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Evaluation of Soil Stiffness and Strength for Quality Control of Compacted Earthwork

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***Abstract*—**Microstructure and fabric of soils play an important role on structural properties e.g. stiffness and strength of compacted earthwork. Traditional quality control monitoring based on moisture-density tests neither reflects the variability of soil microstructure nor provides a direct assessment of structural property, which is the ultimate objective of the earthwork quality control. Since stiffness and strength are sensitive to soil microstructure and fabric, any independent test methods that provide simple, rapid, and direct measurement of stiffness and strength are anticipated to provide an effective assessment of compacted earthen materials' uniformity. In this study, the soil stiffness gauge (SSG) and the dynamic cone penetrometer (DCP) were respectively utilized to measure and monitor the stiffness and strength in companion with traditional moisture-density measurements of various earthen materials used in Thailand road construction projects. The practical earthwork quality control criteria are presented herein in order to assure proper earthwork quality control and uniform structural property of compacted earthworks.

***Keywords*—**Dynamic cone penetrometer, moisture content, relative compaction, soil stiffness gauge, structural property.

I. Introduction

TYPICAL earthwork compaction acceptance criteria are based on adequate dry density of the placed earthen materials achieved through proper moisture content and compaction energy. 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. Although traditional monitoring compaction quality through moisture-density measurements (i.e., nuclear moisture-density gauge, sand cone density test etc.) is relatively simple and can be applied to generate data for a statistical evaluation of compaction quality, 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 structural properties have traditionally caused engineers to rely on the relative compaction alone. It is important to realize that the soil density is not a reliable indicator of structural property but only a quality index used to judge compaction acceptability and thus is not the most relevant property for engineering purposes. For compacted roadway, railroad, airfield, parking lot, mat foundation, subgrades and support fills, the ultimate engineering parameters of interest are often the soil stiffness and strength, which are direct structural properties for determining load support capacity and deformation characteristic in engineering design.

Stiffness and strength of compacted earthen materials are influenced by suction, moisture content, density, and compaction energy [1], [2]. Microstructure and fabric of soils also play an important role on stiffness and strength [3], which varies along the construction site, roadway route or in different parts of a burrow pit. The traditional approach based on moisture-density relationship, however, does not reflect the variability of soil microstructure and hence its stiffness and strength. Even if the compacted layers and fills satisfy the earthwork quality control requirement based on density testing, a large variability in soil stiffness and strength can still be observed [4], [5]. Additionally, the comparison between density and stiffness tests suggests that traditional density testing cannot be used to define subtle changes in the modulus of the compacted earth fills [6]. Stiffness and strength are more sensitive measure of soil microstructure and fabric uniformity than density. Since the non-uniformity of stiffness and strength is directly related to progressive failures and life-cycle cost, a simple, rapid, and direct stiffness and strength testing which can be conducted independently and in conjunction with traditional 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.

The soil stiffness gauge (SSG) and the dynamic cone penetrometer (DCP) have been successfully utilized to measure the stiffness and strength of various compacted earthen materials as well as exhibit potential for adaptation to earthwork control [3], [7]-[10]. In this study, both SSG and DCP are respectively employed to assess the soil stiffness and strength of various compacted materials used in earthwork from different road construction sites in Thailand along with traditional earthwork compaction acceptance criteria via nuclear moisture-density gauge.

II. Earthwork Quality Control Using Soil Stiffness and Strength

The soil stiffness gauge (SSG) (Fig. 1 (a)) provides direct, simple, and rapid means of in-place stiffness assessment

