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Research Paper

Compaction Control Using Degree of Saturation and Plasticity Index on Tropical Soil

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Abstract

Soil compaction in the field is conventionally controlled using maximum dry density, $(\rho d)_{max}$, and optimum moisture content, $(w)_{opt}$, as the target properties. However, achieving accurate control of these target properties can be difficult due to variation of compaction energy level (CEL) and soil type. Recently, a novel soil compaction control approach using optimum degree of saturation, $(Sr)_{opt}$, as the target properties has been proposed. It was argued that $(Sr)_{opt}$ can be a better compaction control property as the value is less sensitive to the variation of CEL and soil type. This paper presents an investigation of the compaction characteristics of tropical soils from several locations in Indonesia based on both primary and secondary data. This study was performed by exploring the relationships between (i) dry density (ρd) and Sr, (ii) (ρd) and plasticity index (PI), (iii) (ρd) and CBR, as well as (iv) (ρd) and permeability. This study showed that the $(Sr)_{opt}$ of the soils was 91.2%, with variation between 81.2% and 96.5%. This study also showed that $(\rho d)_{max}$ can be related to PI at a given CEL. It is expected that the proposed relationships can be better references for field compaction control practices in Indonesia.

Keywords: *CBR; degree of saturation; permeability; plasticity index; soil compaction; tropical soil.*

Introduction

Conventionally, soil compaction in the field is controlled using the maximum dry density, $(\rho_d)_{max}$, and the optimum moisture content, $(w)_{opt}$, as the target properties. These target properties can be obtained from a laboratory compaction test. The compaction test is carried out by exert a certain compaction energy level (CEL) on a soil sample. However, achieving accurate control of these target properties in the field can be difficult due to the variation of CEL and soil type. Furthermore, the achievable field CEL has repeatedly been raised since the first time the method was introduced by Proctor [1] due to the development of construction technology. Consequently, higher $(\rho_d)_{max}$ values can be achieved. Moreover, inefficient and over-compaction may occur if the moisture content in the field, w_{field}, is equal to w_{opt} obtained from a laboratory test, but the field CEL is considerably higher than the laboratory CEL. Even if the moisture content, soil type, and CEL are fixed at a given site, the result of ρ_d and w will still inevitably vary. Also, Sungkono [2] stated that fluid is a common cause of embankment instability when compaction is performed during construction. Therefore, it is very difficult to evaluate and control field soil compaction accurately.

Tatsuoka [3-5] proposed a concept of soil compaction control using a unified compaction curve. The unified compaction curve presents the relationship between the ratio of dry density and maximum dry density, $\rho_d/(\rho_d)_{max}$, and the difference between the degree of saturation and the optimum degree of saturation, $Sr-(Sr)_{opt}$. Here, the optimum degree of saturation, $(Sr)_{opt}$, is defined as the degree of saturation, Sr, at $(\rho_d)_{max}$. The value of $(Sr)_{opt}$ was argued to be insensitive to the variation of CEL and soil type. These studies used one thousand compaction tests data from Ohio (Joslin [6]) and eleven compaction tests data from soils in Japan. Based on these studies, the $(Sr)_{opt}$ of the soils was 82%. Furthermore, these studies also discussed the California bearing ratio (CBR) and permeability tests of the compacted soils. The CBR is a measure that represents the strength of compacted soil.

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All findings in the previous studies were based on soil samples from non-tropical regions. The tropical soils in Indonesia are formed by different geologic origins and climates and therefore may have different physical properties. Gusti [7] performed a similar soil compaction study using sandy soil samples from eighteen different sites in Indonesia. The study was performed to investigate the $(Sr)_{opt}$ of the soils. The study developed (i) an equation for ρ_d, plasticity index (PI), and CEL, (ii) the correlation between $(\rho_d)_{max}$, PI, and CEL, as well as (iii) the correlation between ρ_d, Sr, and the secant modulus (E50) obtained from a triaxial UU test. The study concluded that the $(Sr)_{opt}$ of sandy soils in Indonesia varied between 72% and 94%. This implies that $(Sr)_{opt}$ may have some sensitivity to the soil type and soils in Indonesia may have different $(Sr)_{opt}$ than soils in other geologic and climate regions. However, a strong conclusion could not be drawn since the variation of $(Sr)_{opt}$ produced in the study was still too large. Therefore, it was necessary to obtain more accurate data through primary sampling.

This study aimed to further investigate the compaction characteristics of tropical soil from several locations in Indonesia. This study was performed by exploring the relationships between (i) dry density (ρ_d) and Sr, (ii) (ρ_d) and plasticity index (PI), as well as (iii) (ρ_d), CBR, and the coefficient of saturated hydraulic conductivity. The relationships were constructed based on both primary and secondary data. Considering the limitation of compaction control in the conventional procedure, it was expected that this study could promote a better compaction control approach using the optimum degree of saturation $(Sr)_{opt}$. Furthermore, it was expected that the relationships produced in this study could be used as guidance for field soil compaction practices in Indonesia.

Laboratory Tests

This study used both primary and secondary data from laboratory compaction tests. The primary data was produced from 24 soil samples that were collected in eight locations in Indonesia, namely, Subang I (West Java), Subang II (West Java), Bogor (West Java), Sumedang (West Java), Boyolali (Central Java), Palembang (South Sumatra), Sadawarna (West Java), and Kuningan (West Java). This study also used primary data on 9 samples from a CBR_{soaked} test and 23 samples from a permeability test. The laboratory tests were conducted between January 30th, 2019, and December 31st, 2021. The tests consisted of index properties tests (e.g., Atterberg limit test), compaction test, soaked CBR (CBR_{soaked}) test, permeability test, and unconfined compressive test (UCT). For the compaction test, three CELs were used, i.e., 1 Ec (Standard Proctor), 4.5 Ec (Modified Proctor), and 6 Ec. The tests were carried out following ASTM. The test for CEL with 6 Ec was done by increasing the number of blows.

