Influence of external pressure changes acting on unsaturated submerged soils

L'influence des variations de la pression externe agissant sur les sols non-saturés au dessus du niveau de la nappe phréatique

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ABSTRACT: In engineering practice soils below piezometric line are commonly considered to be saturated and the pore fluid is rated being incompressible. Near the piezometric surface this two phase model is not consistent with natural conditions. Even smallest quantities of gas bubbles change the physical properties of the pore fluid. The paper deals with the results of laboratory measurements and numerical simulations. It explains the results of external pressure changes on the soil deformation in such conditions. The effective stress may be reduced, leading to soil structure changes especially in non cohesive soils. Heaving and settling of the soil and even interweaving soil movements (fluidisation) may be induced.

RÉSUMÉ: Dans la practice de l'ingénieur on regarde les sols sous le niveau piézométrique comme parfaitement saturés et le fluide interstitielle comme incompressible. Près du niveau piézométrique ce modèle a deux phases n'est plus compatible avec des conditions naturels. Même des petites quantités des bulles de gaz peuvent changer le comportement du fluide interstitiel. Dans cette article il s'agit des résultats des mesures dans le laboratoire et des simulations numériques du phénomène. On explique l'influence des changes de la pression extérieure sur la déformation du sol. La réduction de l'effort effectif conduit aux changements de structure particulièrement dans sol granulaires. Des gonflement ou des tassements de la surface résultent et même une fluidisation peut apparaître.

1 INTRODUCTION

1.1 *Unsaturated submerged soils*

The pore fluid in the submerged soil skeleton below piezometric line contains fine dispersed microscopic gas bubbles, that are always present in natural conditions. The physical properties of such unsaturated submerged soils changes due to the gas content in the pore fluid and need to be taken into account in transient states. This may be performed by applying a three phase model. The compressibility β of the pore fluid inside the submerged subsoil is much dependent on the quantity of such bubbles. Regarding the soil stiffness, water permeability and the prevailing stress environment of the subsoil, delayed pore water pressure dissipation may easily be registered as a time dependent excess pore water pressure $\Delta u(z,t)$. The delayed pore pressure response of the deforming submerged soil may be described by Biot's (1941) consolidation equation.

1.2 *Soil behaviour due to external pressure changes*

Due to external fluctuating pressures, such as pressure changes induced by water waves, water level draw down, static and dynamic loading or even meteorological variations in air pressure, the gas bubbles inside the gas-water mixture would like to react immediately in volume change. This process is hampered by low permeability. The gas bubbles inside the pore fluid counteract variations of external pressures by inflating or deflating the gas volume, thus causing local transient micro flow. Therefore these gas bubbles play an additional key role in soil behaviour contributing to soil structure deformation and soil failure.

2 EXPERIMENTAL SET-UP OF LABORATORY TESTS

In order to observe the deformation and structure changes in a submerged sand bed a pressure tank has been custom built, in which a pressure environment of up to 300 kPa may be applied. Figure 1 shows the test equipment and the cross section of the sediment layers together with the position of the installed pressure gauges (g1...g8). Several adjustable endoscope inlets allow the observation of the endangered soil areas in order to measure the mixing of the soil particles and structure changes inside the sand induced by water level changes. By using image processing technique the magnitude and the frequencies of the motions has been deduced from the sampled images. With this measurement technique the soil has been examined on a microscopic scale (Spies et al. 2000). In the tests a uniform silty sand of a mean di-

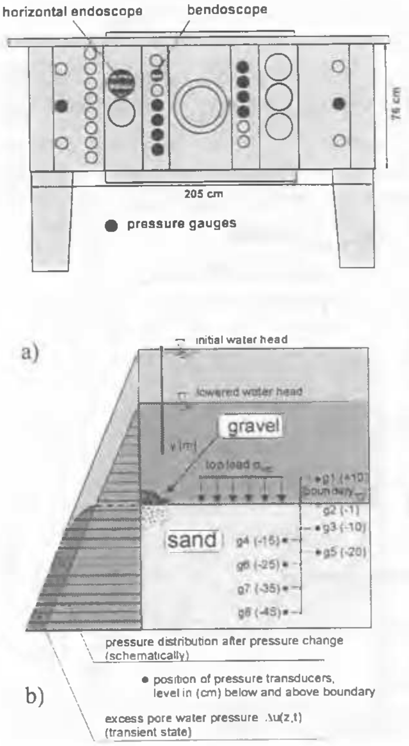

Figure 1. Experimental set-up in use for the deformation and fluidisation tests of submerged sand caused by fluctuating water level a) side view of the pressure tank and instrumentation layout, b) cross section of the sand bed protected by a 10 cm thick gravel layer and different additional top load

ameter d_{mean} = 0.2 mm has been used, stabilised by different top load σ_{top} acting on a 10 cm thick gravelly draining filter layer.

