USE OF A PERTH SAND PENETROMETER (PSP) DEVICE TO DETERMINE THE ENGINEERING PARAMETERS OF SANDS

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Abstract

Determining the in-situ engineering parameters of sandy soils has always been a challenge for geotechnical engineers, resulting in several methods having been developed so far. The Perth Sand Penetrometer (PSP) test is one of the most versatile of these methods. It is a considerably faster and cheaper tool than boring equipment, especially when the depth of the exploration is moderate. In the present research, a methodology for the use of a PSP device to evaluate the engineering parameters of sandy soils in laboratory conditions is discussed and the repeatability of the test results is studied. First of all, the tests were performed on typical Tehran young alluvial deposits (poorly graded sandy soil, SP) consistently prepared to 5 densities using the sand raining or pluviation technique. Next, the normal and logNormal distributions of the test data using the Kolmogorov-Smirnov normality test were examined. After that, based on the obtained results, the relationship types between the dynamic point resistance index (q_d) and other parameters, such as the relative density (Dr), the modulus of elasticity (E), the shear modulus (G) and the friction angle of the soil, were determined. The results show that the obtained relationships were semi-logarithmic and logarithmic, and most of the obtained experimental formulas had a high coefficient of determination (>90%). To evaluate the accuracy of the results, 95% confidence and prediction bands were also used and the results show that all the obtained experimental relationships were appropriate. Finally, the repeatability of the test results was evaluated by calculating the coefficient of variations, which was less than 30% for all the tests.

1 INTRODUCTION

The engineering parameters of sandy soil at an earthwork, such as a foundation design on sandy soils, are commonly assessed using penetrometer testing. The most commonly employed dynamic method is the Standard Penetrometer Test (SPT), which involves the driving of a split-spoon sampler using a 63.5 kg drop weight [1]. While such devices are useful tools for larger-scale site investigations, their applicability for large-scale projects is limited by the scale of the apparatus and its relative insensitivity for shallow depths. Dynamic probing is a continuous soil investigation technique and is assumed to be one of the simplest soil penetration tests. It basically consists of repeatedly driving a metaltipped probe into the ground using a drop weight with a fixed mass and travel. Testing is carried out continuously from ground level to the final penetration depth. The continuous sounding profiles enable the easy recognition of

Table 1. Some of the dynamic probing devices and their specifications.

Penetrometer specifications	Mackintosh	Dynamic Cone Penetrometer (DCP)	Perth Sand Penetrometer (PSP)	Dynamic Probing Light (DPL)	Dynamic Probing Medium (DPM)	Dynamic Probing High (DPH)	Dynamic Probing Super High (DPSH)
Hammer weight (kg)	4.5	8	9	10	30	50	63.5
Fall height (m)	0.3	0.575	0.6	0.5	0.5	0.5	0.75
Cone diameter (mm)	27.94	20	-	35.7	35.7	43.7	50.5
Area at the base of cone (cm^2)	6.13	3.15	-	10	10	15	20
Diameter of rod (mm)	12.7	16	16	22	32	32	32
Tip angle (deg)	30	60	-	60	60	60	60
Standard range for number of blows	3-50 (for 10cm of penetration)	<20 (for 5cm of penetration)	<20 (for 5cm of penetration)	3-50 (for 10cm of penetration)	3-50 (for 10cm of penetration)	3-50 (for 10cm of penetration)	5-100 (for 20cm of penetration)
References	[5]	[7]	[2]	[2]	[11]	[11]	[11]

dissimilar layers and even thin strata using the observed variation in the penetration resistance.

There are many dynamic probe devices in the world, such as Dynamic Cone Penetrometer (DCP), Mackintosh probe, Dynamic Probing Light (DPL), Dynamic Probing Medium (DPM), Dynamic Probing High (DPH), Dynamic Probing Super High (DPSH), Perth Sand Penetrometer (PSP), etc. Table 1 shows some of the dynamic probing devices and their specifications.

The Perth Sand Penetrometer (PSP) is a lightweight dynamic penetrometer, a tool that is considerably faster and cheaper than boring, particularly when the depth of exploration is low and the soils being investigated are not coarse gravel [2, 3].

Most of the larger cities in parts of the world such as in Southern Australia, Northern Iran and Central UAE are situated on the coast or desert and many have extensive coastal deposits of clean, aeolian and alluvial sands. In earthwork projects like the construction of roads, dwellings and lightweight commercial and industrial structures, a determination of the engineering parameters of sandy deposits is important.

The Perth Sand Penetrometer is described in detail in Australian Standard AS1289.F3.2 [4]. Since then, it has been used for the site characterization of pavement layers and foundations in other countries such as Iran [2]. There are some correlations between the dynamic probing devices (except PSP) and the engineering parameters of different soils [e.g. 5, 6, 7, 8], thus the main objectives of this paper are to describe the capability of the PSP to study the engineering parameters of sandy soils.

2. THE PERTH SAND PENETROMETER (PSP)

The Perth Sand Penetrometer is described in detail in Australian Standard AS1289.F3.3 [4]. The physical arrangement of the PSP is summarized in this part, and illustrated in Fig. 1. It consists of a 9kg sliding weight that delivers a measured quantity of energy by falling through a height of 600mm onto an anvil block. This energy is used to push a 16mm blunt ended steel rod into the ground. The steel rod is usually scribed at increments of 50mm and the results are expressed as the number of blows required to drive the rod through a distance of 150mm. The total mass of the device is less than 20 kg, making it relatively portable. Mohammadi et al. [9] explained that the results of dynamic penetrometer tests with a flat tip (e.g., the PSP) are more repeatable and accurate compared to other penetrometers such as the DCP. Thus, it is better to use the PSP device instead of other dynamic penetrometers. Raising and releasing of the weight is achieved by hand, with a certain amount of care required to ensure that

- The weight is lifted through the full 600mm height,
- There is negligible impact on the upper stop at the top of the lift, and
- The weight is released cleanly and allowed to fall without interference.

