Influence of Moisture on the Shear Parameters of Partially Saturated Cohesionless Soils

by

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Introduction

THE shear strength characteristics of soils play a very important role in the design of earth and earth retaining structures and the structures supported by the soils. Granular soils like sand and gravel are usually taken as cohesionless and the shear strength is expressed in terms of angle of internal friction ϕ' with respect to effective stresses. Further it is assumed that this parameter is unaffected by the presence of moisture as long as the stresses applied are under fully drained conditions.

However, it is well-known that in case of partially saturated soils, due to capillarity, the pore water is under tension, *i.e.*, a negative pore pressure exists in the pores of soil mass which contributes to the shear strength. This contribution is more or less independent of external stresses and is commonly known as apparent cohesion.

The apparent cohesion is in general neglected in the study of long-term stability as it depends, among other factors, mainly on the moisture content of the soil which varies with seasonal changes. However, the apparent cohesion is of considerable significance in case of temporary excavations and struttings, *etc.* This point is illustrated by the fact that in practice, construction slopes in cohesionless soils are found to be stable at a slope much greater than ϕ', though in stability analysis on the basis of friction only, a slope is not supposed to be stable at an angle greater than ϕ'.

Review of Literature

Terzaghi's effective stress equation

$$\sigma' = \sigma - u \quad \ldots (1)$$

is no more valid for partially saturated soils. Bishop (1960), Atchison and Bishop (1960), modified the Terzaghi's expression (1) for soils with air

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and water in the pore space in the following form :

$$\sigma'=\sigma-u_a'+\chi\,(u_a-u_w) \qquad ...(2)$$

where u_a = air pressure in pore space

u_w = water pressure in pore space

u_a-u_w = suction

χ = factor depending upon degree of saturation, soil type, cycle of wetting and drying.

Since pressures are usually referred to atmospheric and if the pore air pressure is atmospheric Equation (2) may be written as (Jennings 1960, 1962)

$$\sigma'=\sigma-\chi u_w$$
$$=\sigma+Kp'' \qquad ...(3)$$

where K = parameter depending on soil type and degree of saturation.

p'' = soil moisture suction.

For convenience Equation (3) may be written as

$$\sigma'=\sigma+\sigma'' \qquad ...(4)$$

where $\sigma''=Kp''$

With the relation (4) the shear strength equation for partially saturated cohesionless soils can be written as

$$s=\sigma'\tan\phi'$$
$$=(\sigma+\sigma'')\tan\phi'$$
$$=\sigma''\tan\phi'+\sigma\tan\phi'$$
$$=c'+\sigma\tan\phi' \qquad ...(5)$$

Where $c'=\sigma\tan\phi'$ is the apparent or capillary cohesion. This equation is used in evaluating the drained triaxial tests carried out on unsaturated sands in the present investigation.

APPARENT COHESION C'

To get an idea about the magnitude of apparent cohesion in granular soils Abel (1968) analyses regular packings of spheres of equal diameter (the densest quadratic and hexagonal packings) and extended the results of Wittke (1963) for the shear strength of these packings to include the effect of apparent cohesion and arrives at the following relations:

$$\sigma_{1max.}=2\,\frac{2+\sqrt{2f}}{1-\sqrt{2f}}\,\sigma_3+\frac{3\,(1+\sqrt{2f})}{2\,(1-\sqrt{2f})}\,H/R^2 \qquad ...(6)$$

—(densest hexagonal packing)

$$c'=\frac{3(1+\sqrt{2f})}{4(2+\sqrt{2f})}\sqrt{\frac{2+\sqrt{2f}}{1-\sqrt{2f}}}\,H/R^2 \qquad ...(7)$$

—(densest hexagonal packing)

$$\sigma_{1max.} = 2\frac{1+f}{1-f}\sigma_3 + \frac{1+3f}{\sqrt{2}(1-f)}H/R^2 \qquad \ldots(8)$$

—(densest quadratic packing)

$$c' = \frac{1+3f}{4\sqrt{1-f^2}}H/R^2 \qquad \ldots(9)$$

—(densest quadratic packing)

where f=Coefficient of material friction.

H=The force at a contact point due to capillarity in gm.

R=Radius of the sphere.

These relations are valid for a degree of saturation $S_r \leqslant$ 24 per cent.

From these relations for 1 mm. diameter spheres with f=0·3, these equations give a c' value of 7 gm./cm^2. for the densest hexagonal packing and 4 gm./cm^2. for the densest quadratic packing.

