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Correlation between Miniature Cone Tip Resistance and Shear Strength Parameters of Clean Sand and Sand added with Silica Fume using Conventional Triaxial Setup

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Abstract:
Silica fume is produced by electric arc furnaces as a by – product for the production of metallic silicon or ferrosilicon alloys. Their large production worldwide, especially in industrialized countries, has reached alarming proportions. This has a hazardous environmental impact as it causes the pollution of air or groundwater and loss of productive land. The safe disposal of the silica fume has become a very critical issue, and in order to tackle this problem, the silica fume is utilized for several geotechnical applications such as for the construction of embankments, backfill material for retaining walls, stabilization of clay soil and sub-base material for pavement construction. For estimating the stability of any geotechnical structures, on natural ground or on reclaimed land, it is necessary to know in-situ shear strength characteristics of the soil strata at different depths. It was found from the literature that most of the correlations are limited to clean sands and clayey soils. In the present paper an attempt is being made to develop correlation between miniature cone tip resistance and shear strength of sand- silica fume mixtures. The testing was however, performed only for the dry state of material with the absence of any pozzolanic reaction. The ultimate tip resistance of the cone was determined by employing a miniature cone penetrometer of diameter 19.5mm in conventional triaxial equipment. A number of penetrometer tests were carried out for clean sand and sand with considerable proportion of silica fume. The variation of the tip resistance was found by varying the effective vertical stress from 50Kpa-300Kpa and also at three different relative density states corresponding to loose, medium dense, dense states respectively. It was noted that an addition of silica fume in sand for the same range of relative density leads to significant reduction, in ultimate tip resistance of the cone. This occurs due to decrease in friction angle upon addition of silica fume. By incorporating the effect of the over burden stress on friction angle, it was noted that the magnitude of ultimate cone tip resistance vs. effective vertical stress increases linearly with friction angle. The obtained values of ultimate cone tip resistance were compared with two widely used correlations in literature and also from the published data on miniature cone tip resistance. It is expected that the study will be useful for developing correlation between shear strength parameter and the cone tip resistance for cohesionless deposits at different values of effective over burden pressure at different relative density states.

Keywords: cone penetrometer test, sand, silica fume, correlation, Shear strength, cone tip resistance.

