Properties of compacted soil as a function of dry density and the degree of saturation

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ABSTRACT

The conventional fill compaction procedure controlling the dry density \( \rho_d \) and the water content \( w \) has several limitations due mainly to significant effects of compaction energy level CEL and soil type on the \( \rho_d \) vs. \( w \) relation of compacted soil despite great difficulty in the prediction of in-situ CEL and soil type. The optimum degree of saturation \((S_r)_{opt}\) defined as \( S_r \) where \((\rho_d)_{max}\) is obtained for a given CEL and the \( \rho_d(\rho_d)_{max} \) vs. \( S_r \) relation of compacted soil are independent of CEL and insensitive to soil type variation. The unsoaked and soaked strength and stiffness and the saturated coefficient of hydraulic conductivity \( k \) are controlled by \( \rho_d \) and “\( S_r \) during compaction” and can be represented by empirical equations with variables of \( \rho_d \) and compacted \( S_r \) not including CEL. A new compaction control method achieving compacted \( S_r \) close to \((S_r)_{opt}\) and compacted \( \rho_d \) large enough for the soil properties required in design of a given soil structure, with pre-compaction control of water content, is proposed.

Keywords: compaction, dry density, the degree of saturation, CBR, hydraulic conductivity, compaction energy

1 INTRODUCTION

The conventional soil compaction procedure controls the dry density \( \rho_d \) and the water content \( w \) based on a compaction curve by laboratory compaction tests on a representative sample using a certain compaction energy level CEL, such as curve B-B in Fig. 1. However, even with nominally the same soil type and the same CEL at a given site, actual soil type and actual in-situ CEL inevitably vary and the in-situ compaction curve moves accordingly, which makes it very difficult to know the in-situ compaction curve at each location.

In Fig. 1, the compaction curve moves toward upper left as CEL increases, Ishii et al. (1987) showed that the CEL when compaction a 35 cm-thick soil layer by 16 passes of a flat surface 10 ton-vibratory steel roller, which is typical of modern fill compaction works, is rather equivalent to the modified Proctor (4.5Ec). In such a case as above, the in-situ optimum water content \( \omega_{opt} \) is much lower than “\( \omega_{opt} \) by laboratory compaction using the standard Proctor (1Ec)”, while the in-situ \( \rho_d \) may exceed “the maximum dry density \((\rho_d)_{max}\) for 1Ec”. Compaction at \( w \) higher than “\( \omega_{opt} \) for 1Ec” is often recommended in practice aiming at avoiding large collapse deformation and a large decrease in the strength and stiffness upon wetting. However, “\( w \) higher than \( \omega_{opt} \) for 1Ec” becomes much higher than “in-situ \( \omega_{opt} \)”, which results in inefficient compaction, and even over-compaction may take place.

Fig. 1. Compaction curves of sandy loam by full-scale and laboratory compaction tests with contours of unsoaked CBR (by analysis of the data reported by Nemoto & Sasaki, 1994).

Fig. 2. Sandy loam used in the tests described in Figs. 1, 3 and 4.

In this paper, it is shown that the optimum degree of saturation \((S_r)_{opt}\) defined as \( S_r \) when \((\rho_d)_{max}\) is obtained for a given CEL and the \( \rho_d(\rho_d)_{max} \) vs. \( S_r \) \((S_r)_{opt}\) relation

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of compacted soil are essentially independent of CEL and insensitive to soil type variation. Besides, the CBR values before and after soaking and the coefficient of hydraulic conductivity of saturated soil are a function of \( \rho_d \) and “\( Sr \) during compaction”, not including CEL as a variable. Based on these findings, a new fill compaction control achieving \( Sr \) of compacted soil close to \( (Sr)_{opt} \) and \( \rho_d \) large enough for the soil properties required in design of a given soil structure, with pre-compaction control of water content, is proposed.

