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<th>Erosion tests on Hannover clay</th>
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<tbody>
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Abstract

Erosion tests have been performed on three different clay types from dikes in Lower Saxony, Germany, in the rotating cylinder erosion device of GeoDelft. The same clay types have been tested in the Large Wave Flume in Hannover to investigate the erosion at the inner slope of a dike due to overtopping, waves.

The test results qualitatively agree with those in Hannover and also with the past experience in the Netherlands.

A complicating factor was that the preparation of the samples did not work out as planned. Recommendations are given to avoid such problems in the future and to repeat some tests.

In spite of the differences in scale, in clay condition and in type of loading by the flowing water, between the situation of the reported tests and those in Hannover, there was enough correspondence to allow for a semi-quantitative comparison between flow velocities critical for the start of erosion. This comparison showed some differences for which explanations have been found: the duration of a certain extreme load has an important influence on the erosion. Aging may help to increase the erosion resistance.
Executive Summary

Erosion tests have been performed on three different clay types from dikes in Lower Saxony, Germany, in the rotating cylinder erosion device of GeoDelft. The same clay types have been tested in the Large Wave Flume in Hannover to investigate the erosion at the inner slope of a dike due to overtopping, waves.

The composition of the 3 clay types was such that, according to the Dutch standard, one clay type would have high erosion resistance, one would have a very low erosion resistance and the third would belong to clays at the boundary between moderate and low erosion resistance. This categorisation is supported by the results of both the large scale flume tests and the rotating cylinder erosion tests. In general, the test results are in line with the past experience in the Netherlands. The results also agree with those in Hannover, at least qualitatively.

A complicating factor for a more quantitative comparison was that the preparation of the samples did not work out as planned. Recommendations are given to avoid such problems in the future and to repeat some tests.

In spite of the differences in scale, in clay condition and in type of loading by the flowing water, between the situation of the reported tests and those in Hannover, there was enough correspondence to allow for a semi-quantitative comparison between flow velocities critical for the start of erosion. This comparison showed some differences for which explanations have been found: the duration of a certain extreme load has an important influence on the erosion. Aging may help to increase the erosion resistance.

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This publication is part of:

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<th>Kust en Rivier (Coast and River)</th>
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<td>Waterbouwkunde en geotechiek (Hydraulic and geotechnical engineering)</td>
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</tr>
<tr>
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<td>Dr ir M.R.A. van Gent WL Delft Hydraulics</td>
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<td>Number of involved PostDocs</td>
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<td>2 Ir. M.B. de Groot</td>
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1 Introduction

Within the framework of an extensive investigation related to the processes of dike failure, erosion tests have been performed with the rotating cylinder erosion device of GeoDelft. Three clay types have been tested, which are taken from dikes in Lower Saxony in Germany. The properties found by the Universität Essen are reported in Appendix 1. This University sent 5 kg samples to GeoDelft. The ‘history’ of the samples is described in Appendix 1 as well.

The rotating cylinder erosion device enables to quantify the erosion properties of cohesive soils. With the results of the test a comparison can be made with the tests performed by the Leichtweiss Institut in Braunschweig in the Groszen Wellenkanal (Large Wave Flume) in Hannover [Oumeraci, 2001].

The report is written within the framework of the Delft Cluster project “Dijkdoorbraakprocessen”.

2 Methods of investigation

2.1 Description of the rotating cylinder erosion device

The rotating cylinder erosion device (Figure 2.1) consists of a vertical placed metal cylinder with 1 cm wide blades attached on the inside. The internal diameter of the metal cylinder is 16 cm. The cylindrical soil sample, with the following dimensions: diameter 6.6 cm, height 5 cm, is placed between two spindles with spikes which penetrate the sample for a few millimeters. The sample and the two spindles are placed on a vertical metal axis. The axis is pierced through the center of the sample and the spindles. The spindles are fixed to on the axis. The axis is placed between two ferrules, ensuring an independent rotation of the sample with respect to the rest of the apparatus.

![Schematic drawing of the erosion test-set-up](image)

By rotating the metal cylinder, the water inside it flows around the sample, which applies a torsion on the sample. Due to the fact that the sample is independent hung from the rest of the apparatus, this torsion can be measured constantly. The erosion is measured each 10 minutes by means of measuring the weight of the sample. The measurement of the weight is done during a break in the test, so that water movements do not have an influence on the measurement.
The measurement of the weight and the speed of the cylinder is controlled by means of a computer, which also registers the data. Due to this set-up all combinations of speed, duration, mass measurements and direction of the flow can be applied. The limitations of the apparatus are as follows:

- Maximum acceleration: $136 \text{ rpm}^2 = 0.0378 \text{ Hz/s}$
- Maximum speed: $1600 \text{ rpm} = 26.7 \text{ Hz}$

The test procedures is generally such that the rotation speed is kept constant during a certain period and increased in steps. There are three standard procedures:

- Short procedure
- Normal procedure
- Wave procedure.

