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Estimation of the compaction characteristics of soils using the static compaction method

Kamil KAYABALI[a], Ramin ASADİ[a], Mustafa FENER[a], Orhan DİKMEN[a], Farhad HABİBZADEH[a] and Özgür AKTÜRK[b*]

[a]*Department of Geological Engineering, Faculty of Engineering, Ankara University, Ankara, Turkey*
[b]*Department of Geological Engineering, Faculty of Engineering, Akdeniz University, Antalya, Turkey*

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ABSTRACT

Ground improvement using mechanical stabilization is commonly applied by performing the standard Proctor compaction test, which requires a significant quantity of soil, usually obtained from open pits. A static compaction test is an alternative laboratory compaction test. Although researchers have shown that the results of miniature size static compaction tests are comparable with that of standard Proctor tests in terms of the maximum dry density and the optimum water content, no attempt has been made to compare the two fundamental properties of the compacted soil: undrained shear strength and hydraulic conductivity. The scope of this investigation was to estimate the level of static compaction energy required to (1) obtain a compaction curve similar to that of the standard Proctor test; (2) reconstruct compacted soils using the standard Proctor and static compaction tests at the optimum water content; and (3) compare the undrained shear strength and hydraulic conductivity of compacted soils. The compacted soils at the predetermined energy level were subjected to hydraulic conductivity tests using the rigid-wall falling-head permeability method. Undrained shear strength tests were performed by employing a high-capacity laboratory vane shear apparatus on compacted samples of both the standard Proctor and static compaction tests. The present investigation revealed that the static compaction test, requiring about only 10% of the soil necessary to perform the standard Proctor method, provides comparable results in regard to hydraulic conductivity and undrained shear strength.

1. Introduction

Soils play two major roles: as a construction material and as a foundation for buildings. Their engineering properties such as strength, compressibility and permeability are usually unsatisfactory for the planned use in both cases. The common practice is to stabilize or improve the engineering properties of such soils. Stabilization is accomplished by a variety of means. Amongst these, mechanical stabilization, or compaction is the most common method of soil improvement because it is a cost-effective alternative to many other stabilization techniques.

The benefits of compaction include the increase in soil density and strength, and the reduction of permeability and compressibility. This modification yields a significant reduction in potential settlement; an increase in bearing capacity and slope stability and a decrease in detrimental effects such as swelling and shrinkage and seepage potential in earthen structures (Basheer, 2001).

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* *Corresponding author: Özgür AKTÜRK, akturko@akdeniz.edu.tr*

The common procedure for compacting soils for engineering works in the field is small-scale physical modeling in a laboratory. Typical tests on this include vibration, impact, kneading, and static compaction methods. Proctor tests (standard and modified) have been extensively used in physical modeling of soils in a laboratory to determine the maximum dry density in which a soil gains its highest strength and lowest compressibility state. This way, soils are compacted under a certain level of energy per unit volume and the final product of the process is a dry density versus water content graph.

Although the theoretical energy to be delivered onto soil in the compaction mold is about 600 kJ/m^3 for the standard Proctor method, the rammer diameter is smaller than the compaction mold and a significant portion of energy is wasted due to the bulging of compressed soil around the rammer during impacts. Day and Daniel (1985) reported that the maximum dry unit weights produced with the reduced compactive effort, by using only 10 blows of the compaction ram per lift rather than the usual 25 blows per lift, were approximately 90% of the values obtained with full compactive effort. Bell (1977) investigated the compaction energy relationships for cohesive soils using the impact, kneading, and static compaction methods and concluded that static compaction was the most efficient method for all moisture conditions. Hadas (1987) compared the fast (i.e. the impact) compaction with the slow (i.e. static) compaction in regard to compaction energy and concluded that the energy ratio of slow to fast method ranged from 0.10 to 0.43 to give the same bulk density. On average, this ratio was 0.2, meaning that the static compaction method needs only one fifth of the compactive effort required for the impact (Proctor) method. The energy loss associated with the impact method is attributed to the smaller diameter of the falling rammer (64 mm) than that of the soil specimen (102 mm) (Venkatarama Reddy and Jagadish, 1993). The kinetic energy losses involved in the impact method include the energy dissipated into heat, sound, and high-frequency elastic vibrations (Sridharan and Sivapullaiah, 2005).

