Effects of Non-Plastic Fines on the Behavior of Loose Sand– An Experimental Study

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ABSTRACT

The behavior of sand is affected by the content of non-plastic fine particles. How and to what degree the fines content affects the minimum and maximum void ratios, angle of internal friction and bearing capacity have been studied in detail. A systematic experimental study is performed of the variation of minimum and maximum void ratios, angle of internal friction and bearing capacity with contents of fines for sands. It is shown that the fines content plays an important role in determining the minimum and maximum void ratios, angle of internal friction and bearing capacity. Results of the laboratory tests shows that maximum and minimum void ratios of clean sand decreases as fine content increases from 0 to 20% and increases if fines content exceeds 20%. Results also indicate that angle of internal friction and bearing capacity decreases on the addition of fines due to compressibility of fines.

KEYWORDS: Minimum and maximum void ratio; Bearing Capacity; Fines content; Angle of internal friction.

INTRODUCTION

Along the Indo-Gangetic planes, the Indian subcontinent has vast deposits of silty sands along the bank of perennial Himalayan Rivers, where the river sands as are obtained with varied proportions of non plastic silts. The authors have diverse experiences with the soil exploration of these deposits for structural foundations [1]. As per soil classification systems, the sand and silt are coarse and fine grained granular materials. It is obtained in abundance as geological deposits in the earth crust. They occur with varied surface textures and shapes ranging from angular to spherical with moisture in void space. In modern times, some of the granular industrial byproducts deposited as structural fill with common range of specific gravity, unit weight and grain characteristics are often classified for sizes as sand and silts [2].

Over past fifty years there were intensive attempts to characterize sandy soil without fines [3-6]. However there were efforts to map the engineering behavior of silty sands. It is observed that silty sands are deposited largely in a low to medium density states with mixed proportions of moisture. This material supports structural rafts and deep foundations for multistoried buildings, underground excavations, tunnels and pipelines. There is a need to characterize this granular media as an engineering material. The role of non-plastic silt on the behavior of loose sand is a matter of interest for the engineers. Natural sands contain a significant and varying amount of fines, whereas the current knowledge is primarily based on clean sands [7, 8]. Silty sands are one of the most common soils which are encountered during construction of footings.

This study was undertaken to investigate the influence of fine content on the minimum and maximum void ratios, angle of internal friction and bearing capacity of clean sand. By testing both clean sand and silty sand under similar conditions, conclusions can be drawn.

MATERIALS AND METHODS

The study was conducted on clean sand which was used after washing. After washing sand contains 0% fines and it was designated as clean sand. It is standard, clean quartz sand with grain size distribution shown in Fig. 1. The specific gravity of the sand particles was 2.67 which were determined by the pycnometer method [9]. The non plastic fines which passes through IS 75μ sieve were used. The fines were prepared in the laboratory. Numbers of soil sample were taken from nearby area and then wet analysis was carried to know the percentage of particles passing 75 μ sieves. After processing, soil was finalized for the preparation of fines which have a maximum amount of particles passing 75 μ. A wet analysis was carried on the selected soil samples. The material which passes through 75 μ was collected in a container and allowed to settle. Then the passing material is dried in the oven and pulverized. The pulverized material was again sieved though 75 μ sieve. Then a hydrometer analysis was carried out [10] to know the amount of clay particles. The amount of clay particles was found insignificant. The specific gravity of fines was 2.63. The maximum and the minimum dry densities of the sand were found to be 1.77 kN/m^3 and 1.57 kN/m^3 and the corresponding values of the minimum and the maximum void ratios was 0.50 and 0.70, respectively determined [11]. Clean sand was classified as SP according to Unified classification system. The effective size (D_{10}),the mean grain size(D_{50}), coefficient of uniformity (C_u), and coefficient of curvature(C_c), for sand were 0.19 mm, 0.50 mm, 2.9, 1.007, respectively. Fig. 1 shows the grain size analysis of clean sand, sand with varying percentage of fines and that of fines. Clean sand particles are round to angular.

