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Development of Light Dynamic Penetrometer for Application in Dense Soil

A. Nasirifar[a], M. Khodaparast*[b]

[a] University of Qom, Faculty of Engineering, Qom, Iran
[b] University of Qom, Faculty of Engineering, Civil Engineering Department, Qom, Iran

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ABSTRACT

The dynamic probing test is effective for compaction control in road embankments and pavement layers. However, challenges exist to its use in dense soil types to obtain valid results. The main purpose of this research is to use light weight penetrometer in dense soils and obtain valid results. This study developed and tested three light dynamic penetrometers with different cone geometries in dense soils and compared their results with those of conventional dynamic penetrometers. Over 72 dynamic penetration tests were performed in the field in dense natural soil. The results showed a 50% reduction in the number of blows compared to the dynamic probing light penetrometer (DPL). The coefficients of variation of the results of 8.6% to 15.9% indicate desirable repeatability. To further evaluate the efficiency of these penetrometers, the correlations between their results and the soil characteristics of the dry unit weight in place, compaction percentage and peak shear strength were assessed by statistical residual analysis. This approach showed that these relationships were satisfactory.

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1. INTRODUCTION

The dynamic penetration test is a method of identifying soil strength characteristics. In this method, the dynamic energy resulting from the fall of a hammer having a certain weight from a certain height will cause a rod with a conical tip to penetrate the ground. The number of blows required for the rod to penetrate into the soil is a criterion for measuring the hardness and density of materials. The penetration depth at each step is usually 10 to 20 cm and the test result is denoted as N_{10} and N_{20}. The dynamic penetration index (DPI), which is measured as the number of millimetres per impact (mm/blow), also can be used. In general, an increase in the strength or hardness of the soil will cause the DPI to decrease [1, 2]. Various techniques can be used for soil improvement in road embankment and geotechnical engineering [3].

A conventional dynamic probe used in soil mechanics in Iran and other countries is the dynamic probing light (DPL). However, the large amount of energy required for penetration into hard and dense soil prevents the use penetrometers such as the DPL in this type of soil. In current standards, including BS EN ISO 22476-2, ASTM D 6951 [4] and the national standard of Iran 12305-2 [1], the maximum number of blows allowed to penetrate 10 cm of soil is limited to 50 blows. However, the results of penetration testing with light probes such as the DPL in hard and dense soil indicate that this limit can be quickly exceeded, which reduces its validity. The standards recommend that heavier dynamic penetrometers should be used in such situations, but field experiments show that the weight of equipment such as the heavier types of penetrometers strongly decreased the tendency to use this test.

This study investigated the use of a light penetrometer in dense soil. To achieve this purpose, the energy produced by the penetrometer must be increased adequately. There are two general solutions to increase energy. Increasing the hammer weight and height of the fall or changing in the geometry of the cone.

The present study changed the geometry of the cone, including the diameter and angle of the cone tip, to allow penetration tests to be carried out in dense and hard soil. It will also be possible to investigate the effect of the

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*Corresponding Author Email: khodaparast@qom.ac.ir
(M. khodaparast)

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change in the cone tip angle on the penetration power. Twelve urban areas were selected to test the efficiency of the new penetrometer. It was evaluated and compared with other standard penetrometers and was found to be a suitable dynamic penetrometer as an alternative to the DPL penetrometer. By conducting penetrations tests in the specific soil with different penetrometers, the amount of changes in the results can be checked. In other words, the independence of results from the type of penetrometers can be evaluated.

1. 1. Applications of Dynamic Penetration Test

The method and equipment used in this test are basic, making them a fast and economical method of evaluating important in situ soil resistance parameters. Figure 1 shows the schematic of cone penetration into the soil per hammer blow.

Studies are being done on the applied components of this test, such as evaluation of the unit weight [5, 6] and relative density [7-9]. The relationships between DPI and other soil parameters from various laboratory and field studies are summarized in Table 1. Other important parameters such as compaction percentage [10, 11] and shear strength [12-14] also stated in this table.

1. 2. Dynamic Cone Resistance Parameter ($\mathbf{q_d}$)

Another way to use the results of this test is to calculate the dynamic cone resistance parameter (q_d). It is assumed that the penetration of a dynamic penetrometer cone into the soil corresponds to a pile. Pile foundations are used in civil structures to transfer the structural load to the depth of the soil or rock layers [15]. Pile-driving theory measures the soil resistance against the number of dynamic blows. The cone dynamic resistance parameter is presented as:

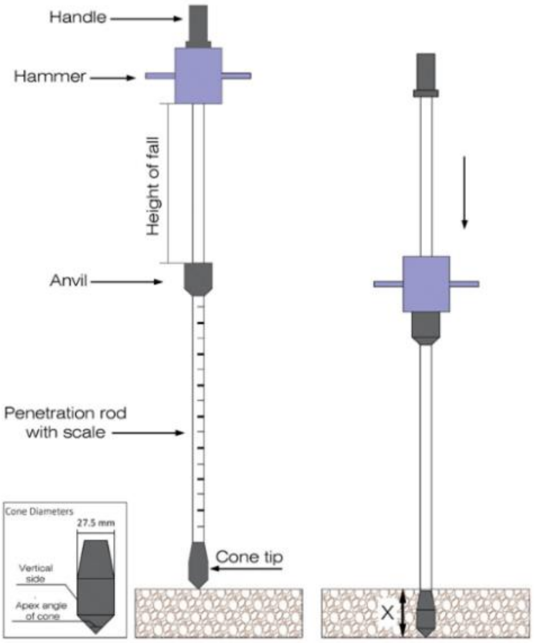

Figure 1. Schematic of dynamic penetration steps

TABLE 1. Correlations between dynamic penetrometer results and soil engineering properties