The sounding rods are configured so that once driven, the hammer can be removed and additional rods added to enable the testing to continue to depths of several meters. In the author's experience, the maximum practical depths are of the order of 5 or 6 m in exceptionally loose conditions. Beyond these depths, difficulties in the

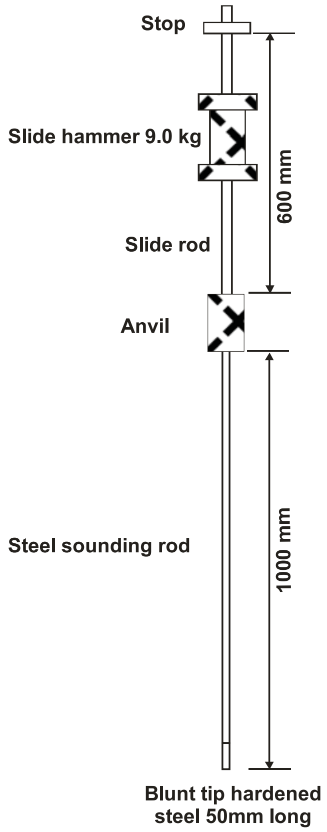

Figure 1. Perth Sand Penetrometer [4].

retrieval of the rods and the risk of lost rods through damage become too great.

The main advantages of the PSP include:

(1) Speed of operation;
(2) Use in difficult terrain where access is poor;
(3) The requirement for minimal equipment and personnel;
(4) Low cost of the equipment;
(5) Simplicity of operation and data recording/analysis;
(6) Use in the interpolation of soil strata and properties between trial pits and boreholes;
(7) Reduction in the number of boreholes required.

3 PROBABILISTIC AND STATISTICAL METHODS

The application of probabilistic and statistical methods in geotechnical engineering has increased remarkably in recent years. In this paper, some probabilistic and statistical methods were used to evaluate the laboratory test results obtained from laboratory tests on studied river sandy soil. One of the methods used is the assessment of the distribution properties of the data. The Normal probability density function (pdf) is an appropriate model to assess the data distribution. The function of the Normal distribution is [10]:

$$f_x(x|\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2\right\} \quad (1)$$

in which μ is the mean and σ^2 the variance. The pdf is symmetrical about a mode at μ, and falls off quickly as x deviates from the mean. The Normal pdf is usually tabulated or calculated numerically using its Standard Normal form, with a mean of zero and a variance of one, N (0,1).

Sometimes probability distributions are chosen simply because they appear to fit the observed data. This rationale has nothing to do with physical law. This is often the case in fitting probability distributions to, say, soil data. One observes that when the frequencies of undrained strength measurements are plotted against the strength value they might exhibit a bell-shaped form characteristic of the Normal pdf, and thus a Normal distribution model is used to approximate them [10].

Various statistical methods can be used to test whether the match between the empirical data frequencies and the theoretical pdf model is close enough to assume that the differences between the observed and the modelled could simply be due to sampling variability [10]. The most common of these tests are the Chi-square goodness of fit and the Kolmogorov-Smirnov maximum deviation test. In many cases, however, the easiest way to assess the quality of the fit of a theoretical distribution to an observed distribution is to plot the observed distribution against the theoretical distribution.

A probability grid is a specialized graph paper with horizontal and vertical scales designed such that the cumulative frequencies of a particular form of pdf (e.g., a Normal distribution) plot as straight lines. Thus, empirical data can be plotted on a probability grid and a visual determination made as to whether they are well approximated. The effect of the Normal probability grid can be achieved by using cumulative frequencies as arguments to an inverse standard Normal cumulative distribution function.

Another graphical tool for comparing data with analytical distributions is the quantile-quantile (Q-Q) graph. A Q-Q graph shows the observed quantile of the data plotted against the theoretical quantile of the best fitting distribution. If the frequency distribution of the sample data is reasonably approximated, the empirical and analytical quantile should be approximately the same, and the data pairs should lie on a 45-degree line [11].

An assessment of the regression line confidence can be checked using confidence and prediction bands. To achieve that, 99% and 95% confidence bands are useful in geotechnical engineering.

Finally, the correlation coefficient R^2 between two types of data, such as soil parameters, is determined by [10]:

$$R^2 = \left(\frac{\sum(x-\overline{x})(y-\overline{y})}{\sqrt{\left[\sum(x-\overline{x})^2\sum(y-\overline{y})^2\right]}}\right)^2 \qquad (2)$$

Where:

x: the value of the obtained data
y: the value of the measured data

4 MATERIALS AND METHODS

In order to achieve the main objectives of this paper it was necessary to select a suitable sample. First of all, the appropriate sampling area was selected and the sampling was done. Then, the selected sample was prepared in the laboratory.

4.1 Sampling area

The materials used in this research included typical Tehran young alluvial deposits (a poorly graded sandy soil) taken from the west of Tehran. Geologically, the Tehran young deposits comprise subrounded sand grains with 5% gravel. The X-ray analysis results show that it is comprised of quartz, feldspar, pyroxene and calcite.

4.2 Sample preparation

The data used in this paper was obtained from laboratory tests undertaken by the author at the Geotechnical Engineering Laboratory of Bu-Ali Sina University, Hamedan, Iran.

To prepare the soil sample for testing, alluvial deposits were oven dried and passed through sieve No. 4. Fig. 2 shows the gradation curves of the original soil and the sample after passing sieve No. 4, which is classified as poorly graded sand (SP) according to the Unified Soil Classification System. The index properties of the soil are shown in Table 2.

Table 2. The index properties of used soil.

Parameter	value
e_{max} (-)	0.97
e_{min} (-)	0.46
Gs (-)	2.66
γ_d *(max)* (KN/m^3)	17.85
γ_d *(min)* (KN/m^3)	13.24
Cu (-)	1.16
Cc (-)	1
value of clay (%)	0
value of silt (%)	2
USCS soil classification	SP

To achieve a uniform sample, the sample in the testing mould was remoulded using a sand pluviation set that was designed and constructed at Bu-Ali Sina University. It has a height and diameter, both of 1m. The experimental arrangement used to generate a suitable sample for this study is schematically shown in Fig. 3. The sand was rained from the hopper, through holes ranging in size from 6mm to 15mm diameter, at a spacing (*S*) ranging from 20 to 100mm, with the holes arranged in a triangular pattern.

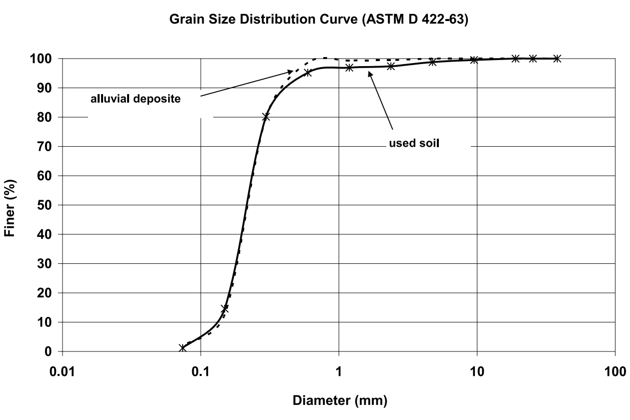

Figure 2. Gradation curves of alluvial deposit and used soil.

