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Development of correlation between dynamic cone resistance and relative density of sand

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Abstract
Sand fill is required for many purposes, for example, backfill of earth retaining structures, backfill in foundation trenches, reclamation of low lands and construction of road embankments etc. In all these situations good compaction of fill should be ensured to avoid future subsidence, failure of foundation and moreover liquefaction. Relative density is the most appropriate index to control the compaction of sand fill. Dynamic Cone Penetrometer (DCP) and Dynamic Probing Light (DPL) were performed on sand fills of known relative densities in calibration chamber. Generalized correlations between dynamic cone resistance and relative density of sand were developed. Sand cone method of field density measurement was used to verify the correlations. The correlations worked well in the field and it is concluded that DCP and DPL can be used to determine relative density of sand fill.

Keywords: Dynamic Probing, Relative Density, Dynamic Cone Penetrometer, Field Density

1. Introduction

The density of granular soil varies with the shape and size of grains, the gradation and the manner in which the mass is compacted. The term used to indicate the strength characteristics in a qualitative manner is relative density (D_r) which describes the state condition of cohesionless soils. It is commonly used to identify liquefaction potential under earthquake or other shock-type loading. So, relative density is a very important index for a sandy soil. Relative density is 0% for loosest condition of sand and 100% for densest condition of sand. If maximum index density and minimum index density of sand is determined in laboratory as per ASTM D4253 and D4254, and field dry density is determined by any one of the methods such as Sand Cone Method (ASTM D1556), Sleeve Method (ASTM D4564), Rubber Balloon Method (ASTM D2167), and Drive-Cylinder Method (ASTM D2937), relative density can be calculated using the following formula.

$$D_r = \left(\frac{\gamma_d - \gamma_{\min}}{\gamma_{\max} - \gamma_{\min}}\right) . \left(\frac{\gamma_{\max}}{\gamma_d}\right) .100 \quad (1)$$

where,
γ_d = Field dry density of sand deposit
γ_{max} = Maximum index density
γ_{min} = Minimum index density

Relative density can be expressed in terms of void ratio as follows:

$$D_r(\%) = \left(\frac{e_{max} - e}{e_{max} - e_{min}}\right).100 \tag{2}$$

where, e_{max} = Maximum possible void ratio
e_{min} = Minimum possible void ratio
e = void ratio in natural state of soil

Sand fill is required for many purposes, for example, backfill of earth retaining structures, backfill in foundation trenches, reclamation of low lands and construction of road embankments etc. In all these situations good compaction of fill should be ensured to avoid future subsidence, failure of foundation and moreover liquefaction. Relative density is the most appropriate index to control the compaction of sand fill. Depending on the importance of structure, minimum relative density generally is specified as 70% to 95%.

In Bangladesh, quality control of sand fill is done by determining field density near the top surface of fill using Sand Cone Method (ASTM D 1556-90, 2006). It has limitations. This method is very difficult to perform at deeper locations as it requres excavation. Sand Cone Method has to be applied to control the quality of sand fill after compaction/densification of each layer of fill. For this reason it is time consuming and expensive. Sand Cone Method cannot be applied in saturated sand or where water table is high.

Dynamic Cone Penetrometer (DCP) (ASTM D 6951 – 03) and Dynamic Probing Light (DPL) (DIN EN ISO 22476-2:2012-03) are two portable dynamic cone penetration tests which are usually used for insitu measurement of resistance of cohesionless soil. Since the resistance of cohesionless soil mainly depends on relative density and particle size of sand, correlation between relative density and dynamic cone resistance was established and presented in this paper.

2. Dynamic probing

To drive a pointed probe (cone), a hammer of mass M and a height of fall H are used. Typical arrangement of Dynamic Probing is shown in Figure 1. The hammer strikes on anvil which is rigidly attached to extension rods. The penetration resistance is defined as the number of blows required to drive the probe a defined distance, e.g. 10 cm or 20 cm. After proper calibration, the results of dynamic probing can be used to get an indication of engineering properties, e.g. relative density, compressibility, shear strength, consistency etc. Depending on the hammer mass and cone size, Dynamic Probing has four categories; (i) Dynamic Probing Light (DPL), (ii) Dynamic Probing Medium (DPM), (iii) Dynamic Probing Heavy and (iv) Dynamic Probing Super Heavy. DPL is used in the study as it is portable and light. Specification of DPL is shown in Figure 1. Dimensions of DPL cone are shown in Figure 2. DPL can be used up to 8m depth.

