Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering
© 2005–2006 Millpress Science Publishers/IOS Press.
Published with Open Access under the Creative Commons BY-NC Licence by IOS Press.
doi:10.3233/978-1-61499-656-9-1689

Earthwork quality control using soil stiffness

Controle de la qualite des ouvrages en terre par la mesure de la rigidite

T. Edil & A. Sawangsuriya
Department of Civil and Enviromental Engineering, University of Wisconsin-Madison, Wisconsin, USA

ABSTRACT
The quality of the engineered earthwork depends on the suitability and compaction of the materials used. Earthwork compaction acceptance criteria typically are based on adequate dry density achieved through proper moisture content and compaction energy. This paper presents the implementation of a non-destructive testing device called the soil stiffness gauge (SSG) for construction quality and design parameter control of earthwork

RÉSUMÉ
La bonne tenue des ouvrages en terre dépend considérablement de l'aptitude au compactage des matériaux utilisés. Les critères d'acceptation du compactage sont typiquement basés sur une correcte densité sèche, suffisamment atteinte à la fois par une teneur en eau et une énergie de compactage adéquates. Ce article présente l'implémentation d'un appareil expérimental non destructif appelé «Soil Stiffness Gauge – SSG» utilisé pour contrôler la qualité de la conception et de la mise en œuvre des remblais en terre.

1 INTRODUCTION

The quality of the engineered earthwork depends on the suitability and compaction of the materials used. Earthwork compaction acceptance criteria typically are based on adequate dry density of the placed earthen materials achieved through proper moisture content and compaction energy. According to this approach, by achieving a certain dry density using an acceptable level of compaction energy assures attainment of an optimum available level of structural properties and also minimizes the available pore space and thus future moisture changes. Conventional approach is also based on the premise that monitoring dry density as opposed to a structural property is relatively simple and can be applied to generate data for a statistical evaluation of compaction quality. However, monitoring compaction quality through density measurements, including nuclear moisture-density gauge and sand cone density test, are generally time consuming, labor intensive, and costly. Furthermore, the question of the achieved structural property, which is the ultimate objective of quality control, remains unfulfilled. In important projects, various laboratory and field tests are employed to relate the achieved level of compaction to structural properties. These tests are often limited in number and do not yield a statistical basis of earthwork quality. The difficulty and expense of acquiring quality relevant engineering properties such as stiffness have traditionally caused engineers to rely on discrete density tests. The relative compaction alone is not a reliable indicator of the soil mechanical property (i.e., stiffness and strength). Moreover, the soil density is only a quality index used to judge compaction acceptability and is not the most relevant property for engineering purposes. For compacted highway, railroad, airfield, parking lot, mat foundation, subgrades and support fills, the ultimate engineering parameter of interest is often the soil stiffness and (or) modulus, which is a direct structural property for determining load support capacity and deformation characteristic in engineering design.

Stiffness of compacted soils depends on density and moisture but also on soil texture which varies along the roadway route or in different parts of a burrow pit. The conventional approach of moisture-density control, however, does not reflect the variability of the soil texture and fabric and hence its stiffness. Even if the soil layers satisfy a compaction quality control requirement based on density testing, a large variability in soil stiffness can still be observed (Sargand et al., 2000; Nazarian & Yuan, 2000). Additionally, the comparison between density and stiffness tests suggests that conventional density testing cannot be used to define subtle changes in the modulus of the compacted earth fills (Fiedler et al., 1998). Soil stiffness is a more sensitive measure of the texture and soil fabric uniformity than density. Since the non-uniformity of stiffness is directly related to progressive failures and life-cycle cost, a simple, rapid, and direct stiffness testing which can be conducted independently and in conjunction with conventional moisture-density testing without interference with the construction process is anticipated to increase test coverage, to improve statistical evaluation, and to reduce variability, thus substantially enhance construction quality control of the entire earthwork.

This paper presents the implementation of soil stiffness in practice for construction quality control of earthwork. A non-destructive testing device called the soil stiffness gauge (SSG) exhibits potential for adaptation to earthwork control and is therefore employed to assess the soil stiffness of various materials used in earthwork from different construction sites around the state of Wisconsin, U.S.A. along with the conventional compaction control tests such as nuclear moisture-density gauge and gravimetric moisture content measurement. Use of SSG both for compaction quality control and for design parameter control is presented.

