Consolidation and strength evolution of Dollard mud
Measurement report on laboratory experiments

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Abstract

Many harbours in the world suffer from high siltation rates in their basins. To guarantee safe shipping, harbour authorities have to maintain the navigable depth by having dredged large amounts of mud. Some authorities relate the navigable depth to a depth at which the density is equal to a certain value, e.g. 1200 kg/m$^3$. However, the shear strength might be a more direct criterion to relate the navigable depth to.

A research project is conducted to develop a model to describe the consolidation behaviour and strength evolution of mud layers. The third series of experiments for this project, executed at Delft University of Technology, are described in this report. The analysis of the data is left for future work.

The sedimentation and consolidation of Dollard mud was simulated in segmented consolidation columns. By using segments well-defined and undisturbed samples of the mud bed were obtained. For this reason, more accurate shear vane measurements of the samples could be done than if conventional consolidation columns had been used.

Four segmented consolidation columns and one conventional consolidation column were set up. To study the time evolution of the strength of the mud bed, the segmented columns were dismantled at different times. After the dismantling, shear vane tests were carried out and density measurements were done with a conductivity probe. The density profiles of the mud layer in the conventional column were measured with a $\gamma$-ray densimeter. Pore water pressures were measured at several times. From these measurements effective stresses and permeabilities were calculated. Various rheological parameters were derived from four different types of shear vane measurements. Flow curves were also measured.

It turned out that significant segregation occurred, resulting in a mud bed formed on top of a layer of approximately 5-8 cm with a relatively large coarse silt fraction and high densities. For the mud layer it turned out that the effective stresses could be approximated by a power law. Furthermore, the rheological parameters turned out to be approximately linearly interrelated, even though the parameters were derived from different types of rheological experiments. Both the relationships between peak shear stress and density, and between peak shear stress and effective stress show time dependency.
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Many harbours in the world suffer from high siltation rates in their basins. To guarantee safe shipping, harbour authorities have to maintain the navigable depth by dredging large amounts of mud, which involves substantial costs.

Typical for these basins is that a bottom is hard to define since the density increases gradually from the water surface to deep in the bed. Some authorities relate the navigable depth to the depth at which the density of the mud is equal to a certain value, e.g. 1200 kg/m$^3$. However, the (shear) strength seems to be a more relevant parameter for defining the navigable depth. Although density and shear strength of mud are interrelated, this relationship is not unique and may be time dependent. Both parameters are related to the consolidation behaviour. A definition of the navigable depth based on shear strength might give rise to a change in the dredging strategy and possibly result in lower costs.

Presently, a research project, which is financed by The Netherlands Technology Foundation, is conducted to develop a mathematical model of strength evolution in a mud bed. This model can be used to translate results from laboratory experiments to field conditions. The model formulation requires knowledge of consolidation and strength evolution processes. In this respect, important parameters are effective stress, permeability and (peak) shear stress. These parameters can be calculated from measurable quantities as bulk density, pore water pressure and torques exerted onto a vane introduced into a mud sample. During the period from April 28th until July 19th 1997, a first series of experiments was carried out at the University of Oxford and reported in Merckelbach (1998b). A second series of experiments was carried out at the Hydromechanics Laboratory of Delft University of Technology, Department of Civil Engineering and Geosciences during the period from April 14th until July 17th 1998 and reported in Merckelbach (1998a). In both experiments Caland-Beer Channel mud was used.

A third series of experiments was also carried out at the Hydromechanics Laboratory of Delft University of Technology during the period of October 12th 1998 until January 13th 1999. The results are reported herein. However, the analysis of the data will be left for future work. It is noted that the data reported herein are also available on CD-ROM.

