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Static Compaction for Sustainable Geotechnical Solutions: A Comprehensive Study

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Abstract

The objective of this research is to develop an improved uniaxial static compaction method to address the limitations of the traditional Proctor's dynamic approach for soil compaction. This new approach offers reduced labor, enhanced soil density, and increased compactness. The study compares of static soil compaction characteristics with various soil parameters and explores the concept of Equivalent Static Compaction Energy (ESCE). A diverse range of fine-grained soils with varying range of plasticity was investigated, and a significant correlation of compaction parameters attained by static compaction was observed with the corresponding value of static compaction energy, degree of saturation, void ratio, and plastic limit of soil. The research resulted in the creation of constant-energy curves for static compaction, which were compared to dynamic compaction curves from four compaction attempts. From the study, the ESCE corresponding to standard Proctor, reduced standard Proctor, and reduced modified Proctor tests were found to be within the range of 180-340, 155-308, and 532-664 KJ/m3, respectively. It was also observed for the static compaction method that after reaching the maximum level of compaction, the dry unit weight of the soil specimen remains constant with further increases in compaction energy.

Keywords: *Dynamic Compaction, Maximum Dry Unit Weight, Statistical Analysis, Static Compaction Static Compaction Energy*

1.0 Introduction

In geotechnical engineering, less permeable clayey soil is commonly used for building pavements, highways, railway embankments, and containment barriers. Compaction is a technique used to improve the geotechnical properties of soil by increasing its density and altering its structure. The strength and usefulness of a well-compacted subgrade depends on its physical properties, which can be tested using the dynamic compaction test originally proposed by Ralph Roscoe Proctor[1]. The Standard Proctor Test ASTM D698-91 and Modified Proctor Test ASTM D1557-91 are commonly used for soil compaction based on the requirements of the field and structure.

Proctor discovered that each soil has an optimal moisture content at which it can achieve maximum density, and that stability decreases as the moisture content rises above this point but increases as it falls below it. However, soil compacted below the optimal moisture content can only retain its higher stability if it does not get wet. In 1937, Hogentogler CA made an observation that compressed soil samples undergo four distinct stages of wetting before reaching complete saturation with water[2]. These stages are hydration, lubrication, swelling, and saturation.

During the compaction process, the energy applied to the soil has a significant impact on its properties such as shear strength, permeability, and swelling pressure.

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Studies have shown that increasing the compaction energy can increase the shear strength of cohesive soil when it is compacted on the dry side of the compaction curve. Dynamic compaction has been the traditional method, but Reddy *et al.* pointed out significant drawbacks in the test[3]. They found that the properties of the soil calculated in the dynamic Proctor test, such as Optimum Moisture Content (OMC) and Maximum Dry Unit Weight (MDUW), can vary depending on the energy input and quality of compaction energy given to specific soil types. To address these issues, Reddy *et al.* developed a new laboratory static compaction method that allows for the energy input per unit volume to be easily varied[3]. Another researchers, Mesbah A *et al.* have redesigned the testing mould to regulate boundary friction[4]. The gap between predicted compaction properties in the laboratory and desirable properties in the field is highlighted by Hafez MA *et al.*[5], who found that the nature of the static pressure curve is similar to the Proctor curve for fine-grained soil types. Static compaction is widely regarded as a more convenient, straight forward, and time-efficient method in comparison to dynamic compaction. Bernhard RK *et al.* have also compared the effectiveness and efficiency of static and dynamic compaction techniques[6]. For studying fine-grained soil compaction behavior, Sridharan A *et al.* proposed a new laboratory approach that requires only about 1/10th of the volume of soil needed for the standard and Proctor test[7]. Additionally, Escobar *et al.* also observed that Proctor's dynamic compaction method cannot determine stress history or hydraulic path during compaction[8].

Furthermore, research has been carried out to predict soil compaction characteristics from soil index properties by Sridharan A *et al.*[9,10].

Several research studies have investigated the effects of laboratory static compaction on soil properties. Sharma, B *et al.* found that increasing static pressure led to significant increases in dry unit weight, but the variation became negligible at higher pressure levels[11]. They also identified an equivalent static compaction pressure that correlated with the energy input required to achieve MDUW in standard Proctor tests[12]. Sharma, B *et al.* expanded on this work by studying multiple soil types and determining the equivalent static compaction pressures needed to achieve MDUW in reduced standard Proctor and reduced modified Proctor tests[13]. Xu L *et al.* investigated the relationship between soil compaction and saturation degree, introducing the concept of optimum saturation degree to represent the degree of saturation corresponding to MDUW and OMC[14]. They also found that specimens subjected to static compaction tests had slightly higher matric suction than those subjected to dynamic Proctor tests at the same moisture content. Crispim FA *et al.* examined the impact of static and dynamic laboratory compaction procedures on compaction curves and mechanical strength in two soil types, and found that soil structure plays a significant role in compaction and mechanical properties[15]. Kayabalı K *et al.* conducted a comparison of undrained shear strength and hydraulic conductivity of soil under static and dynamic compaction methods[16].

