Creep, stress relaxation, and rate effects in sand

Ecoulement, Relaxation de Stress, et les Effets de Taux dans le Sable

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ABSTRACT
Observations of time effects in triaxial compression tests performed on crushed coral sand with constant strain rate, creep tests at different stress levels, and stress relaxation tests initiated at different stress levels are presented. The classic time effects found in most materials, i.e. increasing stiffness and strength with increasing strain rate and corresponding creep and stress relaxation behavior, are not observed in sand. Observations from the experiments show that strain rate effects are negligible for crushed coral sand, unlike for clays in which strain rate effects are significant. Further, the observed stress relaxation behavior was not in "correspondence" with the measured creep behavior. Therefore, the amount of stress relaxation predicted on the basis of model parameters determined from creep experiments is too small. It is concluded that sands do not exhibit viscous effects, and their behavior is indicated as "nonisotach," while typical behavior of clay is termed "isotach." Thus, there are significant differences in time-dependent behavior patterns of sands and clays. In another investigation on Antelope Valley sand the measured responses in creep and stress relaxation tests and in constant strain rate tests exhibited similar behavior as the crushed coral sand but with smaller discrepancy between the creep and stress relaxation tests. An explanation for these non-viscous and dissimilar effects for different sands is proposed and relates to the amount of grain crushing that occurs in different sands.

RÉSUMÉ
Nous présentons les observations des effets temporels induits par des essais de compression tri-axiale menés sur le sable corail écrasé à taux de tension constant, des essais d'écoulement aux différents niveaux de stress, ainsi que des essais de relaxation de stress aux différents niveaux de stress initial. Les effets classiques observés dans la plupart de matériaux, à savoir une rigidité et une fermeté croissantes avec le taux d'écoulement ainsi que les comportements d'écoulement et de relaxation de stress correspondants, ne sont pas observés avec le sable. Les données expérimentales montrent que les effets imputables au taux de tension sont négligeables pour le sable corail écrasé, à la différence du comportement observé avec de la glaise, pour laquelle de tels effets demeurent importants. En plus, le comportement de relaxation de stress observé n'était pas en correspondance avec les mesures d'écoulement. Ainsi, la valeur de la relaxation de stress prédite sur la base de paramètres de modèle déterminés à partir des expériences d'écoulement s'avère trop petite. Nous concluons que le sable n'exhibe pas des propriétés visqueuses, et son comportement est désigné comme "non-isotache", pendant que le comportement type de la glaise est désigné "isotache". Ainsi nous constatons des différences significatives dans les comportements temporels des sables et des glaises. Une autre campagne de mesures menée sur le sable à Antelope Valley a mis en évidence des résultats tout-à-fait similaires. Nous proposons une explication pour ces effets non-visqueux qui traite aussi des effets contrastés sur des sables différents, et que se relève de la quantité d'écrasement des grains produite avec les sables différents.

Keywords : creep, , rate effects, sand, stress relaxation, triaxial compression

1 INTRODUCTION

Long term settlement of granular fill "plays a crucial role in the development potential of the land and the settlement of structures founded on the fill" (Day 2005). Significant settlement due to self weight of these recently placed fills is often observed, and part of this is due to creep and part is due to collapse of the grain structure caused by changes in moisture content of the fill material. Soil creep and relaxation also cause long-term deformation and pressures on buildings, bridge abutments, earth retaining structures, and slopes. Excessive deformation with time may cause structures to fail.

Time dependent behavior of granular materials is quite different from the viscous behavior observed in clays (Augustesen et al. 2004). The effects of strain-rate, creep and stress relaxation of clays follow a classic pattern of viscous behavior observed for most materials. For such materials the stiffness and strength increase with increasing strain rate and phenomena such as creep, relaxation and strain rate effects are governed by the same basic mechanism. This behavior is denoted as "isotach" behavior, i.e. there is a unique stress-strain-strain rate relation for a given clay. For such materials, the creep properties may be obtained from, say, a triaxial compression test and used for prediction of stress relaxation in another experiment.

For granular materials the effects of strain rate or loading rate are observed to be small to negligible, and while creep and stress relaxation are caused by the same phenomenon, namely grain crushing followed by grain rearrangement, the prediction of one phenomenon can apparently not be accomplished on the basis of the other. Such behavior is referred to as "nonisotach" behavior. The role of grain crushing is explained, and the transfer of forces through the grain structure is different in creep and relaxation tests. While each phenomenon follows similar patterns, the strains produced after one day of creep does not produce a result that correlates with the changes in stress due to one day of stress relaxation.