Reference	Correlation	Description	Soil type
Harison [16]	Log (CBR) = 2.81 – 1.32 × log (DPI)	Laboratory tests	Granular and cohesive soils
Livneh et al. [17]	Log (CBR) = 2.46 – 1.12 × log (DPI)	Field and laboratory tests	Granular and cohesive soils
Chennarapu et al. [5]	γ_d = 2.67 (DPI)$^{-0.131}$	Field tests	Silty sand
Hamid et al. [6]	γ_d = 2.02 (DPI)$^{-0.04}$	Laboratory tests	Poorly graded sand
Mohammadi et al. [9]	Dr = 189.93 (DPI)$^{-0.53}$	Laboratory tests	Poorly graded sand
MacRobert et al. [8]	Dr = 148 – 50 × log (DPI)	Laboratory tests	Sandy soils
L. Lin et al. [18]	Dr = – 80.63 + 37.63 × log ($D_{50}^{-0.34}C_u^{-0.17}q_d$)	Field and laboratory tests	Granular soils
Ampadu and Arthur [11]	Log (Rc) = 2.148 – 0.337 × log (DPI)	Laboratory tests	Granular soils
Khodaparast et al. [10]	Rc = 16.654 × $q_d^{0.193}$	Field and laboratory tests	Fine grained soils
Fakher et al. [19]	Cu = 2.5 M	Field tests	Soft clay
Lee et al. [20]	$\phi^\circ = 45.6 - 0.2 \times \frac{\mathrm{DPI}}{\mathrm{D_{50}}}$	Laboratory tests	Silty sand soil
Lee et al. [12]	$\phi^\circ = 0.0116 \times q_{d.n} + 47.8$	Laboratory tests	Poorly graded sand with low fines content
Kim and Lee [13]	τ_f = 223.8 (DPI)$^{-0.9}$	Laboratory tests	Silty sand soil

Note:
CBR: California bearing ratio (%); DPI: dynamic penetration index (mm/blow); γ_d: dry unit weight of soil (kN/m^3); Dr: relative density (%); D_{50}: Average particle diameter (mm); C_u: Uniformity coefficient; q_d: dynamic cone resistance (kPa); Rc: Compaction percentage (%) ; Cu: undrained shear strength (kPa); M: number of blows for 100 mm penetration; ϕ: friction angle of soil (degrees); $q_{d.n}$: normalized dynamic cone resistance (kPa); τ_f: Peak shear strength (kPa)

$$q_d = \left(\frac{M}{M+m}\right) \cdot \frac{M.g.h}{A.x} \tag{1}$$

where A is the cross-sectional area of the cone; x is the penetration length of the cone per blow, h is the height of the hammer fall, M is the hammer mass, m is the mass of the penetrometer without a hammer and g is the gravity acceleration. The advantage of qd is that, due to the contribution of the penetrometer energy, the geometry of the cone and the mass of its attachments, the value of this parameter has little dependence on the type of penetrometer selected [21].

One factor affecting the results of the dynamic penetration test is the overburden stress in the soil mass. This stress increases as the depth increases. An increase in the overburden stress and the subsequent increase in lateral pressure on the penetration cone will affect the penetration results differently depending on the soil type. Some researchers believe that the results of penetration tests should be modified depending on the depth. In the standard penetration test (SPT), this correction is referred to as the overburden correction [22].

In dynamic penetration tests, vertical stress can also affect the results. Lee et al. [12] eliminated the effect of the confining pressure on the dynamic cone resistance by introducing the normalized dynamic cone resistance ($q_{d.n}$) as:

$$q_{d.n} = \frac{\left(\frac{q_d}{p_a}\right)}{\left(\frac{\sigma_m}{p_a}\right)^{0.5}} \tag{2}$$

where q_d is the dynamic cone resistance, P_a is a reference value such as the atmospheric pressure (100 kPa) and σ_m is the mean principal stress [12].

2. MATERIALS AND METHODS

2. 1. Introducing the Three New Dynamic Penetrometer

The standards provide specific work criteria for each impact (E_n) generated by a hammer falling on an anvil as the parameter that determines the amount of energy produced by the penetrometer. To increase the penetration power, it is possible to increase the potential energy of the hammer (m. g. h) or reduce the cross-sectional area of the penetration cone (A) as:

$$E_n = \frac{M\cdot g\cdot h}{A} \tag{3}$$

Increasing the potential energy requires an increase in the mass of the hammer and height of the fall. This will increase the energy consumed by the operator and will reduce the acceptance of the penetrometer. Thus, an increase in the mass and height of the hammer should be avoided whenever possible. The use of motorized penetrometers is recommended to solve this problem, but transportation and other limitations of these penetrometers should be taken into consideration.

After conducting initial field tests and reviewing the characteristics of dynamic penetrometers for different standards, three new dynamic penetration instruments (ADP25, ADP60 and ADP90) with the specifications presented in Table 2 and Figure 2 were developed.

