Study on the Applicability of the Hilf Method for Compaction Control in Hong Kong

GEO Report No. 373

F.L.F. Chu & P.W.K. Chung

Geotechnical Engineering Office
Civil Engineering and Development Department
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Preface

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. The GEO Reports can be downloaded from the website of the Civil Engineering and Development Department (http://www.cedd.gov.hk) on the Internet.

Raymond W M Cheung
Head, Geotechnical Engineering Office
February 2024

Foreword

This report presents a review of the applicability of the Hilf method in compaction control based on the results of 102 field trials and 271 pairs of results conducted in public works projects. The findings of the review suggested that the Hilf method can provide an alternative option for density control and water content control in compaction works should quick results be required. Recommendations on the use of the Hilf method are also provided.

The study was carried out by Ms F.L.F. Chu and Mr P.W.K. Chung. Mr A.L. Wong assisted in reviewing the potential sources of error of the Hilf method. Public Works Regional Laboratories (Tsuen Wan) arranged and carried out the tests in laboratory and in field. The findings of the review were circulated to GEO - HKIE Geotechnical Division Joint Working Group on the Review of Selected Issues relating to Fill Compaction for review and comments have been incorporated as appropriate. All contributions are gratefully acknowledged.

Thomas

T.K.C. Wong
Chief Geotechnical Engineer/Standards and Testing

Abstract

This Report presents a review of the applicability of the Hilf method in compaction control based on the results of 102 field trials and 271 pairs of results conducted in public works projects. The results show that there is a reasonably good correlation between "degree of compaction" from the Hilf method and sand replacement test. There is no significantly difference in the "deviation from optimum water content" determined from the Hilf method and conventional oven drying method. The potential sources of error of the Hilf method leading to uncertainties of test results have been reviewed with precautionary measures suggested. The findings of the review suggested that the Hilf method can provide an alternative option for density control and water content control in compaction works should quick results be required.

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1 Introduction

The need of compaction control is well-recognized to ensure safety and satisfactory performance of fill body. Minimum relative compaction (RC), which is a ratio of field dry density (ρ_d) to maximum dry density (ρ_{dm}) of the compacted soil, is commonly used in the end-product specification for earthworks. Field water content (w_f) within a specific range from the optimum water content (w_o) may also be specified in compaction control of fill materials. In Hong Kong, ρ_{dm} is determined using Proctor compaction test method in laboratory while ρ_d is calculated using the equation "$\rho_d = \rho_w$ / $(1 + w_f)$", where field wet density (ρ_w) (also known as in-situ bulk density) and w_f are measured by sand replacement test (SRT) and conventional oven drying method, respectively. SRT has been used for many decades, which is a reliable and economic method. Conventional oven drying method for measuring water content usually takes at least 24 hours to complete. And, additional time is required to spend on (i) delivering samples from field to the laboratory; (ii) non-operating hours of laboratory; and (iii) administrative procedures and quality control process in the laboratory, such as checking of all relevant test results. Consequently, the information on RC may only be available at least 2 days after the SRT, which probably cause inconvenience or even interruption to the construction works.

It would be of great advantage to the construction works if the field compaction results could be obtained as soon as possible, in particular for large-scale backfilling works such as fill reclamation. Therefore, many methods in the past have been proposed to obtain results rapidly. Hilf (1957 & 1961) proposed a method to determine the RC and the deviation of w_f from w_o without the need to determine w_f of the soil. Usually, the results of only three additional Proctor compaction tests are required after the SRT and these can be completed in less than two hours.

The Hilf method has been widely used in the USA since its development in 1957. Subsequently, it has been codified as testing standard in Australia (AS, 2006), Brazil (ABNT, 1991) and the USA (USBR 1990 & 2012; ASTM, 2017). Historically, it should be noted that the method was introduced for cohesive soil and was used in compaction control on such soil satisfactorily (Hilf, 1961). As stated in some testing methods, the method is applicable on wider range of soils.

In Hong Kong, the Hilf method has been included in General Specification for Civil Engineering Works (GS) (HKG, 1992) since 1990s as an alternative method to determine RC, ρ_{dm} and w_o of compacted fill with particles retained on 37.5 mm BS test sieve not exceeding 20%. The compaction effort is limited to the use of 2.5 kg rammer to compact the fill materials either into a 1 litre or CBR compaction mould subject to the grain-size distribution of the fill material. According to the test procedure in GEOSPEC 3 (GEO, 2017), the compaction efforts of Proctor compaction test with the use of 2.5 kg and 4.5 kg rammer are about 596 kN-m/m^3 and 2681 kN-m/m^3, respectively.

The Hilf method is rarely adopted in practice though it has been incorporated in GS. The reason of not adopting the method in the past three decades by the practitioners is not known. With the potential benefits of using the method, it may be worthwhile to promote its use in compaction control. Considering the limited local experience in using the Hilf method and the fact that this method was originally developed for cohesive soil, the designers may concern the applicability of the method in Hong Kong, in particular whether the method is suitable for more commonly used coarse-grained soil in compaction works and for a higher compaction effort provided in the laboratory (i.e. 4.5 kg rammer). This report aims at (i) reviewing the applicability of the Hilf method for compaction control on four major types of soils commonly used as fill materials in Hong Kong including sandy GRAVEL, gravelly SAND, silty/clayey SAND and sandy SILT/CLAY; (ii) studying the application of the method with higher compaction effort using 4.5 kg rammer; and (iii) providing recommendations regarding the use of the method. List of symbols used in this report is summarized in Appendix A for easy reference.

2 The Hilf Method

RC can either be expressed as a function of wet density or dry density, see also Figure 2.1.

$$\mathrm{RC} = \frac{\rho_d}{\rho_{dm}} = \frac{\rho_d(1 + w_f)}{\rho_{dm}(1 + w_f)} \quad \text{................................ (2.1)}$$

After the SRT in the field, additional soil samples surrounding the SRT spot are taken. When the soils are transported back to the laboratory, typically three compaction tests using Proctor equipment are conducted on the soil samples to obtain the wet densities. The water content of the three specimens for the compaction tests is normally pitched at $z = 0, \pm 2\%, \pm 4\%$, where z is defined as the added/removed water in reference to w_f in percentage of soil wet mass before adding any water in laboratory (see Equation (2.2)). The " ± " sign depends on whether w_f is estimated to be less than or greater than w_o. For example, if w_f is estimated to be less than the w_o, then the three water contents could be $z = 0$, + 2% and + 4%.

$$z = \frac{wM_s - w_f M_s}{M_s(1 + w_f)} = \frac{w - w_f}{1 + w_f} \quad \text{................................ (2.2)}$$

where M_s is the dry mass of soil and w is the water content of soil. Hence $1 + z$ is given by:

$$1 + z = \frac{1 + w}{1 + w_f} \quad \text{..................................... (2.3)}$$

Each soil compaction test on the additional soils taken from the field gives a point on a plot with wet density as ordinate and z as abscissa (see P_1, P_2 and P_3 in Figure 2.2, assume positive z). For each of these three points, the ordinate is divided by $(1 + z)$ to obtain a so-called converted wet density (also known as converted bulk density). A parabola may be fitted to the three converted wet density data points. The maximum value of this parabola can then be obtained (see point A in Figure 2.2). The converted wet density (CWD) is calculated from dividing the wet density of soil by $(1 + z)$,

$$\mathrm{CWD} = \frac{\text{wet density}}{1 + z} = \frac{\rho_d(1 + w)}{1 + z} = \frac{\rho_d(1 + w)}{\dfrac{1 + w}{1 + w_f}} = \rho_d(1 + w_f) \quad \text{........... (2.4)}$$

Since w_f is a constant, the maximum value of the CWD (i.e. the vertex of the parabola, MCWD) must be $\rho_{dm}(1 + w_f)$, i.e. point A in Figure 2.2. Equation (2.4) also shows that when $w = w_o$,

$$\frac{\rho_{dm}\,(1 + w_o)}{1 + z_m} = \rho_{dm}(1 + w_f) \quad \text{..............................} \quad (2.5)$$

where z_m is the abscissa of point A.

RC (also known as ratio D in Hilf method) can now be obtained from ordinates of Point F in Figure 2.1 and Point A in Figure 2.2:

$$\text{RC or } D = \frac{\rho_d}{\rho_{dm}} = \frac{\rho_d\,(1 + w_f)}{\rho_{dm}\,(1 + w_f)} = \frac{\text{ordinate of Point F (Figure 2.1)}}{\text{ordinate of Point A (Figure 2.2)}} \quad \text{..........} \quad (2.6)$$

As far as density control of fill compaction is concerned, in addition to a specified minimum RC, many specifications also require w_f be close to w_o, for example, a tolerance of ± 3% of w_o. The Hilf method provides information of the difference between w_f and w_o (i.e. w_f - w_o) without the determination of the w_f of the compacted fill material. Refer to the converted wet density curve in Figure 2.2, the z value corresponds to the peak point (A) is z_m. Rearrange Equation (2.5) to give:

$$w_o - w_f = z_m\,(1 + w_f) \quad \text{..................................} \quad (2.7)$$

where z_m can be obtained from Figure 2.2 but w_f is unknown. From Equation (2.4),

$$\frac{(1 + w_o)}{1 + z_m} = \left(1 + w_f\right) \quad \text{..................................} \quad (2.8)$$

Substitute Equation (2.8) into (2.7),

$$w_o - w_f = \frac{z_m}{1 + z_m}\,(1 + w_o) \quad \text{.........................} \quad (2.9)$$

The right hand side of Equation (2.9) cannot be evaluated unless w_o is known or estimated. Hilf then made use of about 1,300 data set compiled by the Bureau of Reclamation of US to establish a correlation between the maximum wet density (ρ_{wm}) and w_o. An updated version of this plot is given by ASTM (2017) (see Figure 4.7). As Point B (i.e. ρ_{wm}) shown in Figure 2.1 and Figure 2.2 are known, the corresponding w_o can be estimated from the plot. The difference between w_f and w_o (i.e. w_o - w_f) is then calculated from Equation (2.9).

