Stress dilatancy relation of sea deposits off Mumbai coast

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ABSTRACT: It is not unusual for the offshore deposits to carry loads in excess to their ultimate capacity, when these soils bear the loads of heavy oil platforms. These soils contain high calcium carbonate content, which make them prone to particle-crushing at these high loads. This paper investigates the effect of particle breakage on the load response of offshore marine deposits. Two sea deposits off Mumbai coast were chosen for the tests. Both the soils had similar mineralogical composition. In this study, dilatancy was studied as a function of particle crushing at crushing stresses up to 4.5 MPa. A series of direct shear tests were performed on samples which were crushed to various loads. The experimental results showed that with increase in extent of crushing, dilatancy decreased up to a point and then increased. It also indicates that crushing takes place to a considerable extent even after settlements have reached a near constant value. The decrease in dilatancy with increase in particle crushing was more pronounced in angular particles than sub rounded and rounded particles. This was also confirmed from the SEM images. Stress-dilatancy equations of both the soils were developed using drained shear tests. Particle breakage seem to significantly affect the measured coefficient of friction and hence the dilatancy component.

Keywords: Dilatancy, particle crushing, shear strength

1. Introduction

Any country‘s economic growth is closely related to the energy demand which is most often satisfied by the oil and natural gas industry. Offshore platforms have moved to deeper depths, where the mechanical characteristics of the soft soil sediments can altogether be different. Many researchers have worked on the geotechnical investigation and site characterisation of offshore construction. Loads of the order 10,000 to 30000 tonnes can be expected to be imposed on foundations of these structures. Such heavy loads cause the soil to crush under the foundation because of very high compressive stresses. All this would affect the soil dilatancy. It is an important characteristic of the soil which governs its strength at high confining pressures especially in these case. Particle crushing is one of the factors which can alter dilatancy of the soil. Crushing influences the peak strength of the soil which in turn is a function of stress dilatancy and the friction angle at critical state. Hence study on effect of crushing on dilatancy of soil would be empirical to understand its strength behaviour.

1.1 Background

Reynold (1885) coined the term dilatancy after his observation on volumetric response of dense materials during shearing. For given stress levels, loose sands contracts upon shearing and reach a state of constant shear stress and constant volume called as critical state (Schofield and Worth 1968). However, dense sands show a volumetric increment i.e. dilation as the shearing progresses and reach critical state at very large strains. Taylor (1948) was the first to study stress-dilatancy relation. Taylor considered strain energy and developed the following equation (Eq.1) based on conservation of energy during shearing.

$$\frac{\tau}{\sigma}+\frac{d\varepsilon_v}{d\gamma}=\mu \qquad (1)$$

Where, τ = Shear stress mobilized on the shear plane, σ = effective normal stress across shear plane, $d\varepsilon_v$ = volumetric strain increment, $d\gamma$ = shear strain increment and μ = coefficient of friction

Houlsby (1991) carried out theoretical and numerical analysis on effect of dilatancy on various practical problems such as slope stability, bearing capacity of surface footings and piles. A fivefold increase in bearing capacity of pile was observed when dilation angle was varied from 0^0 to 20^0 indicating the significance of dilatancy at high confinement pressure.

Many researchers have worked on the methods to quantify the particle crushing. Marshal (1973) used grain-size distribution before and after crushing and defined a term called breakage factor (B_g) that represented the sum total of increase in the mass retained on each sieve used to perform gradation. Miura and Ohara (1979) defined breakage as change in specific surface area as he assumed, soil particles to be spherical in shape and calculated specific surface area using mean diameter of each sieve. Luzzani and Coop (2002) investigated relation between volume change and particle crushing through ring shear testing.

1.2 Objective

Objective of the study is to find the effect of particle crushing on dilatancy characteristics of offshore deposits. This was accomplished by inducing particle crushing in the soil by the way of applying high compressive stress under a compression frame and then determining its strength and dilatancy property by direct shear testing. Particle crushing was quantified based on a term called relative breakage (Br) introduced by Hardin (1985). Br is defined as

$$B_r = \frac{B_t}{B_p} \tag{2}$$

Where, B_t = the total breakage defined as area between initial and current grain-size distribution; B_p is the breakage potential defined as the area between initial distribution and cutoff distribution of silt size particles(75 micron).Dark grey and light grey portions in Fig. 1 represent the terms B_t and B_p respectively.