2. 2. Field and Laboratory Tests

A series of tests then were performed to evaluate the repeatability of

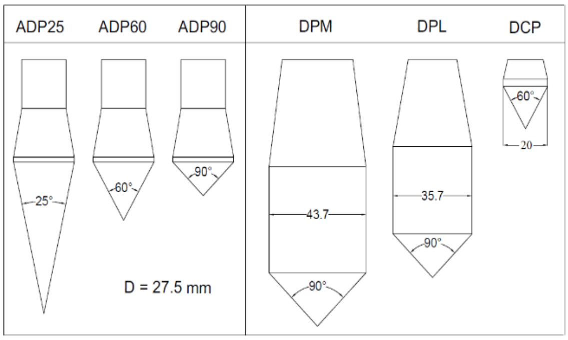

Figure 2. Specifications and appearance of penetrometer cones showing dimensions

TABLE 2. Characteristics of novel and standard penetrometers

Penetrometer	DPL	DPM	DCP	ADP25	ADP60	ADP90
Hammer mass (kg)	10	30	8	10	10	10
Height of fall (mm)	500	500	575	500	500	500
Cone diameter (mm)	35.7	43.7	20	27.5	27.5	27.5
Cone tip angle (deg)	90	90	60	25	60	90
Specific work per blow (kJ /m^2)	49	98	143	82.6	82.6	82.6
Standards	BS EN ISO 22476-2		ASTM D 6951	Introduced in this study		
Reference	[2]		[4]	-		

the results at four sites in accordance with the national standards of Iran 12305-2 and BS EN ISO 22476-2. The efficiency of the penetrometers was determined in hard and dense soils at 12 sites and, as a method of comparison, the results of the DPL and DPM types for BS EN ISO 22476 2 and type DCP for ASTM D 6951 [4] were determined. Figure 3 shows the research methodology in this article.

Dynamic penetration tests were carried out using the six penetrometers (DPL- DPM- DCP- ADP25- ADP60- ADP90) in natural soil in 12 areas around the city of Qom that have high density hard soil. The penetration depths in these tests were from the ground surface to a depth of 60 cm. The results were recorded in terms of the penetration number (N_{10}), which indicates the number of blows required for the penetration of the cone to a depth of 10 cm into the soil. Figure 4(b) shows the distance between the points of the penetration tests. Because of the possibility of soil surface tamping and proper establishment of the penetrometer in the soil, the initial 10 cm results were omitted.

The soil in these locations primarily comprised silt and sandy clay, which have high resistance and compaction due to low humidity. Table 3 shows the characteristics and classes of these soils according to ASTM D2487 (Unified Soil Classification System) [23]. The particle-size distribution curve of these materials is shown in Figure 5. Because of the low penetration depth, dryness of materials and the larger diameter of the cone on the penetration rod, the friction between the soil and the penetration rod were largely ineffective [15, 24, 25].

During in situ tests was observed that pulling out the penetration rod after performing test was easy. There is no friction between penetration rod and soil almost and so that the penetration rod can be entered into the initial cavity without any force.

According to what is mentioned in penetration test standards, the tip of the penetration cone should be checked and replaced in case of injury. The high density and hardness of the materials, likewise a low-angle cone, increase the injury of the cone tip. Hence, in this research, the cones were review before commencement of penetrations tests and were replaced if needed.

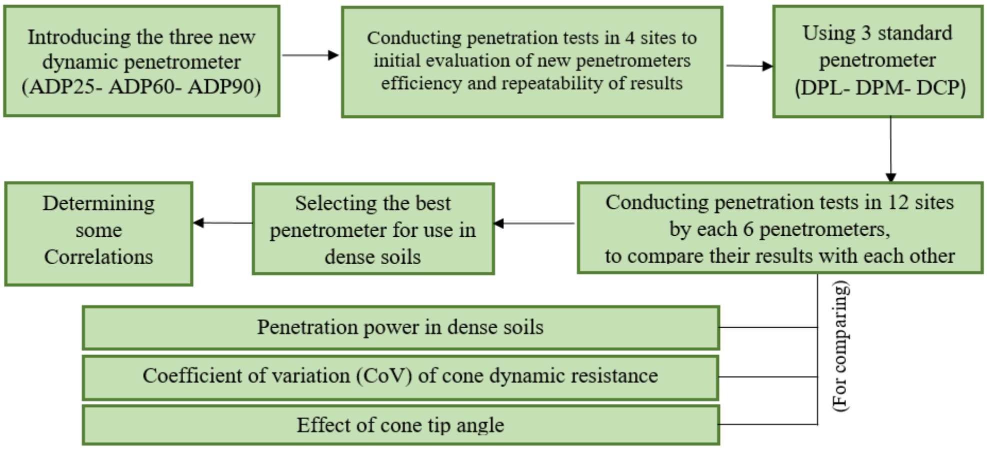

Figure 3. The process of conducting penetration tests in this research

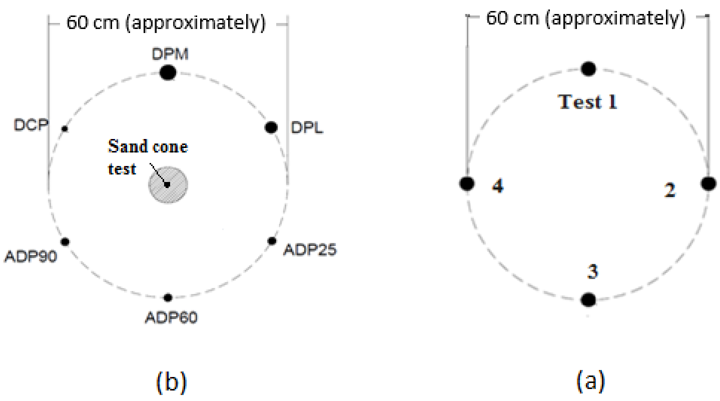

Figure 4. Spacing of penetration test points: (a) repeatability tests; (b) tests using different penetrometers

TABLE 3. Soil properties of penetration sites

Site No	Soil Type	Materials Percentage (%)			γ	ω
		Fines	**Sand**	**Gravel**		
1	CL	86	13	1	1.76	2.5
2	ML	51	44	5	1.76	3
3	ML	64	35	1	1.81	3.6
4	CL-ML	80	18	2	1.76	6.5
5	CL-ML	65	31	4	1.71	5.6
6	ML	57	37	6	1.92	7.8
7	CL-ML	86	14	0	1.75	9
8	ML	68	29	3	1.59	4.2
9	SC-SM	39	35	26	2.02	6.9
10	ML	52	30	18	1.64	12.3
11	SC-SM	37	42	21	1.9	8.2
12	GC-GM	20	36	44	1.9	3.3