Furthermore, the Hilf method provides information on the relation between the compaction effort used in the field and in the laboratory. Considering point F in Figure 2.1 and point P_1 in Figure 2.2, as they both represent soil compaction at w_f, the compaction efficiency ratio (C) as defined in Equation (2.10) gives the relative compaction efforts. C is normally expressed in percentage and C larger than 100% suggests the field compaction effort higher than that of the laboratory.

$$C = \frac{\rho_w}{\rho_{w,P1}} = \frac{\rho_d\left(1 + w_f\right)}{\rho_{d,P1}\left(1 + w_f\right)} = \frac{\rho_{df}}{\rho_{d,P1}} \quad \text{.........................} \quad (2.10)$$

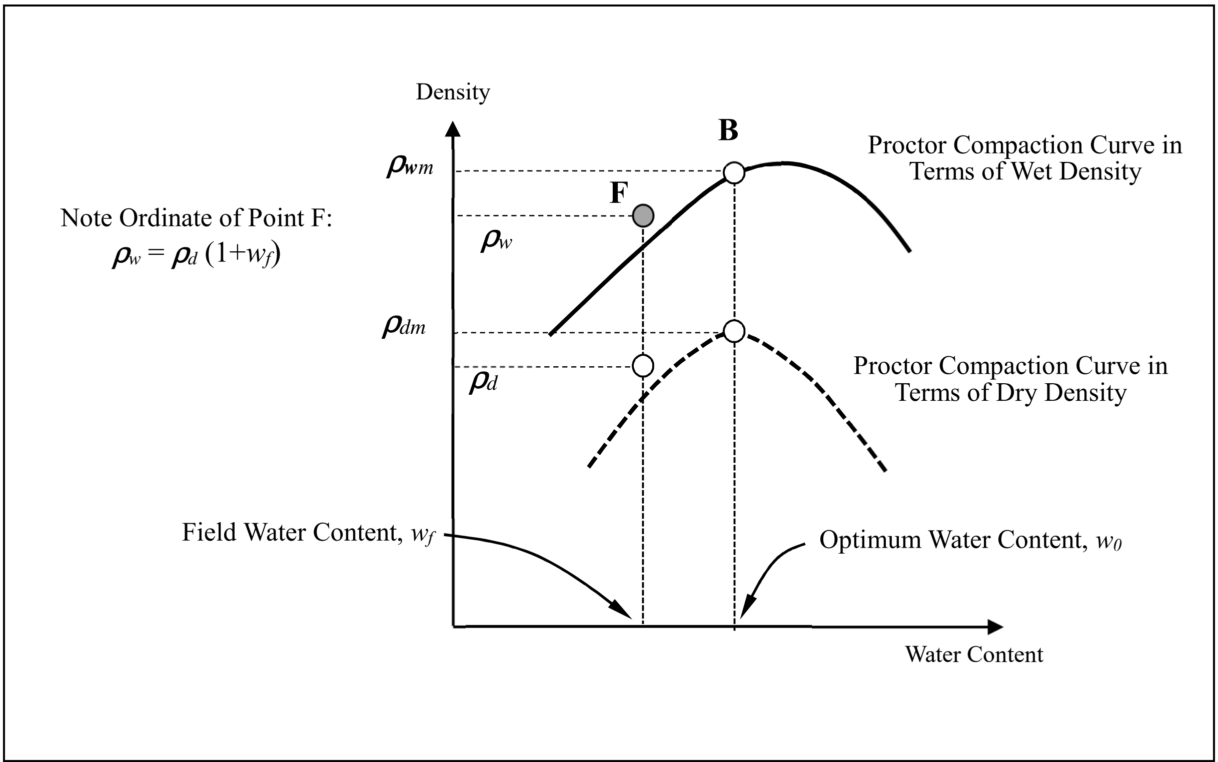

Figure 2.1 Proctor Compaction Curve

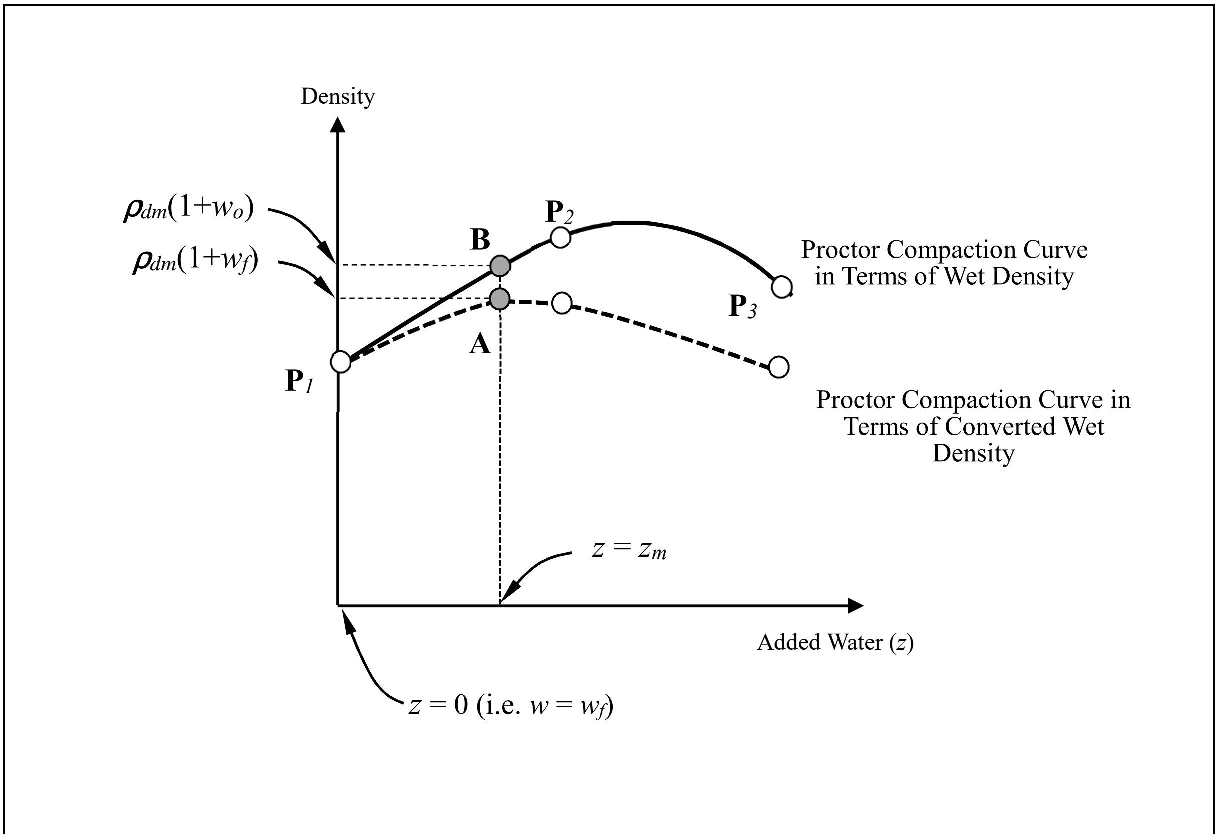

Figure 2.2 The Hilf Method Compaction Curve

3 Field Test Programme

A total of 102 field trials were conducted in 40 different construction sites. Amongst the field trials, 77 of them used 2.5 kg rammer in Proctor compaction test while the remaining adopted 4.5 kg rammer. Usually, more than one SRT is carried out for one batch of fill compaction works according to GS. Therefore, in total, 271 pairs of results for various soil types were obtained from these trials to compare the RC values calculated from the Hilf method to that determined from SRT. Analysis of the difference between w_f and w_o determined from the Hilf method and conventional oven drying method was also carried out. Distribution of the data set collected from the trials in terms of soil types and compaction efforts in Proctor tests is presented in Table 3.1.

Table 3.1 Distribution of Soil Types in Field Trial

Soil Type	Compaction Effort Used in Proctor Test	Number of Data Set Collected from Trials	Percentage in Entire Set of Data
sandy SILT/CLAY	2.5 kg	22	8.1%
silty/clayey SAND	2.5 kg	18	6.6%
gravelly SAND	2.5 kg	128	47.2%
sandy GRAVEL	2.5 kg	46	17.0%
sandy GRAVEL	4.5 kg	57	21.0%
Total number of data set		271	100%

The fill materials covered in this study were mainly coarsely grained soils and classified as sandy GRAVEL and gravelly SAND, with some silty/clayey SAND and sandy SILT/CLAY. The soils which adopted 4.5 kg rammer in Proctor test were all classified as sandy GRAVEL. The range of grain-size distributions of four soil types in two compaction efforts are shown in Figure 3.1. Only few samples contained more than 40% by mass of SILT/CLAY. Majority of samples had fines content between 0 and 30%. All samples contained particles retained on 37.5 mm BS test sieve within 10% and within the applicable range of the Hilf method specified in GS. The distribution of ρ_{dm} and the corresponding ρ_{wm} at w_o against w_o are presented in Figure 3.2. ρ_{dm} of the soils ranged between 1.51 Mg/m^3 and 2.21 Mg/m^3, with ρ_{wm} fell within the zone of 1.90 Mg/m^3 and 2.36 Mg/m^3 and w_o lied between 6.5% and 26%. Chung & Chu (2020) established a relationship between ρ_{dm} and w_o (i.e. ρ_{dm} = 3.703 $w_o^{-0.266}$) for sandy GRAVEL, gravelly SAND and silty/clayey SAND which was based on a review of about 12,000 Proctor test results collected from public works projects in Hong Kong. The relationship is shown as a black dash line in Figure 3.2. As shown in the Figure, fill materials in this study had ρ_{dm} and w_o close to this line.