The sand and fines selected for evaluation of its bearing capacity was characterized by various established techniques. X-ray diffraction study was carried out to identify the various phases present in the sand and fines as shown in Fig. 2. X-ray diffraction of sand showed that the existence of SiO_2 phase only .The fines contain $Al_3\,Si_3\,O_{10}\,(OH)_{10}$ phase along with SiO_2 phase. However the volume fraction of $Al_3\,Si_3\,O_{10}\,(OH)_{10}$ is very less as compared to SiO_2.In addition to this X-ray diffraction of fines also shows the peak shifting at higher diffraction angle with peak broadening which is clearly indicate that fines has more disordering as compared to sand. The identification of specific crystalline mineral was based on Bragg's equation,

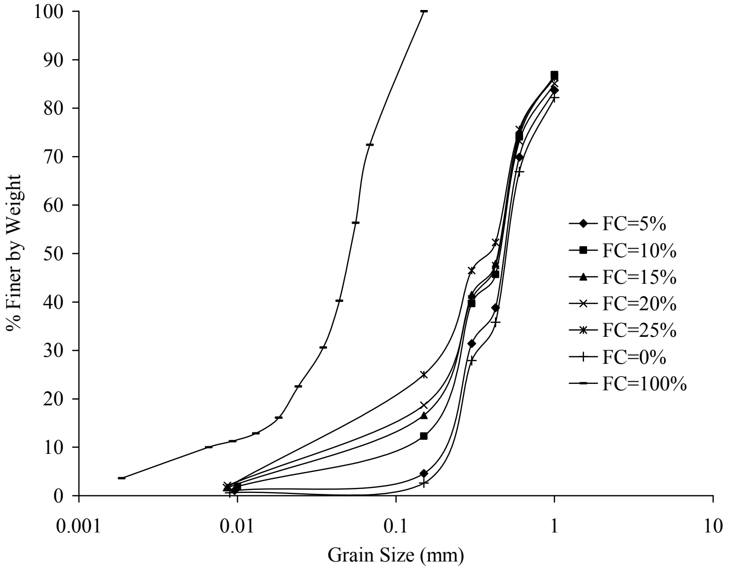


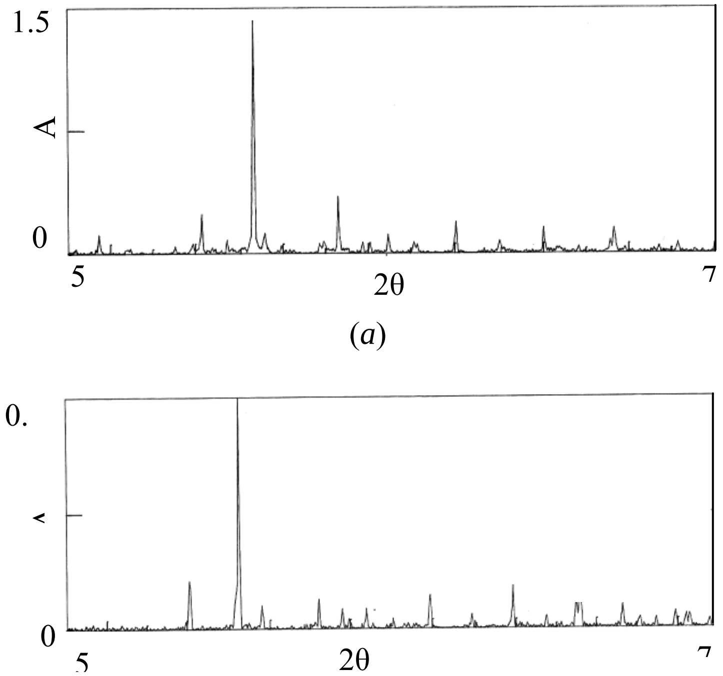
Figure 1: Grain size distribution of clean sand, silt and sand with varying proportion of fine.

$$\lambda = 2d \sin 2\theta \qquad (1)$$

Where λ is the wave length of X-ray specific to the Cu target element (=1.542 Å) and d is the inter planner spacing. The test was conducted between 10° and 100° (2θ), at the rate of 2°/s using the CuK_{α} characteristic radiation of Cu target element. The inter planner spacing of respective peaks on the X-ray pattern were calculated from the corresponding 2θ angle. These peaks were associated with the characteristic minerals.

EXPERIMENTAL PROGRAM AND PROCEDURES

In order to explain the effect of fines on the behavior of clean sand, an experimental programme was developed. The experimental study was carried out for fine content in the range of 0 to 25%. A series of triaxial shear tests, relative density tests and model plate load test were performed to assess the effect of fine content on angle of internal friction, minimum and maximum void ratios and bearing capacity of clean sand. A summary of the experimental program is given in Table 1 (a), (b) and (c).