This report is organized as follows. In Chapter 2 the experimental programme is discussed and the measurement techniques used. In Chapter 3 the results are presented. Concluding remarks are stated in Chapter 4.
Chapter 2

Experiments

The laboratory experiments described here, follow up the experiments on Caland-Beer Channel mud, described in Merckelbach (1998a). Again, the aim is to simulate the formation of a mud layer formed by deposition from a suspension and to study the self-weight consolidation behaviour and strength evolution of this mud layer. Therefore, the experimental set-up used in earlier experiments, was reused, albeit with some minor modifications. This time we used a different type of mud, so that the data would not be restricted to one type of mud. Of the marine types of mud available in The Netherlands, we chose Dollard mud, since we expect that Dollard mud has a composition that differs most from that of Caland-Beer Channel mud.

2.1 Experimental set-up

A brief description is given here only. For a more detailed description of the experimental set-up and procedures, the reader is referred to (Merckelbach, 1998a).

We used consolidation columns to simulate the deposition and the consolidation behaviour. Four segmented columns and one conventional column were set up. The columns were 1.6 m high and they had an inner diameter of 10 cm.

The segmented columns were designed such that at some time, the consolidating bed could be sliced into well defined samples of 10 cm in diameter and 5 cm in height. Accurate shear strength measurements were done on these samples with a miniature vane.

So-called column segments were used to obtain the samples. In Figure 2.1, a sketch of a column segment is presented. In fact, only the consolidated bed at the time of dismantling needs to be covered with column segments, so that the remaining part of the column was constructed in one piece. One step of the dismantling procedure is shown in Figure 2.2. The procedure was repeated until all segments were isolated.

The drawback of this procedure is that after dismantling a column, the consolidation experiment could not be continued. Studying the strength evolution requires multiple, equally set-up columns. Therefore, four segmented columns were set up. Subsequently, these columns were dismantled after 9, 29, 63 and 95 days of consolidation.1 Throughout this report the segmented columns are labelled as TDLxx, where xx denotes the duration of the particular experiment in days, and the conventional column is labelled TDLC.

1The measurements on Caland-Beer Channel mud were done on days 9, 24, 58 and 95.
Figure 2.1: A base plate, a column section and a complete segment

Figure 2.2: A schematic picture of the dismantling of a segmented column

a) Set-up during consolidation.

b) Lower section after removal of upper section. The column section of the uppermost segment is pushed on to the base plate (1), then, the segment is slid aside (2).

c) The removed segment with the sample, ready for the shear vane test.
2.2 Measurement techniques

Basically three parameters were measured: pore water pressure, density and bed strength. In each column pore water pressure ports were let into the column at twelve discrete levels. Tubes connected the pressure ports to a pressure measuring unit. A pressure measuring unit is a device that controls the actual connection between the pressure transducer and the pressure ports by means of valves, with a maximum of 24 pressure ports per transducer. Hence, three pressure measuring units were used to serve all five columns. The accuracy of the pore water pressure readings is 10 Pa.

Bulk densities of the bed in the segmented columns were measured with a conductivity probe after dismantling and the shear vane tests. The bulk density of the bed in the conventional column was measured with a non-destructive γ-ray densimeter, which was provided by the dredging company H.A.M. Several density profiles were measured of the conventional column. From these density profiles, together with the corresponding pore water pressure profiles, the permeability could be estimated. Regarding the set-up used in earlier experiments, the traversing system of the γ-ray densimeter has been automated, so that continuous density profiles could be measured. The accuracy of the density measurements is ± 5 kg/m³. The vertical resolution is about 1.7 cm. The improved γ-ray densimeter system is discussed in more detail in Appendix B.

Rheological measurements were done with a UDS 200 rheometer, manufactured by Physica GmbH. Two devices were used: a five-bladed vane, 2.0 cm high and 1.0 cm in diameter, for strength measurements and a concentric cylinder geometry for the flow curve measurements. The vane tests were carried out on the samples confined in the isolated segments. On each sample four different vane tests were carried out:

**Rate controlled 1:** The rotation speed was set at 1.0 rpm and the torque was recorded over a range of two complete revolutions. The data are characterized by four parameters: peak shear stress, $\tau_{\text{peak}}$, the peak angle $\phi_{\text{peak}}$, the residual shear stress, $\tau_{\text{residual}}$, and the tangent to the curve in the origin, $\frac{\delta \tau}{\delta \phi}$. See Figure 2.3 for the definitions.