I. INTRODUCTION

Silica fume is a by-product or a very fine pozzolanic material, composed of mostly amorphous silica produced by electric arc furnaces during the production of elemental silicon or ferrosilicon alloys in smelters using electric arc furnace. These metals are used in many industrial applications which include aluminum and steel production, computer chip fabrication, and production of silicones, which are widely used in lubricants and sealants. While these are very valuable material, the by-product silica fume has a hazardous environmental impact. Before the late 1960's in Europe and mid 1970's in the United States, silica fume simply went up the stack as smoke vented into the atmosphere. Only with the implementation of tougher environmental laws during the mid – 1970's did silicon smelters begin to capture and collect the silica fume, instead of sending into atmosphere. The proper disposal of silica fume, an industrial by product, is one of the major issues for environmentalists worldwide since dumping of silica fume as a waste material may cause severe environmental problems and hazards. Silica fume was used in cement industry and in recent times it is also used in geotechnical applications. The low specific gravity, freely draining nature, ease of compaction, and good frictional properties of silica fume can be exploited in various geotechnical applications like construction of embankments, backfill material for retaining walls, in the reclamation of low-lying areas and to some extent in pavement construction. For assessing the stability of any geotechnical structure, it is necessary to know in situ shear strength characteristics of the soil strata at different depths. If the variation of shear strength of a given soil stratum with depth can be suitable established, one can explore the possibility of usage of silica fume as a filler in locally available soil to design the associated geotechnical structure. Through the usage of static cone penetration tests, one can estimate the in situ shear strength of the soil strata provided the correlations between cone penetration resistance and shear strength of soil mass are available. It is found from the literature that the existing correlations between cone penetration resistance and shear strength parameters of soil are available for sandy and clayey soils and more recently a correlation between miniature cone tip resistance and shear strength parameters were established for clean and silty sands and sand with flyash by Kumar and Raju (2008, 2009). The present research was attempted to introduce new material silica fume, with the intention of developing the correlations between the miniature cone tip resistance and the shear strength of sand – silica fume mixtures. The testing was however, performed only for the dry state of the material in the absence of any pozzolanic reaction, which often leads to an increase in the strength of the soil – silica fume mix. In an ideal situation, the silica fume needs to be disposed and mixed with locally available soil at optimum moisture content of the soil – silica fume mixture before subjecting to compaction. However, this may not always feasible in actual practice, as the silica fume is simply disposed in a dry state. The present research work is an attempt to determine the in situ shear strength of the material, arriving from a dry disposal of silica fume, comprising of a mixture of dry silica fume and dry sand with the help of miniature cone penetrometer tests. For developing correlations between cone tip resistance and shear strength parameters of soils, large scale calibration chambers are employed by various investigators of sizes of calibration chambers varying between 0.55 to 2.1m (Been et al. 1986, 1987, Houlsby and Hitchman 1988; Ghionna and Jamiolkowski 1992, Hsu and Huang, 1998, Huang and Hsu 2005). It is quite an expensive and time consuming exercise to carry out controlled tests in a large size calibration chamber. The task becomes even much more difficult when a sample comprising of either silt or clay has to be prepared. As a result, most of the available test results using calibration chambers are generally for sandy soils. Kumar and Raju (2008) have used a miniature cone of diameter 19.5 mm and a triaxial cell with a 91 mm diameter and conducted a series of miniature cone penetrometer tests and established correlations between shear strength parameters and miniature cone tip resistance. Also Kumar and Raju (2009) extended the work for sand – fly ash mixtures. However in the present paper, a new material silica fume is introduced and it is attempted to establish the correlations between shear strength and miniature cone tip resistance for sand - silica fume mixtures in dry state. All the miniature cone penetration tests in the present study are conducted in large triaxial chamber of diameter 180mm with cone diameter equal to 19.5mm. The chamber to cone diameter in the present study is 9.23 which is higher than the chamber to cone diameter of previous work of Kumar and Raju (2008, 2009) which is 4.67. The effect of relative density of the samples at different vertical overburden stress was explored. The obtained values of the tip resistance, for several combinations of friction angle and effective overburden stresses, were compared with the correlation curves of Durgonoglu and Mitchell (1975), Robertson and Campanella (1983) and Kumar and Raju (2008), which are applicable for cohesionless soils. It should be however be noted that the test results obtained in the present study will not represent the true tip resistance of the standard electric cone at the standard penetration rate primarily on account of (i) the boundary effects, as the ratio of chamber (cell) diameter to probe diameter in the present experiments is just 9.23; (ii) the difference in the rates of penetration between the laboratory and field testing; in the present study all the tests are conducted at a penetration rate of 0.1 mm / sec, where as the penetration of cone in the field is 20 mm / sec; (iii) the smaller size of the cone as compared with the standard 35.7 mm diameter cone. However, the comparison of the results with those available in published literature has already been found to be quite satisfactory in the author previous research study for clean and silty sands (Kumar and Raju 2008) and on sand fly ash mixtures (Kumar and Raju 2009).

II. DESCRIPTION OF TESTING APPARATUS

A complete description of the apparatus as well as the associated testing procedure is given in Kumar and Raju (2008, 2009); therefore only a brief explanation is provided herein. A cone of diameter 19.5 mm, with an apex angle of 60o, was connected to the bottom of the piston having a diameter of 19.5 mm; a schematic sketch of the set up is shown in Fig.1. The photograph of the chosen triaxial cell and the cone is also shown in Fig.2. In the present study the cone and the piston diameter is however the same and there is no reduced area behind the cone similar to the standard electric cone which has the same diameter of the sleeve and tip. The ratio of the cell diameter to cone diameter in the present study is 9.23. A thin rubber disc, 1.5 mm thick and 180 mm diameter, was first placed a little above the bottom surface of the cell; the rubber disc was supported by means of an annular ring placed around the bottom circular pedestal (which is otherwise used as a base for supporting the cylindrical soil sample) so that the disc remained horizontal while pouring and compacting the sample material over the top of it. A silicone sealant was applied everywhere around the periphery of the rubber disc and the sealant was left overnight for complete drying to ensure that no leakage of water takes place in the applying the water pressure. The soil was then allowed to pour vertically from a controlled height of fall (0 – 50 cm) by using a hopper (45 mm diameter) which was connected with a nozzle (5 mm diameter) at its lower end. Fixed number of wooden blows with a constant height of fall was being employed in order to increase the relative density of soil mass and twelve layers of equal thickness were being used to completely fill the cell with the soil sample. It was observed that with the chosen sample preparation technique it is possible to achieve desired uniform density. The gap between the bottom surface of the cell and the rubber disc was filled with water. The water below the rubber disc was pressurized by means of oil water controlled pressure system. With the help of the pressure system, a vertical effective pressure of a given magnitude was maintained in the same manner as is done for a typical triaxial test for maintaining either the confining pressure or the back water pressure. The cone was driven vertically downward in the soil sample at a uniform rate. All the tests were conducted at a penetration rate of 6 mm / minute, which was the maximum allowable rate for the chosen triaxial machine. The variation of the tip resistance with axial deformation was then carefully monitored so as to find the magnitude of the ultimate tip resistance; load cells and dial gauges were used to measure the magnitudes of loads and vertical displacements.