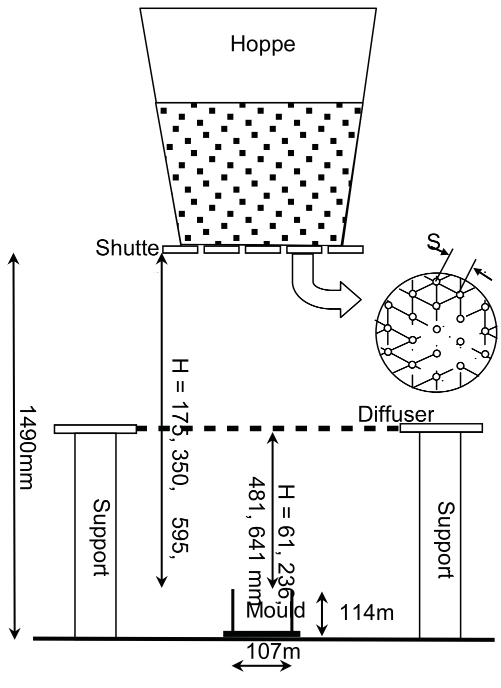

Figure 3. Experimental arrangement used in this study.

Table 3. The index properties of used soil.

Dr(%)*	Mean of Water content (%)	Dry unit weight (gr/cm^3)
25	0.04	1.44
35	0.04	1.48
50	0.04	1.55
60	0.04	1.60
75	0.04	1.67

* Relative density

In all cases, a single diffuser screen with an aperture size of 2.36mm was employed (except where the pluviation rate was so great that sand accumulated on the screen, at which point, the diffuser was removed). The fall heights (free fall distance travelled by the sand from the diffuser to the top of mould) considered were 61mm, 236mm, 481mm, and 641mm. A 1 liter mould (107mm in diameter and 114mm in height) was used to catch the sand for the density control. Details of the tests on samples having different densities are indicated in Table 3.

To prepare the soil sample for the direct shear test, a circular shear box with 60 mm diameter and 25 mm height was used. To achieve a uniform compaction in the circular shear mould of the direct shear machine, tamping by a small circular steel plate with a 60 mm diameter was used. All the direct shear tests were also carried out in dry conditions.

4.3 Testing procedures

Several tests including the Perth Sand Pentrometer (PSP) test, the Plate Load (PLT) and direct shear tests were undertaken on the compacted materials as described in the following sections.

4.3.1 The Perth Sand Pentrometer tests and its repeatability

As previously mentioned, the PSP tests were used to determine the engineering parameters of sandy soil in laboratory conditions. To achieve some relation between the PSP results and the engineering parameters of sandy soils, several tests according to the ASTM standard were undertaken. Table 4 shows the program of laboratory tests.

The result of the PSP tests is shown by the q_d index, where q_d is the dynamic point resistance (Pa), which is determined using [12]:

$$q_d = \frac{W}{W + W'} \cdot r_d \qquad (3)$$

Where:

q_d is the unit point resistance value (Pa)
W is the mass of the hammer (kg)
h is the height (m)

Table 4. Testing program for laboratory investigations.

Dr (%) of sand samples	PSP (number of tests)	PLT* (number of tests)	Direct shear (number of tests)
25	3	3	7
35	3	3	7
50	3	3	7
60	3	3	7
75	3	3	7
Total -	15	15	35

* Plate Load Test

g is the acceleration due to gravity (m/sec2)
A is the area at the base of the cone (m2)
e is the average penetration per blow
W' is the total mass of the extension rods, the anvil and the guiding rods (kg)

Fig. 4 shows the q_d index values obtained from the laboratory PSP tests that were undertaken on sandy soil at the testing mould.

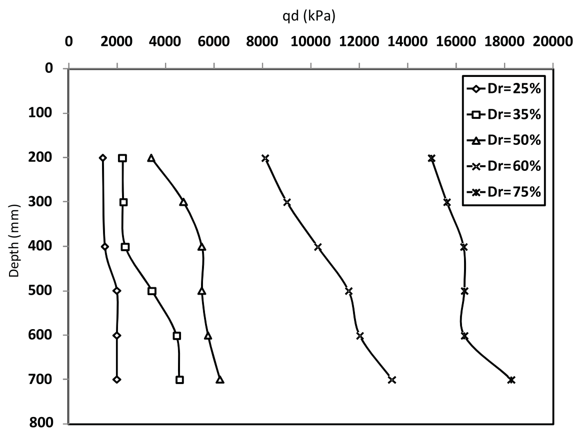

Figure 4. Average of q_d index versus depth for studied soil at the testing mould.

The repeatability of the PSP test results is an important consideration. To evaluate the repeatability, several tests were carried out. Each testing series included three PSP tests on studied soil with different relative densities (Loose, Medium and Dense). In order to study the repeatability of the results, it was important to choose a suitable parameter that represented the repeatability. The use of the standard deviation value, *s*, was not appropriate for this purpose because it is large for large values of NPSP [5]. However, the coefficient of variation (*COV*) can be considered as an indicative parameter because it represents a Normalized standard deviation. The *COV* parameter is calculated using Eq. (4):

$$COV = s / \overline{X} \qquad (4)$$

Where:

$\overline{X}$: the average of NPSP at each depth
s : the standard deviation of NPSP at each depth

Table 5 shows the coefficient of variation (*COV*) for the results obtained from some of the dynamic probe devices reported by various researchers.

Table 5. Coefficient of variation for results obtained from some dynamic probe devices.

Dynamic probe devices	Range of *COV* (%)	Mean of *COV* (%)	References
Standard penetration test (SPT)	27–85	30	[12]
Dynamic Cone Penetrometer (DCP)	3-58	17	[7]
Mackintosh probe	0-39	11	[5]
Dynamic Probing Light (DPL)	0-23	8	[11]
Dynamic Probing Medium (DPM)	0-17	5	[11]
Dynamic Probing High (DPH)	0-55	16	[11]
Dynamic Probing Super High (DPSH)	0-44	13	[11]

The sources of variability in soil properties differ, and accordingly the coefficients of variation differ for different dynamic devices [5]. It can be seen that the variation of the *COV* for the results of the Standard Penetration Test (N), which is basically a super heavy dynamic probe test, is higher than the other dynamic devices that are reported to be between 27% and 85% with a mean value of 30% [13]. The repeatability of the SPT test results could be used as a measure of the repeatability of the PSP results by comparing the *COV* values of the two methods. In the present research, the values of the *COV* have been determined for each depth in each series of tests.

