An Experimental Study on the Estimation of Field Compaction States and Stress-Strain Properties of Unbound Granular Materials from Laboratory Test Results

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Abstract Field fill materials often contain gravel particles larger than the allowable limit for standard laboratory compaction tests. In such cases, the maximum dry density $(\rho_d)_{max}$ of a material containing large gravels is obtained by correcting laboratory test results for specimens without large gravels. Usually, the Walker–Holtz (WH) method is used for this correction, but there are many materials whose gravel ratio (P) is $0.3 - 0.4$, which is usually considered to be the application limit. Moreover, accurate stress-strain properties under field compaction conditions are necessary for relevant stability analysis of soil structures including embankments. However, with unbound granular materials, it is difficult to obtain undisturbed samples for laboratory tests or to carry out field shear tests. Also, large-scale triaxial compression tests on specimens containing large gravels are difficult to perform in ordinary engineering practices. In this study, a series of laboratory compaction tests were performed changing the maximum particle size (D_{max}), compaction energy level (CEL) and P to examine the validity of the WH method and a series of drained triaxial compression tests were performed varying the D_{max} and the degree of compaction. Based on the test results, a method to modify the WH method is proposed to properly estimate the $(\rho_d)_{max}$ value after adding or removing gravel particles when compacted at a certain CEL. Also, a method is proposed to correct the strength for a given gravel ratio to estimate the in-situ strength from the strength obtained from laboratory tests.

Keywords Compaction control · The degree of compaction · Gravel content

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1 Introduction

In the conventional control of field soil compaction of embankments for roads, railways and residential and industrial areas, etc., the dry density ρ_d and the water content w are measured in the field and controlled based on the maximum dry density $(\rho_d)_{max}$ and the optimum water content w_{opt} obtained by standard laboratory compaction tests performed on representative samples of the field fill material at a specified compaction energy level (CEL) (usually Standard or Modified Proctor, $1E_c$ or $4.5E_c$). Field fill materials often contain large particles, such as gravels and rock fragments, the size of which exceeds the allowable limit for standard laboratory compaction tests. In this case, it is necessary to estimate the values of $(\rho_d)_{max}$ and w_{opt} of the field fill material by correcting the values obtained by laboratory compaction tests on samples obtained by removing gravel particles of which the sizes exceed the allowable limit. When the gravel ratio P (will be described later in Chap. 2) of a given field fill material is lower than 0.3 or 0.4, the Walker–Holtz (WH) method [1, 2] is usually used for this estimate. The WH method assumes that the ρ_d value of the fine particle portion inside the whole sample after adding large particles is the same as the value of the sample comprising only fine particles compacted at the same CEL. However, it is known that, with an increase in P of the whole sample, the CEL transmitted to the fine particle portion inside the whole sample decreases, therefore the ρ_d value of the fine particle portion decreases. Besides, this trend may not be negligible even when P is lower than 0.3 or 0.4.

In addition, stability analysis of soil structure requires relevant shear strength values of compacted fill material. Because the stability may decrease as a fill material becomes wet or saturated, the strength under wet or saturated conditions is usually used in design. Like the laboratory compaction tests, the shear strength characteristics are often evaluated by performing triaxial compression (TC) tests on samples obtained by removing gravel particles of which the sizes exceed the allowable limit for standard TC tests.

There are studies that approach each problem [3, 4], but there are few researches that studied these two issues related to each other by performing compaction tests and TC tests on the same soil type compacted in the same way. In this research, a set of samples having different maximum particle diameters D_{max} were prepared by consecutively removing larger particles from a typical field fill material. A series of laboratory compaction tests were then performed on these samples at $\text{CEL} = 1E_c$ and $4.5E_c$ to evaluate the effects of P on the value of $(\rho_d)_{max}$ for various values of D_{max} and CEL. Also, a series of laboratory consolidated-drained TC tests were performed on these samples to evaluate the effects of P on the shear strength characteristics of specimens compacted otherwise under the same conditions.