The details of the normal procedure will be presented in Figure 2.2.

2.2 Description of the tests

2.2.1 Classification tests

Three clay types were tested in this investigation. In order to investigate the general properties of the clay types, the following standard laboratory tests were performed:

- Particle size distribution
- Atterberg limits
- Proctor test
- Specific mass (mass of particles).

The results are discussed in section 3.1.

2.2.2 Preparation of the samples and testing

The test samples were prepared by densifying parts of the 5 kg samples in the proctor apparatus. Given the results of the proctor test performed in the preliminary investigation, water contents were chosen in order to obtain samples with a certain density. Two water contents were chosen, one corresponding to the maximum proctor density and a higher one corresponding to 95% of the maximum proctor density.

The actual test samples were prepared by means of a tube sampler which was pushed into the densified mass. The sample was then pulled out of the tube and was subsequently trimmed to the desired dimensions and subsequently placed in the erosion device. The water content was measured of the parts removed in the trimming process. The density was measured on the sample itself.

The original scheme included a saturation phase under vacuum in an exsiccator, by means of which the saturation of the test samples would be as high as possible. This was planned to be done in order to keep the preparation as much as possible in correspondence with the test executed in the Large Wave Flume in Hannover. In Hannover, the material in the flume was intensively moisturized before the tests were executed. However, the two sandiest samples failed during the saturation in the exsiccator. Other test samples remained intact, but because it was the intention to give all samples the same treatment, this procedure was abandoned.

As an alternative the normal saturation procedure is followed, which implies that, before the actual execution of the test, the samples were kept under water in the apparatus for half an hour. The tests have been executed conform the normal procedure. This procedure is graphically displayed in Figure 2.2.
Figure 2.2  Schematic representation of the normal procedure

Each test is stopped if one of the following conditions is met:
- the mass of the sample is reduced with 25% to 40% of its original mass
- the complete procedure is finished.

The tests were executed in two series. Series 1 comprised the testing of samples which were compacted at the optimal water content. In series 2 samples were tested which were compacted at a water content corresponding to 95% of the maximum proctor density.
3 Results

3.1 Classification tests

The results of the classification test are summarized in Table 3.1.

<table>
<thead>
<tr>
<th>GeoDelft nr.</th>
<th>1</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay type</td>
<td>EG 9.0</td>
<td>CG</td>
<td>EG 3.5</td>
</tr>
<tr>
<td>Soil type according NEN 5104</td>
<td>Cs13</td>
<td>Csi2</td>
<td>Sac</td>
</tr>
<tr>
<td>Particle size distribution</td>
<td>2.42</td>
<td>48.8</td>
<td>14.8</td>
</tr>
<tr>
<td>&lt; 2 µm</td>
<td>38.6</td>
<td>77.3</td>
<td>23.2</td>
</tr>
<tr>
<td>&lt; 16 µm</td>
<td>36.8</td>
<td>40.4</td>
<td>33.0</td>
</tr>
<tr>
<td>&gt; 2 µm and &lt; 63 µm</td>
<td>39.0</td>
<td>10.8</td>
<td>52.2</td>
</tr>
<tr>
<td>&gt; 63 µm</td>
<td>36.8</td>
<td>40.4</td>
<td>33.0</td>
</tr>
<tr>
<td>Atterberg limits</td>
<td>20</td>
<td>30</td>
<td>21</td>
</tr>
<tr>
<td>w&lt;sub&gt;L&lt;/sub&gt; [%]</td>
<td>37</td>
<td>74</td>
<td>26</td>
</tr>
<tr>
<td>w&lt;sub&gt;P&lt;/sub&gt; [%]</td>
<td>16</td>
<td>43</td>
<td>5</td>
</tr>
<tr>
<td>Proctor test</td>
<td>19.0</td>
<td>27.9</td>
<td>16.5</td>
</tr>
<tr>
<td>ρ&lt;sub&gt;d,max&lt;/sub&gt; [g/cc]</td>
<td>1.70</td>
<td>1.44</td>
<td>1.75</td>
</tr>
<tr>
<td>Specific density [g/cc]</td>
<td>2.6578</td>
<td>2.7155</td>
<td>2.7297</td>
</tr>
</tbody>
</table>

Table 3.1 Results of the classification tests

in which:

EG : Elisabethgroden
CG : Cäciliengroden
C : clay (fraction < 2 µm)
Sa : sand (fraction > 63 µm)
si : silt (fraction > 2 µm and < 63 µm)
1 : low content
2 : moderate content
3 : high content
ρ<sub>d,max</sub> : maximum proctor density (dry)
w<sub>opt</sub> : water content corresponding to the maximum proctor density
w<sub>L</sub> : liquid limit
w<sub>P</sub> : plastic limit
I<sub>P</sub> : plasticity index (w<sub>L</sub> - w<sub>P</sub>)

In appendix 2 the complete particle size distribution are displayed and in appendix 4, the proctor curves.