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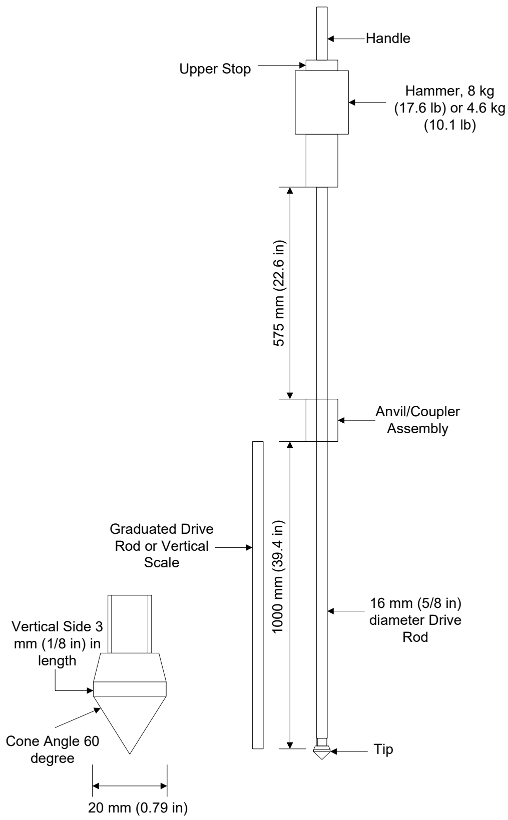
(K_{SSG}) of compacted earthen materials [7]. The dynamic cone penetrometer (DCP) (Fig. 1 (b)) is simple, rugged, economical, and able to provide a rapid in-place strength index in term of DCP penetration index (DPI) of compacted earthen materials [7]. A number of past studies [3], [7]-[10] suggested that both SSG and DCP can be effectively used in companion with traditional moisture-density measurements in order to enhance the quality control during earthwork construction. The ultimate goals of utilizing the SSG and the DCP with an independent nuclear moisture-density gauge are to achieve more uniform structural properties as well as to meet typical earthwork compaction acceptance criteria.

(a)



(b)

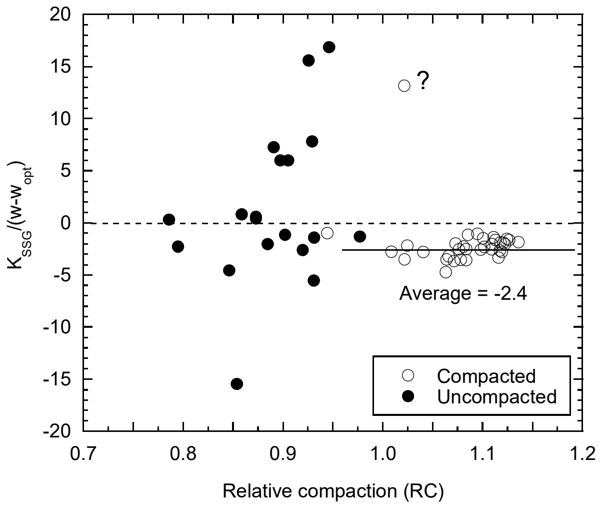
Fig. 1 (a) Soil Stiffness Gauge and (b) Dynamic Cone Penetrometer

Edil and Sawangsuriya [3] indicated that when the SSG stiffness (K_{SSG}) and the DPI are normalized with respect to the deviation of the compaction moisture content from the optimum moisture content (w-w_{opt}), constant values equal to -2.4 and -8.4 are obtained for compacted natural subgrade in Wisconsin, U.S.A. as shown in Figs. 2 (a) and (b), respectively. They also found that for compacted soils with the typically rather narrow range of RC, the effect of dry unit weight on stiffness and strength is relatively minor compared to moisture content. Their studies proposed two significant plots: (1) the normalized stiffness vs. RC and (2) the normalized strength vs. RC in order to account for the uncoupled effects of moisture content and dry unit weight on stiffness and strength of a test soil. Both normalized stiffness and strength varied fairly little with RC for properly compacted soils, while a larger variation was observed for uncompacted soils perhaps due to their more complex microstructure and fabric. Consequently, the use of the SSG and the DCP for earthwork quality control is considered a promising approach which can be accomplished by measuring K_{SSG} and (or) DPI along with an independent moisture-density measurement.