(*a*)

(*b*)

Figure 2: X-ray diffraction pattern of: (*a*) Fines; (*b*) Sand

Table 1(a): A Summary of Experimental Program for Relative Density Test

Test Series	Parameter	FC (%)	No. of Tests
1.	Maximum Void ratio	0, 5, 10, 15, 20, 25%	06
2.	Minimum Void ratio	0, 5, 10, 15, 20, 25%	06
3.	Natural Void ratio	0, 5, 10, 15, 20, 25%	06

Table 1(b): A Summary of Experimental Program for Triaxial Shear Test

Test Series	FC (%)	Cell pressure (kPa)	No of Tests
A	0	50,100,150	03
B	5	50,100,150	03
C	10	50,100,150	03
D	15	50,100,150	03
E	20	50,100,150	03
F	25	50,100,150	03

Table 1(c): A Summary of Experimental Program for Model Plate Load Test

Test Series	FC (%)	Diameter of Footing (m)	No. of Tests
1.	0, 5, 10, 15, 20, 25%	0.10	06

Minimum and Maximum Void Ratios

The concept of relative density is used in the present study despite having been subjected to some criticism. The criticism has focused on difficulties in obtaining $e_{\min}$ and $e_{\max}$**,** particularly for sands with more than 15% fines content [13, 14]. However, careful execution of a specific procedure to determine $e_{\max}$ and $e_{\min}$ does lead to reasonably reproducible numbers. Additionally ,important advantage are offered by the use of relative density , notably that relative density allows unification of the description of the density or degree of compaction of granular soils with fine content ranging from 0 to 20 % with respect to the densest and loosest possible states of these soils.

In their studies of the undrained properties of Brenda tailings sand, Kuerbis, Nagussey and Vaid [15] found that the maximum and minimum void ratios of silty sand decreased as silt content increase from 0 to 20%.Similar results were observed by Ladd and Yamannuro [16] for Navada and Ottawa sands mixed with non-plastic fines and in the present study, clean sand mixed with varying percentages of fines.

In the present study minimum and maximum void ratios were determined [11]. Minimum density was obtained by pouring sand into a standard mold with a volume of 3000cm^3 using a thin wall funnel. Maximum density was obtained by densifying dry sand in a standard mold of 3000cm^3 using a motorized vertically vibrating table at a frequency of 3600 vibrations per minute, a vibrator amplitude variable between 0.05 and 0.65 mm under a 115 kg load. The loaded specimen was vibrated on vibrating table for 8 minutes.

Table 2: Values of relative density, unit weight, maximum and minimum void ratios on the addition of fines content

Sr. No.	FC (%)	$\gamma_{\min}$ (kN/m^3)	$\gamma_{\max}$ (kN/m^3)	γ_{nat} (kN/m^3)	RD (%)	e_{min}	e_{max}	e_{nat}	e_{sk}
1	0	15.6	17.7	16.6	50.77	0.51	0.71	0.61	0.61
2	5	15.6	18.5	16.95	50.80	0.44	0.71	0.57	0.66
3	10	15.5	19.0	17.15	51.98	0.40	0.72	0.55	0.73
4	15	15.6	19.3	17.32	51.80	0.38	0.71	0.54	0.81
5	20	15.7	19.5	17.58	54.87	0.37	0.70	0.52	0.89
6	25	15.4	19.2	17.15	51.88	0.39	0.73	0.56	1.07

For a given overall void ratio, there is a fines content for which they completely (or almost completely) separate adjacent sand particles. An easy way to determine the fines content for which this happens is based on the concept of the skeleton void ratio e_{sk} [15], which is the void ratio of the silty sand calculated as if fines were voids

$$e_{sk} = \frac{(1+e)}{(1-f)} - 1 \tag{2}$$

Where e=overall void ratio of soil; and f =ratio of weight of fines to total weight of solids. Whenever e_{sk} is greater than the maximum void ratio $(e_{max})_{f=0}$ of clean sand, the sand matrix exists with a void ratio higher than it could achieve in the absence of fines. It means that the sand particles are, on average, not in contact, and the mechanical behavior is no longer controlled by the sand matrix.

Table 3 gives value of specific gravity of clean sand and sand with varying percentages of fines content. From the table it is clear that that value of specific gravity decreases on the addition of fines up to 10% and it attains a constant value of 2.64 if fines are further added.

Table 3: Angle of Internal Friction and Specific Gravity with Varied Proportions of Fines

FC (%)	γ_{nat} (kN/m^3)	RD (%)	ϕ (degrees)	G
0	16.9	62.84	40.75	2.68
5	17.3	62.68	39.53	2.67
10	17.8	69.81	38.97	2.64
15	18.4	79.37	37.62	2.64
20	18.6	80.00	36.99	2.64
25	18.1	75.85	36.69	2.64

Triaxial Shear Test

A series of triaxial shear tests were performed on clean sand and on sand with varying fine content [12] in order to know the effect of fines on the value of angle of internal friction. The samples were prepared by estimating the weight of sand and silt needed for desired percentage of fine content. The weighed amount of silt and sand were then mixed properly. The samples were prepared in accordance [12] and was fitted into position. The cell pressure of 50 kPa was then applied. After the required cell pressure is applied, the sample was sheared by applying additional axial stress. The process is to be repeated for the next higher value of cell pressure. By the same procedure two more sample were tested at a cell pressure of 100 and 150 kPa for different sample of soil having different proportions of fines. The results are shown in Table 3. It is noticed that the as proportions of fines are increased, the angle of internal friction decreases.