Comparison with the results found in Essen (appendix 1) shows for the Elisabethgroden 9.0 that the clay content and sand content found here are larger and the silt content consequently significantly smaller. The liquid limit and the consequent plasticity index are slightly smaller here, whereas the maximum proctor density is slightly larger. This seems consistent with the deviations in grainsizes.

Comparison for the Cäciliengroden 9.0 shows that the clay content found here is much larger than found in Essen, whereas the sand content is nearly the same and the silt content consequently significantly smaller. Nevertheless, the Atterberger limits, the optimum water content and the maximum proctor density do not differ much.
Comparison for the Elisabethgroden 9.0 that the clay content and the silt content found here are slightly larger than found in Essen, and the sand content consequently smaller. The Atterberger limits, the optimum water content and the maximum proctor density differ slightly.
3.2 Erosion tests

In Table 3.2 some general characteristics of the tested samples are listed.

<table>
<thead>
<tr>
<th>sample nr &amp; test nr</th>
<th>material</th>
<th>series</th>
<th>preparation date</th>
<th>w_{desired}</th>
<th>w_{meas}</th>
<th>ρ_w</th>
<th>ρ_d</th>
<th>m.p.d.</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>EG 9.0</td>
<td>1</td>
<td>24-sep-2002</td>
<td>19</td>
<td>19.77</td>
<td>1.964</td>
<td>1.64</td>
<td>96.3%</td>
<td>85%</td>
</tr>
<tr>
<td>1-2</td>
<td>EG 9.0</td>
<td>2</td>
<td>20-dec-2002</td>
<td>22</td>
<td>19.35</td>
<td>2.034</td>
<td>1.70</td>
<td>100.1%</td>
<td>92%</td>
</tr>
<tr>
<td>3-1</td>
<td>CG</td>
<td>1</td>
<td>24-sep-2002</td>
<td>28</td>
<td>40.10</td>
<td>1.837</td>
<td>1.31</td>
<td>91.2%</td>
<td>102%</td>
</tr>
<tr>
<td>3-2</td>
<td>CG</td>
<td>1</td>
<td>24-sep-2002</td>
<td>28</td>
<td>42.38</td>
<td>1.871</td>
<td>1.31</td>
<td>91.4%</td>
<td>108%</td>
</tr>
<tr>
<td>3-3</td>
<td>CG</td>
<td>2</td>
<td>20-dec-2002</td>
<td>34</td>
<td>40.75</td>
<td>1.732</td>
<td>1.23</td>
<td>85.6%</td>
<td>92%</td>
</tr>
<tr>
<td>3-4</td>
<td>CG</td>
<td>2</td>
<td>20-dec-2002</td>
<td>34</td>
<td>44.11</td>
<td>1.708</td>
<td>1.19</td>
<td>82.4%</td>
<td>93%</td>
</tr>
<tr>
<td>4</td>
<td>EB 3.5</td>
<td></td>
<td>not tested</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>

Table 3.2 General characteristics of the tested samples

in which in addition to Table 3.1:

- series 1: testing of samples prepared with the optimal water content
- series 2: testing of samples prepared with a water content corresponding to 95% of the maximum proctor density
- preparation date: date at which the samples were prepared in the proctor apparatus
- w_{desired}: water content corresponding to 100% or 95% maximum proctor density [g/g]
- w_{meas}: measured water content
- ρ_w: wet density
- ρ_d: dry density
- m.p.d.: density related to the maximum proctor density
- S: degree of saturation

The determination of water content, volume weight and such was always performed just before execution of the erosion tests. The erosion tests were performed sometimes 2 months later, compare Table 3.1 and Table 3.2.

In Table 3.3 the results of the erosion tests are listed.