The preceding review points out that the impact method is not an energy-efficient method. More importantly, the most common impact method (i.e. the standard Proctor method) requires a significant amount of soil to sample. The requirement of the American Society of Testing Materials (ASTM) D698 standard is 16 kg (ASTM, 2003). Such a huge amount of soil can only be obtained from open pits. When the earthwork involves construction of a large dam, for instance, hundreds of thousands of cubic meters of soil are needed. Even though there exists a nearby geological formation capable of providing such an enormous volume of material, the open pit sampling does not permit a geotechnical engineer to characterize the geological materials at greater depths. In this case, the geotechnical engineer should rely on soil samples from boreholes, which would not meet the quantity requirement of the standard Proctor test. Therefore, it is inevitable to work with a compaction method that can characterize the restricted amount of soil samples obtained from a borehole.

Sridharan and Sivapullaiah (2005) devised a mini compaction test apparatus for fine-grained soils. Their equipment consisted of a mold 3.81 cm in diameter and 10 cm in height, the volume of which was only one tenth of standard Proctor. They employed two types of hammers, i.e. 1 kg and 2.5 kg in mass, to simulate the standard Proctor and modified Proctor tests, respectively. Tien et al. (2004) used a mold 30 cm in height and 7 cm in diameter to examine the compaction characteristics of bentonite-sand mixtures. They employed the static compaction method and concluded that their model greatly reduced the amount of soil for compaction tests on composite mixtures.

This investigation aimed to determine the proper level of the compactive effort for the static compaction test and compare the compaction characteristics from standard Proctor and static compaction tests. The next step involves comparing the undrained shear strength and hydraulic conductivity obtained from both tests.

2. Materials

The present investigation included the use of ten soil samples of different gradational and plasticity characteristics, as presented in table 1 and figure 1. The tools employed for the research consisted of an automated standard Proctor unit, a loading frame for static compaction along with a recording unit for the work done during static compaction, and standard and miniature sized molds. Undrained shear strengths were measured using a miniature vane shear test (VST) device equipped with an electronic transducer for

Table 1- Basic properties of soils used in the investigation.

No	LL (%)	PL (%)	PI (%)	USCS	FC (%)	Sand (%)
01	44.9	23.1	21.8	SC	24	76
02	43.8	21.3	22.5	SC	19	81
03	45.2	23.1	22.1	SC	13	87
04	40.1	21.9	18.2	SC	21	79
05	40.5	21.4	19.1	SC	13	87
06	41.1	21.7	19.4	SC	22	78
07	36.4	19.2	17.2	SC	22	78
08	34.4	20.8	13.6	SC	15	85
09	33.7	16.3	17.4	SC	19	81
10	31.8	15.3	16.5	SC	17	83

measuring the applied torque. The maximum capacity of torque is 3 N.m, which is equivalent to shear stress of about 700 kPa when the smallest size blade (12.7 x 12.7 mm) is used. For the hydraulic conductivity tests, a rigid-wall type of apparatus was employed along with the falling-head permeability test method.

3. Methods

Standard Proctor and static compaction tests were the compaction methods employed for this investigation. For the standard Proctor, the ASTM D668 standard was employed (ASTM, 2003). The theoretical energy delivered to compacted soil in this test was 592.7 kN-m/m^3. As for the static compaction test, the following procedure was employed. The compaction mold was 5 cm in both diameter and height, with a volume of 98.17 cm^3, which is about 1/10 th of that of the standard Proctor mold (V=944 cm^3). The compaction apparatus includes a mold, a collar, and a rammer. Approximately 200 g of soil was used to generate a single point on the graph of the dry density versus water content. As in the case of the standard Proctor test, the static compaction procedure included three compacted layers, each of which was constructed under a predetermined amount of work. The amount of work to be applied onto each of three soil layers was computed as follows. First, the compactive effort for the standard Proctor had to be expressed:

$$\text{Compactive effort} = \frac{2{,}495\text{ kg }(9{,}81\text{m/s}^2)(0.3048\text{m})(3\text{ layers})(25\text{ drops/layer})}{0{,}944 \times 10^{-3}\text{ m}^3} = 592{,}7\text{ kN.m/m}^3$$

where 2.495 kg is the mass of the rammer and 0.3048 m is the drop height. The amount of work to be delivered to each layer had to be calculated using the area under the force-displacement curve in figure 2:

$$\text{Compactive effort} = \int_0^h F\Delta h$$

To obtain the compaction energy per layer:

$$592{,}7\text{ kN.m/m}^3 = \frac{\int_0^h F\Delta h\ (3\text{ layers})}{98{,}17 \times 10^{-6}\text{ m}^3}$$

which eventually becomes:

$$\int_0^h F\Delta h = 19{,}4\text{ N.m (per layer)}$$

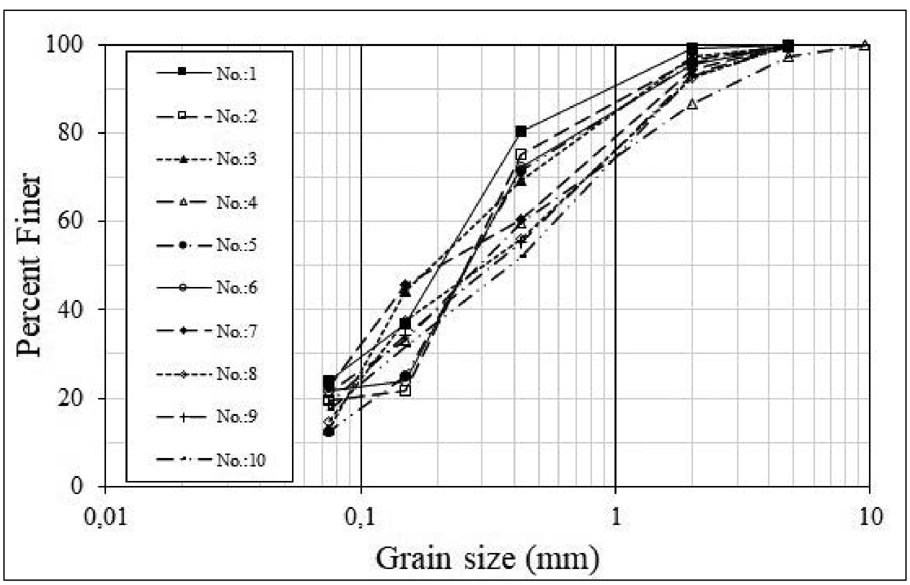

Figure 1- Gradation curves for soil samples.

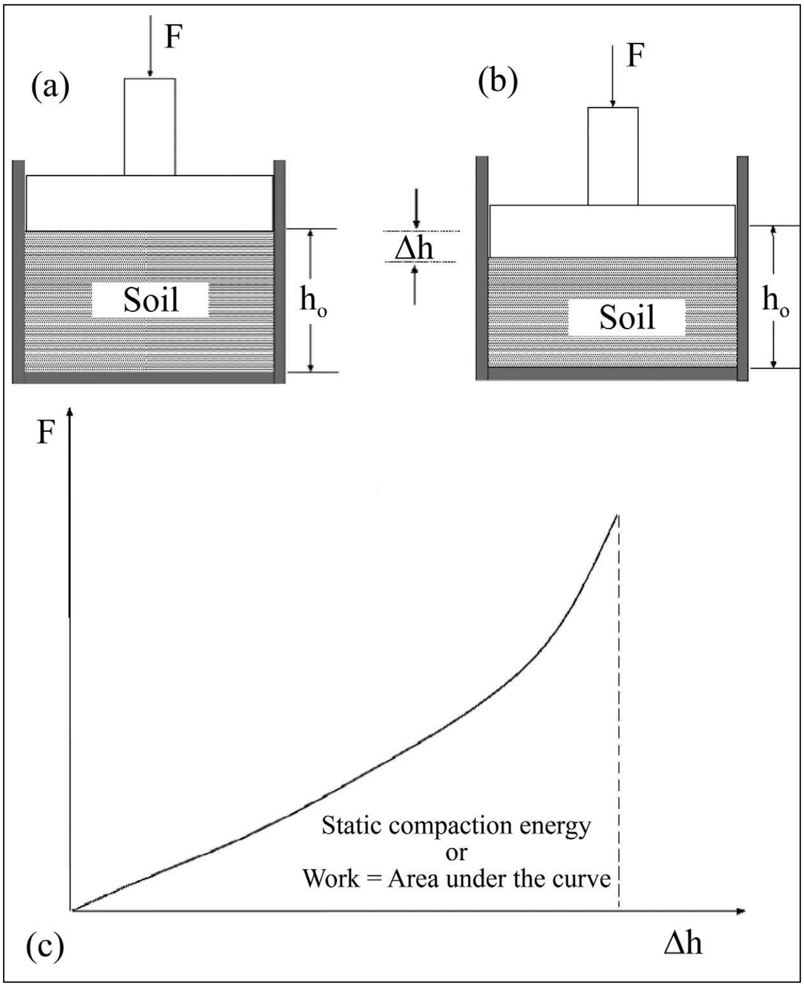

Figure 2- The principle of static compaction and the definition of work done by it.