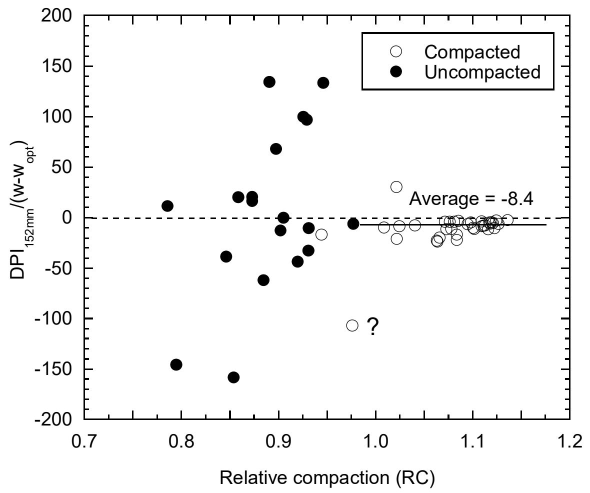
III. Test Methods and Materials

A Humboldt SSG was used to measure the in-place stiffness (K_{SSG}), in MN/m, of the compacted earthen materials in this study. The SSG stiffness measurements were made in accordance with ASTM D6758. A DCP was used to measure the in-place strength index of the compacted earthen materials in this study. The DCP penetration index (DPI), in millimeters per blow, was used to estimate the shear strength of compacted earthen materials in accordance with ASTM D6951 and was calculated by weighted averaging the DPI values across the penetration depth of 150 mm.

Disturbed earthen materials e.g. natural subgrade, sand embankment, fine-grained aggregate subbase, and crushed rock base were collected from road construction sites in Thailand [11]. They included (1) Highway No. 35: Samutsakorn-Amphoe Pakto, (2) Highway No. 351: connection to Sukhapiban 1–eastern outer ring road, and (3) Keharomkroa road development project. A summary of their index properties, soil classification, and compaction characteristics are tabulated in Table I. The particle size distribution curve is illustrated in Fig. 3. Note that according to Thailand standard and specifications for highway construction, the crushed rock base is generally classified into Grade A, Grade B, and Grade C. Each field trial strip had approximately 100-200 m long for each material type. After the compaction procedure, the SSG, DCP, and nuclear moisture-density gauge were made at every 10 m depending on the length of field trial strip. The SSG measurements were made first, followed by nuclear moisture-density gauge and DCP measurements, respectively per one test location. Every measurement was made at the adjacent location.



(a)



(b)

Fig. 2 Normalized stiffness and strength vs. relative compaction [3]

IV. Results and Discussion

As shown in Fig. 4, majority of the RC of the compacted earthen materials ranged from 85 to 110% with moisture contents dry of the optimum moisture content. The RC tended to decrease with increasing the deviation of compaction moisture content from the optimum moisture content ($w-w_{opt}$). Fig. 5 shows the variations of K_{SSG} and DPI with ($w-w_{opt}$) for the compacted earthen materials. Some dependencies of K_{SSG} and DPI on moisture content were evident for moisture contents dry of the optimum moisture content. Of course, there were other factors that affected K_{SSG} and DPI values such as dry unit weight, microstructure and fabric of soils. The dispersion in K_{SSG} and DPI for a given moisture content was attributed to these factors. The normalized K_{SSG} vs. RC and the normalized DPI vs. RC are plotted in Figs. 6 (a) and (b), respectively. Both normalized K_{SSG} and DPI values varied within a range of -10.0 and 0.0 for compacted earthen materials. Results are remarkably consistent with the previous studies [3], where the normalized K_{SSG} and DPI was remarkably constant around -2.4 and -8.4, respectively for compacted natural subgrade in Wisconsin, U.S.A.

Typical earthwork compaction specifications call for RC $\geq$ 95% of the maximum dry density based on the standard or the modified Proctor compaction test. The reason for this is to ensure that the void space is kept to a practical minimum to limit water content changes due to post-construction environmental conditions. Ultimately, it is the moisture content that has significant role on the structural properties and needs to be limited after construction. For the structural properties evaluation for earthwork quality control, the stiffness and strength must be pre-specified. This study highlighted the implementation of the normalized stiffness and strength indices in term of $K_{SSG}/(w-w_{opt})$ and $DPI/(w-w_{opt})$, which were previously introduced by Edil and Sawangsuriya [3]. For a properly compacted earthen material, such pre-specified normalized indices falling within -10.0 to 0.0 may imply proper earthwork quality control and structural uniformity of compacted earthen materials.