<table>
<thead>
<tr>
<th>Sample nr &amp; test nr</th>
<th>material</th>
<th>series</th>
<th>test date</th>
<th>rpm_{max}</th>
<th>t_{max}</th>
<th>m_{loss}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>EG 9.0</td>
<td>1</td>
<td>10-okt-2002</td>
<td>600</td>
<td>60</td>
<td>36.99</td>
</tr>
<tr>
<td>1-2</td>
<td>EG 9.0</td>
<td>2</td>
<td>13-feb-2003</td>
<td>1200</td>
<td>240</td>
<td>43.11</td>
</tr>
<tr>
<td>3-1</td>
<td>CG</td>
<td>1</td>
<td>09-okt-2002</td>
<td>800</td>
<td>150</td>
<td>35.38</td>
</tr>
<tr>
<td>3-2</td>
<td>CG</td>
<td>1</td>
<td>09-okt-2002</td>
<td>1000</td>
<td>160</td>
<td>25.87</td>
</tr>
<tr>
<td>3-3</td>
<td>CG</td>
<td>2</td>
<td>14-feb-2003</td>
<td>1200</td>
<td>360</td>
<td>5.22</td>
</tr>
<tr>
<td>3-4</td>
<td>CG</td>
<td>2</td>
<td>17-feb-2003</td>
<td>1200</td>
<td>200</td>
<td>92.31</td>
</tr>
<tr>
<td>4</td>
<td>EB 3.5</td>
<td></td>
<td>not tested</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.3 Results of the erosion tests

in which:
- rpm_{max}: maximum speed of the rotating cylinder for that test
- t_{max}: duration of the test
- m_{loss}: loss of weight of the sample at the end of the test (at t=t_{max})

In appendix E, the results of the tests are graphically displayed.
The sample from Elisabethgroden km 3.5 was not tested because the sample already failed by dispersion of the particles during the saturation phase. The material was too sandy to perform the test.

As can be seen from Table 3.2, the water contents of the samples of clay type 3 (Cäciliengroden) differ a lot from the water content at which the samples were supposed to be prepared. Striking is moreover that while the preparation water content for this material was 28%, respectively 34%, the water contents of the tested samples varied between 40% and 44%. The cause of this large discrepancy is not clear. The samples were stored at a constant temperature of 10°C and a high relative humidity (approximately 95%). There are no records of the water content of the material during the preparation of the samples, so the water content during the preparation is not actually known.

The densities of the Cäciliengroden samples were lower than they were supposed to be. The samples prepared with the optimal water content had a density of about 91% of the maximum proctor density, and the ones prepared with the water content corresponding with a relative density of 95%, had a density of ca 84% of the maximum proctor density. This deviation, however, corresponds to the higher water content. In fact the densities of the samples 3A and 3B were high for their high water content (compare the proctor curve in appendix 4).

The densities of the Elisabethgroden km 9.0 samples were also different from what they were supposed to be. When it was planned to have a sample with a relative density of 100%, the actual relative density was 96%. And when it was planned to have a sample with a relative density of 95%, the actual relative density was 100%. However, this is in line with the measured water contents.

In view of the differences in the densities with respect to the maximum Proctor density the samples of the two soil types are not comparable very well. Nevertheless, the results of the erosion tests show that the Cäciliengroden material, although having relative low densities, is generally more resistant to erosion than the Elisabethgroden km 9.0 material, as one might expect.

The results of the Elisabethgroden km 9.0 samples appear to be in correspondence with their relative densities. A higher relative density corresponds to a higher resistance to erosion. However, the difference in density is small, whereas the difference in erosion resistance is very large. A possible explanation for this could be that the time between preparation and testing was about 2 weeks for series 1, while it was about 2 months in series 2. Due to this the samples in series 2 were possibly capable of gaining more strength as a result of aging.

When looking at the results of the Cäciliengroden samples, the results of the tests are in contradiction with the relative densities of the samples. The samples with the lowest relative densities are the most resistant to erosion. A possible explanation, also here could be that the time between preparation and testing was about 3 weeks for series 1, while it was about 2 months in series 2. Due to the differences in aging period, the samples of the two series are not comparable very well. When looking at the differences between the Cäciliengroden samples tested within one series, the results of the test correspond to their relative densities. The differences between the samples in series 1 are very small, with respect to their relative densities as well as with their resistance to erosion. The differences between the samples in series 2 are larger, both with respect to the relative densities as the resistance to erosion.