2 Walker–Holtz Method

In the WH method, the dry density ρ_d' of a sample after adding large gravel particles with the same CEL as a sample before adding gravel particle is obtained by Eq. (1):

$$\rho_d' = \frac{\rho_d \cdot \rho_s}{(1 - P) \cdot \rho_s + P \cdot \rho_d} \tag{1}$$

where ρ_d is the dry density of the sample before adding gravel particles; ρ_s is the density of gravel particles; and P is the mass ratio of the added gravel to the whole sample after adding gravel particles. In this study, it is reasonably assumed that the density of particles other than the gravel particles is the same as ρ_s. In addition, the S_r value does not change by adding gravel particles when following Eq. (1). In the WH method,

On the other hand, the dry density ρ_d'' of the portion composed of fine particles not containing large gravel particles inside the whole sample containing large gravel particles compacted at a certain CEL is correctly obtained by Eq. (2):

$$\rho_d'' = \frac{(1 - P) \cdot \rho_d \cdot \rho_s}{\rho_s - P \cdot \rho_d} \tag{2}$$

where ρ_d is the dry density of the whole sample before removing the gravel particles; and P is the mass ratio of gravel particles to the whole sample. Note that we need no assumption to derive Eq. (2).

3 Soil Samples and Test Methods

The field fill material used to construct a road embankment in Kamaishi City, Iwate Prefecture, Japan (hereafter called Kiten soil) was used in this study. Figure 1 shows
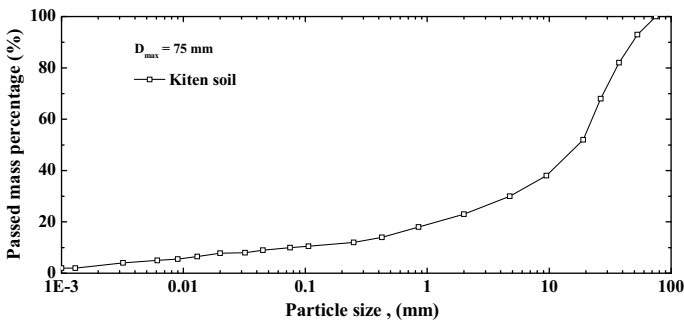

Fig. 1 Grading curves of original material

the grading curve of the field material with $D_{max} = 75$ mm. A set of samples with $D_{max} = 53$ mm, 37.5 mm, 19 mm, 9.5 mm 4.75 mm, and 2 mm were produced by consecutively removing larger gravel particles.

The mold having an inner diameter of 15 cm and a volume of 2209 cm^3 was used for laboratory compaction tests on samples with $D_{max} = 37.5$, 19, 4.75, and 2 mm. A 2.5 kg rammer was dropped freely from a height of 30 cm, and the number of tamping was 55 for each of in total three layers. The CEL, in this case, is $1E_c$, and E_c is the energy per unit volume and is calculated by Eq. (3).

$$E_c = \frac{W_R \cdot H \cdot N_L \cdot N_B}{V} \tag{3}$$

where W_R is the weight of the rammer; H is the drop height of the rammer; N_L is the number of layers; N_B is the number of tamping per layer; and V is the volume of mold.

Furthermore, a 4.5 kg rammer was dropped freely from a height of 45 cm and tamped 55 times for each of in total 5 layers. The CEL in this case is $4.5E_c$. A mold having an inner diameter of 30 cm and a volume of 25,000 cm^3 was used for samples with $D_{max} = 75$ and 53 mm. For $1E_c$, a 10 kg rammer was dropped freely from a height of 45 cm. The number of tamping was 104 times for each of in total 3 layers. For $4.5E_c$, a 10 kg rammer was dropped freely from a height of 45 cm and the number of tamping was 468 times for each of in total 3 layers. The total mass of a whole compacted sample was measured before and after oven-drying.

A series of drained TC tests were performed on specimens with $D_{max} = 19$, 9.5, and 4.75 mm. Table 1 shows the compaction conditions of the specimens having different D_{max} values. $[D_c]_{1Ec}$ in the table represents the degree of compaction at $1E_c$. The specimens were prepared by compaction in 5 layers in the mold. In order to evaluate effects of D_{max} on shear strength at the same ρ_d value, the tests were performed on specimens compacted to $\rho_d = 1.872$ g/cm^3 and $S_r = 80\%$ for each D_{max}. The specimens were 100 mm in diameter and 200 mm in height for $D_{max} = 19$ mm; and 75 mm in diameter and 150 mm in height for $D_{max} = 9.5$ mm and 4.75 mm. After saturation, the specimen was consolidated to an effective confining pressure of 50 kPa with a back pressure of 300 kPa, and loaded monotonically at an axial strain rate of 0.01%/min under drained conditions.