Donald (1956) carried out drained direct shear and triaxial tests on fine sands (0·1 to 0·04 mm.) under different pressure deficiencies of the pore water. A maximum value of about 0·07 to 0·14 kg./cm^2. was obtained for the effective stresses due to moisture films. With a value of ϕ'=35° this amounts to an apparent cohesion of about 0·05 to 0·1 kg./cm^2.

ANGLE OF INTERNAL FRICTION ϕ'

It is generally assumed that the angle of internal friction ϕ' of granular soils is independent of moisture, *i.e.*, both dry and saturated granular soils tested under fully drained conditions give the same value of ϕ'. For example, Terzaghi & Peck (1948) state that shear strength of quartz sand is unaffected by moisture. Based on shear tests on sands Taylor (1948) also comes to the same conclusion.

However, Zeller and Wullimann (1957), based on the results of a number of triaxial shear tests on coarse well graded gravels (consisting of quartz 38 per cent, feldspar 54 per cent and mica 8 per cent) in wet and dry conditions come to the conclusion that the value ϕ' is affected by moisture.

One of the major factors which contributes to the angle of internal friction ϕ' is the coefficient of material friction between individual grains. Tschebotarioff (1951) and Horn and Deere (1962) performed sliding tests on block samples of different materials and reported that water reduces friction between smooth blocks of layer-lattice minerals such as mica. Direct shear tests performed on mica gave friction values of 27° for oven dry condition, 24° for air dry condition and 16° for saturated drained condition. They however found that in case of quartz sand moisture does not affect the ϕ' value.

Drained triaxial tests on fine to medium clean sand at dry and saturated condition reported by Bishop and Eldin (1953) indicate that there is a considerable effect of moisture on the angle of internal friction. The difference was found to be about 5° for dense sand and 2° for loose sand.

Lee *et al* (1967) performed drained triaxial tests on Antioch sand at three states of moisture content, namely oven dry, air dry and saturated. The mineral composition of sand is quartz grains 50 per cent, aggregate grains 20 per cent, heavy minerals 10 per cent, others 10 per cent with mica less than 1 per cent. From this study, it is concluded that oven dry strength of sand is 35 per cent greater than that for saturated sands and dry sands are stiffer than the saturated ones. Similar tests on three more types of sands showed that the ratio of oven dry strength to saturated strength varies from 1·0 to 1·5.

Experimental Work

EXPERIMENTAL SET-UP

Drained shear tests are carried out with the standard triaxial apparatus. In all the tests samples of 3·8 cm. (1·5 in.) diameter and 7·6 cm. (3 in.) height are used.

The volume change of the specimen during the test is measured by observing the quantity of water entering or leaving the cell as the cell pressure and the axial loads are varied. The volume gauge consists of two limbs of inverted U-tube filled with two liquids of different densities. The accuracy of volume change measurements is 0.05 cc.

The lateral pressure is provided by self-compensating mercury control unit (Bishop and Henkel 1962).

SPECIMEN PREPARATION

For the preparation of the sample at different water contents, sand is mixed with the required amount of water and sealed in plastic bags and kept for 24 hours, for uniform distribution of moisture. For zero moisture tests oven dry sand has been used. The tests were performed at three different densities. The loosest density was obtained by pouring sand into the sand former with a funnel from a minimum possible height. Other densities were achieved by vibrating the sand former sufficiently while placing the sand in about 3 layers. Slight negative pressure of the order of 5 p.s.i. was applied to the drainage line to strengthen the sample while the sand former was removed.

For all the tests, the specimen was first consolidated under alround confining pressure to equilibrium indicated by no further volume change due to the pressure. The sample was sheared by increasing the deviator stress. The rate of strain applied was 0·5 mm. per minute (0·02 in. per minute) to ensure fully drained condition.

SOILS TESTED

The tests were conducted on the following two types of sands. The grain-size distribution curves of these sands are given in Figure 1.

Yamuna Sand is uniformly graded having flatter grains 0·1 to 1·0 mm.). Most of the mineral contents are quartz, feldspar and mica.

Tests were performed at three different densities, namely 1·36 gm./cc., 1·45 gm./cc., 1·56 gm./cc. and four different moisture contents, namely oven dry, 1·2 per cent, 1·88 per cent and 2·95 per cent for each density.

