Effect of pore-size distribution on the collapse behaviour of anthropogenic sandy soil deposits

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Abstract. In the former open-pit mines of the Lusatian region in Germany, several liquefaction events have occurred during the recent years in the anthropogenic deposits made of very loose sandy soils. These events are related to the rising ground water table after the stop of controlled ground water lowering. The very loose state is due to the formation of sand aggregates (pseudo-grains) during the deposition process. The pseudo-grains enclose larger voids of dimension greater than the single sand grain. Wetting induced collapse of the pseudo-grains is presumed to be one of the possible mechanisms triggering liquefaction. In the present study, the effect of larger voids on the wetting induced deformation behaviour of sandy soils is experimentally investigated by laboratory box tests. The deformation field in the sample during wetting was measured using Digital Image Correlation (DIC) technique. The results show that the observed deformations are affected by the pore size distribution, thus the amount of voids between the pseudo-grains (macro-void ratio) and the voids inside the pseudo-grains (matrix void ratio). The global void ratio of a sandy soil is not sufficient as single state parameter, but the pore size distribution has to be taken into account, experimentally as well as in modelling.

1 Introduction

In the former open-pit mines of the Lusatian region in Germany, several liquefaction events have occurred during the recent years in the anthropogenic deposits made of very loose sandy soils. These events have occurred spontaneously, i.e. they were not caused by an earthquake or other dynamic loading source. The deposits have an average thickness of about 50 m. Due to the technological process of deposition the sandy soils are of varying composition and density, leading to unknown direction and magnitude of the principal stresses inside the deposit. Mostly, the deposits are in a very loose state, in extreme cases showing a void ratio greater than $e_{\max}$.

In general, the liquefaction events are related to the rising ground water table in the deposits due to the stop of controlled ground water lowering for about 25 years. Wetting induced collapse of larger voids inside the deposit is presumed to be one of the possible mechanisms triggering liquefaction.

The influence of soil structure on the soil behaviour is well known to be relevant for properties such as shear strength, compressibility, hydraulic conductivity, and soil-water characteristics of a soil. Soil structure changes with stress state, transfer of water and air, temperature, long-term gravimetric actions, and weathering. Natural and man-made geomaterials frequently exhibit two scales of porosity. A substantial amount of research work has been undertaken regarding the coupled hydro-mechanical

behaviour of compacted clays. These soils typically are made-up of aggregates, leading to at least two different levels of pores: macro-pores between the aggregates and micro-pores inside the aggregates [1-7].

Wheeler (1988) [8] has proposed a conceptual model for describing the behaviour of marine sediments containing large discontinuous gas bubbles. Biogenic (degradation of organic matter), thermogenic or volcanogenic processes are the origin of gas in deep sediments. The soil matrix (silty, clayey sediment) is saturated, and discrete large gas bubbles having a pore radius much larger than the pores inside the soil matrix exist as long as the gas pressure is greater than the water pressure from the surrounding saturated soil matrix.

However, effects of porosity at different levels are usually not considered for coarse grained soils like sandy soils.

The following hypotheses with regard to the formation of larger gas filled voids exist: (1) formation of sand aggregates (pseudo-grains) during the technological deposition process and (2) biogenic processes inside the deposit [9]. In the former, the pseudo-grains enclose larger voids of dimension greater than the single sand grain forming a double-porosity soil system. The biogenic processes are the microbial transformation of organic matter (mainly coal) into CO_2 and the formation of CO_2 due to buffering of existing acid rich regions by carbonatic constituents. However, size and shape of the gas filled voids in-situ are not known.

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Based on the above considerations, an experimental program was designed to investigate the possible effect of larger gas filled voids of various amount and size on the wetting induced collapse of sandy soils. The results of the experimental study are presented in this paper. The larger gas filled voids are defined to be voids with a diameter much larger than the diameter of the grains. Thus, the large voids can be regarded as cavities inside the soil matrix. In the following, the large voids will be called bubbles. The total volume of voids inside the soil is composed of the volume of the bubble(s) and the volume of the “standard” void space inside the sand matrix. In order to investigate the possible effect of bubbles on the collapse behaviour, the amount and size of the bubbles were varied while keeping the total volume of voids constant, leading to a variation in pore size distribution inside the soil.

