MEASURING THE PENETRATION RESISTANCE OF SOIL USING DYNAMIC CONE PENETROMETER

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Submitted By

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I, Shubham Srivastava, Roll No. 2K16/GTE/18 of M.Tech. GEOTEHNICAL ENGINEERING, hereby declare that the project Dissertation titled **"MEASURING THE PENETRATION RESISTANCE OF SOIL USING DYNAMIC CONE PENETROMETER"** which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of technology, is original and not copied from any source without proper citation. This work has not been used for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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I hereby certify that the Project Dissertation titled **"MEASURING THE PENETRATION RESISTANCE OF SOIL USING DYNAMIC CONE PENETROMETER"** by **Shubham Srivastava**, Roll No. **2K16/GTE/18**, Department of Civil Engineering, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted in parts or full for any Degree or Diploma to this University or elsewhere.

Place, Delhi, India

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ABSTRACT

Recognition of the importance of soil compaction is increasing, but instrument cost, repeatability of measurements, and data interpretation restricts its measurement. Developed by Scala (1959), the dynamic cone penetrometer (DCP) device has been substantially utilized in recent decades for quality control of compaction of soils. The dynamic cone penetrometer described in this study follows the design of the American Society of Testing and Materials standards.

The penetrometer cone is pushed into the soil by giving successive hammer blows. Penetration resistance is calculated as the work done by the soil needed to stop the motion of the cone divided by the distance that the cone penetrates. The work done by the soil is defined as the kinetic energy of the hammer while it impacts the strike plate. The height of fall of the hammer has been varied for each test to vary the kinetic energy on impact. The effect of the variation of the apex angle of the cone on the Dynamic Cone Penetration Index(DCPI) and the soil penetration resistance has also been studied in this work. Numerous cone angles other than the standard 60 degree cone were designed and used for testing the effects and the results have been compared.

The results show that the average soil penetration resistance obtained for a depth of 15 cm is almost similar for the various tests on the same soil sample, each with a different height of fall of the hammer. The penetration resistance for four soil samples was then calculated using a fixed height of fall of 400 mm for each. The results also show that the DCPI value decreases as the apex angle of the cone is increased further from the standard 60°, although this similar sort of trend is not observed for the lower values of the cone angle.

Keywords: Dynamic cone penetration index (DCPI), apex angle of the cone, soil penetration resistance, kinetic energy, height of fall of the hammer.

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LIST OF SYMBOLS AND ABBREVIATIONS

DCP	-	Dynamic Cone Penetrometer
DCPI	-	Dynamic Cone Penetrometer Index
CBR	-	California Bearing Ratio
ASTM	-	American Society for Testing and Materials
AS	-	Australian Standard
HVS	-	Heavy Vehicle Simulator
DCPT	-	Dynamic Cone Penetratrometer/Penetration Test
SCP	-	Static Cone Penetrometer
SCPT	-	Static Cone Penetrometer/Penetration Test
IS	-	Indian Standard
KE	-	Kinetic Energy

CHAPTER 1

INTRODUCTION

1.1 General

Extended interest in the effects of soil compaction on soil quality has created a demand for instruments which measure soil penetrability or penetration resistance on a routine basis (Romig et al., 1995). The most usual method for measuring compaction is to determine cone index values by using the static cone penetrometers. Static cone penetrometers are designed to measure the force required to push a cone through the soil at a constant (static) velocity. Dynamic cone penetrometers form a second general class (Perumpral, 1987).

The early development of the DCP was reported by Scala from Australia in 1959 as an *in situ* geotechnical assessment approach for evaluating the strength of subgrade soils and base and sub base materials of new and existing flexible pavement structures (Scala 1959). The DCP test is also used for quality control of the compaction of certain soils. It is also used in shallow subsurface investigations as an alternative to other highly-priced and time-eating techniques. Relationships have been developed between DCP and other testing techniques, for example, California bearing ratio and unconfined compressive strength tests (Scala, 1959; De Beer, 1991; Webster *et al.*, 1994 and Chen *et al.*, 1999).

Originally, the DCP equipment was developed by Scala. It had a cone tip angle of 60° and a hammer drop mass of 8.0 kg falling from a height of 575 mm. The parameters of the DCP, such as the drop mass, the height of fall and the cone tip layout are varied with the testing method from different investigators and groups. Van Vuuren (1969) from South Africa developed and proposed a new DCP tool with 10 kg mass and 460 mm height of fall. Van Vuuren also indicated that his DCP is applicable for soils with CBR values ranging from 1 to 50. The DCP layout of the American Society for Testing and Material (ASTM) test procedure D6951 uses an 8 kg hammer having a height of fall of 575mm and a 60° cone, while the Australian standard DCP (AS 1289.6.3.2-1997) uses a 9 kg hammer falling from a height of 510 mm. The potential energy per drop for each DCP apparatus is represented in Table 1.1 below.

Table 1.1: Potential energy per drop for different DCP designs (BaoThach Nguyen et.al. 2012)

DCP design	Hammer mass (kg)	Height of fall (m)	Potential Energy per drop (J)
Scala (1959)	8.0	0.575	45.1
Van Vuuren (1969)	10.0	0.460	45.1
ASTM D6951 (2003)	8.0	0.575	45.1
AS 1289.6.3.2 (1997)	9.0	0.510	45.0

It can be seen that for all the penetrometers listed in the table above, the potential energy per drop is equivalent to that of the original design from Scala (1959). In this study the DCP design of the American Society for Testing and Material (ASTM) is chosen.

1.2 Factors affecting Dynamic Cone Penetration Test (DCPT) Results

- Alignment of DCP rods – While testing, the bottom and top rods of the DCP should be straight and the cone should be seated freely in position on the material to be tested. If the penetrating rod is tilted during testing, resistance around the rod (i.e. skin friction) will amplify because of contact with the confining pavement layers which leads to a reduction in rate of penetration. Such conditions may also arise when the DCP rod penetrates through collapsible granular material.

- Depth of testing - DCP test outcomes are very susceptible to the depth of testing. When the bottom rod of the DCP used is longer than the standard penetrating rod, correction to the DCPI value should be applied because vertical confinement and skin friction around the rod increase resistance to the penetrating rod.
- Damaged cone tip – If the cone tip of the DCP is damaged it will give flawed test results
- Hammer weight – If the weight of the hammer is less than that specified, then the rate of penetration will diminish and vice versa.
- Lifting height of hammer – During DCP testing, the hammer should be lifted to the top restraint plate and freely dropped for each and every blow. During testing, if the hammer is not lifted to the standard height, the impulse force exerted by the cone will decrease and thus the values of penetration will also decrease.
- Apex angle of the cone – The rate of penetration will be significantly affected by change of apex angle of the cone from 30° to 60° since the upward frictional force on a cone surface with a 60° apex angle will be greater.
- Moisture content – DCP test results are very susceptible to changes in moisture content present in the test materials. As the moisture content increases, the rate of penetration of also increases and vice versa. Due to this reason, DCP tests are conducted after the monsoon season is over because during those times the granular and the sub-grade layers become soft and their minimum strength is recorded.
- Material composition – DCPI varies with test material composition, soil class, coefficient of curvature and uniformity, density of the layer material and plasticity of the soil.

- Intensity of compaction – DCPI will be influenced by the intensity of compaction and confinement of granular and sub-grade layers.