III. PROPERTIES OF DIFFERENT CHOSEN SAMPLES

A number of miniature cone penetrometer tests were conducted of samples comprising a mixture of both oven dried sand and silica fume. The sand chosen for the present study is river sand which is easily available in and around Bangalore city. The silica fume used in this study was obtained from Millennium building private limited, Bangalore, India. It is a by-product of silicon or ferrosilicon alloys. Silica fume is dark grey in color containing high content of amorphous silicon dioxide (Surface area 20,000 m2/kg). The specific gravity (G) of this silica fume (material solids) was found to be 2.2. In the present study two percentages (by mass) of the silica fume namely 15% and 30% by dry weight were added to sand. All the samples were first oven dried and kept in an air tight container. The values of the grain size parameters d10, d30, d60, where dN (where N=10, 30 and 60) is the size corresponding to which N% of the material by dry mass is smaller than that size along with uniformity coefficient (Cu) and coefficient of curvature (Cc) of the three materials are provided in Table1. It can be noted that the material hardly comprises any clay size fractions (< 2μm). The average specific gravity (G) of the sand and silica fume was found to be 2.67 and 2.2, respectively. The values of the minimum unit weight (γmin), maximum unit weight (γmax), and the associated relative density (Dr) of the chosen samples of sand – silica fume mixtures are provided in Table 2 and Table 3. Direct shear tests were conducted to determine the values of the friction angle (ϕ) at different vertical normal stresses (σv). From the direct shear test, the friction angle (ϕ) was determined by using the relationship, $\phi =$ tan-1(τf / σv), where τf is the magnitude of shear stress at ultimate shear failure. It should be noted that no apparent cohesion was assumed in this expression as all the chosen materials were perfectly dry and cohesion less. The variation of ϕ with vertical effective normal stress (σv) for all the chosen materials at three different chosen densities is provided in Fig 3. It should be noted that an increase in the magnitude of σv on the sample leads to a decrease in the magnitude of ϕ ; this occurs primarily on account of an increase in the rate of dilation (an increase in the volume during the shear failure) at lower stress levels (Vesic and Clough 1968; Bishop 1972; Billam 1972; Kumar et al. 2007). It is noted that an addition of silica fume in sand leads to a decrease in the friction angles for the same range of relative density. The value of ϕ was seen to vary in between (i) 29.47o and 40.62o for clean sand, (ii) 27.06o and 34.7o for sand with 15% silica fume, and (iii) 25.06o and 32.06o for sand with 30% silica fume.

