Effect of compaction conditions on the saturated strength and deformation characteristics of sandy soil

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ABSTRACT

Drained and undrained shear strength and creep characteristics of saturated Hokota sand were evaluated by triaxial compression (TC) tests. Among the specimens, the degree of compaction $D_c = \rho_d / (\rho_d)_{\text{max}} \times 100 \%$, where $\rho_d$ is the dry density and $(\rho_d)_{\text{max}}$ is the maximum dry density for the compaction energy level (CEL) equal to the standard Proctor ($1.0E_c$), and the degree of saturation, $S_r$, were changed. Compressive strength $q_{\text{max}}$ in undrained TC increases significantly with $D_c$, becoming significantly higher and lower than drained $q_{\text{max}}$, as $D_c$ increases and decreases from about 90 %. This result indicates that, despite that the drained strength is often used irrespective of drain condition in seismic design, the undrained strength should be used where relevant. For the same $D_c$, the effects of $S_r$ at compaction on $q_{\text{max}}$ are insignificant. In practice, CEL used in a laboratory test is often equal to 1.0$E_c$ ($E_c$ is compaction energy) and the field compaction is done at a water content higher than its optimum value for 1.0$E_c$, $(W_{\text{opt}})_{1E_c}$. However, the actual CEL in the field is variable and usually unknown. CEL in the modern earthwork can easily exceed 1.0$E_c$. In that case, $w$ higher than $(W_{\text{opt}})_{1E_c}$ may become too high in that, despite an increase in CEL, $\rho_d$ may not increase noticeably while the strength and stiffness may not increase efficiently. Besides, $S_r$ may become too high and the risk of over-compaction becomes high. On the other hand, "the optimum degree of saturation $(S_r)_{\text{opt}}$" defined as $S_r$ where $(\rho_d)_{\text{max}}$ is obtained at a given CEL is independent of CEL. So, it is recommended to control the field $S_r$ to be equal to $(S_r)_{\text{opt}}$ so that $(\rho_d)_{\text{max}}$ is obtained for the current unknown CEL, while ensuring the $(\rho_d)_{\text{max}}$ value to be high enough to achieve the design drained or undrained $q_{\text{max}}$ value.

Keywords: soil compaction, shear strength, drain condition, the degree of compaction, the degree of saturation

1 INTRODUCTION

The degree of compaction, $D_c$, is defined as “the dry density $\rho_d$ in the field”/“the maximum dry density $(\rho_d)_{\text{max}}$ by laboratory compaction tests at a specified compaction energy level CEL)” x 100 %. In the soil compaction control, the $D_c$ value is controlled to be at least the allowable lower limit specified according to the type of soil structures. Besides, to prevent excessive collapse and a large reduction in the strength and stiffness upon wetting/saturation, usually the water content $w$ higher than the optimum water content $W_{\text{opt}}$ by the laboratory test is used. In many cases, the CEL value adopted in the laboratory test is the standard Proctor ($1.0E_c = 550 \text{ kJ/m}^3$).

Aiming at higher $\rho_d$ values for a higher stability of soil structure, heavier compaction machines have been introduced in the modern earthwork. Now, it is easy to achieve a CEL much higher than 1.0$E_c$. Then, the $w$ value higher than $W_{\text{opt}}$ for 1$E_c$ may become too high in that, despite an increase in CEL, $\rho_d$ does not increase efficiently, so the strength and stiffness does increase efficiently. Addition, as the degree of saturation, $S_r$, becomes too high approaching 100 %, the risk of over-compaction becomes high.

It has been found that “the optimum degree of saturation $(S_r)_{\text{opt}}$” defined as $S_r$ where $(\rho_d)_{\text{max}}$ is obtained for a given CEL is independent of CEL. (Fujishiro et al., 2013; Tatsuoka, 2013). On the other hand, the field CEL is highly variable and usually unknown. Even in such a case, the $(\rho_d)_{\text{max}}$ value for a given but unknown CEL can be obtained by achieving $S_r = (S_r)_{\text{opt}}$. In so doing, it is also necessary for the $(\rho_d)_{\text{max}}$ value to be high enough to achieve the design shear strength of compacted soil.