**Rate controlled 2:** The rotation speed was set at 0.10 rpm and the torque was recorded over a range of 35 degrees. The data are characterized by three parameters: peak shear stress, $\tau_{\text{peak}}$, the peak angle $\phi_{\text{peak}}$, and the tangent to the curve in the origin, $\frac{\delta \tau}{\delta \phi}$. See Figure 2.3 for the definitions.

**Stress controlled:** The applied torque was increased from 0.01 mNm until 10 mNm logarithmically in a time interval of 300 s and the rotation angle was recorded. However, each measurement was aborted shortly after the material started to flow. The data are characterized by two parameters: the yield stress, $\tau_{\text{yield}}$, and the yield angle, $\phi_{\text{yield}}$. See Figure 2.4 for the definitions.

**Oscillating, rate controlled:** The vane was oscillated with an angular frequency ranging from 0.6 rad/s to 30 rad/s, and a rotation angle amplitude of 1.0 mrad. The storage modulus $G'$ and the loss modulus $G''$ were recorded. The data are also characterized by two parameters: the storage modulus $G'$ and the loss modulus $G''$ for an angular frequency of 1.57 rad/s. See Figure 2.5 for the definitions.

For experiment TDL63 and TDL95 only, oscillating vane tests were also carried out directly after the rate controlled vane test at $\Omega = 1$ rpm. In this way the residual storage modulus and the residual loss modulus were measured.
Figure 2.3: A typical recording of a rate controlled measurement.

Figure 2.4: A typical recording of a stress controlled measurement.

2.3 Mud preparation

The mud that was used, originated from the Ems-Dollard Estuary, The Netherlands. It was dredged in September 1998, near Nieuwe-Staten Zijl. Its bulk density was about 1400 kg/m$^3$. A few properties of Dollard mud are listed in Table 2.1. The corresponding properties of
Figure 2.5: A typical recording of an oscillation measurement.

Caland-Beer Channel mud are also presented. Particle size distributions are presented in Figure 2.6

Table 2.1: Properties of Dollar mud and Caland-Beer Channel mud

<table>
<thead>
<tr>
<th></th>
<th>Dollar</th>
<th>Caland-Beer Channel</th>
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<tbody>
<tr>
<td>density of solids (x10^3 kg/m³)</td>
<td>2.6362 ±0.006</td>
<td>2.5278 ±0.006</td>
</tr>
<tr>
<td>sodium adsorption ratio (-)</td>
<td>42</td>
<td>70</td>
</tr>
<tr>
<td>cation exchange capacity (cmol/kg)</td>
<td>18.0</td>
<td>20.1</td>
</tr>
<tr>
<td>specific surface (m²/g)</td>
<td>108.23</td>
<td>96</td>
</tr>
<tr>
<td>humus (% by weight)</td>
<td>3.05</td>
<td>3.99</td>
</tr>
</tbody>
</table>

The mud used in the experiments was diluted to a density of approximately 1075 kg/m³. The diluent was tap water with NaCl added, until the water had a density of 1003.5 kg/m³, which is equal to the density of the pore water. Before the mud suspension was introduced into the columns, it had been mixed thoroughly for one hour.

An overview of the initial conditions is presented in Table 2.2.
Figure 2.6: Particle size distribution

Table 2.2: Properties of the mud suspensions introduced

<table>
<thead>
<tr>
<th>Pore water density (kg/m$^3$)</th>
<th>Initial bulk density (kg/m$^3$)</th>
<th>Initial height (m)</th>
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<tr>
<td>TDL9</td>
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<td>TDL95</td>
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<tr>
<td>TDLC</td>
<td>1003</td>
<td>1072</td>
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</table>
Chapter 3

Results

3.1 Mud-water interface settlement

The level of the mud-water interface was measured at different times during the experiments. The measurements are shown in Figure A.1 (logarithmic time scale) and Figure A.2 (linear time scale). The interface dropped from 1.53 m (initial height) to about 0.65 m within one day. Subsequently, the settling velocity gradually decreased. Significant deformations did not occur anymore after about 50 days. The correspondence between the interface heights of the different columns is good. The discrepancy between the interface heights around 0.4 days is artificial and caused by missing data points.

