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Compaction Quality Control of Coarse-grained Soils Using Dynamic Penetration Test Results through Correlation with Relative Compaction Percentages

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ABSTRACT

In this study, in order to control the compaction quality of the coarse-grained soils used in sub-base and base layers of several road construction projects, the dynamic penetration test (DPT) has been conducted on 50 locations using both dynamic penetrometer of light (DPL) and dynamic penetrometer of medium (DPM). First, in order to obtain the results independently from the penetrometer type, the dynamic cone resistance (q_d) values were calculated in each location based on hammer blows of both DPL and DPM. Next, the average values of q_d obtained by both the penetrometers, were correlated with the percentages of relative compaction (*RC*) in the same location obtained by performing the sand cone test on location and modified proctor test in laboratory. Accordingly, it was extracted a power correlation between the q_d values and *RC* percentages, with the determination coefficient (R^2) of about 0.64. Then, for considering the effect of soil grains size using the median particle size (D_{50}), a more accurate power correlation was obtained which as a result, the R^2 value enhanced to 0.89. Furthermore, in order to consider the soil vertical stresses caused by depth of testing as well as obtaining a normalized relationship, the q_d values were divided by the vertical stresses and correlated with the *RC* percentages. Afterwards, regarding the effect of soils grains size and also their gradation properties, this time by using the dimensionless coefficients of uniformity (*Cu*) and curvature (*Cc*), it was extracted an other normalized power correlation. The results showed that the R^2 value enhanced from about 0.49 to 0.92.

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1. INTRODUCTION

Dynamic penetration test (DPT) is one of the in-situ tests which is employed for estimating the resistive properties of soils. DPT is an economical and simple method for assessing and determining the strength of the soil layers in civil projects. In this test, the dynamic energy resulting from a hammer drop with a specific weight and height, causes the penetration of a rod with conical tip into the ground, and the number of hammer blows needed for a specific penetration of cone is a criterion for evaluating the materials compaction. In each step of cone penetration, typically the number of blows for penetration of 10 and 20 cm, is recorded as N_{10} and N_{20}, respectively. The NF P94-105 [1], BS 5930 [2], EN ISO 22476-2 [3] and ASTM D6951/D6951-09 [4] are among the accepted standards.

In addition to the number of blows achieved by DPT, the dynamic penetration index (DPI) or dynamic cone penetration index (DCPI) which is usually presented in the unit of millimeters/blow, explains the penetration depth of cone's tip into the soil for every hammer blow. Generally with increasing the strength or toughness of the soil materials, the number of blows for a specific penetration is increased, and consequently the DPI value is decreased.

Other way for using the DPT results, is calculating of the dynamic cone resistance (q_d). Sanglerat [5] assumed that the penetration of cone into soil is similar to a driven pile and accordingly, showed that the q_d is calculated as follows:

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$$q_d = \frac{m}{m+m'}.(\frac{mgh}{Ae}) \quad (1)$$

where A is cross-section area of the cone, e is the average of cone penetration in each blow (the DPI can also be used instead of e), h is the height of hammer drop, m is hammer mass, m' is total mass of penetrometer (except hammer) and g is gravity acceleration.

In Some standards, Equation (1) is also suggested [3], and just instead of e, the values of $0.1/N_{10}$ (e.g. DPL and DPM) and $0.2/N_{20}$ (such as DPH_B) are substituted. As shown in Equation (1), the advantage of using the q_d parameter is that it has less dependence to the type of chosen penetrometer due to consider the value of penetrometer energy, the cone geometry and the penetrometer mass [6].