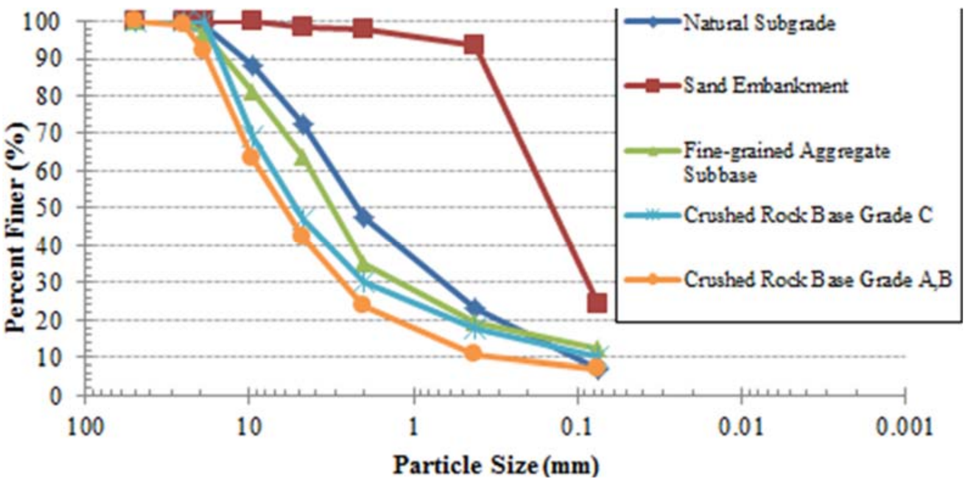


Fig. 3 Particle size distribution curve

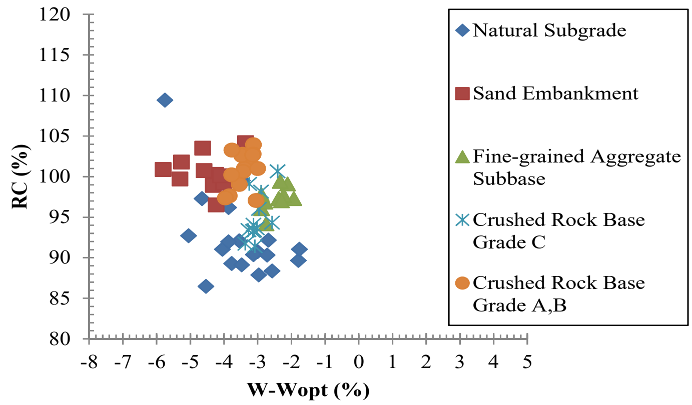
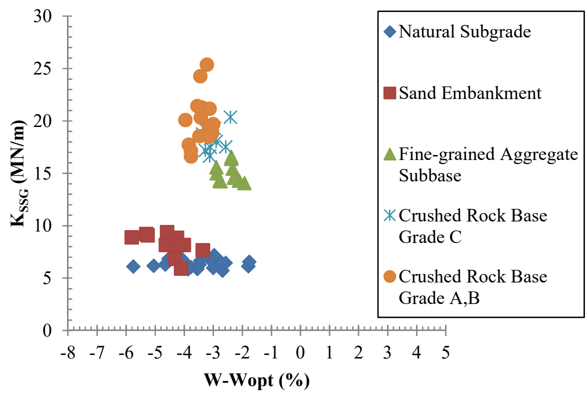


Fig. 4 Relative compaction vs. deviation of moisture content from the optimum moisture content



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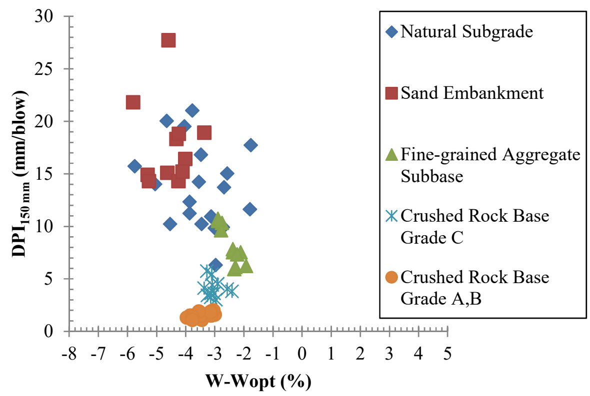


(b)