Model Plate Load Test

Series of laboratory model tests were conducted in a test box, loading frame assembly. The soil beds were prepared in a test tank with inside dimensions of 0.60 m X 0.60 m X 0.60 m. The sand particles were deposited in the tank-box by rain fall method. The model tests were conducted for footing of diameters 0.1 m diameter in dry condition for different proportions of fines (i.e. 0-25%). After the soil surface was set up, the footing was placed on position, and the load was applied on it by the hydraulic jack. The load was applied in increments. The displacement of the plate was monitored using pre-calibrated settlement gauges of least count 0.01mm. Each load increment was maintained constant until the footing settlement is less than 0.02mm/hour. The total assembly including hydraulic jack, proving ring and the plate was aligned with the help of plumb bob to attain verticality [4].

The typically sketch of the apparatus is illustrated in Fig. 3. The typical pressure settlement plots are shown in Fig. 4. The pressure settlement plots have varying stages of implicit failure at each data point. At a low settlement ratio (*S/B*) only limited failure is initiated. The settlement ratio is defined as a ratio of settlement (S) to the width of the footing (B) [4]. In the present study the ultimate capacity is evaluated as the bearing pressure, which produced a relative settlement of 10% of diameter of footing (i.e. $S/D=0.1$). Although choosing to define q_{ult} at a relative settlement of *S/D* is completely arbitrary, it (i) is convenient and easy to remember, (ii) may actually be close to the average soil strain at failure, (iii) forces a fixed value at q_{ult}, and (iv) treats the displacement of all footing sizes the same [4, 17]. The test program consisted of carrying out series of tests on the circular model footing to study the effect of fines. Initially, the behavior of the footing supported on the clean conditions was determined. Then, each series of the tests was carried out to study the effect of fine content.

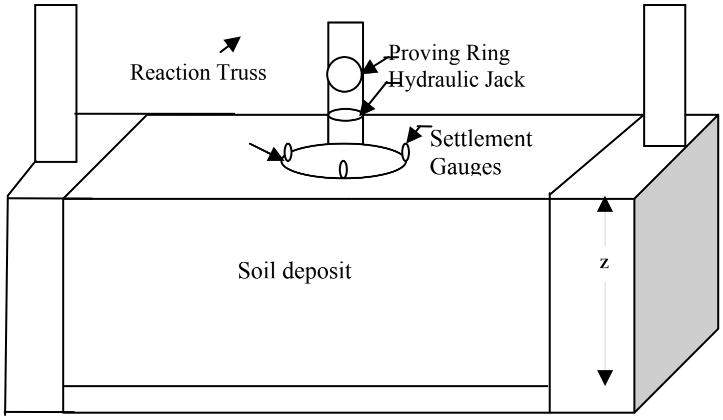


Figure 3: Line sketch of plate load test (free scale)

RESULTS AND DISCUSSIONS

In the present study minimum and maximum void ratios were determined [11]. Table 2 gives maximum and minimum void ratios of clean sand and sand with varying amount of fines content. From the table it is clear that e_{max} and e_{min} of clean sand decreases as fine content increases from 0 to 20%. The e_{max} and e_{min} increases if fines content exceeds 20%.

Ladd and Yamannuro [16] have explained the pattern of decreasing the maximum and minimum void ratios of silty sand with increasing fine content. With increasing percentage of fines in a dense or loose sand matrix, most particles initially occupy the voids among sand particles. This represents the reduction in void ratio with increasing the amount of fines. Some silt particles, however, end up between the surfaces of adjacent sand particles. Such particles would tend to cause an increase in void ratio, as they do not occupy the natural void space left by the sand matrix. This process pushes sand particles apart.

Fig. 4 shows the skeleton void ratio as a function of void ratio for 5, 10, 15, 20 and 25% fines. For each gradation, a limit void ratio (and a corresponding limit relative density) can be defined. For Ghaggar clean sand, with $e_{max} = 0.72$, these relative densities are 28.52% for 5% fines, 50.96% for 10% fines, 70.98% for 15% fines, and 93.23% for 20% fines. From the Fig. 4, it is also clear that the calculation of limit void ratio is not possible for a fine content of 25%. For relative densities lower than the limit relative density, the fines control and the behavior becomes that of a sandy silt or sandy clay, depending on the nature of the fines. For soils denser than the limit relative density, the behavior is that of sand, modified by the presence of fines.