One of the important factors that can be effective on the results of all penetration tests, is the vertical stress emanated from the overburden of soil mass which increases with an increase in depth. Increasing the vertical stress and consequently, increasing the lateral pressure on the cone's penetrometer will affect the results of the test, but its effect varies in different soils. Accordingly, some studies that the penetration test results should be corrected for different depths. Also, in the standard penetration test (SPT) which is used significantly in literature [7, 8]. This correction is referred to as overburden correction [9]. In DPT such as SPT, the existence of overburden stresses can affect the results obtained by the test. Lee et al. [10] introduced the normalized parameter of dynamic cone resistance ($q_{d,n}$) to eliminate the effect of vertical stress and its lateral pressure. Also, other important factor can affect on DPT results is while the DPT is carried out in a hand excavated pit [11].

As mentioned before, simple equipments have been used in DPT, hence this test is considered as a inexpensive, simple and fast method. Due to the mentioned advantages, this test is a common favored test in everyday application to identify the important physical and strength parameters in different soils. Accordingly, this test has been used in various studies for different purposes, including the estimation of density and unit weight [12-14], relative density [15-17], shear strength and its related parameters [10, 18, 19], etc.

In order to use the DPT results and their relation with geotechnical properties of fine-grained soils, various studies have been conducted, especially in compaction quality control of the soils layers in road projects [20, 21]. This is while that the majority of previous studies on DPT results and their relation with compaction control of coarse-grained soil layers, have been performed on physical models made in laboratory [22-25]. In these studies, DPT is mainly carried out on a physical model with limited dimensions. While in the mentioned studies, it has been tried to keep the dimension of the models to be close to the real conditions in a location, but due to problem of the model boundary effects on the test results in physical models, the results of DPT in these models significantly differ from the test results in location. Therefore, using the DPT in a location with realistic conditions makes the results have been more exact, compared to the tests performed in a physical model made in laboratory.

So far, in the field of compaction quality control of coarse-grained soil layers, various studies have been performed in location using DPT and other tests like California bearing ratio (CBR) test [26-28]. These studies mainly show the relationship between DPI and CBR values. But studies about the relation of DPT results and *RC* values, are scarce in location with coarse-grained soils.

Jayawickrama et al. [29] studied the *RC* of coarse-grained soils using the dynamic cone penetrometer (DCP) test (a lightweight kind of DPT). The tests were conducted on a range of granular materials that have been used as backfills and embedment for buried structures, including thermoplastic pipes. Jayawickrama et al. [29] conducted a series of DCP tests according to ASTM D2321 Classes I and II. Accordingly, they showed the profiles of DCP blows count with respect to the penetration depth of penetrometer in different granular soil, for two methods of soil compaction, including an impact rammer and a vibratory plate compactor. Results showed that for a given soil, the DCP blows count per penetration depth in impact rammer has been significantly higher than the vibratory plate compactor which means that the soils reach a higher compaction quality. Finally, the researchers suggested to present the data in the form of DCP blow count profiles per penetration depth, which then can used as the basis to compare between different soils, compaction equipments, and levels of compaction energy.

As mentioned before, in the field of compaction quality control of soil layers, studies that can explain the relationship between DPT results and relative compaction (*RC*) of the coarse-grained soil layers as an index of the compaction control, are scant in a location with realistic conditions. However, the coarse-grained soils are widely used in different parts of road construction projects, including subgrade, sub-base and base. On other hand, the parameter of *RC* is a good dimensionless index for the compaction quality control of soil layers and hence it has a global application. So, obtaining a appropriate correlation between the DPT results and *RC* values, can be used as a quick and non-destructive way to control the compaction quality of road layers compared to the time-consuming methods with high degree of destruction such as conventional methods of *RC* determination. It should be noted that the operation of *RC* determination of soil is normally carried out by in-situ tests and through digging holes on the road materials such as sand cone test and using the standard or modified proctor testing in laboratory. The mentioned tests are time-consuming and expensive, and it is necessary to perform the tests many times to control the compaction quality of road layers.