The secondary data consisted of 118 soil compaction test results, 186 CBR_{soaked} test results, 18 $CBR_{unsoaked}$ test results, and 8 permeability test results for soils from various locations in Indonesia. The tests were carried out between 2018 and 2021 at the Soil Mechanics Laboratory, Bandung Institute of Technology. A summary of the data is shown in Table 1. Subsequently, data analysis was performed by combining the primary data and the secondary data.

Table 1 Summary of primary data used in the analysis.

Data	Compaction Samples		CBR Samples (Soaked and Unsoaked)		Permeability Samples	
	Number of Locations	Number of Samples	Number of Locations	Number of Samples	Number of Locations	Number of Samples
Primary	8	24	3	9	1	22
Secondary	27	118	43	204	3	8

Result and Discussion

Optimum Degree of Saturation and Unified Compaction Curve

Figure 1 shows the relationship between $(\rho_d)/(\rho_d)_{max}$ and $(w)_{opt}$. This figure was constructed using 142 samples from 34 different locations in Indonesia (i.e., 24 samples from the primary data, and 118 samples from the secondary data). The figure shows a linear trend between the variables. Eq. (1) presents a representation of the relationship based on the linear fitting of the data:

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$$(\rho_w)/(\rho_d)_{max} = 0.011(w)_{opt} + 0.393 \quad (1)$$

The $(Sr)_{opt}$ and the representative specific gravity, Gs, can be obtained from the relationship in Eq. (1). Based on this relationship, the $(Sr)_{opt}$ and the Gs of the soils were 91.2% and 2.54, respectively. Note that these values are different from the previous study by Tatsuoka [5]. Tatsuoka produced an $(Sr)_{opt}$ and a Gs of 82% and 2.749, respectively. This implies that $(Sr)_{opt}$ may have some sensitivity to soil type.

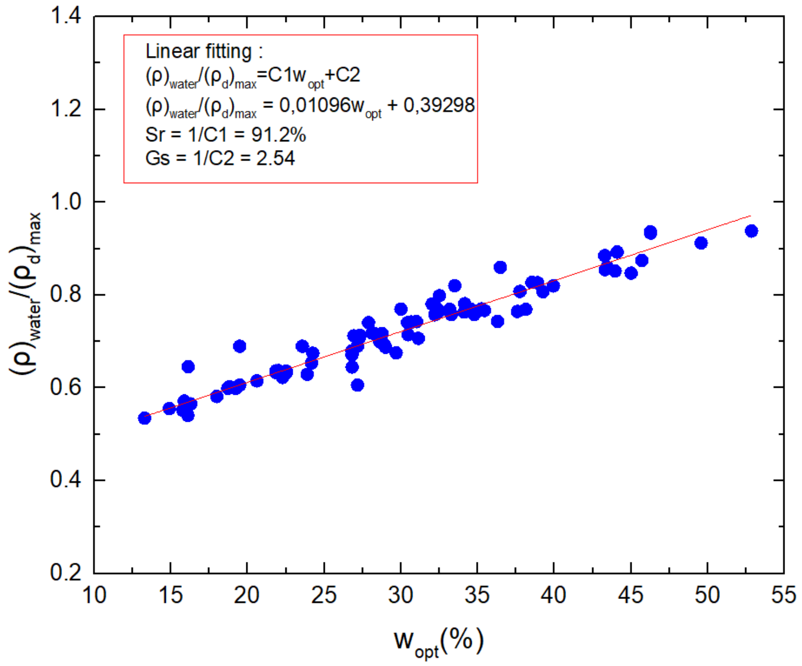
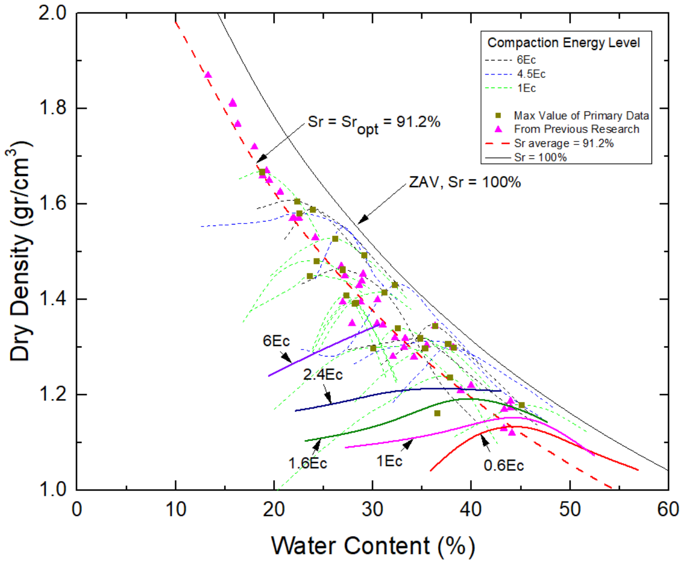
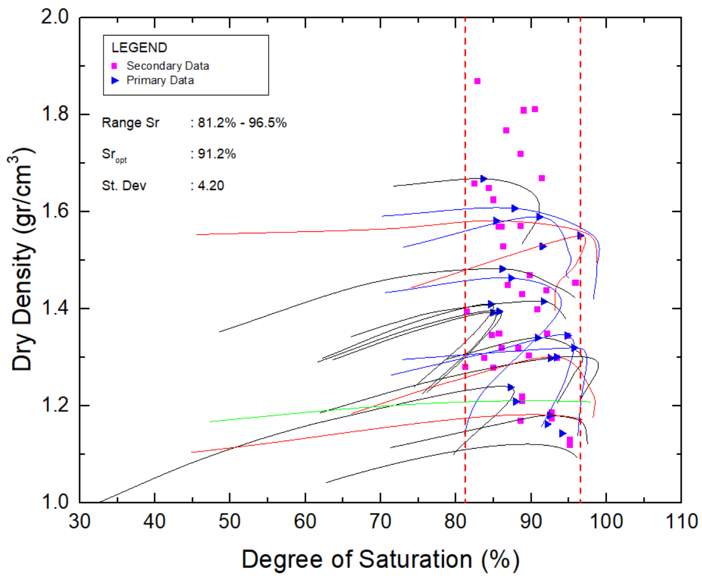


Figure 1 Relationship between $(\rho_w)/(\rho_d)_{max}$ and $(w)_{opt}$.