The soil was compacted in a brass mold by compression from one end only. After compaction, the sample was extruded from the mold and weighed, then a moisture sample was taken and the water content and dry density were computed. Each of these compaction tests was repeated 5-7 times for all soil samples to construct dry density versus water content plots.

Unconfined compression tests were performed on compacted soils at optimum water contents. A miniature vane shear was employed to conduct shear strength tests on compacted specimens of both the standard Proctor and the static compaction. The VST apparatus recorded the torque by an electronic transducer, which eliminated the use of springs of different stiffness. The tests were performed in accordance with the ASTM D4648 standard (ASTM, 2000). The rate of shear strain was 75°/min, matching a median value for the suggested range of 60-90°/min in the ASTM standard.

A series of falling-head permeability tests were performed on ten soil samples, which were compacted at optimum water contents. As shown in figure 3, molds containing compacted soil specimens were placed in a permeability testing apparatus and a hydraulic gradient of 20-25 was applied. The test duration ranged from one to two weeks to ensure that at least one pore volume of water permeated through the compacted specimen. Three specimens were tested for each of the soil samples for each compaction procedure. Daily readings were taken and the permeabilities were computed by the following equation:

$$k = (aL/A\Delta t)\ln(h_1/h_2)$$

where k is permeability (cm/s), a is the cross sectional area of standpipe (cm^2), L is the height of specimen (cm), A is the cross sectional area of specimen (cm^2), and Δt is time (s) for standpipe head to decrease from the height h_1 to height h_2. The average permeability was

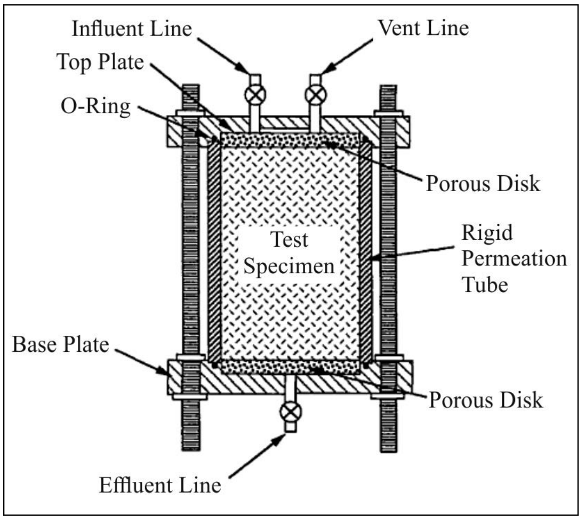

Figure 3- Schematic illustration of the permeameter used to conduct hydraulic conductivity tests.

computed using the overall results per specimen, and the representative permeability for each compaction method per soil sample was taken as the average of three specimens.

4. Results of Experiments

The mechanics of standard Proctor and static compaction tests are totally different. The rate of loading for the static compaction tests is considered to affect the test results. To observe whether or not this is the case, different loading rates were applied on static compaction specimens under constant compaction energy conditions. The selected strain rates were 2.5 mm/min, 5.0 mm/min, and 10 mm/min. Figure 4 shows a comparison between the standard Proctor curve and the curves of static compaction for different strain rates. The level of energy applied on soil 1 was 40% of the standard Proctor compactive effort. A close look at figure 4 reveals that the effect of strain rate on the shape of the compaction is insignificant. The strain rate of 10 mm/min was subsequently selected as the loading rate for the proceeding static compaction tests.

Another series of static compaction tests was performed on soil sample 7 to observe the effect of the compaction energy on the test results. In essence, the goal of such a procedure is to set the appropriate level of the compaction energy for the static compaction test, whose experimental curve matches the compaction curve of the standard Proctor. Figure 5 shows the experimental curves of the static compaction for the energy levels of 15%, 20%, 30%, 35%, 40%, and 50% for soil number 7 in comparison with the compaction curve of standard Proctor. Figure 5 reveals that the level of energy for static compaction curve matching the curve of standard Proctor should lie somewhere between 30% and 50%.