In this paper, first the DPT is conducted using both dynamic penetrometer of light (DPL) and dynamic penetrometer of medium (DPM) and the results are converted to q_d values and presented a reasonably accurate relationships between the mentioned values and the percentages of *RC* in different kinds of coarse-grained soils with different gradation. Also, the other relationships are extracted by considering the effect of grains size and gradation properties of the soils. The structure of the paper includes, definition of the DPT and its kinds and standards, a brief reviewing of the studies related to DPT, reviewing of the studies related to the present study, the necessity, innovation and scope of this study (*Introduction section*), specifications of the construction road projects in terms of geology, coarse-grained soils used, different types of the tests performed (*Material and Method section*), explanation of the results obtained by the all the tests, presentation of correlations and discussion about them (*Results and Discussions*), a brief explanation of the present study and results and classification of all the correlation obtained by this study (*Conclusion section*). Figure 1 presents the flowchart of the research methodology.

2. MATERIALS AND METHODS

The material studied in this paper, are coarse-grained soils used for sub-base and base layers of several road construction projects in two cities of Qom and Asaluyeh in Iran. Qom is a city in Qom province and in terms of geological divisions, is located in the central part of Iranian plateau, and has a hot and dry climate (desert climate). According to studies, this city has generally four alluvial layers. Layer 1 includes fill soils and surficial alluviums, and usually has less than 15 m thickness. Layer 2 has medium to coarse-grained alluviums with thickness ranging from 5 to 52 m. Layer 3 consists of a thick aquifer, which is composed of fine-grained and medium-grained alluviums, and is thickest layer along the central area of Qom and along the Qomrood river, with 250 m thickness, and the lowest thickness of the layer in the south-east area of Qom, with 95 m thickness. Layer 4 as the bedrock, is made of marlstone and limestone marl. Asaluyeh city is a port of Bushehr province and in terms of geological divisions, it is located in the Zagros structural zone (External Zagros) and on the Arabian basement. This city has a hot and humid climate, and its average elevation from the sea level, is about 5 m. The surface of this area mainly consists of alluvial deposits. This area includes the Mishan formation (grey marls, clay limestone and claystone), Aghajari formation (brown to grey sandstone, gypsum, cream to red marls, siltstone), Bakhtyari formation (conglomerate, sandstone, limestone, clayey marl, siltstone, claystone), Asmari formation (brown to cream limestone, cream marls associated with fossil), Guri formation (sandstone, limestone, lime marl), and Surmeh formation (dolomitic lime, dolomite, clay limestone). Figure 2 shows the situation of mentioned projects.

Table 1 summarized the specification of coarse-grained soils studied in this paper. The soils classification is according to ASTM D2487 (Unified soil classification system) [30]. As stated in Table 1, for each type of soil, the locations where the sand cone tests and DPT tests using both types of DPL and DPM has been conducted, are mentioned. Moreover, in this study, two types of SW soil with different gradation were used, which are stated as SW1 and SW2 in Table 1. As is illustrated in Figure 3, each location where all the tests are performed (DPL, DPM and sand cone test), comprises a small circular area with 50 cm diameter, so that the soil conditions remain identical for all the tests. In addition to specifications of the mentioned soil in Table 1, the gradation curves of this materials are presented in Figure 4.

The Conventional dynamic penetrometers which are usually used in engineering projects include light-type penetrometers (e.g. DPL and DCP), and medium-type penetrometer (e.g. DPM). These penetrometers because of their low costs, simplicity to work and their lighter