Often in practice, the shear strength when $D_c$ is equal to the allowable lower limit is used as the design shear strength. However, this conventional method could be too conservative when the average of the actual $D_c$ values is noticeably higher than the allowable lower limit as a result of good compaction. Moreover, in practice, the drained strength is often used even in the cases where the use of undrained strength is relevant.

In view of the above, in this study, drained and undrained shear strength and creep characteristics of
saturated Hokota sand were evaluated by changing the values of $D_c$ and $S_r$ at compaction among the specimens.

![Grain size distribution curve (Hokota sand).](image1)

**Fig. 1.** Grain size distribution curve (Hokota sand).

![Compaction curve and compaction states of TC specimen.](image2)

**Fig. 2.** Compaction curve and compaction states of TC specimen.

### 2 EXPERIMENTAL OUTLINE

The grain size distribution curve of Hokota sand used in this study is shown in Fig. 1. The compaction curves by using standard Procter (CEL = 1.0E₃) and modified Procter (CEL = 4.5E₃ = 2475 kJ/m³) are presented in Fig. 2. The specimens (75 mm in diameter and 150 mm in height) for triaxial compression (TC) tests were compacted by wet-tamping in five layer in the mold. The target values of $ρ_d$ and $w$ (thus, $D_c$ and $S_r$) are shown in Fig. 2. It may be seen that the value of $(S_r)_{opt}$ is essentially the same for the two different CELs. The solid and open data points represent the compacted states of respectively the drained and undrained TC tests. For data points, ○ and ●, $S_r = 71\%$, equal to $(S_r)_{opt}$, while, for data points, △ and ▲, $S_r = 50\%$, much lower than $(S_r)_{opt}$.

The stability of soil structure at the critical condition that may be encountered during the design life is evaluated in design. Many soil structures may become nearly or fully saturated by prolonged or heavy rainfalls or submerging. In view of the above, the TC specimens were made fully saturated by means of the double suction method. The specimens were de-aired by applying a suction of about – 95 kPa then supplying highly de-aired pore water at an effective confining pressure of 20 kPa under a back pressure of 200 kPa. Then, the specimens were isotropically consolidated to an effective confining pressure of 50 kPa and left for 60 minutes. Then, monotonic compression at an axial strain rate of 0.01 %/min was started in the drained or undrained condition. The volume change of the specimen was measured in the drained tests, while the pore water pressure was measured in the undrained tests. The creep characteristics of specimen were evaluated by keeping the deviator stress to 80 kPa for two hours in each drained or undrained TC test.

![Relationship between deviator stress $q$ and axial strain $ε_a$ by drained TC tests.](image3)

**Fig. 3.** Relationship between deviator stress $q$ and axial strain $ε_a$ by drained TC tests.

![Relationship between deviator stress $q$ and axial strain $ε_a$ by undrained TC tests.](image4)

**Fig. 4.** Relationship between deviator stress $q$ and axial strain $ε_a$ by undrained TC tests.

### 3 TEST RESULTS AND THEIR ANALYSIS

Fig. 3 shows the relationship between the deviator stress, $q$, and the axial strain, $ε_a$, from the drained TC tests. In the figure, the target values of $D_c$ for 1.0E₃ and $S_r$ at the compacted states are indicated. Their actual values are used in the data plots presented later. As
expected, the maximum deviator stress, $q_{\text{max}}$, increases noticeably with $D_c$. Even at axial strains larger than 10%, the strength still increases with $D_c$, showing that larger axial strains are necessary to reach the residual state where the strength becomes independent of initial $D_c$. Besides, for the same $D_c$ value, the effects of $S_r$ at compaction on the stress-strain behavior are insignificant if any.

Fig. 4 shows the $q$-$\varepsilon_r$ relations from the undrained TC tests. The effects of $D_c$ on the stress-strain behavior in these undrained TC tests are much more significant than in the drained TC tests. Also in the undrained TC tests, the effects of $S_r$ at compaction on the stress-strain behavior are insignificant.

These results indicate that the effects of compaction on the $q_{\text{max}}$ value of saturated soil, in particular the value under the undrained conditions, is significant. As the effect of $S_r$ at compaction for the same CEL on the $q_{\text{max}}$ value is insignificant, the maximum value of $q_{\text{max}}$ for a given CEL is obtained when $\rho_d$ is equal to $(\rho_d)_{\text{max}}$ for that CEL. That is, the maximum value of $q_{\text{max}}$ for the same compaction efforts is obtained when $S_r$ is equal to $(S_r)_{\text{opt}}$ irrespective of CEL.

