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Research article

Application of the dynamic cone penetrometer test for determining the geotechnical characteristics of marl soils treated by lime

Amir Hossein Vakili [a,*], Mahdi Salimi [b], Mohammad Shamsi [c]

[a] Department of Civil Engineering, Faculty of Engineering, Zand Institute of Higher Education, Shiraz, Iran
[b] Faculty of Engineering, Hamedan Branch, Islamic Azad University, Hamedan, Iran
[c] Department of Civil Engineering, University of Hormozgan, Bandar Abbas, Iran

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ABSTRACT

Quantitative estimation of mechanical characteristics of soils and determination of their behavior using in-situ experiments have always been one of the main concerns of geotechnical engineers. So far, various methods have been introduced to achieve this goal, among which the Dynamic Cone Penetrometer (DCP) test has become more popular as one of the most accurate and efficient methods. Therefore, in this study, an attempt was made to examine the correlation between different soil parameters by performing DCP test along with a series of conventional tests including Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) tests on marl soil samples containing 2, 5, 8% lime at 1, 7 and 15 curing days. Furthermore, since the subgrade reaction coefficient (K_s) is needed in the design of pavements and their underlying materials, Plate Load Test (PLT) was performed to determine K_s. The results showed that the addition of lime up to 5% increased UCS, CBR and K_s and decreased dynamic penetrometer index (DPI) of marl soil samples. Further addition of lime had a negative effect on the mechanical characteristics of the samples. Moreover, using the equations obtained from the correlations in this study, strength characteristics and subgrade reaction coefficient of the stabilized marl soil can be estimated by knowing the DPI of the samples. The results of this study showed that the use of the DCP test as a cheap and easy-to-use method can provide a comprehensive view of soil behavior in civil engineering projects with an acceptable coefficient of determination to geotechnical engineers.

1. Introduction

In-situ experiments performed on intact samples have always been much more recommended due to the fact that the results are close to reality compared to disturbed samples. It is almost impossible to make samples similar to undistributed ones because the soil structure is different from those found in nature. Moreover, accurate measurement of soil parameters by laboratory methods requires a large number of samples collected from the site and carry out laboratory tests on them. This process is considered very time-consuming, tedious and costly. Therefore, the application of in-situ tests in geotechnical studies is of great importance, among which dynamic probing can be mentioned. Some researchers have proposed guidelines for determining mechanical properties of the subgrade and layers of road pavement through field trials, which use DCP is one of these solutions. This experiment has been considered as an easy, fast and simple method with low running cost compared to other geotechnical tests [1, 2, 3]. DCP test results are usually expressed in terms of dynamic penetration index (DPI) which is measured in mm/blow or inch/blow [4]. Many studies have shown that there is a correlation relationship between DPI (penetration rate) and many of the engineering properties of soils and granular materials such as California Bearing Ratio (CBR), resilient modulus, elasticity coefficient, uniaxial compressive strength, cohesion and friction angle [5, 6, 7, 8]. Furthermore, the DCP has also been provided for the assessment of soil liquefaction potential [9, 10].

This experiment can be used to evaluate the characteristics of different types of problematic clay and sandy soils. Marl soils are one of the challenging soils that have rarely been studied. Marl is a term with broad meaning which is assigned to the material, whether soil or rock-like, containing 35%–65% carbonate and the rest of the clay fractions [11, 12, 13, 14]. Marl soils are formed by the physical and chemical weathering of parent carbonate rocks, including limestone, dolomite and carbonate sandstones [15]. These soils are widely scattered in many places in the world, so that many reports have been published on the

* Corresponding author.
E-mail address: amirhoseinvakili@gmail.com (A.H. Vakili).

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presence of these soils in Canada, America, Britain, Austria, Iran, the Persian Gulf region, Saudi Arabia and areas of southeastern France [12, 16, 17]. They have a significant bearing capacity in dry conditions, but their strength and stiffness strongly decrease with changes in moisture content [14, 18]. Furthermore, this type of soil is known as a material with collapsible, swelling and dispersive behavior [19]. By and large, variations in the behavior of marl soil arise from differences in mineral composition, history of soil, type of presence of carbonate minerals, microstructure, degree of cementation and finally the amount of clay particles [11, 20, 21].