2 IN SITU TEST METHODS FOR SOIL STIFFNESS ASSESSMENT DURING CONSTRUCTION

A number of dynamic non-destructive testing methods to assess in situ soil stiffness have become increasingly available (Lytton, 1989; Siekmeier et al., 1999; Stokoe & Santamarina, 2000; Livneh & Goldberg, 2001; Müller, 2003). A portable device for assessing soil stiffness should not interfere with the construction process but rapidly provide reliable stiffness values. In other words, the measuring device must allow considerably more tests than the conventional moisture-density testing.

The SSG provides direct, simple, and rapid means of stiffness assessment. The SSG is a portable, non-nuclear, and non-destructive testing device that employs an electro-mechanical means. Additional information and operation of the SSG is given in Humboldt (1999a). The test is conducted in accordance with ASTM D 6758, Standard Test Method for Measuring Stiffness and Apparent Modulus of Soil and Soil-Aggregate In-Place by an Electro-Mechanical Method and takes a few minutes to conduct with automatic data acquisition. Sawangsuriya et al. (2002; 2004b) showed that the SSG measures the stiffness of a finite volume of soil below surface. The zone of SSG measurement influence was estimated to be less than 300 mm lateral distance and a maximum depth of approximately 300 to 380 mm. The effect of layered materials on SSG measurements indicated that the SSG starts to register the stiffness of an upper-layer material of 125 mm or thicker and the effect of the lower material may continue to be present even at an upper-layer material thickness of 275 mm, depending on the relative stiffness (or contrast) of the layer materials (Sawangsuriya et al., 2002; 2004b).

3 COMPACTION QUALITY CONTROL

Subgrade soils from seven highway construction sites in Wisconsin, U.S.A. were monitored in terms of their stiffness, dry unit weight, and moisture content (Sawangsuriya & Edil, 2004). The subgrade soils consisted of predominantly granular natural earthen materials with fines content (percent passing No 200 sieve, 0.075 mm size) up to 35% (USCS designations of SC, SC-SM, SP-SM) and also predominantly fine-grained soils with fines content greater than 59% (USCS designations of CL). Tested materials also included industrial by-products such as granular coal combustion bottom ash, foundry slag, and foundry sand (with bentonite mixed). There was also a fly ash stabilized fine-grained soil and a crushed rock of predominantly gravel size (termed "breaker run"). Some of the soils were tested after they were compacted in the field and some were in natural uncompacted state (Sawangsuriya & Edil, 2004).

Fig. 1 shows the relationship of the state of density (i.e., relative compaction, RC defined as the ratio of the field dry unit weight divided by the laboratory maximum standard Proctor dry unit weight) to the deviation of moisture content from the respective optimum moisture content ($w\text{-}w_{opt}$) for the natural subgrade soils tested. Typical compaction specifications call for RC ≥ 95%. Most of the RC of field compacted soils are from 90 to 112.5% with moisture contents dry of the optimum moisture content, whereas uncompacted soils (all CL soils) in their natural state exhibit low dry densities and much wider moisture contents including some wet of the optimum. Furthermore, RC decreases with increasing $w\text{-}w_{opt}$. Fig. 2 shows the variation of SSG stiffness (K_{SSG}) with $w\text{-}w_{opt}$ for the natural subgrade soils. Strong dependency of stiffness on moisture content is evident as stiffness varies from 2 to 12 MN/m for a moisture content deviation of about ±8% of the optimum moisture content. The compacted soils have moisture contents mostly dry of optimum. Of course, there are other factors that may affect stiffness such as dry density, texture, and soil fabric and they cause the spread in K_{SSG} for a given moisture content.