1.3 Applications of DCP

DCP testing can be applied to the characterization of sub-grade and base material properties in a number of different ways. Perhaps the greatest strength of the DCP equipment lies in its ability to supply a continuous record of relative soil strength with depth. By plotting a graph of dynamic cone penetration index (DCPI) versus depth below the testing surface, a user can observe a soil profile showing layered depths, thicknesses, and strength conditions. This can be particularly helpful in cases where the original as-built plans for a project were lost, never created, or found to be inaccurate. The DCP's other strength lies in its small and relatively lightweight design. It can be used in confined areas such as inside buildings to evaluate foundation settlements, or used on congested sites (trees, steep topography, soft soils, etc.) that would prevent larger testing instruments from being used. The DCP is ideal for testing through core holes in existing pavements. The following applications outline either existing or proposed uses of DCP testing.

- Preliminary Soils Surveys - DCP testing can be done during preliminary soil investigations to quickly map out areas of weak material. It can also be used to locate regions of potentially collapsible soils. To locate such a region, an initial DCP test should be run, and then the area should be flooded and then running another test. If a noticeable increase in the DCPI (less shear strength) is observed, that might indicate a potentially collapsible or moisture sensitive soil that would warrant a more detailed investigation.
- Construction Control - The DCP is an ideal piece of equipment for monitoring all aspects of the construction of a pavement sub-grade and base. The level and uniformity of compaction over a project can be verified by the use of DCP. It can also be used to define problem areas that develop due to unavoidable soil conditions brought on by inclement weather. Some have suggested it would be a good tool to use in lieu of test rolling ion projects

that are too short (to justify expense of test rolling) or have shallow utilities (which would prevent test rolling).

- Structural Evaluation of Existing Pavements - one of the major applications of DCP testing has been in the structural evaluation of existing pavements. South Africa has used DCP testing extensively in conjunction with their Heavy Vehicle Simulator *(HVS)* to investigate both shallow and deep pavements with light cementitious gravel layers. The effects of traffic moulding caused by HVS loading were also evaluated by DCP tests.
- Future Applications - Due to the DCP's small size and simplicity of operation, there is no doubt new applications will be found for its use. one of these applications may be as mentioned before, a substitute for final testing rolling of grades before pavement placement. Yet another might be its use in measuring the frost/thaw depth in cold climate pavements during the spring months. This could enhance an engineer's decision to invoke or remove load restrictions.

1.4 Objective

- To design a DCPT device according to ASTM D6951 (2003) standard with different apex angles of the cone (30°, 45°, 60°, 75°, 90° and 120°).
- To conduct numerous DCP tests, each with a different height of fall of the hammer on the same soil.
- To obtain the average soil penetration resistance for a penetration depth of 15 cm using the kinetic energy and work done principle.
- To infer the suitability of the DCP device for measurement of the average soil penetration resistance from the values obtained above.
- To conduct another set of DCP tests, each with a different apex angle of the cone on a different soil type.
- To study the effect of the change in cone angle on the DCPT results.
- To obtain the soil penetration resistance values for a penetration depth of 50 cm with each cone separately.

CHAPTER 2

LITERATURE REVIEW

2.1 Static Cone Penetrometer

The static cone penetrometer (SCP) tool is used to determine the geotechnical engineering properties of soils and delineating soil stratigraphy. The Dutch Laboratory for Soil Mechanics in Delft, initially developed the SCP in the 1950's to research soft soils. Based on this history it has also been known as the "Dutch cone test". These days, the SCPT is one of the most widely used and accepted soil technique for soil investigation worldwide.

The test technique consists of pushing an instrumented cone, with the tip facing down, into the ground at a constant velocity. The resolution of the SCPT in delineating stratigraphic layers is related to the dimensions of the cone tip, with usual cone tips having a cross-sectional area of either 10 or 15 cm^2, corresponding to diameters of 3.6 and 4.4 cm.

Numerous static designs for the SCP are commercially available. Most consist of a firm, unyielding, cone-tipped rod attached to pressure measuring equipment. The measuring equipment is usually made up of a load cell or a strain gauge fixed to an analog dial gauge or a pressure transducer to observe the readings. The force applied by the operator is normalized to the base area of the cone to form a parameter known as the cone index (i.e. pressure applied to the cone), generally reported in kilopascals (kPa).

Manually operated static penetrometers suffer from several limitations. They

i. Are relatively expesive.

ii. Must be moved through the soil at a constant velocity.

iii. Must be recalibrated on a regular basis in order to generate consistent, repeatable measurements.

iv. Are designed for a relatively limited range of soil resistance.

Manually operated penetrometers often give inconsistent results when used by the same operator and especially when used by different operators because of differences in the rate of penetration. Correct analysis of static penetrometer data also requires insertion into the soil at a constant velocity, so that the soil resistive force can be assumed equal to the total force applied to the penetrometer. If penetrometer velocity changes, then the soil resistive force will be either more (for negative cone acceleration) or less (for positive cone acceleration) than measured by the operator for a constant velocity. Constant velocity is very difficult to maintain in manually operated penetrometers.

In addition to inconsistent penetration velocities within a single measurement, different operators usually develop different average penetrometer velocities because of different physical strength and leverage. Laboratory studies have demonstrated that differences in average penetrometer velocities alone can result in 11% variation in cone index for a soil material (Fritton,1990).

The problem of variable penetrometer velocity can be eliminated by using a mechanical device which adjusts the penetrometer force and provides just the required amount to maintain a constant velocity (Clark et al., 1993; Barone and Faugno, 1996). They are often used in making routine measurements; however, such usage is limited by cost parameters and the need to transport a large platform with a power supply to each and every measurement point. The flexibility or range of soil conditions to which such strain gauge penetrometers can be applied is limited by the strength and weight of the operating personnel. This range can be increased by using cones of different dimensions. However, it is extremely difficult to compare data from penetrometers using different cones, and the error related to the conversion procedures is quite high (Fritton, 1990).

A. Trivedi et. al. (2004) conducted static cone penetration tests on compacted ash fill. They interpreted the resistance to penetration of the standard cone at varying depths on ash fill compacted at varying relative densities. They came to the conclusion that the static cone penetrometer is an excellent tool for the assessment of the geotechnical design paramteres of the coal ash deposit. They also suggested correlations to estimate bearing capacity and settlement characteristics of coal ash on the basis of static cone penetration test results.

2.2 Dynamic Penetrometers

DCP does not apply a continuous force to the penetrometer and thus also does not attempt to push the penetrometer through the soil at a constant velocity. DCP supplies the kinetic energy of the falling hammer mass to the penetrometer, which causes it to penetrate a certain distance through the soil. This distance through which the penetrometer moves into the soil depends upon the kinetic energy applied, the geometry of the cone, and the soil's resistance to penetration itself. DCP's are not prone to errors arising due to operator variability since they do not rely on a constant penetration velocity, and the kinetic energy applied by the DCP equipments can be mechanically controlled. This can be done by having a fixed hammer mass and drop heights for given equipment.

The DCP designs that are available these days include some devices that are dropped directly onto the soil from a particular height (e.g. drop cones), and other devices that are driven into the soil by the action of repeated blows from a hammer. The drop cone method measures the penetration depth resulting from dropping a cone of a fixed mass from a specified height. This method has been successfully implemented to measure shear strength of soils (Campbell and Hunter, 1986:

Godwin et al., 1991). The hammer-type penetrometers use a sliding hammer of fixed mass and falling height so that a consistent amount of kinetic energy is applied with each and every blow. Either the penetration depth per blow, or the number of blows needed to penetrate a particular depth is measured in this method.