To throw further light on the effects of time on the behavior of sand, and as background for development of constitutive models incorporating time effects, presented here is a study of strain rate effects, creep, and stress relaxation in crushed coral sand.

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2 EXPERIMENTAL STUDY OF SAND

The time-dependent behavior of sand was studied in a conventional triaxial apparatus. Modifications to this equipment were made to improve its capability to carry out long-term tests with steady stresses and accurate measurements at a constant temperature. Mechanical equipment with negligible drift in applied pressures and loads and measurement systems without zero drift or devices in which the zero position could be verified during experiments were employed for all testing. The triaxial equipment, the loading systems, the deformation measurement systems, and the temperature control were explained by Lade and Liu (1998).

The sand tested was crushed coral sand. The gradation consisted of grain sizes between the No. 30 and No. 140 U.S. sieves (0.60 to 0.106 mm) with a nearly straight line gradation between these two sizes. The maximum and minimum void ratios were 1.22 and 0.70. The specific gravity of sand grains was 2.88. The tests on crushed coral sand were performed on specimens with a relative density of 60% corresponding to a void ratio of 0.91.

3 STRAIN RATE EFFECTS

Triaxial compression tests were performed on crushed coral sand with an effective confining pressure of 200 kPa and with five different, constant axial strain rates varying from 0.00665 %/min to 1.70 %/min, corresponding to a 256-fold increase in strain rate. The results of these tests are shown in Figs. 1(a) and 1(b). They indicate that the influence of strain rate on the characteristics of the stress-strain and volume change curves is negligible. Thus, the slopes of the curves as well as the strengths are very little affected by the strain rate. Similar results for sand have been found by Yamamuro and Lade (1993) and by Matsushita et al. (1999). This departure from classic time-dependent behavior, according to which the stiffness and the strength increase with increasing strain rate, is significant, because it indicates that it may not be possible to employ conventional viscous type models to capture the time-dependent behavior of sands. Such models have been successfully used to characterize a number of other materials, including soils such as clays (see Liingaard et al. (2004) for comprehensive review of time effect models).

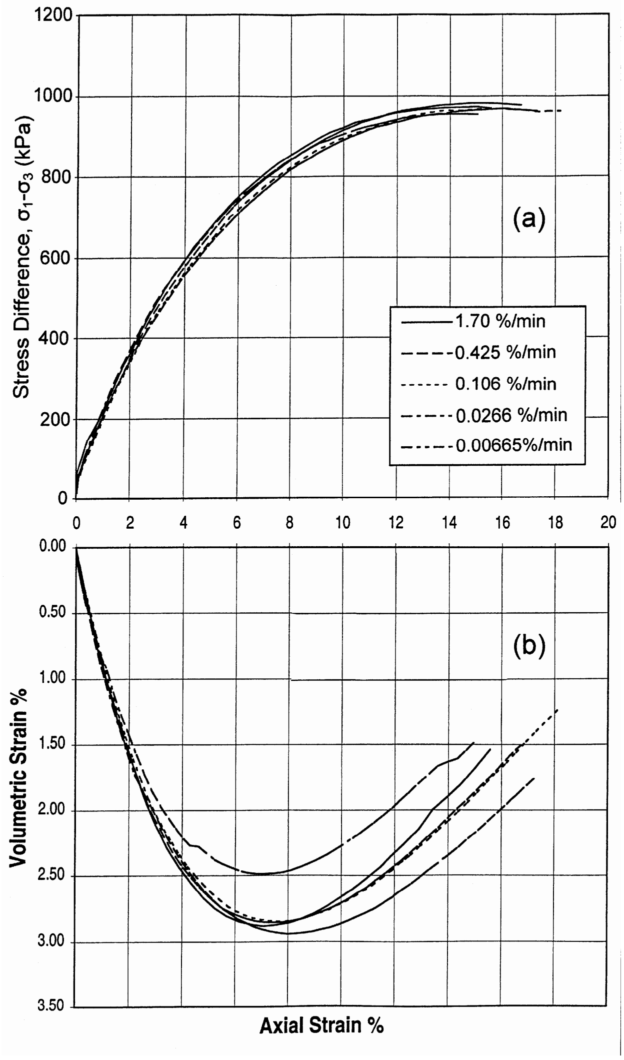

Figure 1. Comparison of (a) stress-strain and (b) volume change relations for drained triaxial compression tests on crushed coral sand performed with five different strain rates.