The scope of the present study is to develop a modified uniaxial static compaction technique for generating a series of static compaction curves, also known as constant-energy curves. The study involves analyzing test result data and conducting a statistical analysis to propose general prediction equations for MDUW and OMC of statically compacted soil. These prediction equations correlate with other soil indices, such as peak saturation level (Sp), static compaction energy (E_{static}), and plastic limit (Wp). The study also investigates the existence of an Equivalent Static Compaction Energy (ESCP) corresponding to the MDUW achieved at different dynamic compaction efforts for fine-grained soils with varying plasticity characteristics. Additionally, the study analyzes the behavioral pattern of statically compacted soil.

2.0 Soil Compaction Test

2.1 Dynamic Compaction of Soil

The Proctor test, or dynamic compaction test, is a soil compaction method that involves applying a specific amount of energy. It utilizes a standard mould filled with moist soil, which is compacted by striking the topsoil with a standard hammer. Two levels of compaction are used: Standard Proctor and Modified Proctor, with different compaction energies (592.5 KJ/m^3 and 2703.88 KJ/m^3, respectively). The compaction energy can be adjusted by changing the hammer weight, drop height, blows per layer, and compacted layers. The compaction energy per unit volume can be calculated using the equation:

$E = (N \times n \times W \times H) / V$

Where N is the blow count/layer of soil, n is the number of the soil layer, H is the free fall of the standard rammer, H is the height of the filled soil and V is the total volume of the compacted soil. This study examined four levels of compaction energy: standard Proctor (Es = 592.5 KJ/m^3), modified Proctor (Em = 2703.88 KJ/m^3), reduced standard Proctor (Ers = 355.5 KJ/m^3), and reduced modified Proctor (Erm = 1622.33 KJ/m^3).

2.2 Static Compaction of Soil

The static compaction test was performed in a mould similar to the Proctor mould, with a diameter of 10 cm and a height of 12.7 cm, with a modification. Earlier research claimed that test sample thickness does not significantly affect its dry unit weight[11]. Therefore, the soil was filled into the mould with an initial sample height of 106 mm. To minimize the effect of wall friction during the compaction process, silicon grease was added to the inner wall of the mould. The test setup was then placed in the loading frame under a cylindrical plunger with a diameter of 50 mm, and the soil sample was compacted statically at a rate of 1.25 mm/min. The load was applied through a proving ring with a proving ring constant of 0.99 kg/div. To uniformly distribute the applied static load throughout the soil depth in the mould, two surcharge plates with diameters of 99.50 mm and thicknesses of 6 mm and 15 mm, respectively, were placed at the top surface of the soil inside the mould.

The rigid plunger applies a static load to the metal plate placed on top of the soil sample, causing uniform settlement of both the plates and the soil. During the compaction process, sufficient care was taken to ensure smooth plunger movement. The penetration height of the metal plate and the compressed soil from the top surface were carefully measured, corresponding to the different applied static loads.

The static compaction technique used in this study follows the constant peak stress-variable stroke approach. The application of static load was continued until the compressed height of the soil within the mold became constant or the penetration of the metal plate stopped. Since the moisture content of each soil sample was known, the corresponding dry unit weight was determined.

Based on the test results of a set of static compaction tests for a specific soil type, constant-energy curves were identified, considering identical compaction energy. For each load increment, static pressure (P), compaction energy (E), void ratio (e), and degree of saturation (S) were determined. The objective of this study is to create an extensive dataset for future use in regression analysis.

3.0 Materials

For the sake of experimentation, a total of 17 different fine-grained soils with varying plasticity properties were chosen. The physical characteristics of each soil sample were measured according to the recommendations of the Bureau of Indian Standards (BIS) and the results are shown in Table 1. The MDUW and corresponding OMC for each soil sample were determined under different levels of energy input, following the guidelines provided in IS:2720-7 (1980) and IS:2720-8 (1983). Total 4 classes of fine-grained soil are selected for the present study: CH ($33.60 < PI < 58.52$), CI ($21.89 < PI < 30.58$), CL ($12.64 < PI < 25.65$), and ML ($5.34 < PI < 10.20$).

Table 1 provides a list of abbreviations used in the study, including SPMDUW for Std. Proctor's Max. Dry Unit Weight, SPOMC for Std. Proctor's Optimum Moisture Content, MPMDUW for Modified Proctor's Max. Dry Unit Weight, MPOMC for Modified Proctor's Optimum Moisture Content, RSPMDUW for Reduced Std. Proctor's Max. Dry Unit Weight, RSPOMC for Reduced Std. Proctor's Optimum Moisture Content, RMPMDUW for Reduced Modified Proctor's Max. Dry Unit Weight, and RMPOMC for Reduced Modified Proctor's Optimum Moisture Content.

4.0 Experimental Investigations Outcome

The study conducted static compaction tests on various soil types at different moisture levels and applied static loads. Respective values of input compaction energy, dry unit weight, void ratio, and degree of saturation were measured. Furthermore, variations of dry unit weight with moisture content at different energy levels were also obtained. The relationship between dry unit weight and moisture content for a particular soil type at a specific energy level is found to be parabolic. The