The use of the second type (the one's which use a hammer) of penetrometers has been mostly restricted to drilling applications where standard drilling equipments (core samplers or split spoon sampler) are being used as penetrometers (Swanson, 1950). The Annual Society of Testing Materials (1992) has described a standard procedure for a split-spoon or split-barrel penetrometer which uses a 63.5 kg hammer falling from a height of 75 cm. This procedure was also described earlier by Davidson (1965). Due to their large size and bulky design these penetrometers are usually not appropriate nor are they convenient for quick and easy soil testing.

BaoThach Nguyen *et al.* (2012) studied the effects of vertical confinement from the CBR mould on the DCPI, and worked on the development of a lightweight DCP that can be used in the laboratory as well as in field conditions with similar results. Their results showed that the effects of vertical confinement are very important, especially with mass of the hammer larger than 4.6 kg. Their results also indicated that the influence of the vertical confinement on the DCPI is not important when the hammer mass is less than 2 kg. Based on these results, they proposed a new lightweight DCP with a hammer mass of 2.25 kg, which could be used in the laboratory in the CBR mould and also in field conditions with similar results for a similar soil.

Parker *et al.* (1998) proposed an idea for an automated DCP. Basically, this penetrometer is a vertical frame with wheels for raising and releasing the hammer. The data of penetration is captured and sent to a computer. Fumio *et al.* (2004) also developed an automated data collection system for a portable DCP with a hammer mass of 3 kg. This was mainly done for investigation of soil layers on steep slope.

Webster *et al.* (1992) at the US Army Corps of Engineers proposed the dual mass DCP, a modified version of the original DCP. In the dual mass DCP instrument, the mass of the hammer was decreased to 4.6 kg. This mass for the hammer reduced the DCPI value by half of that of the original DCP with a hammer mass of 8 kg.

Furthermore, extensive and vast research has been performed to study the factors affecting the DCPI values. Kleyn and Savage (1982) investigated the effects of moisture content, soil gradation, density and plasticity characteristics of soils and came to a conclusion that these parameters were important and influenced the DCPI values.

In addition, by conducting a study on the influence of several factors on the DCPI values, Hassan (1996) conducted several tests and concluded that moisture content, soil classification, confining pressure and dry density affect the DCPI for fine-grained soils, whereas the DCPI values for granular material are significantly influenced by the confining pressure, maximum aggregate size and the coefficient of uniformity.

As it can be seen from the above literature survey that most of the studies have focused on the hammer mass of the DCP and automating the DCP device and its laboratory and field applications. Most of the studies have tried to build a lightweight or a portable DCP device for quick and reliable results. The objective of this study was to use one such portable DCP device for quick and easy testing and using it for finding the average soil penetration resistance via the kinetic energy and work done principle. The effects of the change in the cone angle on the dynamic cone penetration index (DCPI) and the soil penetration resistance values have also been studied.

CHAPTER 3

METHODOLOGY

3.1 Materials

Four different types of locally available soils have been used in this study. The first type of soil used is Yamuna sand, the second type of soil used is dune sand lifted from the kabaddi court within the college campus. The third type of soil is the ground soil of DTU which is a type of silty sand and is commonly referred to as DTU soil and the fourth and final soil is locally available silty clayey soil. The physical properties of these soils were determined according to the Indian Standards (Specific Gravity: IS-2720-3-1980; Grain size analysis of soil: IS-2720-4-1980; Relative density or density index of soil: IS-2720-14-1980; Liquid limit and Plastic limit of soil: IS-2720-5-1980; Standard Proctor Test: IS-2720-7-1980). The particle size distribution curve for all four types of soil is shown in Fig. 3.1 below. From the graph the D_{10}, D_{30} and D_{60} values can be found out easily which can then be used to calculate the uniformity coefficient (C_u) and the coefficient of curvature (C_c) using their respective formulas for the sandy soils. The summary of the test results are listed in Table 3.1 below.

Since the uniformity coefficient values for yamuna sand and dune sand is less than 6 the sands can be classified as poorly graded even though their coefficient of curvature lies in the range of 1 to 3. DTU soil has a coefficient of uniformity of 12 which is greater than 6 but its coefficient of curvature is 0.414 and does not lie in between 1 to 3 thus this soil can also be classified as poorly graded. The percentage of fines (particles less than 75 microns in size) in DTU soil is more than 12% and the fines lie in the size range of silt, thus this soil is a type of silty sand which is poorly graded and thus the classification is SP-SM. From the fineness modulus values obtained all three sandy soils can be classified in a particular grading zone according to IS 383-1970. Soil sample 1 (S-1) and Soil sample 3 (S-3) have a fineness modulus of 2.825 and 3.108 respectively which lies between 4.0-2.71 thus these soils can be put into the grading zone I. Soil sample 2 (S-2) has a fineness modulus of 1.485 which lies between 2.25-1.35 thus the soil can be put into the grading zone IV.

The locally bought silty clayey soil's grain size distribution curve is also shown below in Fig. 3.1. From the figure, it is clear that 97.9% of the soil passed through the 75 micron. The soil consists of 30% clay-sized particles (<2 μm), 67.9% silt-sized particles (2 μm to 75μm), and 2.1% sand-sized particles (75 μm to 2 mm). Atterberg limits test and proctor tests were also conducted on this soil. From the liquid limit and plastic limit values obtained for the soil and the percentage of clay and silt particles, this soil can be classified as clay with silt of intermediate plasticity (CI-MI).