Figure 2(a) presents the relationship between the $(w)_{opt}$ and the $(\rho_d)_{max}$ of the soils. The obtained $(Sr)_{opt}$ and the zero-air void (ZAV) line (Sr = 100%) were also plotted. It can be observed that the $(Sr)_{opt}$ line curves almost in parallel with the ZAV line. The line appears to intersect each compaction curve close to their $(\rho_d)_{max}$. The degree of saturation can be studied in more detail in Figure 2(b). This figure presents the relationship between $(Sr)_{opt}$ and $(\rho_d)_{max}$. This figure shows that the $(Sr)_{opt}$ values were in the range between 81.2% and 96.5%. Note that this variation is smaller than in the previous studies by Gusti [7] and Pramudita [8].



(a)



(b)

Figure 2 (a) Relationship between $(\rho_d)_{max}$ and $(w)_{opt}$ from compaction tests at all CELs. (b) Relationship between $(\rho_d)_{max}$ and $(Sr)_{opt}$ from compaction tests at all CELs.

Maximum Dry Density and Plasticity Index Correlation

According to Nawir [9], shear strength is related to shear strain. The higher the CEL value, or the greater the compaction quality, the higher the shear strength, which is correlated with the shear strain. Figure 3(a) presents the relationship between $(\rho_d)_{max}/(\rho_w)$ and the plasticity index (PI). This figure was also constructed using both the primary and the secondary data. The data points were plotted according to the CELs. The figure shows the trend of $(\rho d)_{max}$ under the variation of the plasticity index (PI) and CEL. The PI used a variety of values, ranging from about 10% to 58%. The values also represent typical tropical soil, which has a wider range of PI and is more sensitive. The relationship can be represented by Eq.(2), where variable A is a constant coefficient of the normal logarithm of PI and variable C is a function of CEL.

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$$(\rho_d)_{max}/(\rho_w) = A \ln (PI) + C \quad (2)$$

Eq. (2) is fitted for each CEL (i.e., 1Ec, 4.5Ec, and 6Ec). For all CELs, the coefficient A was similar, i.e., A = -0.305.

Figure 3(b) presents the relationship between the CELs and coefficient C. The figure shows a linear trend of coefficient C as a function of CEL as shown in Eq. (3):

$$C = f(CEL) = 0.030\ CEL + 2.311 \quad (3)$$

With the obtained coefficient A and function C, the value of $(\rho_d)_{max}$ as the function of PI and CEL can be generated as shown in Eq. (4):

$$(\rho_d)_{max}/(\rho_w) = -0.305 \ln (PI) + 0.030\ CEL + 2.311 \quad (4)$$

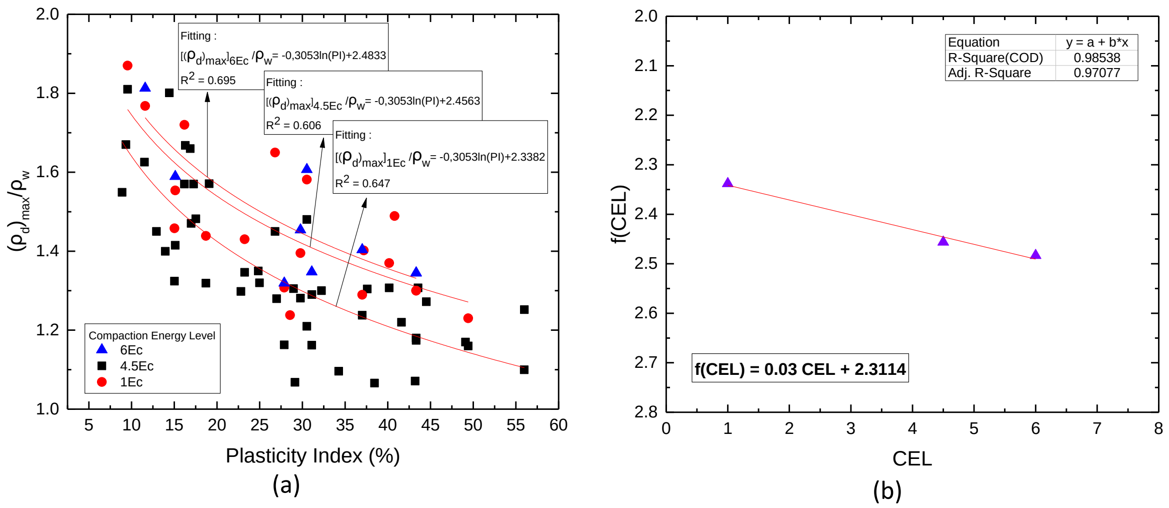

Figure 3 (a) The relationship between $(\rho d)_{max}/(\rho w)$ and PI, with variation in CEL. (b) Coefficient C as a function of CEL.

CBR_{soaked} as a Function of ρ_d and Sr at the End of Compaction

Tatsuoka [5] proposed an equation to estimate the value of CBR_{soaked} as a function of ρ_d and Sr at the end of compaction. The equation is shown in Eq. (5), where variables b and c are constants:

$$CBR = f_{CBR}(Sr) \times [(\rho_d)/(\rho_w)-b]^c \quad (5)$$

Dewi [10] expected that tropical soils in Indonesia will follow the same equation. Thus, the equation was reconstructed using 204 samples from various locations in Indonesia. The samples consisted of 186 samples of CBR_{soaked} and 18 samples of $CBR_{unsoaked}$ (including secondary data).