3. Dynamic Cone Penetrometer (DCP)

Basic principle of Dynamic Cone Penetrometer (DCP) is similar to Dynamic Probing. Specification of DCP is shown in Figure 3. Dimensions of DCP cone is shown in Figure 4. Differences between DCP and DPL are shown in Table 1. DCP was developed in 1956 in South Africa as in situ pavement evaluation technique for evaluating pavement layer strength (Scala, 1956) which also known as the Scala penetrometer. Since then, this device has been extensively used in South Africa, the United Kingdom, the United States, Australia and many other countries, because of its portability, simplicity, cost effectiveness, and the ability to provide rapid measurement of in situ strength of pavement layers and subgrades. Recently DCP is standardized by ASTM (ASTM D 6951-03). The DCP has also been proven to be useful during pavement design and quality control program. The DCP, however, was not a widely accepted technique in the United States in the early 1980s (Ayers, 1990). De Beer (1991), Burnham and Johnson (1993), Burnham (1997), Newcomb et al (1994) and Hasan (1996) have shown considerable interest in the use of the DCP for several reasons. First, the DCP is adaptable to many types of evaluations. Second, there are no other available rapid evaluation techniques. Third, the DCP test is economical.

4. Methodology and testing program

A steel cylinder of diameter 0.5 m, height 1 m and thickness 13 mm was used as a calibration chamber. Top and bottom of the cylinder was open. Two sands of different grain sizes were used to develop the correlation between dynamic cone resistance and relative density of sand. Grain size distrinution of these sands are shown in Figure 5. Some index properties of these sands are tabulated in Table 2. It is necessary to fill the the calibration chamber with sand of uniform relative density. Dry air pluviation method was used to fill the calibration chamber. Plastic bowls were holed at 35 mm spacing with triangular pattern as shown in Figure 6. Sands were discharged from these bowls maintaining constant height of fall to make uniform relative density. Using small cylindrical mold, relative density vs height of fall relationships were established first. Relative density vs heights of fall relationships are shown in Figures 7 and Figure 8. The relationship proved that maintaining a constant height of fall, calibration chamber can be filled with uniform desired relative density. The calibration chamber was placed on a level ground. A sand deposit of desired relative density was prepared by dry air pluviation method. DCP and DPL tests were performed on the sand deposit of calibration chamber. After performing DCP and DPL on the sand deposit in the calibration chamber, weight of sand in the chamber were measured and relative density were verified each time. By varying height of fall sand deposits of different relative densities for fine sand and medium sand were prepared in the calibration chamber and DCP and DPL tests were performed each time. Penetration of cone was recorded for every blow of hammer. N10 and Pindex value of DCP and DPL tests were determined. N10 is the number of blows per 10 cm of penetration of dynamic cone and Pindex is the penetration rate of cone in mm/blow. Figure 9 shows the procedure of determining N10 and Pindex. To get a generalized correlation for various sizes of sand, Pindex values were normalized by multiplying it with √D50. Then a generalized correlation between relative density and Pindex√D50 were found for DPL and DCP for clean sand of any particle size. Finally the generalized correlation was verified from the test results in two dredge fill sites. At the same location relative density was determined using Sand Cone Method and dynamic cone resistance data. This data helped to improve the generalized correlation by incorporating depth correction factor (R_d) and fines correction factor (R_{FC}).

5. Results and discussion

5.1 Calibration of air pluviation method

The plot of relative density against height of fall for fine sand is presented in Figure 7. Discharge bowls with 3.5 mm and 4 mm opening were used for fine sand. Figure 8 is the plot of relative density against height of fall for medium sand. Discharge bowls with 4 mm and 5 mm openings were used for medium sand. From Figure 7 and 8 it is seen that for a certain diameter of hole of discharge bowl the relative density of sand increases with increase of height of fall. For a specific sand type and a fixed height of fall, relative density decreases with increase of opening size of discharge bowl. That means if the rate of discharge of sand decreases, relative density increases for a constant height of fall. To prepare sand deposit of known relative density, Figure 7 and 8 were used to find the height of fall required for that relative density.

5.2 Determination of P_{index} and N_{10}

Sand deposit of desired relative density was prepared in calibration chamber, then one DCP or one DPL tests were performed in the chamber. Then recorded cumulative numbers of blows were plotted against depth. Figure 9 and 10 show such plots for medium sand of relative density 69%. Some unreliable data points up to depth of 30 cm were eliminated because of presence of very low confining pressure on top of sand deposit. It is observed that cumulative number of blows increases linearly with depth. Figure 9 and 10 indicates uniform density of sand from top to bottom of sand deposit. P_{index} was calculated from the average slope of the cumulative number of blow vs depth plot. Then N_{10} value was calculated as $100/P_{index}$.

It was difficult to obtain relative density more than 72% by dry air pluviation method. So, by using concrete vibrator; sand deposit of relative density 90% was prepared. DCP and DPL test result on fine sand of relative density 90% are shown in Figure 11 and 12. From these figures it was seen that sand deposit was almost uniform throughout the depth. Since the DPL cone diameter is larger than DCP cone, penetration index of DPL is less than that of DCP for the same relative density and grain size of sand.