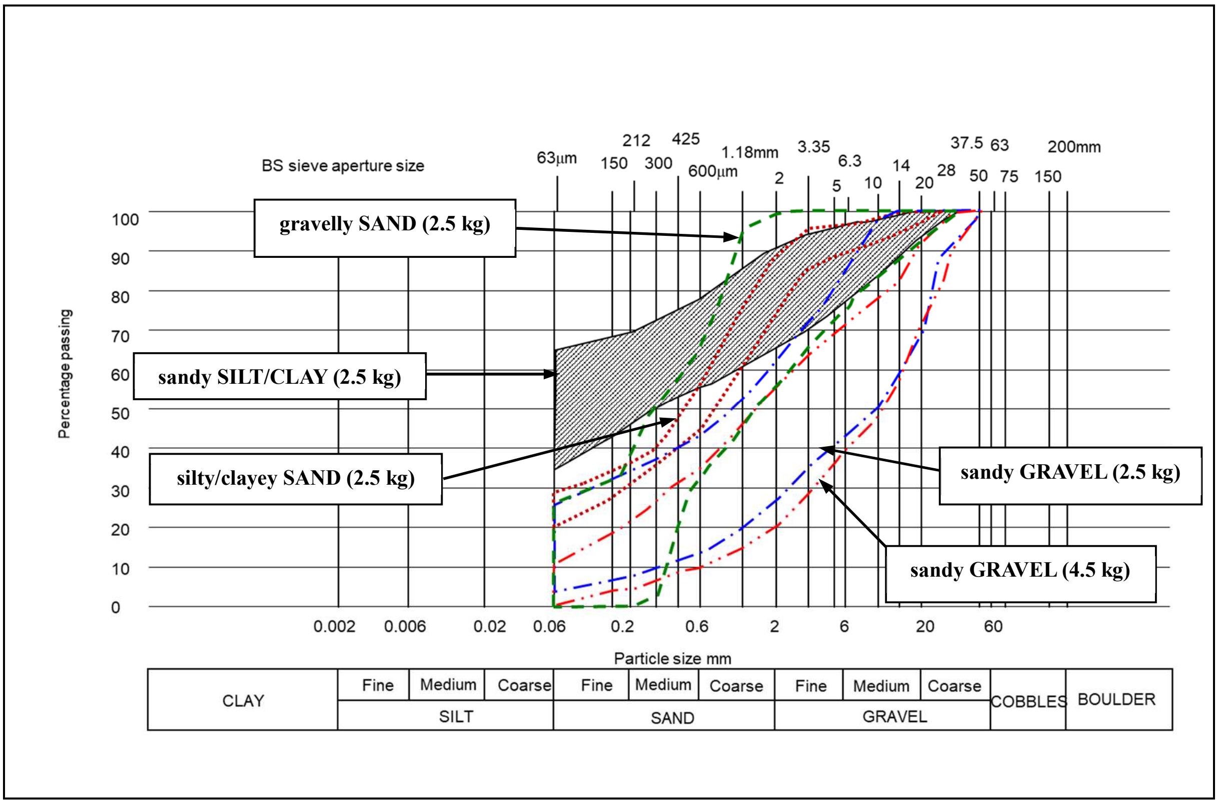

Figure 3.1 Range of Grain-size Distribution of Soils in Field Trials

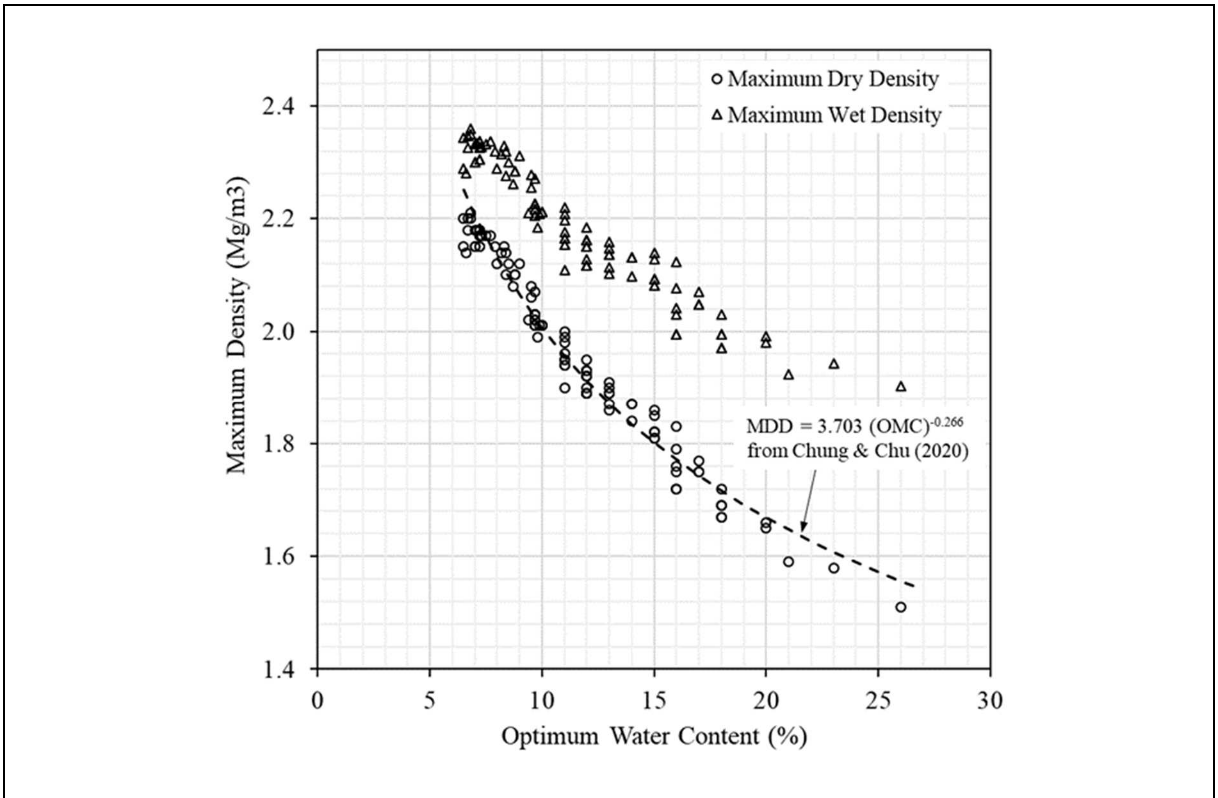

Figure 3.2 Maximum Density Versus Optimum Water Content of Soils in Field Trials

For each trial, besides carrying out the requested SRTs, sufficient soil from the compaction layer near one of the SRTs was collected for the additional Proctor compaction tests under the Hilf method. The soil was kept in a sealed plastic bag to preserve its w_f. Upon returning to the laboratory, the soil was screened over 20 mm BS test sieve and subdivided into equal portions. First portion of the soil was compacted at its w_f in a standard cylindrical mould according to the procedure of the Proctor test. The rammer used in the Hilf method followed the one used to determine ρ_{dm} through Proctor test for the calculation of RC.

Specific amount of water which equalled to certain percentage of the wet mass of the soil was added to or removed from other portions of the soil (e.g. z = ± 2%). The soil with adjusted water content was compacted in the same way. Converted wet density was then calculated from the wet density divided by $(1 + z)$. For each trial, the w_f was also determined from oven drying method so that assessment on the applicability of the Hilf method in prediction of the difference between w_f and w_o can be made. In general, 3 to 4 compaction tests were carried out for each trial. It took about 2 hours to complete sample preparation and additional compaction tests in the laboratory.

Oversize materials (i.e. gravel with size larger than 20 mm) are removed for compaction tests under the Hilf method in Hong Kong, if the weight fraction of gravel is greater than 5% and lower than 20% (HKSARG, 2006). This would result in a lower density determined, as compared with the source of fill material. To this end, size correction factor proposed in Maddison (1944) was adopted (see Equation (3.1)) to determine the maximum converted wet density:

$$\mathrm{MCWD} = \mathrm{MCWD}_{20}\left[1 + \frac{m}{1 + \frac{z_m}{100}}\left(1 - \frac{\mathrm{MCWD}_{20}}{G_S}\right)\right] \quad (3.1)$$

where MCWD = maximum converted wet density
MCWD_{20} = maximum converted wet density of the material passing the 20 mm BS test sieve
m = mass of gravel expressed as a fraction of the wet mass of soil
G_S = specific gravity of the gravels

4 Discussion

4.1 Density Control by the Hilf Method

Relative compaction value (D) obtained from the Hilf method was compared with the RC value obtained from SRT (Figure 4.1). In general, D value increased with the increase of RC value. Regression analysis was conducted. A linear relationship between D and RC values with the R-squared of 0.71 was determined. Most of the results had the absolute difference between D and RC values within 3% (84% of the data). The mean of the difference ($\overline{X}_{D\text{-}RC}$) and the standard deviation of the difference ($S_{D\text{-}RC}$) were 0.32% and 2.22% respectively.

The distribution of the difference between D and RC values was further evaluated based on soil type and compaction effort used in the compaction test. As shown in Figure 4.2 and Table 4.1, the differences were concentrated within ± 3% irrespective of soil type and level of compaction effort used (i.e. 2.5 kg and 4.5 kg). Figure 4.3 presents D and RC values according to the soil types and compaction efforts used in the test. The trend of the relationship between *D* and RC values for different soil types and compaction efforts were similar to the data considered in one single group. If RC ≥ 95% is adopted as the compliance criterion in fill compaction control, only a small proportion of data (about 2.9% bounded by the red dashed box) was interpreted as compliance results based on the Hilf method but non-compliance in accordance with the SRT results.

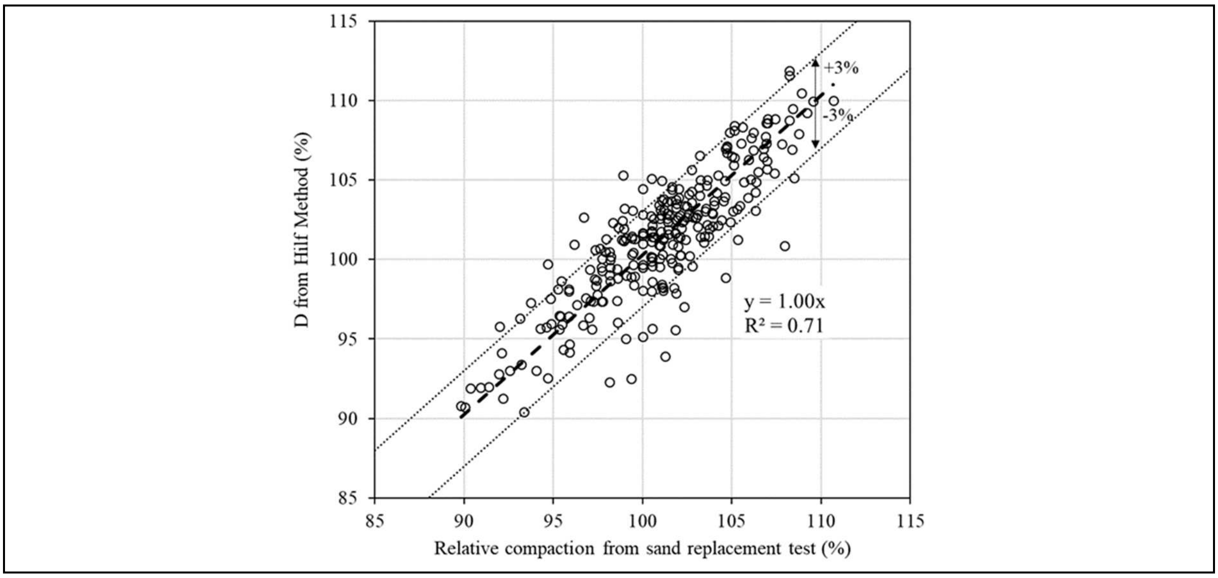

Figure 4.1 *D* Values Versus RC Values

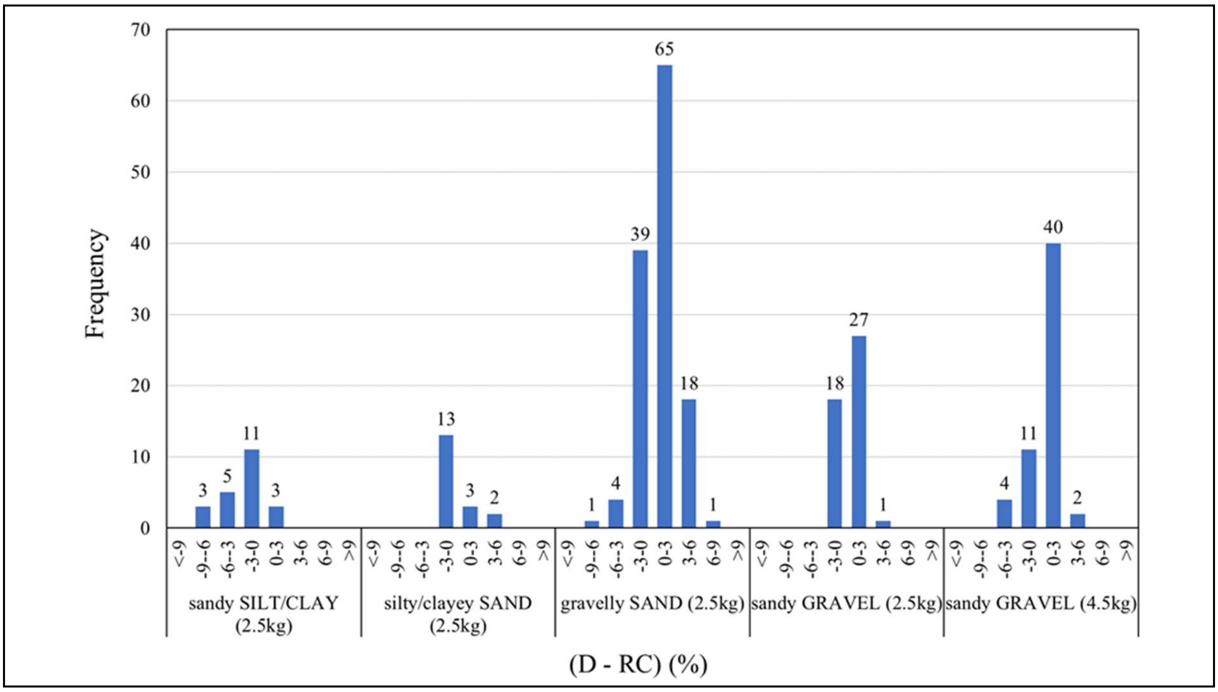

Figure 4.2 Distribution of Difference between *D* Values and RC Values

Table 4.1 Distribution of Difference between *D* Values and RC Values for Various Soil Types and Compaction Efforts

Soil Type (Compaction Effort Used in Proctor Test)	*D* - RC						Total No. of Test
	-9 to -6	-6 to -3	-3 to 0	0 to 3	3 to 6	6 to 9	
sandy SILT/CLAY (2.5 kg)	3 (13.6%)	5 (22.7%)	11 (50%)	3 (13.6%)	0 (9.5%)	0 (0%)	22
silty/clayey SAND (2.5 kg)	0 (0%)	0 (0%)	13 (72.2%)	3 (16.7%)	2 (11.1%)	0 (0%)	18
gravelly SAND (2.5 kg)	1 (0.8%)	4 (3.1%)	39 (30.5%)	65 (50.8%)	18 (14.1%)	1 (0.8%)	128
sandy GRAVEL (2.5 kg)	0 (0%)	0 (0%)	18 (39.1%)	27 (58.7%)	1 (2.2%)	0 (0%)	46
sandy GRAVEL (4.5 kg)	0 (0%)	4 (7.0%)	11 (19.3%)	40 (70.2%)	2 (3.5%)	0 (0%)	57

Notes:

(1) The compaction effort of Proctor compaction test with the use of 2.5 kg rammer is about 596 kN-m/m^3 according to the test procedure in GEOSPEC3 (GEO, 2017).