2 FULL-SCALE COMPACTION TESTS

A series of full-scale compaction tests using a wide variety of compaction machines was performed in a large concrete pit (24 m-long, 3.5 m-wide and 1 m-deep) during a period of 1965 and 1990 (Nemoto & Sasaki, 1994). Overlying a 60 cm-thick base soil layer, a 30 cm-thick surface layer of sandy loam (Fig. 2) was prepared repeatedly at different water contents for respective compaction machines. After soil spreading with preliminary compaction by eight passings of a light compaction machine, a full-scale compaction test was performed measuring \( \rho_d \) of the 10 cm-thick upper soil layer four times by the sand-replacement method after respective passings of \( N = 0, 2, 4, 8 \) and 16. \( \rho_d \) of the 10 cm-thick lower soil layer was measured only after \( N = 16 \). The data points \( ▲, ○, ●, □ \) and \( ■ \) in Fig. 1 denote the average values of \( \rho_d \) and \( w \) from a test series using a 1.6 ton-vibratory pneumatic tire roller. CBR values were measured three times after respective \( N \) values. Broken curves are contours of CBR depicted as explained later. The data points \( X \) and \( + \) denote the results of laboratory compaction tests (1Ec & 4.5Ec) performed at Tokyo University of Science in 2012.

In Fig. 1, the compaction curve by the full-scale tests moves toward upper left with an increase in \( N \). The CEL in the upper soil layer when \( N = 4 \) already exceeds 1Ec and the value when \( N = 16 \) is much higher than 4.5Ec. When \( N = 16 \), the \( \rho_d \) values in the lower soil layer (denoted as 16L) are much lower than those in the upper soil layer, indicating that a lift thinner than 30 cm results in a too large variation of \( \rho_d \) with depth.

Fig. 3a shows the CBR vs. \( \rho_d \) relations for different \( w \) values when \( N = 8 \) from all the tests. Similar results are obtained for other \( N \) values. For a fixed \( w \) value, although CBR increases with an increase in \( \rho_d \) until \( \rho_d \) becomes a certain value, it decreases as \( \rho_d \) further increases. This is due to negative effects on CBR of the increase in \( Sr \) associated with an increase in \( \rho_d \) at a fixed \( w \) that are dominant over the positive effects of the increase in \( \rho_d \). The same data as Fig. 3a have been re-plotted in Fig. 3b changing the parameter from \( w \) to the degree of saturation \( Sr \). For any fixed \( Sr \), CBR consistently increases with an increase in \( \rho_d \), while the CBR - \( \rho_d \) curves for different \( Sr \) values exhibit nearly the same shape showing a large decrease in CBR with \( Sr \) when \( Sr \) becomes larger than around 50 %.

Fig. 4 shows the CBR - \( \rho_d \) relations when \( Sr = 30 - 40 \% \) from all the test series. Similar results are obtained for other \( Sr \) values. This result reconfirms that the CBR - \( \rho_d \) relation for a fixed \( Sr \) is independent of \( N \) and compaction machine type (i.e., independent of CEL). Accordingly, the test data were fitted by:

\[
CBR = f_{CBR}(Sr) \cdot (\rho_d / \rho_w - b)^c
\]

where \( \rho_w \) is the density of water; \( b = 0.4 \) and \( c = 0.9 \),
which are the positive material constants; and \( f_{\text{CBR}} \) is a function of \( S_r \). The values of \( f_{\text{CBR}} \) obtained from the relation shown in Fig. 4 and others are plotted against \( S_r \) in Fig. 5. In Figs. 3a and b, the relations obtained from Eq. 1 are presented, which fit the data very well.

The contours of unsoaked CBR from Eq. 1 are depicted in Figs. 1 and 6a. On the other hand, the soaked CBR is a relevant index of the strength and stiffness of saturated soil usually referred to in the design of soil structures that would be submerged or would become wet by heavy/prolonged rainfalls sometime during their lifetime span (Tatsuoka et al., 2014b). In Fig. 6a, the contours of CBR after soaking are also depicted, which were obtained by incorporating the effects of soaking on the function \( f_{\text{CBR}} \) in Eq. 1 evaluated by laboratory CBR tests performed at Tokyo University of Science on unsoaked and soaked samples compacted to different \( \rho_d \) and \( w \) states using the same soil type as the full-scale compaction tests (Tatsuoka et al., 2014a). The soaked CBR is also a function of \( \rho_d \) and “\( S_r \) during compaction”. The drained stress-strain behaviour of saturated specimens of a number of well-graded sandy and gravelly soil types compacted to different \( \rho_d \) and \( w \) states exhibit similar effects of \( \rho_d \) and “\( S_r \) during compaction” (Tatsuoka, 2011). As “\( w \) during compaction” is not the basic controlling parameter for the stress-strain properties of soil, the shape of the CBR contours in Figs. 1 and 6a is very complicated.