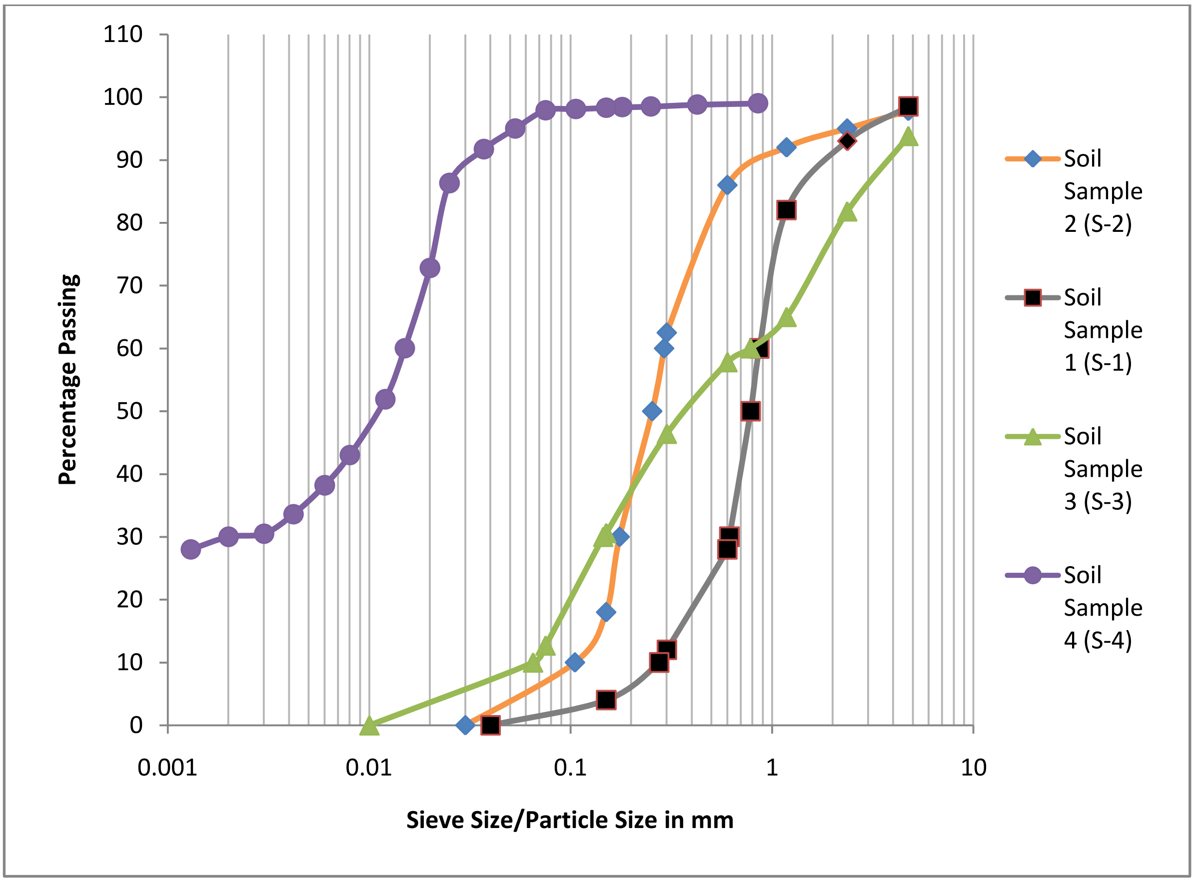

Fig 3.1 Grain size distribution curves for the two soils used in the study.

Table 3.1: Physical properties of soil samples used in this study

Soil properties	Soil Sample 1 (S-1)	Soil Sample 2 (S-2)	Soil Sample 3 (S-3)	Soil Sample 4 (S-4)
Name of the soil	Yamuna Sand	Dune Sand	DTU Soil	Silty Clay
Specific Gravity, G	2.67	2.61	2.72	2.64
Soil Classification	Poorly graded sand (SP)	Poorly graded sand (SP)	Poorly graded silty sand (SP-SM)	Clay with silt of intermediate plasticity (CI-MI)
Coefficient of Uniformity, C_u	3.145	2.77	12	N/A
Coefficient of Curvature, C_c	1.585	1.002	0.414	N/A
Fineness Modulus	2.825	1.487	3.108	N/A
Grading Zone	Zone - I	Zone - IV	Zone - I	N/A
Maximum dry density (kN/m^3)	N/A	N/A	N/A	16.75
optimum moisture content (%)	N/A	N/A	N/A	19
Liquid limit (%)	N/A	N/A	N/A	42
Plastic limit (%)	N/A	N/A	N/A	19

3.2 Test Apparatus

The 8-kg DCP is shown schematically in Fig. 3.4 and in photograph in Fig. 3.5. It consists of the following components:

- A 15.8 mm (5⁄8 - inch.) diameter steel drive rod with a replaceable point or disposable cone tip. The rod is topped with an anvil that is connected to a second steel rod. This rod is used as a guide to allow the hammer to be repeatedly raised and dropped.

- An 8 kg hammer which is dropped from a fixed height of 575 mm (22.6-inch.), a coupler assembly, and a handle. Shown in Fig. 3.6. Markings were made on the hammer slide rod to drop the hammer from the necessary height required.
- The cone tip has an included angle of 60 degrees and a diameter at the base of 20-mm (0.79-in.). (See Fig. 3.2)
- The apparatus is typically constructed of stainless steel, with the exception of the replacement point tip, which may be constructed from hardened tool steel or a similar material resistant to wear.
- The following tolerances are recommended:
    1. Hammer weight measurement tolerance is 0.01 kg.
    2. Tip angle measurement of 60 degrees included angle; tolerance is 1 degree
    3. Tip base measurement of 20 mm tolerance is 0.25 mm.
- A vertical scale graduated using increments of 1.0 mm (0.04-inch.), or measuring rod longer than the longest drive rod if the drive rod(s) are not graduated. The vertical scale of the DCP used in this study can measure penetration up to a depth of 1 m.
- An optical sliding attachment for use with a separate scale or measuring rod.

Apart from the standard 60° cone numerous other cones each with a different apex angle were also prepared for testing purpose. These cones had an apex angle of 30°, 45°, 75°, 90° and 120°. The base diameter of each cone was kept as 20 mm, same as that for the standard 60° cone. Each cone is detachable and can be easily attached or removed from the driving rod. The test is conducted with each cone attached to the drive rod using the standard test procedure as mentioned below on Soil S-2 and the results are obtained and interpreted. The cones are shown below in Fig. 3.3

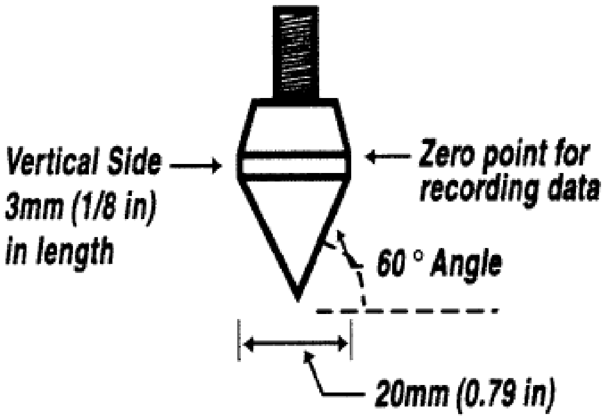

Fig 3.2 Standard replaceable cone tip

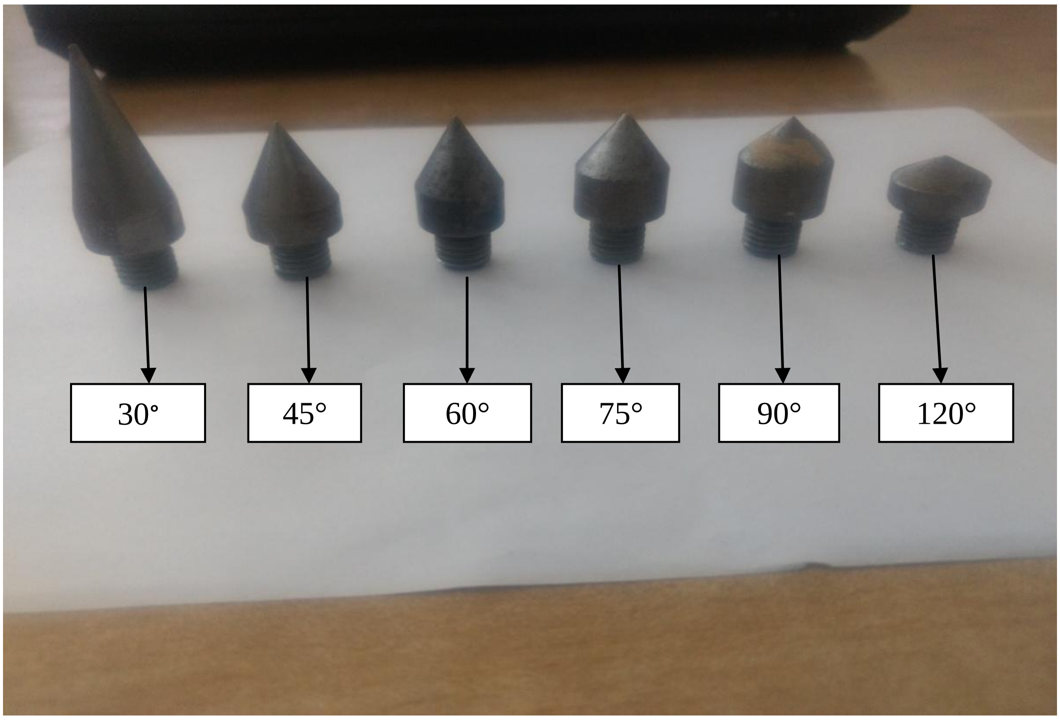

Fig 3.3 Various cones used in the study.