Table 1 TC specimens

D_{max} (mm)	19			9.5			4.75		
S_r (%) when compacted	60	70	80	60	70	80	60	70	80
$[D_c]_{1Ec}$ (%)	95	95	95 96 100	95	95	90 95 100 105	95	95	90 95 100 102

4　Results and Discussions (Laboratory Compaction Tests)

4.1　Results

Figure 2 shows the compaction curves for $1E_c$ and $4.5E_c$ of the samples having different D_{max} values. The $(\rho_d)_{max}$ value increases as the D_{max} value increases and as CEL increases. In comparison, the S_r value when $\rho_d = (\rho_d)_{max}$ along each compaction curve, which is defined as the optimum degree of saturation $(S_r)_{opt}$ [5], is quite independent of D_{max} and CEL and has value of 81%.

　　In Fig. 3a, the curves with data points are the measured compaction curves of the specimens with $D_{max} = 75, 53, 37.5, 19, 9.5, 4.75$, and 2 mm of Kiten soil compacted at $1E_c$. The set of solid curves are the compaction curves of the specimens are those calculated by Eq. (1) when adding particles larger than 2 mm in diameter to the basic specimen with $D_{max} = 2$ mm. It may be seen that the $(\rho_d)_{max}$ value for $1E_c$ is over-estimated by Eq. (1) to a larger extent with an increase in D_{max} (i.e., with an increase in the mass ratio P of particles larger than 2 mm to the whole sample containing these added large particles). On the other hand, the compaction curves of the portion of fine particles with $D_{max} = 53, 37.5, 19, 9.5, 4.75$, and 2 mm inside the basic sample with $D_{max} = 75$ mm compacted at $1E_c$ were calculated by Eq. (2). In Fig. 3b, these calculated compaction curves are compared with the measured curves of the specimens comprising fine particles that were compacted at $1E_c$. The $(\rho_d)_{max}$ value calculated by Eq. (2) becomes smaller than the measured one obtained by compaction at $1E_c$. This means that the $(\rho_d)_{max}$ value for $1E_c$ is under-estimated by Eq. (2) to a larger extent with an increase in D_{max}.

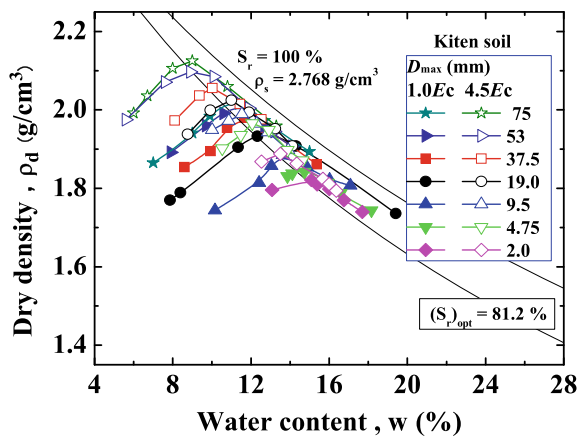**Fig. 2** Compaction curves for different D_{max} values

Fig. 3 a Compaction curves for $1E_c$ of the specimens obtained by adding large particles to the basic sample with $D_{max} = 2$ mm calculated by Eq. (1) and measured curves of these samples compacted at $1E_c$; **b** Compaction curves of the fine particle portion inside the basic specimen with $D_{max} = 75$ mm compacted at $1E_c$ calculated by Eq. (2) and measured compaction curves of specimens composed of the same fine particles compacted at $1E_c$
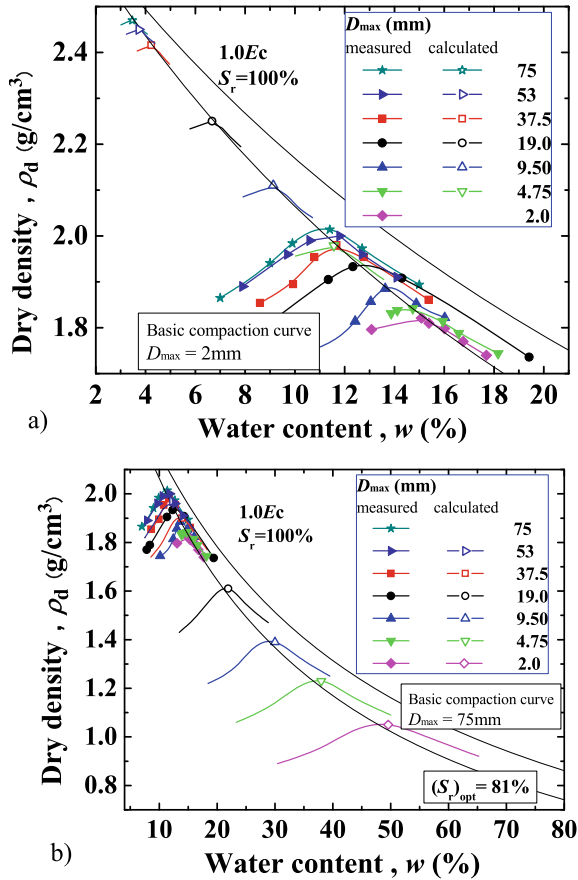