In the present study, the effect of amount and diameter of large voids on the wetting induced collapse of sandy soils is experimentally investigated by laboratory box tests. Five different configurations of size and amount of large voids were tested. The wetting process was observed using Digital Image Correlation (DIC) technique, which allowed for the measurement of the deformation field.

2 Material

The material used was sand named Lohsa II, sampled from a former open pit mine in Lusatian region in Germany. The grain size characteristics are given in Table 1. The maximum and minimum void ratio was measured according to the German standard DIN 18126 and was $e_{\max} = 1.109$ and $e_{\min} = 0.435$, respectively. Initial water content was 5%.

Table 1. Measured material properties of Lohsa II sand.

d_{10} (mm)	d_{30} (mm)	d_{50} (mm)	C_u (-)	C_c (-)	ρ_s (kg/m ³)
0,13	0,21	0,35	2,8	1,01	2,63

3 Methods used

3.1. Experimental programme

Table 2 presents an overview about the experimental programme. Five tests were performed with different bubble configurations. The test name indicates the amount of bubbles and the diameter of the single bubble. The global void ratio e_{global} corresponds to maximum void ratio $e_{\max}$ and was the same for all tests. The global void ratio is composed of the volume of voids inside the sand matrix (e_{micro}) and the volume of the large bubble(s) (e_{macro}).

The deformation field in the box test during wetting was measured using Digital Image Correlation (DIC) technique. The total settlement at the sample surface was measured by displacement transducers. The box test represents a plane strain condition; therefore, the bubble

Table 2. Experimental program.

Test name	Test configuration	e_{global} (-)	$e_{\text{bubble}} = e_{\text{macro}}$ (-)	$e_{\text{matrix}} = e_{\text{micro}}$ (-)	ratio $e_{\text{macro}} / e_{\text{global}}$
0B	0 Bubble	1.109	0	1.109	0
1B/35	1 Bubble/ Ø35 mm	1.109	0,033	1,076	0,03
1B/50	1 Bubble/ Ø50 mm	1.109	0,067	1,042	0,06
2B/35	2 Bubbles/ Ø35 mm	1.109	0,067	1,042	0,06
4B/25	4 Bubbles/ Ø25 mm	1.109	0,067	1,042	0,06

void ratios (e_{macro}) were calculated based on the area of the large bubble.

The final settlement of the five tests was compared. Test 0B is the reference test of the sand matrix without large bubble. In this test, e_{global} is equal to e_{micro} and e_{macro} is zero. Tests 1B/35 and 1B/50 (series 1) will show the effect of increasing increasing e_{macro} while the amount of bubble and e_{global} remained constant, and e_{micro} decreases. Tests 1B/35 and test 2B/35 show the effect of increasing e_{macro} by increasing the amount of bubble (series 2). Tests 1B/50, 2B/35 and 4B/25 were performed to investigate the effect of pore size distribution of the bubbles on the wetting induced settlements, while e_{global} , e_{macro} and e_{micro} remained constant (series 3). This was realized by an increasing number of large bubbles with a corresponding decreasing bubble diameter.

3.2. Experimental set-up

Figure 1 shows a schematic of the box used for the wetting tests (Fig. 1a) and a photograph of the whole experimental set-up including DIC camera and data acquisition system (Fig. 1b). The sample dimensions were 27 cm width, 24 cm in height, and 10 cm thickness. The sample is placed on a filter paper which itself is separated by a geotextile from the stiff bottom steel plate with holes. Below the steel plate is a space which allows for an equal water level over the width of the box after start of the inflow from the water vessel (Fig. 1a).

The sample consists of 6 layers of 4 cm height; the border between each layer is marked by a thin layer of coloured sand grains. The layers are named L1 (layer 1, top of bottom layer) to L6 (layer 6, top surface), see Fig.

1a. The results of the DIC measurement are presented for selected points. These points are in the vertical centre axis on top of each layer as well as at the top and the bottom of the large bubble(s). They are marked by a red dot in Fig. 1a.

A water vessel (overflow vessel) providing a constant upper pressure head is connected by a tube to the bottom of the box. Target water level was at top of level 5 corresponding to 20 cm of initial sample height. At the end of the test, full saturation was reached in the whole specimen.