In the case of subgrade soils subjected to the same state of stress (i.e., near-surface), moisture content and dry unit weight of a test soil play significant role on its stiffness and their effects are hard to uncouple. To account for the effect of moisture content, K_{SSG} is divided by ($w\text{-}w_{opt}$). This normalized stiffness is plotted versus RC in Fig. 3. The normalized stiffness varies very little with relative compaction for compacted soils with an average value of -2.4, which can be used to estimate K_{SSG} of a wide variety of properly compacted soils. A larger variation is observed for uncompacted soils perhaps due to their more complex fabric. The implication of this for compacted soils with the typically rather narrow range of RC is that the effect of dry unit weight on stiffness is relatively minor compared to moisture content.

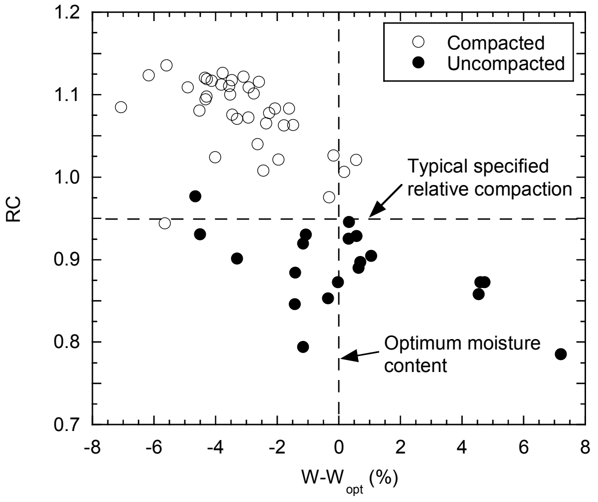

Figure 1. Relative compaction vs. deviation of moisture content from the optimum moisture content for natural earthen materials.

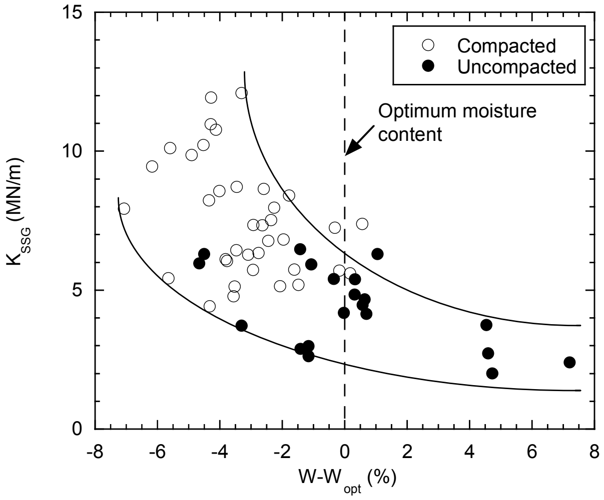

Figure 2. SSG stiffness vs. moisture content variance for natural earthen materials.

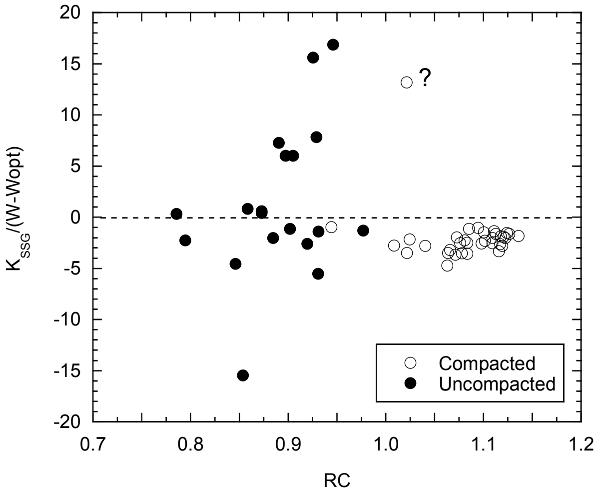

Figure 3. Normalized SSG stiffness vs. relative compaction.