The average value of the *COV* was about 5.60% and its standard deviation was 9.51. In more than 68.7% of the tests, the value of the *COV* was 0%, and in 12.5% of the tests, this value was 20.28%. In the tests undertaken, the values of the *COV* varied between 0 and 28.3%, and for all cases it was less than 30%. Therefore, the results of the PSP tests for the three relative densities (Loose, Medium and Dense) can be considered as repeatable when compared with the values presented in Table 5.

4.3.2 Plate Load Test (PLT)

The Plate Load Test (PLT) is a useful site investigation tool and has been used for the proof testing of pavement layers in a lot of European countries for many years. Currently, it is used for the evaluation of both rigid and flexible pavements [14]. The PLT, at full or reduced scale, is sometimes considered as the best means of determining the deformation characteristics of soils, but it is only used in exceptional cases because of the costs involved [15]. In the present research, a round plate of 230mm diameter was used. The PLT was used as a reference test to obtain the strength parameters of the soil under investigation. A loading frame was designed to fit the mould and its support. To perform the test, the bearing plate and hydraulic jack were carefully placed at the centre of the samples under the loading frame (Fig. 5). The hydraulic jack and the supporting frame were able to apply 60 tons load. For the measurement of deformations, dial gauges that are capable of recording a maximum deformation of 25.4 mm (1 in.) with an accuracy of 0.001 in. were employed. The ASTM-D1195 [16] standard method was followed to perform the test.

The elastic modulus is always considered as a more important deformeability parameter for a geomaterial. As in the case for other stress-strain tests, different elastic moduli can be obtained from the PLT. The soil elastic moduli can be defined as: (1) the initial tangent modulus; (2) the tangent modulus at a given stress level; (3) reloading and unloading modulus and; (4) the secant modulus at a given stress level [14]. In this study, since the stress--strain curves had a clear peak point, the initial tangent modulus was determined for all the plate load tests. To determine the initial modulus ($E_{PLT(i)}$), a line was drawn at a tangent to the initial segment of the stress-strain curve, then an arbitrary point was chosen on the line and the stress and deflection corresponding to this point

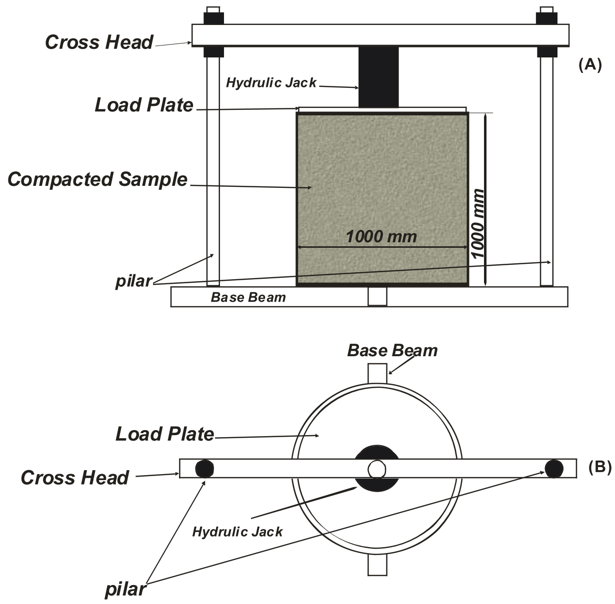

Figure 5. A schematic diagram of the Plate Load Test (PLT) set up (A) side view (B) plan view.

were determined for a calculation of the initial modulus. Fig. 6 describes the deformations and stresses used for determining $E_{PLT(i)}$. A reloading stiffness modulus called $E_{PLT(R2)}$ was also determined for each stress-strain curve.

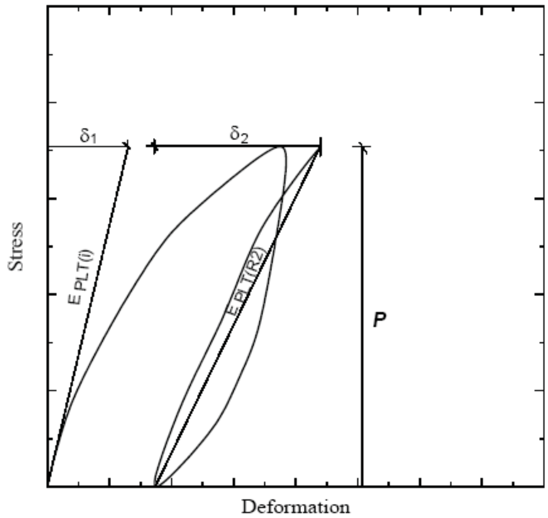

Figure 6. Definition of the modulus from PLT results [13].

The second parameter that can be calculated from the PLT results is the shear modulus (G). The shear modulus is defined as the ratio of the shear stress to the shear strain [15] and is calculated using Eq. (5) [17]:

$$G_{PLT} = \frac{qD}{\rho}\frac{\pi}{8}(1-\nu) \qquad (5)$$

where:

q : bearing pressure
D : diameter of the loading plate
ρ : settlement
ν : Poisson's ratio

4.3.3 Direct shear test

In order to determine the soil friction angle, 35 direct shear tests (Table 4) were undertaken in a circular shear mould with a diameter of 60mm. Due to the nature of the soil samples (non-cohesive), the cohesion parameter (C) was equal to zero and thus, the friction angles were calculated. The ASTM-D 3080-98 [18] standard method was followed to perform the test.

5 RESULTS AND DISCUSSIONS

As mentioned previously, one of objectives of the present research was to obtain the correlations between the q_d index and some engineering parameters of sandy soils. In the following sections, the results of the tests and their correlations with important engineering parameters of the studied soil are discussed.

5.1 q_d index of studied soil

To determine the q_d index, Eq. (3) was used. The values of q_d were changed between 1400 kPa and 18270 kPa for the studied sandy soil. Fig. 7a shows the distribution of Plate Load Test on a logNormal chart. Also, the Kolmogorov-Smirnov Normality test is shown (fig. 7b). The q_d index falls nearly along a line in this plot and the P-Value is more than 0.05, from which one would infer that they are well modelled as a logNormal distribution.