According to the conditions of construction projects, there are various physical and chemical techniques to improve the soils. Some examples of common physical techniques include dynamic compaction [22], geosynthetic reinforcement [23], installation of stone columns [24] and pile foundations [25]. Furthermore, chemical stabilization is one of the most common methods for overcoming destructive characteristics of these calcareous soils. So far, several studies have been done in relation to the improvement of soils, by lime, cement, fly ash and other similar chemical stabilizers [26, 27, 28, 29, 30, 31, 32, 33]. In general, the application of such additives in the soil contributes to changes in soil properties, such as strength parameters, modulus of elasticity and subgrade reaction coefficient [34]. Obtaining these parameters directly through conventional experiments to have a comprehensive view of the studied soil requires a lot of time and cost. Therefore, the development of correlations between different soil parameters through easier tests can be very important. The DCP has been used in recent years in many countries because of its simplicity, low cost, relatively light weight, and most importantly speed of testing compared to conventional tests [35]. Despite the studies, less attention has been paid to determine the geotechnical properties of marl stabilized with chemical additives using DCP tests. The main purpose of this study is to evaluate the feasibility of the DCP test to predict the engineering properties of lime-stabilized marl soils. To this end, marl soil samples stabilized with lime (up to 8%) were made and cured for 1, 7 and 15 days. Thereafter, by performing a series of conventional tests such as UCS and CBR, along with PLT and DCP tests, the mechanical characteristics of the samples as well as subgrade reaction coefficient (K_s) were determined. Then, the correlations between the obtained parameters with an acceptable coefficient of determination were presented.

2. Materials and methods

2.1. Materials

In this study, the marl soil was used which was procured from the Shiraz region of Iran. Preliminary tests of physical, chemical and mechanical identification were performed according to ASTM standards on the soil studied and results are presented in Tables 1 and 2. The Scanning Electron Microscopy (SEM) micrograph corresponding to the marl soil is shown in Figure 1. As can be seen, studied soil is classified as clay of low plasticity (CL) according to the Unified Soil Classification System. Moreover, the pure hydrated lime ($Ca(OH)_2$) was used to stabilize the soil. For this purpose, different quantities of lime (2, 5 and 8% by weight) were added to the marl soil. It is worth noting that in most previous studies, the optimum amount of lime for soil stabilization has been reported to be around 5% [36]. The range of up to 10% lime used in stabilizing marl soils has also been applied. Therefore, in this study, in line with Al-Amoudi et al. [11], and Yong and Ouhadi [12], the amount of lime up to 8% was considered to include the optimal lime range.

Table 1. Physical and mechanical characteristics of the studied marl soil.

Characteristics	Quantity measured
Percentage passing No. 200 sieve (%)	88.9
Liquid limit (LL), %	31
Plasticity index (PI), %	15.56
Soil classification	CL
C (unsaturated), Kg/cm^2	0.18
C (saturated), Kg/cm^2	0.21
ϕ (unsaturated), deg.	21
ϕ (saturated), deg.	19
Maximum dry density, gr/cm^3	1.7
Maximum wet density, gr/cm^3	2.02
Optimum moisture content, %	19.39
Unconfined compression strength, Kg/cm^2	0.98
CBR (unsaturated), %	7
CBR (saturated), %	6

Table 2. Chemical properties of the studied marl soil.

Chemical constituents:	Marl soil
XRD results:	
$Ca(CO_3)$	37.5
SiO_2	51.3
$CaMg(CO_3)_2$	11.2
XRF results:	
SiO_2	34.7
Al_2O_3	9.3
MgO	7.3
CaO	18.3
Fe_2O_3	4.8
K_2O	1.23
Cl	0.023

2.2. Methods

2.2.1. Tests procedure

In this research, the changes in geotechnical properties of marl in north of Shiraz were examined by chemical stabilization using lime. At first, the necessary tests were carried out to determine the physical and mechanical properties of marl soil. Unconfined compressive strength (UCS) and California bearing ratio (CBR) tests were performed in accordance with the standards D 2166-87 and D 1883-87, respectively, to evaluate the mechanical properties of marl soil stabilized with lime. In addition, dynamic cone penetrometer (DCP) and plate load tests (PLT) were carried out ten times by making a mould according to the existing reference [7]. So that the pure soil and soil stabilized with lime at 2, 5 and 8% were evaluated separately in three different periods of 1, 7 and 15 days.