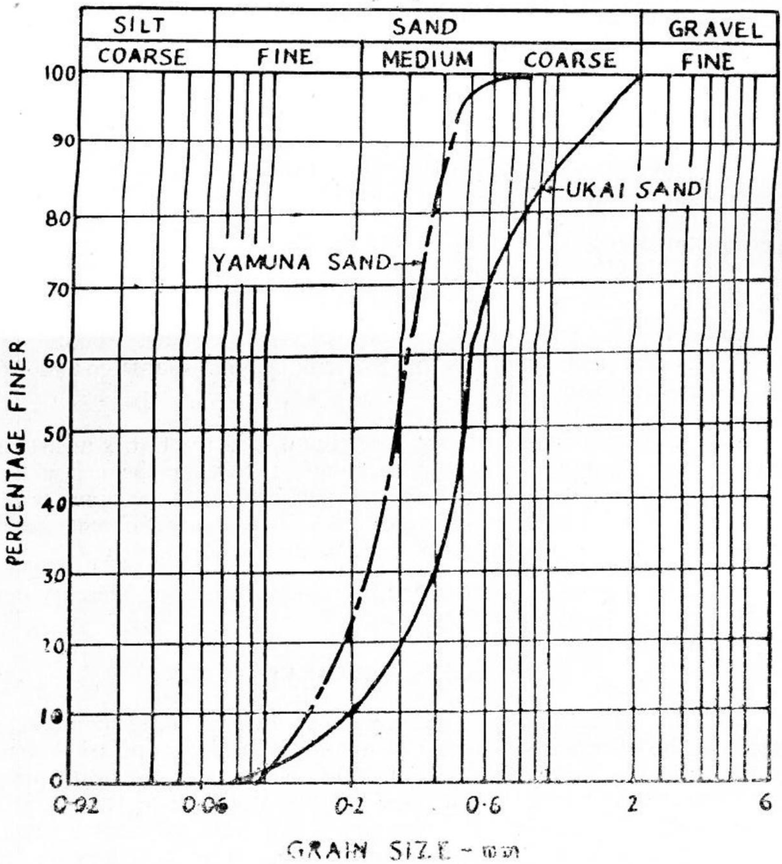

FIGURE 1: Grain-size distribution curves for the tested soils.

Ukai Sand is well graded having subrounded to rounded grains (0·08 mm. to 2·0 mm.) and is dark in colour. From examination under the petrological microscope minerals such as quartz, feldspar and mica were found to be embedded in rust coloured matrix which is probably ferruginous material.

Tests were performed at three different densities, namely 1·71 gm./cc., 1·82 gm./cc. and 1·92 gm./cc. and at four different moisture contents, namely oven dry, 0·5 per cent, 2·2 per cent and 3·2 per cent for each density.

EVALUATION OF TEST RESULTS

For all the tests angle of internal friction ϕ' and apparent cohesion c' are determined. In all these calculations peak deviator stress has been used. The cross-sectional area is computed from the assumption that the sample deforms as a right circular cylinder. Deviator stresses are corrected for volume dilation, using the equation for energy correction (Bishop 1954).

$$(\sigma_1'-\sigma_3')_r=(\sigma_1'-\sigma_3')+\frac{\delta \dot{v}}{V\delta t_1}\sigma_3' \qquad \ldots(10)$$

where $(\sigma_1'-\sigma_3')_r$=corrected deviator stress.

$(\sigma_1'-\sigma_3')$=measured deviator stress.

$\frac{\delta \dot{v}}{V\delta t_1}$ =slope of the volume strain *versus* vertical strain corresponding to peak deviator stress.

σ_3'=effective minor principal stress.

Results and Discussions

The results of all the tests are summarised in Tables I and II and some of them are presented in Figures 2 to 5. Figures 2 and 3 show deviator stress axial strain relationships at different moisture contents for both

TABLE I

Results of the Drained Tests on Yamuna sand at different Densities and Moisture Contents.

	γ_d (gm./c.c.)									
	1·36				1·45				1·56	
ω (%)	0	1·20	1·88	2.95	0	1·20	1·88	2·95	0	1·20
φ′ without energy correction in deg.	38·00	36·00	33·00	32·75	38·25	36·50	34·50	33·50	39·50	37·50
φ′ with energy correction in deg.	36·75	34·00	31·75	31·75	37·00	34·50	32·50	32·50	37·50	35·00
c′ (kg./sq. cm.)	0	0.042	0·037	0·021	0	0·088	0·070	0·037	0	0·140

TABLE II

Results of the Drained Tests on Ukai sand at different Densities and Moisture Contents.