Table1. Physical properties of the tested soil samples

Soil No	W_L (%)	W_P (%)	PI (%)	G_S	% Sand	USCS type	SP MD-UW (KN/m^3)	SP OMC (%)	MP MD UW (KN/m^3)	MP OMC (%)	RSP MD UW (KN / m^3)	RSP OMC (%)	RMP MD UW (KN/m^3)	RMP OMC (%)
1	59.11	16.86	42.25	2.55	5	CH	17.02	14.84	18.53	14.11	16.58	15.09	18.11	14.56
2	36.57	26.54	10.03	2.83	7	ML	15.73	24.00	16.81	22.78	15.12	24.57	16.23	23.36
3	36.59	31.19	5.40	2.82	20	ML	14.35	29.95	15.58	27.09	13.93	30.17	14.86	28.26
4	45.17	19.52	25.65	2.8	28	CL	17.57	17.53	18.74	16.24	17.11	17.94	18.07	16.85
5	32.13	19.49	12.64	2.65	40	CL	16.19	17.36	17.24	16.13	15.71	17.82	16.86	16.91
6	59.55	18.95	40.60	2.6	3	CH	16.91	16.87	17.87	15.58	16.29	17.04	17.33	16.12
7	27.53	22.19	5.34	2.82	4	ML	16.93	19.62	17.66	18.04	16.17	20.11	17.22	18.34
8	33.64	27.41	6.23	2.72	19	ML	14.18	25.15	15.22	24.12	14.02	25.66	14.73	24.83
9	72.21	18.93	53.28	2.75	23	CH	16.97	17.46	17.95	17.17	16.65	17.51	17.77	17.29
10	48.84	18.26	30.58	2.72	20	CI	16.42	18.57	17.51	18.39	16.13	18.63	17.32	18.49
11	45.52	19.17	26.35	2.63	27	CI	16.12	18.64	16.95	17.84	15.87	18.78	16.75	18.42
12	78.65	20.13	58.52	2.77	24	CH	16.51	18.61	17.63	18.37	16.25	18.65	17.3	18.41
13	57.42	16.33	41.09	2.65	21	CH	17.23	15.45	18.24	15.14	16.92	15.54	18.04	15.26
14	39.54	17.65	21.89	2.73	24	CI	16.72	17.59	17.88	17.36	16.47	17.65	17.72	17.44
15	30.18	23.27	6.91	2.80	23	ML	15.95	22.22	16.88	21.8	15.78	22.25	16.63	21.88
16	38	27.8	10.20	2.78	22	ML	14.51	20.35	15.64	19.17	14.15	20.81	14.97	19.74
17	65.20	31.60	33.60	2.66	25	CH	15.21	23.28	16.44	21.4	15.03	23.64	15.88	22.36

typical relationship between dry unit weight and moisture content, corresponding to different energy levels for CI soil (soil no. 10), is shown in Figure 1.

In Figure 1, the static compaction curves for different input compaction energy are superimposed with dynamic compaction curves corresponding to four unique compaction energy inputs. Figure 1 represents a series of constant-energy curves for CI soil, where energy varies from 10.69 KJ/m^3 to 610.70 KJ/m^3. Similar curves were obtained for all the tested soil samples, and the average range of static compaction energy required for maximum compactness is presented in Table 2. It has been observed that to achieve MDUW under static compaction, the required range of energy for CH is comparatively higher

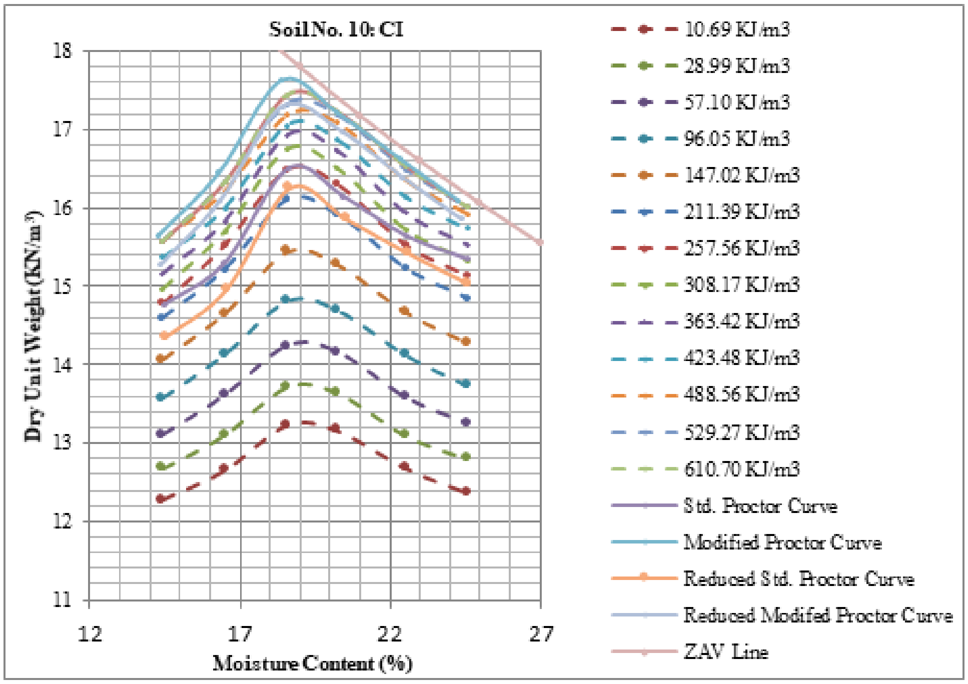

Figure 2. Variation curves of dry unit weight *w.r.t.* moisture content at different energy inputs for CI soil.