4 CREEP EXPERIMENTS

Conventional creep experiments were performed after the specimen had been loaded corresponding to the average strain rate of 0.106 %/min. Once the desired deviator stresses of 500, 700, and 900 kPa had been reached, the specimen was allowed to creep for approximately one day (= 1440 min). After the creep stage, the deviator stress was again increased sufficiently to join the virgin or primary stress-strain curve before another creep test was initiated.

Fig. 2(a) shows the stress-strain and volume change curves, and superimposed on these diagrams are the results of a corresponding load controlled experiment. As creep proceeds at a given stress, the plastic yield surface moves out to higher stresses. This may be seen from the fact that further loading first produces what appears to be elastic reloading.

The volume change curves corresponding to creep, shown in Fig. 2(b), do not follow the reference curve, unlike in previous experiments on Antelope Valley sand presented by Lade and Liu (1998). This means that the potential for inelastic creep strains cannot be taken to be the same as the potential for plastic strains, as was the case for the Antelope Valley sand. The potential for inelastic strains for crushed coral sand must be inclined such that the creep volumetric strains are more contractive than those obtained from the plastic potential at the same stress point.

5 STRESS RELAXATION EXPERIMENTS

Stress relaxation experiments were performed after primary loading with a strain rate of 0.106 %/min. Once the desired stress differences of 500, 700, and 900 kPa had been reached, the axial deformation was held constant to observe the stress difference relax. Relaxation periods of 1000 min (i.e. a little less than one day) were employed in all but a few experiments in which longer relaxation periods were used. After the stress relaxation stage, the stress difference was again increased sufficiently to join the virgin or primary stress-strain curve before another relaxation test was initiated.

Fig. 3(a) shows the stress-strain relations obtained from the basic experiment performed with stress relaxation at the three stress differences and at a stress point beyond peak failure. Reloading after stress relaxation exhibits structuration effects similar to those observed after periods of creep, i.e. a temporary increase in the deviator strength beyond that corresponding to the primary loading curve. In all cases, the stress-strain curve appears to unite with or become the primary stress-strain relation well before the next stress relaxation point is reached.

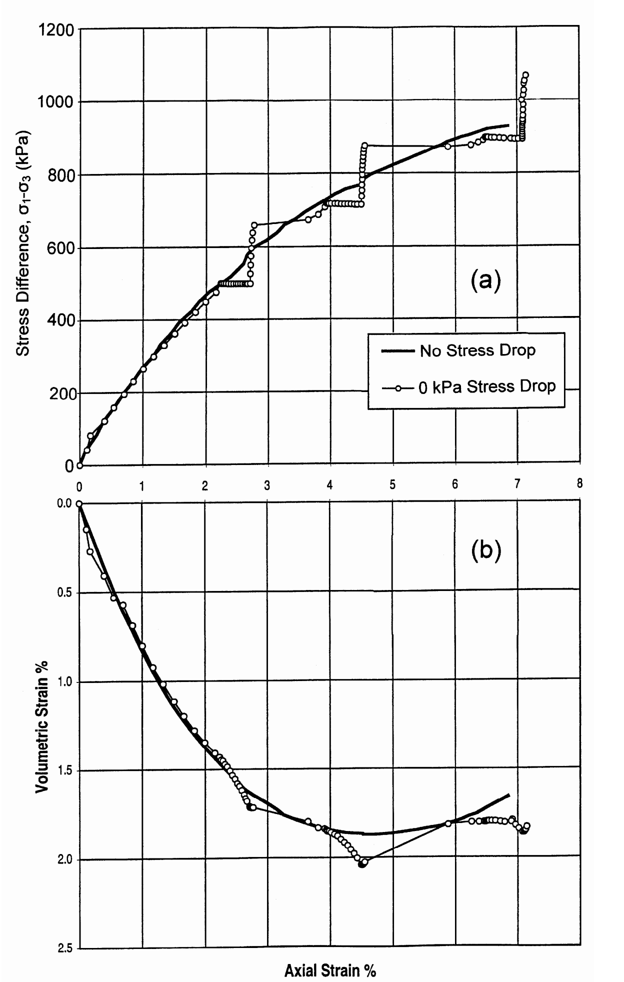

Figure 2. (a) Stress-strain and (b) volume change relations from load controlled drained triaxial compression test on crushed coral sand with creep stages of 1440 min. at stress differences of 500, 700, and 900 kPa. Comparison with results from load controlled test without creep stages.

Fig. 3(b) shows that volumetric contraction of the specimen is associated with relaxation of the stress difference, whether or not the specimen is contracting or dilating during primary loading. These periods of volumetric contraction produce offsets in the volume change curve and like the stress-strain relation, the volume changes also seem to recover to the basic volume change curve upon reloading.