	γ_d (gm./c.c.)											
	1.71				1·82				1·92			
ω (%)	0	0.5	2·2	3·2	0	0·5	2·2	3·2	0	0·5	2·2	3·2
φ′ without energy correction in deg.	41·00	39·00	38 50	38·25	42·25	40·00	38·75	38·50	43·50	40·50	39·00	39·00
φ′ with energy correction in deg.	38·00	36·25	35·75	35·50	—	37·00	36·25	—	—	37·50	—	—
c′ (kg./sq. cm.)	0	0·192	0·141	0·098	0	0·267	0·197	0·211	0	0·281	0·210	0·178

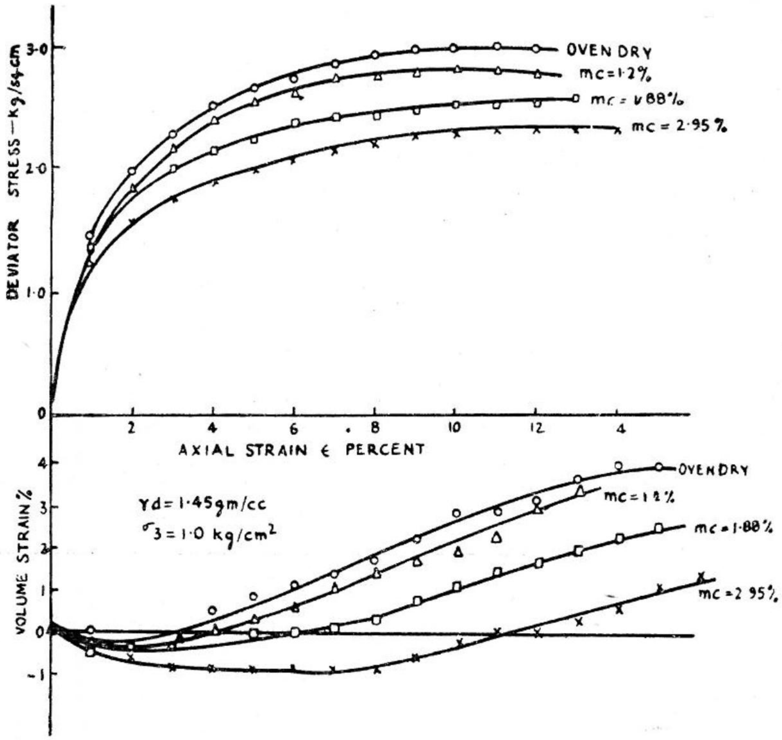

FIGURE 2 : Effect of moisture on the drained strength of Yamuna sand.

Ukai and Yamuna sands. The results correspond to the confining pressure of 1 kg./cm². and dry density of 1.45 gm./cc. in case of Yamuna sand and 1·71 gm./cc. for Ukai sand. The qualitative behaviour at other confining pressures and other dry densities is similar and as such the results are not presented in the form mentioned above.

The results indicate that the peak deviator stress is higher in case of oven dry sample, for the confining pressures used in the texts, than at other moisture contents, the former decreasing progressively with increasing moisture in the tested water content range of about 0 to 3 per cent. The failure strain increases with increasing moisture content from 11 to 15 per cent for Yamuna sand and 6 to 9 per cent for Ukai sand. Also the stiffness decreases with increasing moisture.

From the volumetric strain-axial strain curves it is evident that even for the same initial density the tendency to dilate decreases with increasing moisture content. This could be due to the capillary tension in the pore water which is equivalent to the additional confining pressure tending to hold the grains together. However, in the region of failure all the curves are nearly parallel and the energy correction due to dilatancy is nearly same in all the cases.

By comparing the results of tests with different confining pressures it was found (as is to be expected) that the tendency of dilation decreases