IV. COMPUTATION OF SHAFT RESISTANCE OFFERED BY THE PISTON

All the cone penetration tests were carried out up to a maximum of 100 mm of vertical penetration of the cone in the soil sample. The cone was attached to the bottom of the piston having a diameter of 19.5 mm which is equal to the diameter of the miniature cone. In the earlier studies by Kumar and Raju (2008, 2009) the diameter of the piston is kept smaller than the cone so that not much resistance was offered by the piston shaft. However the standard electrical cone penetrometer has the same diameter of the sleeve and cone. So in the present study the cone and the shaft diameter are kept equal and there is no reduced area behind the cone. It was a difficult task to experimentally measure explicitly the shaft resistance offered by the piston shaft itself. However, in order to get an estimate of the shaft resistance offered by the piston, Ko state (at rest) of stress in the soil mass surrounding the piston shaft was assumed. The value of the earth pressure coefficient (Ko) at rest was taken equal to (1-sin ϕ), and the interface friction angle (δ) between the soil mass and the piston shaft, which was made of stainless steel, was taken equal to ϕ /2 (Kumar and Raju, 2008). It was based on guidelines given by Durgunoglu and Mitchell (1975) and Susila and Hryciw (2003) for the case when the diameter of the shaft is kept exactly the same as that of the cone. The exact value of δ, however, will not only depend on the roughness of the chosen steel shaft, but also on the type of soil mass and the magnitude of the applied stress; however, no attempt was made to measure the exact value of δ in this experimental program. For a given magnitude of cone penetration, the total load taken by the shaft will accordingly depend on the total surface area of the piston in contact with the soil mass. Since the shaft area of the piston will increase with an increase in the magnitude of the cone penetration, the total frictional resistance exerted by the surface area of the shaft will also increase with an increase in the penetration of the cone in the soil mass. The computed values of the total shaft resistance (load) offered by the piston, as a percentage of total measured resistance (total load) corresponding to the penetration of the cone at ultimate tip resistance for all the samples used in this study, are shown in Table 4. For clean sand, the total shaft resistance corresponding to the ultimate tip resistance was found in between 1.13% to 6.64%, sand with 15% silica fume it was found in between 4.94% to 24.50% and sand with 30% silica fume it was found in between 5.68% to 24.73%. The shaft resistance decreased with an increase in the relative density of the sample; this is due to the fact that the value of the term Kotan(ϕ /2), in the expression of the total shaft resistance, reduced from 0.134 to 0.121 with an increase of ϕ from 30o (loose state) to 45o(dense state). Also with increase in vertical effective stress the shaft resistance was found to increase for all the samples. In addition the shaft resistance was found to become lower for a smaller content of silica fume. It is expected that the shaft resistance offered by the piston will be higher in the present case as compared to the studies of Kumar and Raju (2008, 2009), as in the present study the piston shaft and cone are of same diameter.

V. THE VARIATION OF CONE TIP RESISTANCE

The variation of the cone tip resistance, obtained by deducting the contribution of the shaft resistance from the total measured load for a given level of penetration, with increase in the vertical displacement of the cone is shown in Figs.4-6 for loose clean sand, sand with 15% silica fume in loose state, and sand with 30% silica fume in loose state, typical results are given only for loose states in all the three materials whereas all other graphs are not provided herein just for restricting the size of the article. It should be mentioned that for the conventional cone penetration testing, the cone is driven at a much faster rate (20 mm / sec), and therefore the magnitude of the ultimate resistance is arrived at instantaneously. On the other hand, in the present case, the rate of penetration of the cone is much slower, which are 1 / 200 of the rate of the penetration usually employed, and, therefore, it was possible to monitor the gradual increase of the load with the increase in displacement until ultimate failure. It can be clearly seen that an increase in the magnitude of the vertical stress leads to a clear increase in the magnitude of the tip resistance for a given magnitude of cone penetration in the soil mass. Also, it is observed that for a given soil mass an increase in the density of soil mass leads to an increase in the tip resistance of the cone. The variation of the ultimate cone tip resistance with an increase in the effective vertical stress in case of sand with 15% silica fume in loose state and sand with 30% silica fume in loose state are shown in Figs.7-8, all other figures are not showed herein just to restrict the size of the article. The addition of silica fume in sand decreases both the minimum and maximum unit weights of the material. Also it is noticed that with increase in percentage of silica fume to sand for the same range of relative density decreases the magnitude of ultimate cone top resistance (qcu). The values of qcu for given values of soil friction angle and vertical stress were also determined from the correlation curves of Durgunoglu and Mitchell (1975), Robertson and Campanella (1983) and Kumar and Raju (2008) which are applicable for normally consolidated cohesionless deposits.

Also it is established by Kumar and Raju (2008) that by employing a chamber diameter of 91 mm the experimental values lie generally in between the predictions of Durgunoglu and Mitchell (1975), Robertson and Campanella (1983). For sand with 15% silica fume and Sand with 30% silica fume the results compare reasonably well with the predictions of Durgunoglu and Mitchell (1975), Robertson and Campanella (1983) and Kumar and Raju (2008).

