

Soil moisture and strength index for earthwork construction quality control

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Abstract. This paper presents the implementation of soil moisture and strength index measurements for earthwork construction quality control as well as a link between the in situ testing and structural property of earthen materials. Use of the convenient Dynamic Cone Penetrometer (DCP) in conjunction with conventional moisture-density measurements enhances quality control by achieving acceptable level of compaction, more uniform structural properties, and aids developing a controlled design parameter during the earthwork construction. Soil strength in term of DCP index normalized by the deviation of compaction moisture content from the optimum moisture content is proposed as performance criteria for a variety of engineered earth fills and special engineering assessment, prevention, and mitigation of geohazards e.g. earthen flood defense embankments.

1. Introduction

Typical earthwork compaction acceptance criteria are based on specified target dry density of the placed earthen materials achieved through proper moisture content. 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.

The difficulty and expense of acquiring quality relevant structural properties have traditionally caused engineers to rely on density tests. The relative compaction alone is not a reliable indicator of the structural properties of compacted earthen materials. In addition, the relative compaction is only a quality index used to judge compaction acceptability and is not the most relevant property for engineering purposes. For engineered earth fills and special engineering assessment, prevention, and mitigation of geohazards e.g. earthen flood defense embankments, 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.

Since the non-uniformity of structural property is directly related to progressive failures and life-cycle cost, a simple, rapid, and direct structural property testing which can be conducted

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independently and in companion 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 earth fills. This paper presents the implementation of strength index from the Dynamic Cone Penetrometer (DCP) in conjunction with the conventional compaction control and moisture content measurements for earthwork construction quality control and structural performance of engineered earth fills.

2. Structural property measurement for earthwork quality control

Edil and Sawangsuriya [1] adopted the Soil Stiffness Gauge (SSG) for assessing the soil stiffness of various materials used for the earth fills from different construction sites around the state of Wisconsin, U.S.A. along with the conventional approach of moisture-density control. They investigated the variation of SSG stiffness with the relative compaction (RC) and the deviation of moisture content from the respective optimum moisture content ($w-w_{opt}$) for the natural subgrade soils tested. To account for the effect of moisture content, Edil and Sawangsuriya [1] also proposed a plot of K_{SSG} divided by $(w-w_{opt})$, i.e., normalized stiffness, as a function of RC. They indicated that the normalized stiffness varied very little with RC for compacted soils, while a larger variation was observed for uncompacted soils. The implication of this for compacted soils with the typically rather narrow range of RC was that the effect of compaction levels on stiffness was relatively minor compared to moisture contents [1].

Taesiri *et al.* [2] examined the use of the SSG and the DCP for assessing the in-place stiffness and strength index of pavement layer materials, respectively in the highway construction projects around the city of Bangkok, Thailand. The SSG stiffness and DPI were also correlated with the elastic modulus (E) and California bearing ratio (CBR) of the earthen materials, respectively. A good correlation was obtained between E -value from the SSG and CBR from the DCP [2]. Their studies indicated that both devices exhibited good potential for future implication in the pavement material evaluation. The in-place stiffness and strength properties of various earthen materials can be rapidly and directly monitored in companion with the conventional moisture-density measurements during earthwork construction. Direct monitoring of stiffness and strength of the pavement materials using these two devices appeared to be an effective approach during construction quality control monitoring [2].

According to Thailand Department of Highways (DOH)'s quality control criteria and construction specifications, Wachiraporn *et al.* [3] recommended the DCP for assessing the structural uniformity of layer thickness and routine earthwork quality control evaluation in companion with the conventional moisture-density control test during highway construction in Thailand. Wachiraporn *et al.* [4] suggested an adoption of the DCP as a mechanistic quality control tool during highway construction as well as future development for performance specifications. Based on their studies conducted in the laboratory test box and in the field trial, the DCP provided instantaneous in-place strength index monitoring in term of DCP penetration index (DPI) for earthwork quality control and also exhibited good potential for quality control monitoring of the earthen materials [4]. In addition, Wachiraporn *et al.* [4] studies suggested that the CBRs estimated from the DCP were considerably smaller than the field CBRs (ASTM D4429), while the laboratory unsoaked CBR (ASTM D1883) tended to give the highest value.