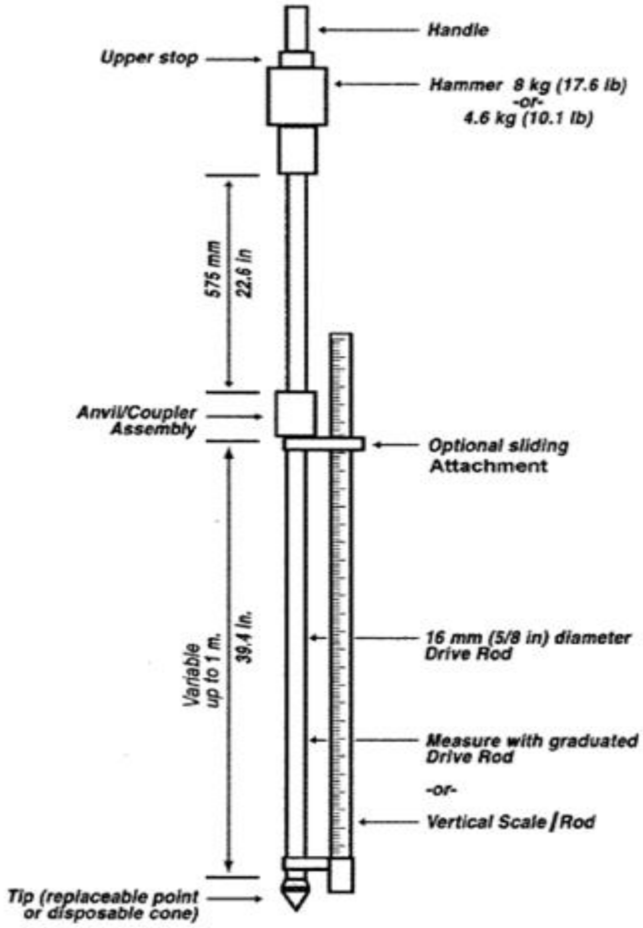

Fig 3.4 Schematic of DCP device (ASTM D6951)

Fig. 3.5 The DCP device fully assembled.

Fig. 3.6 The hammer and the sliding rod.

3.3 Test Procedure

1. Before beginning a test, the DCP device is inspected for fatigue-damaged parts.
2. *Basic operation* - The operator holds the device by the handle in a vertical or plumb position and lifts and releases the hammer from the standard drop height. The recorder measures and records the total penetration for a given number of blows or the penetration per blow.
3. once the test apparatus is assembled the DCP is placed at the test location and the initial penetration of the rod is recorded to provide a zeroing scale. This is done by keeping the DCP vertically and the tip seated such that the top of the widest part of the tip is flush with the surface of the material to be tested. An initial reading is obtained from the graduated drive rod or a separate vertical scale/measuring rod. The distance is measured to the nearest 1-mm (0.04-in.). Some sliding reference attachments allow the scale/measuring rod to be set/marked at zero when the tip is at the zero point.
4. Then while holding the rod vertically, the hammer is raised to the top of the rod 575 mm above the anvil and dropped.
5. The penetration of the rod is measured after each drop.
6. The test shall be terminated if the desired depth is reached or if the rod penetrates less than 1/8-inch in 10 drops.

All tests were conducted according to the above specified standard procedure. The height of fall of the hammer was varied for every new set of test in the soil S-1 and the apex angle of the cone was varied for every new set of test in the soil S-2. After the results from tests on soil S-1 were obtained, interpreted and compared and the suitability of the equipment for measurement of average soil penetration resistance was determined, a suitable fixed height of fall (which was 400 mm) was chosen and the average penetration resistance of four soil samples (S-1, S-2, S-3, S-4) for a penetration depth of 15 cm were determined and compared. The tests were conducted in the laboratory in a large cylindrical box which has a height of 1 m and a diameter of 30 cm. The cylindrical box was filled with soil in layers up to a height of 0.6 m, with each layer given a constant no. of blows with a tamping rod for compaction purpose.

Fig. 3.7 The DCP device and the testing container.

Fig. 3.8 Test being performed in the container filled with soil.

3.4 Units and Calculations

The DCP apparatus and testing procedures described above can be used to calculate the penetration resistance of soil averaged across the distance the cone moves through the soil after each blow of the hammer. The penetration resistance of soil is nothing but the reactionary force applied to the penetrometer by the soil causing it to decelerate from its initial velocity, resulting from the hammer blow, to zero velocity. This resistance can be calculated as the work done by the soil to completely stop the movement of the penetrometer divided by the distance the penetrometer travels within the soil:

$$R = \frac{W}{P} \tag{3.1}$$

In the above equation (3.1), R is the soil penetration resistance in Newton (N), W is the work done by the soil to stop the penetrometer in Joules (J), and P is the distance that the penetrometer travels within the soil in metres (m).

The work done by the soil is calculated according to the kinetic energy and work done principle. When the hammer is raised to the specific height of fall and the dropped on the strike plate, the kinetic energy of the hammer is transferred to the penetrometer cone which drives the penetrometer through the soil. When the pentrometer is stopped by the soil, its kinetic energy is zero. Therefore, the work done by the soil equals the kinetic energy transferred to the cone from the penetrometer when the hammer comes in contact with the strike plate. An assumption has been made in making these calculations, that all of the hammer’s kinetic energy at the moment of impact on the strike plate is transferred to the cone and that there is no loss of kinetic energy.

Thus, a hammer mass falling a distance of 0.5 m will have a velocity (v) of 3.13 m/s just before it comes in contact with the strike plate (Eq. (3.2)).

$$v = \sqrt{(u^2 + 2 \times a \times S)} \tag{3.2}$$

Where u is the initial velocity of the hammer at time 0 (0 m/s), a is the acceleration due to gravity (9.81 ms^{-2}) and S is the height of fall of the hammer. The kinetic energy (KE) for a hammer of 8 kg falling from a height of 0.5 m is 39.24 J (Eq. (3.3)).

$$KE = W = \frac{1}{2} mv^2 \tag{3.3}$$

The penetration resistance value of soil for each hammer blow can now be calculated by substituting KE into Eq. (3.1) for W. The resistance obtained by this method represents the average value of soil resistance across the distance that the penetrometer moves through the soil. This approach does not assume soil uniformity because it generates an average resistance across the depth the cone travels. These average numbers are clearly more informative for soils which are relatively uniform within the depth increment covered by each strike of the hammer.

Also, the repeatability of measurements of the DCP device depends on the consistency of the height of fall of the hammer. The error can be reduced to ≈1 mm by always raising the hammer to the set mark. This is equivalent to just 0.08 J per strike for a 8 kg hammer.