The mould was built to investigate the dynamic cone penetrometer and plate load tests on marl soil based on the Mohammadi et al. [7]. As can be seen in Figure 2, a vertical cylinder which was made from rigid metal with a diameter of 75 cm and a height of 70 cm, was attached to a rigid base plate with a thickness of 5 mm. Finally, the mould was filled with marl soil in order to perform the desired test. Then two rigid base members were attached on both sides of the cylinder on the plate and upper beam was finally fixed with two nuts below and above the vertical stand.

2.2.2. Unconfined compressive strength (UCS)

To prepare samples of unconfined compressive strength test, first lime was added to the soil with specific percentages and then by adding water equal to the Optimum Moisture Content (OMC), the samples were compacted into a mould. All the specimens were 38 mm and 76 mm in diameter and height, respectively, after removal of the mould. thereafter, they were placed into airtight plastic bags for 1, 7, and 15 days. Finally, after the completion of the curing times of the samples, the UCS test was conducted on them according to ASTM D2166-16.

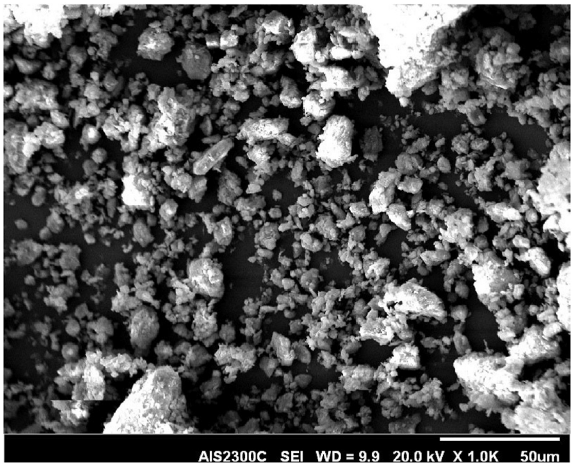

Figure 1. SEM analysis of the studied marl soil.

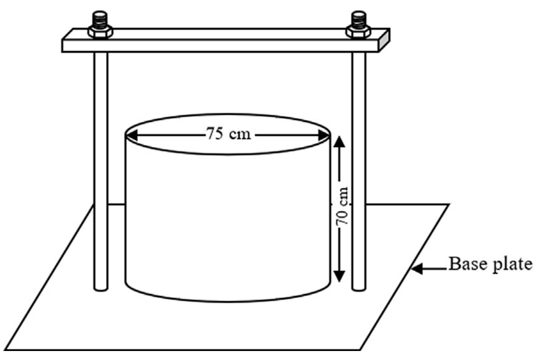

Figure 2. Schematic drawing of the mould used for dynamic cone penetrometer and plate load tests.

2.2.3. California bearing ratio (CBR)

To prepare the specimens of CBR test, similar to the method presented in the UCS test, oven-dried soil and lime with specific percentages were mixed and then water was added to them to reach the OMC. Then, they were completely blended to obtain homogeneous samples and finally compacted into a 6-inch-diameter, 4.8-inch-height cylindrical mould in five layers. In the next step, the mould with the sample in it was placed in an airtight plastic bag and after the certain curing time, they were immersed in water for 96 h to simulate the worst possible conditions and then all samples were tested according to ASTM D 1883-16.