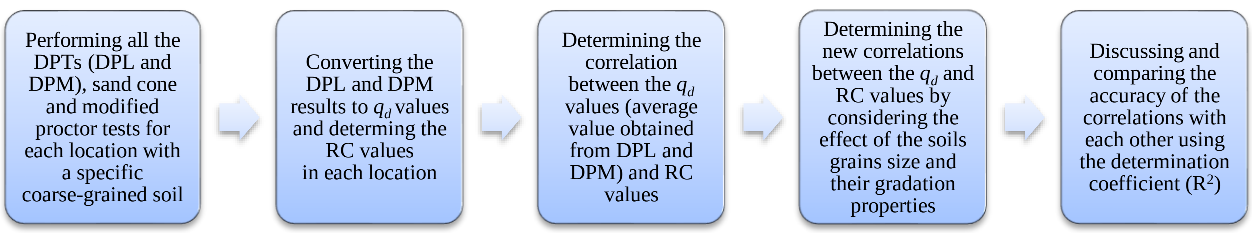


Figure 1. Flowchart of the research methodology

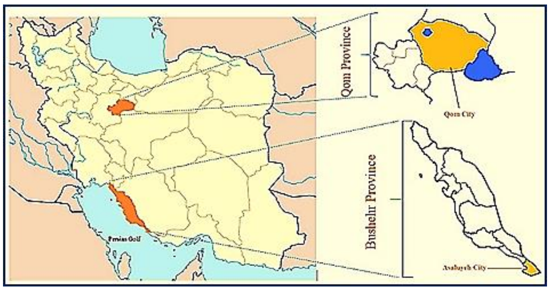


Figure 2. The situation of the road construction projects in this study

weight are employed in various projects compared to their heavier types such as heavy (DPH) and super heavy (DPSH) penetrometers, especially in road construction projects, which it is not required to investigate the resistance parameters in high depths. In this research, to perform the DPT in each location both the DPL and DPM according to EN ISO 22476-2 [3] is performed. Table 2 summarized the specification of penetrometers used in this study. Figure 5 depicts their schematic and penetrating cone.

TABLE 1. The specifictaions of soils used and number of the locations for all the tests in each soil type

Number of locations for all the tests	Soil type	D_{50} (mm)	Coefficient of Uniformity (*Cu*)	Coefficient of Curvature (*Cc*)	Plasticity Index (%)
9	GW	4.8	52.3	1.62	-
9	SW1	3.5	38.57	1.244	-
14	SW2	3.6	34.37	1.63	-
6	GW-GC	5.2	11.67	2.14	5.7
12	SP	3.1	16.67	0.96	10.1

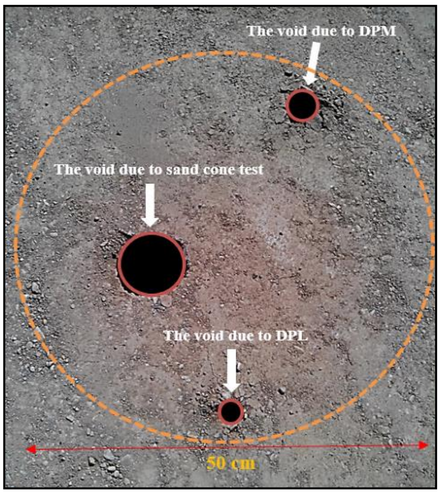
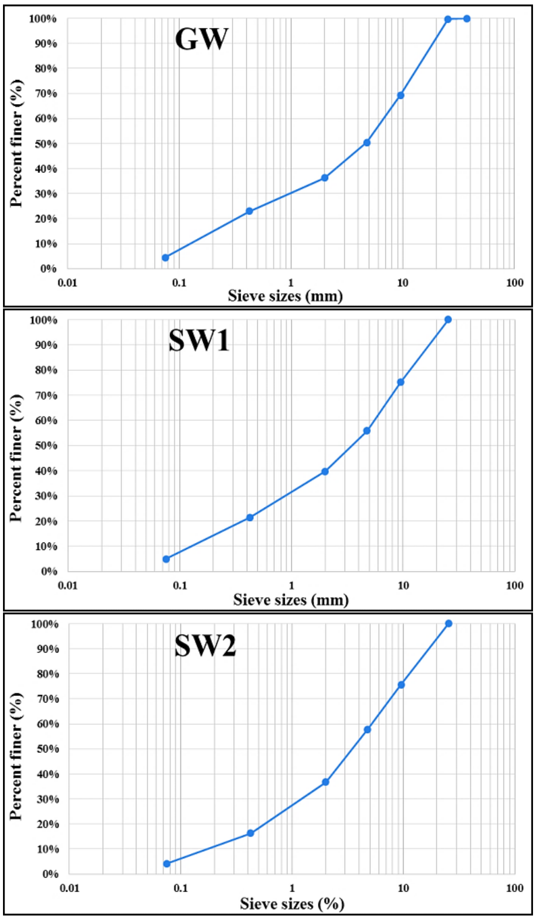
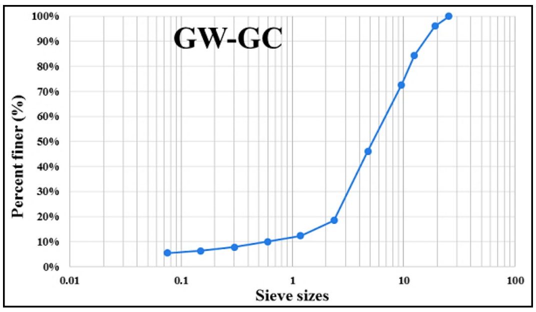