Figure 4(a) presents the relationship between (ρ_d) and CBR_{soaked}. The data were sorted based on the variation of the Sr in soaked condition. The data were fed into Eq. (5). By trial and error, it was obtained that b = 0.3 and c = 6.5. Figure 4(b) presents the relationship between f_{CBR} and each Sr. This relationship was produced to obtain the f_{CBR} function for Eq. (5). The figure shows that f_{CBR} decreased with the increase in Sr. This relationship can be represented by Eq. (6):

$$f_{CBR}(Sr)_{soaked} = 0.639 - [7.5 \times 10\text{-}19 \times (Sr_{soaked})8.905\ ] \quad (6)$$

Figure 4(c) presents the relationship between Sr_{soaked} and $Sr_{unsoaked}$. This relationship is required to convert the variable from soaked condition to unsoaked condition, which occurs at the end of compaction. This figure was constructed using eighteen data of paired CBR (soaked and unsoaked). The relationship can be represented by Eq. (7):

$$(Sr)_{soaked} = 0.579(Sr_{unsoaked}) + 46.572 \quad (7)$$

The same procedure was carried out to obtain the ρ_d in unsoaked condition, as shown in Figure 4(d). The relationship can be represented by Eq. (8):

$$(\rho_d)_{soaked} = 0.976(\rho_d)_{unsoaked} \quad (8)$$

By using Sr = Sr_{opt} = 91.2%, Eqs. (7) and (8), the relationship between CBR_{soaked} and ρ_d for tropical soils can be formed as shown in Eq. (9):

$$CBR_{soaked} = 0.181[0.976(\rho_d)_{\underline{unsoaked}}/(\rho_w)\text{-}0.3)^{6.5} \quad (9)$$

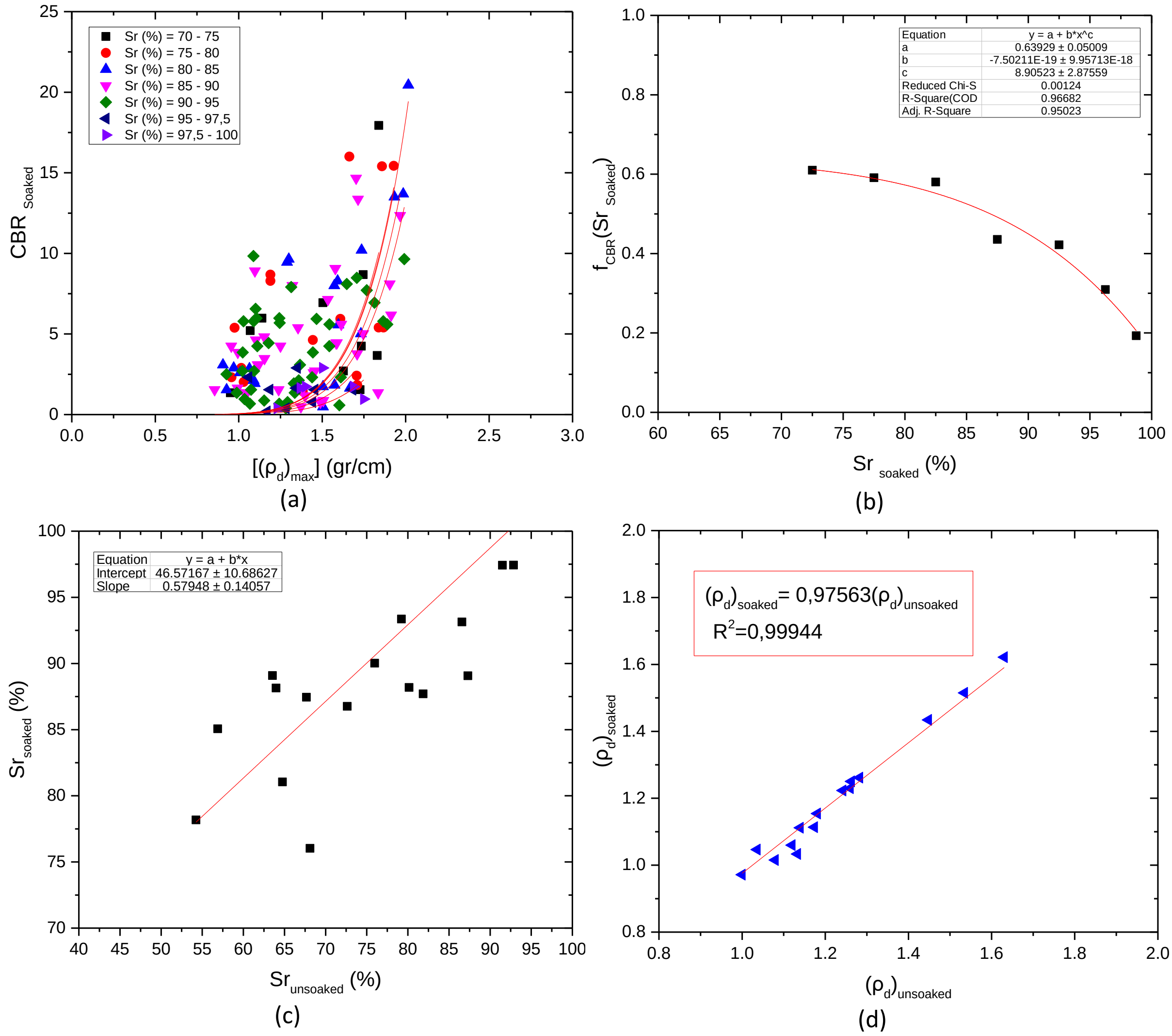

Figure 4 (a) The relationship between CBR_{soaked} and ρ_d. (b) The relationship between Sr_{soaked} and $f_{CBR}(Sr)_{soaked}$. (c) The relationship between Sr_{soaked} and $Sr_{unsoaked}$ (d) The relationship between $(\rho_d)_{soaked}$ and $(\rho_d)_{unsoaked}$.

