Material behaviour of dry sand under cyclic loading

Comportement d'un sable sec sous chargement cyclique

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ABSTRACT: The here presented investigations show that abrasion has a reasonable influence on the deformation behaviour in the small stress domain. The macroscopic behaviour of two different sands in triaxial cyclic tests is shown. The observed behaviour of discontinuity in common cyclic shakedown area can be explained with abrasion. A microscopic view shows the meaning of abrasion due to single grains. With this study the verification of abrasion in a microscopic and macroscopic sense is succeeded.

RÉSUMÉ: Les résultats présentés ci-dessous montrent, que l'abrasion a une influence importante sur la déformation dans le milieu des petites contraintes. Le comportement macroscopique de deux sables différents est montré dans des essais triaxial cycliques. Le comportement des discontinuités surtout le cyclic shakedown peut-être expliqué par l'abrasion. L'influence de l'abrasion du point de vue microscopique est montrée pour certains grains. Avec ces études l'abrasion a été vérifiée dans le sens microscopique et macroscopique.

1 INTRODUCTION

The behaviour of sand under cyclic loading is important for all buildings with often changing load, e.g. lanes of cranes, machine foundations, oil and gas storages and off shore platforms. Cyclic loading is referred to a loading with changing intensity, neglecting any forces of inertia. The scope of this contribution is to focus on such cyclic loadings which are small against the ultimate failure load. Experiments shows that sand under cyclic loading has permanent plastic strain increments and that sometimes sudden additional plastic deformation occur. The reasons for this additional plastic strain increments can be found in a rearrangement of the grain skeleton. The decisive release of the skeleton rearrangement is the modification of the single grain due to abrasion. Grain crushing is divided into grain breakage and abrasion. Grain breakage means the dissection of grains in parts with nearly the same dimension. Abrasion means the break off of very small particles from the grain surface. While grain breakage only appears in the domain of high stress levels, abrasion is a phenomena which is independent of the stress level.

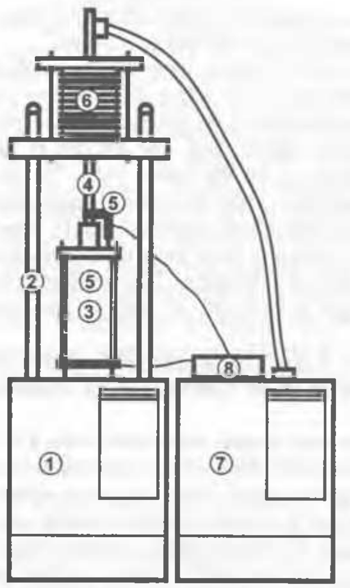

Figure 1. Triaxial test equipment.

2 TRIAXIAL EXPERIMENTS

To examine the abrasion triaxial tests under cyclic loading were performed. For the test a triaxial test apparatus with a hydraulic controlled load was used. The triaxial test equipment consists of a conventional servo controlled triaxial test apparatus and a hydraulic system which controls the cyclic loading (Fig. 1). With the test equipment a vertical load up to 10 kN with a loading frequency of 5 Hz and a maximum vertical deformation of 1 mm per load cycle can be obtained. The dimensions of the cylindrical test specimen were 10 cm in diameter and 20 cm in height. As a key feature of the measuring system the load and deformation devices are plugged directly on the test specimen. The load cell for the vertical load is attached directly above the specimen and is balanced against the cell pressure, so only the deviatoric part of the load is measured. The cell pressure is measured and controlled with a digital pressure controller. The deformation of the test specimen is measured with hall effect strain transducers. Two axial and one radial transducer is used for measurement. The transducers are plug in the mid third of the specimen so bedding and end restrained errors will not be measured. The transducer have an accuracy of about 10μm, which is necessary to record the small strain in the performed load cycles.