6 COMPARISON OF CREEP AND STRESS RELAXATION

The stress relaxation may be compared with the creep observations by plotting the points of initiation and the end points after a certain amount of time on the same diagram. To overcome the small differences in the primary stress-strain curves from the two experiments in Figs. 2 and 3, the stress-strain curve shown in Fig. 3(a) is used as the base curve from which creep and stress relaxation are initiated.

The comparison of stress relaxation and creep after one day is shown in Fig. 4 in which the points of initiation of creep have been located on this base curve, while the end points obtained after approximately 1 day of creep are shown relative to the initiation points. The data from both types of tests are very consistent, and they show how much the axial strains change due to creep and how much the axial stresses change due to relaxation, respectively. It is clear that the amount of creep and the amount of relaxation resulting after 1 day define curves that are located at quite different positions.

Fig. 5 shows a comparison of creep and stress relaxation effects after one day plotted from a common stress-strain curve for comparable experiments performed to study time effect on Antelope Valley sand (after Lade 2007). As for the crushed coral sand, the experiments on Antelope Valley sand showed that strain rate effects are negligible (Lade 2007), and Fig. 5 indicates that the observed stress relaxation behavior does not correspond with the measured creep behavior. It is concluded that neither the crushed coral sand, nor the Antelope Valley sand exhibits classic viscous effects. Note also that the amounts of disagreement between the stress-strain relations after one day of creep or stress relaxation are quite different for the two sands.

The fact that the same basic mechanism can account for creep, stress relaxation, and rate dependency and can serve as basis for prediction of one from the other, as is the case for clays, indicates that the material complies with the "correspondence principle" according to Sheahan and Kaliakin (1999). The experiments presented here showed noticeable amounts of creep and relaxation but no strain rate effects. Further, the stress relaxation and the creep responses do not

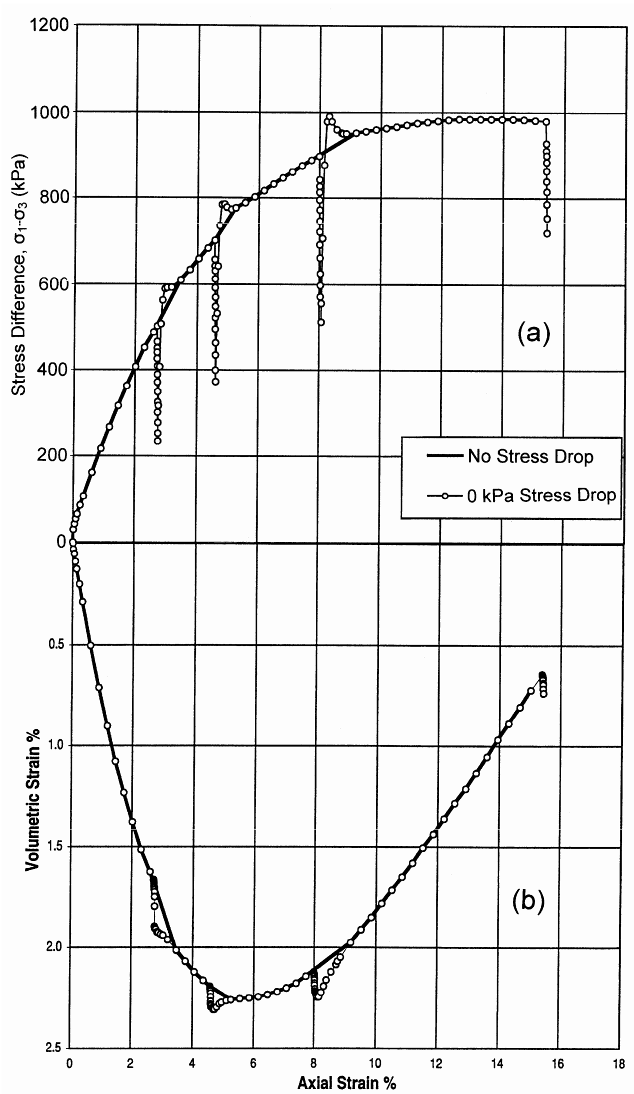

Figure 3. (a) Stress-strain and (b) volume change relations from deformation controlled drained triaxial compression test on crushed coral sand with stress relaxation stages of 1000 min. at stress differences of 500, 700, and 900 kPa. Comparison with results from deformation controlled test without stress relaxation stages.

appear to follow the correspondence principle, i.e. two different stress-strain relations are obtained after 1 day, as indicated for two different sands in Figs. 4 and 5. Thus, it appears that the phenomena of creep, stress relaxation and strain rate effects in sand cannot be predicted from the same type of test using a viscous type model. The type of behavior observed for sands is referred to as "nonisotach" behavior.