Note:
γ : unit weight of soil (gr/cm^3); ω: Moisture Content (%)

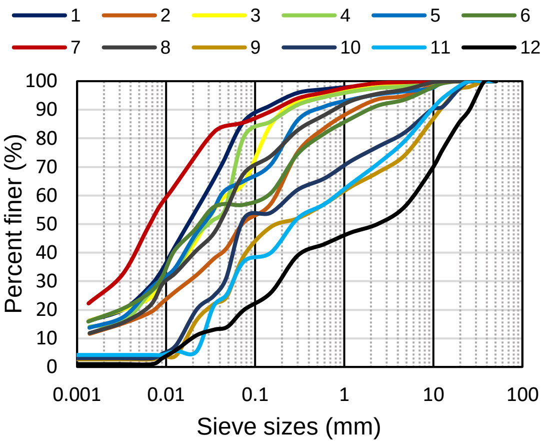

Figure 5. Particle-size distribution curves of soils

Researchers have effective factors such as the length of penetration rods (depth of penetration), the fall of the hammer without conflict with the guidance rod and the fixing of the connections, in the amount of energy dissipation [15, 26, 27]. In this study, due to the short length of the penetration rod and continuous examination of the connections. Energy dissipation are negligible and the amount of energy transferred to the cone is assumed to be equal to the value of the theory.

Rebounding of cones and penetrating rods is an issue that can occur in very hard (often gravely) soils. In these soils, due to the extremely high density and hardness of the soil, the penetrometer is not able to penetrate in the soil. In this situation, the energy from the hammer falling is returned to the penetrometer and caused interferes in measurement of penetration depth. In this study, such soils were not encountered and this problem was not observed.

In order to further expand the application of the developed penetrometers, the correlation between the results of the most appropriate new penetrometer and the soil resistance parameters have been presented. For this purpose, in-situ unit weight tests (ASTM D 1556 [28]), compaction tests (ASTM D 1557 09 [29]) and direct shear tests (ASTM D 3080 [30]) were performed.

3. RESULTS AND DISCUSSION

3. 1. Efficiency of Developed Penetrometers

Figure 6 shows the average penetration numbers (N_{10}) for depths of 10 to 60 cm for all dynamic penetration tests performed at the 12 locations. The penetration number for cones ADP25, ADP60 and ADP90 decreased by 50%, 46% and 40%, respectively, compared to the DPL penetrometer. Also, the N10 of the instrumented ADP25 was equal to that of the DPM penetrometer, a semi-heavypenetrometer (hammer weight of 30 kg), which indicates proper performance of the designed cones. In

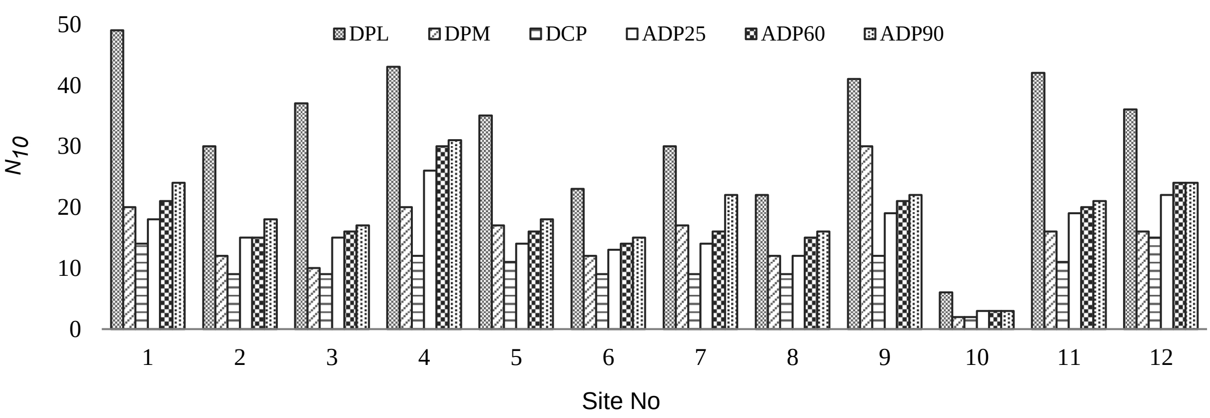

Figure 6. Average of N_{10} at depths of 10 to 60 cm for all dynamic penetration tests

the specifications of the new penetrometers, the decrease in the number of blows was caused by a decrease in the cross-sectional area of the penetration cone and a change in the angle of the tip. The lowest value of the N_{10} parameter is related to the DCP penetrometer, which has the highest amount of specific work for each impact (E_n).

It should be noted that the small diameter of the cone in this penetrometer (18 mm) compared to other penetrometers causes it to quickly become defective in the penetration tests in dense and hard soils.

3. 2. Repeatability of Developed Penetrometer Test Results

The coefficient of variation (CoV) was used to evaluate the repeatability of the results of the in-situ penetration tests. The CoV of each random variable was obtained by dividing the standard deviation (S) by the mean of the data ($\overline{X}$) (Equation (4)) and is expressed as a percentage [1, 10]. In this study, the repeatability of the results of the penetration tests was determined by calculating the CoV of N_{10} obtained from 48 penetration tests.

$$\text{CoV (\%)} = \frac{S}{\bar{x}} \times 100 \tag{4}$$

Studies have shown that increasing of the soil compaction and stiffness will increase the CoV of the dynamic penetration test results [9]. Figure 7 also shows that an increase in the CoV was caused by an increase in the number of penetrations. The average CoV was calculated and is shown in Table 4. The instrumented ADP25 with a CoV of 8.56% had the most repeatable results of the developed penetrometers.