The samples were first consolidated by a pressure of 150 kN/m² and than loaded with a sinusoidal changing load between 200 kN/m² and 350 kN/m² with a frequency of 1 Hz. These tests were performed up to 5 million load cycles. After this the loading amplitude was raised in several steps. Eight different tests were performed with two different materials and several placement densities of the specimen. On the one hand a well rounded quartz sand was used, on the other hand an angular grained industrial breaked gabbro sand was used. The grain size distribution of both medium grained sands was nearly the same. The quartz sand is from a sand/gravel-pit in the upper Rhine-graben. The sand is fluviatil rounded over a long transportation distance form the river Rhine. The grains of the quartz sand consists mainly of pure quartz and have a high strength. The gabbro sand comes form a quarry in the Odenwald. The origin rock is a volcanic material. It is breaked twice in an industrial process to produce ballast. So it is a very angular material. The grains of the gabbro sand consists of a conglomerate of different crystals, mainly feldspar, calcite and mica. Because of the heterogeneous structure and the participating minerals the gabbro has a low grain strength (McDowell & Bolton, 1998; Nakata et al., 1999). With both materials triaxial tests were performed under the same conditions.

Exemplary two tests will be shown. One test with gabbro sand and the other with quartz sand to show the occurring differences. Figure 2 shows the vertical strain of the sample against the number of loading. The upper curve shows the minimal vertical strain, which occurs in a load cycle and the lower curve shows the maximum vertical strain in a load cycle. The distance between both curves is equal to the elastic strain in a load cycle. It is recognisable that the distance decreases slowly with increasing number of loadings. The test result shows that the plastic strain increments become smaller with increasing number of loading within a certain region. This behaviour is called cyclic shakedown and can be described with a logarithmic function in a similar way as it is shown by Heineke (Heineke et al., 2001). The cyclic shakedown state is not a steady state. After some loading new increasing plastic strain increments occur. This 'local failure' can be explained by the modification in the grain texture due to abrasion. This behaviour could be observed only after numerous loadings, which leads to long time experiments of one or two month of duration – this means 3 – 5 million loading cycles with 1 Hz frequency. Remarkable is that even by a number of loading of 4.0 Mill. additional plastic strain increment occurs. The assumption of a final shakedown could not be verified.

In Figure 3 the stress strain hysteresis loops of the gabbro sand are shown for the same test as the strain development in Figure 2. The hysteresis loops have the typical concave-converse trend, which is characteristic for dense sand. The number at the loops gives the number of loading for the drawn loop. The increasing gradient of the loop show clear the slowly decreasing elastic part of the load cycles. The included area of each hysteresis loop gives the dissipated energy in each loop. So it is shown that energy is dissipated over all load cycles. The predominant part of the dissipated energy is believed to lead to abrasion (Arslan et al. 2000).

By comparison the figure 4 and 5 shows the development of the vertical strain and the stress strain hysteresis loops of dense quartz sand.

In the first step the quartz sand sample was loaded with a cyclic load amplitude of 150 kN/m². This is the same as in the above mentioned test with gabbro sand. Contrary to the gabbro sand the deformation history of the quartz sand is a nearly uniform monotonic slow increase of vertical strain without shakedown regions. The magnitude of the strain is lower as by the gabbro sand. Because of the uniform behaviour the load amplitude was successive risen in the following steps. In the steps two to four the typical shakedown behaviour can be observed. the 'local failure' behaviour of gabbro sand could not be observed. In figure 5 the stress strain hysteresis loops are shown for the first load step. Compared to the loops of gabbro sand this one has a higher gradient and the included area is much smaller. This shows that less energy is dissipated and this is the reason why the deformation behaviour is more uniform. That the quartz has a greater grain strength than gabbro and that in the quartz sand test less energy is absorbed are the reasons that no clear effects of abrasion could be observed. This leads to the statement that the influence of abrasion to the deformation behaviour of sand is dependent to the mineralogy of the sand as we will show in the following chapter to the grain shape.