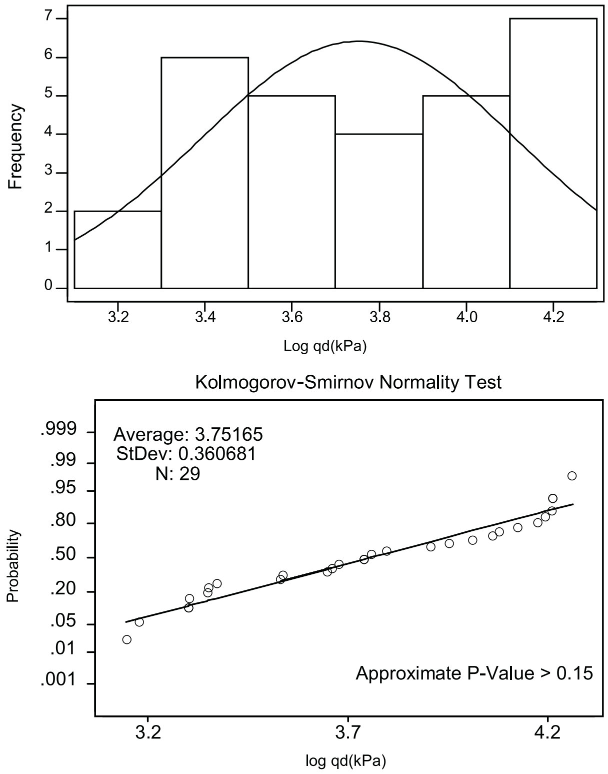

Figure 7. LogNormal distribution of the q_d index shown by (a) histogram of data and (b) the Kolmogorov-Smirnov Normal test.

5.2 q_d versus Dr(%)

The relative density (Dr) is a useful parameter to describe the consistency of sands [19]. To obtain the correlation between the average q_d and Dr, first of all, a statistical distribution of Dr values was investigated. Figs. 8a and 8b show the Normal histogram curve and the Normal probability plot of a Kolmogorov-Smirnov test for relative density, respectively. As shown, the distribution of the Dr values of the studied soil is Normal.

After that, the correlation between the average q_d and Dr was investigated. Because the distribution of Dr is Normal and the distribution of q_d is logNormal, thus the equation for Dr-q_d will be Semi-Logarithmic. Eq. (6) and fig. 9 suggest a good correlation between these two parameters. The determination coefficient (R^2) of Eq. (6) is 0.98.

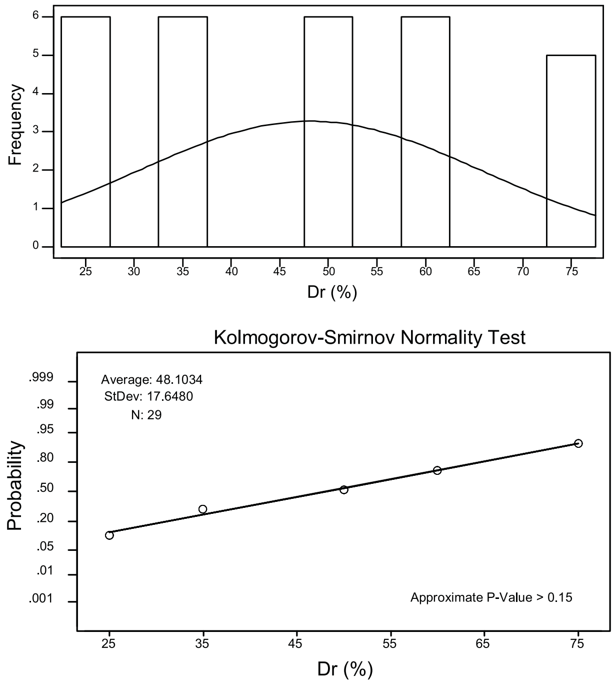

Figure 8. Normal distribution of the *Dr* shown by (a) histogram of data and (b) the Kolmogorov-Smirnov Normal test.

Also, fig. 9 shows the 95% confidence and prediction bands of the line regression. As can be seen, all the data is limited to the prediction band area.

$$Dr(\%) = -181.18 + 406.38(Logq_d) \quad (R^2=0.96) \qquad (6)$$

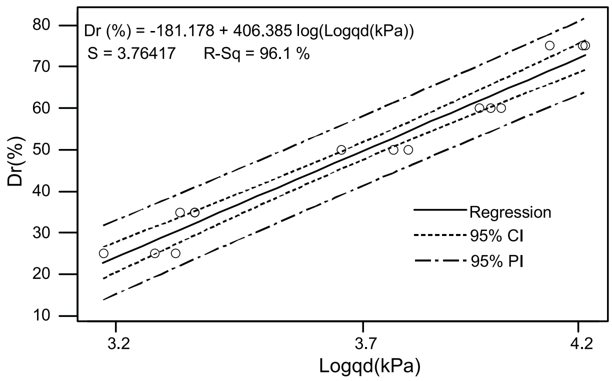

Figure 9. Correlation between q_d index and $Dr(\%)$.

5.3 q_d versus modulus of elasticity (E)

As mentioned previously, the modulus of elasticity (E) is a useful parameter in earthworks. To evaluate the Normality of the modulus of elasticity, all the data obtained from the PLTs such as $E_{PLT(i)}$ and $E_{PLT(R2)}$ were tested using the Normal histogram curve and the Normal probability plot of the Kolmogorov-Smirnov test (figs. 10 and12). The results show that $E_{PLT(i)}$ and