Figure 5(a) presents the relationship between CBR_{soaked} and ρ_d based on the empirical model in Eq. (5), at various values of Sr. The model was capped at an Sr of 92%. Above this, the Sr in soaked condition would be insensible (i.e., more than 100%). Figure 5(b) presents the relationship between the CBR_{soaked} and ρ_d curves for various constant values of w. The figure also shows the relationship lines of $(Sr)_{opt}$ = 91.2% and Sr = 100%, which were computed using Eq. (5). For compaction with a constant w, an increase in ρ_d can be associated with an increase in CEL. As shown in the figure, CBR_{soaked} of each w increased with an increase in ρ_d (or CEL), until it reached its peak value. At the peak, the Sr was still lower than $(Sr)_{opt}$. After the peak, CBR_{soaked} decreased with an increase in ρ_d. The $(Sr)_{opt}$ value could be achieved with a ρ_d within this region.

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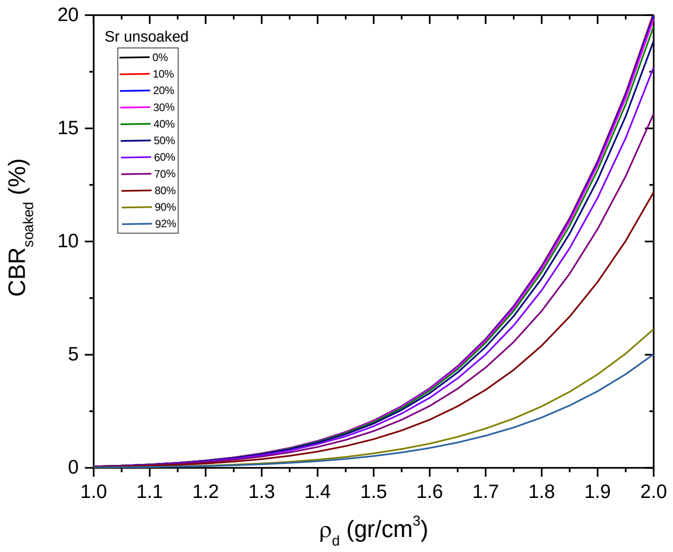
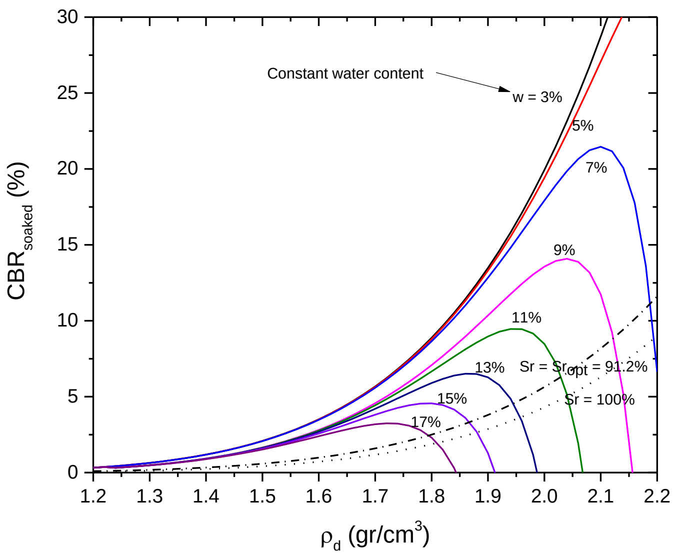


(a)



(b)

Figure 5 (a) The relationship between CBR_{soaked} and ρ_d based on the empirical model described in Eq. (4). (b) The relationship between CBR_{soaked} and ρ_d under various constant values of w.

Relationships of Hydraulic Conductivity to Dry Density and Degree of Saturation

Figure 6 presents the relationship between permeability or coefficient of saturated hydraulic conductivity (k) and moisture content (w) for 22 samples of compacted core material from Leuwikeris Dam at five different compaction energy levels (CEL, i.e. 0.6 Ec, 1 Ec, 1.6 Ec, 2.4 Ec, and 6 Ec). This figure shows that with reference to w, k was strongly affected by the given CELs. At the same w, the value of k decreased as the value of CEL increased. Figure 7 presents the relationship between k and Sr of the same soil samples. This figure shows that with reference to Sr, k had less variability under the variation of CELs. At the same Sr, the difference in k due to the difference in the given CEL was less significant (Dewi [10]).

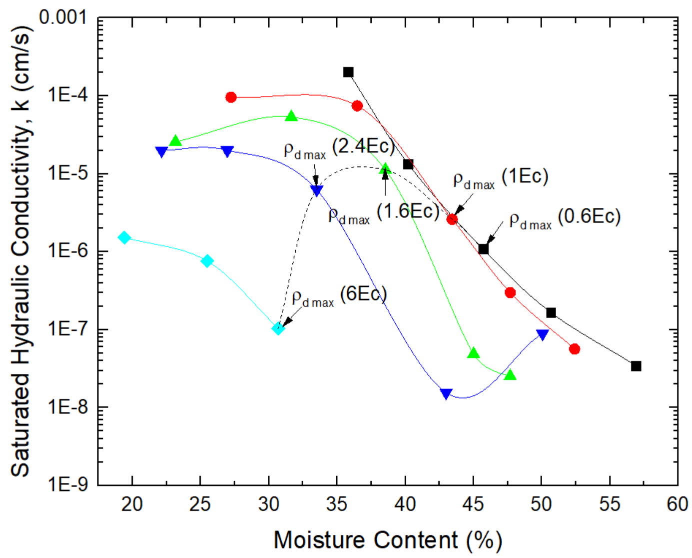


Figure 6 Relationship between w and k for 22 compaction samples from the Leuwikeris Dam core material for various CELs.