The figures in Appendix E show the relationship between the average shear stress, $\tau$, executed by the water flowing along the sample, as calculated from the measured torsion, and the velocity of the metal cylinder. This relationship appears to vary from test to test. Striking is the relative low shear stress of ca 12 Pa in the test on sample 3C during a long period with the highest revolution speed of 1200 rpm. Most likely the surface of the sample remains smooth for a long time, which is an indication of high homogeneity. Sample 3D had a lower density, but may also have been less homogenous, because an average shear stress of ca 36 Pa was reached as soon as the frequency arrived a value of 800 rpm.
A close visual examination of the samples revealed that the homogeneity was sometimes not optimal, thus confirming the variability of the samples.
4 Comparison with erosion tests in Hannover

4.1 Value of quantitative comparison
A quantitative comparison of the erosion observed here in the rotating cylinder erosion device and the erosion observed in the Large Wave Flume in Hannover has a limited value:
- the scales are different: one 0.066 m diameter sample or a 0.6 m thick and many square meters wide layer of clay
- the history and condition of the clay is different
- the load is different: a continuous Couette flow here and a discontinuous free surface flow in the flume.
Nevertheless a semi-quantitative comparison is done to find whether the small scale experiments, as reported here, can be of any help to predict the behaviour at a much larger scale.

4.2 Comparison of clay conditions
The history of the clay before the reported testing in Delft is summarised in appendix 1. Then, the clay was compacted in the Proctor apparatus under addition of water. The blocks brought into the apparatus had dimensions of centimeters. The resulting density was 96% to 100% of the proctor density for the Elisabethgroden 9.0 and 82% to 91% for the Cäciliengroden. Some samples had the opportunity to ‘age’ for ca 2 months, others just for 2 weeks. The water contents were ca 19.5% for the Elisabethgroden and 40% to 44% for the Cäciliengroden at the moment before the samples were placed under water. The samples were kept under water during the erosion tests. The Elisabethgroden 9.0 was probably not yet saturated and its water content probably raised above 19.5%. The Cäciliengroden, on the other hand, was probably saturated and its water content remained constant.

The history of the clay in Hannover is equal to the one tested in Delft until the moment of ‘taking sub-samples by shovel’, point 4 in appendix 1. The clay in Hannover was placed by the (small) shovels on the slope in layers of 0.3 m. The clay was treated with care: only large blocks of clay were broken up in smaller ones without disturbing the inner structure, as reported in section 4.3.1 of [Oumeraci et al 2001]. Thus, the clay blocks in Hannover had probably dimensions of decimeters. Subsequently, the clay was compacted with a ‘Tandem Vibrations Walze’. The resulting density, relative to the maximum Proctor density, was probably 80% to 90%, according to the ‘Testfeldversuche’ reported in section 4.2.1, tabel 2 (Binnenböschung) of [Oumeraci et al 2001]. The time for ‘aging’ was no more than 1 week.

The water content of the Elisabethgroden 9.0 started with \( w \approx 17\% \) during the first part of ‘Versuch 3’ (see section 4.3.1). It increased during the test due to the wave overtopping with \( \Delta w = 10\% \) in the upper decimeter of the clay layer. In ‘Versuch 5’, the water content was brought to about the same level (\( w = 27\% \)) by artificial raining before the wave erosion started.

The watercontent of the Cäciliengroden on the slope was \( w = 37\% \) to 44% at the start of the first test (‘Versuch 1’). It did not change much in the upper decimeter during the test (Abbildung 27). The watercontent was slightly higher in Versuch 2.

4.3 Loading by flowing water in rotating cylinder erosion device
The loading of the clay in the rotating cylinder erosion device consists of a continuous Couette flow. The water flows tangentially in the 0.047 m wide space between clay sample surface and the metal cylinder. At the clay surface, the tangential flow velocity is zero. At the surface of the metal cylinder, the flow velocity is equal to the velocity of the surface of the metal cylinder. Last velocity = \( R \cdot \omega = 0.08 \text{ m/s} \cdot 2\pi \cdot \text{rpm}/60 = 0.00838\cdot \text{rpm} \) (in m/s). Velocities and shear stresses in this flow are briefly discussed below.
The shear stress parallel to the clay surface between the water layers is inversely proportional to
the distance to the axis in order to meet the equilibrium associated with constant flow velocities. Thus, the
shear stress near the clay surface is $16/6.6 = 2.4$ times the value near the metal cylinder.

The flow is turbulent, with largest turbulent eddies and corresponding mixing length in the middle. This
yields a flow velocity distribution with the following gradients of the tangential flow velocity:

- small gradients in the middle
- large gradients in the turbulent boundary layer near the clay surface
- large gradients in the turbulent boundary layer near the metal cylinder.

The gradients in the boundary layer near the clay will be slightly stronger than those in the other
boundary layer, in view of the larger shear stress. Consequently, the water in the middle (at $z = 0.024$
m distance from the clay surface) will have a tangential flow velocity which is probably slightly
higher than half the velocity of the metal cylinder, e.g. 60%. Thus, $v(0.024\text{m}) = 0.005\text{rpm}$ (in m/s).