Table 2. Average range of static energy for maximum compactness

Soil Type	Static Energy (KJ/m³)
CH	670 – 777
CI	570 – 650
CL	550 – 620
ML	530 - 600

due to the presence of high fine particles and plasticity. Both dynamic and static compaction curves are parabolic, and they shift upward, representing higher MDUW with a rise in energy.

It has also been observed that static compaction results in a higher density than dynamic compaction at a specific compaction energy, but no static compaction curve lies above the modified Proctor curve. For all tested soil samples, a static enengy ranging from 160 KJ/m^3 to 385 KJ/m^3 is required to attain SPMDUW associated with a specific energy input of 592.5 KJ/m^3. Additionally, to reach RSPMDUW associated with a specific energy input of 355.5 KJ/m^3 in the dynamic compaction method, static compaction utilizes an energy input ranging from 160 KJ/m^3 to 330 KJ/m^3. Therefore, it can be understood that in static compaction, when static energy reaches the level of standard Proctor's energy, a much higher dry unit weight of the soil can be obtained compared to the standard Proctor test. Similar findings were observed in the case of reduced standard and reduced modified Proctor compaction tests.

5.0 Statistical Analysis of Static Compaction Characteristics

From static compaction curves, a huge dataset has been generated comprising MDUW, OMC, and the corresponding value of static compaction energy (E_{static}), peak saturation level (Sp), void ratio (e), and plastic limit (Wp). All the soil parameters are determined in the laboratory following the BIS specifications. Considering MDUW and OMC as dependent variables and the rest of the parameters as independent variables, this study attempted to generate two multilinear regression models. The reason behind the selection of the independent variables is that each independent variable significantly affects the static compaction.

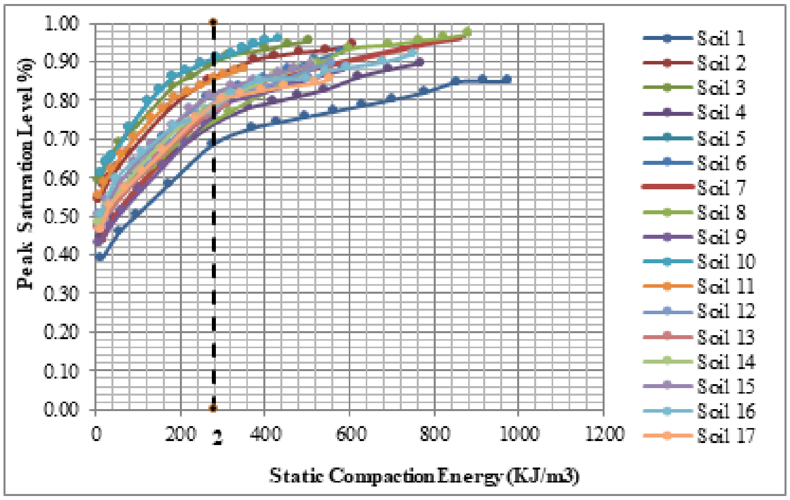

Figure 2. Variation curves of peak saturation level w.r.t. static compaction energy.

In Figure 2, we present the variation curves of Sp along with the corresponding E_{static} values for all the tested soil samples. We observed that as the E_{static} increases, Sp gradually rises until it reaches a range between 0.70 and 0.75, with the induced compaction energy ranging from 260 KJ/m^3 to 300 KJ/m^3. However, after reaching an average compaction energy of 280 KJ/m^3, the variation curve of SP shows a decreasing slope, and its values now span between 0.70 and 0.90. Therefore, to ensure consistency and reliability in the regression model, we omitted Sp values corresponding to compaction energies up to 280 KJ/m^3 and only used values higher than 0.70. It is worth noting that the manual filling of soil into the compaction mould might not have been entirely uniform, and this could have led to unevenly compacted soil samples. Consequently, we decided to disregard the initial test results obtained at lower static energy levels.

75% of the total dataset is used as a training dataset in the construction of the correlation models and the rest of the data is used for validation of the model. The descriptive statistics of the training dataset such as means, standard deviations, minimum and maximum values, skewness, and kurtosis are presented in Table 3. The descriptive analysis of the soil data produced significant

Table 3. Descriptive statistics

Variable	N	Minimum	Maximum	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
E_{static}	368	7.936	982.792	280.32172	228.843634	0.984	0.127	0.266	0.254
Sp	368	0.3904	0.9874	0.745384	0.1444302	-0.357	0.127	-0.857	0.254
e	368	0.4177	1.5514	0.78603	0.2294107	0.546	0.127	-0.219	0.254
Wp	368	16.36	27.47	20.9854	3.62347	0.61	0.127	-1.054	0.254
OMC	368	15.28	29.93	19.886332	4.2107737	1.113	0.127	0.257	0.254
MDUW	368	10	18.6684	15.650328	1.7022124	-0.644	0.127	-0.067	0.254

new information about each variable's features. We looked at measures like mean, standard deviation, minimum, maximum, skewness, and kurtosis for each variable in the dataset, which contained 368 observations. The findings revealed significant variances in the data, with E_{static} displaying a broad range from 7.936 to 982.792 and a significant standard deviation of 228.8436. With standard deviations of 0.1444 and 0.2294, respectively, Sp and e showed comparatively less fluctuation. Both the Wp and OMC displayed moderate variability. Unusually, MDUW exhibited a distribution that appeared to be slightly left-skewed, with a relatively narrow range from 10 to 18.6684. Skewness measures the asymmetry of the distribution, while kurtosis measures the peakedness or flatness of the distribution. Values close to zero indicate normal distribution. Overall, these descriptive statistics provided vital information on the traits and distribution of the variables in the soil data set and formed the groundwork for additional analysis, such as the multilinear regression.