To set the appropriate level of compaction energy for the static compaction method, another series of static compaction tests was performed on all soils at the energy levels of 30%, 40%, and 50%. The strain rate was 10 mm/min in each case. Figure 6 shows the curves of static compaction for the energy levels of 30%, 40%, and 50% in comparison with the standard

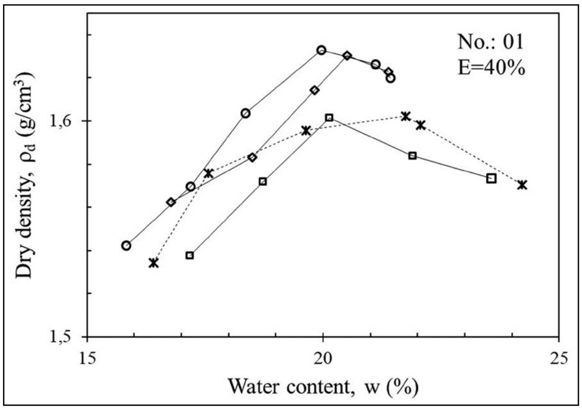

Figure 4- Static compaction curves obtained using the loading rate of 2.5 mm/min (circles), 5.0 mm/min (diamonds), and 10 mm/min (squares) along with the compaction curve of the standard Proctor (asterisks) for soil No. 1.

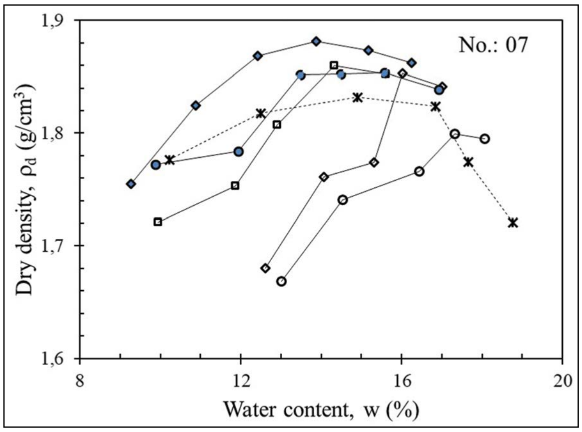

Figure 5- Static compaction curves obtained using different compactive efforts: 15% of standard Proctor energy (SPE, open circles), 20% of SPE (open diamonds), 25% of SPE (squares), 30% of SPE solid circles), and 40% of SPE (solid diamonds) along with the standard Proctor compaction curve (asterisks) for soil No. 7.