VI. CORRELATION BETWEEN Q_{CU}/Σ_V AND ϕ

The correlation between qcu/σv and ϕ for all the tests results are shown in Fig.9. It should be mentioned that the dependency of peak friction angle (ϕ) as given in Fig.3 has been taken into account. It is noteworthy that the entire miniature cone penetration data, associated with the different range of relative densities and vertical effective stresses for all the three materials, namely, clean sand, sand with 15% silica fume and, sand with 30% silica fume, almost lie on a straight line, the equation of which can be defined by means of the following expression:

$$\frac{q_{cu}}{\sigma_v} = 12.229\phi - 342.58$$

For the chosen data, the square of the regression coefficient (r) for the above expression was found to be equal to 0.8213. It is expected that the above correlation, will provide a reasonable good estimation for determining the magnitude of peak friction angle from the known values of qcu and σv for sand – silica fume mixtures; this correlation will be valid for ϕ > 28.01o (qcu/ σv > 0).

VII. DISCUSSION

As mentioned in the studies of Kumar and Raju (2008, 2009), there are primarily three factors that make the values of qcu of the standard electric cone penetrometer different from those predicted by the miniature cone used in the present investigations. The differences arises mainly on account of (i) smaller size of the chosen cone, (ii) smaller size of the cell (calibration chamber), and lower rate of penetration employed in the experiments. A brief discussion on the effects of these factors is provided herein.

VIII. EFFECT OF CONE SIZE

De Lima and Tumay (1991) carried out a detailed in-situ investigation at five different sites using cone penetrometers with cross-sectional areas of 1.27 cm2, 10 cm2 and 15 cm2. The soils in these sites comprise of sands, silts and clays. De Lima & Tumay (1991) found that the cone resistance from 1.27 cm2 cone penetrometer was consistently greater than the standard 10 cm2 penetrometer. For practical purposes they recommended that for a cone with an area 1.27 cm2, a multiplication factor of 0.85 could be used to obtain the reference 10 cm2 cone tip resistance. They also concluded that no significant correction was necessary for correcting the cone resistance and friction ratio of 10 cm2 and 15 cm2 penetrometers. In conclusions it was suggested that in practice cone penetrometers ranging in cross section from 5 cm2 to 15 cm2 will give almost similar cone resistance in most soils. For an area of the cone outside this range it was suggested that a correction needs to be employed. Therefore, for the present 3 cm2 cone, the correction factor should range between 0.85 and 1.0. As the research study of De Lima and Tumay (1991) is on sites comprising of sands, silts and clays, it is expected that the conclusions derived from this investigation will remain applicable for sand mixed with dry silica fume.

IX. EFFECT OF CHAMBER SIZE

The problem of determining the influence of the calibration chamber size on the penetration resistance has been extensively addressed (Ghionna and Jamiolkowski 1992; Schnaid and Houlsby 1991; Lunne et al. 1997). Although a few discrepancies exist between the different studies, it has been generally noticed that (i) penetration tests performed at smaller Dcc/dct ratios often have a lower penetration resistance than at higher Dcc/dct ratios and (ii) the effect of the boundary conditions on the penetration resistance is generally more substantial as the relative density of soil mass is increased, where Dcc and dct are the diameters of the calibration chamber and cone, respectively. Kulhawy and Mayne (1990) proposed the following relationship to the calibration chamber data for cohesionless soils:

$$q_{c-field} = q_{c-lab}\left[\frac{(D_{cc}/d_{ct} - 1)}{70}\right]^{-0.005D_r}$$

Where qc-field and qc-lab refers to the values of qcu determined under identical conditions from field and laboratory (using a calibration chamber), respectively. This relationship is based on the assumption that there are no boundary effects when Dcc/dct equals or exceeds 70. As per this equation for the present experimental set up, the value of the correction factor will increase from 1.53 for Dr = 40% to 2.35 for Dr = 80%. It needs to be mentioned that the relationship proposed by Kulhawy and Mayne (1990) is valid mainly for cohesionless soils. However, it cannot be simply concluded that this relationship will still hold true for sand mixed with a considerable percentage of dry silica fume. Therefore, a number of laboratory tests will be further needed, for various sizes of calibration chambers, on sand mixed with different percentages of silica fume to comment about the applicability of the relationship proposed by Kulhawy and Mayne (1990). The present data when compared to earlier studies of Kumar and Raju (2009), for Dcc/dct = 4.67 the correction factor varies from 1.80 for Dr = 40% to 3.25 for Dr = 80%. As in the present experimental set up the ratio of Dcc/dct = 9.23, so it can be noted that as the ratio of Dcc/dct increases the correction factors tends to decrease.