In Fig. 6a, compaction curve A when \( N=16 \) in the full-scale compaction test has been depicted to be fitted to the data point while referring to compaction curve B. Fig. 6b shows the relationships between the unsoaked and soaked CBR and “\( w \) during compaction” along compaction curves A and B. When compacted to \( S_r<(S_r)_{\text{opt}} \), although the unsoaked CBR is relatively large, they drop largely upon soaking. Collapse deformation is also significant if \( \rho_d \) is low (Tatsuoka & Shibuya, 2014). When compacted to \( S_r=(S_r)_{\text{opt}} \), irrespective of CEL, CBR drops only slightly upon soaking, while the soaked CBR is only slightly smaller than its peak value along the respective compaction curves. Besides, collapse deformation upon soaking is insignificant (Tatsuoka & Shibuya, 2014). When compacted to \( S_r>(S_r)_{\text{opt}} \), although the drop of CBR upon soaking is very small, CBR is low and becomes lower with an increase in \( S_r \). Then, over-compaction may take place in the field. These results indicate that the \((S_r)_{\text{opt}}\) state is the relevant compaction target irrespective of CEL, thus this state can be reached without knowing in-situ CEL.

In Fig. 7a, the data presented in Fig. 1 have been re-plotted changing the horizontal coordinate from \( w \) to \( S_r \) and another set of laboratory compaction test data (Murata et al., 2011) have been added. The compaction curves from the laboratory and full-scale compaction tests at different CELs exhibit nearly the same shape with essentially the same \((S_r)_{\text{opt}}\) value, 81.3 % on average. Then, the \( \rho_d/\rho_{\text{max}} \) vs. “\( S_r-(S_r)_{\text{opt}} \)” relations of these data are rather unique (Fig. 7b). The trend is also valid for different CELs with each soil type (Fig. 10) and with many different soil types for the same CEL (Fig. 11b). The other data available to the authors (Tatsuoka, 2011) also show the same trend. As a result, the relations shown in Figs. 7b, 10 and 11d can be represented by the following simple equation:
\[
\rho_d/(\rho_s)_{\text{max}} = f_{\text{pd}}[S_r - (S_r)_{\text{opt}}]
\]

where \(f_{\text{pd}}\) is a function of “\(S_r - (S_r)_{\text{opt}}\)”. As \((S_r)_{\text{opt}}\) is independent of CEL (e.g., Figs. 7 & 9), Eq. 2 does not include CEL as a variable. As both \(\rho_d\) and \((\rho_d)_{\text{max}}\) are those obtained for the same soil type using the same CEL, \(\rho_d/(\rho_d)_{\text{max}}\) denotes the true degree of compaction \((D_c)\) along the same compaction curve.

Fig. 8. Core material (sieved), Miboro dam (Mikuni, 1962).

Fig. 9. a) \(\rho_d - w\) relations of sieved core material compacted at different CELs; and b) \(k - w\) relations of saturated samples, Miboro dam (Mikuni, 1962).

Fig. 10. \(\rho_d/(\rho_d)_{\text{max}}\) and “\(S_r - (S_r)_{\text{opt}}\)” relations of compacted soil from the data plotted in Fig. 9a.

For a wide range of soil type from soft clay to well-graded gravelly soil, the variation of \(f_{\text{pd}}\) of Eq. 2 is not very small (Fig. 11d). With data of a wide range of soil available to the authors, the range of \((S_r)_{\text{opt}}\) is not small, of the order of 30%. However, for nominally the same soil type in a given fill compaction project, the variation of soil type is not very large, therefore the variation of \(f_{\text{pd}}\) and \((S_r)_{\text{opt}}\) may be insignificant. Then, irrespective of in-situ CEL, the true degree of compaction \((D_c)\), at a given location is readily obtained by substituting a measured in-situ \(S_r\) and “\(S_r)_{\text{opt}}\) by laboratory compaction tests of a representative sample using a certain CEL” into Eq. 2. Then, the distribution of \((D_c)\) in a given site can be obtained by many similar measurements, which is more representative of actual in-situ compaction state than that of the nominal \(D_c\) defined as the ratio of “each in-situ \(\rho_d\) value” to “a fixed \((\rho_d)_{\text{max}}\) from a compaction test of a representative sample using a certain CEL”.