2.2.4. Dynamic cone penetrometer (DCP)

Dynamic cone penetrometer is a simple method for estimating soil parameters and infiltration plays an important role in in-situ identification of soils. This technique is cheaper and faster than traditional methods of soil boring and geotechnical studies, and therefore in many cases is used for studying layers of soil, especially when the desired depth is not too large [7]. The Dynamic Cone Penetrometer used in this research, according to the ASTM standard D 6951-18 consists of a steel rod with a diameter of 15.8 mm, which is attached to the end of the cone with a 20 mm base diameter and 60-degree cone angle. The device is driven into the soil by successive blows of the 8 kg hammer, falling from the height of 575 mm (Figure 3). To perform the DCP test, first different amounts of soil and lime were mixed together and then the optimum amount of water content (OMC) was added to the mixtures to reach the maximum dry density (MDD). The blend was then mixed well to be completely homogeneous. Finally, the mixture was poured into the

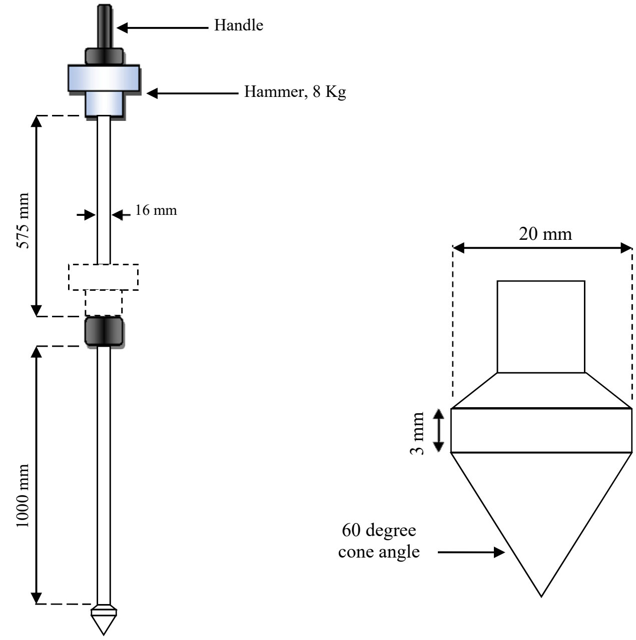

Figure 3. Schematic drawing of DCP with its details and dimensions.

mould in five separate soil layers so that it was completely filled to the top. At this stage, the surface of the mould was completely covered with a plastic bag to prevent moisture loss, and after 1, 7 and 15 days of curing, the DCP test was performed on it. It should be noted that these steps were performed separately for different amounts of lime. Noted that testing is conducted continuously from the soil surface in the mould (as shown in Figure 2) to the final penetration depth.

In this test, the relationship between the penetration depth (mm) and the number of blows during the test is shown by a parameter called the dynamic penetration index (DPI), which is calculated through Eq. (1):

$$DPI = \frac{P}{B} \tag{1}$$

where P and B indicate the final penetration (mm) and the total number of blows, respectively.

In this study, an attempt has been made to establish good relationships between dynamic cone penetrometer test results and parameters derived from other tests, especially plate load test, with which to predict the parameters of engineering for marl soil stabilized with lime by relying on results of dynamic cone penetrometer test. For this purpose, the EzyFit toolbox in MATLAB R2011b software (Mathworks Inc., Natick, MA, USA) was used to fit the curve and find the relation between results from the DCP test and those from other tests.

2.2.5. Plate load test (PLT)

To perform the plate load test according to what was described in the previous section, soil samples were blended with different amounts of lime and after adding the required water (OMC) to them, they were compacted in the mould to reach MDD. In this way, different wet samples containing marl and lime soil were carefully placed in the mould in five separate soil layers. Each layer was then compressed with a hammer weighing 68.6 N with a compaction energy equivalent to 250 blows from a height of 0.5 m. Finally, after the compaction process was complete, the surface of the sample was carefully smoothed before the experiments.

As shown in Figure 4, marl soil samples were compacted into the mould and then the plate load test device was placed in it for carrying out PLT. In this study, to calculate the relationship between the applied