4.2 Modification of the WH-Method

It is seen from Fig. 3a that it is necessary to modify Eq. (1) to obtain the correct ρ_d value of a specimen after adding larger particles that are compacted at a certain CEL from the ρ_d value of the basic specimen compacted at the same CEL. It is seen from Fig. 3b that it is also necessary to modify Eq. (2) to obtain the correct ρ_d value of a specimen after removing larger particles that is compacted at a certain CEL from the ρ_d value of the basic specimen compacted at the same CEL. To unify these trends of behavior in a single framework, the maximum dry density ratio X was defined as the ratio of the $(\rho_d)_{max}$ value when compacted at a certain CEL calculated by Eqs. (1) or (2) to the measured $(\rho_d)_{max}$ value of the same sample compacted at the same CEL.

In the top–right quarter zone of Fig. 4, the X values of the specimens to which different amounts of gravel particles larger than 2 mm in diameter were added to the basic specimen with $D_{max} = 2$ mm are plotted against the gravel mass ratio P of these specimens after adding particles larger than 2 mm. These data were obtained from

**Fig. 4** X–P relation from data for compaction at $1E_c$ in Fig. 3a, b
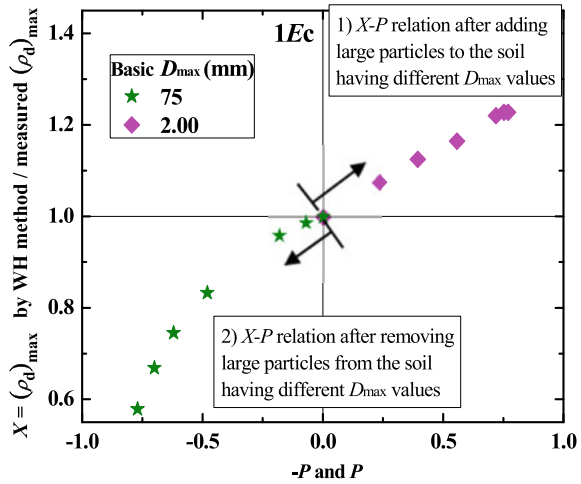
those plotted in Fig. 3a. The X value increases consistently from 1.0 as P increases from zero. That is, as P increases, the $(\rho_d)_{max}$ value after adding gravel particles when compacted at a certain CEL is over-estimated to a larger extent than if calculated by Eq. (1) based on the $(\rho_d)_{max}$ value of the basic specimen compacted at the same CEL. Importantly, X is noticeably higher than 1.0 when $P = 0.3 - 0.4$, which is conventionally considered as the upper limit for the application of the WH method.

In the bottom-left quarter zone of Fig. 4, the X values of the specimens from which different amounts of gravel particles smaller than 75 mm in diameter were removed from the basic specimen with $D_{max} = 75$ mm are plotted against $-P$, where P is the mass ratio of the gravel particles that were removed from the basic specimen with $D_{max} = 75$ mm. These plots were obtained from the data presented in Fig. 3b. The X value decreases consistently from 1.0 as P increases. That is, as P increases from zero, the CEL transmitted to the fine particle portion becomes smaller than $1E_c$, which was applied to the whole of the basic specimen containing gravel particles. By this mechanism, the calculated dry density becomes smaller than the value obtained by compaction at $1E_c$.

Figure 5 shows the X–P relations obtained for the two different CELs ($1E_c$ and $4.5E_c$) and different basic D_{max} values equal to 75, 53, 37.5, 19, 9.5, 4.75 and 2 mm. It may be seen that the X–P relations for these different CEL and basic D_{max} values are rather unique. This result is consistent with the results of the previous experimental study [6] showing that the X–P relation is rather unique regardless of the basic D_{max} value and CEL, and regardless of the different soil types with similar particle size distributions.