Fig. 11. Eight soil types around Miboro dam site (Mikuni, 1962; Asao, 1964): a) grading curves; b) \(\rho_d - w\) relations ; c) \(k - w\) relations; and d) \(\rho_d/(\rho_d)_{\text{max}}\) and “\(S_r - (S_r)_{\text{opt}}\)” relations of compacted samples.
3 PERMEABILITY OF SATURATED SOIL

Fig. 9b shows the coefficients of hydraulic conductivity $k$ of saturated sieved sample of the core material of Miboro dam (Fig. 8) compacted at different $w$ values using five different CELs (Fig. 9a). For 1Ec, $k$ becomes the minimum at point A, where $w > w_{	ext{opt}}$ for 1Ec". Compaction at $w$ at point A is often recommended for dam cores and river dykes. However, if in-situ CEL is 4Ec, compaction at $w$ at point A results in a small increase in $\rho_d$ and a small decrease in $k$, while a lower $k$ value is obtained by compaction at "w at point B" = "$w_{\text{opt}}$ for 4Ec". The minimum $k$ for 4Ec is obtained by compaction at "w at point C", which is much lower than "$w_{\text{opt}}$ for 1Ec". In any case, as the in-situ CEL is usually unknown, $w$ for the minimum $k$ at a given location is usually unknown.

$\rho_d (\text{g/cm}^3)$

$\text{w (%)}$

$S_r = 100\%$ 60\%

$1.60 - 1.65$

$1.85 - 1.90$

$1.90 - 1.95$

$4.86 - 0.128x$

Fig. 12. $\log k \sim S_r$ relations from the data plotted in Fig. 9b.

It was found that, with the data shown in Fig. 9, $\log k$ for any fixed $S_r$ is proportional to $-5.02 \cdot \rho_d$ on average. Accordingly, the values of "$\log k$ when $\rho_d = (\rho_{d_{\text{max}}})_{1Ec} = 1.872 \text{ g/cm}^3$", denoted as $f_k(S_r)$, were obtained by substituting the values of $k$ and $\rho_d$ of these data into Eq. 3 and plotted against $S_r$ in Fig. 12:

$$\log k = \log f_k(S_r) + 5.02(1.872 - \rho_d / \rho_{d_{\text{max}}})$$  (3)

$f_k(S_r)$ is rather constant when $S_r < 60\%$, while it decreases fast with a further increase in $S_r$ (Fig. 12). As Eq. 3 does not include CEL as a variable, without knowing CEL, the in-situ k value at a given location can be obtained by substituting in-situ values of $\rho_d$ and $S_r$ into Eq. 3. Eq. 3 also fits very well the $k - w$ relations presented in Fig. 11c when taking into account the effect of particle size on $f_k(S_r)$ (Tatsuoka, 2014). If a set of field data is available, an empirical equation in the framework of Eq. 3 can be derived.

Fig. 13 shows the likely mechanism of the effects of "$S_r$ during compaction" on the micro-structure of compacted soil and associated effects on the strength and stiffness and saturated hydraulic conductivity, $k$. When compacted to point C, where $S_r < (S_r)_{\text{opt}}$, a coherent micro-structure is formed with fine particles sticking to coarse particles due to high matric suction. This micro-structure is relatively stable with relatively large voids, resulting in strong and stiff properties with high $k$ values. The terminology "flocculated" used to describe this micro-structure of clay is not used in this study dealing with sandy and gravelly soils. When compacted to point D, where $S_r > (S_r)_{\text{opt}}$, a dispersive micro-structure is formed with fine particles filling in a dispersive manner voids formed by coarse particles due to low suction. This micro-structure is relatively unstable with relatively small voids, resulting in weak and soft properties with low $k$ values.

4 NEW SOIL COMPACTION CONTROL

In Fig. 14, contours of $k$ and compaction curves for $\log k \sim S_r$ relation from the data plotted in Fig. 9.

Fig. 14. Contours of $k$ and compaction curves for $\log k \sim S_r$ relation from the data plotted in Fig. 9.