3 MODIFICATION OF THE PARTICLE SHAPE

In the last chapter the macroscopic behaviour of sand under repeated loads are shown. The gabbro sand indicated a behaviour

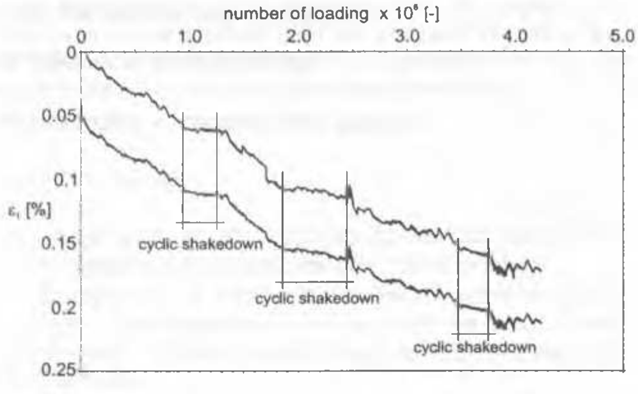

Figure 2. Development of vertical strain of dense gabbro sand.

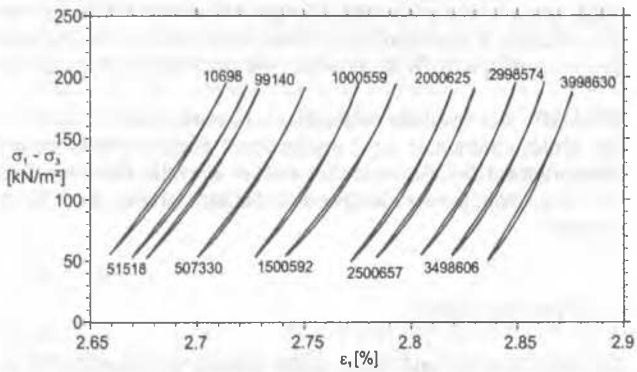

Figure 3. Stress strain hysteresis loops of dense gabbro sand.

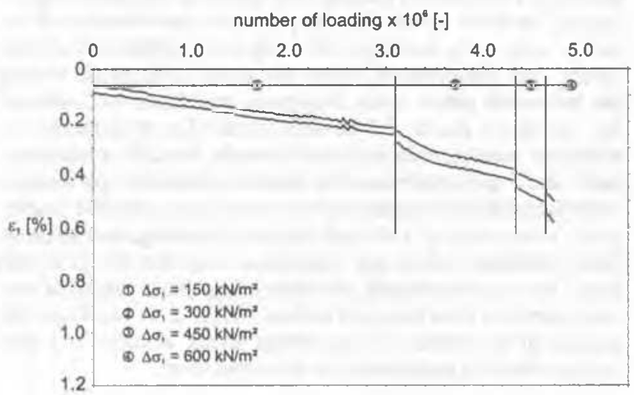

Figure 4. Development of vertical strain of dense quartz sand.

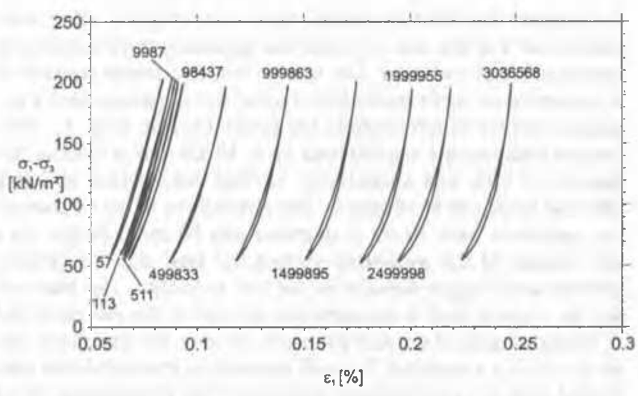

Figure 5. Stress strain hysteresis loops of dense quartz sand.

which can be subdivided into different regions which are separated by a discontinuous deformation behaviour. This behaviour was related to abrasion. In contrast abrasion could not be observed by the quartz sand in a macroscopic point of view. Sieve analysis before and after the performed triaxial tests showed no alteration of the grain size distribution, so grain breakage can be neglected. In this chapter the microscopic observation at the grains are shown to get a better understanding what means abrasion.