The next step is to establish the relationship equation by performing a multiple linear regression analysis. The general relationship of static compaction MDUW and OMC with E_{static}, Sp, Wp, and e for fine-grained soil based on multiple regression analysis are:

$$MDUW=14.51+9.8\times Sp-0.3\times Wp-1.4\times e-0.001\times E_{static} \quad (i),$$

and

$$OMC=-7.56+7.9\times Sp+0.814\times Wp+6\times e-0.001\times E_{static} \quad (ii)$$

The coefficient values assigned to each factor indicate their respective contributions and directions of influence. The positive coefficient for Sp suggests that higher degrees of saturation tend to enhance MDUW, possibly due to improved particle packing. Conversely, the negative coefficients for Wp and e imply that greater plasticity and void ratios are associated with reduced MDUW. The reversal of the relationship between MDUW and E_{static} when other independent variable are included in the model can be attributed to a phenomenon known as multicollinearity. The Variance Inflation Factor (VIF) is used to assess multicollinearity among independent variables in a regression analysis. In this case, VIF values for each independent variables are within the acceptable range between 2 to 3. The p-values associated with each coefficient, which indicate the significance of each independent variable's contribution to the model were also less than the chosen significance level (often 0.05).

Table 4 displays the fitness values for both correlations. This table provides information on R, R2, adjusted R2, and the standard error of estimates. 'R' represents the multiple correlation coefficients, which can be considered as one of the qualitative measures for predicting the dependent variable[17]. A value of 0.94 for both predicted models indicates a high level of prediction accuracy. The R2 value, or coefficient of determination, signifies the proportion of variance explained by the independent variable[17]. Considering the R2 value in Table 4, it can be inferred that the independent variables explain 88% of the variability in the dependent variables MDUW and OMC. R-squared is initially intuitive and provides insight into how well a regression model fits a dataset. However, for a comprehensive understanding of the model, it's essential to consider adjusted R2 and the standard error of estimates in addition to R2. Adjusted R2 holds particular importance in data interpretation. A value of 0.88 in Table 4 indicates that a true 88% of the variation in the outcome variable is explained by the predictors that are retained in the model. Table 4 shows that the R2 values and adjusted R2 values are very close, suggesting a good fit of the data[17]. The standard error, a measure of model accuracy, represents the standard deviation of the residuals. The standard error decreases with higher R2 values[17]. From

Table 4. Regression analysis model fitness metrics for MDUW and OMC in relation to E_{static}, Sp, Wp, and e for fine-grained soil

Dependent Variable	R	R Square	Adjusted R Square	Standard Error of the Estimate
MDUW	0.94	0.884	0.883	0.58
OMC	0.94	0.882	0.880	1.4

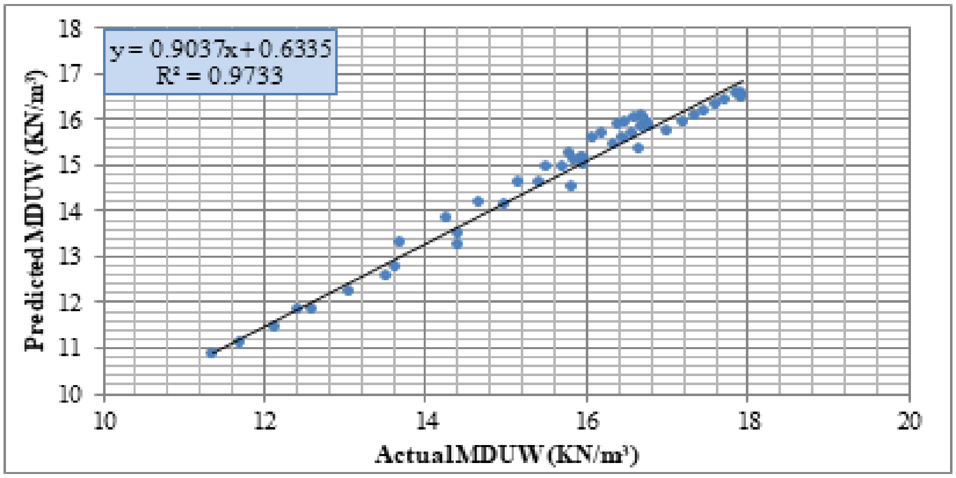

Figure 3. Actual vs. predicted MDUW.

the standard error values, it is evident that the estimations of MDUW and OMC values with the help of E_{static}, Sp, Wp, and e will deviate by 0.58 and 1.4, respectively, which can be considered negligible.

Model validation: The model is validated using 25% of the total dataset, and Root Mean Square Error (RMSE) values are estimated based on the actual and predicted values. In Figure 3, the actual and predicted graph for MDUW values is shown. The RMSE value for the model is found to be 0.93, indicating a well-fitted model. Moreover, the Mean Absolute Deviation (MAD) value came in at 0.88, suggesting acceptable variability in the dataset. This means the data is not spread out too much.