Figure 3. The situation and void types due to the tests conducting for each location





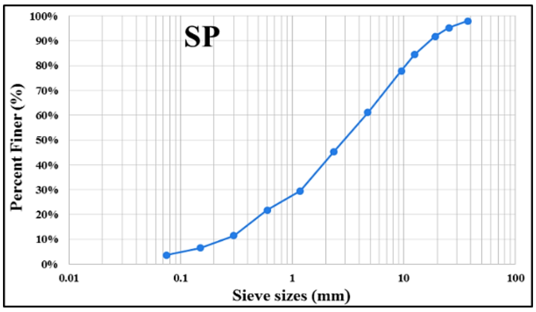


Figure 4. The gradation curves of coarse-grained materials used in the layers of road projects

TABLE 2. The specifications of penetrometers used in this study

Penetrometer	DPL	DPM
Hammer mass (kg)	10	30
Drop height (mm)	500	500
Cone diameter (mm)	35.7	43.7
Angle of cone's tip (degree)	90	90
Cross-section area of cone (cm^2)	10	15
Specific work for each blow(kJ/m^2)	49	98

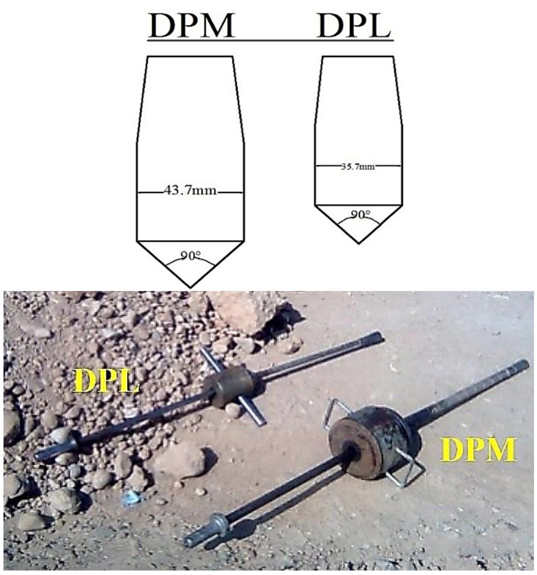


Figure 5. The Penetrometers used in this study (up) and their cone specifications (down)

