SOFT MUD: FIELD PERFORMANCE RELATED TO LAB EXPERIMENTS, MODELLING AND ANALYSIS OF TIME-DEPENDENT PROCESSES AFFECTING CONSOLIDATION
Introduction
Self-weight consolidation plays a major role in the creation of land using mud, the ripening of mud layers and, also, in the storage of contaminated mud and slurries in ponds. There is a significant compaction due to self-weight consolidation at lower stresses (0.1 to 10 kPa) which gives the need for special laboratory tests and accurate modeling. The self-weight consolidation theory according to Gibson was extended to other time dependent processes: Gas production has been included in this theory and in a numerical code [Wichman 1999a and 1999b] and this was validated in the laboratory and the field [Wichman et al. 2000]. The user-friendly numerical tool FSCongas has been developed, including several gas production scenarios with gas dissolution, and a choice of boundary conditions. To this tool also a simple creep model has been added [Greeuw et al. 1999]. In the hydraulic consolidation tests GASCON and HYDCON the loading condition in the Slufter disposal site – with up to 20 metres of mud at maximum effective stress of 10 kPa – has been successfully simulated [Wichman et al. 2000]. In these tests the mud sample was left to consolidate and stiffen for some days, and next it was loaded gently by applying a hydraulic gradient across the mud sample. In the GASCON-tests, after the initial self-weight consolidation was finished, the hydraulic gradient was increased a several times. Settlement and pore pressures at short distances across the sample were monitored. The GASCON-cell allows for the monitoring of gas production and gas accumulation throughout the consolidation process, whereas the HYDCON-cell is suitable for saturated samples, only. In this previous research the experimental conditions were chosen carefully, resembling the field situation, as effects of thixotropy and creep were expected.

Recently, effects of thixotropy and creep were studied more closely by means of the Suction Induced Consolidation test (SIC). Some results are discussed in this article. Initial sample conditions, creep and thixotropy may significantly influence consolidation performance and containment structure stability in the short and long term. Permeability of the sample affects the consolidation speed. The response of the sample permeability to a varying imposed sucking flow rate was studied and compared to the field situation.
Time-dependent processes
Two processes were found to have a major effect at low stress levels, i.e. thixotropic stiffening and creep. Mitchell (Mitchell 2005) says: "Thixotropy is defined as an isothermal, reversible, time-dependent process occurring under conditions of constant composition and volume, whereby a material stiffens while at rest and softens or liquefies upon remolding. This effect is largest in a soil structure with high water content and active clay content, as the soil particles have more freedom to rearrange, react and form bonds. Sills (Sills 1995) has shown that creep can be a major effect at low effective stress levels, i.e. the volume effect induced by creep is one order of magnitude larger than at higher stress levels (say 50 kPa). Creep can be considered as a time dependent adjustment of soil structure at constant effective stress, which gives a reduction in pore volume and an increase in strength. In addition, in permeability testing care should be taken not to disturb the sensitive soil structure. Permeability values might depend on the imposed sucking flow speed, which is discussed in this article.

Experimental set-up
The experimental set-up of the SIC is shown in Figure 1. A sample of freshly mixed mud is placed in a ring in a triaxial cell, which is partly filled with water. The sample can be drained at both sides or at the upper side only. The latter was the case in the consolidation tests presented here. The sample is loaded by pressing the sample against a fixed stamp, by using the load control at the bottom of the triaxial cell. At the bottom of the sample a piston pump is attached that can be used to extract a chosen discharge from the sample. In this way the sample can be consolidated by sucking water from it, but this was not done so in our research. By sucking a small amount of pore water, a permeability test can be done. The load, displacement, differential pore water pressure across the sample and cell pressure (set to 3 Bar) are measured.

The test consists of a series of loading steps with a duration that is long enough for the excess pore pressures to dissipate to a large extend. This is defined as the end of consolidation. At that stage the settlements might still go on, mainly due to creep. At the end of each loading step, i.e. at the end of consolidation, typically after 1 to 3 days, the piston pump was used to determine the permeability of the sample. The pump sucks a chosen constant discharge from the sample, whereas the differential pore water pressure across the sample was measured in time. This was done until the pore pressures reached a steady state. The sucking lasted for about 1000 seconds. Imposed discharge and the resulting change in differential pore pressure were inserted into Darcy’s law, to determine permeability. The imposed discharges were of the same order of magnitude as in the typical field situation (1 to 5 E-08 m/s, see Discussion).

Two SIC tests were performed on mud from the same supply bucket, using the same sequence of loadings. The initial density was 1316 kg/m³ as settled in the supply bucket. The initial sample height was 56 mm. In SIC1 the sample with the filter stone on top was left in the ring for 1 week before further loading, whereas the SIC2 sample was left there for 24 hours. The loading schemes for SIC1 and SIC2 are shown in Figure 2. The total duration of the stepwise
In the creep test consolidation and creep was allowed during 7 days at a constant load of 5N and another 3 days at constant volume, the latter stage giving a decrease in effective stress of 0.1 kPa (2N decrease in load). The creep was found to be dominant in the last 6 days of loading. At the end of the SIC-tests the unloaded sample was tested to determine water content, bulk weight, gas content and undrained shear strength by means of a vane test. For further analysis, the peak shear strength was considered.