3. Test materials and methods

Disturbed earthen materials e.g. natural subgrade, sand embankment, lateritic soil subbase, fine-grained aggregate subbase, and crushed rock base were collected from highway construction sites in Thailand [6]. 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 1. The particle size distribution curve is illustrated in Figure 1. Note that according to

Thailand DOH's standard and specifications, the crushed rock base used in the highway construction is generally subdivided into Grade A, Grade B, and Grade C.

Table 1. Material properties and their classification.

Material Classification and Properties	Natural Subgrade	Sand Embankment	Lateritic Soil Subbase	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-2-4	A-1-a	A-1-a
50.0 mm (1½")	100	100	100	100	100	100
25.0 mm (1")	100	100	97.7	100	100	98.9
19.0 mm (¾")	98.7	100	93.0	96.6	-	91.8
9.5 mm (3/8")	88.0	100	68.8	81.3	69.0	63.3
No. 4	72.2	98.5	40.1	63.8	47.0	42.1
No. 10	47.8	97.8	24.8	35.3	30.0	23.6
No. 40	23.2	93.6	16.4	19.6	18.0	10.5
No. 200	6.7	24.1	8.1	12.4	10.0	6.9
D ₁₀ (mm)	0.12	0.055	0.1	0.051	0.86	0.29
D ₃₀ (mm)	0.7	0.085	3.0	1.4	2.0	3.0
D ₆₀ (mm)	3.0	0.18	7.3	4.1	7.5	9.0
LL (%)	44.6	N.P.	23.4	N.P.	N.P.	N.P.
PI (%)	34.8	N.P.	7.6	N.P.	N.P.	N.P.
W _{opt} (%)	14.5	9.5	6.5	5.4	5.7	6.0
γ _{dry, max} (t/m ³)	1.84	1.94	2.25	2.32	2.31	2.34
CBR (%)	3	26	27	58	83	105
Swell (%)	2.5	-	0.35	-	-	-

N.P. = Non-plastic

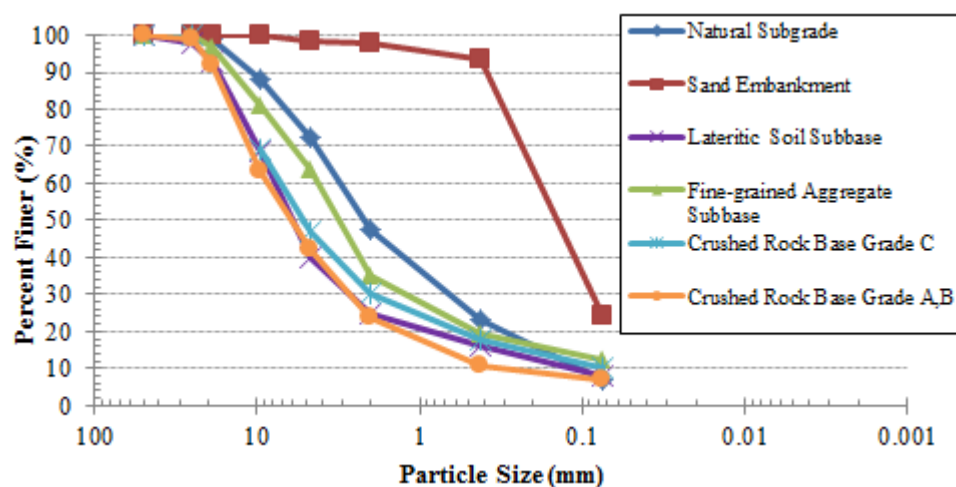


Figure 1. Particle Size Distribution Curve

A DCP was selected to measure the strength index of the earthen materials at these sites. Each field trial had approximately 100-200 m long. The DCP measurements were made at every 10 m depending on the length of field trial. The DCP was simple, rugged, economical, and able to provide a rapid in-place index of strength of earthen materials. It was used for measuring the material resistance to penetration while the cone of the device is being driven into the earth structure. The number of blows during operation was recorded with depth of penetration. The slope of the relationship between number of blows and depth of penetration (in millimeters per blow) at a given linear depth segment was recorded as DCP penetration index (DPI) [5].