According to the manufacturer, the SSG can be also used to estimate the dry unit weight from soil stiffness and an independently measured moisture content using the following analytical-empirical relationship given in Eq. 1 (Humboldt, 1999b) and thus eliminating the need for a nuclear density gauge. Since stiffness is dependent on both moisture content and dry unit weight, the moisture content must be independently acquired in conjunction with the stiffness measurement for this purpose.

$$\gamma_d = \frac{\gamma_o}{1+1.2\left(\frac{wC}{K_{SSG}}-0.3\right)^{0.5}} \qquad (1)$$

where γ_o is the idealized void-free unit weight, C is a stiffness- and moisture-dependent parameter, which is defined based on a linear relationship between C and K_{SSG}/w obtained from companion stiffness, moisture content, and dry unit weight measurements, and the other terms are as defined before. Stiffness, moisture content, and dry unit weight of various materials including industrial by-products, natural earthen materials, and fly ash stabilized soils tested were used to establish such a relationship as shown in Fig. 4. The relationship for C in terms of K_{SSG}/w given in Fig. 4 for the materials tested in this investigation is comparable in slope but slightly different in intercept from the one given by Humboldt (1999b) (i.e., the intercept is 15.41 instead of 21.01). From the measured SSG stiffness, measured gravimetric moisture content, and parameter C from Fig. 4, the dry unit weights were estimated and compared to those measured from the nuclear density gauge in Fig. 5. Compared to the line of equality, all fine-grained soils have lower estimated dry unit weights than those measured using the nuclear gauge. There is a large dispersion of the data. A comparison of gravimetric moisture contents (determined by drying a sample) with those obtained from the nuclear density gauge showed that the latter being consistently lower (Sawangsuriya & Edil, 2004). This also may be contributing to the dispersion of the data. It appears that more evaluations are needed to rely solely on dry density estimated from the stiffness measurement for construction density control. However, if this approach is reliably established, SSG can replace nuclear density device as long as moisture content is also measured. The implementation of Moisture Gauge along with SSG may be considered as a promising means for the moisture content determination in the field.

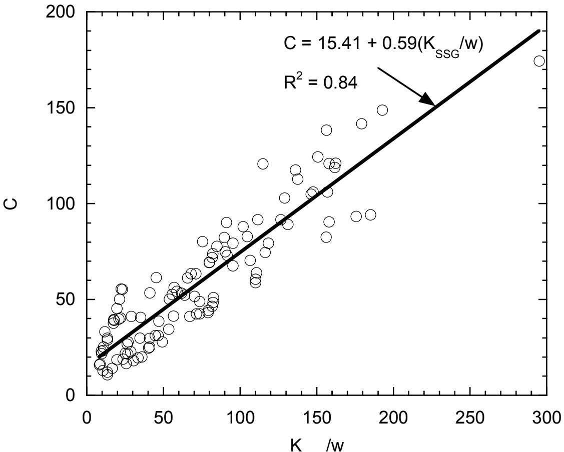

Figure 4. Relationship of C and K_{SSG}/w.

4 DESIGN PARAMETER CONTROL

In general, either the stiffness or strength of compacted earthwork is needed for design. In subgrade and subbase layers for pavement systems, typical structural property used is resilient modulus (elastic modulus under repetitive loading) and/or California Bearing Ratio (CBR). Modulus of soils can be assessed by a variety of methods and it varies with confining stress and strain amplitude. For design, a modulus corresponding to the stress and strain amplitude as well as the moisture state expected under the operating conditions is needed. SSG stiffness can be converted to an elastic modulus obtained near-surface at the moisture conditions prevailing during the measurement with an assumption of Poisson's ratio (Humboldt, 1999a). It is therefore not a modulus necessarily can be used directly in design. However, it can be used to control the structural uniformity of the earthwork and can be also viewed as an index of design modulus. In other words, the SSG stiffness or modulus can be indirectly employed as to control mechanical property for the design.