(2) The compaction effort of Proctor compaction test with the use of 4.5 kg rammer is about 2681 kN-m/m^3 according to the test procedure in GEOSPEC 3 (GEO, 2017).

(3) The number in the bracket represents the percentage of specimens in that range of (D-RC) with respect to the total number of specimens for that soil type.

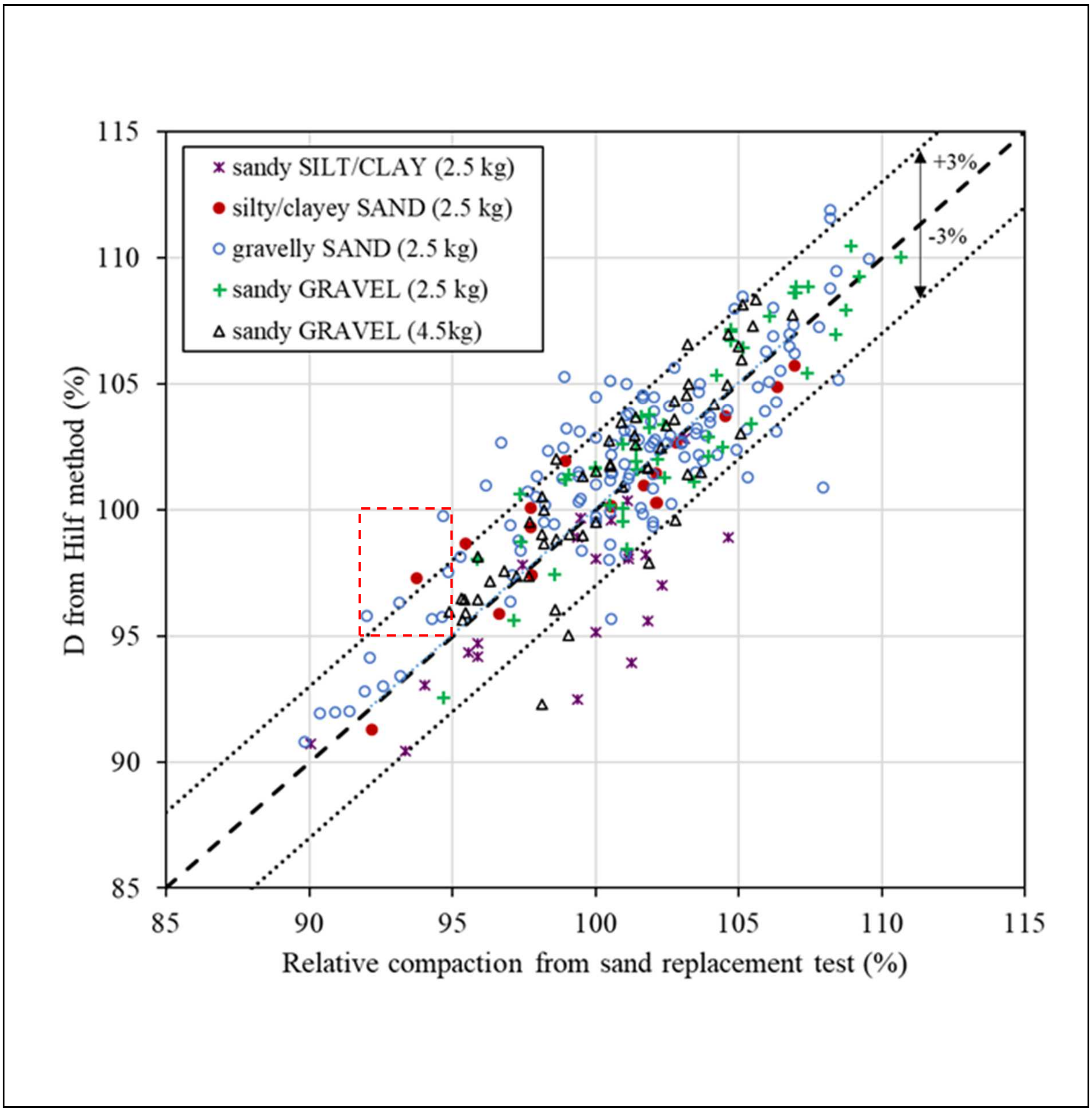

Figure 4.3 ***D*** **Values Versus RC Values for Difference Soil Types and Compaction Efforts**

4.2 Compaction Energy Provided in Laboratory and in Field

Figure 4.1 showed that more than half of the RC values exceeded 100%. This suggested that the field compaction effort was greater than that provided in the laboratory. *C* value, which is a ratio of field wet density to wet density of first additional compaction test at w_f under the Hilf method, as obtained from Equation (2.10) provided insight to this observation. Figure 4.4 shows the distribution of *C* values for the 271 pairs of results. 80% of the results gave *C* larger than 100%. The result was consistent with Figure 4.1 that the compaction energy provided in the field was well above than that in the laboratory.

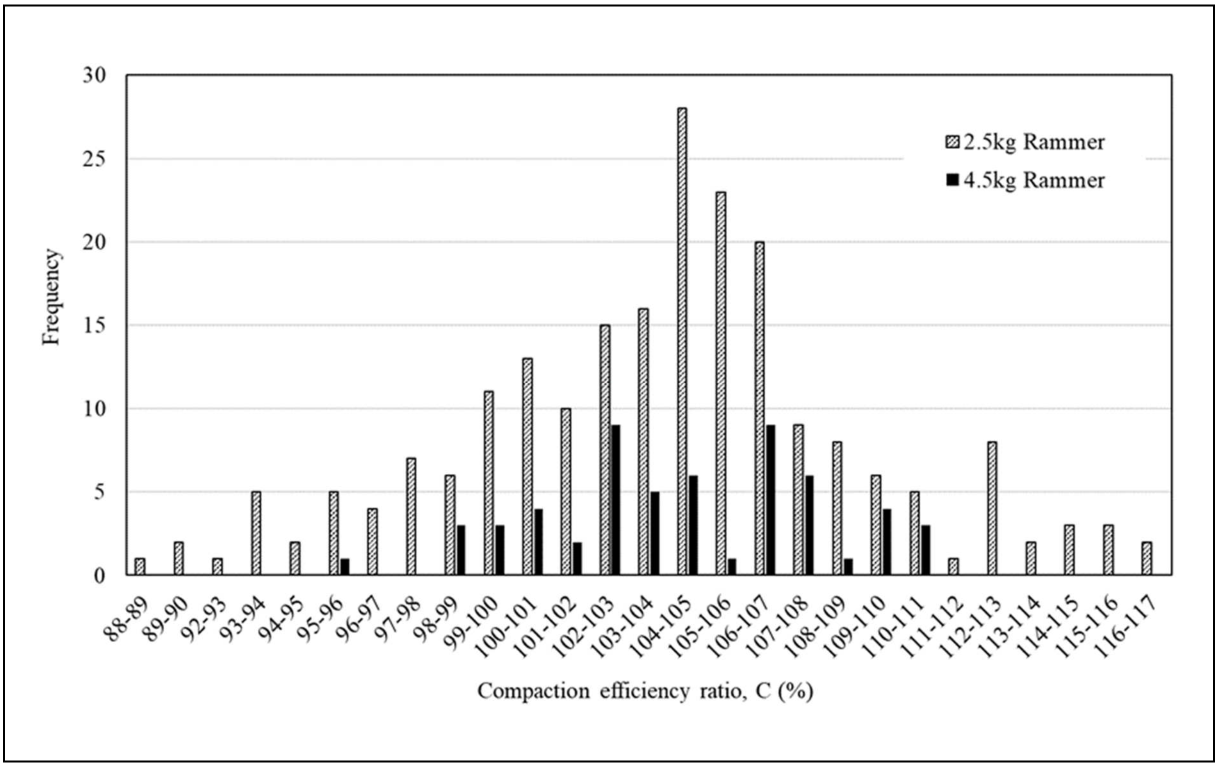

Figure 4.4 Distribution of Compaction Efficiency Ratio with 2.5 kg Rammer and 4.5 kg Rammer Used in the Hilf Method

4.3 Water Content Control by the Hilf Method

The applicability of the Hilf method for water content control was evaluated. In the Hilf method, the deviation of w_f from w_o is estimated based on the relationship between ρ_{wm} and w_o without knowing w_f or w_o for each in-situ density test. For simple application, a water content adjustment value (MA) is introduced which is developed based on a ρ_{wm} - w_o relationship determined for about 1300 soil data came from the Bureau of Reclamation compaction tests (Hilf, 1961; ASTM, 2017). The compaction effort is about 592 kN-m/m^3 which is similar to the standard Proctor compaction test according to GEOSPEC3. Rearranging Equation (2.9), (w_f - w_o) can be calculated as:

$$(w_f - w_o) = -(MA + z_m) \quad \text{.......} \quad (4.1)$$

where $MA = \dfrac{z_m}{(1 + z_m)}(w_o - z_m)$

And z_m is the corresponding water added or removed at the MCWD in the Hilf method compaction curve.

In this study, deviation of w_f from w_o was obtained based on three approaches, (i) calculated with MA determined from CEDD Standard Drawing No. C2006A specified in GS (Figure 4.5); (ii) calculated with MA determined from the graph suggested in ASTM D5080-17 (Figure 4.6); and (iii) calculated with z_m and w_o determined from local ρ_{wm} - w_o relationships with ρ_{wm}. In the first approach, *MA* values are same as that proposed by Hilf (1961) except that the range of z_m extended to 8%. While in ASTM (2017), the data points used to develop the *MA* values are from Hilf (1961). As the best fit curve between ρ_{wm} and w_o is slightly different in ASTM, there is a small variation in the magnitude of *MA* determined from ASTM (Figure 4.6) and CEDD Standard Drawing (Figure 4.5). The range of z_m in ASTM is same as that proposed by Hilf (1961).

The applicability of these graphs on the soils in present study was reviewed. Soil data in the study were superimposed on the scatter diagram given in ASTM D5080-17 (Figure 4.7). The plot showed that all the data in the study fell within the zone bounded by plus/minus twice the standard deviation in w_o. It was therefore reasonably assumed that the *MA* values proposed in ASTM D5080-17 and CEDD Standard Drawing No. C2006A were applicable for the soils in this study.

