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Energy concept and soil compression

Concept d'énergie et compression de sol

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ABSTRACT

Energy exchanges universally exist in all the formation of soils. Work done on soils by various external agents can either harden or soften soils, depending on initial and boundary conditions of soil media. This paper focuses on the absorbed energy of compacted samples from three soils and the variation of their volume-mass properties during compaction processes. The relation of the absorbed energy with dry unit weight and degree of saturation during compaction process was present to illustrate the influence of soil's types and initial moisture content on compaction efficiency. The variation of matric suction of soil samples during compaction, along with the variation of vertical compression stress, was approximated, which provides some insights into the mechanism of soil compaction and will be helpful in predicting the engineering performance of compacted soils. The absorbed energy is also proved to be an effective indicator of shear strength of compacted soils, which is in turn closely associated with dry unit weight and moisture content of compacted soils.

RÉSUMÉ

Les échanges d'énergie existent universellement dans toute la formation des sols. Travaillez fait sur des sols par de divers agents externes peut durcir ou ramollir des sols, selon des conditions d'initiale et de frontière des médias de sol. Cet article se concentre sur l'énergie absorbée des échantillons compacts provenant de trois sols et la variation de leurs propriétés de la volume-masse pendant les processus de tassement. La relation de l'énergie absorbée avec la densité sèche et avec le degré de saturation pendant le processus de tassement était présente pour illustrer l'influence des types du sol et du contenu d'humidité initial sur l'efficacité de tassement. La variation de l'aspiration matric des échantillons de sol pendant le tassement a été rapprochée, qui fournit quelques perspicacités dans le mécanisme du tassement de sol et sera utile en prévoyant l'exécution de technologie des sols compacts, avec la variation de l'effort vertical de compression. On s'avère qu'également l'énergie absorbée est un indicateur efficace de la résistance au cisaillement des sols compacts, qui alternativement est étroitement associée à la densité sèche et à la teneur en humidité des sols compacts.

1 INTRODUCTION

The formation of soil structures always involves energy exchanges, such as those occurring during soil compaction, consolidation under overburden pressures, and sedimentation. Concurrent with energy changes are the changes in soil's physical and mechanical properties.

However, Most of past energy-based methods confined themselves to describe the weakening phase of soils by energy exchange, such as liquefaction during earthquakes (Nemat-Nasser and Shokooh 1979; Berrill and Davis 1985; Figueroa et al. 1994; Tao 2003), disturbance of soils during pile driving, laboratory and field tests to determine shear strength of soils. The exchange of energy also hardens or strengthens soils, such as in the compaction of earth fill materials at an embankment or a retaining wall or in the consolidation of soils under overburden pressures. The contribution of energy exchange to the strengthening phase of soils has received limited attention and is rarely investigated independently. Thus its influence on the mechanical behavior of soils is far from understanding. This paper presents some preliminary results on the relationship between the absorbed energy (Zhang et al. 2005b) and soil physical and mechanical properties. The concept of the absorbed energy is defined as the external work absorbed by soils during soil structural formation. Although a variety of processes involving energy exchanges exist during soil structural formation, only those during soil compaction are of concern in this paper. Mechanical compaction fundamentally causes the expulsion of air from soil voids and the densification of soil structures. Various researchers (Hilf 1956; Lamb 1958) have extensively studied soil compaction and many of them had attempted to explain compaction mechanisms. This paper will re-examine this process through the point view of the absorbed energy concept.

2 LABORATORY TESTS

2.1 *Testing materials*

Three soil types, designated as soil I, II, and III in the following sections, were tested in this study and their physical properties are summarized in Table 1. All of these physical indices were determined in accordance with their respective ASTM procedures. Their particle size distribution curves are shown in Fig. 1. Moisture content and dry unit weight relationships for tested soils were determined by standard Proctor procedure and are plotted in Fig. 2. Accordingly, USCS and AASHTO classifications for these soils were: soil I-CL/A-6, Group Index 11, soil II-CL/A-7, Group Index 10, and soil III-CH/A-7.

Table 1. Physical Indices of Tested Soils

Soil Type	Soil I	Soil II	Soil III
Silt (%)	64.5	30.6	13.7
Clay (%)	27.5	27.9	81.9
LL	34	37	83
PI	12	22	49
w_{opt}(%)	17.5	13.5	33.1
G_s	2.65	2.72	2.73
γ_{dmax} (kN/m^3/pcf)	17.0/108	18.7/119	13.3/85
GI	11	10	5
Classification	CL/A-6	CL/A-7	CH/A-7

Note: LL=liquid limit; PI=plastic index; and GI=group index.