3.1 *Procedure of optical detection of grain shape*

Abrasion is the splintering of small parts of the grain due to a local exceed of the grain strength. This may occur at the contact points in a grain skeleton. To check the influence of abrasion to the grain shape an automatic, electronic procedure to determine the grain shape was developed. The specification of the grain shape is mostly described with a coefficient of roundness. This coefficient is a measure of the 2D image of the grain. The coefficient of roundness is the relation of the area of a grain to its perimeter and can be written as (Cox, 1927):

$$K = \frac{4 \cdot \pi \cdot A}{P^2} \qquad (1)$$

K - coefficient of roundness
A - area of grain image
P - perimeter of grain image

The coefficient of roundness can have values between zero and one. In case of zero the shape is a line and in case of one the shape is a circle, but the coefficient of roundness is the same for all figures of the same shape, regardless of size. That is to say, that a small circle is just as round as a large circle. Furthermore, the value of K for a figure of any given shape represents the percentage ratio that the area of the figure holds to the area of a circle with the same perimeter. The determination of the coefficient should be done with a computer based technique. For that a quantity of grains are placed on a high resolution scanner. The grains must not be in contact for that the computer has to identify the boundary of the grains. After that the pixel based image is analysed. The number of pixels leads in consideration of the resolution of the scanner to the area of the grain image. In the same way the perimeter of the grain can be calculated. For the calculation of the perimeter the position of the pixel in the image has to be taken into account. If the pixel is a corner pixel the length for the perimeter is twice the value as for a pixel lying in the middle of a straight line.

The scanned image of the grains has to be processed to get an good reliable result. In a first step the image has to be purified from uncleanliness and very small particles. Because of the well defined grain size distribution particles under a certain size can treated as scanning errors or dust. If most of the particles are

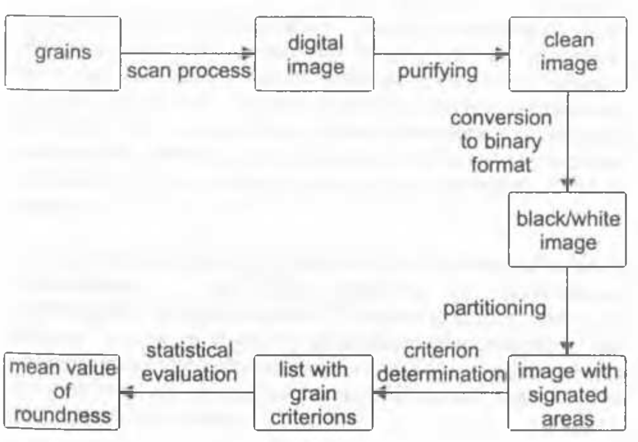

Figure 6. Determination procedure of the coefficient of roundness.

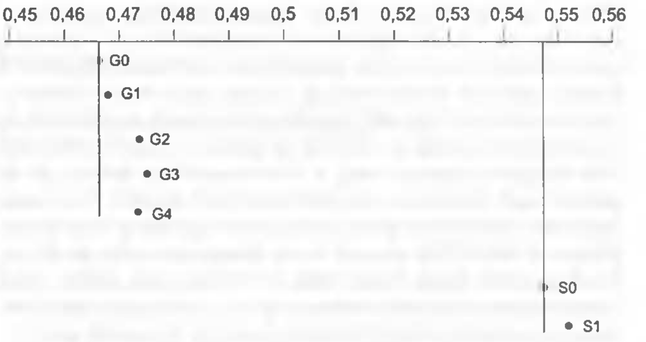

Figure 7. Change of coefficient of roundness in various tests.