In addition to perform the DPT in each location, to calculate the *RC* percentage of road layers in the studied soils, the sand cone test was performed to obtain the soil dry unit weight ($\gamma_{d(field)}$) modified compaction test in laboratory according to ASTM D1557-12 [31] in order to determine the maximum dry unit weight of the soil ($\gamma_{d(\max)}$). So, according to above-mentioned, the percentage of *RC* is obtained as follows:

$$RC(\%) = \frac{\gamma_{d(field)}}{\gamma_{d(\max)}} \times 100 \qquad (2)$$

3. RESULTS AND DISCUSSION

After conducting the DPTs (both the DPL and DPM) in each location with each coarse-grained soils mentioned in this study, the hammer blows resulting from each mentioned test is converted to the q_d values obtained from Equation (1). The variation of q_d values resulting from DPM against the DPL is shown in Figure 6. As is evident, the q_d values of DPM vary linearly with respect to DPL values and with a very high determination coefficient (R^2=0.9927). This means that the difference of q_d values resulting from both the tests is very small. Therefore, it can be concluded that the results of the tests are independent of the penetrometer type.

It should be noted that because in the present study, it was used both the DPL and DPM according to valid standards [3], investigating the results repeatability obtained from these tests, has been neglected.

Also, in a study performed using both the DPL and DPM, Khodaparast et al. [20] observed that more than 70% of the tests results, have the variation coefficient of less than 10% and more than 95% of them have the variation coefficient of less than 30%. These low values of variation coefficient show that the investigation of the results repeatability obtained from these tests (both the DPL and DPM) is negligible. It is noticeable that due to superficial depth of the tests (DPL and DPM) in this study, as well as the larger diameter of the penetrating cone compared to the penetrating rod, the friction between the rod and soil is almost ineffective [5, 32, 33] [6, 36, 37]. Therefore, the effect of the friction on q_d values has been neglected.

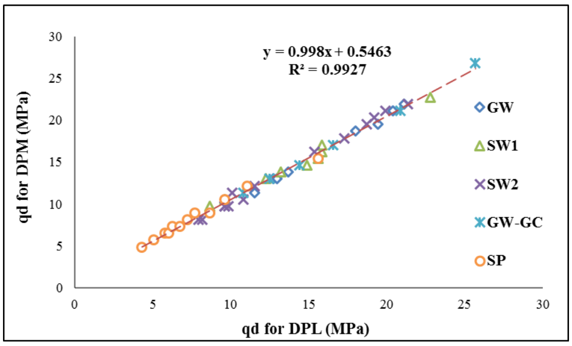


Figure 6. The relationship between the variations of DPM and DPL results

3. 1. Correlations Between the DPT results and *RC* Percentages of the Soils After obtaining the q_d values, and the proximity of DPL and DPM values to each other, and proving the independence of these values from the penetrometer type, it was used the average q_d value of DPL and DPM as the final value of q_d. As mentioned before, according to Equation (2), the *RC* percentages for each location with a given soil, are calculated using the values obtained from dry unit weight in location and maximum dry unit weight in laboratory. Now, in the following, a relationship is presented by fitting a power curve between the final values of q_d and *RC* percentages as shown in Figure 7. By increasing the q_d value, the *RC* percentage increases, i.e. the soil with higher compaction shows more resistance against the penetration of penetrometer, and therefore, for a given penetration, more blows are required. Also, this result is confirmed by Jayawickrama et al. [29]. Moreover, it has been shown other relationship on the same plot, the $\frac{q_d}{D_{50}}$ versus *RC* percentages. It is clear that by dividing the q_d values by D_{50} (median particle size of soil), in fact, it has been considered the size effect of soil grains on the q_d values. As is shown in Figure 7, by considering the D_{50} of coarse-grained soils considered in this study, a desired correlation is achieved. As a result the R^2 values are enhanced from about 0.64 to 0.89, and consequently, the accuracy of the correlation is much better and more acceptable compared to the prior state (while D_{50} is not considered). Lee et al. [34] also used the parameter of D_{50} to consider the grains size effect of sandy soils on DPT results (i.e. DPI values) and as a result they reached the accurate correlations.