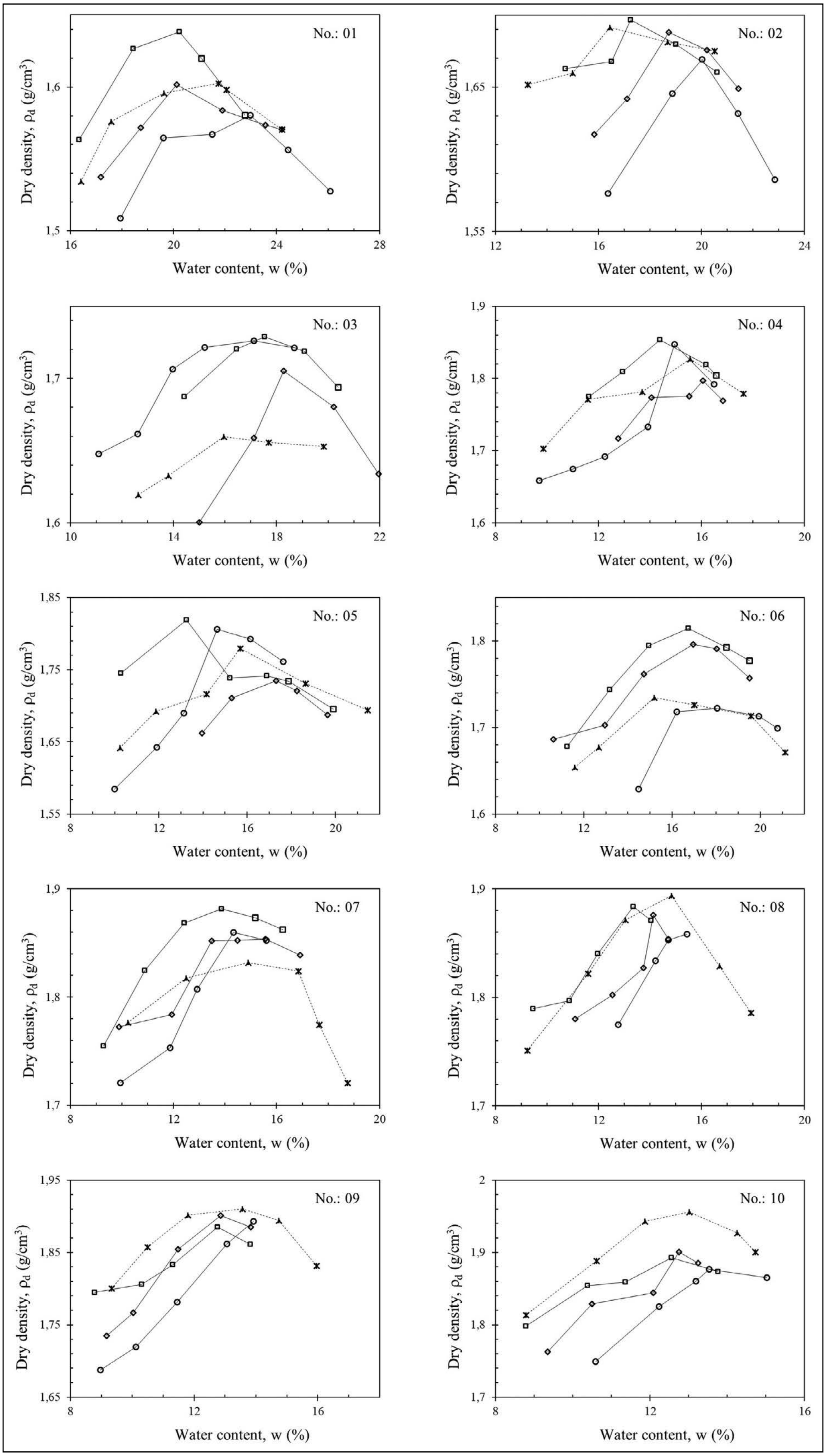

Figure 6- Static compaction curves obtained using 30% of SPE (circles), 40% of SPE (diamonds), and 50% of SPE (squares) along with the standard Proctor compaction curve for all soils.

Proctor curve for all soil samples. The evaluation of figure 6 suggests that the energy level of the static compaction test should be around 40% to match the standard Proctor curve. The difficulty of making a perfect match should be appreciated. The differences between the optimum water contents and the maximum dry densities are not large and considered to be within acceptable ranges.

Permeability tests were performed on three specimens of each soil. Compaction molds were used as the rigid-wall permeameters. Tests were conducted on the compacted soils at the optimum water contents. For the static compaction specimens, the samples were prepared at the 40% energy level along with the optimum water content. Table 2 shows the results of permeability tests along with their mean values. A plot for a comparison between the results of two different techniques would better serve the purpose. However, there is not a systematic relationship between the two sets of hydraulic conductivity values. Table 2 illustrates the comparison of the ratio of the hydraulic conductivity of one method to that of the other method. A quick glimpse at table 2 reveals that, generally, the difference between the permeabilities of the soil samples compacted using the two different techniques is less than one order and that the permeabilities of soils using the Proctor method are a few times higher than those of the soils of the static compaction method.

Undrained shear strength tests involved the use of a laboratory vane shear with a high torque capacity. The compacted specimens at the optimum water content for the standard Proctor test were subjected to the undrained shear strength test from both ends. As expected, the top end of the specimen yielded a slightly higher strength value for almost all samples and the average of the two was assigned as the undrained shear strength of the tested specimen. Because the static compaction mold was not as high as that of the standard Proctor test, the undrained shear strength tests using the VST apparatus were performed only once at the mid-level of the specimen. Two specimens for each soil sample compacted using both the static and standard Proctor compaction tests were subjected to undrained shear strength tests. Table 3 shows the results along with their mean values. Like the comparison of the permeability test results, the undrained shear strength values obtained for the compacted specimens using the standard Proctor technique were compared with those of the static compaction method in the form of a ratio for the very same reasons at the last column of table 3. The undrained shear strength values obtained over the soil samples compacted using the standard Proctor method were higher than those determined over the compacted

Table 3- The results of the undrained shear strength tests (kPa).