3. 2. 1. Effect of Cone Tip Angle on CoV

Table 4 shows that the lowest CoV was for the ADP25 penetrometer, which could be attributed to the power the penetrometer. Although the specific work per impact (E_n) was the same for all three penetrometers, the difference in the cone tip angle increased the penetration power of the ADP25 penetrometer. As a result, the CoV of the results was less than of other the two penetrometers. During the penetration tests, when the density and hardness of the soil increases significantly and the penetrometer is not able to penetrate into the soils (N_{10} more than 30), the repeatability of the results decreased and the number of blows irregularly increased. Therefore, in most studies and standards, the acceptable number of blows for penetration of 10 cm into the soil was limited to 3 to 50 blows.

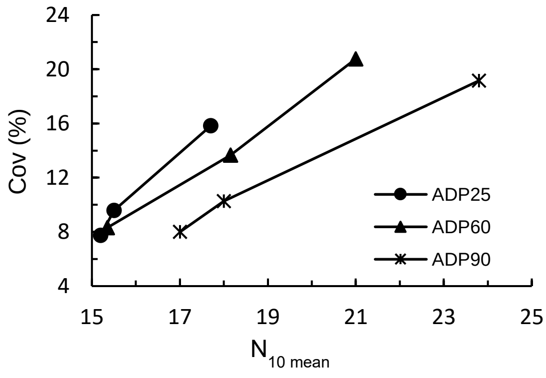

Figure 7. Variation in CoV(%) values due to the increase of $N_{10\ \text{mean}}$

TABLE 4. Mean of CoV (%) for N_{10}

CoV (%)		
ADP25	**ADP60**	**ADP90**
8.56	15.86	11.39

3. 2. 2. CoV of Cone Dynamic Resistance Parameter (q_d)

The cone dynamic resistance parameter is an intrinsic feature of the soil and should not change if the penetrometer is changed. But, in practice, because factors such as energy wasted and the cone tip angle are not included in Equation (1), there are differences between the values of this parameter as measured by different penetrometers. In this study, the effect of the cone tip angle on the cone dynamic resistance also was clearly observed. One challenge of dynamic probing test is the independence of the results from the type of penetration used. In this study, in order to evaluate these changes, the CoV that relates to repeatability was used. Table 5 shows the mean CoV (q_d) of all six penetrometers and the states in which the developed penetrometers (ADP25, ADP60 and ADP90) and the standard ones (DPL, DPM and DCP) differed.

Table 5 indicates that the value of the dynamic cone resistance obtained from the six different penetrometers had a CoV of less than 20%, which indicates that q_d was independent of the type of penetrometer. The calculation of the CoV of q_d has not been done in previous research and a recommended value for it was not available. The recommended value of the CoV of the results of common penetration tests such as SPT was 30% and for the static cone penetration test (CPT) was 15 to 35% [31]. Therefore, the CoV obtained for the dynamic penetration test was considered acceptable.

3. 3. Correlation of ADP25 Penetrometer Results and Soil Engineering Properties

Dynamic penetrometer tests were done using the three new penetrometers and their results were estimated in terms of penetration power in hard and dense soil and the repeatability of results. Based on these results, ADP25 was selected as the penetrometer on which to further explore the abilities of this device. The correlation between the results for ADP25 and the dry unit weight, compaction percentage and peak shear strength of the soil are presented below.

3. 3. 1. Dry Unit Weight (γ_d)

To determine the correlation between the in-situ dry unit weight and ADP25 penetrometer results, the sand cone test was performed at the site of dynamic penetration tests. After measuring the moisture content of the samples, the dry unit weight was obtained. Figure 8 and Table 6 show the diagram and correlations for the dry unit weight.

Figure 9 shows the comparison of dry unit weight versus DPI in the present study with data reported by Chennarapu et al. [5]. As can be seen the trend observed between DPI and dry unit weight in two research is similar. Though the dry density values in this study are lower than those from Chennarapu et al. [5]. The lower DPI values for a given Dry unit weight from the present study when compared to Chennarapu et al. [5] could be due to the different penetrometers and soil type used in the two studies. The specific work per blow (En) parameter of this research penetrometer is equal to 83 (kJ/m^2), while the specific work per blow used penetrometer in Chennarapu et al. [5] is equal to 143 and 112 (kJ/m^2), respectively.

TABLE 5. Mean of CoV (%) for q_d

CoV (%)		
DPL-DPM-DCP	**ADP25-ADP60-ADP90**	**All penetrometers**
17.9	11.93	18.3

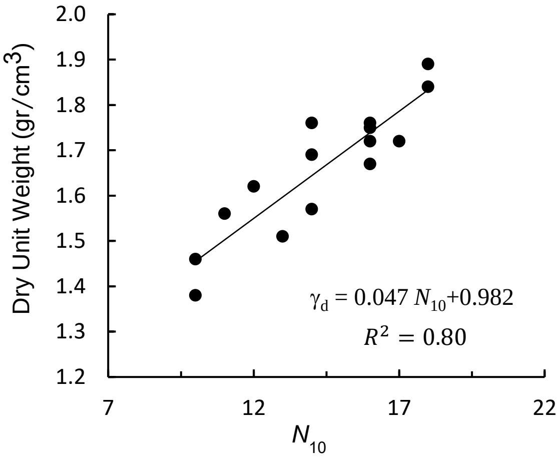

Figure 8. Correlation of γ_d and N$_{10}$

TABLE 6. Correlations of γ_d and dynamic penetration test results

Correlations	R^2
$\gamma_d = -0.084\,DPI + 2.27$	0.79
$\gamma_d = 3.59\,DPI^{-0.396}$	0.80
$\gamma_d = 0.047\,N_{10} + 0.98$	0.80
$\gamma_d = 0.087\,q_d + 0.98$	0.80

γ_d in (gr/cm^3) and q_d in kPa.