3.2 Density profiles

In contrast with the conventional column, in which several density profiles were measured, only one density profile was measured of each segmented column. In Figures A.3 through A.6 the density profiles of the four segmented columns (TDL9, TDL29, TDL63 and TDL95) are shown together with the corresponding density profile of the conventional column.

In all columns exceptionally high densities were measured in the lowest 8 cm of the bed. The reason for these high densities is probably that coarse silt and fine sand particles segregated in the initial dilute suspension and settled very quickly. Particle size distributions, determined from samples taken from different segments are in support of this, see also Section 3.3.

The correspondence between the density profiles measured with the conductivity probe and the γ-ray densimeter is quite good for the experiments of TDL29 and TDL63. Unfortunately, the density measurement with the γ-ray densimeter of day 9 failed. Therefore, the measurement of day 8 is shown instead. The difference in height of the interface is mostly the result of the difference in time of measuring.

More serious deviations are observed between the density measurements after 95 days. The discrepancy is most likely the result of the presence of gas bubbles. A number of gas bubbles with a diameter up to about 5 mm were observed during the dismantling of TDL95. In contrast with the conductivity probe, the density data obtained with the γ-ray densimeter are not point measurements, but are averaged over the cross-section of the column. Therefore, if gas bubbles were present, it is likely that densities measured with the γ-ray densimeter are more reduced than densities measured with the conductivity probe.
Furthermore, it is noted that the density near the bottom measured with the conductivity probe is consistently higher than the density measured with the \( \gamma \)-ray densimeter. Unfortunately, the confidence in data obtained with both methods is low, because i) the range for which the \( \gamma \)-ray densimeter in the present set-up could be calibrated was limited to 1000 – 1300 kg/m\(^3\), and ii) the samples taken from the lowest segment to calibrate the conductivity probe, were too thick to measure the density with either the DMA35N density measurement system or density measurements based on the evaporation of pore water. The problem with the latter method was that because of the high viscosity, the volume of the sample could not be determined accurately. Fortunately, these data are not of great importance, since the bed in the lowest 5 to 8 cm consisted mostly of coarse silt or fine sand, see also Section 3.3.

In Figure A.7 all density profiles measured in the conventional column are collected. This figure shows the development of the density distribution of the conventional column (TDLC) with time.

### 3.3 Particle size distributions per segment

Mud samples of a number of segments of experiment TDL29 and of all segments of TDL95 were analyzed for the particle size distribution. Here, \( z \) denotes the height above the base of the column. The mass density and cumulative mass percentages are shown in Figures A.8 through A.11.

The results of both experiments are consistent. The particle size distributions for \( z \geq 10 \) cm are almost equivalent and the coarse silt and fine sand fractions are almost completely absent. For \( 0 \leq z < 5 \) cm, i.e. the lowest segment, the coarse silt fraction and the fine sand fraction spectacularly increased at the expense of the clay and fine silt fractions. This result is in agreement with the measured density profiles. The region \( 5 \leq z < 10 \) cm can be regarded as a transition zone.

### 3.4 Excess pore water pressure profiles

The excess pore water pressure profiles are shown in Figures A.12 through A.16. The results of the pore water pressure measurements of the segmented columns do not show any anomalies. The dissipation of the excess pore water pressure with time can clearly be observed.

### 3.5 Effective stress data

Generally, the effective stress is defined as the total stress minus the pore water pressure. Total stresses are easily obtained by integration of the density profiles. The effective stress data are shown in Figures A.17 through A.20. Figures A.17 and A.18, in which the effective stress is plotted against the particle volume fraction, show that a power law relationship exists between effective stress and particle volume fraction if the particle volume fraction is smaller than about 0.16. For larger values the relationship seems to deviate, which is most likely a result of segregation.