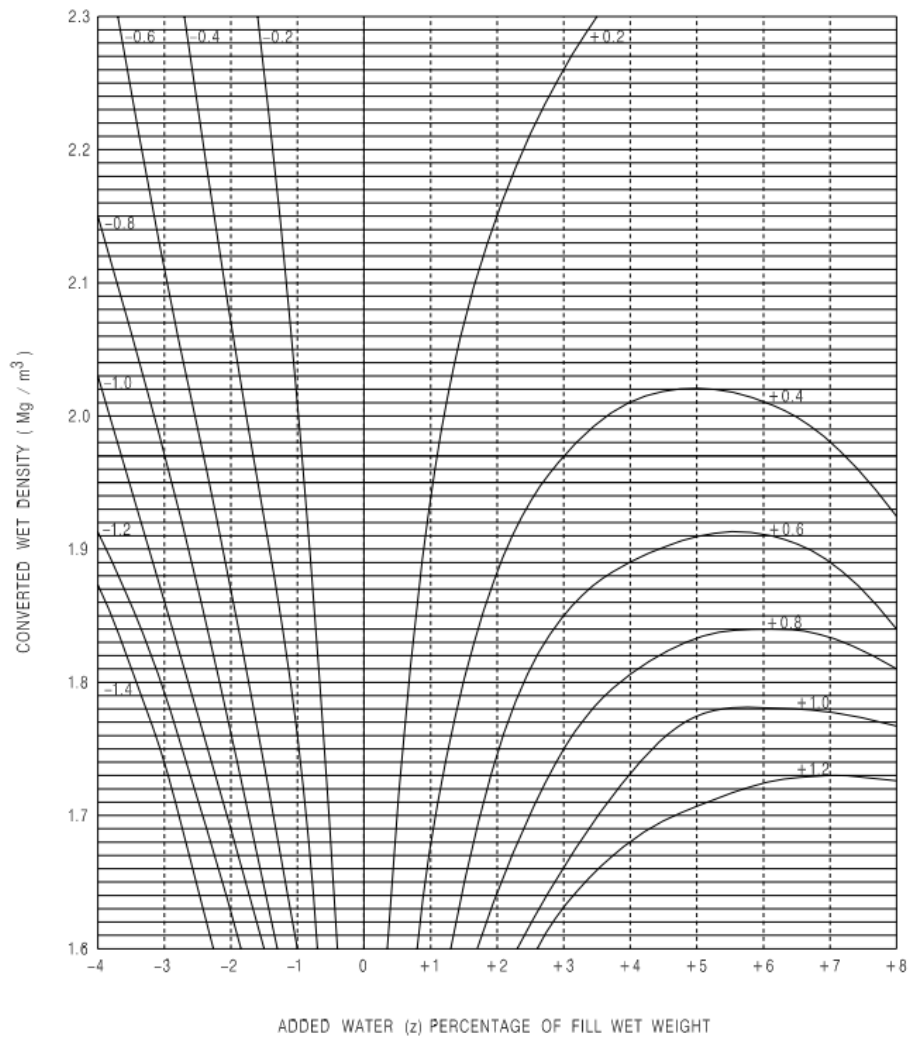

Figure 4.5 CEDD Standard Drawing No. C2006A (HKSARG, 2006)

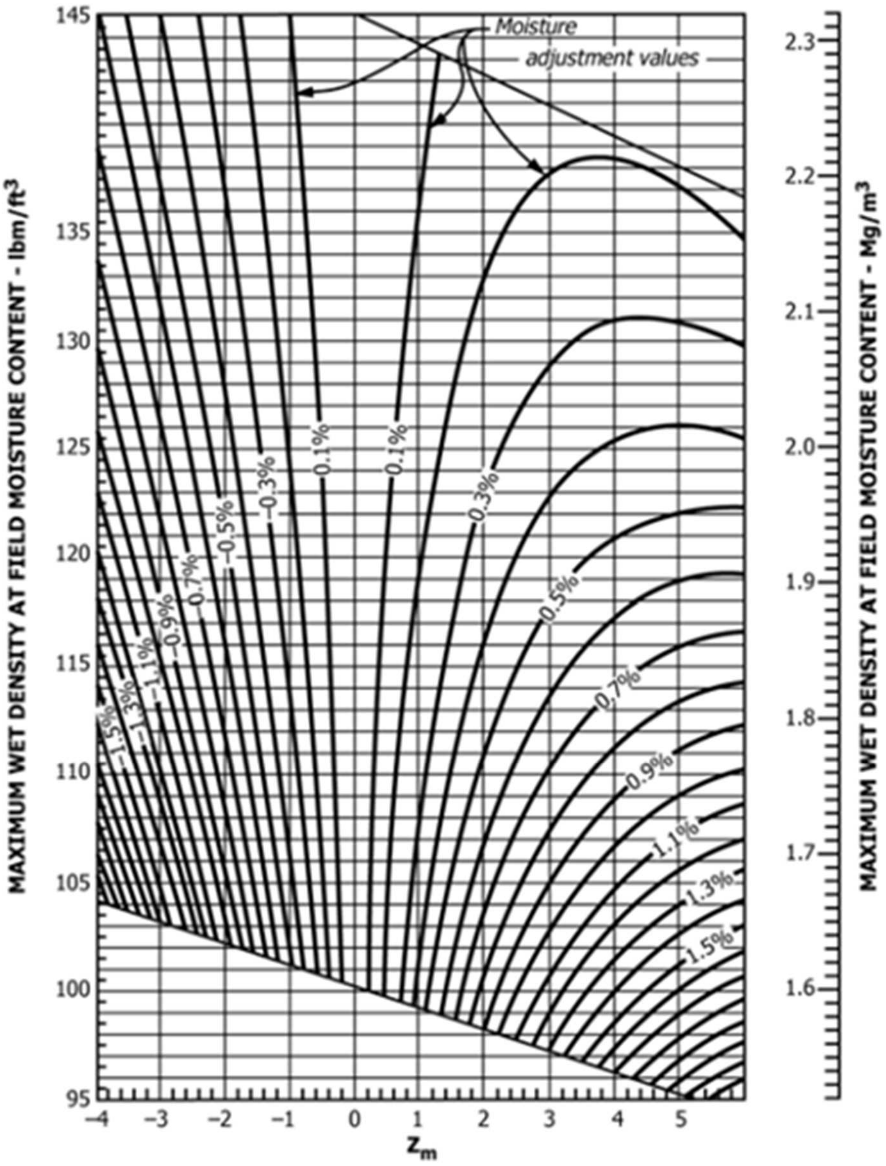

Figure 4.6 Water Content Adjustment Values (ASTM, 2017)

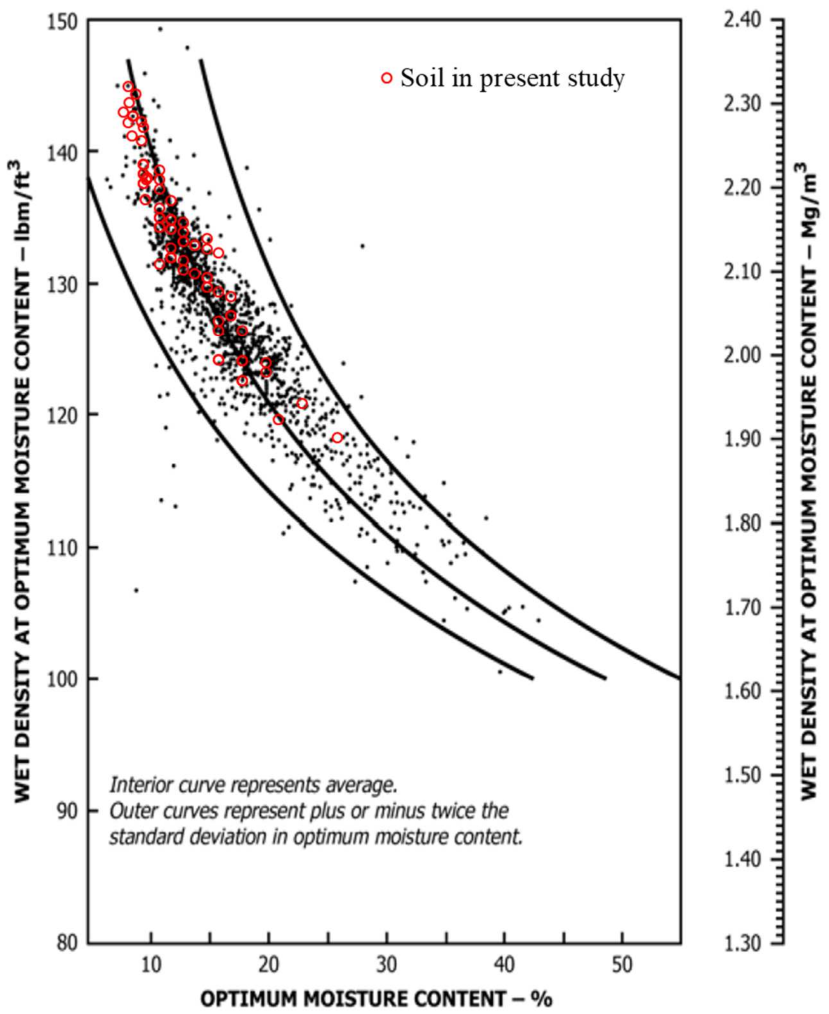

Figure 4.7 Wet Density at Optimum Water Content Versus Optimum Water Content (ASTM, 2017)

In the third approach, local ρ_{wm} - w_o relationships were used. They were determined from a review of 15,952 results of Proctor tests conducted between 2014 and 2018 under public works projects in Hong Kong. Relationships between ρ_{dm} and w_o were first established for 4 different soil types and 2 different compaction efforts. Further to that set of data, the relationships between ρ_{wm} at w_o and w_o with the highest R-squared were determined. The relationships are presented in Table 4.2. Figure 4.8 shows the distribution of data for four soil types in two different compaction efforts. With the measured ρ_{wm}, w_o was calculated based on these relationships. (w_f - w_o) was then determined using Equation (2.9) based on z_m and w_o.