5.3 Development of correlation between relative density and P_{index}

To calculate the density of sand in calibration chamber all the sands were removed from the chamber and weighed after completion of DCP and DPL on prepared sand deposit. Then the relative density was calculated from the density. Following the procedure described in the previous sub-section, P_{index} and N_{10} value for DCP and DPL was determined. To get a generalized correlation, P_{index} value is multiplied by $\sqrt{D_{50}}$ of sand where D_{50} is in mm. Then relative density vs $P_{index}\sqrt{D_{50}}$ is plotted in Figure 13 and 14. It is observed that Penetration Index increases exponentially with decrease of relative density. By fitting the data in an exponential equation, a eneralized correlation for DCP was found as:

$$D_r(\%) = 97.4035.e^{\frac{-P_{index}\sqrt{D_{50}}}{80.7707}} + 3.0971 \tag{3}$$

Generalized correlation for DPL was found as:

$$D_r(\%) = 104.3312.e^{\frac{-P_{index}\sqrt{D_{50}}}{18.1307}} - 1.4769 \tag{4}$$

where,
D_r = Relative density (%),
P_{index} = Penetration Index (mm/blow)
D_{50} = Mean diameter of sand particles in mm

5.5 Verification of correlation from field data

After establishing generalized correlation between relative density and P_{index} from the test results in calibration chamber, the correlation was verified by the field test data. Field tests were performed in two dredge fill sites; one is near Bangabandhu Bridge named as Jamuna Site and another is Inland Container Terminal of Pangaon, Narayanganj named as Pangaon site. Penetration Index at any depth was calculated as an average penetration rate (mm/blow) of cone in five blows around that depth. A typical plot of depth vs Penetration Index is shown in Figure 15. Using generalized correlation mentioned in Equation 3 and 4, relative density was calculated from Penetration Index which is shown in Figure 16.

Field dry density at various depths of the same location where DCP and DPL test was performed was determined using Sand Cone Method. After determination of maximum and minimum index density of that sand, relative density was calculated from the field dry density obtained from Sand Cone Method. Relative density thus obtained from DCP and DPL at various locations was compared with that obtained from Sand Cone Method which is shown in Figure 17. It shows that DCP and DPL give less relative density than Sand Cone Method. Two reasons were assumed to be the cause of these differences between results from DCP-DPL and Sand Cone Method. One is the depth and another is fines content. At shallow depth and ground surface, DPL and DCP encounter less resistance of penetration due to zero to very low confining pressure. On the other hand, during calibration of DCP and DPL in calibration chamber the sand was clean sand. In field fines content is about 5% which increases the density of the deposit without increasing cone resistance. Therefore two correction factors were introduced in Equation 3 and 4, one is correction factor for depth (R_d) and another is correction factor for fines content (R_{FC}). Generalized equation for DCP was modified as:

$$D_r(\%) = \left(97.4035.e^{\frac{-P_{index}\sqrt{D_{50}}}{80.7707}} + 3.0971 \right) R_d R_{FC} \tag{5}$$

Generalized equation for DPL was modified as

$$D_r(\%) = \left(104.3312.e^{\frac{-P_{index}\sqrt{D_{50}}}{18.1307}} - 1.4769 \right) R_d R_{FC} \tag{6}$$

where,

$$R_d = \left(\frac{0.8}{d} \right)^{0.03}$$

$$R_{FC} = 1 + 0.003 F_c \tag{7,8}$$

R_d = Correction factor for depth
R_{FC} = Correction factor for fines content
d = depth (m)
F_c = Fines content (%)

Equations 3 and 4 are valid for clean sand having no fines content. Equation 5 and 6 are valid for sand having fines content 0 to 15%. Correction factors in Equations 5 and 6 were established by trial and error method. These two equations should be modified based on more experimental results in sand having different fines contents.

Using equations 5 and 6, relative density at various locations and depth were determined from Penetration Index of DCP and DPL and compared with relative density from Sand Cone Method in Figure 18, 19, 20 and 21. It is clear that relative density from DCP and DPL are in good agreement with the relative density from Sand Cone Method. It is proved that DCP and DPL can be successfully used to determine relative density of sand fill.

6. Conclusions

The following conclusions were drawn from the experimental study:

i. A generalized correlation between relative density and P_{index} were found for DCP and DPL which is applicable to clean sand of any particle size.
ii. Resistance of sand increases exponentially with relative density. The larger the particle size greater the resistance to penetration for a certain relative density of sand. Denser sand gives more resistance for a specific type of sand.
iii. The developed correlation between relative density and penetration index worked well for in-situ measurement of relative density of sand.

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