3 FINITE ELEMENT SIMULATION

The behaviour of a multiphase medium subjected to changes in water pressure was modelled using a simplified 1D finite element analysis. The aim of the simulation was to understand the process qualitatively.

The compressibility of such near saturated soils is governed by the time dependant distribution of the stress between the solid phase and the compressible water-air mixture. The compressibility β of the fluid was expressed in the degree of saturation S, the water compressibility β_w, volumetric coefficient of air solubility h, the environmental pressure p (Bishop & Eldin 1950, Fredlund & Rahardjo 1993):

$$\beta = S\beta_w + \frac{1-S+hS}{p} \tag{1}$$

The viscosity of the water-air mixture was neglected.

The solid part was modelled as an elastic-viscous material with two possible states: solid or fluidised. The fuidisation takes place, if the vertical gradient exceeds the unit weight of the soil. The main effective stress σ has been used to distinguish between the two states and an explicit procedure has been implemented with a corresponding time stepping control.

The model parameter chosen followed the ideas presented by Köhler & Koenders (2001). The mechanical behaviour of a solid-water mixture is controlled by the relative gap between the particles (related to the porosity n) and by the number of particles N, which form the aggregates. The number N is very large for the solid state and decreases to 1 in a fully fluidised material due to the successive disintegration of the particle conglomerates. The elastic modulus is approximately proportional to N.

The viscous strain rate is described by a power law:

$$\dot{\varepsilon}^c = \frac{\sigma^\alpha t^\beta}{f} \tag{2}$$

where σ = main stress, t = time, f = viscous modulus, α and β = empirical constants. The viscous modulus f is proportional to N and to the fluid viscosity μ_w and inversely proportional to the relative gap (Figure 2):

$$f \approx \mu_w \frac{6(1-n)^2}{n^3 N} \tag{3}$$

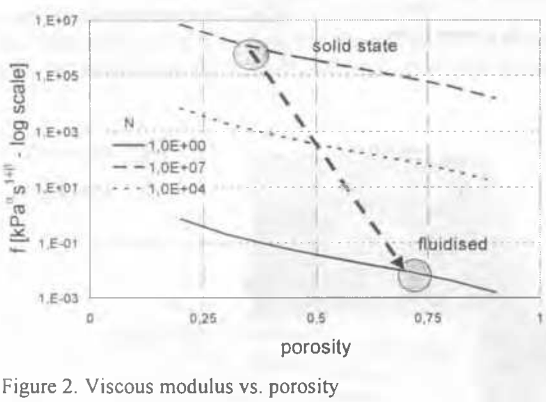

Figure 2. Viscous modulus vs. porosity

The following parameters have been used (Table 1):

Table 1. Model parameters.

	Young modulus	Poisson's ratio	Viscous compressibility	α	β
	E [kPa]	ν	f [kPa$^\alpha$s$^{1+\beta}$]		
solid	20000	0,3	25000	0	-1
fluidized	80	0,45	200	1	0

4 RESULTS OF MEASUREMENTS AND SIMULATIONS

Two typical soil conditions, which can be found at inland navigational canals, have been selected in order to compare the results of finite element simulations with the experimental data gained out of laboratory tests. The assumptions about the deformation characteristics, which have been applied in the finite element simulations, cover both conditions, the mainly elastic and the mainly viscous state.

4.1 *Mainly elastic conditions.*

The first example describes the situation in about 2.3 m depth below the canal water level, which may be found on the embankment, protected by a revetment structure. The second example stands for unprotected soil conditions in about 3.2 m water depth level, which are typical for the conditions at the river or sea bed. The experimental data, presented by Köhler et al. (1999), illustrate heaving and fluidisation processes, which easily may be induced by water level draw down loading, causing transient pore water pressure inside the submerged sandy soil. As soon as the critical hydraulic gradient i_{crit} = 1 is exceeded, fluidisation occurs, if the top load σ_{top} is insufficient compared to the size and draw down velocity of the change in water level.