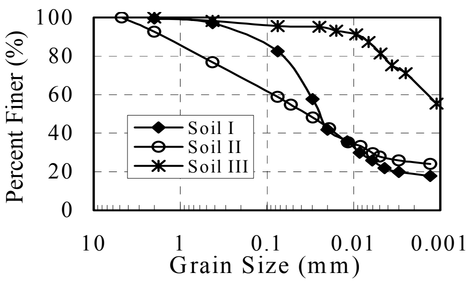

Figure 1. Particle Size Distribution of Tested Soils

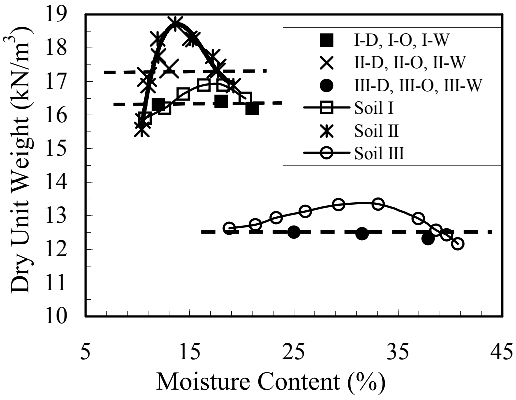

Figure 2. Standard Compaction Curves of Tested Soils

2.2 *Test method*

Specimens with different moisture contents were prepared for the three tested soils using a “compression” (static compaction) procedure in this study. The "compression" procedure was described in detail by Zhang et al. (2005a).

A computer automatically recorded applied compressive force and the deformation of samples during the sample preparation. Thus, this method also made it possible to determine the absorbed energy of each specimen during the sample preparation process. The amount of work done by the hydraulic jack on the sample, which is equivalent to the energy absorbed by the soil specimen, can be readily calculated by integrating the recorded force-displacement curve. Each of these samples was subsequently tested for unconfined compressive strength (ASTM D2166).

3 RESULT ANALYSES

3.1 *Volume-Mass Variation during Compression*

The increase in dry unit weight as a soil specimen absorbed more external energy can be readily calculated for the whole compression process using the recorded force-displacement curve. Figure 3 shows the relations among soil dry unit weight, degree of saturation, and absorbed energy in soil I. Three samples from each tested soils, molded at the dry of optimum, optimum, and wet of optimum conditions, were used to illustrate the variation of their dry unit weights and of the degree of saturation during sample preparation processes. The three specimens are designated I-D for the dry side of optimum, I-O for the optimum, and I-W for the wet side of optimum. They all reached the same final dry unit weight of 16.4 kN/m^3, which is 96% of the maximum dry unit weight. Similar results were obtained for soils II and III except that dry unit weight and degree of saturation varied with the absorbed energy at different rates.

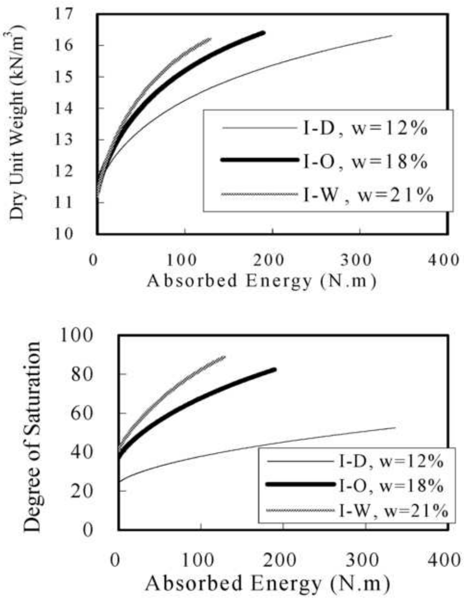

Figure 3. Variation of Dry Unit Weight and of Degree of Saturation during compression for Soil I

It can be noted in general that for different moisture contents, dry unit weight increased as the absorbed energy increased but at a gradually decreasing rate. This can be explained by the fact that the closer soil particles are, the higher particle repulsions are resulted (Mitchell 1993; Yong and Warkentin 1966), resulting in less effectiveness of compression energy. This figure also indicates that the rate of increase in dry unit weight increased with initial moisture content. This was due to lower matric suctions present in samples molded at the wet of optimum and at the optimum than those at the dry of optimum, which provided less resistance against compression.

For samples I-D, I-O, and I-W, the absorbed compaction energies were 128, 189, and 336 Nm, respectively, resulting in an incremental dry unit weight of 5.14 kN/m^3 (from 11.27 to 16.41kN/m^3). Similarly, the degree of saturation increased in general with the absorbed energy, at an ascending order for the samples molded at the dry of optimum, optimum, and wet of the optimum. It was a coupled phenomenon with the increase in dry unit weight, as shown in Fig. 3. Figure 3 indicates that initial moisture content significantly affected the rate at which the degree of saturation increased with the absorbed energy. The efficiency of compaction in terms of the absorbed energy was also depended on initial moisture content and the type of soils.

