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Effect of compaction conditions and fines content on cyclic undrained strength of saturated soils

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ABSTRACT

This study investigates cyclic undrained strength of five types of sandy/silt soils that have various fines contents and are compacted at different combinations of molding water content and dry density. Results of conventional cyclic undrained triaxial testing of saturated compacted soils are compared. The study also investigates fabrics of the soil specimens compacted at different molding water contents using X-ray tomography imaging. The results show that the cyclic undrained strength properties are significantly influenced by the molding water content and dry density, but the trend differs depending on the fines content of compacted soils. In this paper, as a promising way to evaluate the cyclic undrained strength of compacted soils that have different fines contents and thus compaction properties, we describe the cyclic undrained strength as a function of the degree of saturation and dry density.

1. Introduction

The seismic stability of compacted soil structures, such as road and railway embankments, river and costal dykes, residential fills, earth-fill dams etc. is often evaluated based on the cyclic undrained stress-strain properties of saturated soil. The cyclic undrained stress-strain properties are strongly influenced by the compacting conditions, primarily the water content and dry density of compacted soil and microstructure derived from the compaction. Satisfactory seismic stability is achieved with sufficient compaction to make the degree of compaction higher than a specific minimum dry density. As a result, to clarify a relationship between cyclic undrained stress-strain properties and compacting conditions of soil is of great importance. This is the motivation for the work described here.

The relationship between the mechanical properties of compacted soils and their compacting conditions is often investigated. Prior works show that molding water content differently influences the shear strength [22], stiffness [8], permeability [13,14,19] and the cyclic shear properties [26] of soils compacted up to the same dry density. Even if a soil is compacted up to maximum dry density at optimum water content with certain compaction energy, mechanical properties of the soil such as strength, stiffness and permeability etc. are not always the best as a compacted soil structure. The effect of compacting conditions on the cyclic undrained shear behavior was associated with fines content of compacted soils [18], as similarly as reported with relationships between the fines content and liquefaction strength [12,25,27]. Tatsuoka [23] reported the degree of saturation when compacted was a reasonable parameter strongly associated with the mechanical properties of compacted soils rather than the molding water contents.

In this paper, we investigated five types of soils that had different fines content and were compacted at different combinations of molding water content and dry density. X-ray tomography images were taken to visualize the fabrics of compacted soils. Results of conventional cyclic undrained triaxial tests of these different soil types were compared. Based on the results, we explain how the compacting conditions influence the cyclic undrained strength and how the influence differs depending on the fines content. It is shown that a combination of molding water content and dry density is not relevant to properly represent the compacting conditions that control the cyclic undrained strengths of the multiple soil types, whereas a combination of the degree of saturation and dry density is promising.

2. Review of field compaction control and its relationship with degree of saturation

In typical field compaction control, the dry density ρ_d of compacted soil is required to be greater than or equal to a specified value, for example 95% of the maximum dry density $(\rho_d)_{max}$ obtained by laboratory compaction tests performed at a specified compaction energy

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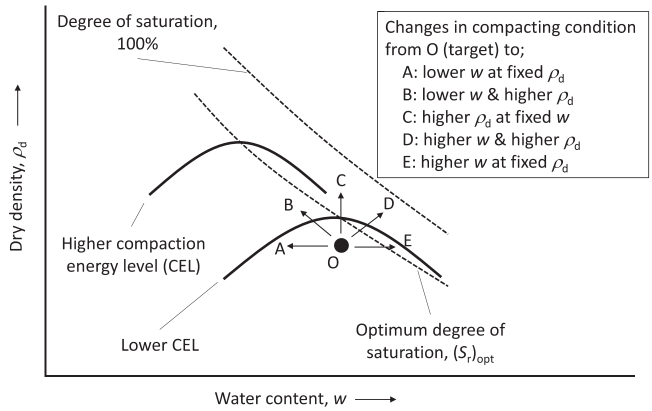


Fig. 1. Concept of optimum degree of saturation of compacted soil.

level (CEL) (e.g. the Standard Proctor, 1Ec). It is usually avoided to compact soils at the water content w noticeably lower than the optimum water content w_{opt} in order to prevent large collapse deformation and large reduction in the soil shear strength upon saturating [15,16,6]. Usually, w of compacted soils is controlled to be either: a) as close as possible to w_{opt} to obtain $(\rho_d)_{max}$; or b) slightly higher than w_{opt} to minimize the coefficient of saturated hydraulic conductivity k [13,14,19]. It is uncertain which method a) or b) or another is relevant to obtain the highest cyclic undrained strengths at the same CEL. As a more fundamental related issue, the higher the CEL is, the lower the w_{opt} value becomes (Fig. 1), which means that if a field CEL is higher than a laboratory CEL, the field w_{opt} value becomes lower than the laboratory w_{opt} value. Besides, in a given earthwork project, both CEL and soil type are inevitably variable and so is the w_{opt} value. Then, the compaction control based on the laboratory w_{opt} value becomes rather subjective.

On the other hand, Tatsuoka [23] and Tatsuoka et al. [24] showed that the degree of saturation S_r at which $(\rho_d)_{max}$ is obtained for a given CEL, which is defined as the optimum degree of saturation $(S_r)_{opt}$ (Fig. 1), is rather independent of CEL for given soil type. They also showed that $(S_r)_{opt}$ is rather insensitive to changes in the soil type. Therefore, it is more relevant to control the S_r value together with the ρ_d value in order to ensure a high quality of compaction. The benefits of the line of optimum degree of saturation on the ρ_d–w plane (called "line of optimum") were also discussed in terms of permeability and collapse of compacted soils by Daniel and Benson [7] and Lawton et al. [15].