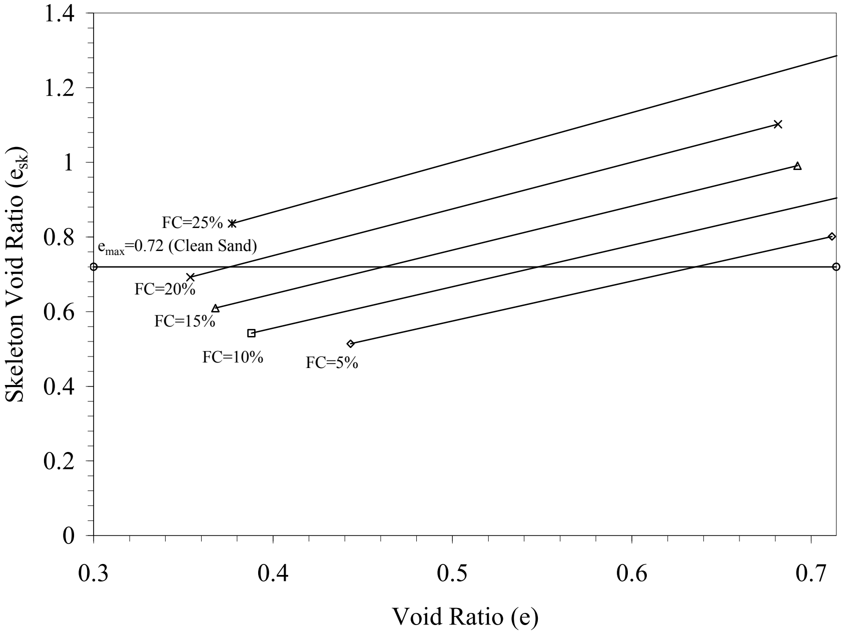


Figure 4: Limit Void Ratio for 5, 10, 15, and 20% Silt Content

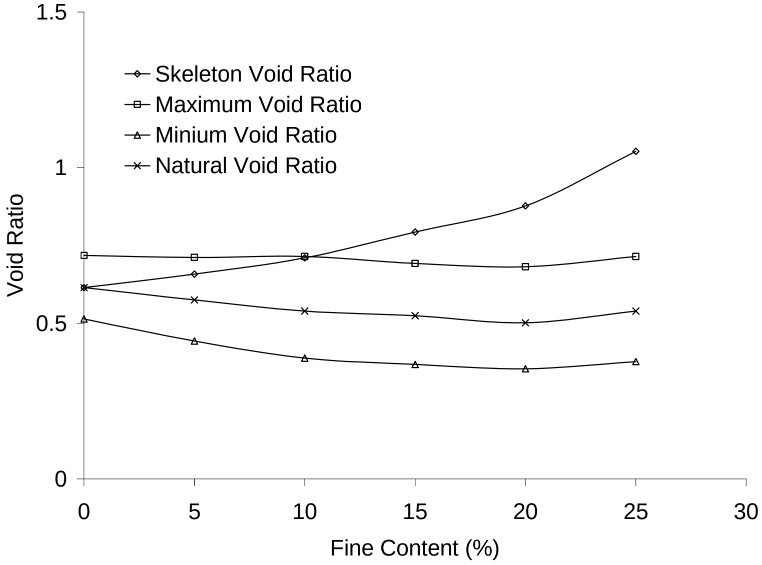


Figure 5: Variation of Skeleton, minimum, maximum, and natural void ratio with fine content.

Fig. 5 shows the variation of different types of void ratios with fine content. From the graph it has been seen that skeleton void ratio increases on the addition of fines whereas natural, minimum, and maximum void ratio decreases when fine content is increased up to 20%.When fines are increased further the void ratios increases. It has also been seen that skeleton void ratio is higher than maximum void ratio when fine content is increased beyond 15%. Skeleton void ratio (e_{sk}) is greater than the maximum void ratio $(e_{max})_{f=0}$ of clean sand corresponding to a fine content of 15%.It means that the sand particles are, on average ,not in contact, and the mechanical behavior is no longer controlled by the sand matrix.