Table 4.2 Local Relationships between Maximum Wet Density (ρ_{wm}) at Optimum Water Content and Optimum Water Content (w_o)

Soil Type	Rammer Used in Proctor Test	Best-fit Relationship	R-Squared	Number of Proctor Test
sandy SILT/CLAY	2.5 kg	ρ_{wm} = -0.021 (w_o) + 2.399	0.789	965
silty/clayey SAND	2.5 kg	$\rho_{wm} = 2.385\ e^{-0.009\ wo}$	0.752	2626
gravelly SAND	2.5 kg	$\rho_{wm} = 2.996\ (w_o)^{-0.134}$	0.756	8084
sandy GRAVEL	2.5 kg	$\rho_{wm} = 2.514\ e^{-0.012\ wo}$	0.691	1487
sandy GRAVEL	4.5 kg	$\rho_{wm} = 2.491\ e^{-0.01\ wo}$	0.467	2790

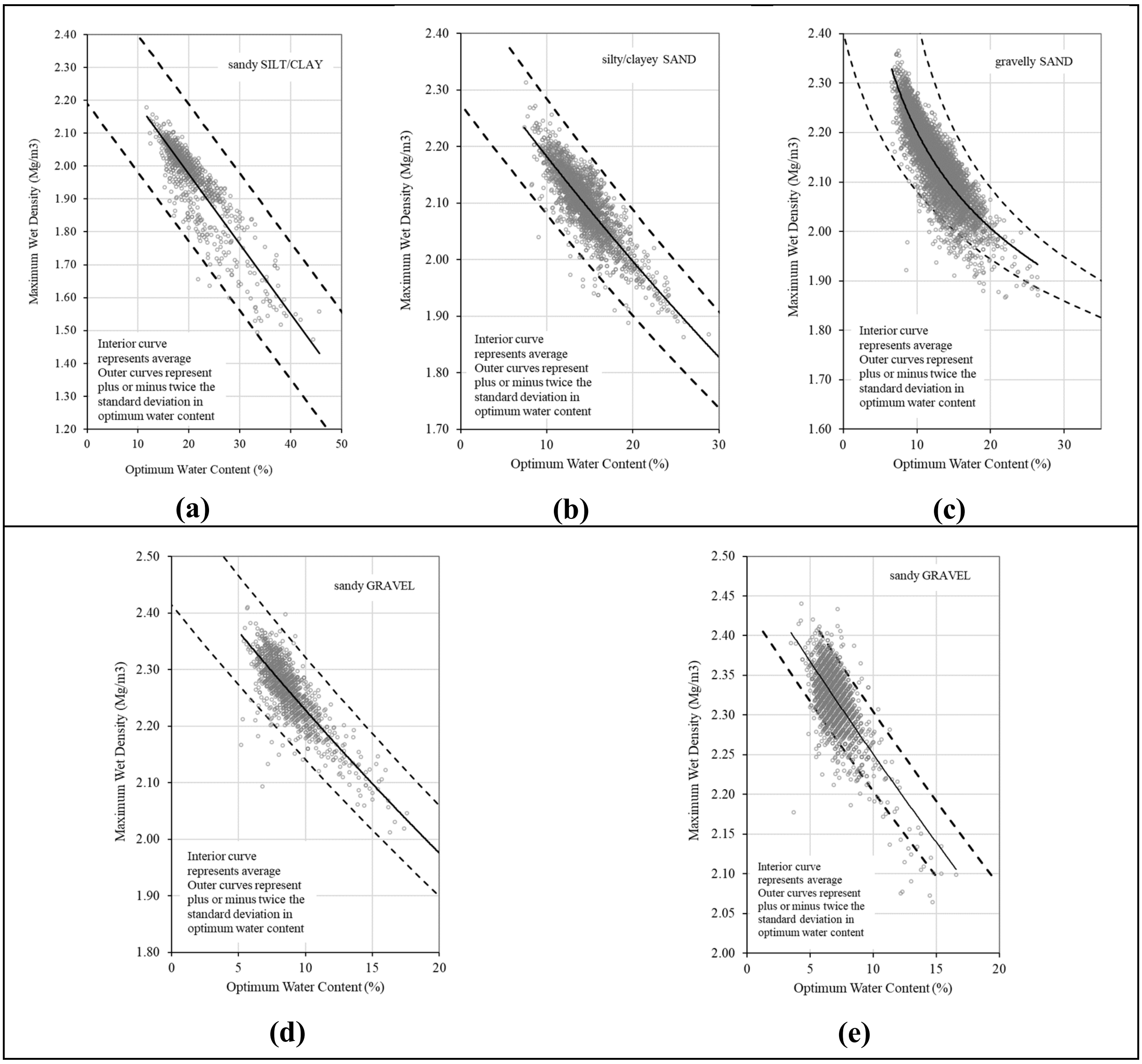

Figure 4.8 ρ_{wm} - w_o Relationship for (a) Sandy SILT/CLAY (2.5 kg); (b) Silty/clayey SAND (2.5 kg); (c) Gravelly SAND (2.5 kg); (d) Sandy GRAVEL (2.5 kg); and (e) Sandy GRAVEL (4.5 kg)

The values of $(w_f - w_o)$ determined from the Hilf method with three different approaches were plotted against the values of $(w_f - w_o)$ with w_f determined from oven drying method and w_o from Proctor test, shown in Figure 4.9, Figure 4.10 and Figure 4.11. As z_m is limited to certain range in ASTM D5080-17 and CEDD Standard Drawing No. C2006A, *MA* cannot be determined if soil is too dry or too wet. Some soils in the present study had w_f deviated a lot from w_o and z_m could not be determined from Figures 4.5 and 4.6. In addition, some trials were conducted using 4.5 kg rammer in the Proctor compaction tests and *MA* could not be determined from these Figures which based on the compaction tests with lower compaction effort. Therefore, the number of data in Figure 4.9 and Figure 4.10 are less than that presented in Figure 4.11. The values of $(w_f - w_o)$ determined from the Hilf method and oven drying method showed a linear relationship. Most of the results had the absolute difference within 3%. The mean of the difference ($\bar{x}_{(wf-wo)Hilf-(wf-wo)oven,Proctor}$) and the standard deviation of the difference ($s_{(wf-wo)Hilf-(wf-wo)oven,Proctor}$) based on three approaches are summarized in Table 4.3. The fluctuation of the prediction amongst three approaches were in similar order.

Table 4.3 Mean and Standard Deviation of Deviation of w_f from w_o Obtained Based on Three Approaches

$(w_f - w_o)_{Hilf} - (w_f - w_o)_{oven\ drying}$	Approaches to Determine $(w_f - w_o)$ under Hilf Method		
	Based on *MA* Graph in ASTM D5080-2017	Based on CEDD Standard Drawing No. C2006A	Based on Local $\rho_{wm} - w_o$ Relationships
Sample Size (n)	178	187	271
Mean (%)	0.25	0.25	0.23
Standard Deviation (σ) (%)	1.21	1.25	1.31

Regression analysis was conducted. As shown in Figures 4.9 to 4.11, more that 90% of the data $(w_f - w_o)$ were found less than zero which indicated that w_f was mostly on the dry side of the w_o. About 50% of the data had w_f less than w_o more than 3%. This observation matched with the review carried out by Chung & Chu (2020) which showed that about 37% of 42,191 SRTs conducted under public works projects had w_f less than w_o more than 3%. The best fit curves established between $(w_f - w_o)$ from the Hilf method and $(w_f - w_o)$ from oven drying method and Proctor test are given in Table 4.4. In which, the best fit curve with adoption of local $\rho_{wm} - w_o$ relationships attained the highest R-squared of 0.844 comparing with the others.

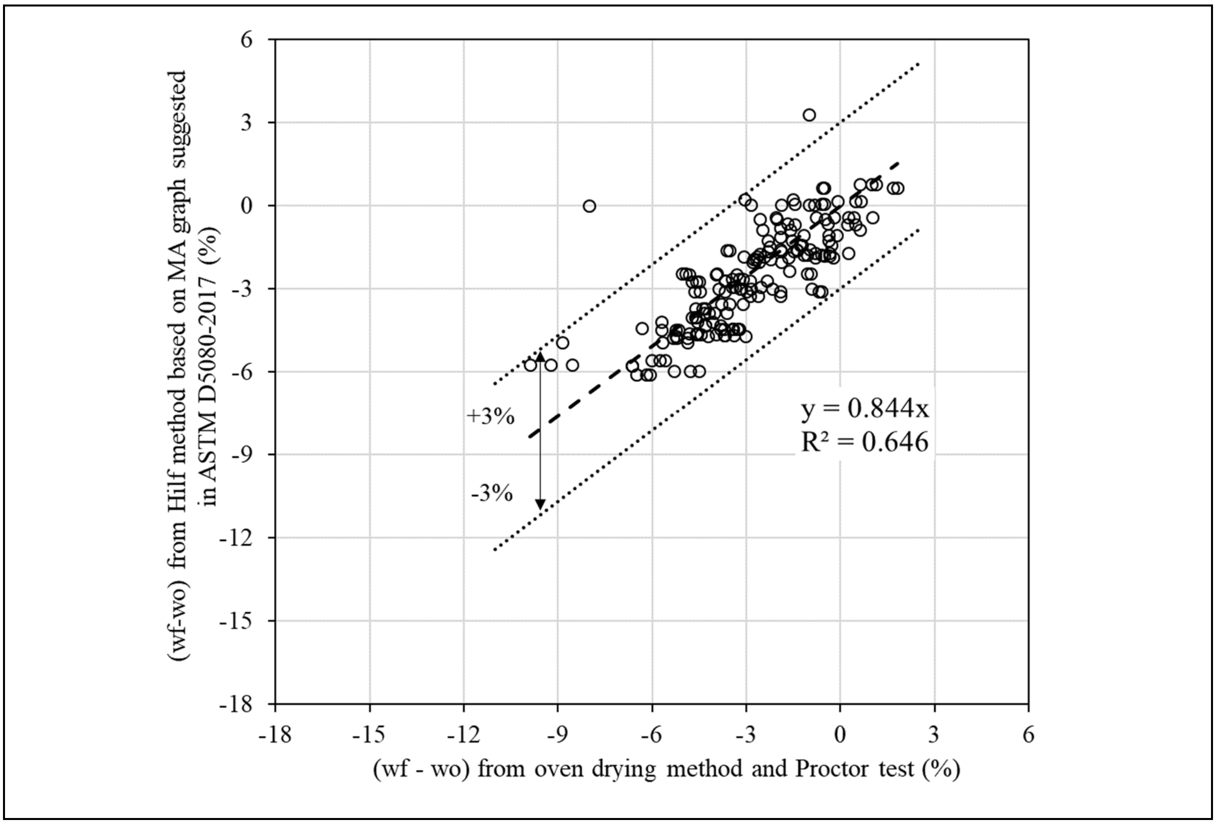

Figure 4.9 (w_f - w_o) Determined from Hilf Method (Based on *MA* Graph Suggested in ASTM D5080-2017) and Oven Drying Method

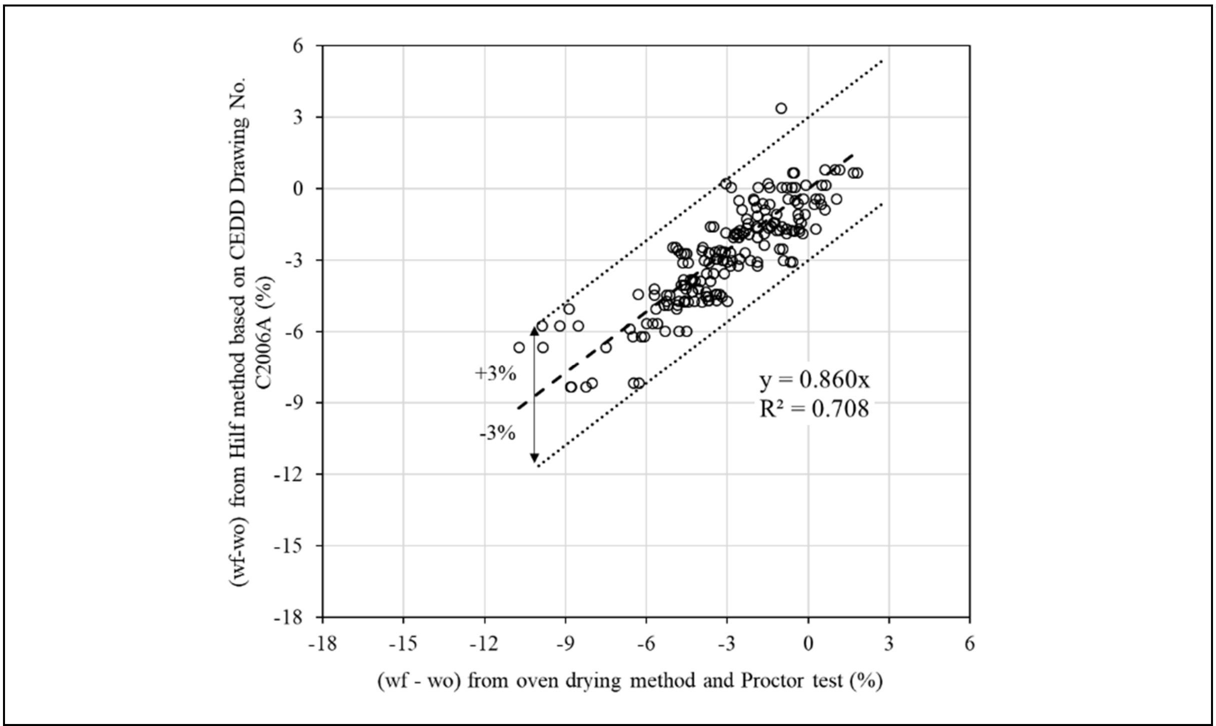

Figure 4.10 (w_f - w_o) Determined from Hilf Method (Based on CEDD Standard Drawing No. C2006A) and Oven Drying Method