6.0 Determination of Equivalent Static Compaction Energy (ESCE)

Since there are similarities in the dynamic and static compaction curves, an Equivalent Static Pressure (ESP) can be identified at which the MDUW for a specific dynamic compaction effort can be achieved[11], presented the equivalent static pressure required to attain the MDUW, which can also be achieved from the standard Proctor test, for specific fine-grained soils. To determine ESP concerning the SPMDUW, a set of two static compaction curves corresponding to specific static pressures has been selected in such a way that the standard Proctor's curve lies between them. Assuming a linear variation of MDUW between the selected static compaction curves, the pressure equivalent to the SPMDUW was established.

In this research, an effort has been made to determine the ESCE, which represents the precise E_{static} required to achieve MDUW according to the standard Proctor test, the reduced Standard Proctor test, and the reduced Modified Proctor test. From Figure 1, it is evident that there is no static compaction curve above the modified Proctor curve. Thus, it is not possible to attain static energy equivalent to MDUW obtained from the modified Proctor test

The ESCE values for Standard Proctor, Reduced Standard Proctor, and Reduced Modified Proctor tests on CH soil (soil no. 13) were determined as 270, 235, and 532 KJ/m^3, respectively. A similar approach was employed to determine the ESCE required to achieve MDUW using the three dynamic compaction efforts across various soil samples with different plastic characteristics. It was revealed during the investigation that, unlike equivalent static pressure, fine-grained soil lacks a unique ESCE value.

The average ESCE ranges for Standard Proctor, Reduced standard Proctor, and Reduced Modified Proctor tests on all tested soil samples were found to be 180-340, 155-308, and 532-664 KJ/m^3, respectively. When considering specific soil types, the range of equivalent static energies according to the Standard Proctor effort was 245-270, 180-280, 280-340, and 205-310 KJ/m^3 for CH, CI, ML, and MI soil, respectively.

The dissimilarity in ESCE values arises due to the dependency of input energy on the deformation of compacted soil. E_{static} is influenced by soil properties such as particle size and shape. Among rounded and angular particles, angular particles exhibit a stronger interlocking phenomenon. This implies that, under the same E_{static}, angular particles will experience more compaction compared to rounded particles. Consequently, achieving the desired compaction level requires more E_{static} for rounded particles than for angular particles.

Similarly, it can be observed that poorly graded soil will experience more compaction than well-graded soil under the same E_{static}. As a result, achieving the desired compaction necessitates more E_{static} for well-graded soil compared to poorly graded soil. Hence, the concept of equivalent static energy cannot be established definitively. Since E_{static} is influenced by soil properties, the equivalent static energy is not constant, leading to the absence of an equivalent static energy value for fine-grained soil.

7.0 Behaviour Characteristics of Static Compaction Curves

The experimental results of the static compaction test for specific fine-grained soil, such as E_{static}, S, and DUW, are presented in the form of graphs. The relationship between DUW and E_{static} corresponding to CL soil is shown in Figure 4. Observing these graphs, it has been found that

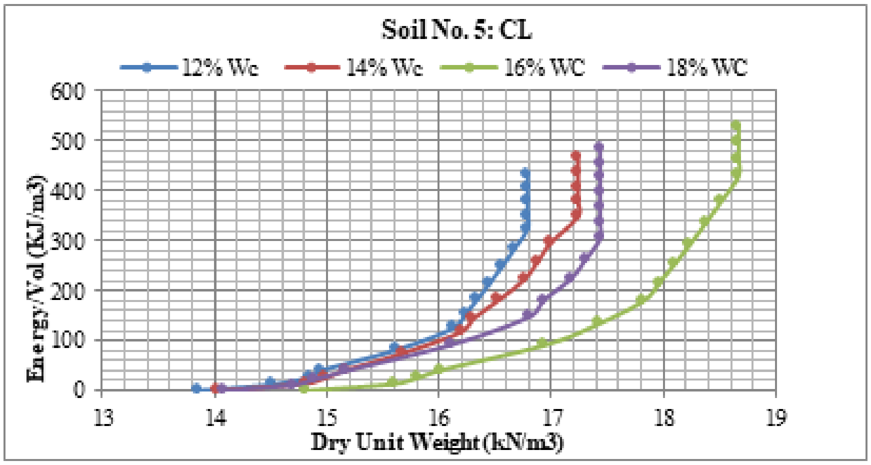

Figure 4. Variation of compaction energy with dry unit weight of soil.

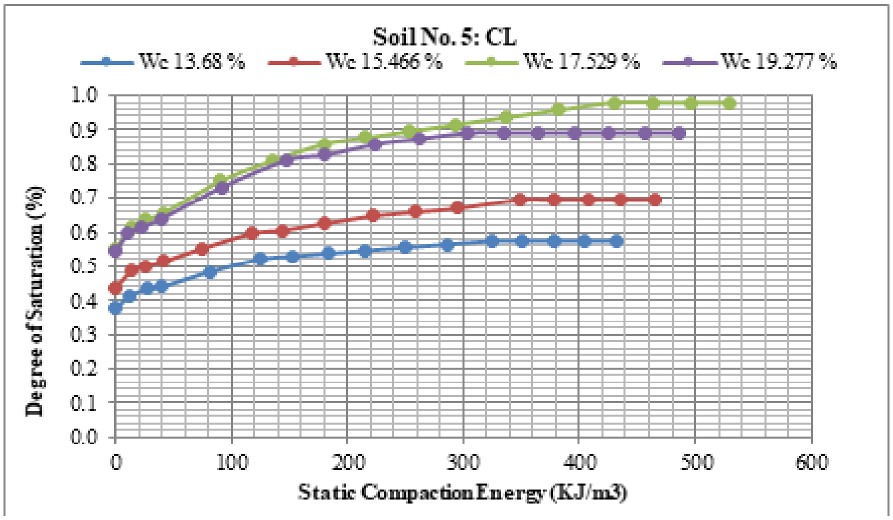

Figure 5. Variation curve of the degree of saturation with static compaction energy.

