiffness to achieve uniformity. The GeoGauge is extremely sensitive to detect the minute differences in stiffness and modulus that is inherent in soil as close as a footstep away. With GeoGauge and process control, uniformity can be easily achieved. With non-uniform stresses, the soil behaves counter to expectation and the resulting distress, dips and bumps, surface failures and loss of smoothness shortly follows. With uniformity the soil reacts to the cyclical loads and seasonal changes in union resulting in less surface failures and longer life.

In Europe, pavement subgrades are designed and carefully constructed to last one hundred years, the subbase for 70 years and the base for 30 years. The reasoning is two-fold. The most costly to replace and the most critical component for a pavement system’s integrity is the subgrade, followed by the subbase and then the base. The pavement surface, similar to the skin on a person, offers no structural support and is merely a protective layer for the pavement components below as well as to provide traction for rubber tires. The moment the subgrade begins to fail the entire pavement will fail. As usually the case only the surface pavement gets the attention and is re-paved. With the still present failed subgrade, or for that matter, subbase or base, the new surface will fail again in short time, adding to the maintenance costs and rushing the decision to replace the entire roadway.

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 earthwork reliability, maintainability and cost are obvious. The GeoGauge 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 GeoGauge is no different. Its current design was geared specifically to measuring a range of modulus and the stiffness to .22 to .3 m (9 to 12 inches) deep in most soils. Its mechanical impedance is "matched" for this function. The GeoGauge's technology has the capability of measuring much deeper, softer (very wet sand, mud, uncured concrete) and harder (asphalt, concrete and rock). The current GeoGauge cannot precisely measure these, future versions will. Development has been initiated towards that end.

Why Stiffness and Modulus?

What is Stiffness?

Stiffness is an engineering property of a structure and is a measure of the structure’s resistance to deflection. A coil spring, such as in an automobile, is designed for a given stiffness for its intended purpose. Pressing down on the coil spring with a load or force will deflect the spring a certain distance. Release the force and the spring will return to it original height. Pressing down with greater force will deflect the spring even more. At some point, with high forces the spring will deflect to the point of being deformed and will not return to its original height or shape. This has exceeded the spring's design parameters and permanently deformed or damage the spring. Each of the components of a pavement system is an independently constructed structure and can be thought of as a series or bed of springs. The load or force from a moving truck tire presses down on the top pavement, which distributes the load to the base, which distributes its load to the subbase and further distributes the load to the subgrade. By the time the load reaches the native earth, the load should be barely measurable, if at all. From bottom up, the stiffer each of the pavement components is, the more broad the load distribution. A broad bottom cone shaped load distribution is ideal as it means less load or force on that pavement component, hence less deflection and longer life. As independent a pavement component is constructed, it is highly dependent on the other components to perform as a system.

The value of stiffness for the designer is in knowing the maximum force for a given deflection without permanent deformation. High stiffness value equals less deflection. Less deflection equals longer life and lower maintenance equals improved life-cycle costs. In addition, stiffness is more variable than density and thus a site's uniformity can be easily monitored and controlled during the compaction process with the GeoGauge. Uniform pavement components as a system work and perform together in unison. A non-uniform pavement system has localized stress sections that greatly increases maintenance and reduces the life of the pavement.

What is Modulus?

Young's modulus is the ratio of stress to strain and is one of the basic engineering properties of all materials. Sometimes called modulus of elasticity, elastic modulus, deformation modulus or coefficient of elasticity. Young's modulus is the relationship of the change in the material's length from original when under tension or compression. In other words, for a column of soil specimen, what is the strain when stress is applied? Shear modulus, another basic engineering property, is the stress needed to deform the material by a given angle. The soil's modulus is determined by the effort applied, moisture content and void ratio.

What is Poisson's Ratio?

In order to establish the Young's modulus of soils, the Poisson's ratio must be known or assumed. Poisson's ratio is the ratio of lateral strain to its axial strain at right angle to each other. In other word, for a column of soil specimen, what is the difference between the vertical compressed strain and the resultant bulge at the side of the column?

Is Soil Elastic?