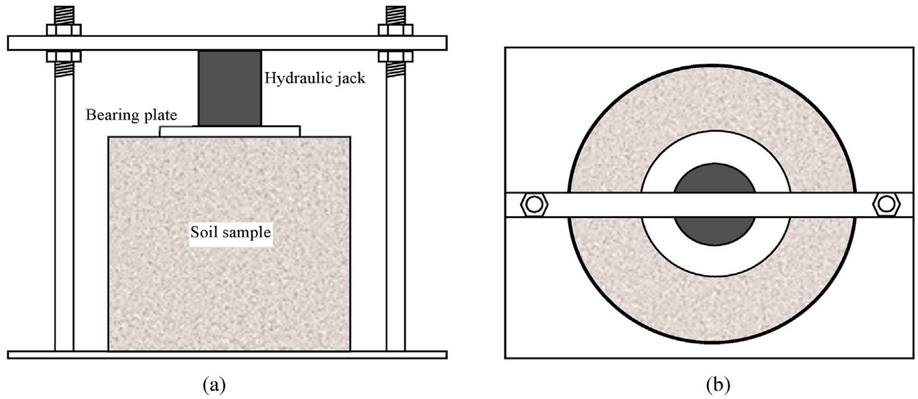

Figure 4. Schematic drawing of PLT set up: (a) side view; (b) top view.

pressures on the samples and the corresponding settlements, the parameter of subgrade reaction coefficient (K_s) was used, which was calculated by Eq. (2):

$$K_s = \frac{\Delta P}{\Delta S} \quad (2)$$

where ΔP and ΔS indicate the applied pressure and measured settlement, respectively.

As mentioned, the plate load test was conducted on untreated marl soil based on the ASTM D 1195. In this case, the value of subgrade reaction coefficient (K_s) was equal to 0.89 kg/cm^3. Then similarly, plate load tests were carried out on the soil stabilized with 2, 5 and 8% of lime after the specified curing times and finally, the values of subgrade reaction coefficient were determined in all cases.

3. Results and discussions

3.1. UCS of the lime-stabilized samples

Figure 5 shows the changes in compressive strength of lime-stabilized marl soils at different curing times. The addition of 2% lime after 1 and 7 days of curing did not have a noticeable effect on the strength, although increasing the curing time to 15 days increases the UCS by about 100%. The results indicated that increasing the lime to the marl soil to a certain extent, equivalent to 5%, improves the strength of the samples, and further amounts of lime reduced the strength. When 5% lime is added to the soil sample, it develops the pozzolanic reactions, which leads to the formation of cementitious products and ultimately improves the mechanical properties of the soil. With 5% lime and 15 days of curing, the UCS increases to 242 kPa compared to 96 kPa for unstabilized marl soil. However, for larger amounts of lime up to 8%, the strength of the samples is reduced, so that the strength decreases to 201 kPa after 15 days of curing. Previous studies have shown that lime does not have good cohesion and friction [37], and therefore its excessive use can act as a lubricant for soil particles, leading to a decrease in the strength of soil samples [38]. In addition, the cementitious gels produced due to the reaction of lime with the soil particles cause large pores in the soil, such that excessive amounts of lime can cause extreme accumulation of this porous medium, which can also lead to a decrease in the strength of the samples.

3.2. CBR of the lime-stabilized samples

In the current research, to better understand the mechanical properties of lime-stabilized marl soil, a CBR test was performed on the samples after different curing times. As shown in Figure 6, the soaked CBR results are fully consistent with the results of the unconfined compression test. The value of soaked CBR increased with the addition of lime up to 5% after 15 days of curing and reached 19.4% compared to unstabilized soil which stood at 6%. However, for 8% lime after 15 days, the value of soaked CBR decreased to 17.3%. The incorporation of lime to a certain content after a long time can produce cementitious materials such as calcium silicate hydrate (CSH) during pozzolanic reactions, which improves soil strength properties [39]. However, it should be noted that the high content of lime can prevent the formation of CSH and lead to the creation of redundant portlandite and calcite, which is accompanied by a significant reduction in the strength [40].

3.3. K_s of the lime-stabilized samples

Subgrade reaction coefficient (K_s) is a conceptual relationship between soil pressure and strain changes caused by it, which is widely used in the design of foundations and therefore has special importance for geotechnical engineers. In this study, PLT was used to determine the variations of K_s of the lime-stabilized samples at different curing times. Figure 7 shows the results of K_s and, as can be seen, the lime was able to improve K_s. Similar to what was stated in the compressive strength and soaked CBR results, the inclusion of lime up to 5% after 15 days of curing was able to increase the K_s value by about 118% (1.94 kg/cm^3). This value reached about 1.79 kg/cm^3 for 8% lime, which can be attributed to the excessive dosage of lime. According to the obtained results, 5% of lime is determined as the optimum percentage for improving the marl soil in this study. Increasing the lime to this optimum level causes short-term and long-term reactions that improve soil engineering properties. These findings indicate that marl soil with lime addition is suitable for use as a road foundation even in the short run.