for specific soil and at any moisture content, an increase in compaction energy leads to an increase in dry unit weight until the maximum value is reached. However, after attaining the maximum value of compactness, there is no further change in dry unit weight even with an increase in compaction energy. Similar findings have been obtained for other soil samples.

The variation of the degree of saturation with static energy is shown in Figure 5. The degree of saturation increases gradually with the increase in compaction energy, but once MDUW is attained, it remains constant. Moreover, considering four different moisture content, curves of the degree of saturation and compaction energy as a function of dry unit weight have been prepared and presented in Figure 6. From the graph, it is clear that there is a linear increase in the degree of saturation with the increase in dry unit weight. By comparing the static compaction curve (for Wc = 22.45%) with Standard Proctor test results (MDUW = 15.95 KN/m^3 and OMC = 22.22%), it was found that to achieve the same state of

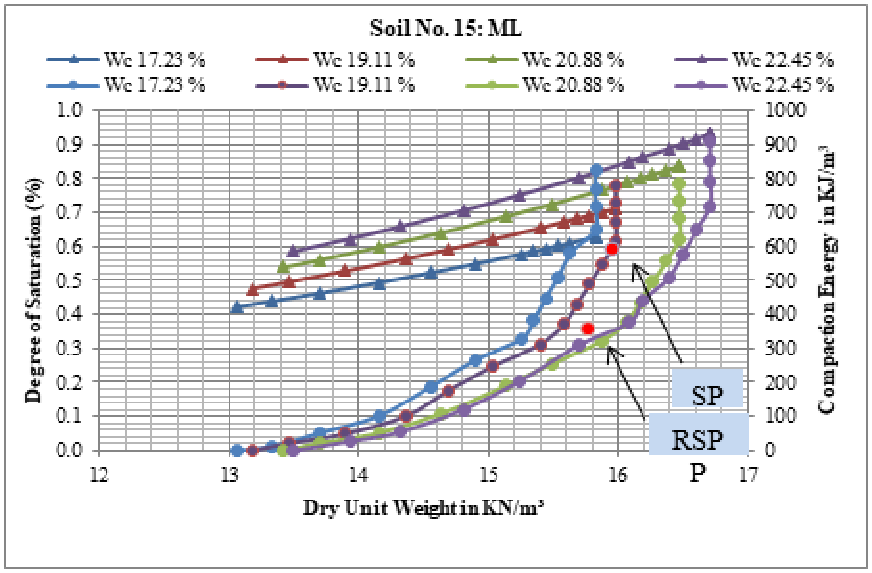

Figure 6. Variation curves of the degree of saturation and compaction energy w.r.t. dry unit weight

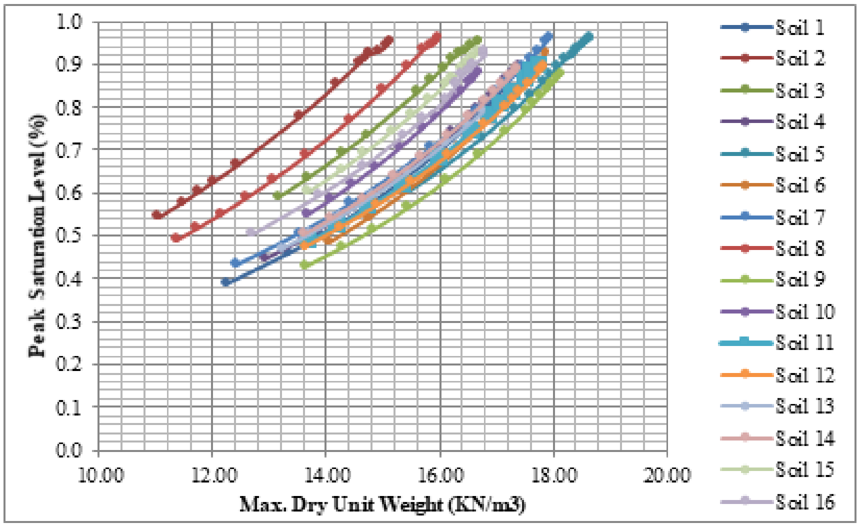

Figure 7. Variation curves of the peak saturation levels *w.r.t.* MDUW

dry unit weight for almost near moisture content, static compaction requires less energy input. The additional compaction energy required in the Proctor test is because of the dissipation of energy, which may be caused by the vibration of the frame or due to the wall friction. In addition, the variation of the Sp corresponding to MDUW for all tested soil samples is shown in Figure 7. The nature of the variation curve follows the power law form, where each point in the curve represents different compaction energy.

8.0 Conclusions

For the present study, a diverse range of fine-grained soils with varying plasticity was chosen and compacted in the laboratory using four different dynamic compaction techniques and a constant peak stress-variable stroke static compaction approach. The static compaction curves for various compaction energy inputs were compared with dynamic compaction curves and presented as a series of constant-energy curves for each soil sample.