Elasticity is the ability of a material to return to its original shape when the load is removed. More accurately, soil is visco-elastic. That means that there is a delayed response when stress or load is applied or removed. This is an important aspect for highway pavements due to the cyclical loading from truck tires. The speed of the vehicle may load the pavement again before it has a chance to recover, impacting its performance and life. The GeoGauge dynamically measures the critical recovery phase of the soil stress-strain curves similar to resilient modulus tests currently being done with a number of state DOTs.

Which is Better - Stiffness or Modulus?

Each of the pavement components, subgrade, subbase, and base, are each a structure and need to be measured as such. Stiffness is a structural property. It takes into account the entire physical properties, such as width, length and thickness, the material's modulus and the stress, load or support on that component. The stiffness changes with any change of the physical parameters. The width and length can be easily measured and often is pre-marked by survey stakes. Thickness is rarely measured and is generally guessed. Stiffness measurements easily remove the importance of this parameter and instills confidence into the designer and contractor that the specifications are being met. Since the designer wants to minimize the deflection of each component to what the materials can safely withstand before permanent damage incurs, it is more sense to have stiffness the parameter of choice.

Just knowing the modulus of the material is not enough. It then becomes critical to establish the thickness at the construction site. Contractors are hard pressed to be certain that the specified thickness has been reached. This unknown contributes to the non-uniformity that impacts its life. It is not sensible to talk about any earthwork in terms of modulus without some reference to its boundary conditions. The modulus for a given material is the same whether it is 0.1m thick or 1.0m thick. However, its stiffness is very different.

History & Usage[3]

'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 GeoGauge 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 GeoGauge's technology, but much 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 GeoGauge when future prototypes were available.

'96 & '97 Construction Seasons

The GeoGauge 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 GeoGauge.

The GeoGauge In Use by MnDOT Figure 3

The use of the GeoGauge by the MnDOT revealed that soil stiffness/modulus played a more significant role in the performance of buried structures than density (Fig. 3). A corresponding reevaluation of how buried structures (large diameter reinforced concrete pipes) 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 GeoGauge by the University of Massachusetts showed promise and a problem. 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 GeoGauge 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

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[3] The use of the GeoGauge by any organization mentioned in this document does not necessarily constitute an endorsement of the GeoGauge. 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 GeoGauge.

equipment.

Although, the use of the GeoGauge by the NYSDOT and the TXDOT was limited 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 GeoGauge has promise and that other methods of measuring modulus in the field left much to be desired.

'98 & '99 Construction Seasons

1998 brought the GeoGauge to production and a widespread 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. 4)

The GeoGauge In Use On Florida I-4
Figure 4

A more detailed listing of current users and their motivation is available form Humboldt (see Appendix). It describes who and where they are, why they are using the GeoGauge 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 testing by current users is in general very thorough. Testing typically includes large spatial sites with many conventional measurements in companion with the GeoGauge.

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 & Thomann [4] and made minor modifications to fit the data.

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

Where

ρ_D = is the dry density

ρ_0 = is the ideal, void free density
m = (% moisture content by weight)/100
K = is stiffness

And

$$C = n(K/m^{.25}) + b$$

Where
n is the slope
b is the intercept.