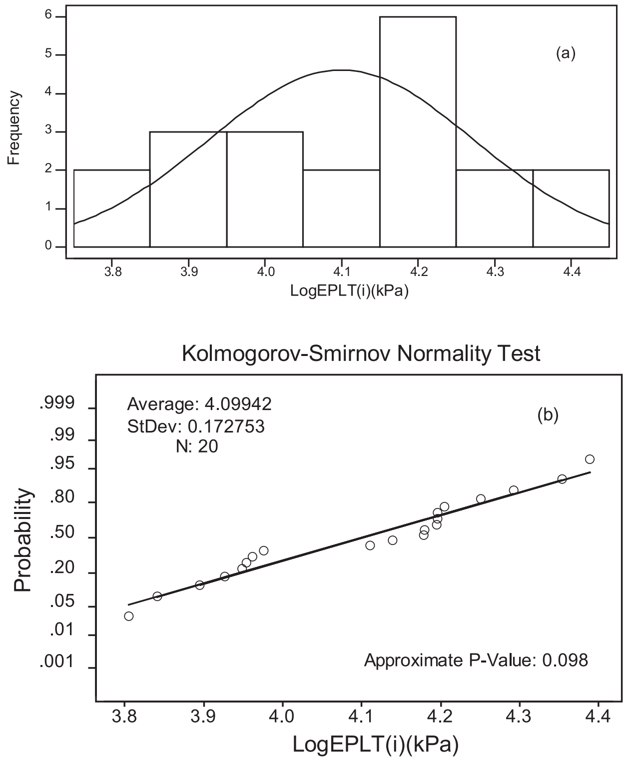

Figure 10. logNormal distribution of the $E_{PLT(i)}$ shown by (a) histogram of data and (b) the Kolmogorov-Smirnov Normal test.

$E_{PLT(R2)}$ are according to the logNormal and Normal functions, respectively. For the data obtained in this study, the best correlations between the average q_d, $E_{PLT(i)}$ and $E_{PLT(R2)}$ are presented in fig. 11 and 13 (Eqs. 7 and 8). However, there is a better correlation (Eq.8) between the average q_d index and the PLT reloading modulus ($E_{PLT(R2)}$) compared to the correlation with $E_{PLT(i)}$. Also, all the data and the regression lines are limited at the 95% confidence and prediction limits, respectively.

$$LogE_{PLT(i)}(kPa) = 2.50 + 0.43Logq_d \quad (R^2=0.90) \qquad (7)$$

$$E_{PLT(R2)}(kPa) = -33870.5 + 11407.1Logq_d \quad (R^2=0.96) \quad (8)$$

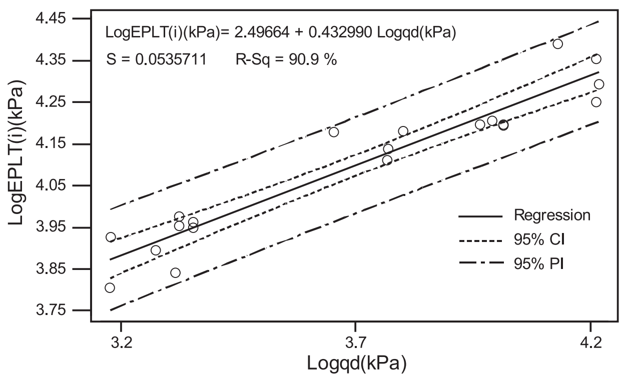

Figure 11. Correlation between q_d and $E_{PLT(i)}$.

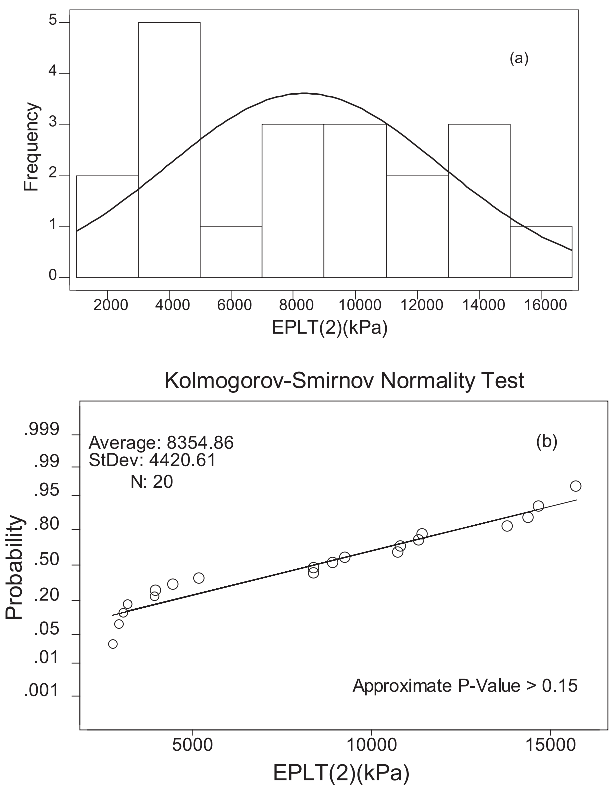

Figure 12. Normal distribution of the $E_{PLT(R2)}$ shown by (a) histogram of data and (b) the Kolmogorov-Smirnov Normal test.

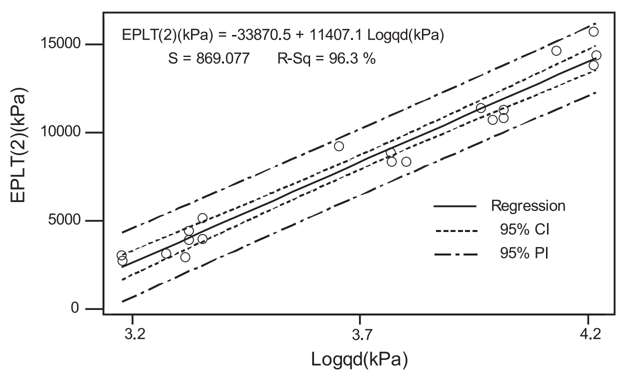

Figure 13. Correlation between q_d index and $E_{PLT(R2)}$.

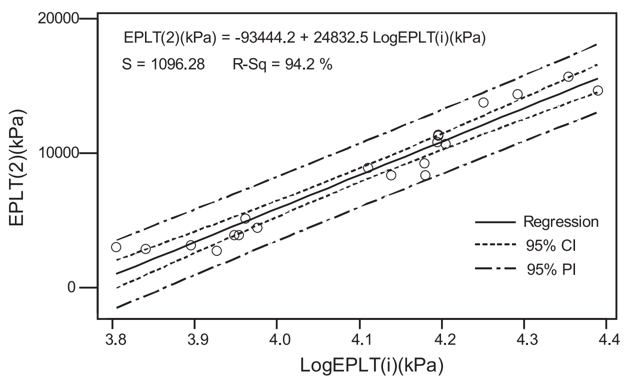

Figure 14. Correlation between $E_{PLT(i)}$ and $E_{PLT(R2)}$.

