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Experimental Study of the Mechanical Behavior of Loose Sand in Oedometric Stress Path

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Abstract: Very loose sand is defined as sand whose state is significantly looser than its critical state. In fact, the detailed stress - strain behavior of very loose sands have received almost no attention in the geotechnical literature. So, this paper is intended as a step towards the study of the behavior of very loose sands . In order to study experimentally the behavior of dry and wet loose sand on oedometric path under low stresses and with high values of voids ratio , we have realized several oedometer tests on different types of sand (such as :Hostun sand RF,sand 70-270 and Ziani sand), for which we have used different water contents As a result of this work, several values of the characteristics of materials studied have bean obtained and which permit to make some observations and conclusions concerning the behavior of loose sand.

Keywords: Sand , Oedometer test , Loose , Behavior

Introduction

Very loose sands occur both as natural deposits and in civil engineering construction , particularly hydraulically placed fill. The term "very loose " is defined as describing sand in a state so much looser than its critical state that if sheared undrained to failure the sand will exhibit a significant postpeak strength loss , a condition necessary for liquefaction . Because of their potential to liquefy , very loose sands can present a considerable hazard to human activities . Although much work has been done in recent years aimed at allowing assessments to be made of the liquefaction potential of soils Castro *et al.*(1982). Detailed studies of the constitutive behaviour of sands have been restricted to sands dense of critical that are dilatant at high strains Stroud (1971); Cole (1967); Lade and Duncan (1975); Nova and Wood (1979). This can perhaps be attributed partly to the difficulties associated with testing very loose sands in the laboratory.

Very loose sands are rarely used intentionally in civil engineering construction but the ability to recognize very loose sands in the field is of importance, both from the point of view of avoiding liquefaction failures and avoiding the significant economic disadvantages that can result from adopting a too conservative approach.

The main purpose of the paper is to present the observed behavior of very loose sands within a rational normalized framework, which can form the basis for future constitutive modeling.

Behavior of Loose Sand According to Literature: Behavior in undrained triaxial compression Fig. 1 shows a typical result of an undrained triaxial test on very loose sand. Triaxial test data are presented in terms of the stress invariants p' (the mean effective stress) and q (the deviator stress). The deviator stress reaches a peak value at low axial strain, then drops to a reasonably constant or "steady state" level with increasing axial strain. Pore pressure and stress ratio increase steadily during the test to a constant "steady state" value and exhibit no clearly defined peak. Stress paths for undrained tests on very loose sands have a characteristic shape, as shown in Critical state concepts were developed by Roscoe and his co-workers Casagrande (1975) as a method of analysis of liquefaction potential. Critical state concepts were developed by Roscoe and his co-workers at Cambridge during the 1950's and 1960's Roscoe *et al.*(1958); Schofield and Wroth (1968) as part of a general study of soil behavior. Following widely adopted critical state notation, the friction constant is defined as $q/p'=M$. The constant M is related to the angle of internal friction at the critical state,φ', in triaxial compression by the formula $M=6\sin\varphi'/(3-\sin\varphi')$. As very loose sands are contractive in shear, M is the maximum stress ratio attainable.

Fig. 2 shows a typical critical state line for sand, and illustrates schematically how sand behavior, in triaxial compression, is affected by its initial state in relation to the critical state line.

Plasticity model: Strains in very loose sands are assumed to be composed of a recoverable, elastic component as well as non-recoverable, plastic one. Elastic components of strain are assumed to be defined by conventional elasticity theory, although elastic bulk and shear modulus are not assumed to be constant. Elastic moduli are not considered constant but can vary with stress level and void ratio. Insufficient laboratory data are available to define either the yield locus or the plastic potential for very loose sands.

It can be observed that there is no well-defined normally consolidated state for sand that uniquely relates stress and void ratio. In this respect, very loose sands can be considered to be always in a state comparable to overconsolidated clays. This suggests that the adoption of a yield criterion similar to that used for overconsolidated clays might meet with some success.

The steady state line (SSL) of soil is defined as the relationship between soil's void ratio (or density) and its residual "steady state" or critical state strength. The tests realized on very low density sand samples indicates that the steady state line approaches a limiting maximum void ratio, representing a considerable departure from the assumption of a linear relationship between the logarithm of steady state strength and void ratio employed in many constitutive models. The testing suggests that a limiting minimum density exists, below which a sample will show no steady state shear strength at all. Moreover, this limiting density appears to occur at a relative density of $D_r \approx 0\%$ to 10%. On the other hand, during the steady state of deformation, the residual or steady state effective friction angle (φ_r') is essentially the same for a given sand regardless of the density and effective confining stress level.