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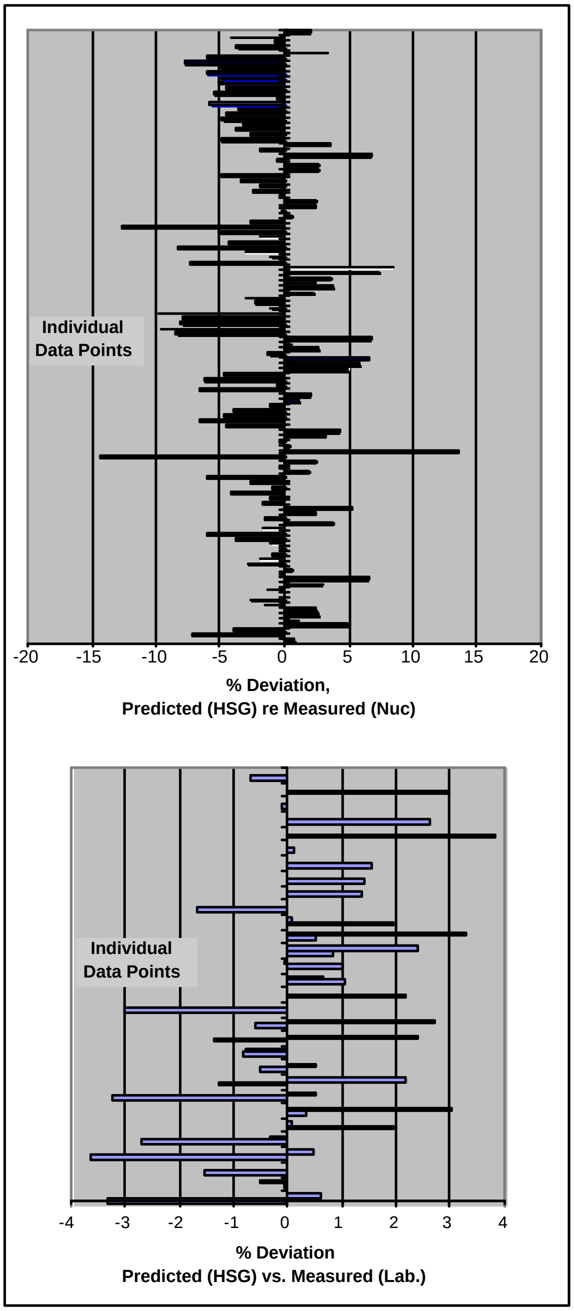
[4] Roman D. Hryciw & Thomas G. Thomann, “Stress-History-Based Model for Cohesionless Soils”, *Journal of Geotechnical Engineering*, Vol. 119, No, 7, July, 1993



Typical Results: Predicted vs. Measured Density
Figure 5

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

This linear relationship between C, K and m allows a more appropriate C to be used in the estimate of each dry density as opposed to selecting a limited number of Cs to be used over several moisture ranges. This approach has worked well with a significant volume of data (100s of measurements) from 6 sites throughout the United States.

Humboldt has issued a report that describes the results of estimating dry density from GeoGauge stiffness measurements and moisture content. It shows that when companion measurements are made with a nuclear density gauge,

- ~88% of the estimated densities were within 5% of the measured values
- ~10% of the estimated densities were within 5% to 10% of the measured values
- ~2% of the estimated densities were within 10% to 15% of the measured values.

The degree of agreement between the estimated and measured density is consistent with the measurement accuracy of most of the current field and laboratory measurements of soil performance (Fig 5). This is very significant. It means the GeoGauge could be used, along with a companion measurement of moisture content, to estimate dry density. For many reasons, engineers, DOT's and contractors want an alternative to the Nuclear Moisture-Density Gauges. GeoGauge is 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 Young’s modulus. For example, TXDOT and MnDOT have been evaluating the GeoGauge with other methods for this purpose. Because of the low measurement frequencies, small deflections and similarity in what is being measured, the modulus measured by the GeoGauge should be about the same resilient modulus as 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. The differences between Young's modulus (GeoGauge) and resilient modulus (AASHTO T292) vary from less that 10% to a factor of 2. The differences are believed to be due to the non-uniformity of compaction around each test location and lack of standard procedures. More testing is on going to understand these differences. FDOT, NCDOT, FHWA and others are also evaluating the relationship between laboratory resilient modulus and the GeoGauge's in-situ modulus.

GeoGauge vs. CBR, DCP, SCP and FWD

Initial work shows there are strong correlation between the GeoGauge and other strength and modulus measurement devices. It must be remembered that the different devices impose unique stresses that inherently changes the soil's parameters and thus the values given. A series of comparisons will demonstrate correlation factors or constants that make the GeoGauge a good alternative. Work is underway that will present factors or constants that can be used for many situations.