These observations allow for the conclusion that the distribution of the tangential flow velocity and
the shear stress in the boundary layer near the clay surface and the adjacent part of the middle, i.e.
between $0 < z < 0.024$ m, will be very similar to the corresponding distributions in the flow along the
slope of the Large Wave Flume dike, if the flow velocity at $z = 0.024$ m is the same and the bed-
roughness is the same.

### 4.4 Loading of inner slope in Hannover by overtopping water

The flow velocity at $z = 0.024$ m above the dike slope can well be derived from the average velocity
and the height of the water tongue ("Überstauhöhe"), assuming a completely developed boundary
layer. No complete information about these values for the different tests is reported in [Oumeraci et al
2001]. However, some estimates can be made from the following basic information: the erosion tests
have been done, according to section 4.3 of this report, with a water level 1.0 m underneath the crest
($R_c = 1.0$ m) and with irregular waves, the significant wave height of which was gradually raised such
that the average overtopping discharge started at 0.5 l/m/s for each test and was gradually raised to 10
l/m/s/ for the very erosion resistant clay.

Abbildung 25 shows values of the average velocity and the height of the water tongue for 'Versuch 4' done at 25 April 2001 to test the worst clay: Elisabethgroden 3.5. As reported, erosion started after a few minutes. Most likely the average overtopping discharge was not raised above $q = 0.5$ or 1.0 l/m/s.
According to Abbildung 25, the number of overtopping waves was ca 1 in 5. The larger overtopping
events, occurring every 5 to 10 minutes (1 or 2% of the waves), showed an average flow velocity of
ca 2 m/s and water tongue heights of ca 0.04 m. Thus, $v(0.024\text{m}) = 2.1$ m/s.

Abbildung 16 shows flow velocities of ca 5 m/s combined with water tongue heights of ca 0.1 m, in
which case $v(0.024\text{m}) = 4.7$ m/s. Although not explicitly stated, this may be for a situation with
average overtopping discharge of $q = 10$ l/m/s. This is verified roughly by applying the equations,
presented in chapter 3 of [Oumeraci et al 2001] to find the relevant parameters for two significant wave
heights. The relevant parameters are $A_{98}$ (Eq.6), $h_A$ (Eq.8), $v_A$ (Eq.10) and $q$ (Eq.12). The flow
velocity at the inner slope just underneath the crest will be slightly larger than $V_A$ and the water
tongue height at that location will be slightly smaller than $h_A$. The wave heights are $H_s = 0.7$ m and $H_s$
= 1.0 m respectively. In both cases $R_c = 1.0$ m is adopted and $\xi_d = 1.25$ is assumed ($T_m = 5.0$ s and 6.0
s respectively). The following values of the parameters are found:

<table>
<thead>
<tr>
<th>$H_s$</th>
<th>0.7 m</th>
<th>1.0 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{98}$</td>
<td>1.31 m</td>
<td>1.88 m</td>
</tr>
<tr>
<td>$h_A$</td>
<td>0.068 m</td>
<td>0.19 m</td>
</tr>
<tr>
<td>$v_A$</td>
<td>2.4 m/s</td>
<td>4.0 m/s</td>
</tr>
<tr>
<td>$q$</td>
<td>1.8 l/m/s</td>
<td>11 l/m/s</td>
</tr>
</tbody>
</table>
The duration of the extreme loadings was limited. If we consider the 2% largest waves, the frequency was once in ca 300 s (5 minutes). With a test duration of one hour (for this wave height), the total number of extreme loadings was 12. If the time of extreme loading was ca 2 s during each wave, the total duration of extreme loading was limited to 0.4 minute. With a test duration of 3 hours (Versuch 2 of Cáciliengroden), the duration of extreme loading was ca 1 minute.

4.5 Comparison between both types of hydraulic loading

The flow velocity at 0.024 m above the clay surface, $v(0.024m)$, appears to be a good parameter for comparison of the load to the clay.

It could be argued that the shear stress along the clay surface could be used as an alternative for this comparison. The average shear stress was measured in the rotating cylinder erosion device. The shear stress could not be measured, however, in the wave flume. The presented shear stresses have been derived by assuming a certain surface roughness ($k_{Nikuradse} = D_{90} = 0.2$ mm) or friction coefficient ($f = 0.02$). These values seem reasonable in the beginning of all tests with rather smooth surfaces. Later on higher roughnesses and consequent higher shear stresses will have occurred.

The average shear stresses measured in the rotating cylinder erosion tests, nrs 1-1, 2-3 and 2-4 at 600 rpm was ca 20 Pa. That corresponds to the same value of $k_{Nikuradse} = 0.2$ mm, if a traditional logarithmic velocity profile is assumed in the boundary layer near the clay surface and the above assumption of $v(0.024m) = 0.005$ rpm (in m/s). The other three tests yield shear stress values of 30 to 40 Pa, indicating significant (e.g. 10 x) higher roughnesses.