Typical results of triaxial shear tests for clean sand and with increasing proportions of fine content are presented in Fig. 6 & 7. It has been seen that with increasing fines content, failure shear stress decreases. p-q diagram is shown in Fig. 8. It is noticed that the slope of failure envelope decreases with increasing fine content i.e. angle of internal friction decreases with increasing fine content. This may be because although density increases on the increasing amount of fines but at the same time compressibility increases and may have a more pronounced influence in comparison to density and it leads to plastic type of behavior. At a fine content of 20%, the soil look like a fine-grained soil and it seems that the coarse-grained matrix is missing in the soil mass matrix.

Circular footing on clean sand and sand with increasing percentages of fines content were tested to investigate the effect of fine content on bearing capacity of clean sand. Typical results of load curves for the footing tests performed in this study are presented in Fig. 9. From the Fig. 9 it is clear that as we increase the fine content bearing capacity decreases and settlement increases. The ultimate bearing capacity was taken at the stress at a footing displacement of 10% of the footing diameter for consistency. Most of the load–settlement curves in this study indicated local or punching shear failure. Local shear failure usually occurs with a footing resting on a sand of medium density whereas punching shear failure occurs in very loose soils.

The results of experiments conducted for estimation of bearing capacity for varying fine content are plotted as shown in Fig. 10. Best-fit trend lines were drawn through the test results. These results show a decrease in bearing capacity on the addition of fines. This may be due to the fact that although density increases on the increasing amount of fines but at the same time compressibility increases and which has a more pronounced influence in comparison to the overall density of the soils. All the tests were performed with a soil layer of sufficient thickness (3B), which has been found adequate for rigid boundary effect below the footing [18] .The tank wall was kept at distance of 2.5B to avoid any lateral pressure interference.

CONCLUSIONS

The objective of this paper was to study the effect of non-plastic fines on the behavior of loose sand. Based on this experimental study, the following conclusions are drawn.

Results of shear tests indicate that the angle of internal friction decreases with addition of fines. Increasing fines, the compressibility increases hence the failure stress decreases.