We herein describe an example of the California Bearing Ratio (CBR) measured before and after soaking of compacted soils that is controlled by ρ_d and S_r at the end of compaction. The CBR value is known as a good index of the mechanical properties of compacted soils, such as drained or undrained shear strength/stiffness of compacted soil, the collapse deformation upon wetting etc. Ampadu [3]. Nemoto and Sasaki [20] reported the results from a comprehensive series of full-scale compaction tests using a wide variety of compaction machines as used in field earthworks. After spreading a sandy loam (Specific gravity 2.83; Plasticity index 12.6; Fines content approximately 30%), the compaction machines passed over the soil layer. The values of ρ_d and unsoaked CBR were measured after the numbers of passing, N, became 0, 2, 4, 8 and 16. During this compaction process, the CEL increased from values lower than the Standard Proctor (1Ec) towards values over the modified Proctor (4.5Ec) [23]. Fig. 2**a** shows the unsoaked CBR vs. ρ_d relationships for different constant w values after N = 8. The solid curves denote an empirical equation (i.e., **Eq.** (1) explained below). With an increase in ρ_d at a fixed w value, CBR increases until ρ_d becomes a certain value and then decreases as ρ_d further increases. This two-stage trend cannot be seen when the data are replotted for different constant S_r values with their monotonic increase curves (Fig. 2**b**).

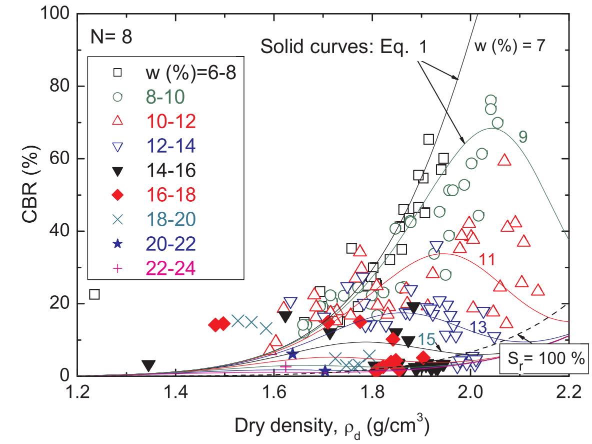
Unsoaked CBR of a given soil type is a function of at least: 1) ρ_d (Fig. 2); 2) the matric suction during the measurement of unsoaked CBR [21]; and 3) the microstructure for a given ρ_d of compacted soil, which becomes more stable with an increase in the matric suction during compaction. The matric suction increases with a decrease in S_r. Due to factors 2) and 3), the unsoaked CBR, and thus the unsaturated strength/stiffness, of the compacted soil decreases with an increase in S_r for a fixed value of ρ_d (Fig. 1, "O" to "E"). On the other hand, S_r increases with an increase in ρ_d at a fixed w (Fig. 1, "O" to "C"). Therefore, when ρ_d increases at a fixed w value, once "the negative effect of the increase in S_r on the unsoaked CBR (i.e. factors 2) and 3) at a fixed ρ_d)" becomes more dominant than "the positive effect of the increase in ρ_d (i.e. factor 1) at a fixed S_r)", the unsoaked CBR decreases despite an increase in ρ_d (Fig. 2**a**). The trends of behavior seen from Fig. 2**a** and **b** were observed irrespective of the numbers of passing, N (i.e., irrespective of CEL) [23].

As seen from Fig. 2**b**, the test data can be fitted by:

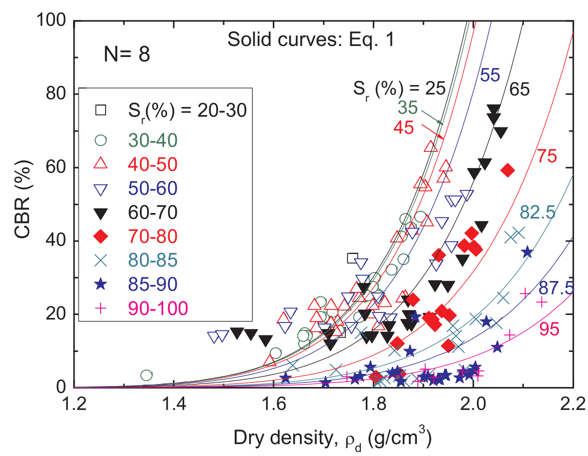
$$\text{Unsoaked CBR} = f_{CBR}(S_r)\cdot(\rho_d/\rho_w - b)^c \quad (1)$$

$$f_{CBR}(S_r) = \text{Unsoaked CBR}/(\frac{\rho_d}{\rho_w} - b)^c \quad (2)$$

where ρ_w is the density of water; b = 0.4 and c = 0.9, which are dimensionless positive material constants; and f_{CBR} is a function of S_r calculated by **Eq.** (2). Fig. 3 shows the f_{CBR} versus S_r relationship. Tatsuoka [23] **and** Tatsuoka et al. [24] reported that the f_{CBR} declines upon soaking and the declining rate increases as S_r decreases from



a)Relationships between CBR and dry density for various constant water contents



b) Relationships between CBR and dry density for various constant degree of saturation

Fig. 2. CBR versus dry density of compacted soils [23].