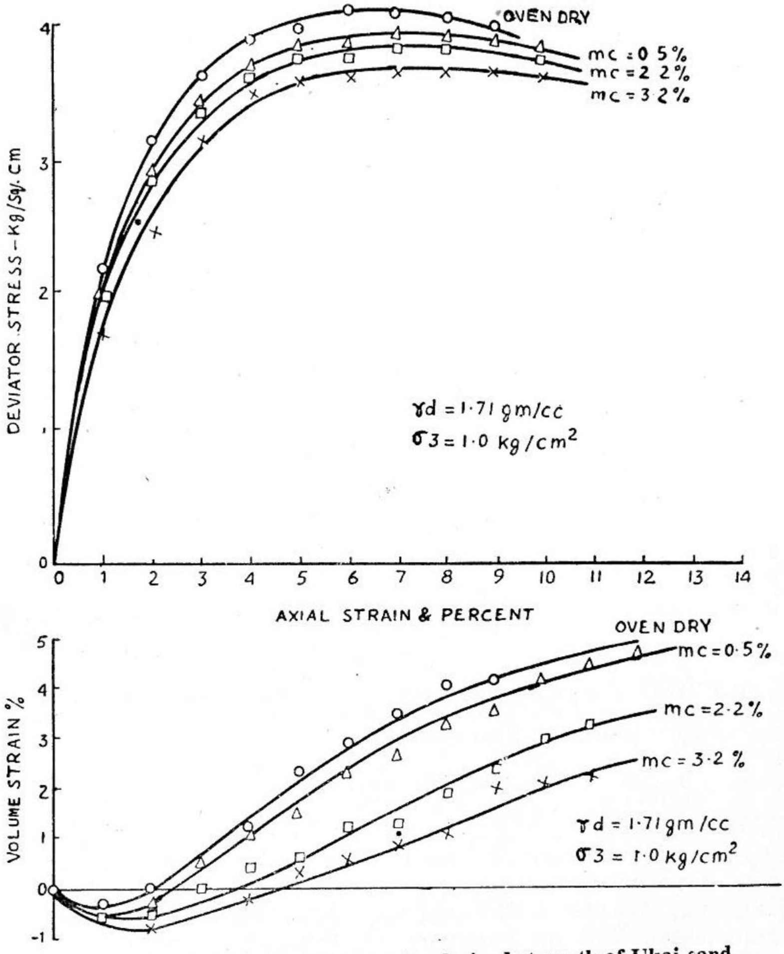

FIGURE 3 : Effect of moisture on the drained strength of Ukai sand.

with increasing confining pressure. Due to space limitation the detailed results are not presented here.

The failure envelopes for all the tests (without energy corrections) for Yamuna sand and Ukai sand are summarised in Figure 4. Figure 5 shows the corresponding results with the energy correction. In all the cases for oven dry condition the failure line passes through the origin as is to be expected in case of cohesionless sands like Yamuna and Ukai sands. With moisture the failure envelope becomes flatter and also gives a cohesion intercept. However, this intercept decreases with increasing moisture indicating that the capillary tension decreases with increasing moisture content as the curvature of the water miniscii in the soil pores decreases with increasing moisture content. The strength envelopes in Figures 4 and 5 are shown up to 1 kg /sq. cm. only. However they were observed to be linear up to the tested range of 4 kg./sq. cm. normal stress.

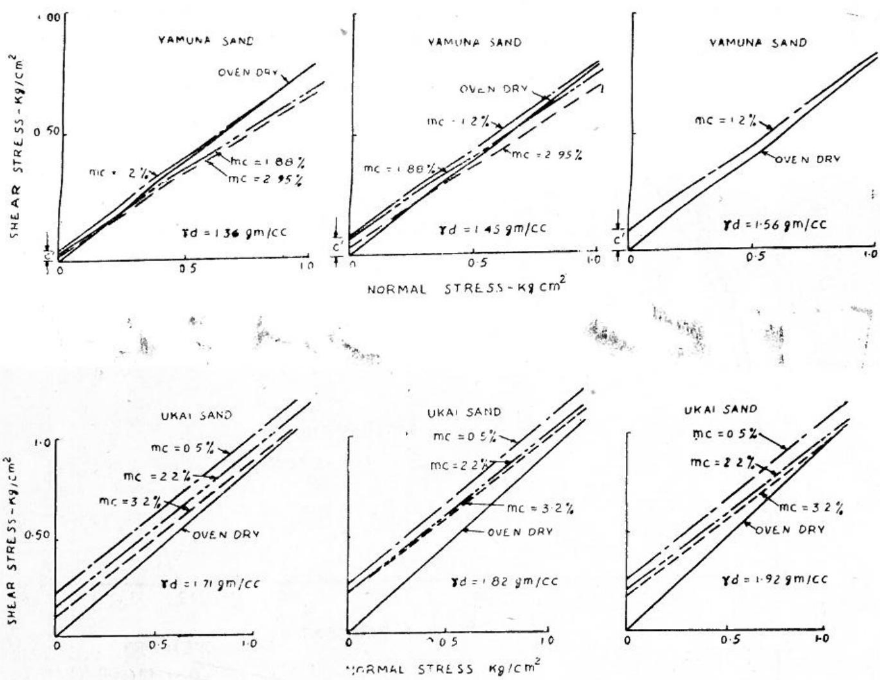

FIGURE 4 : Comparison of strength envelopes without energy correction at different moisture contents and densities for Yamuna sand and Ukai sand.