Figure 3 shows the results of the first example with an initial depth of water level of about 2.3 m for an applied top load of 8.5 kPa (permeable revetment structure) and a change in water level of about 0.92 m within 7.5 seconds. This ramp experiment simulates typical draw down loading effects, caused by navigating vessels in an inland water way. The measured pore pressure response at different depth levels of the subsoil plotted over the

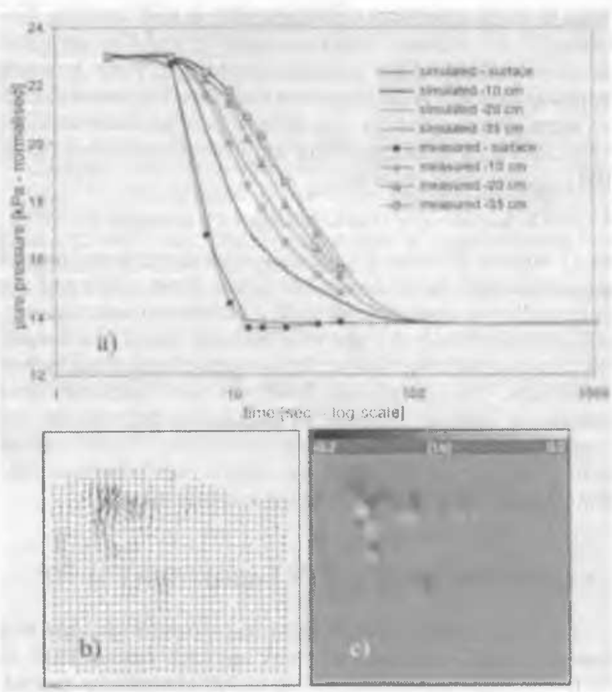

Figure 3. Ramp experiment without fluidisation (top load = 8.5 kPa) a) comparison between measured and computed pore pressure changes, b) observed velocity field, c) image revealing regions with changes of soil structure

elapsed time explains the transient situation, causing the time dependent excess pore water pressure Δu (z,t), acting in the sandy soil. In the upper part (a) of figure 3 the measured and computed pore pressures are compared. The quality of the prognosis was better in the lower layers. Using a fine parameter tuning it would be possible to improve the agreement, but our goal here was to reach only a simple estimation of the process.
In the images of figure 3 below (b and c) results of the endoscopic observations are shown. The image of the size 512 by 512 pixels on the right hand side corresponds to an viewing area of about 6 by 6 mm. By using image processing algorithms the local displacement vector fields are derived from the image sequences during the loading phase, which is displayed on the left hand side (b) of figure 3. Although this experiment describes a so called stable situation of only small soil movements, which could be observed during the period of water level lowering, still some inhomogeneous movements could be detected inside the soil structure. The applied pressure change indicates the onset of fluidisation effects, which occur locally due to the expansion of gas bubbles embedded in the pore water of the submerged soil area.

4.2 *Mainly viscous conditions*

While the loading situation shown in figure 3 explains more or less elastic deformation characteristics, the ramp experiment in the second example (Figure 4) describes the viscous properties of a fluidised soil structure. With the insufficient top load of 1.3 kPa the soil heave exceeds the elastic deformation and changes into that of a viscous state, induced by the ramp load of 1.75 m water level lowering. Nearly the whole depth of the 50 cm thickness of the sand bed is fluidised, which is clearly indicated by the uplift forces of the transient water flow, acting in the whole soil region (see figure 4 b). In Figure 4 a) the measured and the calculated pore pressures are plotted in order to compare the results of experimental data with that gained by the performed finite element simulation. The result of the laboratory experiment and that of the finite element simulation do not quite correspond to each other, but do coincide reasonably well in the time dependant fluidisation characteristic, which is plotted in figure 5. The simple bilinear model can capture only the main characteristic of sand behaviour. In the fluidisation phase the use of a continuos parameter change would substantially improve the