X. PENETRATION RATE EFFECT

Dayal and Allen (1975) have completed several cone penetration tests in silica sand by varying the penetration rate from 1.3 to 811.4 mm/s; the relative density of the sand was changed from a loose state to dense state. It was observed that the tip resistance of the cone in sand for the different relative densities remains almost invariant with respect to the variation in penetration rate. On the other hand, Te Kamp (1982) has shown that a decrease in the penetration rate leads to a decrease in the tip resistance by employing an electrical penetrometer in dense fine sands; the rate of penetration was varied from 0.033 to 100 mm/s (much lower than that used earlier by Dayal and Allen (1975). Te Kamp (1982) further indicated that qcu associated with a penetration rate of 0.2 mm/s is approximately 0.8 – 0.9 times that associated with the standard penetration rate of 20 mm/s. Juran and Tumay (1989) varied the penetration rate between 2 to 100 mm/s and concluded that the penetration rate of the cone has almost no effect on the tip resistance of the cone. The effect of penetration rate on the tip resistance of a miniature cone for different cohesionless materials was examined by Kumar and Raju (2009).

A series of miniature cone penetration tests were conducted for three different materials namely clean sand, silty sand and sand added with fly ash. The penetration rate was varied from 0.6mm/min to 6.0mm/min. It was noted that for clean and silty sand, the effect of penetration rate was found to be marginal where as for sand added with 30% fly ash the effect was found to be significant at lower penetration rates. It was noted that the effect of penetration rate on qcu was seen to increase continuously with a reduction in the rate of penetration. It is also observed that as the penetration rate increases from 3mm/min to 6mm/min there is no effect on the tip resistance of the cone. Hence it can be concluded from the studies of Kumar and Raju (2009) that at a much higher penetration rate which is closer to the one adopted in practice, it is however, anticipated that the effect of penetration rate on qcu especially for clean sand will not remain very significant. As the values of the correction factors, other than those arising from the cone size, are greater than unity, it is expected that the measured value of the qcu will be smaller than the standard electric cone penetrated into the ground at the standard rate; the correction factor due to the chamber size as per eq. (2) may vary in between 1.53 to 2.35. On the other hand, the minimum value of the correction factor as per the observation of De Lima and Tumay (1991), due to the cone size effect will be 0.85. As compared with the standard electric cone employed in field at the standard penetration rate, the miniature cone used in this study for a cohesionless material will generally result in a lower value of qcu. In other words, the measured values of qcu from the miniature cone in a triaxial chamber will have to be generally multiplied with a correction factor greater than 1.0 to obtain the corresponding value associated with the standard electric cone in a very large-size calibration chamber. However the true correction factor will only be known if for the same soil sample, under identical values of the vertical effective stresses, tests are carried out simultaneously both by using the miniature cone as it was done in the present study in a triaxial chamber and standard size cone in a very large size calibration chamber so that the boundary effects remain minimal.

XI. REMARKS

(1) The mode of origin of silica fume is different from that of sand and silts. However, as the present study is focused entirely on the dry states of the material, in the absence of any pozzolanic reaction, the silica fume will remain like a cohesionless soil and therefore, the comparisons of qcu values were made with the applicable correlations for cohesionless materials.

(2) The value of ϕ was obtained from direct shear tests. Direct shear tests were employed on account of simplicity. However, it will be more appropriate to develop correlations based on triaxial shear tests as the penetration of the cone in a cylindrical chamber will simulate more closely than triaxial state of stress.

XII. CONCLUSIONS

An attempt has been made in this article to determine the tip resistance of a miniature cone with the help of a conventional triaxial setup for samples of dry sand added with dry silica fume. The value of the ultimate cone tip resistance (qcu) was found to increase continuously, as expected, with an increase in both the effective stress level and relative density of soil mass. For the same range of relative density, the values of qcu were found to decrease significantly with the increase in the percentage of silica fume to the sand. By incorporating the effect of stress level on the friction angle of the clean sand and sand added with silica fume, it was noted that the magnitude of qcu/σv increases almost linearly with an increase in ϕ. It is expected that this study will be useful in establishing correlations between tip resistance, friction angle and overburden stress for different types of loose to dense cohesionless deposits. As compared to the standard cone which is usually employed in field, the miniature cone used in this study is expected to result in general to be a reasonable good prediction, perhaps sometimes a little conservative estimate, of the cone penetration resistance for a cohesionless medium even though (i) the ratio of the diameter of calibration chamber (cell) to that of cone is not very high, and (ii) the chosen size of the cone is smaller than the standard one.

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