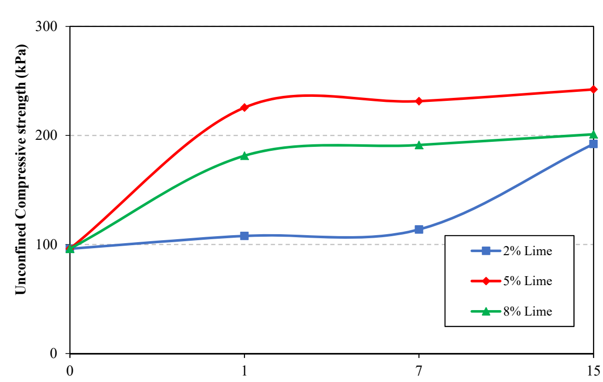

Figure 5. UCS results for lime-stabilized soil samples after several curing times.

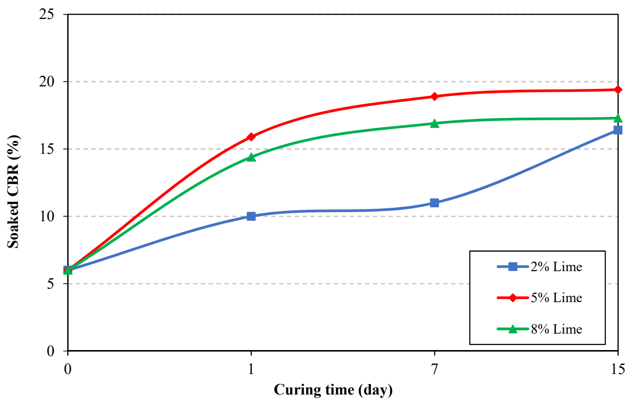

Figure 6. Soaked CBR results for lime-stabilized soil samples after several curing times.

3.4. DPI of the lime-stabilized samples

In this study, the DCP test was performed on lime-stabilized samples at curing times of 1, 7 and 15 days, and the penetration rate was recorded for each blow during the test. Then the total penetration against the number of cumulative blows was plotted. This parameter represents the uniformity of the sample characteristics [41]. Figure 8 shows the results of the DCP test, which showed that one day of curing time for all lime contents had the greatest impact on DPI. As stated in the previous results, 5% lime has the greatest effect on improving DPI. After one day of curing, the DPI value for samples containing 2, 5 and 8% lime was 16, 15 and 11 mm/blow, respectively, which showed a significant decrease compared to marl soil (equal to 25 mm/blow). These values after 15 days of curing were 14, 12 and 9 mm/blow, respectively, which indicates that increasing the curing time can lead to a further decrease in DPI.

3.5. Correlations between DPI and the characteristics of lime-stabilized samples

Past research has shown that there is a correlation between DPI and many soil engineering parameters. In general, a DCP is a simple, low-cost, and relatively lightweight device. It also does not require much experience and a long time to use this device. All of these factors have led to the widespread use of the DCP probe in countries such as Australia, South Africa, the United States, and the United Kingdom. One of the most common areas of DCP application is the estimation of engineering parameters of bed materials, base and subbase layers (e.g., CBR, modulus of resilience, modulus of elasticity, UCS, internal friction angle and cohesion).

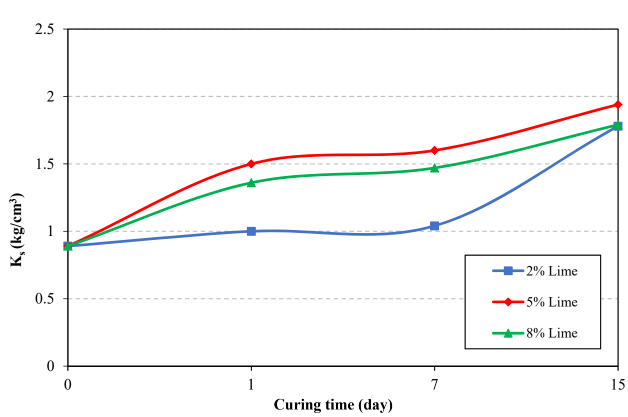

Figure 7. K_s results for lime-stabilized soil samples after several curing times.