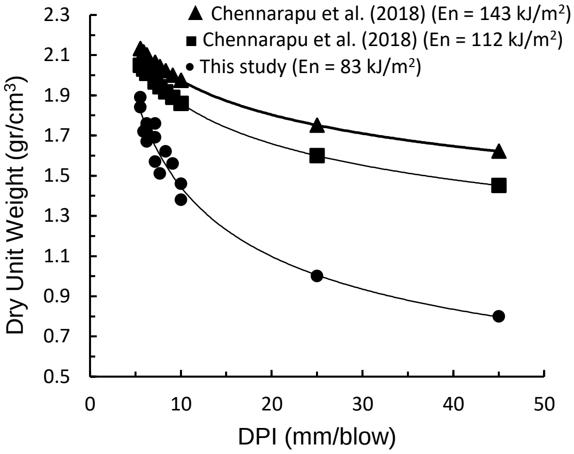

Figure 9. Comparison of Dry unit weight versus DPI in the present study with Chennarapu et al. [5]

The correlation based on the DPI and N_{10} parameters are specific to the used penetrometer in the research, in other words, the values of these parameters will change by changing the penetrometer properties such as hammer weight, fall height and cone diameter. As mentioned earlier, due to the considering of physical and geometric characteristics of penetrometers in dynamic cone resistance equation (Equation (1)), this parameter is not dependent on the type of penetrometers and can use the correlations provided by it, in other penetrometers [21, 31].

Most statistical methods, such as regression, which are used to calculate the correlation between penetrometer results and other soil parameters, will exhibit adequate reliability when the data distribution is normal (or near normal). The standard residual analysis method can be used to evaluate the validity of a linear regression model and derive correlations [32]. In this method, the normality of the data distribution is investigated. Standard residuals are the differences between the actual observation values and those obtained from the correlation. Figure 10 shows the standard residuals versus the calculated γ_d and Figure 11 presents the normal probability plots.

In a standard residual plot, values having a normal distribution show no obvious pattern or unusual structure. If about 95% of these values range from -2 to +2 on the vertical axes, the distribution of the residuals is considered to be normal and the correlation has adequate confidence. In a normal probability plot, when the data

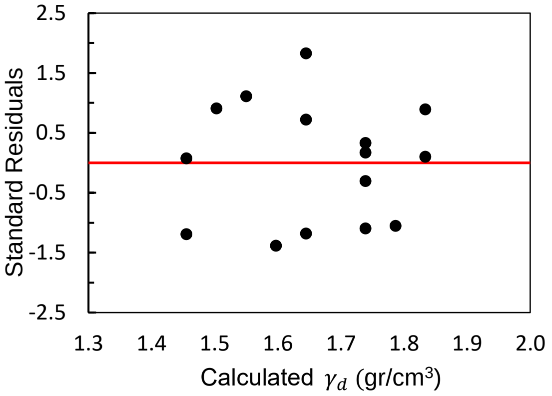

Figure 10. Standard residuals vs. calculated dry unit weight

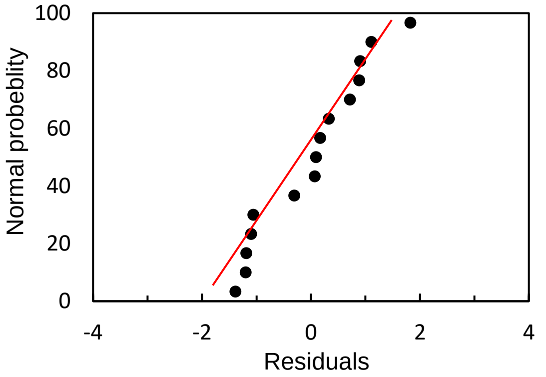

Figure 11. Normal probability of γ_d and N_{10} correlation

distribution is normal, the points will be on a straight line. The proximity of points to the straight line is representative a normal data distribution. The observation points that are some distance from the line indicate the existence of outliers [32, 33]. The results of residual analysis with the appropriate coefficient of determination (R^2) indicate acceptable correlation between the dry unit weight and N_{10}.

3. 3. 2. Compaction Percentage (*R_c*)

The compaction percentage is an important index for assessing the quality of the road subgrade; thus, an easy and fast estimation of this index is desirable. Accordingly, the modified proctor compaction test was performed on the materials from the eight selected locations. Because of the effect of moisture content (ω) on the dry unit weight, this parameter also formed a component of the calculations. Figure 12 and Table 7 show the diagram and correlations of the compaction percentage used to estimate the results of the penetration test. In the horizontal axis of Figure 12, the parameter N_{10}/ω is used (N_{10} divided by ω) because ω is effective in calculating of R_C. The results of the standard residual analysis confirm the accuracy and validity of the correlation.