The results shown above indicate that to obtain the correct value of $(\rho_d)_{max}$ for a given value of CEL after adding large gravel particles, the value obtained by Eq. (1) should be divided by the factor X obtained from the curve shown in Fig. 5. Similarly, to obtain the correct value of $(\rho_d)_{max}$ for a given value of CEL after removing large

Fig. 5 X–P relation for different basic D_{max} values at CEL = $1E_c$ and $4.5E_c$
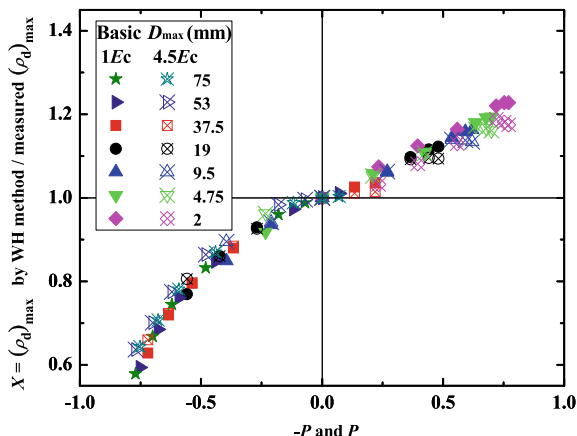
gravel particles, the value obtained by Eq. (2) should be divided by the factor X obtained from the curve shown in Fig. 5.

4.3 Estimation of ρ_d Other than $(\rho_d)_{max}$

It is often required to estimate a ρ_d value other than the $(\rho_d)_{max}$ value after adding gravel particles to a given sample. In this respect, Fig. 6 shows the $[D_c]_{1Ec}$–S_r relation of the samples having different D_{max} values obtained from the data presented in Fig. 2. Even if D_{max} changes, the optimum degree of saturation $(S_r)_{opt}$ does not change noticeably, while the $[D_c]_{1Ec}$–S_r relation still remains rather unique. These results are consistent with the findings reported by Tatsuoka [5] that the $(S_r)_{opt}$ value

Fig. 6 $[D_c]_{1Ec}$–S_r relation for different D_{max}
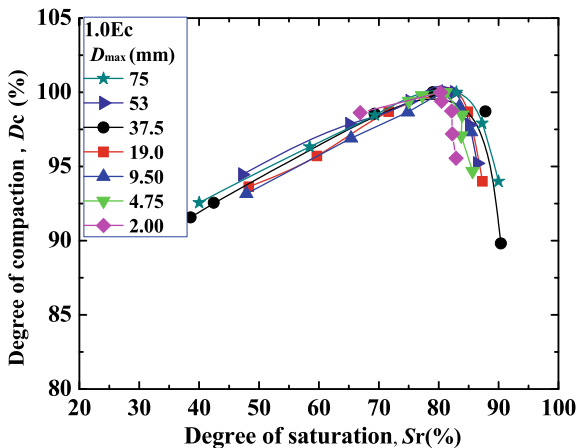
and this relation are rather insensitive to changes in the soil type and CEL. The result presented in Fig. 6 suggests that ρ_d values after adding gravel particles to, or removing gravel particles from, a given sample are correctly estimated by modifying the values obtained by Eqs. (1) or (2) and applying the same X–P relation for $(\rho_d)_{max}$ as presented in Fig. 5.

To confirm this point, X–P relations other than the one for $(\rho_d)_{max}$ were examined. To this end, X was defined as the ratio of the ρ_d value when compacted at a certain CEL and a certain S_r. Then the X values were obtained from the ratio of the ρ_d value calculated by Eqs. (1) or (2) to the measured value of the same specimen compacted at the same CEL and S_r. Figure 7a and b show the X–P relation when compacted to $S_r = 72\%$ and 88%. From Fig. 7a for $S_r = 77\%$, which is lower than $(S_r)_{opt} = 81\%$, the X–P relation is rather unique and in fact it is nearly the same as the relation shown in Fig. 5. In contrast, in Fig. 7b for $S_r = 88\%$, which is higher than $(S_r)_{opt} = 81\%$, the relation is not as unique as the one shown in Fig. 5. This trend corresponds