The accuracy of the effective stress data, which depends on the accuracy of both the pore water pressure measurement and the density measurements, is estimated at ±15 Pa.
3.6 Permeability data

Permeability was calculated from Darcy's law:

$$k = \frac{1}{v_s} \frac{\partial p_e}{\partial z},$$

where \(v_s\) is the settling velocity of the solids, \(k\) is the permeability and \(\frac{\partial p_e}{\partial z}\) the excess pressure gradient. The settling velocity is calculated from two consecutive density profiles. The excess pressure gradient used in (3.1) is the average of the excess pressure gradients pertaining to these two density profiles. The calculation procedure is described in more detail by Merckelbach (1998b).

Since the calculation of permeability requires at least two density profiles, the permeability data are available only for the conventional column (TDLC). The permeability data are presented in Figure A.21. The time indicated for each series of measurements is the average of the times of the two density profiles used in the calculation.

The permeability data for specific times seem to relate to the particle volume fraction according to a power law if \(\phi_p < 0.16\). However, the proportionality factor fluctuates significantly. It is noted that the validity of both the effective stress and permeability power laws is restricted to the range \(\phi_p \in [0.08 : 0.16]\).

The permeability data for \(\phi_p > 0.16\) show serious scatter, which can be explained as follows. The determination of the permeability by the method used here, becomes inaccurate if the settling velocity approaches zero, which follows from (3.1). From Figure A.7 it can be seen that the density remained more or less constant in time for \(\rho = 1260 \text{ kg/m}^3 \approx \phi_p \geq 0.16\), implying very low settling velocities and with that inaccurate data.

The accuracy for \(\phi_p < 0.16\) is estimated at \(\pm 3.0 \times 10^{-7} \text{ m/s}\).

3.7 Shear stress data

Rate controlled shear vane tests

The peak shear stresses (\(\tau_{\text{peak}}\)) and the peak angles (\(\phi_{\text{peak}}\)), measured with the rate controlled shear vane test at \(\Omega=1.0 \text{ rpm}\) and \(\Omega=0.1 \text{ rpm}\), are shown in Figures A.22 through A.25. The segments are numbered starting from the interface and ending at the bottom. Note that each segment has a height of 5.0 cm.

The peak shear stresses increased with increasing depth and time, except for the peak shear stresses measured in the lowest segment. The peak shear stress measured in the lowest segment was initially higher than measured in the other segments, but increased much more slowly with time. The peak shear stresses obtained at a rotation speed of \(\Omega = 1.0 \text{ rpm}\) were generally higher than those obtained at a rotation speed of \(\Omega = 0.1 \text{ rpm}\). Peak angles, on the other hand, did not change significantly and are more or less constant at 0.2 rad, irrespective of depth and time.

The residual shear stresses (\(\tau_{\text{residual}}\)) and the initial curve gradients (\(\frac{d\tau}{d\phi} \big|_{\phi=0}\)) are shown in Figures A.26 through A.29. The residual shear stresses for \(\Omega = 0.1 \text{ rpm}\) were not determined, since these tests only covered the first 35 degrees. The residual shear stresses for \(\Omega = 1.0 \text{ rpm}\) and the initial curve gradients also increased with depth and time, as expected. However, the residual shear stresses measured in the lowest segment were also initially larger than the residual stresses measured in other segments, and increased much more slowly with time. The
initial curve gradient for $\Omega = 0.1$ rpm was generally larger than the gradient for $\Omega = 1.0$ rpm. The initial curve gradient data points show some scatter, which is probably caused by the fitting procedure based on only two data points.

**Stress controlled shear vane tests**

The yield stresses ($\tau_{\text{yield}}$) and the yield angles ($\phi_{\text{yield}}$), measured with the stress controlled shear vane test, are shown in Figures A.30 through A.33. The yield stresses also increased with increasing depth and time, except for the measurements of the lowest segment. The yield angles remained more or less constant at 0.2 rad. It is noted that the measurement of the yield stress and angle of the lowest segment for TDL63 is not available.