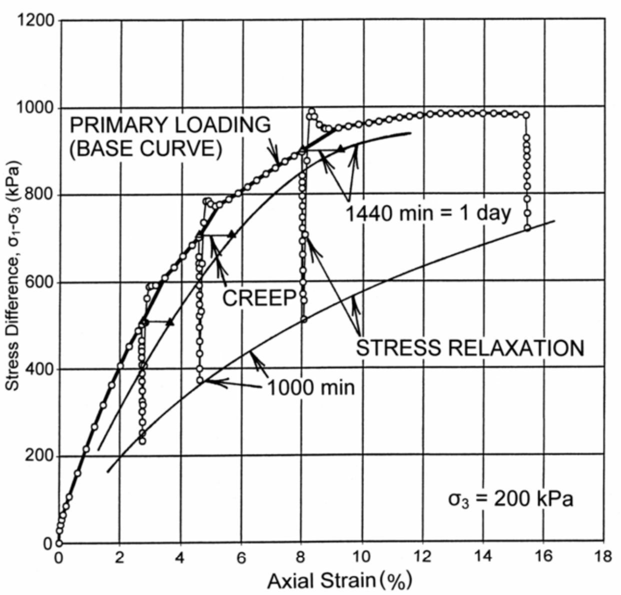

Figure 4. Comparison of creep and stress relaxation experiments performed in two triaxial compression tests on crushed coral sand.

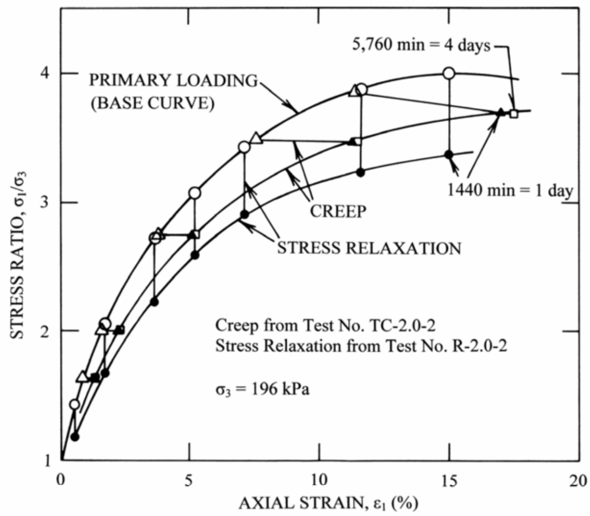

Figure 5. Comparison of creep and stress relaxation experiments performed in two triaxial compression tests on Antelope Valley sand.

7 ORIGIN OF TIME EFFECTS IN SANDS

Particle breakage has often been observed to be associated with time effects in granular materials, and it is proposed that the time effect emanates from crushing of particles, which is a time-dependent phenomenon. Particle breakage may not occur and time effects are negligible in granular materials at very low stresses. Time effects become significant with increasing confining pressure and increasing stress difference, as has been observed in several studies (see Yamamuro and Lade 1993). These studies also noted the association between particle crushing and its occurrence with time.

With only friction (and slippage when the frictional resistance is overcome) and particle breakage (when the strengths of the particles are overcome) as basic behavior constituents, how can the observed time effects be explained for granular materials? Experiments on rock specimens have clearly shown that their strengths are strongly dependent on time (Cristescu and Huntsche 1998). Experiments on sand grains are expected to show similar effects.

8 CONCLUSION

Observations from experiments show that strain rate effects are negligible for crushed coral sand, unlike for clays in which strain rate effects are significant. Further, the observed stress relaxation behavior was not in "correspondence" with the measured creep behavior. Therefore, the amount of stress relaxation predicted on the basis of model parameters determined from creep experiments will be too small. It is concluded that sands do not exhibit classic viscous effects, and their behavior is indicated as "nonisotach", while the typical viscous behavior of clay is termed "isotach". Thus, there are significant differences in the time-dependent behavior patterns of sands and clays.

A mechanistic picture of time effects in sands is proposed in which interparticle friction, grain crushing, and grain rearrangement play the key roles. Grain crushing is a time dependent phenomenon and this accounts for the time dependency observed in granular materials. Additional experimental research is required to understand the behavior of sand and to develop a more correct constitutive framework for the time-dependent behavior of sand.

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