APPARENT COHESION

Apparent cohesion as a function of moisture content and density for both the sands are shown in Figure 6. As is evident from the figure the apparent cohesion starting from zero for the oven dry state increases to a maximum and then starts decreasing with increasing moisture content. This is because to start with some moisture is required for the formation of the miniscii and with further increase in moisture the curvature of the miniscii decreases, resulting in reduction of capillary tension and with it the apparent cohesion. The peak value lies between moisture range of 0 to 1·2 per cent in case of Yamuna sand and 0 to 0·5 per cent in case of Ukai sand. The curve in this portion is shown in dotted lines since no tests were conducted within this range. It is evident that to locate the peak and to find the exact nature of these curves within the mentioned ranges, further tests with moisture contents in this range are necessary. However, this information is purely of academic interests. In addition the following facts become evident from the results obtained :—

(1) The apparent cohesion increases with density, as in case of dense samples the pore sizes are smaller resulting in higher capillary pressures.

(2) The rate of decrease of apparent cohesion with increase in moisture content is more in case of higher density as the same percentage of increase in moisture content will affect the smaller pores more than the bigger ones.

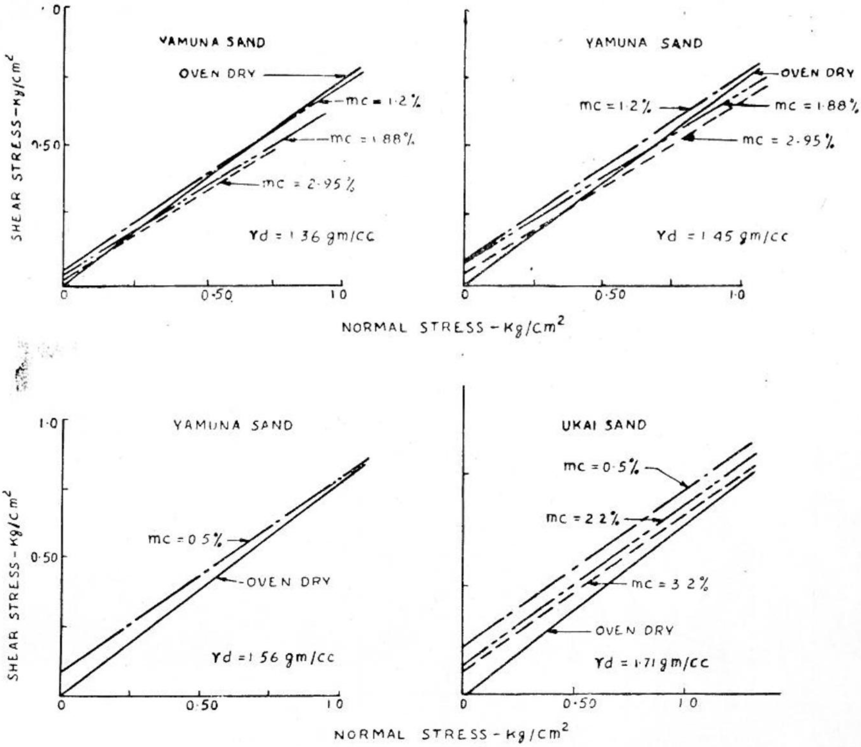

FIGURE 5 : Comparison of strength envelopes with energy correction at different moisture contents and densities for Yamuna sand and Ukai sand.

(3) For the same moisture content the apparent cohesion is more in case of Ukai sand than for Yamuna sand. This is due to the fact that Ukai sand, though coarser than Yamuna sand is well graded resulting in higher densities ($\gamma_{d\ max} = 1{\cdot}92$ gm./cc. in Ukai sand and $\gamma_{d\ max\cdot} = 1{\cdot}56$ gm./cc. in Yamuna sand). Further, the pores in case of Ukai sand are expected to be smaller. Also the value of ϕ' is greater in case of Ukai sand and this should result in higher apparent cohesion even for the same effective stresses due to capillarity as $c' = \sigma'' \tan \phi'$.

ANGLE OF INTERNAL FRICTION ϕ'

The variation of angle of internal friction ϕ' with moisture contents at different densities for Yamuna sand and Ukai sand are shown in Figure 7. The results are given for both the cases of without and with energy correction. In all the cases the angle of internal friction ϕ' decreases with increasing moisture content. This is different from what is generally assumed for granular soils. However, as mentioned earlier there is reported evidence to suggest that depending on mineral contents of the soil grains the coefficient of material friction and with it ϕ' is affected by moisture (Horne and Deere 1962, Lee *et al* 1967). According to Horne and Deere the effect is very particular in case of layered lattice minerals like mica and feldspar. The present results for Yamuna and Ukai sands are in conformity with the reported evidences.