3.2 *Stress History during Compression*

The vertical stress during the compression process can also be readily calculated from recorded compression forces. A model proposed by Fredlund and Xing (Fredlund and Xing 1994) for unsaturated soils can approximate the matric suction during this process, which is given as:

$$\theta_W = \left[\frac{\theta_S}{\left[\ln\left[\exp(1)+\left(\frac{h}{a}\right)^b\right]\right]^c}\right] \qquad (1)$$

Where: θ_w = volumetric moisture content; a = a soil parameter which is a function of the air entry value of the soil, in kPa; b = a soil parameter which is a function of the rate of water extraction from the soil, once the air entry value is exceeded; c = a soil parameter which is a function of residual moisture content.

The parameters a, b, and c in Eq. (1) were approximated by the empirical equations developed by Zapata et al. (2000), which are given in Eqs. (2-a) to (2-d):

$$a = 0.0364(wPI)^{3.35} + 4(wPI) + 11 \qquad (2\text{-a})$$

$$\frac{b}{c} = -2.313(wPI)^{0.14} + 5 \qquad (2\text{-b})$$

$$c = 0.0514(wPI)^{0.465} + 0.5 \qquad (2\text{-c})$$

$$wPI = \text{Passing \#200 x PI} \qquad (2\text{-d})$$

Where: Passing #200= Material passing through the #200 sieve, in decimal; and PI= Plasticity index, in percentage.

The approximation of matric suction implicitly presumed the negligible influence of void ration on matric suction. The relationship between net vertical stress ($\sigma_v - u_a$, σ_v =vertical stress due to compression, u_a =atmospheric pressure), matric suction, and void ratio can be plotted in a three-dimensional coordinate, as shown in Fig. 4 for soil I. Similar trends were obtained during the compaction of soils II and III.

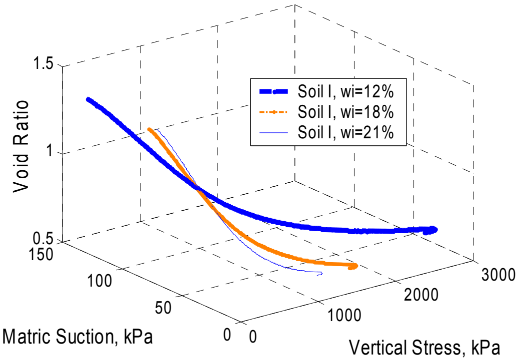

Figure 4. Relationship between Net Vertical Stress-Matric Suction-Void Ratio during Sample Compression for Soil I

Generally, void ratio and matric suction consistently decreased with the increase in net vertical stress. For each soil, the rate at which matric suction decreased was affected by initial moisture content. This was probably due to the difference in soil microstructures formed at different moisture content. The change range of matric suction during the compression was largely dependent on the type of soils, reducing from about 130 kPa to less than 10 kPa for soil I, from about 200 kPa to less than 10 kPa for soil II, and from about 7000 kPa to 200 kPa for soil III. As expected, higher matric suction was associated with soils with higher PI values. Although certain assumptions and uncertainties were associated with the approximation of matric suction, the relationships illustrated in Fig. 4 provide some insights into the mechanisms underlying the compaction process of soils.

3.3 *Unconfined Compressive Strength (UCS)*

The change of soil physical properties due to the absorption of more external energy eventually changes soil strength (Zhang et al. 2005b). Figure 5 shows the specimens for UCS tests for the three soil types. The specimens were prepared using the method discussed previously with predetermined moisture contents and dry unit weights.

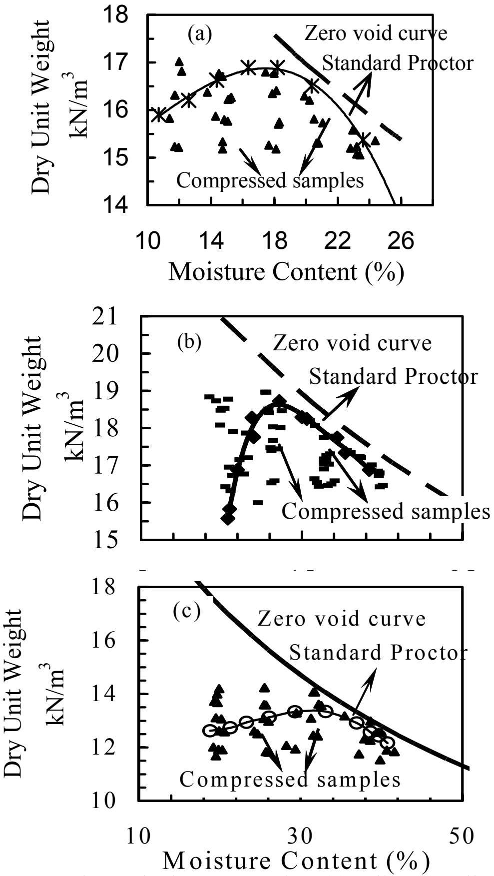

Figure 5. Tested Samples by Compression: (a) Soil I; (b) Soil II; and (c) Soil III