The comparative study of static and dynamic compaction tests showed that static compaction can result in a much higher dry unit weight than dynamic compaction at the same energy level, regardless of the compaction efforts used. Additionally, it was observed that there is no Es, eq for fine-grained soil, unlike equivalent static pressure. The average range of Es, eq for Standard Proctor, Reduced Standard Proctor, and Reduced Modified Proctor for all tested soil samples was found to be 180-340, 155-308, and 532-664 KJ/m^3, respectively. The state of the soil structure at the induced compaction energy and the mineralogical composition of the fine-grained soil were found to be responsible for the variation of ESCE.

Furthermore, this paper investigated the influence of various soil parameters on MDUW under static compaction and developed an acceptable correlation of MDUW with the corresponding peak saturation level, compaction energy, plastic limit, and plasticity index.

Additionally, from the static compaction test, it was observed that the dry unit weight of the soil seems to increase gradually with an increase in compaction energy at a specific moisture content. After reaching the maximum level of compaction, the soil unit weight remains constant with further increases in compaction energy. Finally, it was also noted that initial static compaction test results at lower energy input could be disregarded due to the non-uniformity of soil filling in the compaction mould.

However, the study's focus is on particular soil types, small sample sizes, and controlled laboratory settings. Future research should examine a wider variety of soil types, additional dynamic compaction techniques, long-term performance analysis, correlation studies with various soil parameters, advanced testing techniques, an investigation of soil additives, and microstructural analysis to better understand the underlying mechanisms to address these limitations and advance the field. By including these factors, compaction standards will become more reliable, and applications for geotechnical engineering will have a better grasp of soil behaviour.

9.0 References

1. Proctor R. Laboratory soil compaction methods, penetration resistance measurements, and the indicated saturated penetration resistance. Proceedings of the Second International Conference on Soil Mechanics and Foundation Engineering; 1948. p. 242–247.
2. Hogentogleb CA. Report of department of soils investigations; 273–277.
3. Reddy BVV, Jagadish KS. The static compaction of soils. Geotechnique. 1993; 43(2): 337-341. https://doi.org/10.1680/geot.1993.43.2.337
4. Mesbah A, Morel JC, Olivier M. Comportement des sols fins argileux pendant un essai de compactage statique: d6termination des param6tres pertinents (Clayey soil behaviour under static compaction test). Mater Struct. 1999; 32:687-694. https://doi.org/10.1007/bf02481707
5. Hafez MA, Asmani MD, Nurbaya S. Comparison between static and dynamic laboratory compaction methods. Electron J Geotech Eng. 2010; 15:1641-1650. https://www.researchgate.net/publication/286997245
6. Bernhard RK, Krynine DP. Static and dynamic soil compaction. Highw Res Board Proc. 1952; 31:503–592.
7. Sridharan A, Sivapullaiah PV, *et al.* Mini compaction test apparatus for fine grained soils. Geotech Test J. 2005; 28(3):240–6. https://doi.org/10.1520/GTJ12542
8. Escobar A, Caicedo B, Cabrera M. Interaction between a cylinder and a partially saturated soil for compaction analysis. Transp Geotech. 2021; 30:100600. https://doi.org/10.1016/j.trgeo.2021.100600

9. Sridharan A, Nagaraj HB. Coefficient of consolidation and its correlation with index properties of remolded soils. Geotech Test J. 2004; 27(5). https://doi.org/10.1520/gtj10784
10. Sridharan A, Nagaraj HB. Plastic limit and compaction characteristics of finegrained soils. Proc Inst Civ Eng - Gr Improv. 2005; 9(1):17-22.https://doi.org/10.1680/grim.2005.9.1.17
11. Sharma B, Sridharan A, Talukdar P. Static method to determine compaction characteristics of fine-grained soils. Geotech Test J. 2016; 39(6):1048-1055. https://doi.org/10.1520/gtj20150221
12. Sharma B, Gogoi B, Sridharan A. Static compaction characteristics of coarse and fine grained soils. Sustainable Civil Infrastructures. Springer; 2019. p. 45–57.
13. Sharma B, Deka A. Static compaction test and determination of equivalent static pressure. Lect Notes Civ Eng. 2019; 16:3-10. https://doi.org/10.1007/978-981-13-0899-4_1
14. Xu L, Wong H, Fabbri A, Champire F, Branque D. A unified compaction curve for raw earth material based on both static and dynamic compaction tests. Mater Struct. 2021; 54(5). https://doi.org/10.1617/s11527-020-01595-5
15. Crispim FA, de Lima DC, Schaefer CEGR, Silva CHC, Carvalho CAB, Barbosa PSA, *et al*. The influence of laboratory compaction methods on soil structure: Mechanical and micromorphological analyses. Soils and Rocks. 2011; 34(1):91–98. https://doi.org/10.28927/sr.341091
16. Kayabali K, Asadi R, Fener M, Dikmen O, Habibzadeh F, Aktürk O. Estimation of the compaction characteristics of soils using the static compaction method. Bull Miner Res Explor. 2020; 162:75–82. https://doi.org/10.19111/bulletinofmre.603873
17. Field AP. Exploratory factor analysis. Discov Stat Using SPSS. 2003; (1979):1–36.