Two displacement transducers (DT) were placed on the surface of the specimen (top of layer 6). One of them was located in the centre of the top surface (DTc) and one between DTc and at border of the box (DTs). The latter is marked by a green dot in Fig. 1a. The measurements of displacement transducer DTc were used to verify the DIC measurements at top of layer 6 (L6).

Two DIC cameras (Fig. 1b) are placed in front of the box to record the deformation field over sample height and width during the wetting process. The analysis of the measured data is performed using software DaVis 7.2 of the company LaVision GmbH.

Figure 1(a). Schematic of the box and soil sample (example of test 2B/35)

Figure 1(b). Photograph of experimental set-up (example of test 1B/35)

3.3. Test procedure

The testing program as shown in Table 2 was performed. All tests were performed with 4% initial water content and the respective void ratios (e_{global} , e_{micro} , e_{macro}) as shown in Table 2.

At first, a geotextile of thickness 4 mm covered by a filter paper were placed at the base of the box. Then, the mass of sand needed for each layer of 4 cm height for the

desired matrix void ratio e_{micro} was placed manually. The sand was equally distributed and slightly compacted so as to reach a homogenous sand matrix throughout the sample. At the top of each layer, black sand grains are poured to mark the boundary between two subsequent layers in order to better visualize the deformations of the respective layer.

At the desired location, prepared hollow ice cylinders were placed horizontally to serve as shuttering to create the large voids. Further, sand was placed above the large voids stabilized by the ice cylinders until the target sample height of 24 cm. The sample preparation was finalised before the cylinder was melt.

After end of sample preparation and after the ice cylinder was melt, the water vessel is connected to the box. The data acquisition system for the DIC and the displacement transducers was started. The wetting test started when the inlet valve was opened.

The water firstly distributes in the empty space below the base plate at the bottom of the specimen, and then the water level rises equally over the whole sample width. The piezometric water level can be read from the tube at the left side of the sample box (see Fig. 1a). The water level in the vessel is kept constant while the water level in the sample did increase. Thus, during the test, the hydraulic gradient was not constant. For each test, it took approximately 30 min until the target water level of 20 cm was reached and deformation process has reached equilibrium.

4 Results

In this section, the observations during the tests according to the testing program shown in Table 2 are presented. In the first part, the qualitative observations by DIC technique are described. In the second part, the measured deformations over time and the final deformations of the different test configurations are quantitatively compared.

Figures 2 to 4 present qualitative observations for test 2B/35 (i.e., 2 bubbles of diameter 35 mm embedded in the homogenous sand matrix). Figure 2 shows the initial state of the sample just before start of the wetting process

Figure 2. Initial state at $t = 0$ s of test 2B/35 (obtained from DIC).

Figure 3. DIC sequence of the wetting process for test 2B/35 (blue line marks the top of capillary fringe).

Figure 4. Vertical displacement of test 2B/35 at $t = 1600$ s measured by DIC (yellow indicates maximum displacement, red indicates minimum displacement)

(at $t = 0$). The centre of bubble 1 (lower bubble) is located at about 8 cm height from the sample bottom, the second upper bubble is located at about 16 cm height. The net distance between the circumferences of the bubbles is 4.5 cm. The melting of the ice cylinder caused only very small deformations until an arching was built up in the sand matrix beside the bubble.

Figure 3 qualitatively shows the wetting process in a sequence of six pictures for selected time steps of test 2B/35. Only the centre part of about 10 cm width including the large bubbles was shown for each time step. The blue lines highlight the location of the top of the capillary fringe.

Until $t = 50$ s (picture 2 of the sequence), the rise of the capillary fringe caused uniform settlements. The bubble remained intact while the capillary fringe increased at both sides of the bubble. The water did enter the bubble only when the piezometric water level was about 1 to 2 cm above the lowest point of the bubble. This is in agreement to Wheeler (1988) [8] who stated that a large gas bubble is flooded, when the pressure difference of gas pressure inside the bubble u_g and the water pressure u_w reaches a critical minimum value for

the radius of curvature R_c of the menisci between the sand grains at the bubble boundary. R_c is of the order of the particle size d and is not related to the bubble radius.