Fig. 14 and Eq. (9) show the correlation between $E_{PLT(i)}$ and $E_{PLT(R2)}$, which has a linear trend.

$$E_{PLT(R_2)}(kPa) = -93444.2 + 24832.5 Log E_{PLT(i)}(kPa) \quad (R^2=0.94) \qquad (9)$$

5.4 q_d versus shear modulus (G)

Several methods are available to evaluate the shear modulus of coarse-grained and fine grained soils, such as geophysical methods, the Plate Load Test (PLT), etc., which are all costly. In this research, the PLT shear modulus (G_{PLT}) of the studied sandy soil was determined. Like the sandy soils' modulus of elasticity ($E_{PLT(i)}$) obtained in the present research, the G_{PLT} values were according to the logNormal function (figs 15a and 15b). Several correlations between the average q_d versus G_{PLT} were investigated. The best correlation between the average q_d and (G_{PLT}) is presented in fig. 16 and Eq (10). All the data and regression lines are located at the 95% confidence and prediction limits, respectively. The results show that the shear modulus increases with an increase in the values of q_d. This correlation is linear with a determination coefficient of 0.92.

$$Log G_{PLT}(kPa) = 0.39 + 0.897 Log q_d \quad (R^2=0.92) \qquad (10)$$

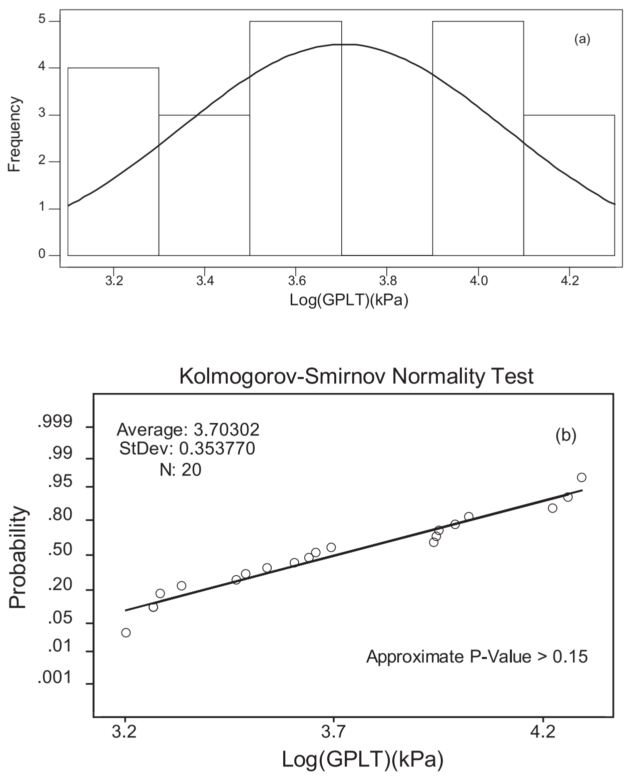

Figure 15. logNormal distribution of the G_{PLT} shown by (a) histogram of data and (b) the Kolmogorov-Smirnov Normal test.

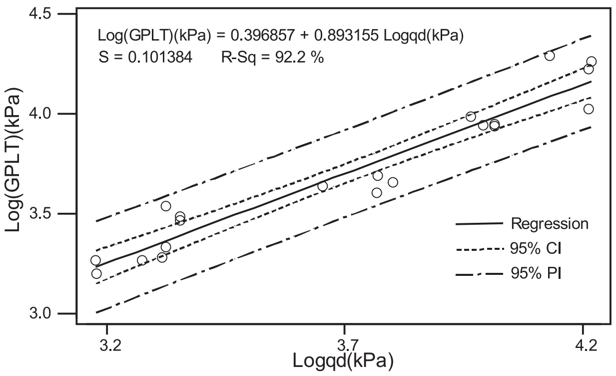

Figure 16. Correlation between q_d index and G_{PLT}.

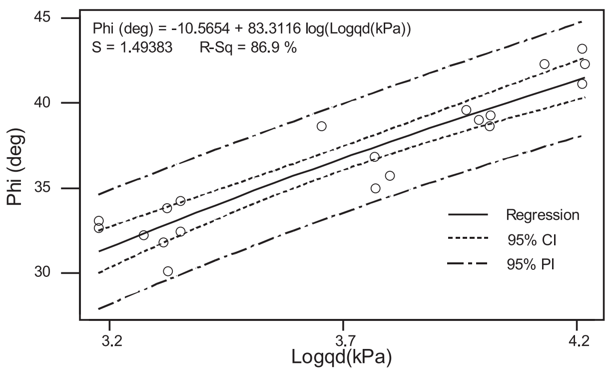

Figure 18. Correlation between q_d index and friction angle (ϕ).

5.5 q_d versus friction angle

The friction angle (ϕ) of sandy soils is an important engineering parameter for the design of the earth structure in earthworks. To assess the Normality of the effective friction angles (ϕ) obtained in the present research, the Normal histogram curve and the Normal probability plot of a Kolmogorov-Smirnov test were used (figs. 17a and17b). The results show that the effective friction angle (ϕ) is according to the Normal function.

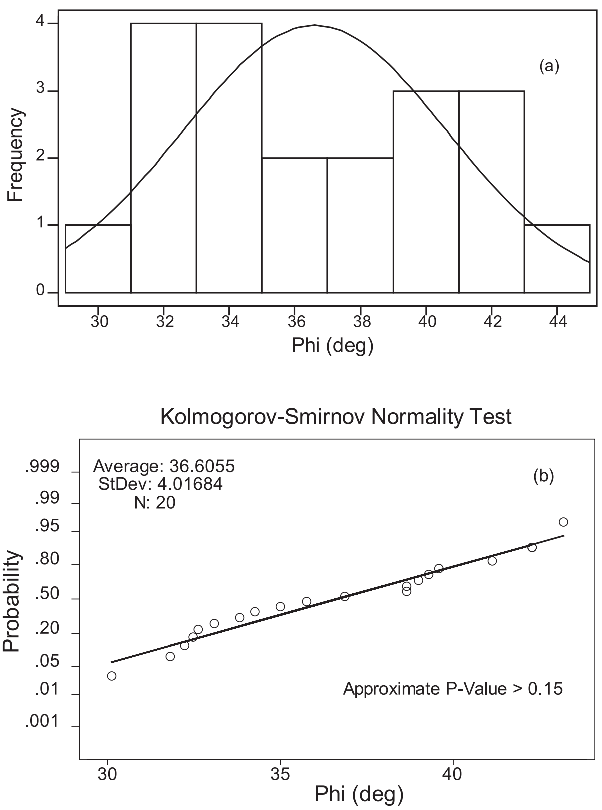

Figure 17. Normal distribution of the friction angle (ϕ) shown by (a) histogram of data and (b) the Kolmogorov-Smirnov Normal test.