3.3.1 *Absorbed Energy versus UCS*

Figure 6 shows the linear correlation between the energy absorbed by specimens and their UCS. UCS in general increased as the compaction energy absorbed by specimens increased. The regression equations between UCS and the absorbed energy for soils I, II, and III are as follows:

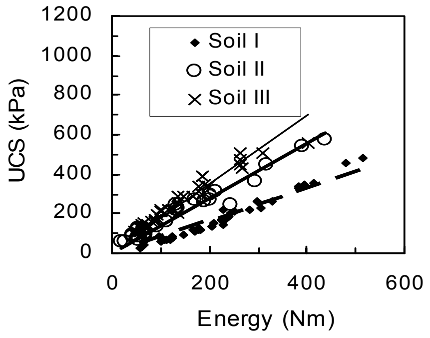

Figure 6. Unconfined Compression Strength versus Absorbed Energy

For soil I: $UCS = 1.193W \qquad R^2 = 0.938 \qquad (3)$

For soil II: $UCS = 1.377W \qquad R^2 = 0.943 \qquad (4)$

For soil III: $UCS = 1.747W \qquad R^2 = 0.918 \qquad (5)$

Where UCS is in kPa and W is the work done on the sample during compaction in Nm.

Figure 6 also illustrates that the efficiency of converting the absorbed energy into compressive strength is soil-dependent. It appears that a soil with a higher PI had a higher energy conversion.

3.3.1 *CS versus Dry Unit Weight and Moisture Content*

Experimental results were also analyzed to correlate soil UCS with their dry unit weight and moisture content. Based on the test data, regression equations are given (Zhang et al. 2005b) as:

For soil I: $UCS = w^{-1.17}(3295.7\gamma_d - 47001) \quad R^2 = 0.901$ (6)

For soil II: $UCS = w^{-1.94}(13921\gamma_d - 209710) \quad R^2 = 0.860$ (7)

For soil III: $UCS = w^{-0.9}(321.55\gamma_d - 3457.5) \quad R^2 = 0.891$ (8)

Where γ_d is dry unit weight in kN/m^3 and w is moisture content in percentage.

3.4 *Absorbed Energy versus Dry Unit Weight and Moisture Content*

The absorbed energy of specimens has changed the indices of soil's weight-volume relations. Of all the indices, only three are independent (i.e. G_s, w, γ_d). Since the specific gravity, G_s, is constant for a given soil, moisture content, w, and dry unit weight, γ_d, should correlate well with the absorbed energy. Regression equations correlating the energy absorbed by soil specimens with their dry unit weight, γ_d, and moisture content, w, proved this hypothesis. These equations were the results of a direct correlation analysis between the absorbed energy, W , and soil indices, given as follows:

For soil I: $W = w^{-1.94}(24437\gamma_d - 353368) \quad R^2 = 0.910$ (9)

For soil II: $W = w^{-1.76}(7351.9\gamma_d - 114145) \quad R^2 = 0.778$ (10)

For Soil III: $W = w^{-0.9}(1361.6\gamma_d - 15011) \quad R^2 = 0.870$ (11)

The symbols as well as their units in the above two equations are the same as those in Equations 3 to 8.

4 CONCLUSIONS

The energy absorbed during soil compression was stored as permanent displacement of soil particles, and it resulted in an increase in soil dry unit weight, an increase in degree of saturation, and a decrease in soil void ratio physically. These physical changes caused a reduction in soil suction potential and an improvement in soil unconfined compressive strength mechanically. Therefore, soil compression was an energy absorption process that changes soil physical and mechanical properties. The efficiency of the absorbed energy in changing soil physical and mechanical properties depended on soil types and initial moisture content. Since soil's unconfined compressive strength as well as its physical status, such as dry unit weight and moisture content, correlates well with the absorbed energy during soil structure formation, it is reasonable to predict that the absorbed energy is one of the major factors that may control other soils engineering properties. The absorbed energy concept provides a novel approach to predict soil's strength and deformation. More research efforts are required to validate or refine the observations obtained from this preliminary study, and to explore the use of this absorbed energy concept in some other seemingly unrelated phenomena in soil mechanics.

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