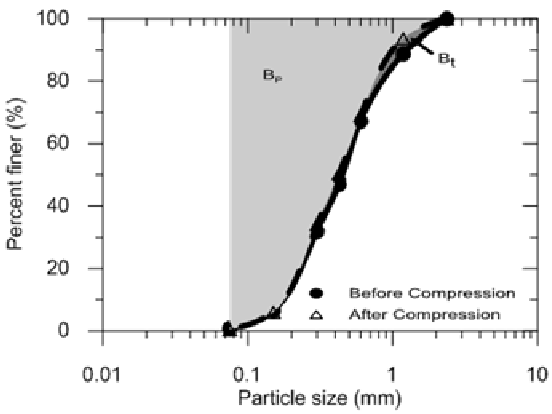


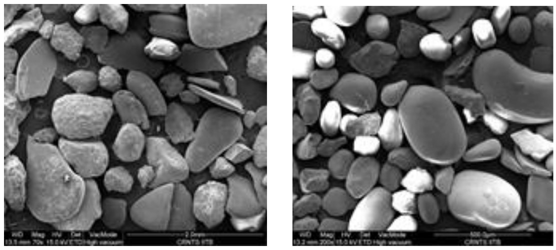
Fig. 1 Grain size distribution curves of sand A, before and after crushing

2. Experimental Investigation

Two offshore samples obtained from the Arabian sea off Mumbai coast were used. These samples are labelled as Sand A and B, respectively, in this study. Physical properties of the test materials are summarised in Table 1

Table 1 Physical properties of soils

Soil	Gs	emax	emin	D10	D50	Cu	Cc
Sand A	2.81	0.802	0.453	0.185	0.495	3.08	1.12
Sand B	2.78	0.834	0.437	0.078	0.19	2.94	0.87



a) Sand A b)Sand B

Fig. 2 SEM Images of offshore deposits.

Sand A consisted of angular particles and Sand B comprised of rounded to sub-rounded particles as observed in Fig. 2. Test samples were prepared by placing the sand in a 50 mm diameter, 24 mm high cylindrical mould. About 75g of the soil was taken for the test. The samples were crushed by applying compressive load of 1 to 4.5 MPa. In each case, the gradation of the soil was determined prior and after the application of the crushing load using a set of sieves. Pressure was applied after the settlement reached a constant value and until 1 to 3 days. However in some samples, the load was applied up to 5 days. Sieve analysis was conducted on the sample after the test also to determine the change in particle size distribution due to crushing. Hardin's Total and relative breakage (B_R) was then obtained from the particle gradation curves.

Crushed sample were then subjected to direct shear testing for determination of angle of dilatancy. The cylindrical mould used for crushing had smaller dimensions, therefore the mass of sample available for direct shear test was lesser than usual test. So sample thickness in the apparatus had to be reduced. This was achieved by using acrylic blocks of dimensions 60mm x 60mm x 13mm as spacer, both at the top and bottom which reduced the thickness of sample to about 10mm.The modified apparatus was calibrated to account for the difference in the measured angle of friction. For this purpose, test was carried out with and without the blocks and the difference in the stress strain response indicated an overestimation of measured friction angle. It is noteworthy that the samples were failed under a normal load of 50 to 150 kN/m^2 which is the usual confining stress experienced by the soils below and surrounding the heavy offshore foundations. This difference was deducted from stress-strain curve of modified apparatus to obtain true stress-strain behaviour of the sample. Bolton's relation (Eq. (3)) was used to determine angle of dilatancy.

$$\Phi_{ps} - 0.8\psi = \Phi_{cv} \quad (3)$$

Where, ϕ_{ps} is peak angle of friction, ψ is angle of dilation and ϕ_{cv} is critical state angle of friction

3. Results and Discussions

Two soil samples were subjected to compressive stresses upto 4.5 MPa and tested using direct shear apparatus for determination of its strength and dilatancy behaviour. On comparing the grain size distribution curves before and after compression the Hardin's total and relative breakage term was obtained. The total breakage was found to be dependent on both the magnitude and duration of stress applied. Fig. 1 shows the initial and current grain size distribution curves of Sand A, when subjected to compressive stress of 4.5 MPa for 5 days. It is evident that the coarser particles had undergone crushing as there is a drift in the gradation curve towards left at larger particle size which gradually coincides with the virgin curve on moving downwards. On the other hand in Sand B which comprised of mainly rounded to sub rounded particles the reverse was true.

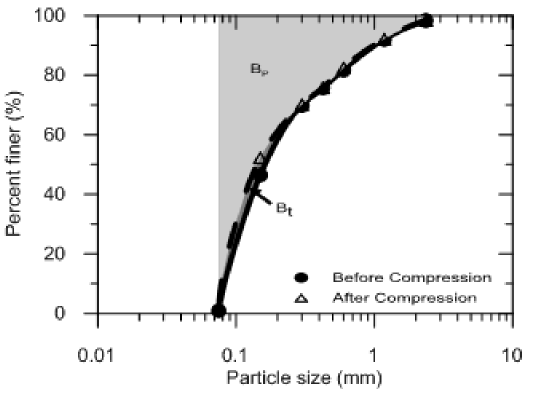


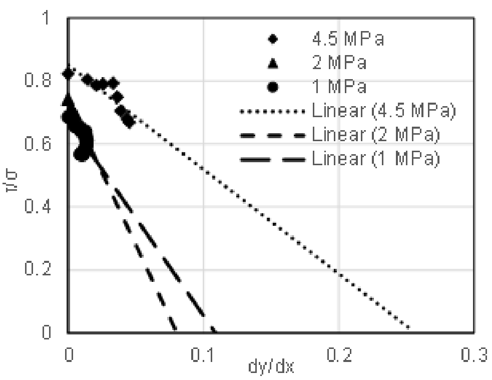
Fig. 3 Grain size distribution of sand B, before and after crushing