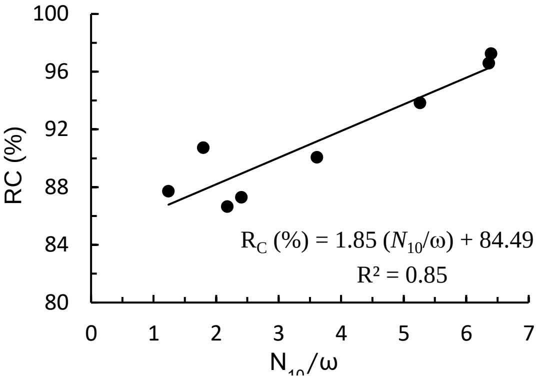

Figure 12. Compaction percentage vs. N_{10}/ω

TABLE 7. Compaction percentage vs. ADP25 device penetration results

Correlations	R^2
$R_C\ (\%)=1.85(N_{10}/\omega)+84.50$	0.85
$R_C\ (\%)=113.43\ (DPI\times\omega)^{-0.063}$	0.73
$R_C\ (\%)=3.39(q_d/\omega)+84.50$	0.85

q_d in kPa.

3. 3. 3. Peak Shear Strength (*τ_f*)

The direct shear test was performed on samples taken from the materials gathered from the eight locations and the soil shear strength was evaluated based on the results of dynamic penetration tests. In the direct shear tests, vertical stresses of 10, 30 and 50 kPa were used and their mean shear strength was applied as the peak shear strength.

Previous studies have estimated the angle of internal friction using the results of the penetration test [4, 7-14, 16-18]. The shear strength of fine-grained soil results from the internal friction angle and cohesion of the soil. The coarse grain fraction and the moisture content of such soil has a direct effect on its shear behaviour; therefore, the internal friction angle, which is only representative of the frictional resistance of the soil, cannot properly correlate with the results of the dynamic penetration test. It is apparent that the correlation between the results of the dynamic penetration test and soil shear strength in which the cohesion resistance also participates is more accurate than the internal friction angle. Figure 13 shows the correlation between the internal friction angle and the penetration index. It can be seen that the coefficient of determination of the proposed correlation was not appropriate. Figures 14 to 16 and Table 8 show the correlations between the peak shear strength and the penetration results.

According to the results of the figures above, it is clear that in fine-grained soils, the correlation between the results of dynamic penetration tests and the peak shear strength of the soil had greater accuracy than the internal friction angle.

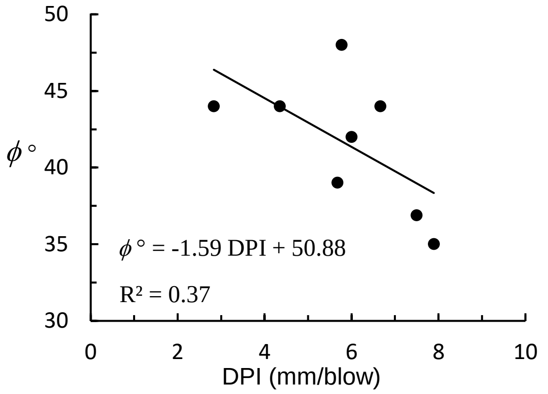

Figure 13. Correlation of internal friction angle and DPI

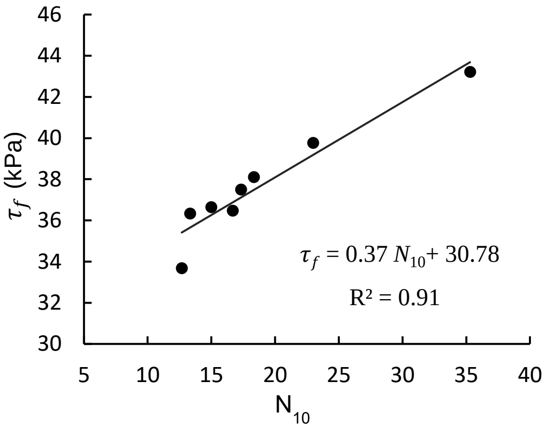

Figure 14. Correlation of peak shear strength and N_{10}

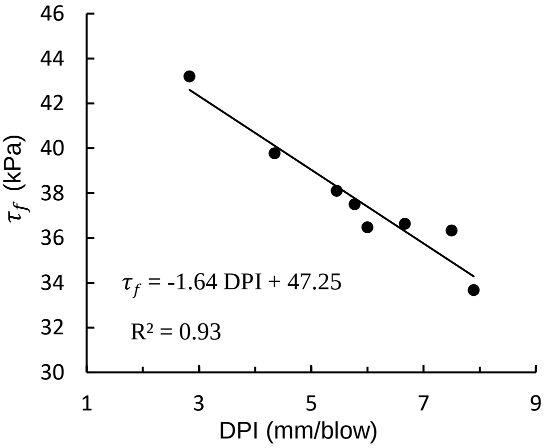

Figure 15. Correlation of peak shear strength and DPI

3. 3. 4. Correlation of Peak Shear Strength (τ_f) and Normalized Cone Dynamic Resistance ($q_{d.n}$)

In this study, the normalized cone dynamic resistance was calculated using Equation (2). Figure 17 shows the correlation between ($q_{d.n}$) and the peak shear strength.