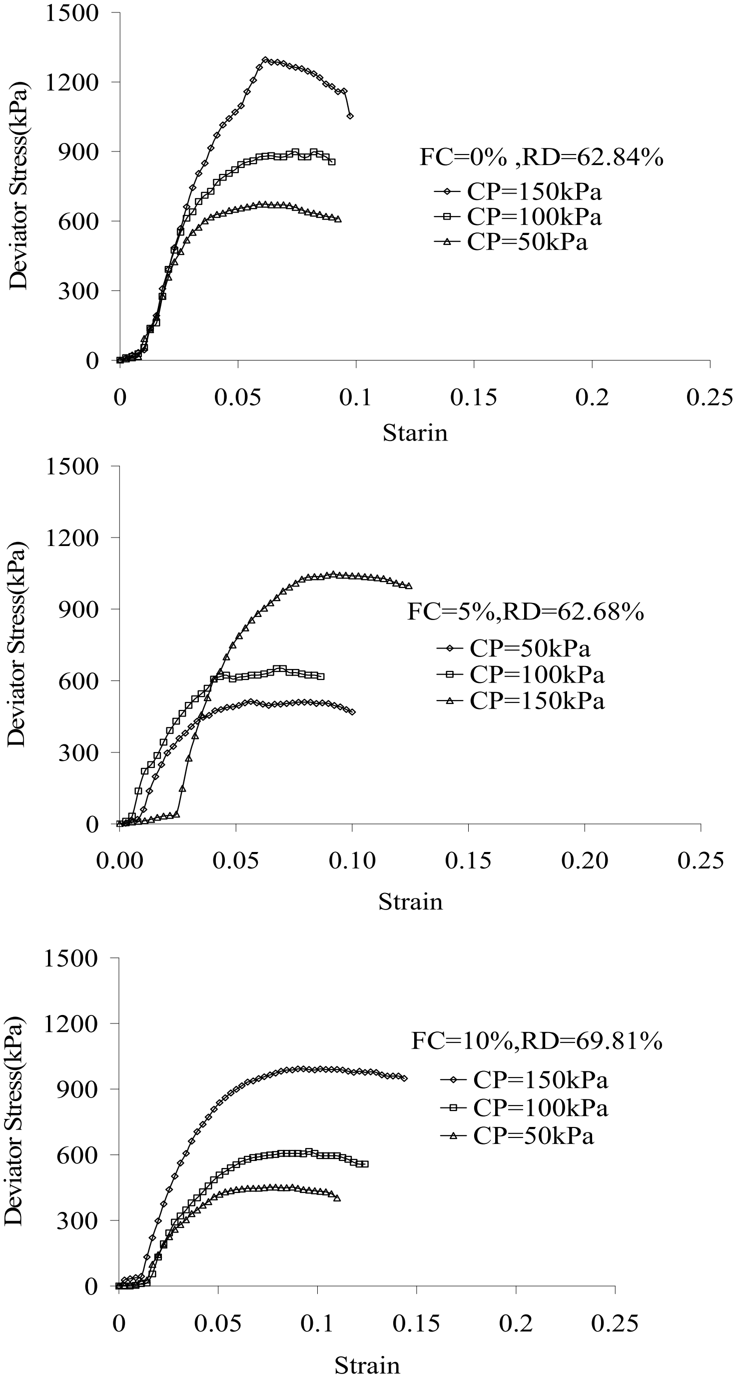


Figure 6: Results of Triaxial shear test for samples of: (a) 0%; (b) 5%; (c) 10%.

2. Results indicate that skeleton void ratio (e_{sk}) is greater than the maximum void ratio ($(e_{max})_{f=0}$) of clean sand corresponding to a fine content of 15%. It means that the sand particles are, on average, not in contact, and the mechanical behavior is no longer controlled by the sand matrix.

3. The values of e_{max} and $e_{\min}$ of clean sand decreases as fine content increases from 0 to 20%.The $e_{\max}$ and $e_{\min}$ increases if fines content exceeds 20%. Increasing percentage of fines in a dense or loose sand matrix, most particles initially occupy the voids among sand particles. This represents the reduction in void ratio with increasing the amount of fines. Some silt particles, however, end up between the surfaces of adjacent sand particles. Such particles would tend to cause an increase in void ratio, as they do not occupy the natural void space left by the sand matrix. This process pushes sand particles apart.

4. The model scale footing tests on clean sand and sand with increasing fines indicate that bearing capacity depends upon the fine content. Bearing capacity decreases with increasing percentage of fines because settlement increases due to compressibility of fines.

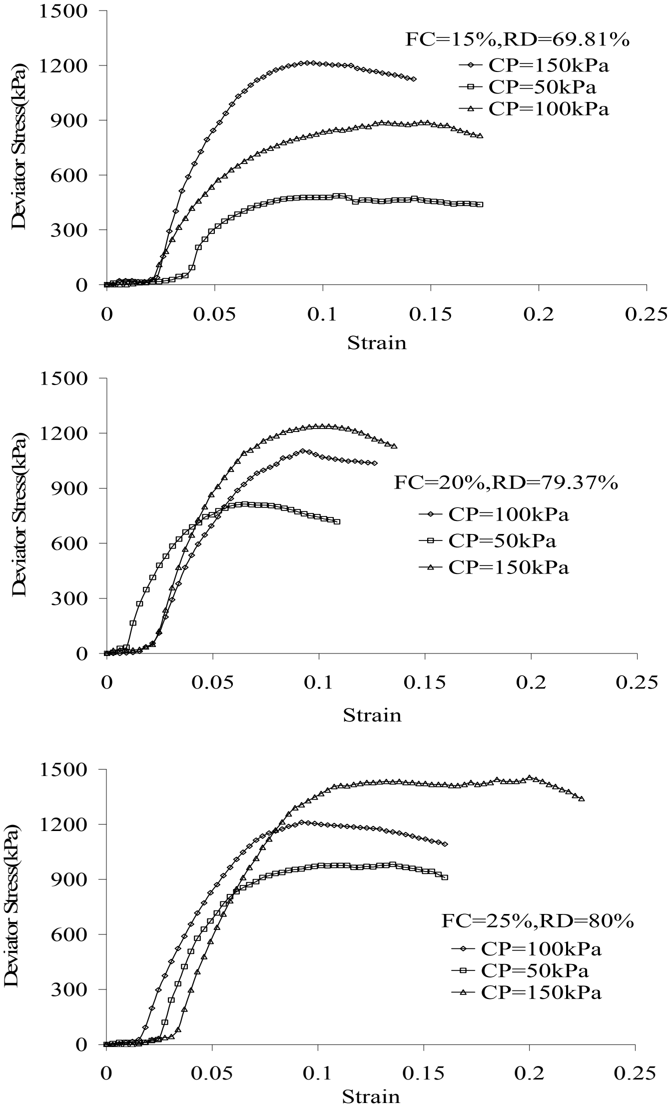


Figure 7: Results of Triaxial shear test for samples of: (a) 15%; (b) 20% ; (c) 25%

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NOTATION

The following symbols are used in this paper:

Cc = coefficient of curvature for the sand;

C_u = uniformity coefficient;

D = footing diameter;

D10 = effective size;