Since DCP testing was basically a measure of penetration resistance, expressed as DPI, the analysis of the DCP data must be interpreted to generate a representative value of penetration per blow for the material being tested. In this study, such representative value was obtained by averaging the DPI across the penetration depth of 150 mm. Two methods of calculating the representative DPI value for a penetration depth of 150 mm are: (i) arithmetic average and (ii) weighted average [5]. Since the weighted average method yielded narrower standard deviation for the representative DPI value and provided better correlations to other field tests than the arithmetic average method based on field data available [5]. Thus, the weighted average method was adopted to calculate the representative DPI value in this study. The weighted average method can be obtained as follows:

$$DPI = \frac{1}{H} \sum_i^N [(DPI)_i \cdot (z)_i] \quad (1)$$

where z is the penetration distance per blow set and H is the overall penetration depth (e.g. 150 mm). After the compaction procedure, the DCP in companion with conventional moisture-density measurements using the nuclear gauge (ASTM D6938) were conducted instantaneously for each material. Every measurement was made at the adjacent location.

4. Results and Discussion

Earthen materials from three highway construction sites in Thailand were monitored in terms of their DPI_{150mm} , dry unit weight, and moisture content [6]. Figure 2 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/modified Proctor dry unit weight) to the deviation of moisture content from the respective optimum moisture content ($w-w_{opt}$) for earthen materials tested. Typical DOH compaction specifications call for $RC \geq 95\%$. Most of the RC of field compacted earthen materials were ranged from 87 to 104% with moisture contents dry of the optimum moisture content, except the lateritic soil subbase having moisture contents wet of optimum moisture content. Furthermore, RC tended to decrease with increasing $w-w_{opt}$. Figure 3 shows the variation of DPI_{150mm} with $w-w_{opt}$ for the earthen materials. Excluding the crushed rock base, a strong dependency of DPI_{150mm} on moisture content was evident as DPI_{150mm} varied from 5 to 30 mm/blow for a moisture content deviation of about -6% to +2% of the optimum moisture content. The compacted earthen materials had moisture contents mostly dry of optimum. Of course, there were other factors that affected DPI_{150mm} such as dry unit weight, texture, and soil fabric and they caused the spread in DPI_{150mm} for a given moisture content.

In the case of earthen materials, moisture content and dry unit weight of a test material played significant role on its DPI_{150mm} and their effects are hard to uncouple. To account for the effect of moisture content, DPI_{150mm} was divided by $(w-w_{opt})$. This normalized DPI_{150mm} was plotted versus RC in Figure 4. The normalized DPI_{150mm} varied very little with RC for compacted earthen materials within a narrow range of ± 10 . It should be noted that those data set having moisture contents near the optimum moisture content ($w-w_{opt} \leq 1\%$) were excluded from the plot as the soil was theoretically in the optimum state of density and moisture. Results were consistent with the previous study [1], which indicated that the normalized stiffness (e.g. K_{SSG} divided by $(w-w_{opt})$) varied very little with RC for compacted soils. Data from Edil and Sawangsuriya [7] were revisited and re-evaluated to develop a plot of the normalized DPI_{150mm} as a function of RC. The normalized DPI_{150mm} was remarkably

constant around -8.4 for compacted soils. Results obtained can be used to establish the performance criteria for a variety of properly compacted engineered earth fills. The implication of this for compacted earth fills with the typically rather narrow range of RC was that the effect of dry unit weight on the strength index was relatively minor compared to moisture content. In addition, those data falling within the proposed envelope indicated proper compaction quality control process and consequently uniform structural properties (e.g. stiffness and strength).

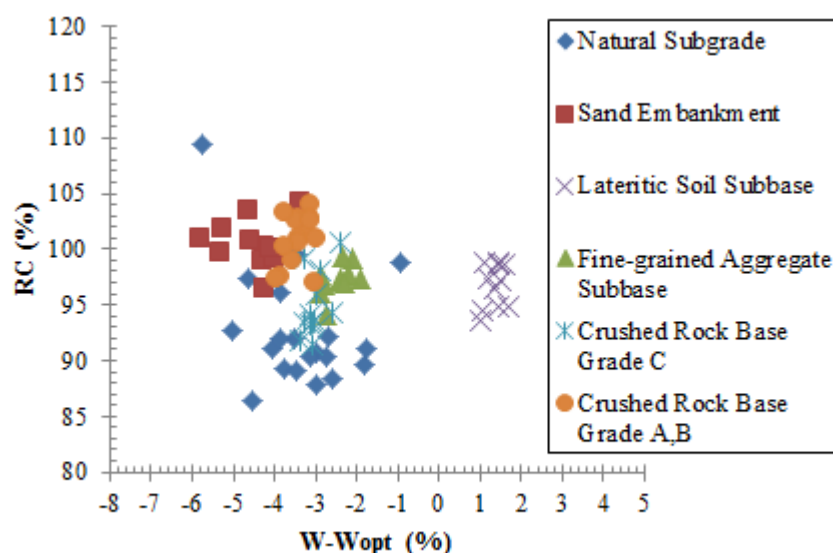


Figure 2. Relative compaction vs. deviation of moisture content from the optimum moisture content for earthen materials tested.