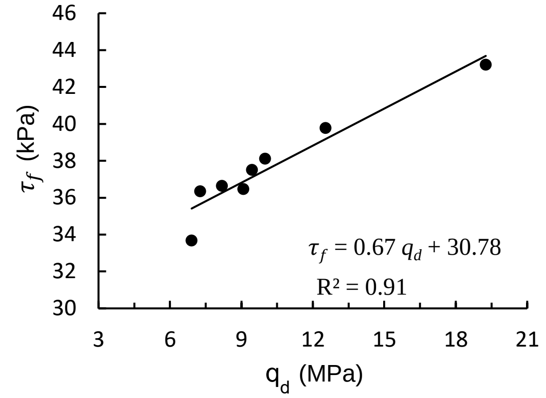

Figure 16. Correlation of peak shear strength and q_d(MPa)

TABLE 8. Correlations of peak shear strength and penetration results of ADP25

Correlations	R²
τ_f (kPa)= $0.37\,N_{10} + 30.78$	0.91
τ_f (kPa) = $-1.64\,DPI + 47.25$	0.93
τ_f (kPa)= $0.67\,q_d$ (Mpa) + 30.78	0.91

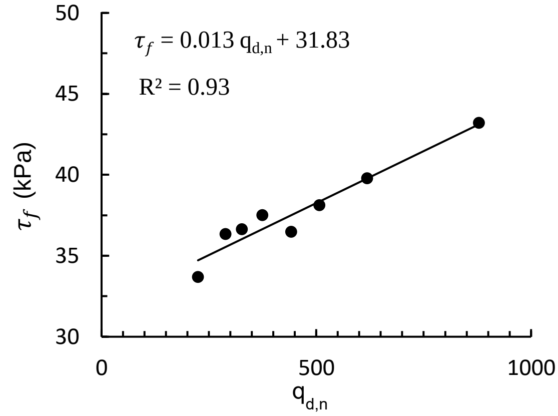

Figure 17. Correlation of peak shear strength and normalized cone dynamic resistance

This figure shows that an acceptable correlation was obtained between these parameters. Since overburden stress and lateral pressure can have a significant effect on the results of dynamic penetration test, using this correlation can get more accurate results. Therefore, this correlation is of higher importance and value than other provided relationships.

4. CONCLUSION

This study investigated the efficacy of light penetrometers for use in hard and dense soil.

consequently, three light dynamic penetrometers with different cone geometries were developed and then were practically evaluated in 12 urban locations with dense and hard sandy fine-grained soil.

To further evaluate the efficiency of these penetrometers, the correlations between their results and the soil characteristics of the dry unit weight in place, compaction percentage and peak shear strength were assessed. Based on the field testing carried out in the present study, the following conclusions are drawn:

1. The penetration numbers (N_{10}) of the three penetrometers (ADP25, ADP60 and ADP90), which differ only in the cone tip angle, were shown to have decreased 50%, 46% and 40%, respectively, compared to those for the DPL penetrometer. According to the method of performing this test, which is usually carry out manually by the operator, reducing the number of blow with the proposed device (ADP25) was very profitable and would increase the accuracy of the test by the operator. Thus, it seems that the ADP25 penetrometer can be used as a suitable alternative for the DPL penetrometer, especially in relatively hard and dense soils.
2. The coefficient of variation (CoV) of the three penetrometers results were calculated 8.56%, 15.86% and 11.39%, respectively, which seems to be appropriate compared to other penetration tests. Based on the results of penetration tests performed in this study, the ADP25 penetrometer showed the best penetrability in hard and dense soil and had the most repeatable results. Thus, this device can be a suitable alternative to the DPL penetrometer. In this way, the ADP25 penetration has a adequate performance in terms of repeatability of the results, and it can be used more reliably in practical soil mechanics studies instead of conventional dynamic penetrometers.
3. The CoV of the cone dynamic resistance (q_d) obtained by performing penetration tests with six different penetrometers at the 12 unit locations was calculated and was shown to be equal to 18.3%. It can be concluded that this parameter was independent of the type of penetrometer used.
4. The correlations between the ADP25 penetrometer results and the dry unit weight, compaction percentage and peak shear strength have been presented. Standard residual analysis was used in addition to the coefficient of determination (R^2) to investigate the accuracy and validity of the proposed correlations. The results of both methods confirmed the acceptability of the presented relationships and were in satisfactory agreement. Also the normalized cone dynamic resistance, which corrects the effect of overburden pressure on penetration test results, was also investigated. The correlation between peak shear strength and this novel and valuable parameter showed high accuracy.

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Persian Abstract

چکیده

آزمایش نفوذسنجی دینامیکی، می تواند به طور موثر در جهت کنترل تراکم خاکریزها و لایه های راهسازی مورد استفاده قرار گیرد، اما یکی از چالش‌های موثر در این امکان استفاده از نفوذسنجهای دینامیکی رده سبک در خاک‌های متراکم و کسب نتایج صحیح از آن می‌باشد. خلاء وجود چنین نفوذسنجهایی در موارد زیادی مشاهده می‌شود. در این پژوهش، با بکارگیری سه نفوذسنج دینامیکی جدید رده سبک با هندسه مخروط متفاوت و مقایسه نتایج آنها با سه نوع نفوذسنج دینامیکی متداول، از طریق انجام بیش از ۷۲ آزمون نفوذسنجی دینامیکی در زمین‌های طبیعی متراکم، به بررسی امکان بهره‌گیری از نفوذسنج‌های رده سبک در خاک‌های متراکم پرداخته شده است. نتایج نفوذسنجی با ابزارهای طراحی شده، کاهش ۵۰ درصدی تعداد ضربات نسبت به نفوذسنج سبک نوع DPL را نشان می‌دهد. همچنین محدوده ضریب تغییرات نتایج ۸/۵۶ تا ۱۵/۸۶ درصدی، بیانگر مطلوبیت تکرارپذیری آنهاست. در نتیجه استفاده از کاوشگرهای مذکور به عنوان جایگزینی برای نفوذسنج‌های سبک متداول می‌تواند مورد توجه قرار گیرد. همچنین به جهت ارزیابی بیشتر کارایی این کاوشگرها، روابط همبستگی میان نتایج آنها و برخی مشخصات مهم خاک مانند وزن مخصوص خشک در محل، درصد تراکم و مقاومت برشی نهایی، ارائه گردیده و به روش آماری آنالیز باقیمانده ها، مورد سنجش و رضایت قرار گرفت.