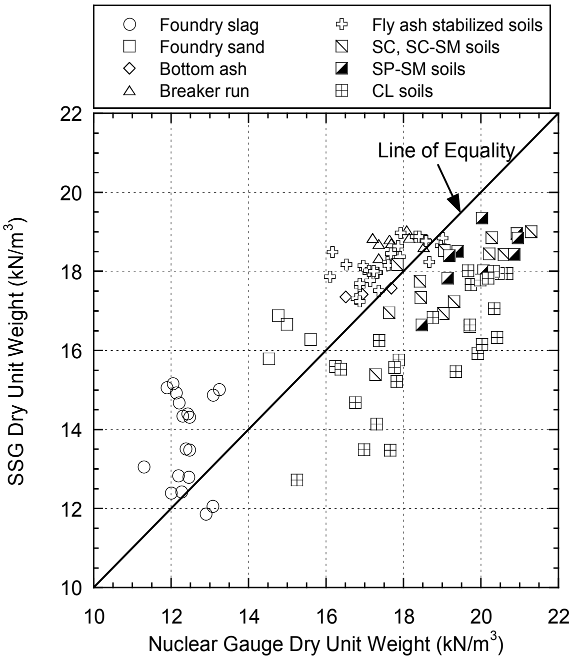

Figure 5. Comparison of dry unit weight from the SSG and the nuclear gauge.

Laboratory tests were performed to establish the general relationship of the SSG modulus with the moduli obtained from other tests on a dry sand and presented on a modulus degradation curve in Fig. 6 (Sawangsuriya et al., 2003). These moduli were determined at the same stress level (confining pressure of 2.6 kPa) over a range of strain amplitudes. The relationship of the SSG modulus to other moduli and particular to the resilient modulus can be seen. Using the modulus degradation curve, the SSG modulus can be adjusted to the modulus at any desired strain level and using the theory stress effects can be taken into account. Alternatively, a modulus ratio can be determined between the SSG modulus and the design modulus on the basis of laboratory tests. Knowing the modulus ratio, the design modulus can be reasonably determined from the measured SSG modulus (Sawangsuriya et al., 2004a). In addition to the modulus variation due to differences in stress and strain levels, one must make the necessary reductions in modulus due to local climatic (i.e., moisture) effects to arrive a design value.

A relationship between the shear strength of soils in term of the CBR and K_{SSG} was given by Sawangsuriya and Edil (2005) as follows.

$$CBR = 0.59K_{SSG}^{\;1.23};\ R^2 = 0.74 \qquad (2)$$

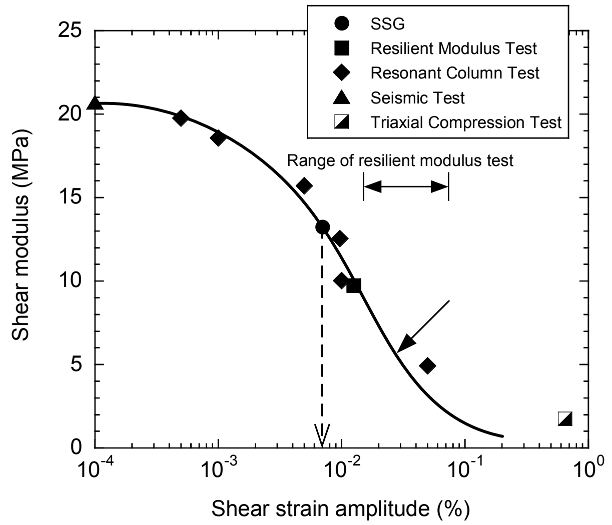

Figure 6. Modulus from different tests (Sawangsuriya et al., 2003).

Using such a relationship, the SSG stiffness can be directly converted to a design CBR and vice versa. Consequently, the CBR value can be used indirectly to control the design soil strength, which is more important during the construction stage. Note that this CBR value can be either obtained in the laboratory or by using the Dynamic Cone Penetrometer (DCP) such that there exists a widely accepted correlation between the DCP penetration index (DPI) and CBR (Webster et al., 1992; Livneh et al., 1995).

5 SUMMARY AND CONCLUSIONS

This paper presents the implementation of a non-destructive testing device called the soil stiffness gauge (SSG) for construction quality as well as design parameter control of earthwork. Use of the convenient SSG in conjunction with conventional moisture-density measurements enhances quality control by achieving more uniform structural property and aids developing a design modulus. SSG stiffness normalized by the deviation of compaction moisture content from the optimum moisture content is remarkably constant around a value equal to -2.4 for compacted natural earthen materials. There is potential for using SSG alone with an independent moisture measurement for both density and stiffness control with further evaluation.