It may be concluded that the flow velocity $v(0.024m)$ appears to be the better parameter for comparison of the load to the clay.

4.6 Survey of comparisons

<table>
<thead>
<tr>
<th></th>
<th>Delft tests in rotating cylinder erosion tests</th>
<th>Hannover tests in Large Wave Flume</th>
</tr>
</thead>
<tbody>
<tr>
<td>ElisabG 9.0</td>
<td>Size clay blocks before densification</td>
<td>O(0.01 m)</td>
</tr>
<tr>
<td></td>
<td>Density: m.p.d.</td>
<td>96% - 100%</td>
</tr>
<tr>
<td></td>
<td>Watercontent w</td>
<td>19.5% - ??</td>
</tr>
<tr>
<td></td>
<td>Flow velocity v(0.024 m) at start of</td>
<td>1.5 m/s</td>
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<tr>
<td></td>
<td>significant erosion.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aging time ≤ 2 weeks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flow velocity v(0.024 m) at start of</td>
<td>6 m/s</td>
</tr>
<tr>
<td></td>
<td>significant erosion.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aging time = 2 months</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flow duration of this loading</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Cácilieng.</td>
<td>Size clay blocks before densification</td>
<td>O(0.01 m)</td>
</tr>
<tr>
<td></td>
<td>Density: m.p.d.</td>
<td>82% - 91%</td>
</tr>
<tr>
<td></td>
<td>Watercontent w</td>
<td>40% - 44%</td>
</tr>
<tr>
<td></td>
<td>Flow velocity v(0.024 m) at start of</td>
<td>3 - 4 m/s</td>
</tr>
<tr>
<td></td>
<td>significant erosion.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aging time ≤ 2 weeks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum flow velocity v(0.024 m)</td>
<td>≥ 6 m/s</td>
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<tr>
<td></td>
<td>Flow velocity v(0.024 m) at start of</td>
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</tr>
<tr>
<td></td>
<td>significant erosion.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aging time = 2 months</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flow duration of this loading</td>
<td>10 minutes</td>
</tr>
</tbody>
</table>

Table 4.1 Comparison of condition parameters with those in Hannover
Thus, although there are some clear differences (size of the clay blocks, loading duration), the most important parameters show a relatively good agreement, at least for the tests on Cäciliengroden. For Elisabethgroden 9.0, the differences in these parameters between the tests in Delft and those in Hannover are large, but still smaller than the variation observed in one laboratory.

It can be concluded that the clay conditions and loading by the waterflow in the tests in Delft correspond enough to those in Hannover to allow for a semi-quantitative comparison between flow velocities critical for the start of erosion. Comparison for the tests with no significant aging shows that the lower critical flow velocities were observed in Delft, especially for the Elisabethgroden 9.0. This may be explained by the much longer duration of the load. It seems justified to take the 50% exceedance value of wave overtopping as a measure of comparison, rather than the 2% exceedance value. The aged Delft samples appear to be more erosion resistant than those in Hannover, although Versuch 2 with Cäciliengroden did not show significant erosion after 3 hours of the most heavy load.
5 Comparison with previous experience in the Netherlands
The previous experience in the Netherlands is summarised in [Kruse and Nieuwenhuis 2000].

An essential observation for the clay present in the unsaturated zone in real dikes is the influence of weathering and aging: the influence of drying out and rain, of plants and animals (earthworms, insects, rabbits etc). Like the clay in Hannover, the clay tested in Delft did not experience such influences. However, the samples is 3 of the 6 tests did experience the effect of 2 months of aging.

Apart from weathering and aging and its influence at the clay structure, the following factors influence the resistance to erosion:
- the composition of the clay and the associated properties as can be derived from grain size distribution and Atterberger limits
- the actual watercontent
- the density.
- organic material and lime content

The first factors are very important and are used for a general erosion classification of clay to be used for dike liners:

I High resistance to erosion if:
liquid limit \( w_L > 45\% \)
AND plasticity index \( I_P > 073\cdot(w_L - 20\%) \)
AND sand content < 40 \%

II Moderate resistance to erosion if:
\( w_L < 45\% \)
AND \( I_P > 18\% \)
AND sand content < 40\%

III Sensitive to erosion in all other conditions:
\( I_P < 18\% \)
OR: \( I_P < 073\cdot(w_L - 20\%) \)
OR: sand content > 40\%

Cäciliengroden belongs clearly to the first category. Elisabethgroden 3.5 belongs clearly to category III. Elisabethgroden 9.0 belongs to category II according to the values measured in Essen, but belongs just to category III according to the measurements done in Delft. The sand content is low enough for category II according to both measurements. However the plasticity index is just high enough according to Essen (\( I_P = 20.8\% > 18\% \)) and just not high enough according to Delft (\( I_P = 16\% < 18\% \)).