No.	Standart Proctor			Static Compaction			$s_{u(Pro)}/s_{u(sta)}$
	Test 1	Test 2	Mean	Test 1	Test 2	Mean	
01	442	407	424	259	432	346	1.2
02	526	515	520	355	453	404	1.3
03	584	520	552	203	484	343	1.6
04	481	328	405	554	514	534	0.8
05	467	453	460	505	381	443	1.0
06	553	553	553	264	481	373	1.5
07	342	451	396	364	362	363	1.1
08	404	411	407	194	418	306	1.3
09	525	492	508	269	208	238	2.1
10	269	518	393	161	206	183	2.1

Table 2- The results of the falling-head permeability tests (cm/s).

No.	Standart Proctor				Static Compaction				k_{Pro}/k_{sta}
	Test 1	Test 2	Test 3	Mean	Test 1	Test 2	Test 3	Mean	
01	9.23E-08	4.91E-08	2.15E-08	5.43E-08	1.37E-08	1.72E-08	2.51E-09	1.11E-08	4.9
02	1.52E-07	1.74E-07	1.01E-07	1.42E-07	4.73E-08	8.21E-08	8.74E-09	4.60E-08	3.1
03	3.3E-07	2.34E-07	1.52E-07	2.39E-07	1.51E-08	3.4E-08	7.89E-09	1.90E-08	13
04	3.13E-08	2.34E-08	2.57E-08	2.68E-08	2.09E-08	3.12E-08	2.12E-08	2.44E-08	1.1
05	1.82E-07	8.24E-08	3.57E-08	1.00E-07	2.5E-08	2.7E-08	2.47E-08	2.56E-08	3.9
06	4.83E-07	1.62E-07	1.12E-07	2.52E-07	3.38E-08	3.14E-08	1.12E-08	2.55E-08	9.9
07	6.57E-08	6.04E-08	3.19E-08	5.27E-08	2.75E-08	5.09E-08	4.5E-08	4.11E-08	1.3
08	6.48E-08	6.17E-08	4.77E-08	5.81E-08	3.26E-08	2.85E-08	3.3E-08	3.14E-08	1.9
09	8.14E-08	5.31E-08	4.57E-08	6.01E-08	7.39E-08	3.22E-08	5.16E-08	5.26E-08	1.1
10	9.05E-08	8.02E-08	5.43E-08	7.50E-08	1.04E-07	4.17E-08	2.18E-07	1.21E-07	0.6

samples using the method of static compaction. The range of variation could be up to 100%.

5. Conclusions

A great portion of the compaction energy is wasted during a standard Proctor test. The compaction curve for a soil could be constructed with 60% less energy when the static compaction method is employed. In the static compaction test, the entire soil mass is subject to displacement, no energy is wasted, and almost all of the energy is used to densify the soil. The level of the compaction energy applied to ten soil samples showed that the required energy level for the static compaction test is about 40% of the standard Proctor method or 237 kJ/m^3.

The compacted specimens were tested for as-compacted undrained strength; the undrained shear strengths obtained using the static compaction test were slightly lower than those obtained using the standard Proctor method. The variations are considered to be within the acceptable ranges.

Likewise, the hydraulic conductivities determined using the static compaction test were slightly lower than those determined using the compacted samples of the standard Proctor method. Considering the large variations of typical permeability tests performed either in the field or in the laboratory, the variations of hydraulic conductivity between the results of the two compaction methods were negligibly small.

The results of this study are based solely on ten soil samples within a rather narrow range of gradation. Further research using a wider range of particle gradation is recommended to validate the findings of the present investigation.

The quantity of soil required for the static compaction test, the volume of whose mold is only 10% of that of the standard Proctor, is less than half a kilogram; the test could be performed on a limited quantity of soils obtained from boreholes. The use of the apparatus is restricted to soils containing particles smaller than 2 mm.

Depending on the skills of the operator, the time duration for the standard compaction test ranges from 1-2 hours to obtain a sufficient number of points to construct a compaction curve, thereby significantly shortening the duration spent for the standard Proctor test.

The static compaction test is environmentally friendly and totally eliminates the noise encountered during the performance of the standard Proctor test, particularly by the automated test. Almost all of the energy is used to densify the soil and no energy is wasted as in the standard Proctor test.

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