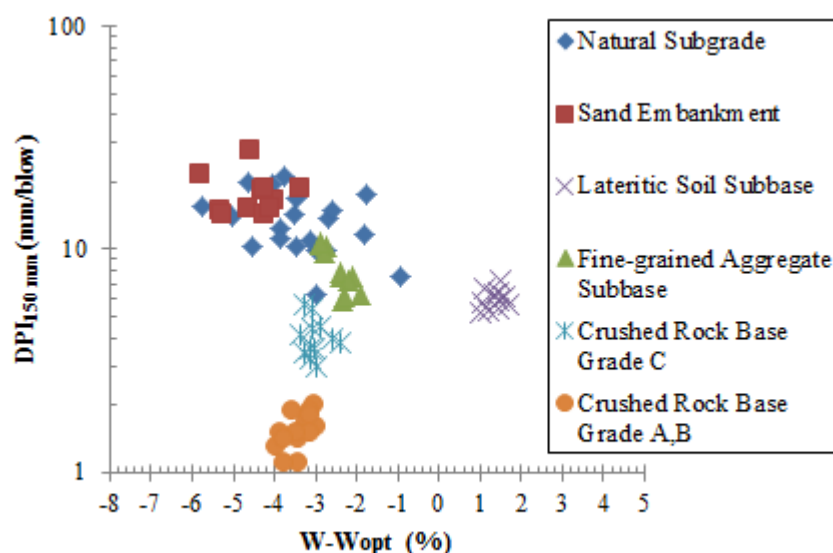


Figure 3. DPI_{150mm} vs. moisture content variance for earthen materials tested.

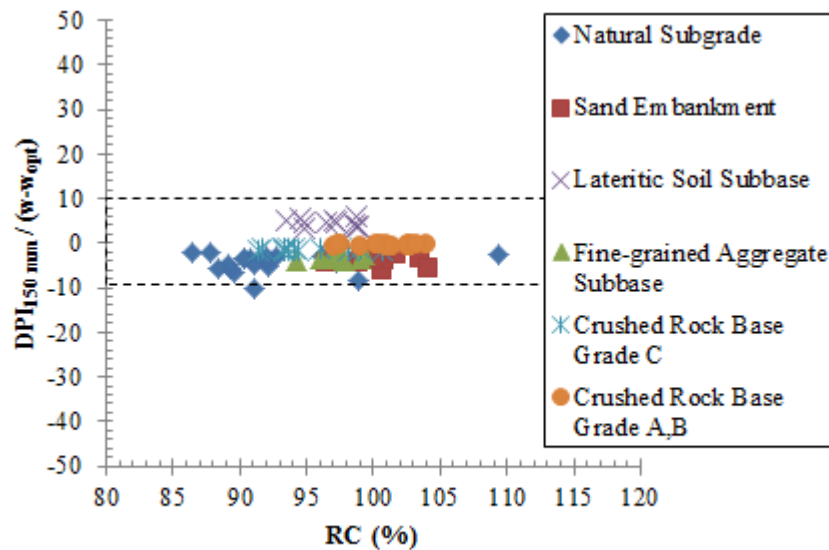


Figure 4. Normalized DPI_{150mm} vs. relative compaction.

5. Conclusions

This paper presents the implementation of soil moisture and strength index from the Dynamic Cone Penetrometer (DCP) measurements for earthwork construction quality control as well as structural performance of engineered earth fills. Use of the convenient DCP in companion with conventional moisture-density measurements enhances quality control by achieving more uniform structural property and aids developing a controlled design parameter during the earthwork construction. DPI_{150mm} normalized by the deviation of compaction moisture content from the optimum moisture content varied within a narrow range of ± 10 for compacted earthen materials and was proposed as performance criteria for a variety of properly compacted engineered earth fills and special engineering assessment, prevention, and mitigation of geohazards e.g. earthen flood defense embankments.

References

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