Fig. 15 shows a new compaction control proposed based on the analysis presented above. This method does not contradict the conventional compaction criteria but unifies them into a single consistent framework comprising steps 1 – 9. Step 1: Target $T$ is determined, where $S_r = (S_r)_{\text{opt}}$ (irrespective of CEL); and $\rho_d = (\rho_d)_{\text{target}}$ that is determined based on such soil properties functions as Eqs. 1 and 3 so that the required soil properties are achieved. Step 2: The in-situ target compaction curve that passes point T is obtained based on Eq. 2 determined by laboratory compaction tests on
a representative sample using a certain CEL.

\[ S_r = (S_r)_{opt} \]

Fig. 15. Soil compaction control to achieve the soil properties required for the performance required in design of a given soil structure.

**Step 3:** The allowable lower bound for \( \rho_d \), DL, is determined in such that the degree of compaction \( D_c = \rho_d/\rho_{\text{target}} = 0.95 \), for example. By specifying DL, too low \( \rho_d \) values due to too low CELs with a given soil type and/or the use of low-compactable soils at a given CEL can be avoided. The purposes of setting this and other bounds are listed in the table inset in Fig. 15. **Step 4:** Point B where \( w = \text{"the value at target T"} \) is obtained along DL. 

**Step 5:** The allowable lower bound for \( S_r \), SL, that passes point B is obtained if no consideration of \( k \) is required. \( S_r \) along SL is equal to \( S_r \) at point B. SL crosses the target compaction curve at point C. When CEL is kept as the same as the one for the target compaction curve, the condition that \( S_r \geq (S_r)_{SL} \) with actual soil types that may be different from the nominal one results in \( D_c \) values equal to, or larger than, "\( D_c \) at point C" (= "\( \rho_d \) at point C"/\( \rho_{\text{target}} \)). This \( D_c \) value, obtained by substituting \( (S_r)_{SL} \) into Eq. 2, is much higher than "\( D_c \) at point B" defined as "\( \rho_d \) at point \( B"/\( \rho_{\text{target}} \). If an allowable maximum \( k \) is specified, referring to Fig. 14, \( (S_r)_{SL} \) is determined in such that the \( k \) values be lower than the allowable maximum. **Step 6:** The lower bound for allowable \( w \), WL, that passes point C is obtained, where \( w = w_{WL} \). **Step 7:** The allowable upper bound for \( w \), WU, where \( w = w_{WU} = w_{\text{target}}+x \), is determined to avoid over-compaction. Trial field compaction tests may be necessary to obtain the reliable value of \( x \). Only the backfill having \( w \) between \( w_{WL} \) and \( w_{WU} \) is allowed to be compacted. **Step 8:** The allowable upper bound for \( S_r \), SU, that passes point D, where WU crosses the target compaction curve, is obtained. **Step 9:** The allowable zone for compacted soil comprising SL, DL, WU and SU is obtained. Bound WL is not necessary for this zone, as compacted soils with \( w > w_{WL} \) can satisfy the required soil properties if located in this allowable zone. If \( w > w_{WL} \), however, it is very difficult to reach this allowable zone even by compaction using a very high CEL. Therefore, compaction at \( w > w_{WU} \) is not allowed.

5 CONCLUSIONS

The optimum degree of saturation \( (S_r)_{opt} \) defined as \( S_r \) where \( \rho_d/\rho_{\text{max}} \) is obtained for a given compaction energy level (CEL) and the \( \rho_d/\rho_{\text{max}} \) vs. \( S_r - (S_r)_{opt} \) relation of compacted soil are independent of CEL and insensitive to soil type variation. The strength and stiffness before and after soaking and the hydraulic conductivity after saturation are a function of \( \rho_d \) and \"\( S_r \) during compaction\". Then, irrespective of in-situ CEL, which is highly variable thus usually unknown, the true degree of compaction \( D_c \) and these physical properties of compacted soil at a given location can be estimated from measured \( \rho_d \) and \( S_r \). It is proposed to examine whether \( S_r \) of compacted soil is close to \( (S_r)_{opt} \) and \( \rho_d \) is large enough to achieve required soil properties, together with pre-compaction control of water content.

REFERENCES