CHAPTER 4

RESULTS AND DISCUSSION

The results of the DCP test in the box for different drop heights of the hammer for soil sample S-1 are summarised in Table 4.1 and shown in Fig. 4.1 below.

Table 4.1 Comparison of penetrometers using different height of fall for each with a 8-kg hammer mass. Data is based on no. of hammer blows needed to reach a penetration depth of 15 cm.

Height of fall (m)	DCPI (mm/blow)	No. of blows for 150 mm penetration	Kinetic Energy per blow (J)	Total Kinetic Energy (J)	Penetration Resistance (N)
0.575	81.00	1.85	45.13	83.57	557
0.500	43.30	3.46	39.24	135.94	906
0.400	31.93	4.70	31.39	147.48	983
0.300	21.68	6.92	23.54	162.91	1086
0.250	17.98	8.34	19.62	163.70	1091

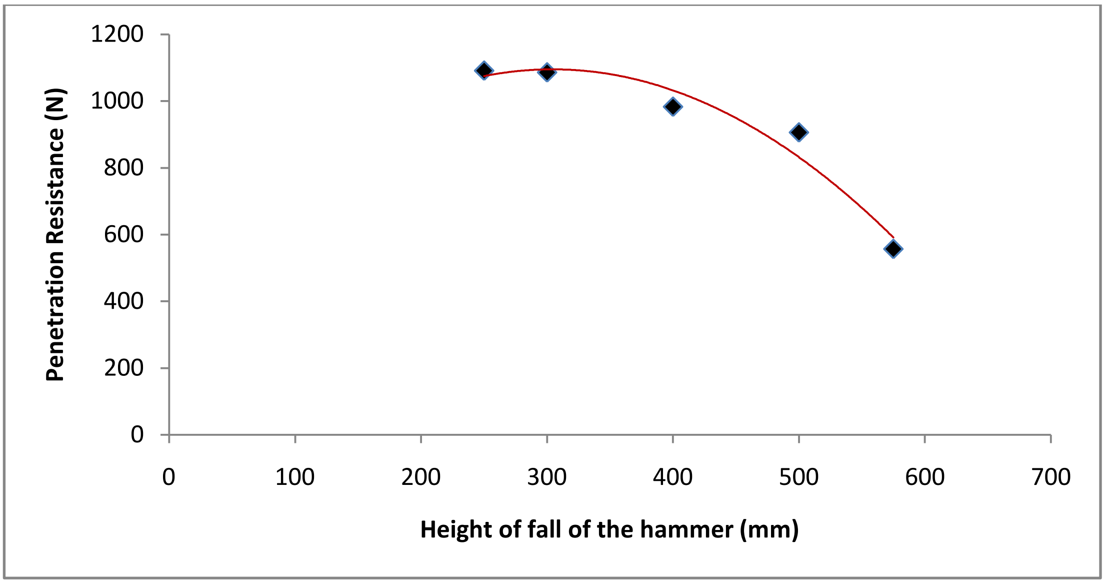

Fig 4.1 Penetration Resistance vs. height of fall of the hammer for soil sample S-1.

The results show that the penetration resistance value decreases as the height of fall of the hammer increases, although this decrease in penetration resistance value is not very significant except for the 575mm height of fall. The penetration resistance values for almost all the cases lie within a certain range of 900 N to 1100 N which should be the case as the average penetration resistance of soil for a given specified depth will be the same no matter what the testing procedure. The little difference that there are in the penetration resistance values could be attributed to the fact that the loss in transfer of kinetic energy from the hammer to the penetrometer could vary for different drop heights. The significant drop in penetration resistance value for the 575 mm drop height could be due to the fact that the averaging of data is done for a very small set of values as the penetrometer reached the depth of 15 cm in just 2 blows in this case.

All these suggest that the DCP device can be used for making quick and easy measurements of the average soil penetration resistance. The drop height of the hammer could be varied according to the level of soil profiling needed. on account of such results a drop height of 400 mm was chosen and tests were conducted on four types of soils (S-1, S-2, S-3 and S-4) and the average penetration resistance of each soil for a depth of 15 cm was found out and compared as shown in Table 4.2.

The gradation curve of each of these soils has already been compared above in Fig. 3.1.

Table 4.2 Average penetration resistance of soil samples for a depth of 15 cm.

Soil Sample	DCPI (mm/blow)	No. of blows for 150 mm penetration	Kinetic Energy per blow (J)	Total Kinetic Energy (J)	Penetration Resistance (N)
S-1	31.93	4.70	31.39	147.50	983
S-2	28.35	5.30	31.39	166.10	1107
S-3	29.57	5.07	31.39	159.25	1062
S-4	22.14	6.78	31.39	212.68	1418

It can be seen from the above table that the penetration resistance is different for different types of soil. The penetration resistance has increased as the soil becomes finer as is clearly observable from the penetration resistance value of the silty clayey soil (S-4). The penetration resistance has also increased as the gradation curve has moved upwards and more towards the left (towards the finer particle size).

The results of the DCP test in the box for different apex angles of the cones are summarised in Table 4.3 and 4.4, and in the figures 4.2, 4.3 and 4.4 below. The test was stopped once a penetration depth of 50 cm was reached.

Table 4.3 Penetration values with each hammer blow for the different cone angles.

No. of blows (N)	Penetration depth for various apex angles of the cone (mm)					
	30°	45°	60°	75°	90°	120°
0	0	0	0	0	0	0
1	96	86	78	63	50	48.5
2	143	135	124	120	115	103.5
3	258	202	195	212	205	174.5
4	303	241	259	262	229	212.5
5	333	294	295	303	259	239.5
6	366	355	361	347	306	286.5
7	433	400	402	382	344	324.5
8	476	449	425	416	381	342.5
9	512	495	455	442	416	386.5
10		527	502	473	451	421.5
11				520	493	467.5
12					510	521.5