**Oscillating shear vane tests**

The storage moduli ($G'$) and the loss moduli ($G''$) at $\omega = 1.57$ rad/s are shown in Figures A.34 through A.37. The residual storage and loss moduli were measured for only TDL63 and TDL95, and are shown in Figures A.36 and A.37.

Both the storage moduli and the loss moduli increased with increasing depth and time, except for the measurements of the lowest segment. The similarity between corresponding $G'$-curves and $G''$-curves is remarkable, for all segments. The curves of the residual moduli are similar to the (ordinary) moduli in all but magnitude.

The tangents of the loss angles, defined by

$$\tan \delta = \frac{G''}{G'},$$

are shown in Figure A.38. It appears that $\tan \delta$ remains more or less constant for all segments but the lowest one, with an averaged value of about 0.154. The loss angles determined from the residual moduli are also more or less constant for all segments but the lowest one, however, the averaged value is slightly larger.

**Flow curve measurements**

Flow curve measurements were obtained with a concentric-cylinder device. The measured shear stresses are presented as function of the shear rate in Figure A.39 and Figure A.40. For shear rates larger than approximately 5 s$^{-1}$, the mud can be considered as a Bingham fluid. The dynamic differential viscosity is, which is a constant for Bingham fluids, is about $40 \cdot 10^{-3}$ Pa s for bulk densities of 1200 kg/m$^3$ and about $80 \cdot 10^{-3}$ Pa s for bulk densities of 1230 kg/m$^3$. The Bingham yield stresses vary slightly more and are not very well reproduced. The Bingham yield stresses are about 24 Pa for bulk densities of 1200 kg/m$^3$ and about 45 Pa for bulk densities of 1230 kg/m$^3$.

The dynamic apparent viscosity is plotted against the shear rate on double logarithmic scales in Figure A.41. For shear rates higher than 4 s$^{-1}$, the dynamic viscosity is approximately proportional to the reciprocal value of the shear rate. The dynamic viscosities for bulk densities of about 1230 kg/m$^3$ are generally higher than the dynamic viscosities for bulk densities of about 1210 kg/m$^3$. 

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Chapter 4
Concluding remarks

The following remarks can be made concerning the present experiments.

Experimental set-up

It was the second time that segmented consolidation columns were used. The segmented columns were designed such, that after some time of consolidation the mud bed could be sliced into well defined samples. Accurate and sensitive shear vane tests were carried out on these samples. The design again proved to be satisfactory.

The procedures and instrumentation with respect to the density measurements with the conductivity probe, the pore water pressure measurements and shear strength measurements were the same as for earlier experiments on Caland-Beer Channel mud. The recommendations regarding the traversing system of the γ-ray densimeter and the calibration procedure, as they were put forward after evaluation of the earlier experiments, have been followed, so that in the present set-up accurate and continuous density profiles could be measured.

Results

The results on the interface settlement, density measurements and effective stress data show a good correspondence between the different experiments, which means that the reproducibility of the experiments can be considered quite good.

All density profiles show a spectacular increase of the density near the bottom, which is very unusual for mud layers. Particle size distributions, determined for several heights in the bed, indicate that a significant amount of the coarse silt fraction had segregated. The high densities that are observed near the bottom, were attributed to the occurrence of segregation.

In earlier experiments on Caland-Beer Channel mud and Combwich mud (Merckelbach, 1998b; Merckelbach, 1998a; Merckelbach et al., 1999) it was found that the effective stress followed a power law of the particle volume fraction. For the present experiments this seems to be true if the data points pertaining to the lowest 8 cm of the bed are excluded, see Figure 4.1. It was shown that the particle size distribution of the bed, ranging from 10 cm of the base and higher, was more or less invariant with the height. From this, it seems likely that a power law relationship between effective stress and particle volume fraction requires a constant particle size distribution throughout the bed.

The rheological experiments showed that the parameters that can be related to strength, all increased with depth and time, if the measurements of the lowest segment are left out of
Figure 4.1: Effective stress data of TDLC as function of $\phi_p$, excluding the data points pertaining to the lowest 8 cm of the bed

consideration. However, this general behaviour is not only qualitative: all parameters are more or less linearly related, see Figure 4.2. Furthermore, it was observed that the rotation angle at which the peak shear stress was reached in the rate controlled measurements, was practically the same as the rotation angle at the yield point in the stress controlled measurements. Moreover, these angles remained constant with respect to depth and time.