Study of the Mechanical Behavior of Loose Sand on Oedometric Path

Equipment and experimental procedure: The compressibility test gives indications at one and the same time on soil compressibility and on its consolidation velocity.

The current practice of laboratories consists of doubling the pressure at each loading step. Each time that a weight is added, we observe the settlement of the sample and we wait to pursue the loading that the settlement be stabilized; For sand, a few minutes can be sufficient.

For the tests, we have used the standard oedometer apparatus and the Terzaghi cell for the tests. The main characteristics of the test procedure are the following: Prepare the sample. Mix the sample with water. Place the material paste in the oedometer at an initial height of sample equal to 24mm. Determine the voids ratio, which are calculated using the final water content and settlements.

Description and characteristics of materials used: Oedometer tests were performed on sand 70-270, Hostun sand (RF), and Ziani sand. Gradation curves for all three sands are presented in Fig. 3.

The material tested, are dry sand consisting of subround medium quartz grains. Table 1 presents relevant index properties for these sands. We have drawn the granulometric curves for the materials studied, to measure the values of D_{60} and D_{10} and calculate the uniformity coefficient C_U, which permits to draw the oedometric curves for the different materials studied in the plane (e-logσ_v) in function of C_U values. The maximum and minimum density, and the mean diameter of grains are also given in Table 1.

Maximum and minimum density determination: Some confusion exists within the geotechnical profession regarding the determination of the maximum and minimum densities (γ_{dmax} and γ_{dmin}), or the corresponding minimum and maximum voids ratios (e_{min} and e_{max}), of a given soil for purposes of relative density evaluation. For example, ASTM currently permits the use of any one of multiple methods for evaluation of e_{min}, though the techniques allowed generally yield different results. The same is true, though to lesser extent, for e_{max} determination.

In these studies, e_{min} was defined as "the void ratio corresponding to the maximum density" which can be achieved by any method, without significant particle breakage. For the sands listed in Table 1, this maximum density was achieved by the modified Japanese method, in which the sand is placed in a mold in thin layers and the mold is struck repeatedly (N-times per layer) with a hammer. The test is repeated several times, using increasing numbers of hammer blows per layer until the additional blows cease to result in a measurable increase in density. On the other hand, e_{max} was defined as "the void ratio corresponding to the loosest stable density that can be achieved by any method in the absence of any capillary tension".

The requirement of no capillary tension (no "bulking" due to apparent cohesion) requires that the sandy soils be either dry or fully saturated. The values of maximum voids ratio have been determined using the ASTM standard method, in order to compare with the values of oedometer curves.

Calculations and oedometric modules: The elementary calculations have as objective, on the one hand to determine the voids ratio of soil before the test and its variation during the test and, on the other hand, to identify the sample by the main identification parameters. Two methods may be used to calculate the voids ratio of the soil sample at any time:

1st method:

$e = (H-h_p)/h_p$ (1)

Where

H= height of the sample at any moment.

h_p = height of equivalent solids

2nd method:

$\Delta H/H=\Delta e/(1+e_o)$ (2)

The oedometric module E_{oed} has the definition

$E_{oed}=\Delta\sigma'/(\Delta H/H)$ (3)

In the compressibility test, we can define:

-An oedometric module for each step of loading

$E_{oed}=\sigma_2'-\sigma_1'/(H_1-H_2)/H_o$ (4)

-Secant modules between two points of the compressibility curve

$E_{oed}(\sigma_1',\sigma_2')=\sigma_2'-\sigma_1'/(H_1-H_2)/H_o=(\sigma_2'-\sigma_1')(1+e)/(e_1-e_2)$ (5)

-A tangent module at each point of the compressibility curve

$E_{oed}(\sigma')=2.3\sigma'(1+e)/(C_c \text{ or } C_S)$ (6)

Mechanical behavior of loose sand on oedometric path: As with most soil behavior, data on the behavior of very loose sand are available from both laboratory testing and field observation. To date very loose sands have only been studied in the laboratory in one type of apparatus, the "triaxial" cell. The majority of this testing has been undrained and has been undertaken to study liquefaction potential and not detailed stress-strain behavior.