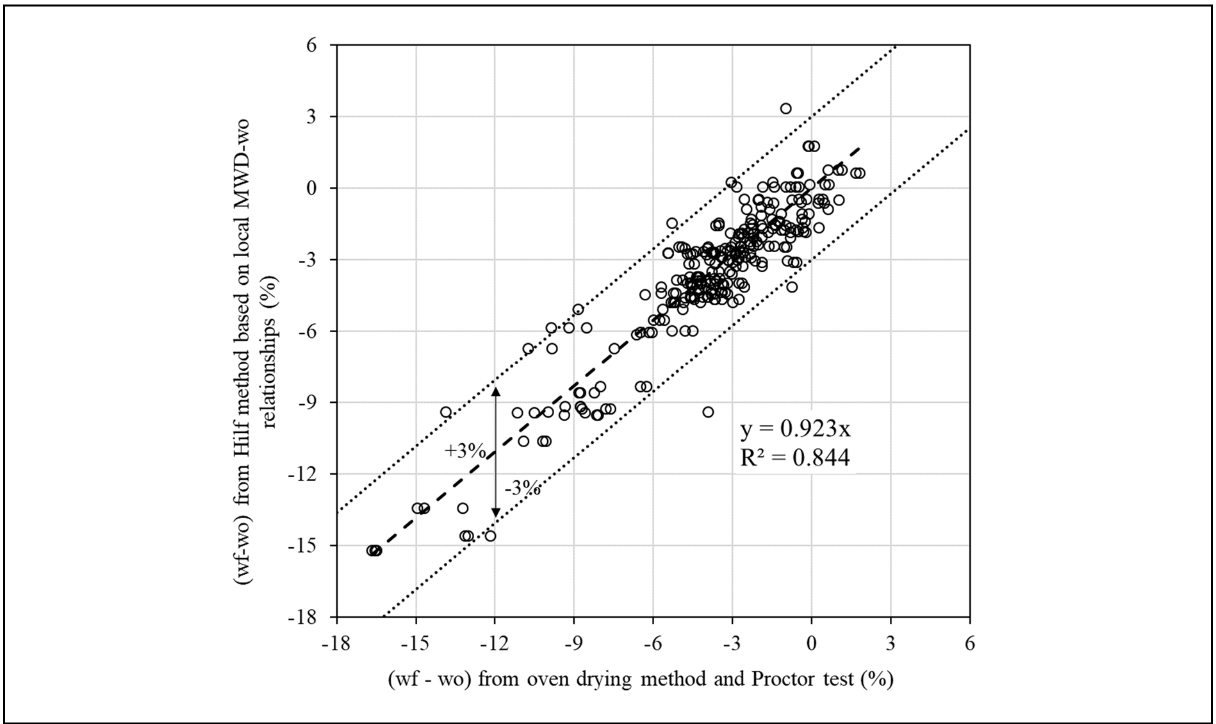

Figure 4.11 (w_f - w_o) Determined from the Hilf Method (Based on Local ρ_{wm} - w_o Relationships) and Oven Drying Method

The best fit curve yielding the highest R-squared showed that Hilf method could predict (w_f - w_o) reasonably based on the local ρ_{wm} - w_o relationships. Comparing with ASTM D5080-17 which only has data came from compaction tests with energy imparted to soil equivalent to Proctor test using 2.5 kg rammer and adopts single best fit curve for prediction of *MA*, using local and specific ρ_{wm} - w_o relationship to estimate w_o with the consideration of soil types and compaction efforts resulted a stronger correlation between (w_f - w_o) determined from the Hilf method and oven drying method.

Table 4.4 Best-fit Relationship between (w_f - w_o) from the Hilf Method and (w_f - w_o) from Oven Drying Method and Proctor Test

$(w_f - w_o)_{Hilf}$ Against $(w_f - w_o)_{oven\ drying}$	Best-fit Relationship	R-Squared	No. of Data
Based on *MA* Graph Suggested in ASTM D5080-17	$y = 0.844\,x$	0.646	178
Based on CEDD Standard Drawing No. C2006A	$y = 0.860\,x$	0.708	187
Based on Local ρ_{wm} -w_o Relationships	$y = 0.923\,x$	0.844	271

Notes: (1) y is (w_f - w_o) determined from the Hilf method.
(2) x is (w_f - w_o) with w_f and w_o obtained from oven drying method and Proctor test respectively.

Similar to the comparison between D and RC values, the data of (w_f - w_o) from the Hilf method and oven drying method was re-analyzed based on soil types and compaction efforts used in compaction tests. As shown in Figure 4.12, the differences were concentrated within ± 3% for all soil types and compaction efforts. Small proportion of the data (about 11% as highlighted in red dash box) indicated that the compacted fill had w_f meeting the requirement in GS (i.e. w_f within ± 3% from w_o) while the compaction did not meet the requirements based on the results from oven drying method (i.e. $w_f < w_o$ -3%).

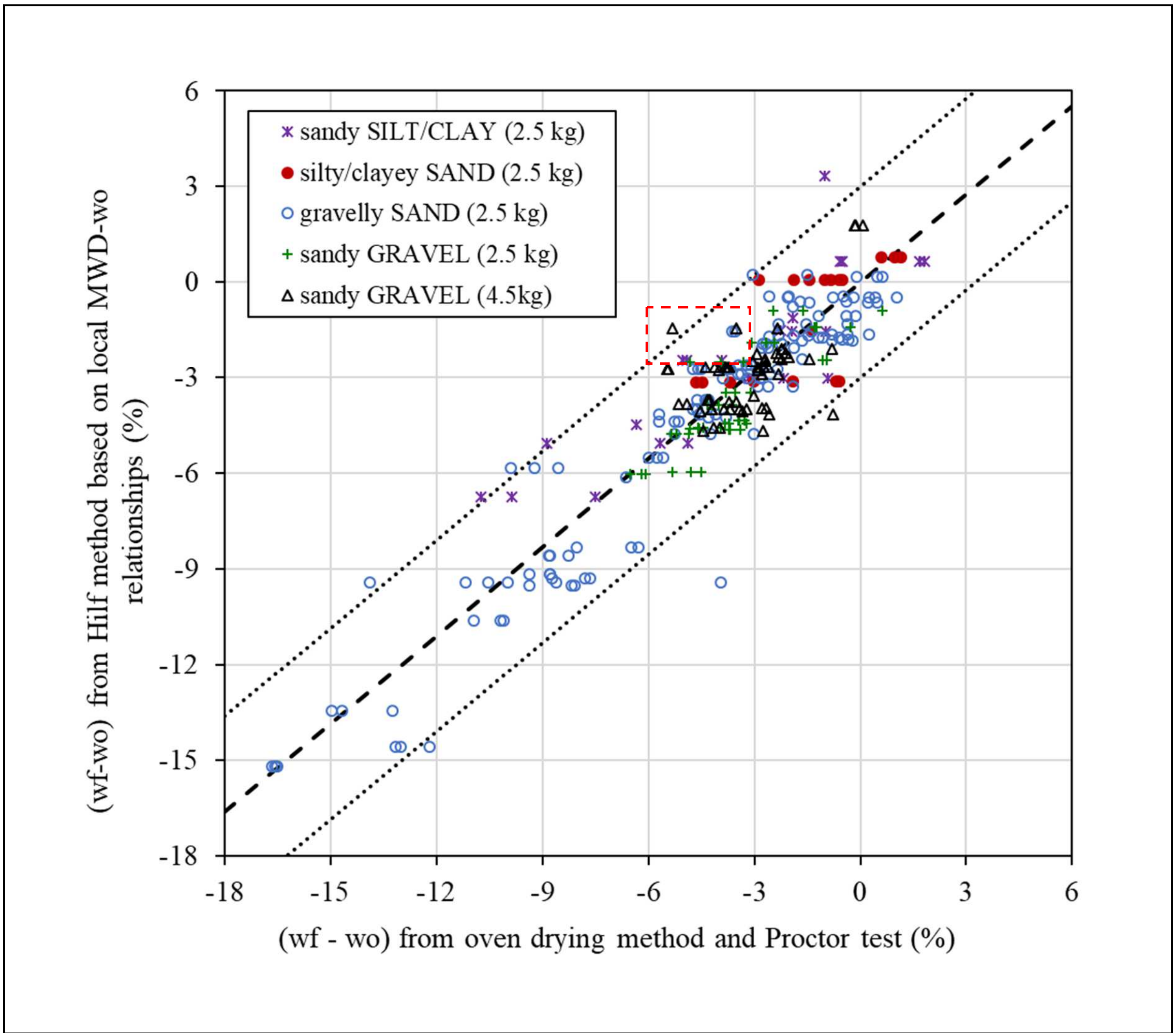

Figure 4.12 (w_f - w_o) Determined from the Hilf Method (Based on Local ρ_{wm} - w_o Relationships) and Oven Drying Method

4.4 Potential Sources of Error of the Hilf Method

Potential sources of error of the Hilf method which could lead to inconsistency of test results have been identified. These potential errors are induced at different stages of the Hilf method, i.e. sampling, testing and interpretation of test results, and summarized in Table 4.5.

Table 4.5 Potential Sources of Error of the Hilf Method

Item	Potential Sources of Error	Potentially Induced in		
		Sampling	Testing	Result Interpretation
(i)	Representativeness of samples	✓		
(ii)	Loss of moisture content	✓	✓	
(iii)	Crushing of soil particles		✓	
(iv)	Compaction effort		✓	
(v)	Determination of apex of converted wet density curve			✓
(vi)	Determination of (w_f - w_o)			✓

Representativeness of samples

Soil samples collected should be representative to the soil that is compacted in field in terms of particle size distribution and w_f. Noting that the maximum converted density, z_m and *MA* are greatly affected by the magnitude of w_f, the predictions from the Hilf method (i.e. *D* and difference between w_f and w_o) cannot reflect the actual condition if there is a significant difference in the water content of the soil under SRT and soil for additional Proctor compaction tests. To this end, fill should be suitably collected from field and divided into batches by quartering, riffling or other suitable means. Each batch should contain similar soil type and is compacted in same compaction effort. The representativeness of sample can be further confirmed by checking the consistency of particle size distribution of soil sample, source of fill and water content.