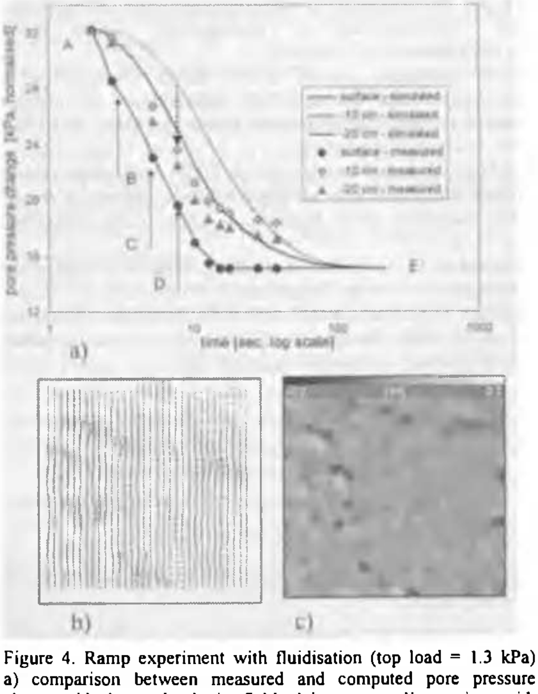

Figure 4. Ramp experiment with fluidisation (top load = 1.3 kPa) a) comparison between measured and computed pore pressure changes, b) observed velocity field, c) image revealing regions with changes of soil structure

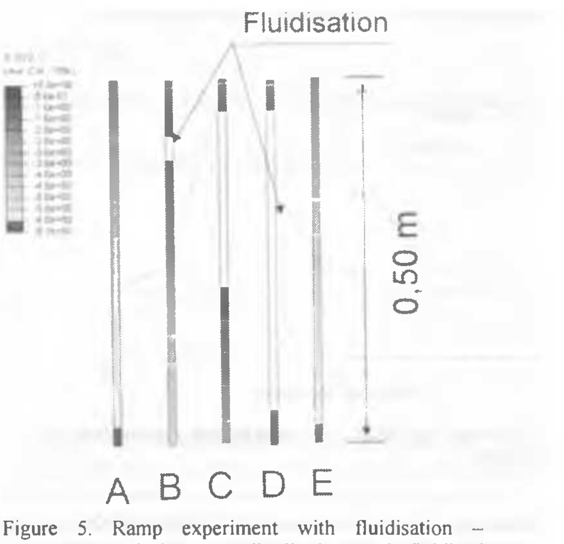

Figure 5. Ramp experiment with fluidisation – computed vertical stress distribution and fluidised domains (Time steps A – E as indicated in Figure 4)

prediction quality. A very difficult problem is still the numerical convergence, due to the very small steps required by the visco-plastic regularisation of the softening material behaviour.
For the different time steps ranging from A to E the development of the fluidised soil region during the experiment is shown together with the corresponding vertical stress distribution plotted over the soil depth of the 0.50 m sand bed thickness. The white parts of the columns B, C and D indicate the fluidised regions of the soil bed, where the effective stress level reaches zero and the acting shear resistance between the soil particles ceases to exist. It is worth pointing out, that fluidisation commences in a certain depth level and not directly at the soil surface (compare the plot of column B in figure 5). Figure 6 presents the evolution of the effective vertical stress for both cases.
From there it spreads simultaneously in both directions, upward and downward into the sand bed. The fluidisation process starts already after the water level lowering has reached a value of about 0.40 m water height almost at the beginning of the ramp loading of altogether 1.75 m water height (see also the arrow at the time step B in figure 4 a). The results gained from this finite element simulation also agree remarkably well with the compilations presented by Roussell et al. (2000).
During the fluidisation process the heaving of the whole soil segment exceeds the size of the elastic deformations by more

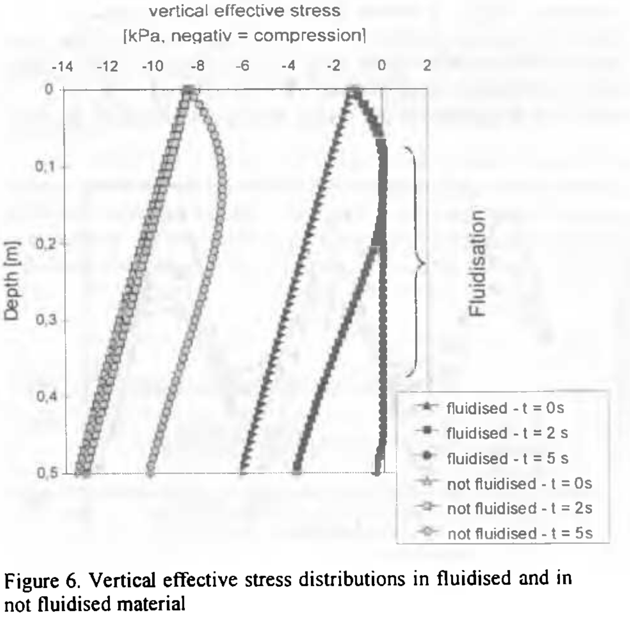

Figure 6. Vertical effective stress distributions in fluidised and in not fluidised material