Table 1. Test characteristics for the test in figure 7.

test	material	placement density	number of loading
G0	gabbro sand		0
G1	gabbro sand	dense	0,15 x 10^6
G2	gabbro sand	dense	2,0 x 10^6
G3	gabbro sand	dense	4,4 x 10^6
G4	gabbro sand	average density	2,2 x 10^6
S0	quartz sand		0
S1	quartz sand	dense	5,2 x 10^6

smaller then a value of about 100 pixel the calculated results are not reliable and a higher scanning resolution has to be chosen. After this first purifying procedure the digital image has to be converted into a binary format. For that the grey tone distribution of the whole image is determined. This is to find the limit between the background and the grains. So it is not necessary to have a pure white background. The grains are much darker than the background. The digital image after that procedure consists of black areas which are the grains and a white background. In the next step the software searches for coherent black areas and gives each area an independent digital signature. Now each grain area can be addressed about its signature and the area, perimeter and coefficient of roundness can be calculated. The whole procedure is software based and needs no intervention of the user. A flow chart of the procedure is shown in figure 6.

3.2 *Results of grain shape investigation*

In a first test about 600 grains were scanned and analysed to check if the distribution of the coefficient of roundness is a normal curve of distribution. The performed χ^2-test showed that a normal distribution is a good approach both for the quartz sand and the gabbro sand with a degree of probability of 0.95. Within the approach of a normal distribution the mean value and the standard deviation can be calculated. Also the statistic showed that the expected sample size is about 600 grains to ensure the degree of probability of 0.95. So determination of the coefficient of roundness were performed an all test specimens after the cyclic triaxial tests and also for the original, unloaded material. Figure 7 gives an overview of the results.

As it could be seen in figure 7 there is a clear difference between the well rounded quartz sand and the industrial breaked angular gabbro sand. But also a clear difference between the origin material and the loaded material can be seen. In the test with gabbro sand there is a dependency between the number of loading of the material and the coefficient of roundness. An increase of the number of loading leads to more rounded grains. Abrasion seams to be a slow and permanent effect. However in the macroscopic view, a end of the abrasive influence of cyclic loading is not seen in the microscopic view too. Also a dependency between the origin placement density and the roundness of the grain exists. How denser the specimen is all the more rounding of grains occur. This observation is explained with the formation of the grain skeleton. In a dense skeleton exists more grain contacts then in a loose skeleton, so the probability of shifting of grain contacts and therefore shear stresses are more likely then in a loose skeleton where shifting without high shear stresses is possible. Also for the well rounded quartz sand an effect of the cyclic loading on the coefficient of roundness can be observed. The analysis of quartz sand is not comparable directly to the gabbro sand because of the different load history. The quartz sand was loaded with up to 5.5 Mill. loadings and at least an amplitude of 600 kN/m² vertical stress change per cycle, so the entered energy is much higher then in the tests with gabbro sand. Under respect of this circumstance it can be estimated that abrasion has a smaller effect of the roundness for the quartz sand.

4 CONCLUSION

The performed triaxial cyclic load tests have shown the meaning of abrasion due to the deformation of sand under cyclic loading. A small plastic strain increment occurs in all performed tests independently of the number of loading. The microscopic study showed the effect of abrasion to the single grains. The used materials showed the tendency to become rounder with increasing number of loading. Also an increase of roundness can be observed with increasing sample density. Abrasion seems to have a different influence on different materials. Angular materials are more influenced on abrasion then rounded materials. Also the mineralogy has an influence on the measure of abrasion of the grains. Further investigations have to show the influence of the abrasion to certain material parameters. Also a mechanical model on the basis of common constitutive laws should be developed, which integrates the effect of abrasion, what means that the splintering of small particles and consequently the dissipation of energy has to be included.

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