This paper is based on data obtained from oedometer tests. All of the results presented here were obtained by means of oedometric tests performed on dry and wet samples. The study has been carried out to investigate the influence of adding water on the behavior of loose sand. Fig. 4 shows a typical result of an oedometer test on a very loose sand. Oedometer test data in the present paper are presented in terms of the voids ratio (e), density, and σ_v.

In fact, the behavior of sand is dependent on the number and orientation of the contacts between grains, displacement of the individual particles, and distribution of the interparticle forces. All particles, irrespective of their shape, move to a stable position, relative to the forces acting upon them.

For a given sand, effective stress conditions at the steady state are found to be a reasonably unique function of voids ratio. Generally, when voids ratio is plotted against the logarithm of mean effective stress at the steady state a linear relationship is observed.

To compare data from different tests it is convenient to superpose the different curves obtained for the different types of sand tested.

Generally, the behavior of sand is known to depend on initial density. To study the influence of the initial density on the behavior of loose sand, a series of tests with varying initial density was conducted. Figs. 5 and 6 show the results of several oedometer tests on different types of sand with different initial void ratios. It can be seen that Ziani sand (the coarser one) has generally

Table 1: Index properties

Type of soil	Range of grain sizes	e_{max}	e_{max} mm	Cc mm	D_{60}	D_{10}	D_{60}/D_{10}
Sand 70-270	0.05-0.25	0.94	-	0.034	0.14	0.08	1.75
Hostun sand RF	0.1-0.6	0.99	0.65	0.01	0.31	0.17	1.8
Ziani sand	0.02-1mm	0.84	0.62	—	0.33	0.12	2.65
Silica M40	0-0.04	1.47	—	0.1	19μ	3.5μ	5.4

the highest compressibility. It can be noted also that the compressibility increases with increasing water content for the same stress levels. In addition, the results in Figs. 7 and 8 show clearly a pressure and an initial density dependence for both the stress-strain behavior and the volumetric strain.

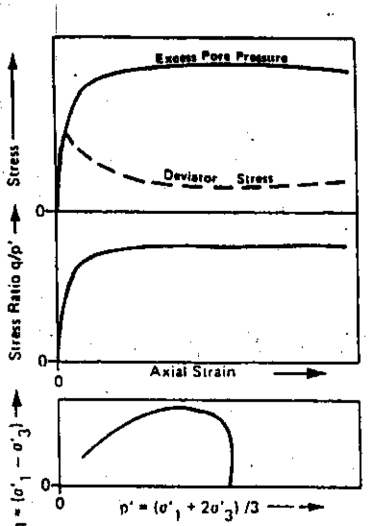
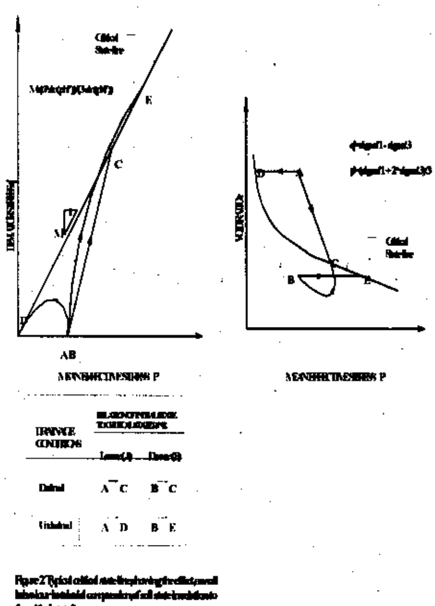
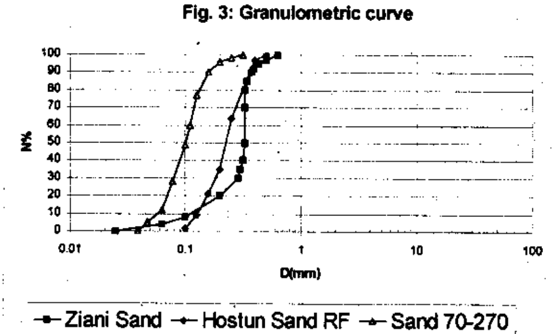


Figure 1. Typical result of undrained triaxial compression test on very loose sand.