D50 = mean size (mm);

e_{max} = maximum void ratio;

emin = minimum void Ratio;

e_{nat} = natural void ratio ;

e_{sk} = skeleton void ratio;

FC = fines content;

G = specific gravity;

S = footing settlement;

S_D = settlement ratio = S/D;

γ_{max} = natural unit weight;

γ_{min} = natural unit weight;

γ_{nat} = natural unit weight;

ϕ = angle of internal friction;

p = $(\sigma 1+ \sigma 3)/2$;

q = $(\sigma 1- \sigma 3)/2$;

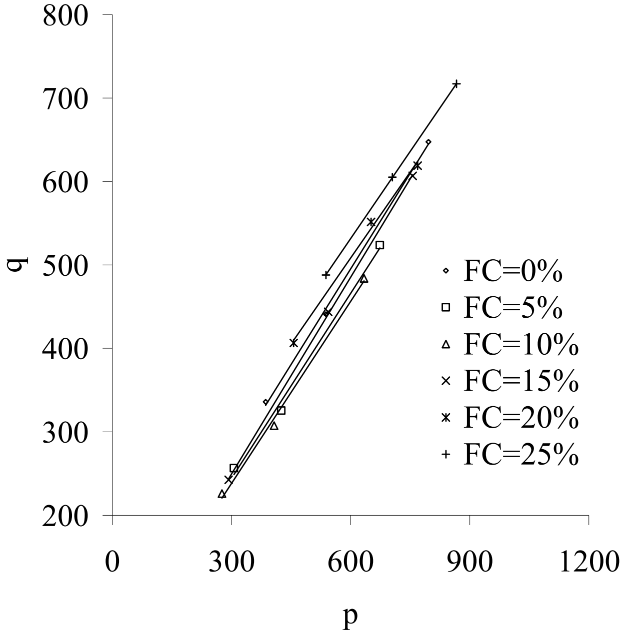

Figure 8: Variation of 'p' with 'q' for different proportions of fines

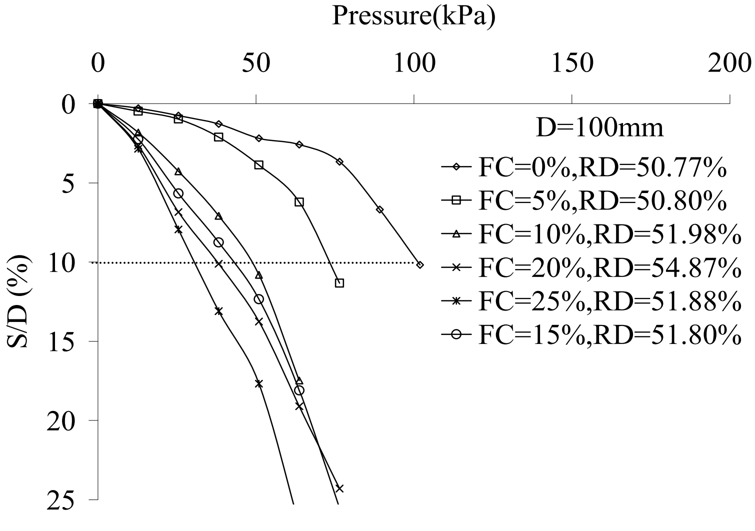

Figure 9: Variation of bearing pressure with settlement for different proportions of fines

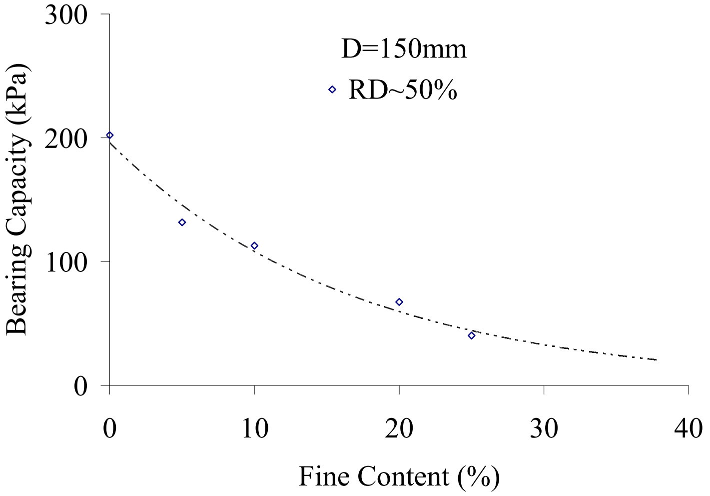

Figure 10: Variation of bearing capacity with different proportions of fines.

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