Fig. 7 X–P relation: **a** $S_r = 72\%$ and **b** $S_r = 88\%$
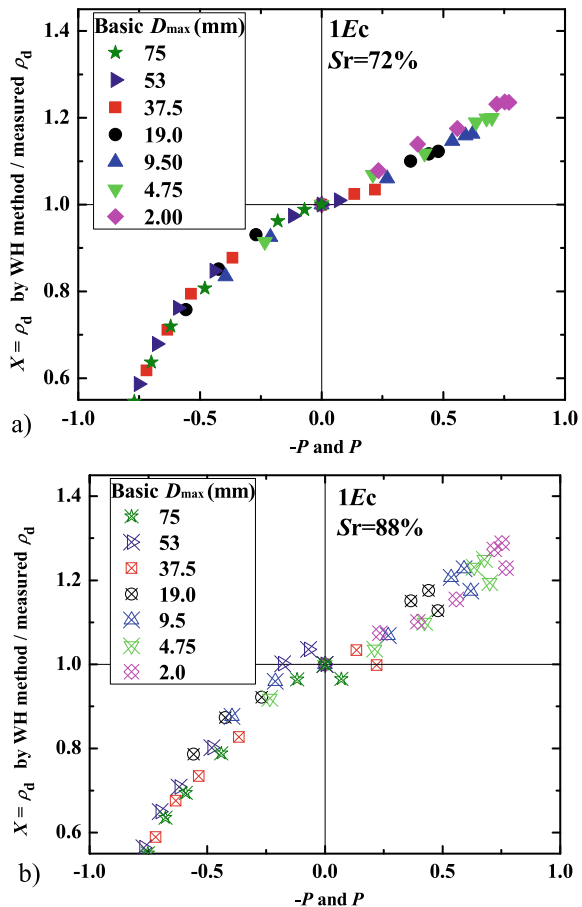
to the fact that the D_c–S_r relation scatters in has relatively largely scatter when $S_r > (S_r)_{opt}$.

In summary, we can conclude that the X–P relation for $(\rho_d)_{max}$ is rather unique even when D_{max} changes exceeding the maximum allowable particle size for the mold of the laboratory compaction tests. Also, the X–P relation for ρ_d other than $(\rho_d)_{max}$ is nearly the same as that for $(\rho_d)_{max}$ corresponding to the fact that the D_c–S_r relation is rather unique regardless of D_{max}.

The detailed procedure based on the analysis described above to obtain the degree of compaction of the field sample that includes large gravel particles is described below.

4.4 $(\rho_d)_{max}$ of Field Sample Including Large Gravel Particles

The degree of compaction for $1E_c$ of fill material compacted in the field, hereafter denoted by $[D_c]_{1Ec.A}$, is obtained by Eq. (4):

$$[D_c]_{1Ec.A} = (\rho_d)_A / \left[(\rho_d)_{max.1Ec}\right]_A \tag{4}$$

where $(\rho_d)_A$ is the field dry density, and $[(\rho_d)_{max.1Ec}]_A$ is the $(\rho_d)_{max}$ of the field fill material compacted at $1E_c$. When laboratory compaction tests cannot be performed on a given field fill material due to the inclusion of gravel particles too large in size, $[(\rho_d)_{max.1Ec}]_A$ is usually estimated by Eq. (1) (i.e., the WH method) from the maximum dry density $[(\rho_d)_{max.1Ec}]_F$ obtained by laboratory compaction tests at $1E_c$ on the specimen obtained by removing large gravel particles from the original sample of field fill material. It may be seen from Figs. 4 and 5 that, in the case of adding gravel particles to a given basic material, even when P is in range of 0.3–0.4, X is approximately 1.1. This means that the field degree of compaction $[D_c]_{1Ec.A}$ is under-estimated by a factor of approximately $1/1.1 \approx 0.9$. This difference of 10% in $[D_c]_{1Ec.A}$ is not negligible in usual geotechnical engineering practice. In view of the above, it is proposed that even when P is lower than 0.3 or 0.4 and always when P is higher than 0.3 or 0.4, Eq. (1) is replaced by Eq. (5) to obtain a proper value of $[(\rho_d)_{max.1Ec}]_A$ for use in Eq. (4):

$$\left[(\rho_d)_{max.1Ec}\right]_A = \frac{\left[(\rho_d)_{max.1Ec}\right]_F \cdot \rho_s}{(1 - P) \cdot \rho_s + P \cdot \left[(\rho_d)_{max.1Ec}\right]_F} \cdot \frac{1}{X} \tag{5}$$

In this case, the X value is obtained by substituting the P value of a given field fill material into the X–P relation relevant for the given type of field fill material (such as the one presented in Fig. 5). In this way, it becomes possible to avoid an unreasonable underestimation of the field degree of compaction.