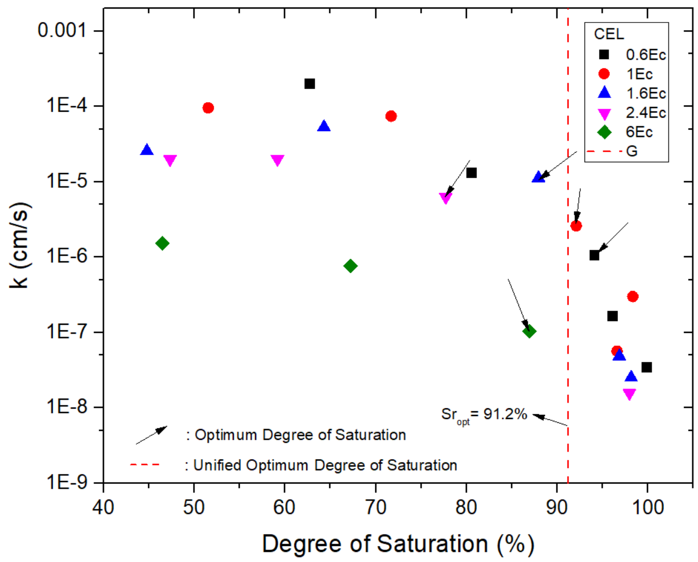


Figure 7 Relationship between Sr and k for 22 compaction samples from the Leuwikeris Dam core material for various CELs.

Figure 8 presents the relationship between k and ρ_d of the same soil samples. The data are grouped according to the Sr at the end of compaction. The figure shows that k decreased as Sr increased. This relationship is compatible with the theory of dispersive microstructure (Tatsuoka [6]). Based on this theory, if soils are compacted with $Sr > Sr_{opt}$, small particles will fill the voids due to the low matric suction. This will result in smaller voids and lower hydraulic conductivity.

The trendline of each Sr group can be obtained from the relationships as shown in the figure and Eqs. (10) to (12):

For Sr = 40% - 86%

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$$\log k = -4.789 + 9.277\,(1.162 - \rho d)/\rho w \tag{10}$$

For Sr = 86% - 95%

$$\log k = -5.535 + 6.301\,(1.162 - \rho_d)/\rho_w \tag{11}$$

For Sr =95% - 100%

$$\log k = -7.321 + 1.985\,(1.162 - \rho_d)/\rho_w \tag{12}$$

The above equations are fitted with Eq. (13):

$$\log k = \log f_k(Sr) + \alpha\,[(\rho_d)_{max\ 1Ec} - \rho_d)]/\rho_w \tag{13}$$

where $\log f_k(Sr)$ is the function of Sr and α is the slope of the equation. The slope α was 7.789. This was obtained by fitting the average slopes of Eqs. (10) to (12). The $(\rho_d)_{max\ 1\ Ec}$ is the value of ρ_d when compacted with energy of 1 Ec. For the Leuwikeris Dam core material, the value was 1.162 gr/cm^3. The ρ_w was assumed to be 1 gr/cm^3.

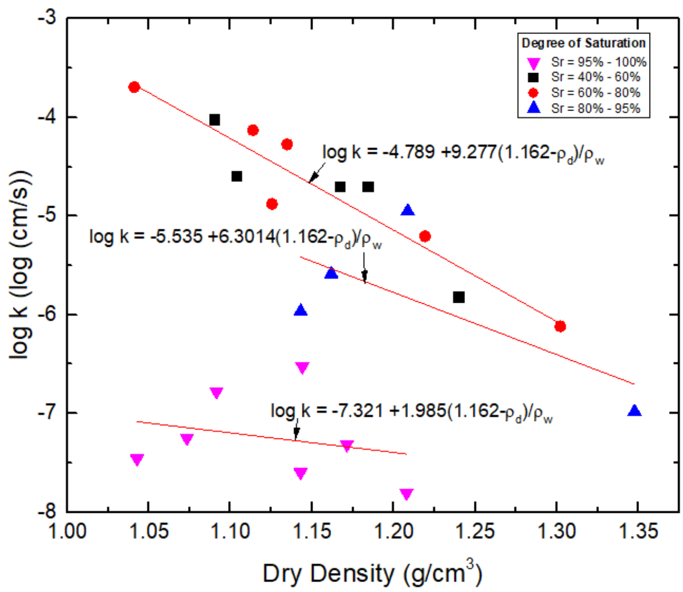

Figure 8 Relationship between (ρ_d) and k for the Leuwikeris Dam core material at the end of compaction.

The result of linear fitting can be seen in Figure 9 and Eqs. (14) to (16):

For Sr = 40% - 86%

$$\log k = -4.782 + 7.789\,(1.162 - \rho_d)/\rho_w \tag{14}$$

For Sr = 86% - 95%

$$\log k = -5.456 + 7.789\,(1.162 - \rho_d)/\rho_w \tag{15}$$

For Sr =95% - 100%

$$\log k = -7.536 + 7.789\,(1.162 - \rho_d)/\rho_w \tag{16}$$

From the fitting result, Eq. (13) was updated into Eq. (17):

$$\log k = \log f_k(Sr) + 7.789\,[1.162 - \rho_d)]/\rho_w \tag{17}$$

Using Eq. (17), the value of $\log f_k(Sr)$ can be obtained by substituting the k and (ρ_d) from the data.

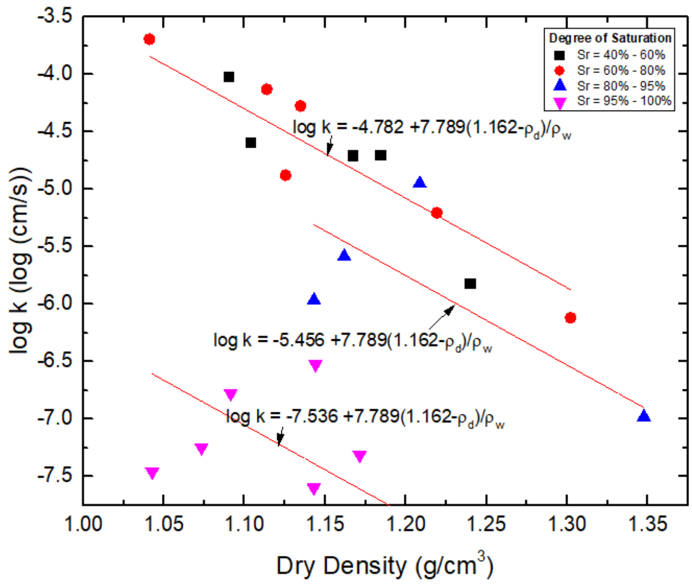

Figure 9 Fitting the result of Sr and k of the Leuwikeris Dam core material.