If the peak shear stress (or any other shear strength parameter) is related to the bulk density, it can be seen that the relationship between peak shear stress and density is time dependent, see Figure 4.3. If, for instance, the strength evolution for $\rho = 1200 \text{ kg/m}^3$ is considered, we see that the peak shear stress increased with about a factor 3 from 9 to 95 days. The time effect seems to be most distinct during the early stage of consolidation.

Figure 4.4 shows the relationship between peak shear stresses and effective stresses. Leaving the data points of the lowest segment out of consideration, i.e. of each curve the data point with the highest effective stress, an approximately linear relationship can be observed. Generally, the peak shear stress increases with time for a given effective stress.

The data will be further analyzed in future work.
Figure 4.2: Dependencies between rheological strength parameters
Figure 4.3: Peak shear stress against density

Figure 4.4: Peak shear stress against effective stress
Chapter 5

Acknowledgement

This work was funded jointly by the Netherlands Technology Foundation (STW) and the Commission of the European Communities, Directorate General for Science, Research and Development, under contract No MAS3-CT97-0082 (COSINUS-project). It was carried out in the framework of the Netherlands Centre for Coastal Research (NCK).
References


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## List of Symbols

<table>
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<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>$A$</td>
<td>cross sectional area</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$A$</td>
<td>calibration constant</td>
<td>kg m$^{-3}$ V$^{-1}$</td>
</tr>
<tr>
<td>$A$</td>
<td>calibration constant</td>
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<tr>
<td>$V_s$</td>
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<tr>
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</tr>
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</tr>
<tr>
<td>$\rho_s$</td>
<td>density of the solids</td>
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<tr>
<td>Symbol</td>
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<td>Unit</td>
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<tr>
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<td>effective stress</td>
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</tr>
<tr>
<td>$\tau$</td>
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</tr>
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<td>peak shear stress</td>
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<tr>
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<tr>
<td>$\Omega$</td>
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<tr>
<td>$\Omega$</td>
<td>angular velocity</td>
<td>rad/s</td>
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Appendix A

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Appendix B

Density measurement

Density measurement

One of the basic parameters measured in the present experiments is density. The measurement technique used, depended on the type of column involved. The bulk density of the mud in the segmented columns was measured by using a conductivity probe, whereas the bulk density of the mud in the conventional column was measured by using a γ-ray densimeter.

The γ-ray densimeter used, was a LB370 densimeter, manufactured by Berthold GmbH. The measurement principle of the γ-ray densimeter, is based on the absorption of γ-rays by matter, similar to the absorption of X-rays, see Been (1980).

The source of the LB370 is Caesium-137, a radioactive material that emits mainly photons of high energy, so called γ-rays. The source is shielded by a lead housing. Locally the shield can be opened to produce a narrow bundle of γ-rays. The γ-rays are passed through the consolidation column and detected at the other side by a NaI-crystal that converts gamma-photons to light-photons. The signal is enhanced by a photon multiplier tube. Subsequently, the light pulses are converted into an electric current. The electric current is manipulated by an electronic unit that eventually produces an output in Volts. A sketch of the γ-ray densimeter is shown in Figure B.1. The bulk density is related to the voltage by the relation

\[ \rho_b = aV + b, \]  

(B.1)

where \( \rho_b \) is the bulk density, \( V \) the output of the γ-ray densimeter and \( a \) and \( b \) are calibration constants. It is noted that the usual exponential relationship between density and the count rate of pulses (Been, 1980) is dealt within the electronic unit.

Procedure of measuring continuous density profiles

Continuous density profiles were obtained by traversing the γ-ray densimeter in the vertical direction. Simultaneously traversing and measuring inevitably results in averaging the measurements in space and thus reducing the vertical resolution. A high vertical resolution requires a low traversing speed and a short observation time. Unfortunately, the readings of the γ-ray densimeter are relatively unstable. In order to obtain an accurate reading, the observation time should be sufficiently long, i.e. several minutes.