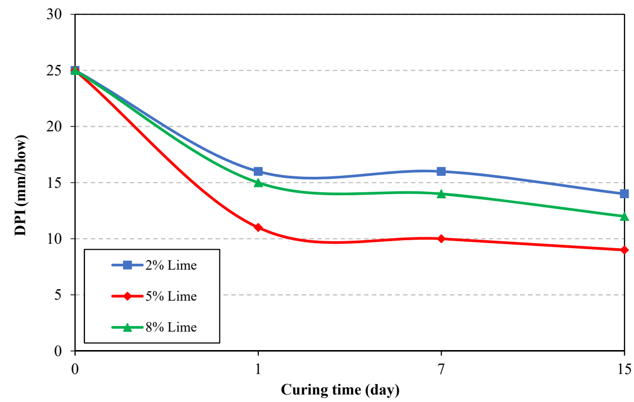

Figure 8. DPI of lime-stabilized soil after several curing times.

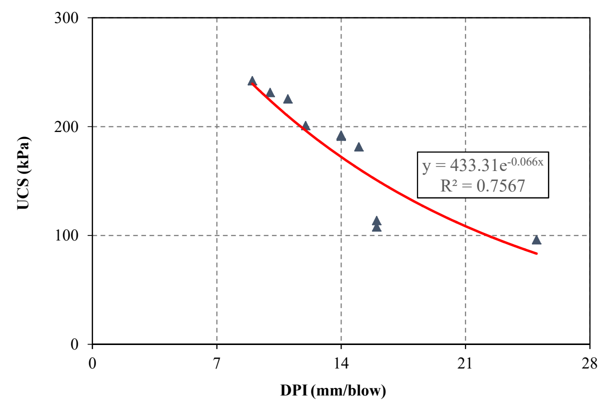

Figure 9. Correlation between DPI and UCS of lime-stabilized soil considering several curing times.

So, predicting geotechnical parameters has always been one of the main concerns of civil engineering. Therefore, finding the appropriate correlation between different parameters can provide a good view of soil behavior in civil engineering designs. It should also be noted that performing various tests on soils in geotechnical studies of a project can be costly and therefore the overall cost of the project can be greatly reduced by prediction of the main soil parameters. Since DPI depends on various factors such as soil type, moisture content, density, and pore water pressure, it can reveal many different soil properties [41]. This technique

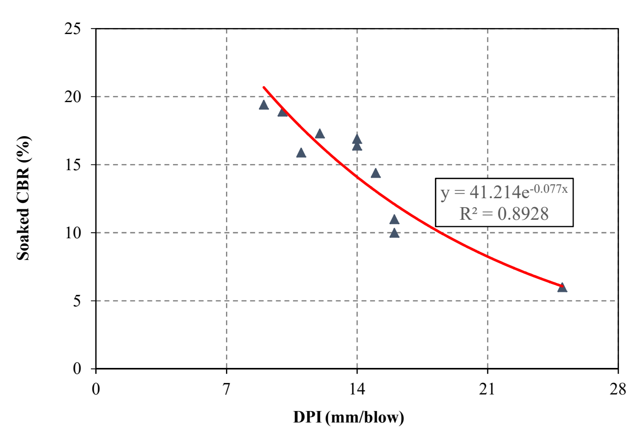

Figure 10. Correlation between DPI and soaked CBR of lime-stabilized soil considering several curing times.