Fig. 5 K_{SSG} and DPI_{150mm} vs. moisture content variance

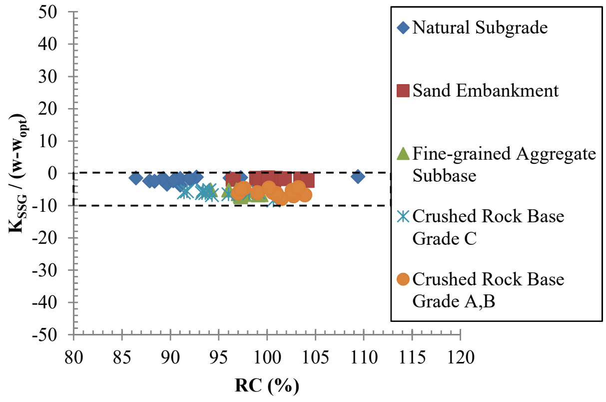
V. Conclusions

Earthwork quality control through the application of simple, rapid, and direct stiffness and strength tests in conjunction with traditional moisture-density measurements has been introduced by Edil and Sawangsuriya [3]. This paper extends the practical implications of two non-destructive testing devices called the soil stiffness gauge (SSG) and the dynamic cone penetrometer (DCP) for earthwork quality control in a variety of earthen materials covering a significant range e.g. natural subgrade, sand embankment, fine-grained aggregate subbase, and crushed rock base collected from different road construction sites in Thailand. Both SSG stiffness (K_{SSG}) and DPI normalized by the deviation of compaction moisture content from the optimum moisture content varied within a range of -10.0 and 0.0 for compacted earthen materials, which are remarkably consistent with Edil and Sawangsuriya [3]. The normalized K_{SSG} and DPI indices falling within a specified range may imply proper earthwork quality control and uniform structural property of compacted earthen materials. Finally, such pre-specified normalized indices can be adopted along with typical earthwork compaction acceptance criteria for a practical earthwork quality control to assure structural uniformity and thus the post-construction performance of compacted earthwork.

TABLE I
Properties of Disturbed Earthen Materials

Properties	Natural Subgrade	Sand Embankment	Fine-grained Aggregate Subbase	Crushed Rock Base Grade C	Crushed Rock Base Grade A,B
AASHTO Classification	A-2-7	A-3	A-2-4	A-1-a	A-1-a
50.0 mm (1½")	100	100	100	100	100
25.0 mm (1")	100	100	100	100	98.9
19.0 mm (3/4")	98.7	100	96.6	100	91.8
9.5 mm (3/8")	88.0	100	81.3	69.0	63.3
No. 4	72.2	98.5	63.8	47.0	42.1
No. 10	47.8	97.8	35.3	30.0	23.6
No. 40	23.2	93.6	19.6	18.0	10.5
No. 200	6.7	24.1	12.4	10.0	6.9
D_{10} (mm)	0.12	0.055	0.051	0.86	0.29
D_{30} (mm)	0.7	0.085	1.4	2.0	3.0
D_{60} (mm)	3.0	0.18	4.1	7.5	9.0
LL (%)	44.6	N.P.	N.P.	N.P.	N.P.
PI (%)	34.8	N.P.	N.P.	N.P.	N.P.
Opt moisture content (%)	14.5	9.5	5.4	5.7	6.0
Max dry unit weight (kN/m^3)	18.4	19.4	23.2	23.1	23.4
Specific gravity (G_s)	2.62	2.67	2.72	2.72	2.72
Soaked CBR (%)	3	26	58	83	105
Swell (%)	2.5	-	-	-	-

N.P. = Non-plastic



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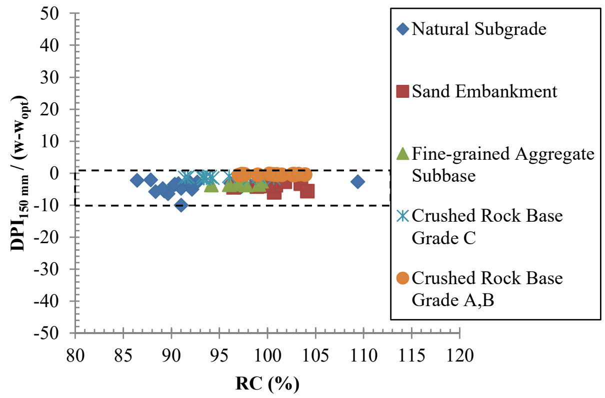

(b)

Fig. 6 (a) Normalized K_{SSG} vs. relative compaction and (b) normalized DPI_{150mm} vs. relative compaction

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