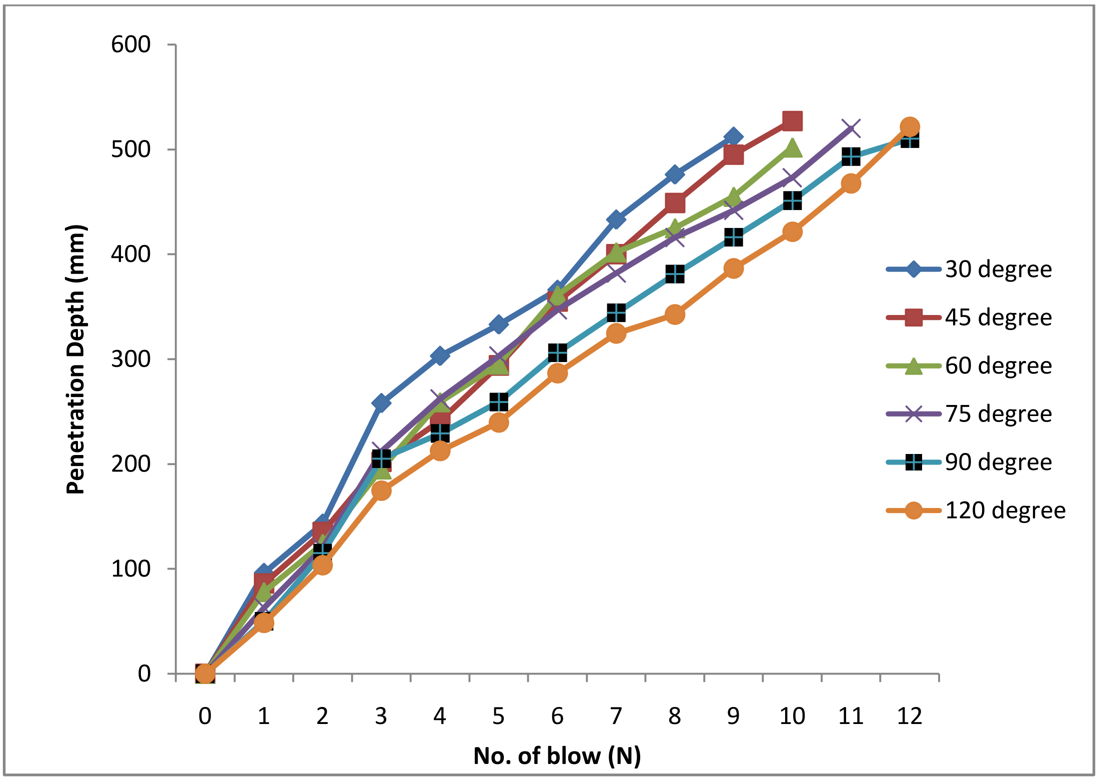

Fig 4.2 Penetration depth vs. No. of blow for each cone angle

From the above graph DCPI (mm/blow) values can be found out by drawing the best fit line for each curve and finding its slope. The linear trend-lines for each curve are shown in fig. 4.3 below. The effect of the apex angle of the cone can be seen from the two graphs. The comparison of the DCPI values and the penetration resistance of soil for each cone angle are summarised below.

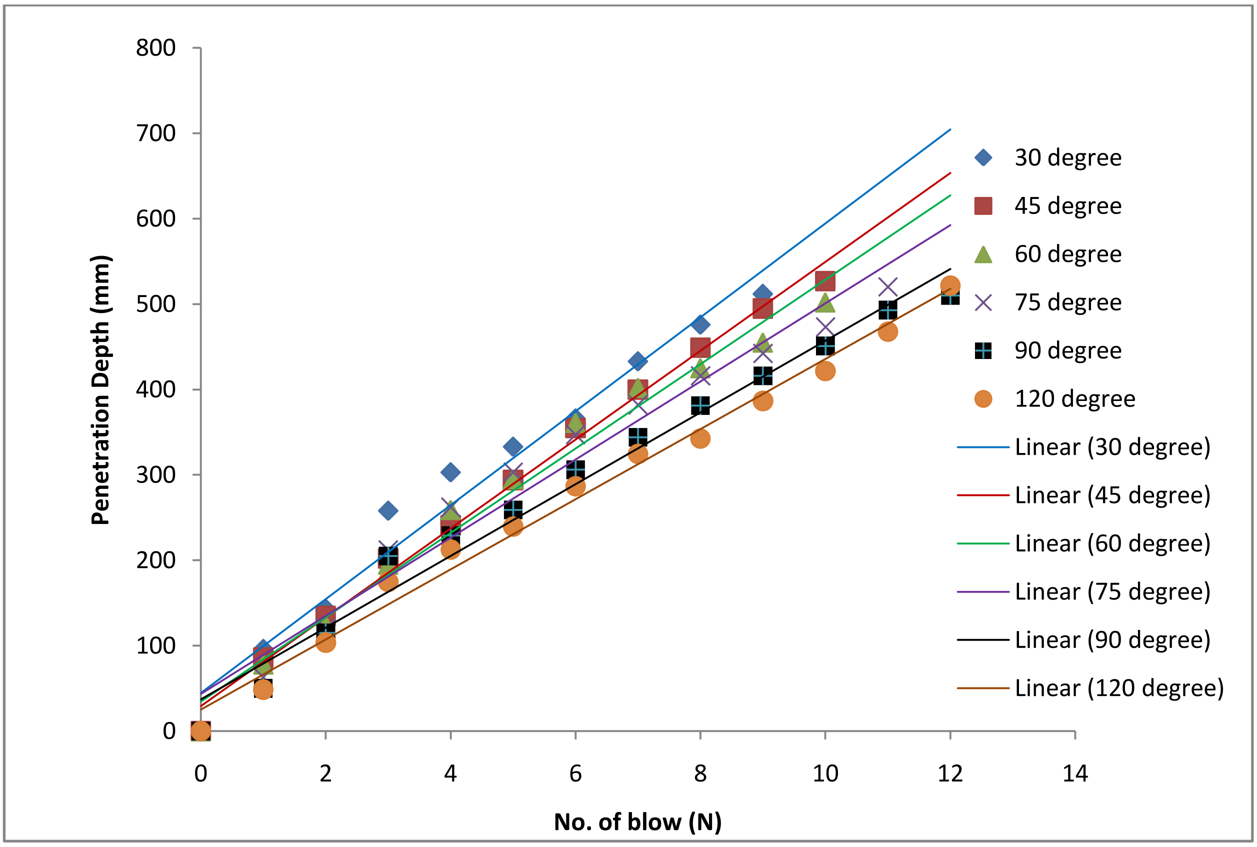

Fig. 4.3 Linear trend-lines for penetration depth vs no. of blow

Table 4.4 Comparison of DCPI (mm/blow) and the soil penetration resistance for each cone angle.

Apex angle of the cone (degrees)	DCPI (mm/blow)	No. of blows for 500 mm penetration	Total Kinetic Energy (J)	Penetration Resistance (N)
30	54.98	9.09	410.37	821
45	52.03	9.61	433.67	867
60	49.43	10.12	456.49	913
75	45.76	10.92	493.05	986
90	41.98	11.91	537.43	1075
120	41.08	12.17	549.21	1098