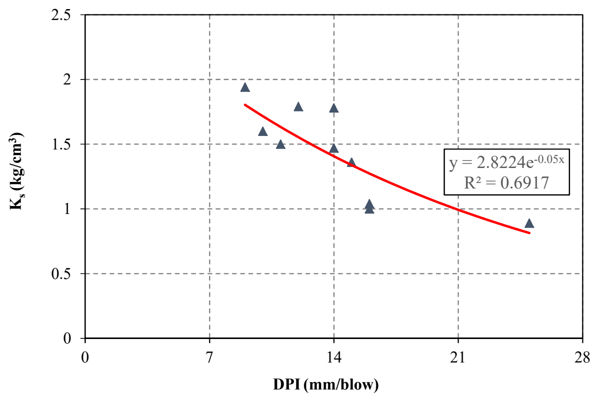

Figure 11. Correlation between DPI and K_s of lime-stabilized soil considering several curing times.

Table 3. Equations and their related R^2 values for regression lines.

Parameter	Formula	R^2
UCS and DPI	*UCS* = 433.31 exp (-0.066DPI)	0.7567
CBR and DPI	*CBR* = 41.21 exp (-0.077DPI)	0.8928
K_s and DPI	*Ks* = 2.8224 exp (-0.05DPI)	0.6917

makes it possible to indirectly estimate the strength and the compaction of the soil by measuring the cone penetration against the number of weight drops. Furthermore, the DCP can also be used to obtain approximate values of CBR, UCS and other geotechnical parameters. The major superiority of DCP is that it does not need any external reaction forces and its function is only by relying on the kinetic energy provided by the drop hammer.

In this study, the relationships between DPI and other geotechnical parameters such as UCS, soaked CBR and K_s are investigated, as shown in Figures 9, 10, and 11, respectively. To this end, the results of lime-stabilized samples after 1, 7 and 15 days of curing time were used, and by drawing regression lines for each set of data, the equation of those lines was determined, which is shown in Table 3. The value of R2 specified for each equation can also be expressed as the variance ratio in the y-axis to that of the x-axis.

Having such equations can be very effective in determining the behavior of this type of soil stabilized with chemicals such as lime, because performing all geotechnical tests can be time-consuming in addition to the cost. Moreover, knowing the DPI of the samples, the values of the other geotechnical parameters can be estimated with a good approximation through these equations. Figures 9, 10, and 11 show that as the DPI value increases, the mechanical properties of the specimens decrease. It is worth noting that these equations can be employed to stabilized marl soils with comparable conditions, and further studies are needed if the test conditions change. As can be seen from the correlations obtained between DPI and UCS, CBR and Ks, the lowest R2 was obtained for the plate load test (K_s). PLT is a difficult and costly that may not be possible at the project site. But the DCP test is a low-cost and convenient test that can be easily used at any depth. In addition, these correlations can provide a good estimate of soil behavior for project designers. Therefore, although it is necessary to perform a limited number of main tests to fully ensure the soil characteristics, the use of these correlation relationships even with a R2 of about 0.7 can get a good view of soil characteristics.

4. Conclusions

The aim of this study was to evaluate the feasibility of the DCP test to estimate the engineering properties of lime-stabilized marl soils after different curing times. To this end, the correlation between UCS, soaked CBR, K_s and DPI parameters was determined and three equations were presented through which the values of other parameters can be estimated with an acceptable approximation using DPC. The following findings are a summary of the results of this study:

- An attempt was made to provide a correlation between DPI and other geotechnical parameters to reach an acceptable estimate of them only by having the DPI values. Since performing various tests on samples in a stabilization design can be costly, these equations can be very important to geotechnical engineers.
- It was found that the DCP test as a cheap and easy-to-use method can present a broad view of soil behavior in civil engineering projects with a suitable coefficient of determination.
- It was ascertained that the inclusion of lime content up to 5% improved UCS, soaked CBR and K_s of marl soil samples. However, increasing the amount of lime up to 8% had the adverse effect on these parameters. Since lime has low friction and cohesion, overuse can act as a lubricant for soil particles, ultimately reducing the strength of the samples.
- The sample containing 5% lime, as the optimum content, after 15 days of processing showed the best values of UCS, soaked CBR, K_s and DPI, which were equivalent to nearly 2.5, 3.2, 2.2 and 0.36 times compared to those of unstabilized marl soil, respectively.

Declarations

Author contribution statement

Amir Hossein Vakili: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mahdi Salimi: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mohammad Shamsi: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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