In large strains, the resistance to rupture is the same for dense sand and loose sand which can be explained by observing the curves of variation of unit weight. Therefore, large strains erase the past for both dense and loose sand, and the unit weight tends to a limit which only depend on the existing isotropic stress: That limit is called "critical unit weight".

Fig. 3: Granulometric curve



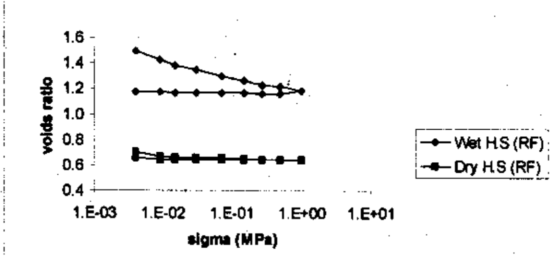


Fig. 4: oedometer tests on hostun sand RF

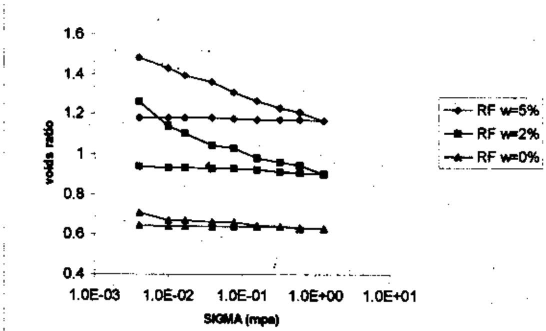


Fig. 5: oedometer tests on hastun sand (RF)

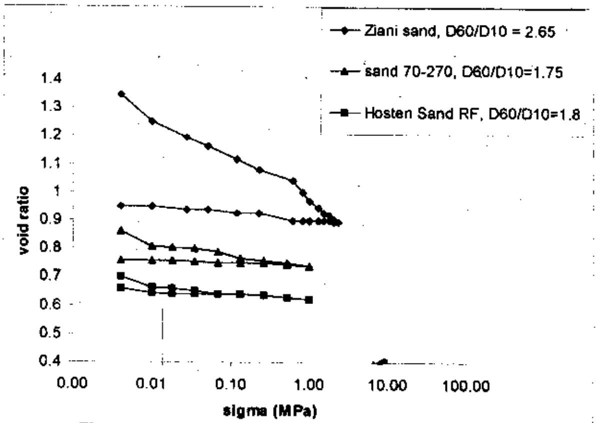


Fig. 6: oedometer tests on different types of sand

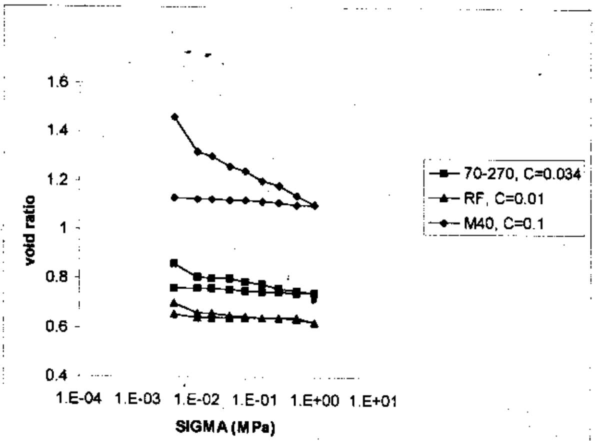


Fig. 9: oedometer tests on dry sand

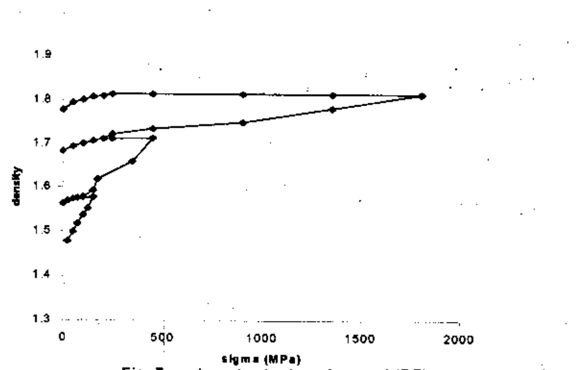


Fig. 7: oedometer test on dry sand (RF)