In the following, in order to normalize the q_d values and obtain a better correlation compared to previous states, and also to consider the overburden weight or depth of conducting DPTs, it is achieved a relationship by creating the correlation between the values of $\frac{q_d}{\gamma z}$ and *RC* percentages, as is shown in Figure 8(a). The γ, is the unit weight of soil in each location, and *z*, is the overburden depth or the penetration depth of penetrometer cone in DPT. Also in Figure 8(b), other relationship is presented to consider the gradation and size effects of soil particles. According to Figure 8(b), to keep the correlation values dimensionless, this time, two dimensionless parameters are used to determine the correlation, namely, the uniformity (*Cu*) and curvature (*Cc*) coefficients of gradation curves of the soils. Therefore, this time, a relationship between $\frac{q_d}{\gamma z.Cu.\sqrt{Cc}}$ and *RC* percentages is presented. By comparing the correlations shown in Figures 8(a) and 8(b), it can be concluded that considering the *Cu* and *Cc* values, has a great impact on the R^2 and consequently, the accuracy of obtained correlation. Therefore, the R^2 value increases from about 0.49 to 0.92. This means that by considering the *Cu* and *Cc* values as coefficients for considering the gradation properties and size effects of coarse-grained soils, it can be reached from a low-accuracy correlation to a high-accuracy and valid correlation. This can be used for controlling the compaction quality of coarse-grained soils used in road layers.

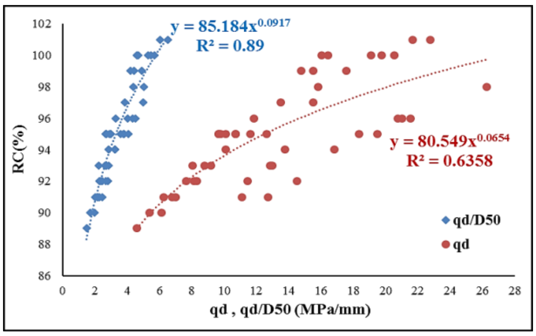
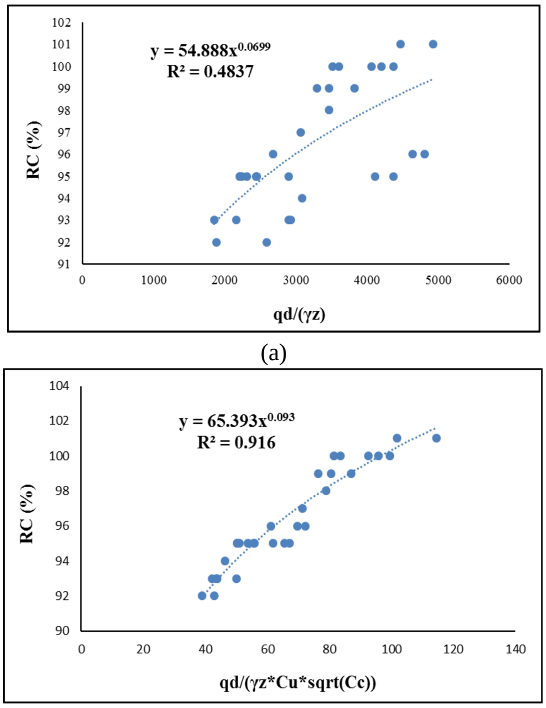


Figure 7. The correlation of q_d and $\frac{q_d}{D_{50}}$ values with the percentage of soils RC



(a)

(b)

Figure 8. The correlation of $\frac{q_d}{\gamma z}$ (a), and $\frac{q_d}{\gamma z.Cu.\sqrt{Cc}}$ (b), with the percentage of soils RC

4. CONCLUSION

In this paper, for controlling the compaction of coarse-grained soil layers which are mainly used in different parts of road layers, five common types of the soils, including GW, SW with two different types of gradation (SW1 and SW2), GW-GC and SP, have been used in sub-base and base layers of several road construction projects in Iran. In each location, both the DPL and DPM were conducted and the results obtained from these tests were converted to q_d values to make the results insensitive to penetrometer type. In addition to the DPT, the sand cone test was carried out in location and modified proctor test was carried in laboratory to determine the *RC* in each location. Then, a series of correlations was presented between the q_d , $\frac{q_d}{D_{50}}$, $\frac{q_d}{\gamma z}$, $\frac{q_d}{\gamma z.Cu.\sqrt{Cc}}$ values and *RC* percentages as follows:

- The correlation between q_d and *RC* percentages:

$$RC = 80.549 q_d^{\ 0.0654} \quad (R^2 = 0.6358) \tag{3}$$

- The correlation between $\frac{q_d}{D_{50}}$ and *RC* percentages:

$$RC = 85.184 (\frac{q_d}{D_{50}})^{0.0917} \quad (R^2 = 0.89) \tag{4}$$

- The correlation between $\frac{q_d}{\gamma z}$ and *RC* percentages:

$$RC = 54.888 (\frac{q_d}{\gamma z})^{0.0699} \quad (R^2 = 0.4837) \tag{5}$$

- The correlation between $\frac{q_d}{\gamma z.Cu.\sqrt{Cc}}$ and *RC* percentages:

$$RC = 65.393 (\frac{q_d}{\gamma z.Cu.\sqrt{Cc}})^{0.093} \quad (R^2 = 0.916) \tag{6}$$

The results obtained from the above correlations, show that the parameters of D_{50}, *Cu* and *Cc* can play a significant role in creating more accurate correlations and as a result, they cause the compaction quality control of the coarse-grained soils be more exact.

It should be noted that the parameters of *Cu* and *Cc* due to obtain a normalized correlation (see Equation (6)) with highest accuracy and considering the effect of soils grains size and their gradation properties in form of dimensionless, are more appropriate than D_{50} parameter.

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Persian Abstract

چکیده

در این پژوهش، به منظور کنترل کیفیت تراکم خاک های درشت دانه، آزمون نفوذسنجی دینامیکی (DPT) با استفاده از هر دو کاوشگر دینامیکی نوع سبک (DPL) و متوسط (DPM) در ۵۰ محل در لایه های اساس و زیراساس چند پروژه راه سازی استفاده شده است. در این خصوص ابتدا در هر محل، بر اساس تعداد ضربات چکش مخروط هر دو کاوشگر DPL و DPM، مقادیر مقاومت دینامیکی مخروط (q_d) جهت مستقل شدن نتایج به دست آمده از نوع کاوشگر، محاسبه شده اند. سپس متوسط مقادیر q_d به دست آمده از هر دو نفوذسنج با درصدهای تراکم نسبی (RC) در همان محل که با استفاده از انجام آزمایش مخروط ماسه درمحل و آزمون تراکم اصلاح شده در آزمایشگاه، به دست آمده اند، مرتبط شدند. بر این اساس، یک رابطه همبستگی توانی با ضریب تعیین (R^2) حدود ۰/٦٤ استخراج شد. سپس با در نظرگرفتن تاثیر اندازه دانه های خاک با استفاده از شاخص اندازه میانی ذرات (D_{50})، رابطه ای با دقت بالاتر به دست آمده که مقدار R^2 به ۰/۸۹ ارتقا یافته است. به علاوه، به جهت درنظر گرفتن تنش های عمودی ناشی از عمق انجام آزمون و همچنین به دست آوردن یک رابطه نرمال شده و بی بعد، مقادیر q_d بر تنش های عمودی تقسیم شدند و با درصدهای تراکم مرتبط شدند. پس از آن، به منظور درنظر گرفتن تاثیر اندازه دانه های خاک ها و همچنین دانه بندی آنها، با استفاده از پارامترهای بی بعد ضریب یکنواختی (Cu) و انحنا (Cc) یک رابطه توانی نرمال شده و بی بعد دیگر استخراج شد. نتایج نشان داد که مقدار R^2 از حدود ۰/٤۹ به مقدار ۰/۹۲ افزایش یافته است.