Loss of water content

The Hilf method assumes that soil sample compacted at 0% of water deviation is at w_f. Loss of water content should therefore be minimized to during sampling, transportation and storage of soil sample by provision of sufficient precautionary measures, e.g. storage of soil samples in sealed plastic containers. Particular attention should be paid in case of long duration of additional Proctor compaction tests as this could result in extra water loss, especially in coarse-grained soils.

In view of the potential water loss during additional Proctor compaction tests, water content of each sub-divided specimen was measured before and after compaction for 74 trials. Measurement of water content before and after compaction test in some trials are shown in Figure 4.13. It was noticed that water lost significantly in some specimens for last two compactions (i.e. 4^{th} and 5^{th} specimen) with a maximum water content reduction of 4%. *D* values for these cases were re-calculated by assuming a water loss of 4% during compaction test and then were plotted against RC values (see Figure 4.14). The regression coefficient of the correlation between D and RC values was improved by 0.04 (i.e. from 0.71 to 0.75). This showed that water content should be preserved for accurate results from the Hilf method.

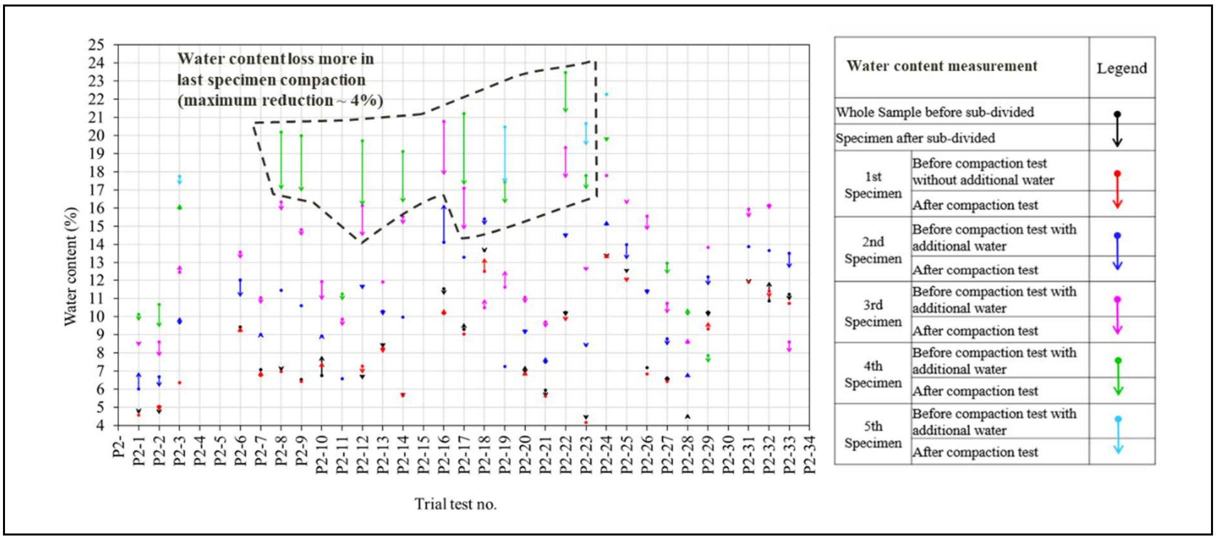

Figure 4.13 Change of Moisture Content during Compaction

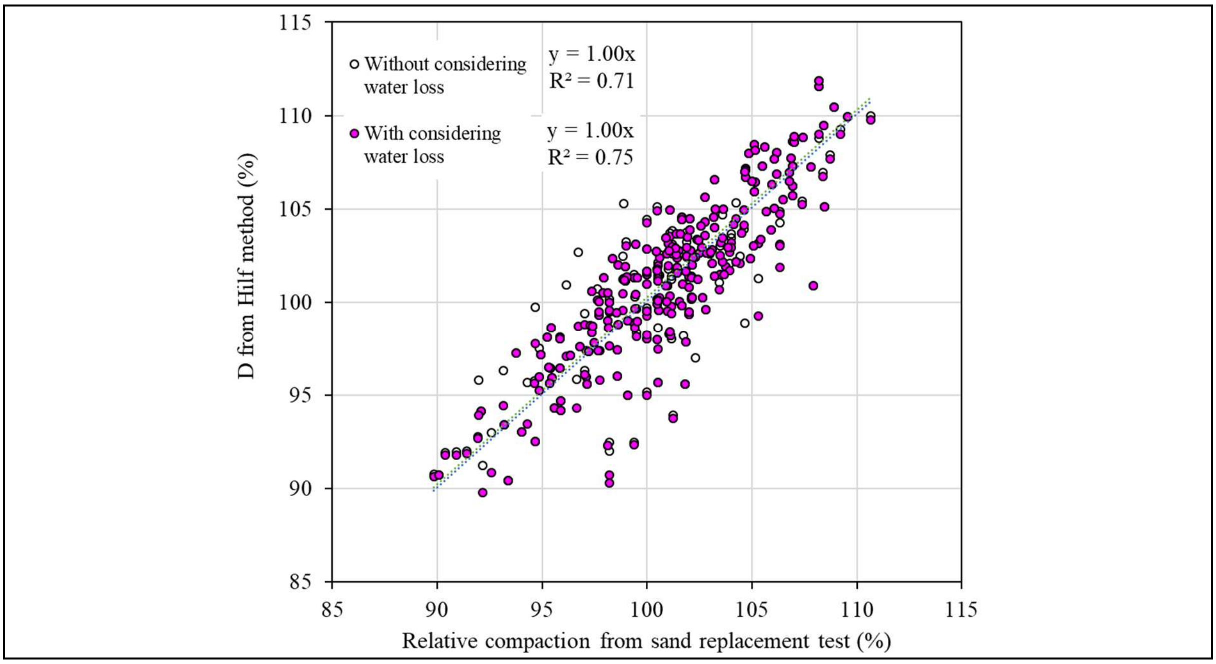

Figure 4.14 Comparison between *D* Values and RC Values with Consideration of Water Loss during Compaction

<u>Crushing of soil particles</u>

For soils that are susceptible to crushing, breakdown of soil grain would alter the soil grading upon Proctor compaction, leading to a reduction in density determined from laboratory. Instead of using one specimen for compacting at different water contents (i.e. single sample approach), different specimens at different water contents should be prepared for each compaction test (i.e. multiple sample approach). Same approach should be adopted in Proctor test and additional Proctor compaction tests under the Hilf method.

Compaction Effort

Inconsistency in compaction effort during Proctor test could result in errors in determining both *D* and RC values from the Hilf method and conventional method, respectively. Same rammer should be adopted in both compaction tests. Besides, in Hong Kong, the use of manual compaction and automatic compaction machine are allowed. Appropriate checking procedure is necessary to ascertain the consistency of performance of automatic compaction machines. For manual compaction, regular proficiency tests should be conducted to evaluate the workmanship of individual laboratory or laboratory operator.

Determination of apex of converted wet density curve

Hilf recommended the use of graphical or analytical to determine the apex of curve of converted wet density. Inconsistency is not envisaged if analytical method is used to solve the apex of parabolic converted wet density curve.

Determination of (w_f - w_o)

To determine water content deviation, correlation between ρ_{wm} and w_o is used. If the properties of soil being tested are deviated from the zone of data used to develop the correlation, the *MA* determined from the graph will not be appropriate. As such, the properties of the soil being tested and the applicability of *MA* given in ASTM D5080-17, CEDD Standard Drawing and the local ρ_{wm} - w_o relationships should be critically examined before use.

5 Recommendations on the Use of the Hilf Method

Based on the potential sources of error that may happen in different stages of the Hilf method, following precautionary measures are recommended if the Hilf method is used:

(a) Water content adjustment values in the Hilf method are derived based on the relationship between maximum wet density and optimum water content of a particular set of soil and compaction effort. Relationships between the maximum wet density and the optimum water content derived based on local data from public works projects in Hong Kong with the consideration of soil types and compaction efforts is suggested to be used. If soil with properties deviated a lot form the data used to develop the relationships, water content adjustment values must be developed for that soil before application of the Hilf method.

(b) Compaction effort used in additional Proctor compaction tests under the Hilf method should be same as that in Proctor test. For example, if 4.5 kg rammer is used in Proctor test to determine the maximum dry density, rammer with same weight should be used in the additional compaction tests.

(c) For soils which are susceptible to crushing, multiple samples for compaction at different water contents should be used in the Hilf method. Sufficient soil samples should be collected from field. Following amount of soil samples are suggested to be collected:

   (i) Minimum 15 kg for material with percentage by mass of particles retained on 20 mm BS test sieve less than 5%;

   (ii) Minimum 20 kg for material with percentage by mass of particles retained on 20 mm BS test sieve between 5 and 20%;

   (iii) Minimum 40 kg for material with percentage by mass of particles retained on 20 mm BS test sieve exceeding 20%.

(d) Grading and water content of soil collected from SRT and soil used for the Hilf method should be consistent. If obvious difference is noted in different spots of SRT, additional soil should be taken from field for additional Proctor compaction tests under the Hilf method. Otherwise, control of fill compaction works based on RC and oven drying method should be adopted.

(e) The apex of the parabolic curve of converted wet density is suggested to be determined analytically.

(f) Relative compaction values and deviation from optimum water content determined from the Hilf method are not exactly same as that using the existing methods. The potential errors increase the uncertainty of the compaction works and hence increase the engineer's risk. It is therefore suggested that the Hilf method cannot replace all compaction control tests using RC and oven drying method as routine procedure.

6 Conclusions

This report has presented the review of the applicability of the Hilf method in compaction control based on the results of 102 field trials and 271 pairs of results conducted in public works projects. The results show that there is a reasonably good correlation between "degree of compaction" from the Hilf method and SRT. There is also no significantly difference in "deviation from optimum water content" determined from the Hilf method and oven drying method. The method can cover soils compacted under a higher compaction effort and the deviation from optimum water content can be determined analytically without using water adjustment value when local ρ_{wm} - w_o relationships are used. The potential sources of error of the Hilf method leading to uncertainties of test results have been reviewed with precautionary measures suggested. The findings of the review suggested that the Hilf method can provide an alternative option for density control and water content control in compaction works for fine to coarse-grained soil should quick results be required.

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Appendix A

List of Symbols

List of Symbols

BS	British Standards
C	Compaction efficiency ratio
CBR	California Bearing Ratio
CWD	Converted Wet Density
D	Fill dry density to laboratory maximum dry density determined from Hilf method
G_s	Specific gravity of gravels
GS	General Specification for Civil Engineering Works
M_s	Dry mass of soil
m	Mass of gravel expressed as a fraction of wet mass of soil
MA	Water content adjustment value
MCWD	Maximum Converted Wet Density
MCWD_{20}	Maximum Converted Wet Density of material passing 20 mm BS sieve
ρ_d	Field dry density
ρ_w	Field wet density
$\rho_{d,P1}$	Dry density of soil compacted in laboratory at field water content
$\rho_{w,P1}$	Wet density of soil compacted in laboratory at field water content
ρ_{dm}	Maximum dry density
ρ_{wm}	Maximum wet density
RC	Relative Compaction
SRT	Sand Replacement Test
w	Water content
w_f	Field water content
w_o	Optimum water content

z	Added/removed water in reference to field water content in percentage of soil wet mass
z_m	Abscissa of the peak point of Proctor compaction curve in terms of converted wet density

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