The correlation between the average q_d and effective friction angle (ϕ) is presented in Fig. 18 and Eq. (11):

$$Phi(Deg) = -10.56 + 83.31 Log(Log q_d) \quad (R^2{=}0.87) \qquad (11)$$

6 SUMMARY AND CONCLUSIONS

The PSP is a lightweight device that can be conveniently used for soil investigations in shallow depths. The results of PSP testing can be used to assess rapidly the variability of soil conditions, allowing different layers to be identified. Based on the results of the present research, correlations can be established between the q_d index and the engineering parameters of sandy soils. A statistical approach was applied to find the best correlations of the results with a high coefficient of determination (R^2). For the results obtained, the determination coefficients (R^2) between q_d and the engineering parameters were mostly greater than 0.90. The statistical methods indicated that the distribution of the data obtained from the PSP was according to logNormal function and the obtained experimental formulas were located in semi-logarithmic and logarithmic classes. Also, all the data and regression lines were located at the 95% confidence and prediction bands, respectively. Table 6 shows the summary of the equations obtained in this study. To control the repeatability of the results of the PSP tests, the values of the coefficient of variation (*COV*) were calculated. This coefficient varied between 0 and 28.3%. Therefore, it can be concluded that the results of the PSP tests for five relative densities (*Dr*) can be considered as repeatable when compared with the values presented by Lee [13].

REFERENCES

[1] Palmer, D.J., Stewart, J.G. 1957. Some observations on the Standard Penetration Test and a correlation of the Test with a new Penetrometer. Proc. 4th Int.

Table 6. Summary of developed equations in this paper.

Parameters	Correlation Type	Equations	Determination Coefficient (R^2)
Dr - q_d	Semi-Logarithmic	$Dr(\%) = -181.18 + 406.38(Logq_d)$	0.96
EPLT(i) - q_d	Logarithmic	$LogE_{PLT(i)}(kPa) = 2.50 + 0.43Logq_d$	0.90
EPLT(R2) - q_d	Semi-Logarithmic	$E_{PLT(R2)}(kPa) = -338705 + 114071Logq_d$	0.96
EPLT(i)-EPLT(R2)	Semi-Logarithmic	$E_{PLT(R_2)}(kPa) = -934442 + 248325LogE_{PLT(I)}(kPa)$	0.94
GPLT - q_d	Logarithmic	$LogG_{PLT}(kPa) = 0.39 + 0.897Logq_d$	0.92
ϕ' - q_d	Semi-Logarithmic	$Phi(Deg) = -10.56 + 83.31Log(Logq_d)$	0.87

Conf. on Soil Mechanics and Foundation Engineering, London, 1, 231–236.

[2] Mohammadi, S.D., Fityus, S.G., Bates, L. 2012. Calibration of the Perth Sand Penetrometer (PSP) for Silica Sands. Iranian journal of Sciences and Technology, Transaction Civil Engineering, 36,13-23.

[3] Sawangsuriya, A., Edil, T.B. 2005. Evaluating stiffness and strength of pavement materials. Geotechnical Engineering, 157, 217-230.

[4] AS1289.F3.3. 1984. Determination of the penetration resistance of a soil with a Perth Sand Penetrometer. Standards Association of Australia.

[5] Fakher, A., Khodaparast, M., Jones, CJFP. 2006. The use of the Mackintosh Probe for site investigation in soft soils. Quarterly Journal Engineering Geology and Hydrology 39, 189–196.

[6] Lee, C., Kim, K.S., Woo, W., Lee, W. 2014. Soil Stiffness Gauge (SSG) and Dynamic Cone Penetrometer (DCP) tests for estimating engineering properties of weathered sandy soils in Korea. Engineering Geology 169, 91–99.

[7] Mohammadi, S.D., Nikudel, M.R., Rahimi, H., Khamehchiyan, M. 2008. Application of the Dynamic Cone Penetrometer (DCP) for determination of the engineering parameters of sandy soils. Engineering Geology 101, 195–203.

[8] Mohammadi, S.D., Nikudel, M.R., Rahimi, H., Khamehchiyan, M. 2012. Unit Skin Friction from the Extended Dynamic Cone Penetrometer (EDCP) Test Supplemented by Measurement of Torque within testing wells. Iranian Journal of Sciences and Technology Transaction Civil Engineering 36, 115-119.

[9] Mohammadi, S.D., Nikudel, M.R., Rahimi, H. 2009. Assesment of the effect of DCP tip angle on its results repeatability. Journal of Iranian Association of Engineering Geology 1, 2, 31-41 (in Persian).

[10] Baecher, B.G., Christian, J.T. 2003. Reliability and statistics in geotechnical engineering. John Wiley & Sons Ltd, England.

[11] Esmailian, M. 2006. SPSS 14 guide book. Tehran Dibagaran, Tehran, Iran (in Persian).

[12] Khodaparast, M. 2006. Expanding of soil geotechnical identification techniques using Dynamic probes. Dissertation, Tehran University, (in Persian).

[13] Lee, I.K., White, W., Ingles, O.G. 1983. Geotechnical Engineering. Copp Clark Pitman; Incorporated.

[14] Abu-farsakh, M., Khalid Alshibi, P.E., Nazzal, M., Seyman, E. 2004. Assessment of in-situ test technology for construction control of base courses and embankments. Report No, FHWA/LA.04/385, Louisiana Transportation Research Center.

[15] Bowles, J.E. 1997. Foundation analysis an design. 5th edition, McGraw-Hill International Editions.

[16] ASTM 1998. Standard test method for repetitive static plate load tests of soils and flexible pavement components, for use in evaluation and design of airport and highway pavements (D1195-93). Annual Book of ASTM Standards 04.08, pp. 110-113.

[17] Timoshenko, S.P., Goodier, J.N. 1970. Theory of Elasticity. 3rd Edition, Mc Graw-Hill Book company, New York.

[18] American Society of Testing and Materials. 2000. Standard test method for direct shear test of under drained conditions (D3080-98). Annual book of ASTM standards 04.08, pp. 894-904.

[19] Coduto, P.D. 2004. Foundation design, principal and practices. Second Edition, Prentice Hall, New Jersey.