Figure 10 presents the relationship between log f_k(Sr) and Sr at the end of compaction. This figure shows that the relationship can be approximated using two linear curves with Sr of 86% as the boundary. For Sr < 86% the log f_k (Sr) tended to be constant at -4.782, while for Sr ≥ 86% the log f_k (Sr) fit with Eq. (18) below:

$$\log f_k(Sr) = 16.529 - 0.245(Sr),\ Sr \geq 86\% \quad (18)$$

Figure 11 presents the same plots as Figure 10 but with additional data points from various soil types. The PI of each soil sample is also shown in the figure. The source of the additional data points is listed in Table 2. The figure shows that the additional data produced similar trends. It can be observed that at the same Sr, soils with a higher PI produced a lower log f_k (Sr). Thus, Eq. (18) can be generalized by including PI as the representation of soil type, as shown in Eq. (19):

$$\log f_k(Sr) = f(PI) + \log f_k(Sr)_C \quad (19)$$

Since PI affects log fk(Sr), Eq. (13) can be changed into Eq. (20):

$$\log k = f(PI) + \log f_k(Sr)_C + 7.789\,[1.162 - \rho_d]/\rho_w \quad (20)$$

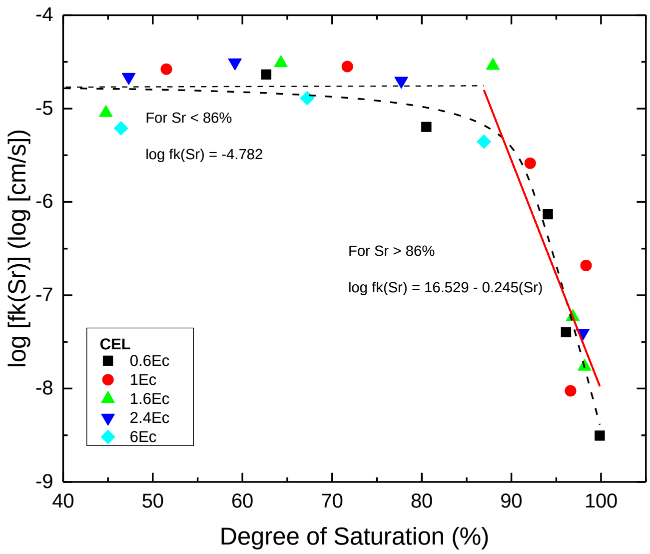

Figure 10 Log f_k (Sr) vs Sr at the end of compaction of the Leuwikeris Dam core material

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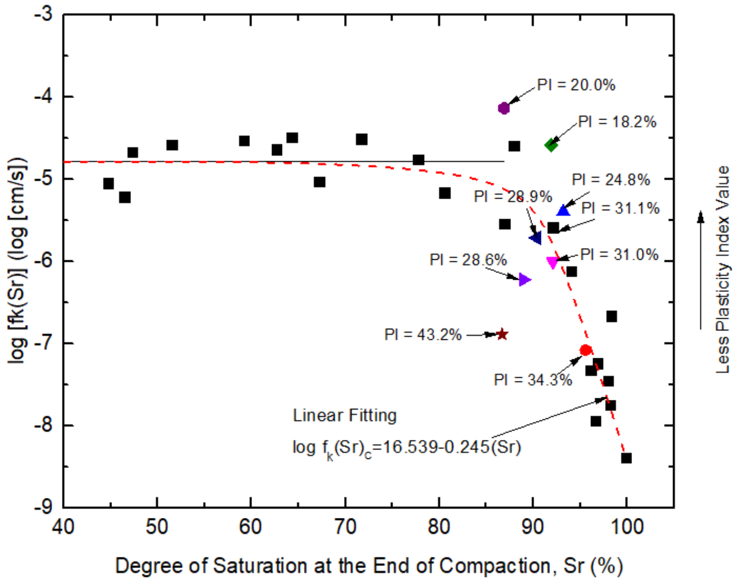

Figure 11 Log f_k (Sr) vs Sr at the end of compaction of various soil types.

Table 2 Summary of secondary data used in the analysis.

Location	Soil Type	Gs	Plasticity Index (%)	MDD (gr/cm^3)	w_{opt} (%)	Sr_{opt} (%)	k (cm/s)	Void Ratio, e
Waduk Karian, Banten 1	MH	2.54	34.26	1.096	49.57	95.6	2.709.E-07	1.318
Waduk Karian, Banten 2	CH	2.50	43.21	1.071	46.27	86.7	6.591.E-07	0.856
Purwakarta, Karawang	MH or OH	2.73	28.56	1.238	39.25	88.9	1.536.E-07	1.141
Subang 1	MH or OH	2.70	18.22	1.322	35.48	91.9	1.490.E-06	1.042
Subang 2	MH or OH	2.64	31.04	1.275	37.35	92.1	1.312.E-07	0.985
Subang 3	MH or OH	2.67	20.01	1.387	30.11	86.9	1.309.E-06	1.157
Subang 4	MH or OH	2.70	24.78	1.347	34.67	93.2	1.458.E-07	0.947
Subang 5	MH or OH	2.79	28.89	1.330	35.55	90.4	9.547.E-08	1.605