![Fig. 5. $q_{\text{max}}$-$D_c$ relationship in drained and undrained TC.](image)

![Fig. 6. $\Delta \varepsilon_a$-$D_c$ relationship in drained and undrained TC.](image)

Fig. 5 shows the relationship between $q_{\text{max}}$ and $D_c$ from results shown in Figs. 3 and 4. As $D_c$ increases from about 90%, the undrained $q_{\text{max}}$ value becomes significantly higher than the drained values. When $D_c$ becomes 100%, the undrained $q_{\text{max}}$ value becomes about three times as large as the drained value. On the other hand, as $D_c$ decreases from about 90%, the undrained $q_{\text{max}}$ value becomes significantly lower than the drained value. When $D_c$ becomes 85%, the undrained $q_{\text{max}}$ value becomes about one third as small as the drained value.

In seismic design, the stability of soil structures, including embankments, is often evaluated using drained shear strength even when the soil structure may become highly saturated sometimes during its life cycle span. As can be seen from Fig. 5, when $D_c$ is higher than a certain value, the seismic stability of a highly saturated soil structure under the undrained condition becomes higher than under the drained condition. In this case, the seismic design using the drained strength is on the safe side, but it becomes less cost-effective if on the too safe side. On the other hand, when $D_c$ is lower than a certain value, the seismic stability of a highly saturated soil structure under the undrained condition becomes lower than under the drained condition. In this case, the seismic design using the drained strength is on the unsafe side. During the 2011 Great East Japan Earthquake, residential embankments for wooden houses collapsed at many places. It is reported that most of the $D_c$ values for 1.0$E_c$ measured in the collapsed embankments of silty sand including gravelly particles were lower than 85% (Tatsuoka and Shibuya, 2014). It is considered that the collapse in this case is due mainly to very low undrained shear strength.

It can be concluded from the above that better compaction is very effective to increase the seismic stability of soil structure, in particular if the soil structure may become highly saturated sometime during its life cycle span. In this case, the use of undrained strength in the seismic design is appropriate.

Fig. 6 shows the relationship between the axial strain increment, $\Delta \varepsilon_a$, by drained or undrained creep loading at $q = 80$ kPa for two hours and $D_c$. In the drained and undrained TC tests when $D_c = 85\%$, this creep test was not conducted as the $q_{\text{max}}$ value was lower than 80 kPa. It may be seen from Fig. 6 that $\Delta \varepsilon_a$ generally decreases with an increase in $D_c$. Yet, the $\Delta \varepsilon_a$ value for the same $D_c$ value is generally larger in the undrained TC than in the drained TC, while the decreasing rate of $\Delta \varepsilon_a$ with $D_c$ is larger in the undrained TC than in the drained TC. For the same $D_c$ value and the same drained condition, the $\Delta \varepsilon_a$ value when compacted at $S_r = 50\%$ is generally lower than when compacted at $S_r = (S_r)_{\text{opt}}$. This difference may be due to that the micro-structure produced by compaction in $S_r = 50\%$ is more stable by the stronger contact of fines particle to coarse particles.

It is to be noted that, when $D_c$ is larger than 95%, $\Delta \varepsilon_a$
is considerably small while the effects of drained condition and the \( S_r \) value at compaction become very small. This result indicates a paramount importance of high compaction to minimize the residual deformation of the soil structures.

2. For the same \( D_c \), the effect of the degree of saturation, \( S_r \), at compaction on the stress-strain behavior is insignificant. Then, for the same compaction energy level (CEL), the maximum value of the shear strength is obtained when \( S_r \) is equal to \( (S_r)_{opt} \) irrespective of CEL. Therefore, even when CEL is unknown, the maximum value of the shear strength is obtained by controlling the compaction in such that \( S_r \) becomes \( (S_r)_{opt} \). That is, the relevant target of a given compaction process using a certain compaction machine at a given water content is \( S_r = (S_r)_{opt} \).

3. Creep strain also decreases significantly with \( D_c \). When \( D_c \) is higher than 95\%, the creep strain becomes very small and the effects of drained condition and \( S_r \) at compaction become insignificant.

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