Failure occurs at the top of the bubble B1, showing a mechanism similar to ground failure.

At $t = 225$ s (picture 3 of the sequence), the void space of bubble B1 was nearly fully closed by the settlement of the above sand layers. At this stage, the capillary fringe has reached the top of the 3rd layer. The upper three layers do not show incremental settlements, and the upper bubble (B2) is still intact.

At $t = 620$ s (picture 4 of the sequence), the capillary fringe has nearly reached the top of bubble B2. B2 is slightly compressed, but has not yet collapsed. At the former location of Bubble B1, the deformed line of the black coloured sand grains indicates the collapse of sand into Bubble 1 which was completely filled by sand.

At $t = 875$ s (picture 5 of the sequence), bubble B2 was filled by sand from the overlaying matrix. Picture 6 at $t = 1600$ s of the sequence represents the final state of the test, where the target piezometric water level was reached.

Figure 4 shows the final state of test 2B/35 observed by DIC including contour lines of the deformation field. It is to be noted that the upper contour lines above the soil sample should be neglected. Maximum displacement occurred at the top of the sample in the vertical centre axis above B2. The deformations in the near region around the centre axis were strongly affected by the presence of the bubbles.

Figures 5a to 5e illustrate the deformations measured

Figure 5(a). Test 0B: measured height of the measurement points versus elapsed time

Figure 5(b). Test 1B/35: measured height of the measurement points versus elapsed time

Figure 5(c). Test 1B/50: measured height of the measurement points versus elapsed time

Figure 5(d). Test 2B/35: measured height of the measurement points versus elapsed time

Figure 5(e). Test 4B/25: measured height of the measurement points versus elapsed time

for each test during the test duration. The left vertical axis refers to the actual height of the various measurement points, whereas the right axis refers to the piezometric water level, designated as WL in the legend of Figs. 5(a) to 5(e). DTc and DTs refer to the displacement transducers at the sample surface (see Fig. 1a). All other lines refer to measurements by the DIC system; they are designated according to their location at the layers (L1 to L6) and at top and bottom of the bubbles.

Figure 5(a) represents the behaviour of the homogenous reference sample without any large bubble. As expected, it shows smooth and continuous settlements at each measurement point, as soon as the water table together with the capillary fringe has started to rise. The cutting point of the water level (WL) with the respective measurement location (L1 to L6) indicates the point when the settlement at the respective measurement location has

stopped. This means, once the water level has reached the actual location of the measurement point, no further settlement has occurred in this measurement location.

In the other 4 tests with different bubble configurations (1B/35, 1B/50, 2B/35 and 4B/25), it was observed that the settlement smoothly increased until the water level has reached the actual location of the respective measurement location. A steeper increase in settlement or sudden settlement has occurred when the water level has reached the top of the bubble(s) (Fig. 5b, 5c, 5d, 5e). In tests 2B/35 and 4B/25, this was more significant when the water level had reached the upper bubble(s).

Figure 6 compares the final maximum settlement measured by the displacement transducers for each test configuration. In all test configurations studied herein the initial global void ratio was constant ($e_{\text{global}} = 1.109$). However, the measured final settlement due to wetting induced collapse was found to be different for each test. In the following, the results are described for the three different series (see section 3.1).

Figure 6. Maximum final settlement versus ratio $e_{\text{macro}}/e_{\text{global}}$ for all tests

Series 1 (0B $\rightarrow$ 1B/35 $\rightarrow$ 1B/50):

The maximum final settlement of the homogeneous reference sample (0B) was about 59 mm. The final settlements of both heterogeneous tests containing a bubble (1B/35, 1B/50) were found to be smaller. This indicates that the decrease in matrix void ratio in both tests 1B/35 ($e_{\text{micro}} = 1.076$) and 1B/50 ($e_{\text{micro}} = 1.042$) as compared to the homogeneous sample 0B ($e_{\text{micro}} = 1.109$) had a dominating effect over the increase in macro void ratio. However, comparing tests 1B/35 and 1B/50 with each other, the further increase in macro void ratio from $e_{\text{macro}} = 0.033$ to $e_{\text{macro}} = 0.067$ by increasing the diameter of the bubble obviously dominated over the respective decrease in matrix void ratio from $e_{\text{micro}} = 1.076$ leading to a higher final settlement.