The tested mud has: 30% sand content, 18% < 2 μm (lutum content), 7% organic content, and the clay consists of mainly illite, kaolinite and montmorillonite with a specific mass of solids = 2580 kg/m³.
The undrained shear strength was expected to increase due to thixotropic stiffening, and this was verified by a sequence of vane tests. The undrained shear strength in time at zero load was measured with a vane in a separate bucket. As the sample height in the SIC is small and almost no water was expelled, the main cause of increase in strength during the waiting period before loading is thixotropic stiffening of the mixed sample.

Figure 3 gives the effective stress and permeability results at the respective loadings for SIC1 and SIC2. In SIC1 significant gas production occurred, which is visible from the difference in the (total) void ratio (that follows from the final sample height) and the void ratio esat of the fluid part that was determined from the water content after the tests were finished. This implies a final gas volume percentage of 19% (at 3 Bar cell pressure) for SIC1. In SIC2 hardly any gas production occurred (<1% gas content). This might be due to the longer storage time (1 month longer) of the bucket of mud before mixing it for use, during which the gas production had slowed down already. Before loading with the first 2N load in SIC1, there was no evidence of gas that had been produced. Therefore, it is likely that the amount of gas in the sample is still limited at the loading step of 2 N and thus the resulting void ratio is close to the void ratio of the fluid part esat.

The error margins for effective stress indicated are obtained from the residual excess pore pressures at the end of the loading steps. This was sufficient for practical purposes, i.e. to determine the effective stress-void ratio regression relation. During the permeability test, the sucking was stopped after the steady state had been reached and, subsequently, the sample was left to equilibrate. In principle the final equilibrated differential pore pressure should be almost equal to the value just before the start of the sucking. The differences observed were taken as an error margin in the analysis of the permeability-void ratio regression relation, as these differences exceeded the measurement inaccuracy. Thus, the accuracy in permeability is better than 20%. In Figure 3, the permeability values that were derived from the change in pore pressure during the sucking are plotted.

In Figure 3, three type of least squares regression lines were added: first, a least square fit of the SIC1 results (including gas), secondly, a line that excludes the effect of gas by connecting the result from SIC1 at 2N (i.e. 0.3 kPa, where little gas had been produced yet) with the SIC1 result at 900 N (i.e. 50 kPa), using esat = 50 kPa and, finally, a least square fit of SIC2 results. The second regression line gives an idea of the effective stress and permeability relations as functions of esat. The measured undrained shear strength values of the mud after mixing are given in Table 1 and are also shown in Figure 3.

At the end of both SIC-tests the undrained shear strength has been measured at three spots in the consolidated sample. The minimum and maximum peak Cu-values for the consolidated sample are shown in Figure 3 with Cu = 18.4 to 18.8 kPa for SIC1 and Cu = 14.4 to 17.2 kPa for SIC2. The permeability data show a range in permeability at the respective void ratios. The higher permeability values were determined from tests with a higher flow rate. For SIC1 the range in flow speed at 28 kPa (900 N, void ratio = 2.19) was a factor of 10, which gives a range in permeability values of factor of 2. This is caused by the fact that the excess pore pressure was not linearly proportional to the flow speed. For SIC2 the range in flow speed was less than a factor of 1.7, which gives only small range (max. factor 1.3) in permeability values at the respective loading steps. The volume change of the sample during all permeability tests was very small and it might partly be due to creep.

The effect of sample stiffening can be described in terms of the time evolution of the undrained shear strength that can be determined with laboratory vane-tests.

**TABLE 1**

<table>
<thead>
<tr>
<th>Time after mixing (days)</th>
<th>0</th>
<th>10</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Cu (kPa)</td>
<td>0.01</td>
<td>0.04</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Discussion

The effect of sample stiffening can be described in terms of the time evolution of the undrained shear strength that can be determined with laboratory vane-tests. In addition, the effective stress can be related to the undrained shear strength. (Merckelbach 2000) reports that for soft mud the undrained peak strength is of the same order of magnitude as the effective stress. In Figure 3, this insight can be used by extrapolating from the lowest stress level to the initial void ratio of 4, at which the effective stresses are 0.1 kPa for SIC1 (using the regression line with esat) and 0.01 kPa SIC2. When comparing these effective stress values with the undrained shear strength in Table 1, it follows that after 1 week of resting, the sample in SIC2 might had stiffened even more than it was the case in the bucket after 10 days. The differences between SIC1 and SIC2 in effective stresses and related shear strength are possibly due to thixotropic stiffening. At a stress level of 50 kPa the peak shear strength is a fraction of 0.32 (SIC2) to 0.37 (SIC1) of the effective stress. This is normal for typical clay with a higher consistency. The deviation between the three effective stress – void ratio and between the three permeability – void ratio relations (i.e. the
regression lines) is caused by gas production, but also due to thixotropic stiffening of the sample before the first load was applied. From Figure 2 it is visible that the sample in SIC2 was much more compressible than that in SIC1, especially at the low loading levels up to 10 N (i.e. 0.74 kPa). It is also visible in Figure 3 that at 50 kPa the results from SIC1 in terms of $e_{\text{sat}}$ and SIC2 (that had no gas) are very similar. This is more in-line with what would be expected for a typical clay with a higher consistency.