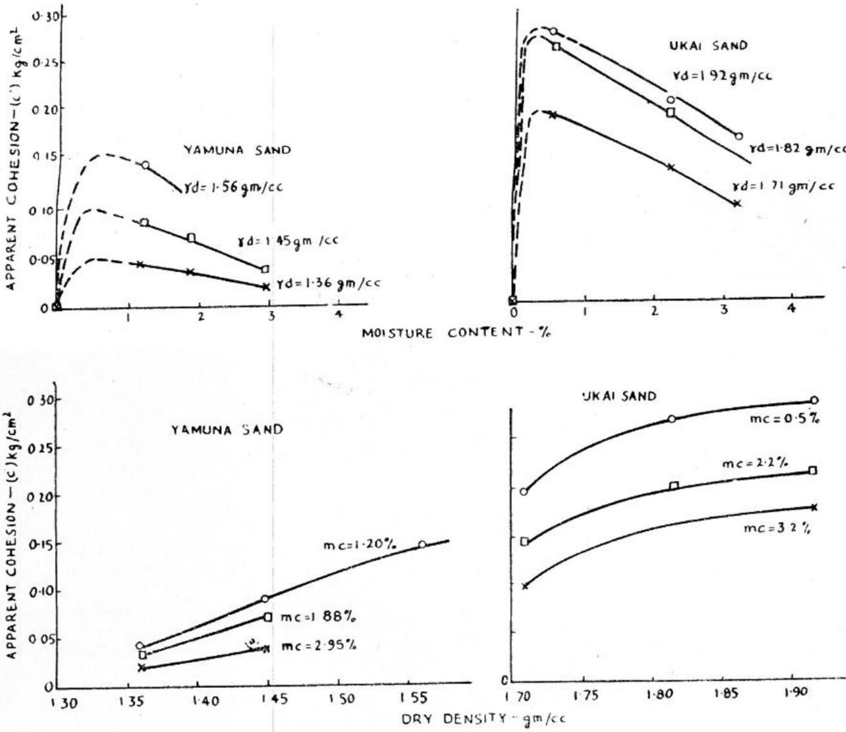

FIGURE 6 : Influence of moisture content and dry density on apparent cohesion for Yamuna sand and Ukai sand.

The rate of decrease of angle of internal friction ϕ' is more at initial stage of moisture increment and the results suggest that after a certain moisture content the value of ϕ' is not affected by further increase in moisture content. This is due to the fact that it is only a thin film of water which influences the frictional characteristics of the grains. However, there is a small moisture range within which ϕ' is affected by moisture. The decrease in ϕ' with moisture depending on density is about 4 to 5·5° in case of Yamuna sand and 3 to 5° in case of Ukai sand. The decrease is more in case of Yamuna sand probably due to the presence of higher quantities of mica.

The curves of ϕ' *versus* moisture content both without and with energy correction are almost parallel because the volumetric strain *versus* axial strain curves are also nearly parallel and the amount of energy correction is nearly the same for different moisture contents.

The angle of internal friction ϕ' for Ukai sand is greater than in case of Yamuna sand due to the difference in gradation and grain characteristics.

The fact that the angle of internal friction ϕ' is affected by moisture content, contrary to the normal assumption, is of considerable practical significance. In general it is the practice in the laboratory to carry out shear tests on dry samples whereas in the field the deposits are subjected