The variation of angle of dilatancy with total breakage was studied. The evolution of Br with crushing load for both the sample is shown in Table 2. It is obvious that relative breakage increases with increase in crushing load. However, it is noticeable that considerable crushing takes place even after the settlement has reached a near constant value. Sand A exhibited comparatively higher crushing than Sand B which can be attributed to angularity in its particle shape.

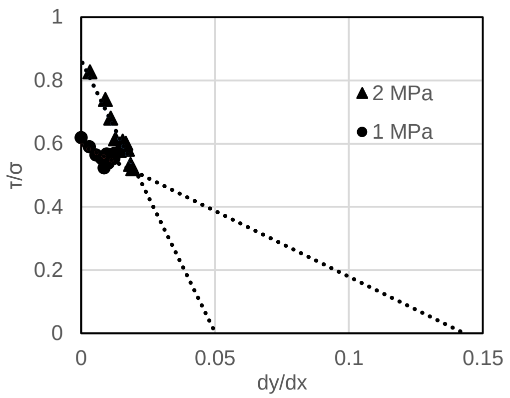
The stress strain behaviour of soil samples post crushing was obtained from direct shear testing. The results were calibrated to account for the modification done to the direct shear apparatus. Figure 4 shows the variation of shear stress normalized by vertical stress and the ratio of vertical strain increment to horizontal strain increment for both the sands. dεv / dγ component in the Taylor's stress dilatancy relation is equal to –dy/dx.

Table 2 Variation of relative breakage with crushing

Sand A			
Crushing stress (MPa)	Duration of crushing (days)	Total breakage, Bt	Relative Breakage, Br
1	5	0.2927	0.001954
2	1	0.032	0.000213
2	3	0.329	0.002196
4.5	1	0.322	0.002149
4.5	5	2.67	0.017825
Sand B			
1	5	0.001	6.67E-06
2	1	0.0095	6.34E-05
2	3	0.256	0.001709
4.5	1	0.3653	0.002438
4.5	5	2.224	0.014847



a) Sand A



b) Sand B

Fig. 4 Stress dilatancy relation for offshore soils

Figure 5 shows the variation of angle of dilatancy with total breakage for both the samples. It can be inferred that for small increment in total breakage B_t, a good deal of decrease in angle of dilation was found. This could be due to decrease in the angularity of the particles. Also the fall in dilation angle was found to be more for angular Sand 'A' than sub-rounded Sand 'B'. This confirms that the initial drop was due to decrease in the angularity of the particles. However, in both cases, it could be seen that the dilation angle goes on decreasing and reaches a minimum value and there after increases. Although the decrease was expected, yet it is difficult to explain the increase in the dilation after the transient drop, especially since both the samples exhibit similar behaviour. One possible reason for this behaviour is that the particle crushing created additional contact points which offsetted the otherwise decreasing trend in the dilatancy component. These additional contact points helped increase the shear strength of both the soils which, in the figure is reflected by the increase in the dilatancy. This effect perhaps also shadowed the otherwise decreasing dilatancy component when the soil roughness reduced by particle crushing. This needs further investigation.

4. Conclusions

Particle breakage was induced on two offshore deposits of Mumbai at high compressive loads.Change in the particle size as a consequence of soil crushing was very less due to low range of crushing stress adopted in the testing. Although with the increase in crushing, the dilatancy decreased initially owing to decrease in the angularity of the particle. The decrease was followed by an increase in dilatancy. Further study on soils crushed at higher stresses would help to better understand the relation between particle crushing and dilatancy. The breakage continued even after the settlement reached a near constant value.

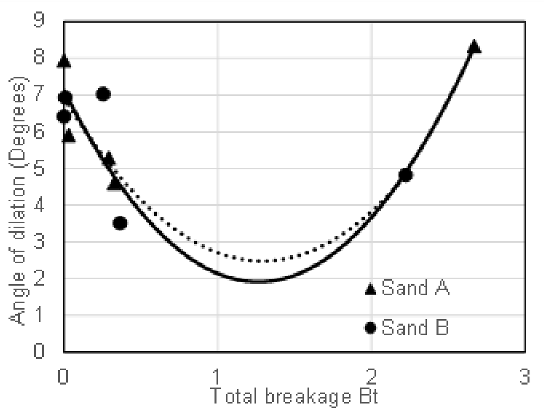


Fig. 5 Variation of Dilation angle with Total breakage

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