Series 2 (0B $\rightarrow$ 1B/35 $\rightarrow$ 2B/35):

In this series, comparing test 1B/35 to test 0B, the same explanation as in series 1 holds true (compensating effect of smaller matrix void ratio over effect of large bubble). Comparing tests 1B/35 and 1B/50 with each other (both configurations have identical e_{global} , e_{macro} and

e_{micro}), indicates that the increasing amount of bubbles lead to a higher settlement.

Series 3 (0B $\rightarrow$ 1B/50 $\rightarrow$ 2B/35 $\rightarrow$ 4B/25):

Again, in this series, global void ratio is the same for the homogeneous reference test and the three heterogeneous tests. Comparing the heterogeneous tests with each other (e_{global} , e_{macro} and e_{micro} are constant) indicates that the increase in amount of bubbles, thus the change in pore size distribution lead to an increase in the final measured wetting induced settlement.

Overall, the test results indicate that consideration of global void ratio of sand may not be the relevant state parameter for describing the soil behaviour.

5 Summary

In the present study, the effect of large voids (gas bubbles) and their pore size distribution on the wetting induced collapse of sand was experimentally investigated by laboratory box tests. Five different configurations of size and amount of large pores were tested. The wetting process was observed using Digital Image Correlation (DIC) technique and displacement transducers at the surface.

Overall, the test results indicate that for a sandy soil system with constant global void ratio, the incorporation of large gas bubbles of different size and amount affected the final measured settlement values to different extent.

In general, the higher the amount of bubbles, the greater were the settlements observed. For a smaller number of gas bubbles (up to 2 in this study), the decrease in matrix void ratio compensated the effect of the large gas bubble(s) leading to smaller or equal settlements as compared to the homogeneous reference sample. In general the study indicates that the assumption of a homogeneous soil system with a global void ratio as a state parameter may not be sufficient to fully describe volumetric soil behaviour.

However, this experimental study is a first attempt to investigate the effect of larger voids on the wetting induced collapse behaviour of anthropogenic sandy soil deposits. For better representing in-situ conditions, tests

at larger scale and at representative stress level need to be performed. The test instrumentation should be enlarged to also measure water content, suction and pore water pressure.

References

1. S. Diamond, Pore size distributions in clays, *Clays and Clay Minerals* **18**, 7-23 (1970)
2. S. Ahmed, C. Lovell, S. Diamond, Pore sizes and strength of compacted clays, *ASCE J. Geotech. Eng. Division* **100**, 407-425 (1974)
3. A. Gens, E. Alonso, A framework for the behaviour of unsaturated expansive clays, *Can. Geotech. J.* **29**, 1013-1032 (1992)
4. P. Delage, M. Audiguier, Y. Cui, M. Howat, The microstructure of a compacted silt, *Can. Geotech. J.* **33**, 150-158 (1996)
5. E. Romero, A. Gens, A. Lloret, Water permeability, water retention and microstructure of unsaturated compacted boom clay, *Engineering Geology* **54**, 1-2, 117-127 (1999)
6. P. Delage, D. Marcial, Y. Cui, X. Ruiz, Ageing effects in a compacted bentonite: a microstructure approach, *Géotechnique* **56**, 5, 291-304 (2006)
7. R. Thom, R. Sivakumar, V. Sivakumar, E. Murray, P. Mackinnon, Pore size distribution of unsaturated compacted kaolin: the initial states and final states following saturation, *Géotechnique* **57**, 5, 469-474 (2007)
8. S.J. Wheeler, A conceptual model for soils containing large gas bubbles, *Géotechnique* **38**, 3, 389-397 (1988)
9. N. Hoth, M. Ussath, A. Simon, Fluid-dynamisch-hydrogeochemische Arbeitshypothesen zu rezenten Bodenverflüssigungen im Lausitzer Revier. Schriftenreihe des Instituts für Bergbau und Spezieltiefbau, TU Bergakademie Freiberg, Hrg. W. Kudla, Heft 5, Beiträge zum 2. Kolloquium Bodenverflüssigung bei Kippen des Lausitzer Braunkohlebergbaus, (2014)