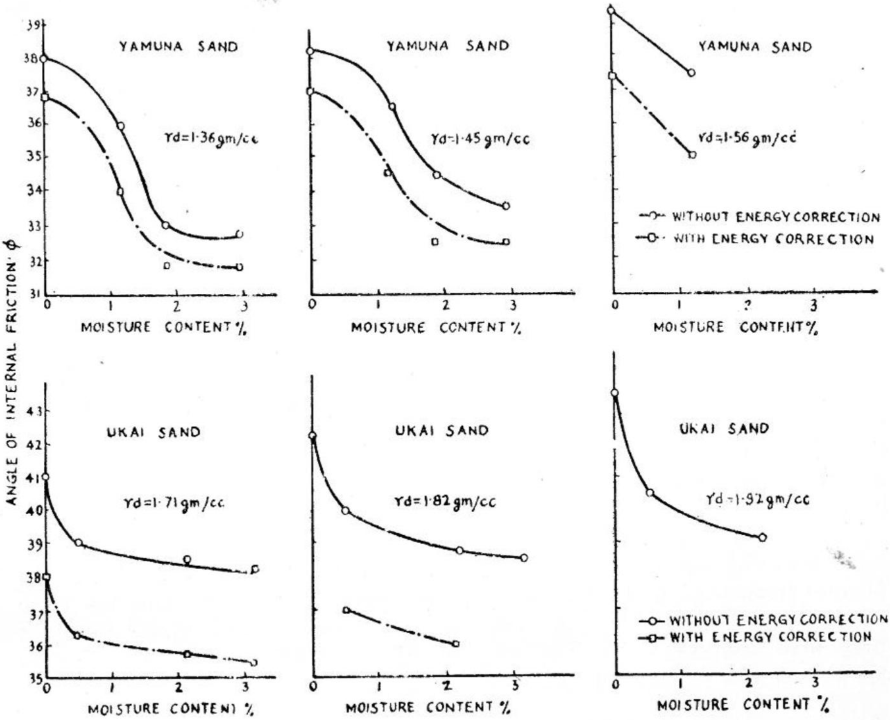

FIGURE 7 : Influence of moisture on the angle of internal friction for Yamuna sand and Ukai sand.

to different degrees of saturation. This would mean that the test results on dry samples would overestimate the shear strength and hence are on unsafe side. Therefore it is essential in practice that even in case of granular soils saturated samples are to be tested to estimate the shear strength for the long-term stability as this would give the smallest value of ϕ' and hence on the safer side. Further a mineralogical study of the soil grains would help to predict the possible decrease in ϕ' with moisture.

SHEAR STRENGTH

As already discussed failure envelopes do not pass through the origin except for zero moisture (oven dry) condition. Also from Figures 4 and 5 it is to be seen that even at the same density failure envelope for oven dry state cuts all other envelopes. The point of intersection can be called as the critical point or critical stress up to which moist cohesionless soils possess a higher shear strength than oven dry soils, though the value of ϕ' is always lesser than that for oven dry soil. This critical normal stress is dependent on both moisture content and density of the sample.

This fact has practical significance in case of slopes of temporary excavations and struttings in these soils, especially when the excavation is shallow. The apparent cohesion, even if it is small, enables slopes of shallow excavations in granular soils to be much steeper than ϕ'. Also the earth pressure against struttings will be less in such cases. No doubt the moisture content in natural soils is a variable phenomenon and depends on many factors including to seasonal changes, but in arid regions and in summer months of tropical regions the moisture content of sands, could be of the order of 2 to 3 per cent. Corresponding to this moisture content the apparent cohesion is about 0·04 kg./sq. cm. in case of Yamuna sand and 0·15 kg./sq. cm. for Ukai sand. For these soils at this condition, the unsupported height of a vertical cut with a factor of safety of 1 is about 1 m. for Yamuna sand and 3 m. for Ukai sand. Instead of a vertical cut, if a steep slope is provided, the permissible depth of unsupported excavation could be higher.

The above example clearly illustrates that the use of apparent cohesion c' leads to considerable economy in the design of slopes of temporary excavations. In view of the above, it is desirable that the apparent cohesion c' for granular soils and the various parameters influencing this are further studied in detail. The main purpose of this investigation has been to highlight this aspect.

However, it is also to be realised that after a certain value of the normal stress (called as critical normal stress) the moist samples have lesser shear strength than the dry samples. This would mean that for long-term stability of the structures the shear strength of moist or saturated samples governs the design.

Conclusions

From the results of the present investigation the following main conclusions are drawn :—

(1) For sands in oven dry condition the failure envelopes pass through the origin. With moisture the failure envelopes become flatter and give cohesion intercepts termed as apparent cohesion c' which is due to capillarity in pore water.

(2) The apparent cohesion starting from zero for the oven dry condition increases to a maximum and then it starts decreasing with increasing moisture content. The peak values measured are 0·14 kg./cm^2. for Yamuna sand and 0·28 kg./cm^2. for Ukai sand. This apparent cohesion c' is of practical significance in stability of slopes of temporary excavations and struttings.

(3) In all the cases it has been found that up to a certain normal stress termed as critical normal stress the moist samples possess a higher shear strength than oven dry samples.

(4) The angle of internal friction ϕ' is affected by moisture due to the lubricating effect of water on soil grains. This decrease in ϕ' which mainly depends on the mineral content of grains,

depending on density is about 4 to 5·5° for Yamuna sand and 2·75 to 4·5° for Ukai sand which is due to the presence of minerals like feldspar and mica in the tested soils. Based on this observation it is suggested that even in case of sands for the design of long-term stability the shear strength parameters as obtained from tests on saturated samples should be used.

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