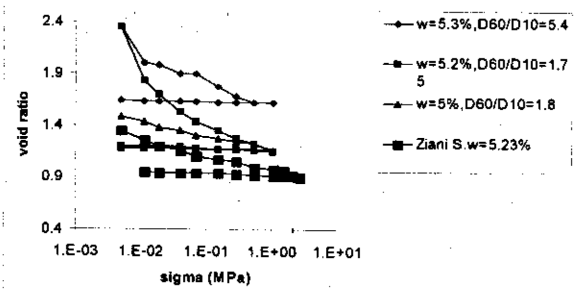


Fig. 10: oedometer curves in function of Cu=D60/D10 for different types of sand

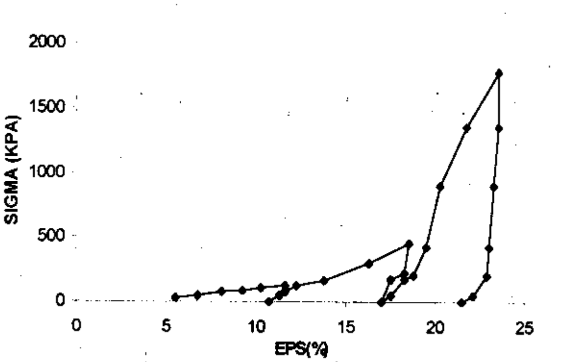


Fig. 8: stress-strain curve [test on dry H. S. (RH)]

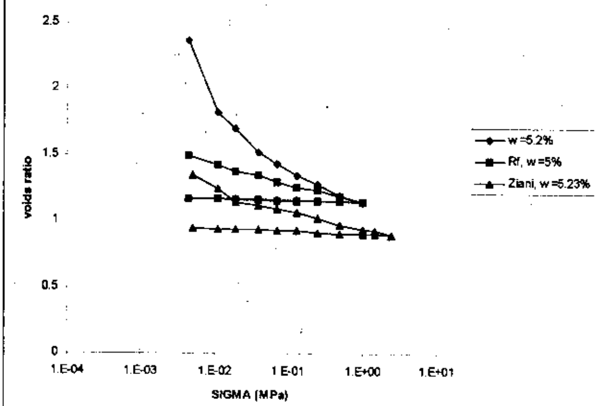


Fig. 11: oedometer tests on wet sand

The results currently obtained for clay are more difficult to observe on sand, because it is practically impossible to obtain a dry normally consolidated sand. On the other hand, if a slightly wet sand is used, a sufficiently high value of voids ratio can be attained to have a normally consolidated behavior. In fact, it is difficult to measure the normally consolidated behavior of sands in an oedometer without crushing the grains.

In the present paper, results of slightly wet sand are presented, which permits to prepare samples having voids ratios higher than e_{max}. Nevertheless, it is possible that the humidity leads to straight lines translated very high towards higher voids ratios. For ordinary densities of sand, an overconsolidated behavior without crushing of grains is observed; If the stress increase, the curve is inflected towards the low voids ratios due to the fact of grains crushing.

Conclusions

The main objective of this paper has been to study the behavior of very loose sands in the oedometer test. Since tests with very loose sand are very rare, then the data presented by the paper represent a significant contribution to the literature. The results of oedometer tests on dry and wet loose sands of very low densities are reported on Figs. (4-11), which permit to conclude the following conclusions:

-The experimental curves (e-logσ_v) show the classical aspect of the loading and unloading. For loose sand, the curves obtained at low stresses are neatly inclined in comparison to the abscissa axis. The physical explanation that can be given is that when the material is loose, the particles can be rearranged freely, in view the voids spaces which they dispose, and give strains.

-Oedometer tests made on dry sand show the classical aspect of loading-unloading curves and follow the general logic of current densities; Remembering that irreversible strains are function of the used density and due to rearrangement of particles. At low stresses, there exists a branch slightly inclined to the horizontal, then a part approximately rectilinear and finally another branch approximately parallel to the first branch. It can be noted also that the variation of voids ratio obtained for loose sand is higher than that of dense sand, which proves that en the initial density decreases, irreversible strains increase. In addition, the curves obtained for loose sand at low stresses are clearly inclined to the abscissa axis.

-The oedometric curve shows the presence of three successive phases during an oedometric loading stage: The first phase is essentially irreversible (rearrangement of grains); A second phase essentially reversible (elastic deformation of grains); and a third phase essentially irreversible (rupture).