5 Results and Discussions (Triaxial Compression Tests)

From the TC test results, the internal friction angles $\phi_{0peak} = \sin^{-1}\{(\sigma_{1f} - \sigma_{3f})/(\sigma_{1f} + \sigma_{3f})\}$ (for $c = 0$) were obtained, where σ_{1f} and σ_{3f} are the axial and lateral stresses at the peak deviator stress. Figure 8 shows the $\phi_{0peak}-D_{max}$ relation for $[D_c]_{1Ec} = 95\%$ for three different S_r values. Regardless of the value of S_r, the ϕ_{0peak} value increases as D_{max} increases. The ϕ_{0peak} value at $S_r = 70\%$ is slightly higher than that at $S_r = 80\%$. However, when compared under the same CEL, the $[D_c]_{1Ec}$ value at $S_r = 80\%$ becomes higher than the value at $S_r = 70\%$ and the ϕ_{0peak} increases correspondingly. As a result, under the same CEL, there is nearly no difference between the ϕ_{0peak} values at $S_r = 70$ and 80%. On the other hand, even for the same $[D_c]_{1Ec}$, the ϕ_{0peak} at $S_r = 60\%$ is clearly lower than that of the specimens at $S_r = 70$ and 80% and this difference increases as D_{max} increases. These results support the proposal by Tatsuoka and Correia [7] that the field compaction target is set at $S_r = (S_r)_{opt}$ to ensure high strength and stiffness after wetting or saturation.

Figure 9 shows the $\phi_{0peak}-[D_c]_{1Ec}$ relation at $S_r = 80\%$ for three different D_{max} values. When compared at the same $[D_c]_{1Ec}$, the ϕ_{0peak} value noticeably increases as D_{max} increases. It is likely that this trend is due to the fact that, as D_{max} increases, the uniformity coefficient of specimen increases, which results in an increase in $(\rho_d)_{max}$ therefore an increase in ρ_d for the same $[D_c]_{1Ec}$. On the other hand, Fig. 10 shows the $\phi_{0peak}-\rho_d$ relation at $S_r = 80\%$ for the three different D_{max} values. It may be seen that the ϕ_{0peak} value is determined by ρ_d regardless of D_{max}. It seems that this result is due to that the effects of the following factors are cancelled: (1) as D_{max} increases, $[D_c]_{1Ec}$ for the same ρ_d value decreases due to an increase in $(\rho_d)_{max}$ (Fig. 2); while (2) as D_{max} increases, the ϕ_{0peak} at the same $[D_c]_{1Ec}$ increases (Fig. 8).

It is known that, for a wide range of grading characteristics, the $\phi_{0peak} - \rho_d$ relation is not unique. However, if such a unique $\phi_{0peak}-\rho_d$ relation as the one shown in

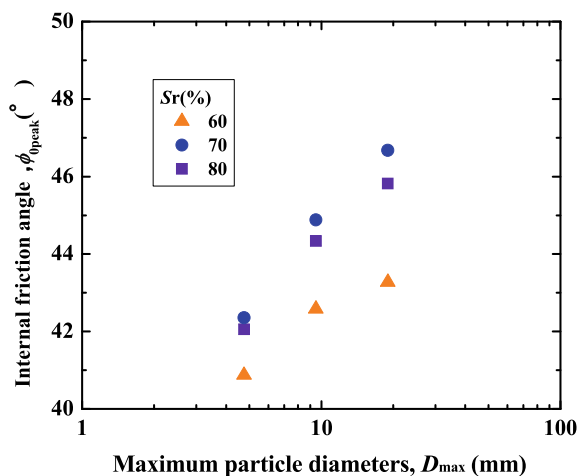**Fig. 8** $\phi_{0peak}-P$ relation for different S_r ($[D_c]_{1Ec} = 95\%$)

Fig. 9 $\phi_{0peak}-[D_c]_{1Ec}$
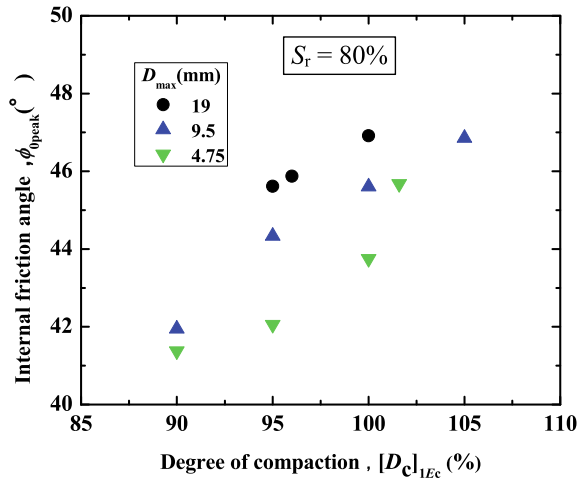relation for different D_{max}