ACKNOWLEDGEMENTS

Financial support for the study describe in this paper was provided by the Wisconsin Department of Transportation (WisDOT). Additionally, Mr. A. Sawangsuriya received financial support through a scholarship from the Royal Thai Government. The conclusions are those of the authors and do not reflect the opinions or policies of WisDOT.

REFERENCES

Fiedler, S. A., Nelson, C. R., Berkman, E. F. and DiMillio, A. F. 1998. Soil stiffness gauge for soil compaction control, *Public Roads*, U.S. Department of Transportation, Federal Highway Administration.

Humboldt Mfg. Co. 1999a. *Humboldt soil stiffness gauge (geogauge) user guide: version 3.3*, Norridge, IL.

Humboldt Mfg. Co. 1999b. *Report estimating dry density from soil stiffness and moisture content*, Norridge, IL.

Livneh, M., Ishao, I., and Livneh, N. A. 1995. Effect of vertical confinement on dynamic cone penetrometer strength values in pavement and subgrade evaluations, *Transportation Research Record 1473*, 1-8.

Livneh, M. and Goldberg, Y. 2001. Quality assessment during road formation and foundation construction: use of falling-weight deflectometer and light drop weight, *Transportation Research Record 1755*, 69-77.

Lytton, R. L. 1989. Backcalculation of layer moduli –state of the art, *Nondestructive Testing of Pavements and Backcalculation of Moduli, ASTM STP 1026*, 7-38.

Müller, C. 2003. *The light falling weight device: a new and innovative compaction testing method –theory and practice*, M.S. Thesis, Institute for Ground Engineering and Soil Mechanics, Vienna University of Technology, Austria.

Nazarian, S. and Yuan, D. 2000. Quality control of compacted layers with field and laboratory seismic testing devices, *Constructing and Controlling Compaction of Earth Fills, ASTM STP 1384*, 311-324.

Sargand, S. M., Masada, T., and Wasniak, D. L. 2000. Variability of initial subgrade modulus at Ohio SHRP test road, *Constructing and Controlling Compaction of Earth Fills, ASTM STP 1384*, 274-289.

Sawangsuriya, A., Bosscher, P. J., and Edil, T. B. 2002. Laboratory evaluation of the soil stiffness gauge, *Transportation Research Record 1808*, 30-37.

Sawangsuriya, A., Bosscher, P. J., and Edil, T. B. 2004a. Application of soil stiffness gauge in assessing small-strain stiffness of sand with different fabrics and densities, *Submitted to Geotechnical Testing Journal*, ASTM.

Sawangsuriya, A. and Edil, T. B. 2004. *Investigation of the DCP and SSG as alternative methods to determine subgrade stability*, Report No. 0092-01-05, Wisconsin Department of Transportation, Madison, WI, 93p.

Sawangsuriya, A. and Edil, T. B. 2005. Use of the soil stiffness gauge and dynamic cone penetrometer for pavement materials evaluation, *Geotechnical Engineering*, Institution of Civil Engineers, U.K. (accepted for publication).

Sawangsuriya, A., Edil, T. B., and Bosscher, P. J. 2003. Relationship between soil stiffness gauge modulus and other test moduli for granular soils, *Transportation Research Record 1849*, 3-10.

Sawangsuriya, A., Edil, T. B., and Bosscher, P. J. 2004b. Assessing small-strain stiffness of soils using the soil stiffness gauge, *Proceedings of the 15th Southeast Asian Geotechnical Society Conference*, 101-106.

Siekmeier, J. A., Young, D., and Beberg, D. 1999. Comparison of the dynamic cone penetrometer with other tests during subgrade and granular base characterization in Minnesota, *Nondestructive Testing of Pavements and Backcalculation of Moduli, ASTM STP 1375*, 175-188.

Stokoe, K. H., II and Santamarina, J. C. 2000. Seismic–wave–based testing in geotechnical engineering –state of the art, *GeoEng 2000*, 1490-1536.

Webster, S. L., Grau, R. H., and Williams, T. P. 1992. *Description and application of dual mass dynamic cone penetrometer*, Instruction Report GL-92-3, U.S. Army Engineers Moistureways Experimental Station, Vicksburg, MS, 17 p.