Stiffness & Process Control

Since the GeoGauge enables rapid and direct measurements of performance in real-time, users are thinking and believe that process control is a practical reality. Users are asking themselves what stiffness, what strength, what durability, what life earthworks should have and why are we not achieving them? The GeoGauge has provoked discussions between design, materials and construction operations in order to define what is required for beneficial and practical 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. Spatial variations in dry density and moisture content come nowhere near the spatial variations in stiffness for a random site. Stiffness is a much 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 readily apparent.

Standardization

During January '99, a presentation was made to ASTM Subcommittee D18.08 regarding the development status of the GeoGauge. The Subcommittee thought that there was sufficient basis and need to warrant the development of a standard method covering the GeoGauge. Such a standard is now under development. During the 2000 year the proposed standard method is undergoing balloting. AASHTO standard will follow.

Conclusion

There is no doubt that profound change in the way soil is compacted and measured is coming. Density has never been the desired property, it is a surrogate and was used just to be able to spec something that contractors can easily use and be judged by. The consensus is there has to be a way to modernize by integrating proven technology to help build better highways. It can only be done by understanding and opening the process of treating compacted soil as an engineered structure to be measured as such.

- There is a need to eliminate or reduce the significance of density-based measurements and empirical design practices and implement and elevate the importance of mechanistic design practices with in-place measurements of engineering properties.

- There is a persistent quest to build better quality structures at lower costs.

The GeoGauge truly fills the above needs. It is not sufficient to know the modulus or other parameters after the work is finished. How then, is it possible to correct problems? What does make rational sense that only by monitoring and controlling the compaction process as it is being constructed, can the process be guided and problems be attend to. The GeoGauge is ideal for this in that it controls the compaction process towards the relevant performance specifications without delay or interference from third party testing.

Available GeoGauge Related Documents

____ **GeoGauge Brochure** (limited summary of the GeoGauge, its applications and benefits)

____ **GeoGauge User Guide** (comprehensive how to use guide)

____ **Typical Test Plans for the Humboldt GeoGauge** (sampling plans for GeoGauge use including comparisons with other test methods)

____ **Current Users of the Humboldt GeoGauge** (A sampling of who is using the GeoGauge, for what and with what results)

____ **Humboldt Report: Estimating Dry Density from Soil Stiffness & Moisture Content** (the basis for using the GeoGauge to estimate dry density)

____ **GeoGauge Principle of Operation** (the physical principles behind the GeoGauge)

____ **GeoGauge & CBR** (the relationship between the modulus derived from the GeoGauge & CBR)

____ **GeoGauge "White Paper"** (a comprehensive summary of the GeoGauge, its history, applications and benefits)

____ **TXDOT Report: Evaluation of In-situ Resilient Modulus Testing Techniques** (comparison of the GeoGauge with FWD, D-SPA & SASW)

____ **MNDOT Report: MnDOT Overload Field Tests of Standard & SIDD RCP Installations** (the importance of soil stiffness to the installation of buried structures and the potential value of the GeoGauge for evaluating it)

____ **MnDOT Report: Comparison of the Dynamic Cone Penetrometer With Other Tests During Subgrade & Granular Base Characterization in Minnesota** (comparison of the GeoGauge with DCP & portable FWD (Loadman). Also a comparison between conventional compaction tests and in-situ modulus tests.)

____ **Univ. of New Mexico Report: Evaluation of the Humboldt GeoGauge on Dry Cohesionless Silica Sand in a Cubical Test Bin** (analytical & mechanical evaluation of GeoGauge precision, bias & depth of measurement.)

____ **CNA Consulting Engineers Report: Comparison of the Humboldt GeoGauge With In-Place Quasi-Static Plate Load Tests** (A determination of what the GeoGauge physically measures)

____ **Letter to TXDOT: The Relationship Between Stiffness and Modulus for the Humboldt GeoGauge** (The origin & description of the subject relationship)

____ **Loughborough Univ. Report: Subgrade Equilibrium Water Content & Resilient Modulus for UK Clays** (The importance of modulus to subgrade performance)

____ **Journal of Geotechnical & Geoenvironmental Engineering: Geomechanical Analysis of Unbound Pavements Based on Shakedown Theory** (An analysis of the mechanical response of pavement to repeated traffic loading)