Creep also plays a role in stiffening of the sample, which is visible from Figure 2 by comparing the settlement in SIC2 at the 5 N step (i.e. at effective stress = 0.45 kPa), at which during 6 days’ additional creep had been allowed to occur, and the 10 N step in which little settlement occurred as the sample had stiffened by then. For comparison: the difference in settlement between the 5 N and 10 N step in SIC1 is much less, so it is likely that stiffening due to the additional creep at 5N limited the settlement at 10 N. These effects are also visible in Figure 3 in which the effective stress points are less in line for SIC2 as compared to SIC1.

Finally, it was found that the permeability values from the SIC-test depend on the imposed flow speed, as the excess pore water pressures generated are less than linearly proportional to the applied sucking flow rate. The flow rate values used in the tests are in the same range as occurring in the field, the flow rates being larger at the start of consolidation. This flow-rate effect needs further study, considering the effective part of the sample porosity through which the water flows. If the effective part of the porosity is larger, less pore water is ‘bounded’ and immobile to the solids structure. The flow speed might affect the amount of water that is ‘bounded’ to the clay particles. The permeability tests in the SIC did probably not disturb the soil structure itself, as during the test the sample volume hardly changed.

**Practical implication**

The results of some FSCongas model runs that are typical for large scale land reclamation are shown in Figure 4. In these runs a layer of 5 metres of mud was deposited under water in 0.5-years’ time with an initial density of 1316 kg/m³. In these model runs all three types of regression lines as shown in Figure 3 were used. The bottom of the layer was assumed to be drained. Figure 5 shows profiles in depth of density and effective stress for the 3 runs just after deposition (at 0.51 years).

In Figure 3, the regression lines from SIC1 contain two effects: a larger void ratio in time for the respective loadings due to gas production, and, at low stresses, a stiffening due to thixotropy. The retarding effect of the gas on self-weight consolidation can be explicitly added (Wichman 1999a and 199b), in case the gas production rate in the field is known. Prediction and quantification of this retarding effect requires further research.
Self-weight consolidation in layers of soft mud is considered as a main cause of settlement and increase in shear strength. This plays a role in the creation of land using mud, the ripening of mud layers and, also, in the storage of contaminated mud and slurries in ponds. This article discusses evidence of time dependent processes affecting self-weight consolidation, such as gas production, thixotropy, creep and flow rate dependent effects. These processes result, among others, in non-unique effective stress-void ratio and permeability-void ratio relations. Suction Induced Consolidation (SIC) tests were performed to investigate the influence of the before-mentioned time-dependent effects.

Numerical simulations of a typical Dutch land reclamation project showed a significant effect on consolidation of the non-unique effective stress-void ratio and permeability-void ratio relations that were obtained from the SIC tests performed. Especially at lower stresses between 0.1 kPa and 10 kPa that are most relevant for land reclamation projects, the effects were found to be largest and they affect a major part of the settlement and resulting densification. It is concluded that, in combination with numerical modelling, the laboratory procedure to determine the consolidation parameters should be established such that significant time dependent processes -alike those acting on full scale- are part of the testing.

The initial (pre-loading) conditions and the type of loading should be realistic, i.e. similar to the field condition. In addition, significant gas production can occur and this retards the consolidation process and the final degree of densification.

Conclusions
Experiments in the SIC set-up turned out to be useful to investigate the effect of thixotropy and creep on the effective stress – void ratio and permeability – void ratio relations that were obtained from these tests. In the first SIC1 experiment gas production occurred, that was considered in determining the effective stress and permeability relations including the gas and without it. From two SIC-test results three types of regression lines were obtained that were used to model a typical land reclamation project. The practical implication of thixotropy and gas production is major, as the stress levels in the field are relatively low and the effect of gas, thixotropy and creep are largest at low stress. In addition, creep is much more significant for soft mud than for consolidated clay, as visible from the sequence in settlements from the SIC-tests reported. In general, the laboratory procedure to determine the effective stress and permeability relations should be established such that significant time dependent processes [as acting on full scale] are part of the testing. As consolidation in the field takes longer than in the laboratory, thixotropy in the field will increase the stiffness of the soil at low stress levels, which is demonstrated best by the results from SIC1 in comparison to test SIC2, where SIC 1 is considered to have a more realistic initial condition, i.e. a longer pre-loading resting period. In testing permeability, the flow rates need to be chosen realistically, i.e. as expected in the field situation, as they affect the permeability values at a given void ratio. Larger flow rates, that occur at the start of consolidation, tend to result in a relatively larger permeability.
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The tests as discussed in this article were executed at the request of and supervised by Royal Boskalis Westminster N.V. Results were applied as input for the design and engineering process for a large-scale reclamation project.

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