The traversing speed was set very low: 0.24016 mm/s, which is about one meter per hour. The signal of the γ-ray equipment was averaged over 10 seconds. Although this duration is much too short to produce an accurate density measurement, such a short time enables the
detection of sharp transitions. If desired, the accuracy of the density measurements can be increased by averaging in the vertical direction afterwards.

**Calibration**

During earlier measurements it was found that the values of the calibration constants $a$ and $b$ varied slightly from day to day. Since calibration samples could not be used because of too short a traversing range, calibration strips were used instead. These strips could be placed between the column and the housing of the source.

In order to determine the equivalent, additional density of each strip, the calibration constants $a$ and $b$ were determined by using four mud samples of known density before the consolidation column was set up. The containers in which the samples were put, were equivalent to a section of the consolidation column. A linear fit resulted in $a = 50.242 \text{ kg/m}^3/\text{V}$ and $b = 903.11 \text{ kg/m}^3$, with $R^2 = 0.9988$. Subsequently, each strip was placed separately between the column section filled with water and the housing of the source and by using (B.1) the additional density could be determined. In total three different strips were used, so that, including a measurement without strips, four calibration points were available before each density measurement. The procedure to determine the additional density of the strips was repeated for water with different salinities. The effect of the salinity is within the accuracy of the measurements, see also Table B.1.

To determine the accuracy of the signal, the conventional column was filled with only water. The density of the water was 1003.5 kg/m$^3$, measured with a hand held densimeter (Anton Paar DMA32N). Before the readings were taken, the $\gamma$-ray densimeter was calibrated. The readings are shown in Figure B.2. Some statistics are presented in Table B.2. The averaged density is practically equivalent to the density measured with the hand held densimeter. The absolute accuracy is of the order $\pm 10 \text{ kg/m}^3$, indicated by the minimum and maximum...
Table B.1: Additional densities of the calibration strips

<table>
<thead>
<tr>
<th></th>
<th>Strip 1 (kg/m³)</th>
<th>Strip 2 (kg/m³)</th>
<th>Strip 3 (kg/m³)</th>
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<tbody>
<tr>
<td>$\rho_w = 998$ (kg/m³)</td>
<td>43.426</td>
<td>90.403</td>
<td>232.44</td>
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<tr>
<td>$\rho_w = 1006$ (kg/m³)</td>
<td>44.871</td>
<td>86.421</td>
<td>232.37</td>
</tr>
<tr>
<td>$\rho_w = 1015$ (kg/m³)</td>
<td>44.214</td>
<td>89.984</td>
<td>239.05</td>
</tr>
<tr>
<td>Averaged</td>
<td>44.170</td>
<td>88.936</td>
<td>234.62</td>
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Figure B.2: A $\gamma$-ray density reading of a column filled with water, $\rho = 1003.5$ kg/m³

recorded densities. However, approximately 95% of the readings is within the range 1003.5 ± 4.8 kg/m³, so we claim that the accuracy of the $\gamma$-ray densimeter is ±5 kg/m³.

The vertical resolution was assessed by the following test. The column was filled with water. A bar of steel (10 cm x 1 cm x 1 cm) was placed vertically on the bottom. Subsequently, a density profile was recorded. Ideally, a sharp transition in density should be observed, however, due to the limited resolution the transition is more gradual. The vertical resolution equals the length of the transition phase, which is 1.7 cm, see Figure B.3.
Table B.2: Statistics of the γ-ray density readings of a column filled with water

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
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</tr>
<tr>
<td>$\rho_{\text{min}}$ (kg/m$^3$)</td>
<td>994.3</td>
</tr>
<tr>
<td>$\rho_{\text{max}}$ (kg/m$^3$)</td>
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<tr>
<td>$\sigma_\rho$ (kg/m$^3$)</td>
<td>2.397</td>
</tr>
</tbody>
</table>

Figure B.3: Density profile of a density step