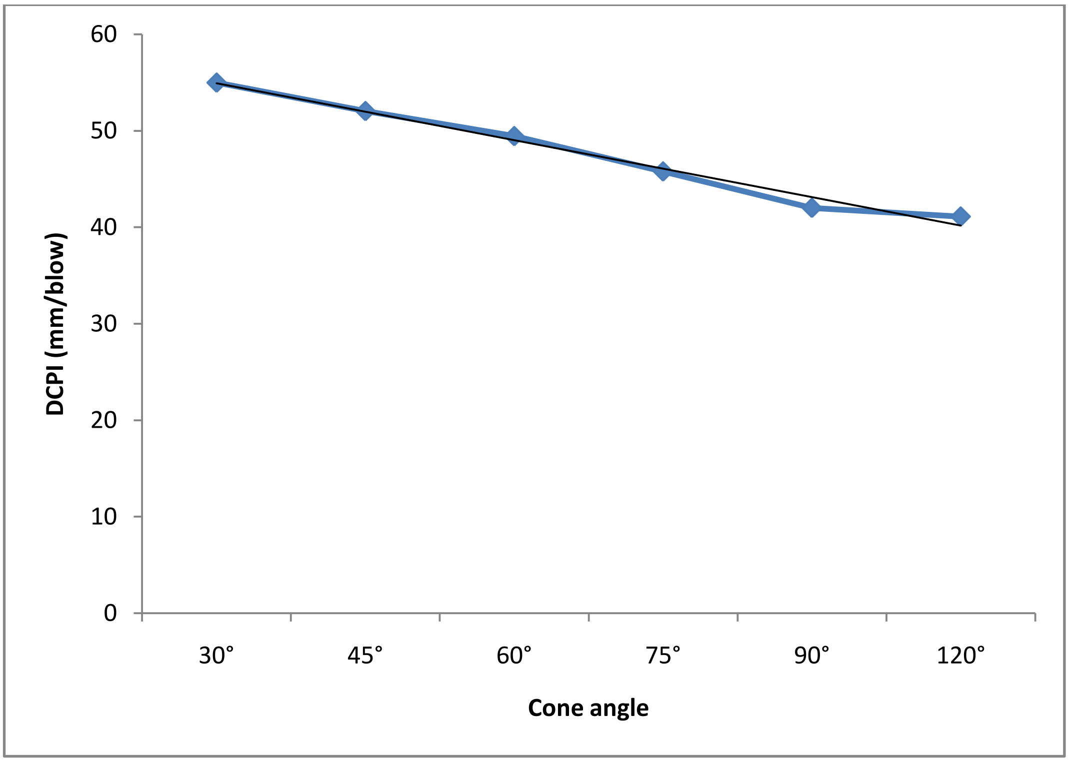

Fig 4.4 Variation of DCPI with the various cone angles.

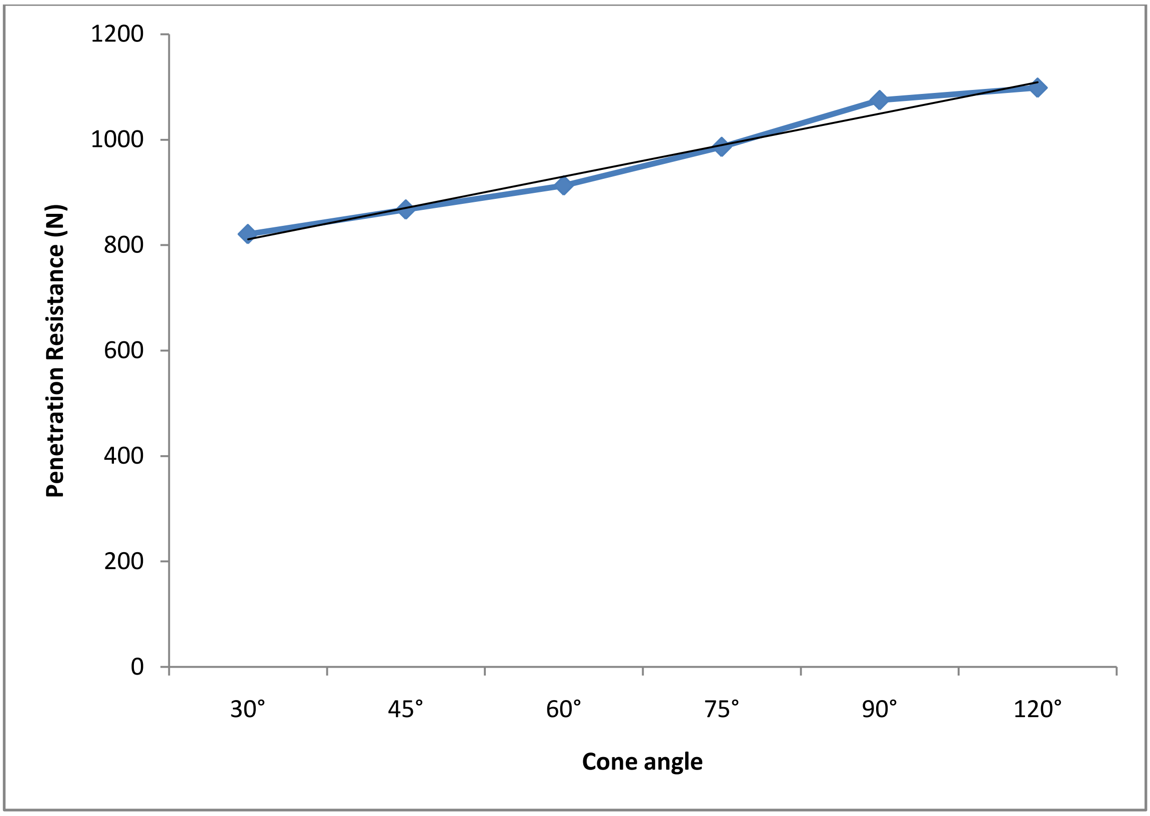

Fig 4.5 Penetration resistance vs cone angle.

From the data and the graphs above the effect of the apex angle of the cone on the DCPI values and the soil penetration resistance can clearly be seen. The DCPI decreases as the cone angle increases, which is due to the fact that the cone tip gets blunt as it angle increases. The 30 degree cone has the highest DCPI value as the cone height is longest in this case and thus offers more penetration. The 120 degree cone is almost flat and thus offers very little to penetration. When you look at the penetration data for each blow as a whole for each cone there is very little that one can differentiate between the cones, but once the DCPI values are calculated the difference is visible. There is not a whole lot of difference between the DCPI values for the cones with angles close to each other whereas the difference between cones with larger angle difference between them is very much significant. Also, the cones are hard to differentiate from each other for low penetration depths (i.e. for the first few blows) and the difference can only be observed when the penetration depth and the no. of blows are increased, as can be seen from Fig. 4.2 where the curves for each cone angle are very close to each other initially and only fan out at later stages.

Similar to the DCPI values the soil penetration resistance values have increased as the cone angle has increased. This is due to the fact that as the cone angle increases its penetrating surface area increases and thus the soil in contact offers more resistance to the penetration.

CHAPTER 5

CONCLUSIONS

The dynamic cone penetrometer (DCP) device used in this study represents an economical, durable and dependable alternative to strain-gauge based equipments. It is particularly suitable for nearly all applications for which a manually operated static cone penetrometer (SCP) could be used. It is very useful for applications where operator consistency is required or where soil conditions are variable. Also, due to its durable, all-steel design and the ease with which it can be used, it can be easily adopted at a wide range of sites for quick and reliable testing of soil.

Equation [3] above clearly accounts for height of fall of the hammer, allowing the kinetic energy delivered with each blow of the hammer to be easily adjusted. This flexibility permits the use of a single DCP on a broad range of soils without a loss in sensitivity or an increase in measurement time. Moreover, it permits the operator to increase the sensitivity in specific zones in which compaction is expected to occur. Thus, the penetrometer can be used to identify areas in soil in which more detailed measurements are required, or to rapidly locate potential zones of compaction within a profile and areas of compaction within a field.

Comparison of penetration resistance values of the four soil types brought into light that the average penetration resistance of soil increased as the percentage of fines increased in the soil. The silty clayey soil (S-4) had the highest penetration resistance value of all the four soils.

The apex angles of the cones certainly have some effect on the DCPI values. The effect can only be observed to some extent for higher penetration depths and. The cones are difficult to differentiate from one another based on penetration data alone for low penetration depths which also brings into consideration that the cones might not be distinguishable from each other in a different kind of soil such as clay which will offer more resistance to penetration than sand.

Also, all these tests were conducted only on four types of soils in the laboratory, three of which were some sort of sand. The results might differ for tests performed directly on the field or on tests performed on some other kind of soil or when the parameters of the soil such as the bulk density and the moisture content are varied. Therefore, further research on a wide range of soil samples both in the laboratory and the field are necessary to confirm these findings.

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