-For low stresses (σ_{vmax}=0.015MPa), important irreversible strains are produced due to the rearrangement of particles and during unloading, the curve e-logσ_v is close to a straight line.

-On the experimental curves (e-logσ_v) , a particular behavior can be noted: at low stresses (≈0.005 MPa, due to the weight of the piston), the decrease of voids ratio shows the high compressibility of the sample.

-The wet sand gives particular curves that traduce the high compressibility of materials at very low densities. For the increasing stresses, the most important settlements obtained are traduced by a considerable drop of voids ratio giving then particular curves. As soon as the first stress of 0.02 MPa (for example) is applied, the voids ratio passes from 1.2 to 1.16 (decrease by 3%), which traduce the high compressibility of materials of very low densities, that is to say a densification even under low stresses (Fig. 4).

-We always observe an initial settlement Δh quasi instantaneous while loading the apparatus.

-It is practically impossible to obtain a dry normally consolidated sand. But if we use a wet sand, we can attain a voids ratio slightly higher than e_{max}, and to curves very high in voids ratio.Nevertheless, it appears that the humidity leads to a neat translation of curves in the plane (e-logσ_v).

-By comparing the curves (e-logσ_v) for the dry and wet loose sand of the same material, we remark that the wet loose sand gives an initial voids ratio neatly higher than that of the dry loose sand; In addition, the change of voids ratio for the wet loose sand is bigger than for dry loose sand, and that the inclination of the loading curve in comparison to the horizontal is neatly higher for the wet loose sand.

-We remark that the decrease of water content gives lower voids ratio. It can also be noticed that the value of C_c decrease with the value of D_{60}/D_{10}.

-For a small stress of 0.005MPa (due to the weight of piston), the decrease of voids ratio shows the high compressibility of the samples. The initial voids ratio passes from 1.22 to 1.2 for an initial density of 1.2 g/cm^3 (which means a decrease of 1.6%), and for an initial density of 1.1 g/cm^3, the voids ratio passes from 1.4 to 1.35 (a decrease of 4%).

-For a given stress during the tests (σ_{1max}=0.1, 0.2, 0.3, ...MPa), it can be observed that the module E_T increases with the increase of initial density, this increase enlarges also with the stress (Figs. 7 and 8). It can also be noticed the increase of initial tangent oedometric module E_{Ti} with the increase of initial density.

-In the plane (e-logσ), the compressibility curve is characterized by the presence of an elbow which separates the behavior of material into two domains: Domain where the soil is normally consolidated and another domain where the soil is overconsolidated.

-The straight lines representing loading-unloading stage in the plane (e-logσ) appear parallel one to another.

-There is no "elastic limit", because there is always important reversible strains regardless of the number and type of cycles of loading in the oedometer (Fig. 8).

-The facts that there is no one-to-one relation between the void ratio and the applied stress. In fact, the behaviour of sand depends highly on the initial void ratio which preclude the application of the Cam-clay model to sand.

-For any value of initial density used, the limit between the elastic domain and the plastic domain (where the crushing of particles is curried out) can be noticed obviously.

-After an oedometer cycle on loose sand (Fig. 8), the strain is composed of an irreversible strain (ε_i) due to rearrangement and rupture of grains and a reversible strain (ε_r) due to deformation of grains. The ratio ($\varepsilon_r/(\varepsilon_i+\varepsilon_r)$) represents the reversibility of the cycle, and the ratio ($\varepsilon_i/(\varepsilon_i+\varepsilon_r)$) represents the irreversibility strain (ε_r) due to deformation of grains. The ratio ($\varepsilon_r/(\varepsilon_i+\varepsilon_r)$) represents the reversibility of the cycle, and the ratio ($\varepsilon_i/(\varepsilon_i+\varepsilon_r)$) represents the irreversibility of the cycle.

-In the rupture domain, the reversibility increases with the increase of initial density and decreases with the increase of maximum stress and the increase of initial density at the start of each cycle.

-During the unloading stage, it can be noted also that the curve e-logσ is approximately a straight line, which is much less inclined to the horizontal axis (stress axis) than the curve in the plane (e-σ).

-If the sample is subjected to several cycles of loading and unloading, and the stress goes beyond the maximum stress of the preceding cycle, then the curve of recompression joins the preceding compression curve (Figs. 7 and 8). It can also be noticed the increase of e_{max} with D_{60}/D_{10} and with dry density (Figs. 11).

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