Figure 12 presents the relationship between PI and log f_k(Sr). The data points area obtained from the soil samples is shown in Table 2. The relationship was linearly fitted and can be represented by Eq. (21):

$$f(PI) = 3.534 - 0.126\,(PI) \quad (21)$$

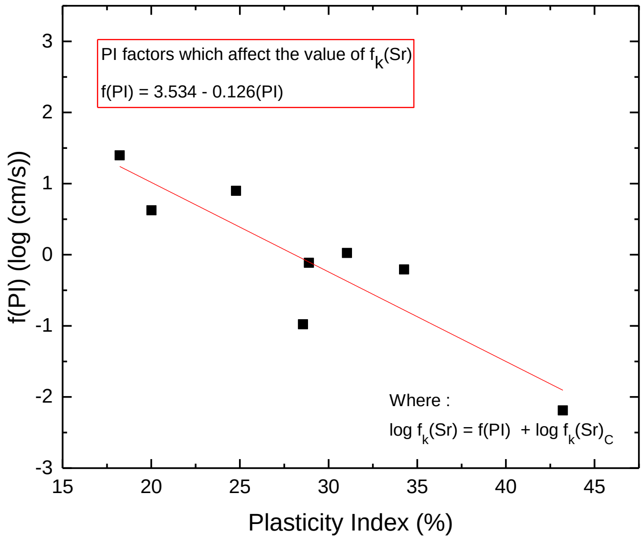

Figure 12 f(PI) vs plasticity index.

For the construction of earth structures such as dams and dikes, soil compaction must be carried out to achieve the k specified in the design requirements. These results show that the required k can be better achieved by controlling the ρ_d and Sr. Furthermore, these results show that k can be estimated if PI, ρ_d, and Sr are known, with the steps listed below:

1. Having the Sr, obtain log $f_k(Sr)_C$ using the relationship between Sr and log $f_k(Sr)_C$ (Figure 10 or using Eq. (18)), limited to Sr ≥ 86%.
2. Having the PI, obtain f(PI) using the relationship between PI and f(PI) (Figure 12), using Eq. (20).
3. Having the log $f_k(Sr)_C$, f(PI), ρ_d, obtain k using Eq. (20).

This method can be useful in practices when limited k data is available from compaction tests. This is especially important since obtaining k in the laboratory is typically more difficult than obtaining the other three properties.

Effect of CEL on Maximum Dry Density Value

Tatsuoka [5] proposed a method to estimate $(\rho_d)_{max}$ at various CELs based on $(\rho_d)_{max}$ at 1 Ec, $[(\rho_d)_{max}]_{1Ec}$. The equation uses coefficient C, which is called the compaction coefficient. Figure 13 shows the relationship between the C coefficient and $[(\rho_d)_{max}]_{1Ec}$. The figure shows a plot of ten tropical soil samples from various locations in Indonesia with the CEL of 4.5 Ec. Data points from the previous studies were also plotted in the figure. It can be observed that the soil samples from Indonesia have different trends compared to the soils from previous studies in other countries. The samples from Indonesia appear to produce a steeper slope, meaning that the coefficient C decreases more with an increase of $[(\rho_d)_{max}]_{1Ec}$. Furthermore, the figure shows that different soil types may produce different relationships. In this case, the clayey soil samples produced a lower coefficient C compared to sandy and gravelly soil samples, at the same $[(\rho_d)_{max}]_{1Ec}$.

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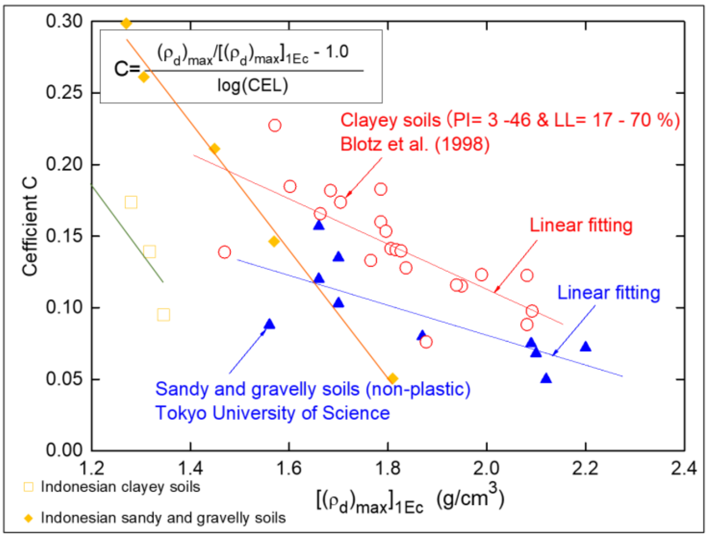

Figure 13 The relationship between the C coefficient and $[(\rho_d)_{max}]_{1Ec}$.

Conclusions

Compaction characteristics of tropical soils from several locations in Indonesia were investigated. Relationships between (ρ_d) and Sr, between (ρ_d) and PI, as well as between (ρ_d), CBR, and k were developed. Several conclusions can be drawn:

1. The $(Sr)_{opt}$ of the soils was 91.2%, with variation between 81.2% and 96.5%. This value is different from the $(Sr)_{opt}$ in the previous studies conducted in other countries. This was expected, since soils in Indonesia have been formed by different geologic origins and climates. This implies that $(Sr)_{opt}$ may have some sensitivity to soil type.
2. The $(\rho_d)_{max}$ can be related to PI at a given CEL. This relationship can be useful as a reference to control the $(\rho_d)_{max}$ obtained from a laboratory compaction test.
3. CBR_{soaked} and k can be related to (ρ_d) and Sr at the end of compaction. CBR and permeability are the physical properties of compacted soils that are frequently used as requirements in a compaction design. Therefore, this relationship can be useful to control soil compaction in the field.
4. The k at the end of compaction can be estimated if PI, ρ_d, and Sr are known. This method can be useful in practices when limited k data is available from the compaction tests.

It should be noted that this study may be improved in several ways. The results of this study are still limited to tropical soils, which have a wider PI range and are more sensitive than other areas. The proposed relationship to estimate CBR_{soaked} was capped to an (Sr) of 92% and the proposed relationship to obtain an approximate value of k was limited for Sr > 86%. Further study should be undertaken to increase the number of primary data and increase the variability of the soil types. This should further improve the accuracy and generalizability of the proposed relationships and coefficients.

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