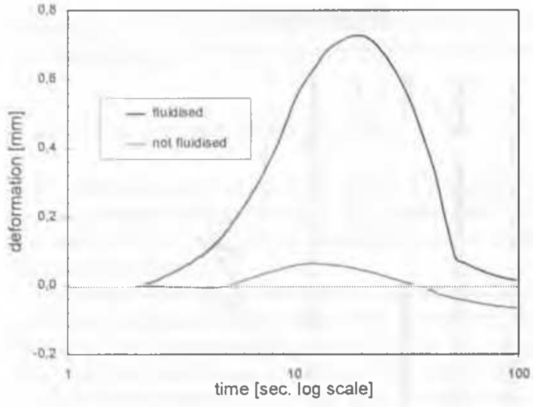

Figure 7. Computed evolution of the sand surface deformation for both experiments

than ten times the observed values (Köhler et al. 1999) and the calculated ones by the performed finite element simulation (see also the plotted evolution of the deformation shown in figure 7).

5 HYDRAULIC FAILURE CONDITIONS CAUSED BY OSCILLATING WATER LEVEL

Due to the fact that the presence of gas in bubble form in soils below the water level is happen to be natural, especially in shallow water conditions, should encourage the engineering praxis to take such phenomena more into account than has been assumed in the past. The constitutive behaviour of a soil-fluid-gas mixture has been presented by quite a number of researchers i.e. Theunissen (1982) and Barends (1980).

Using their expressions for the initial saturation degree S_o in the dependency of the initial pressure p_o together with the initial porosity n_o at the soil water interface a simplified solution for the actual degree of saturation S caused by a change in porosity Δn can be assumed for homogeneous soil conditions as a function of depth. According to an initial gas content of about 5 % the unsaturated conditions of such soils could then easily reach down to depth level of about 30 m below water level. External pressure changes therefor influence the soil behaviour in such way, that even hydraulic failure may be induced (Köhler et al. 1999).

Regarding the possible deformations caused by such loading will become more dangerous with cycling pressures or even oscillating water levels. Heaving, settling and fluidisation of the subsoil may happen, causing solid structure deformation and failure conditions. Figure 8 shows the results of the computed pore pressure response, induced by a sinusoidal wave loading on a shallow sea bed (water depth of 4 m) consisting of uniform sand with a permeability coefficient k = 8.5 exp-5 m/s.

Due to the frequency of the acting pressure oscillations the pore

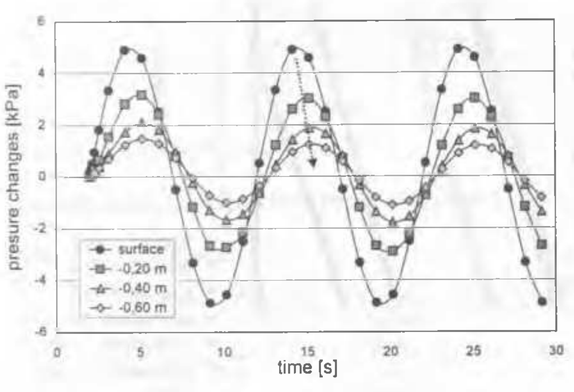

Figure 8. Computed pore pressure changes in different depths due to oscillating water level

pressure response is delayed by a phase shift of the pressure amplitudes and pressure damping with increasing depth is indicated.

6 CONCLUSIONS

With the applied measurement technique using image processing to study soil deformation characteristics in a microscopic scale the motion frequencies and soil structure changes could be observed and finally evaluated by numerical finite element simulations as well as for the mainly elastic and as for the mainly viscous soil behaviour. The analysis of the pore pressure development in unsaturated submerged soils enabled to simulate soil deformations and fluidisation processes due to fluctuating water level changes. In regarding the unsaturated conditions of submerged soils below the piezometric line may lead to a more realistic evaluation of deformations of structures under specific loading and may also lead to better understanding of soil-structure-interaction during different construction phases. The presented considerations and observations about the influence of a deformable 3-phase soil medium (solids, water and gas) below water level should not be neglected in many loading and structure cases.

Further research is necessary to verify the influence of such phenomena.

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