Fig. 10 $\phi_{0peak}-\rho_d$ relation
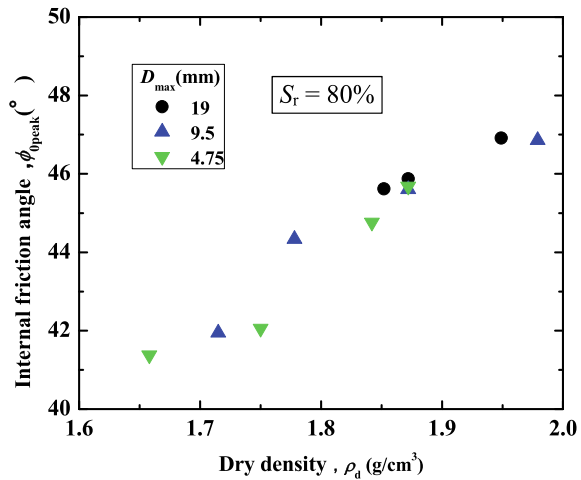for different D_{max}

Fig. 9 is confirmed under certain limited conditions, we can determine design strength
parameters by referring to such a $\phi_{0peak}-\rho_d$ relation shown in Fig. 10. Otherwise, it
is recommended to determine a design strength parameter by referring to the $\phi_{0peak}-$
$[D_c]_{1Ec}$ relation obtained by TC tests performed on samples after removing large
gravel particles with necessary correction for D_{max}. The results shown in Fig. 9 indi-
cate that it is on the safe side when the effects of D_{max} are ignored. When the $[D_c]_{1Ec}$
value ensuring a given design strength parameter can be determined following such
a procedure as explained above, the target value of $[D_c]_{1Ec}$ in field soil compaction
control is determined by referring to this $[D_c]_{1Ec}$ value.

6 Conclusions

The following conclusions can be derived from the results of a series of laboratory compaction tests and drained triaxial compression tests on a set of specimens having different maximum particle sizes D_{max} obtained by consecutively removing larger particles from a field fill material:

- When assuming that the same CEL as the one applied to the whole sample is transmitted to the portion with fine particle (i.e., the WH assumption), the dry density ρ_d at a certain S_r (including $(\rho_d)_{max}$ at $(S_r)_{opt}$) of soil containing large gravel particles compacted at a certain CEL is over-estimated when estimated from the ρ_d value at the same S_r of the specimen after removing gravel particles compacted at the same CEL. Similarly, when based on the WH assumption, the ρ_d value at a certain S_r of the gravel-removed sample compacted at a certain CEL is under-estimated when estimated from the ρ_d value at the same S_r of the specimen containing gravel particles compacted at the same CEL. In both cases, the error is not negligible even when the gravel mass ratio P is lower than 0.3–0.4.

- In order to appropriately estimate the ρ_d value at the same CEL of a specimen after adding gravel from the ρ_d value compacted with a CEL of the specimen before adding gravel particles, it is necessary to modify the conventional equation based on the WH assumption by incorporating a correction factor X that is a function of the gravel mass ratio P. This method is applicable over a wide range of P, from below 0.3 to higher than 0.4.

- The following findings were made from drained TC tests on saturated specimens of gravel-removed samples having different D_{max} values:

- When compacted at the same values of $[D_c]_{1Ec}$ and S_r, the angle of internal friction ϕ_{0peak} noticeably increases as D_{max} increases. This is due likely to the fact that, as D_{max} increases, the uniformity coefficient of the sample increases, which results in an increase in $(\rho_d)_{max}$, thereby an increase in ρ_d for the same $[D_c]_{1Ec}$. This result indicates that it may be on the safe side to estimate the ϕ_{0peak} value of fill material which includes large gravel particles from the value of gravel-removed specimens for the same $[D_c]_{1Ec}$. This effect may be taken into account when necessary.

- As S_r becomes noticeably lower than the optimum degree of saturation $(S_r)_{opt}$, the ϕ_{0peak} value for the same CEL becomes lower than the value when $S_r = (S_r)_{opt}$. This fact supports compaction control setting the field compaction target at $S_r = (S_r)_{opt}$.

- With the same ρ_d, the $[D_c]_{1Ec}$ value decreases with an increase in D_{max}. Due to the combined effects of this factor and factor a) above, when compacted at the same ρ_d value, the ϕ_{0peak} value becomes rather independent of D_{max}. At least within the test conditions employed in this study, taking advantage of this simple empirical rule, the ϕ_{0peak} value of gravel-including field fill material can be estimated from the value of gravel-removed sample for the same ρ_d value.

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