The results of the erosion tests in Delft and in Hannover correspond well with these categories.

From many observations of erosion processes in the Netherlands, it became clear that it is useful to distinguish, according to the scale, between:
- dispersion, i.e. detachment of individual or small groups of colloidal particles, primarily due to excessive absorption of water;
- abrasion, i.e. the removal of particles and small aggregates by drag and small scale lift forces exerted by water flowing over the surface;
- block erosion, i.e. removal of large aggregates by wave impact and slope instability, related to the water pressures exerted in and on the soil.

If dispersion takes place no rotating cylinder erosion tests can be performed, as illustrated with the Elisabethgroden 3.5 sample. So, either abrasion or block erosion are tested in this apparatus. The
erosion of clay is usually not a process of wear of individual grains. The removal of the soil occurs at least in small aggregates or relatively large particles like sand grains. The sensitivity to erosion is largely determined by the nature of the soil structure which in turn is partly related to the composition. ‘Abrasion’ occurs if the fine scale of the structure dominates. This only occurs with homogeneous highly plastic clay and goes rather slowly. Often, however, larger scale structures dominate and some kind of block erosion occurs, at least in the later stage of the process when an uneven surface increases the differences in local hydraulic load, yielding an increase in size of aggregates to be removed.

The sudden increase in weight loss of the samples (test 1-2, 3-1, 3-2 and 3-4) illustrates the large size of the removed aggregates. The behaviour of the samples during the tests corresponds to those of earlier tested Dutch clays.
6 Conclusions and recommendations

According to Dutch experience 3 erosion categories are distinguished, according to parameters of the grainsize distribution and the Atterberger limits. The Cáčiliengroden clay clearly belongs to the category with the highest resistance to erosion. The Elisabethgroden km 3.5 clay clearly belongs to the category with the lowest resistance to erosion. The Elisabethgroden km 9.0 clay can be placed at the boundary between the middle category and the category with the lowest resistance to erosion.

From the results of the tests it can be concluded that the material with the highest clay content (Cáčiliengroden) was the most resistant to erosion, as one might expect. The erosion test on the sandiest material (Elisabethgroden km 3.5) could not be executed, due to the failure by dispersion of the material during the saturation phase. The intermediate material (Elisabethgroden km 9.0) showed an intermediate erosion resistance.

Thus, the results of the rotating cylinder erosion tests qualitatively agree with those in Hannover and also with the experience in the Netherlands.

A complicating factor for a more quantitative comparison was that originally desired densities and water contents were not reached with many samples. Moreover, a close examination of the samples revealed that the homogeneity was sometimes not optimal. Luckily, however, this brought many samples closer to the properties of the clay as tested in Hannover. Another complicating factor is that the time between sample preparation and execution of the erosion tests were not the same for the two phases. The results of the tests show that samples with a longer time between preparation and execution were significant more resistant to erosion. Apparently, the samples are susceptible to aging.

Finally, the smaller scale and the other type of flow, which are basic differences between the situation in Delft with respect to the situation in Hannover, complicate the interpretation of the erosion tests. Nevertheless, clay conditions and loading by the water flow in the tests in Delft correspond enough to those in Hannover to allow for a semi-quantitative comparison between flow velocities critical for the start of erosion.

Comparison for the tests with no significant aging shows that lower critical flow velocities were observed in Delft, especially for the Elisabethgroden 9.0. This may be explained by the much longer duration of the load. It seems justified to take the 50% exceedance value of wave overtopping as a measure of comparison, rather than the 2% exceedance value, as done here.

The aged Delft samples appear to be more erosion resistant than those in Hannover.

As a results of this it is recommended to repeat the test with the following adjustments:
- prepare the samples by hand in steel sample tubes in stead of the proctor apparatus. Moreover it seems better not to take the water content as reference to reach a certain density, but to control the density directly,
- a comparable time between the preparation of the samples and the erosion tests
7 References

Oumeraci, H.; Möller, J.; Schüttrumpf, H.; Richwien, W.; Weismann, R., 2001
Belastung der Binnenböschung von Seedeichen durch Wellenüberlauf- Abschlussbericht
Leichtweiss Institut für Wasserbau Hydromechanik und Küsteningenieurswesen, Technische
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Tunnelbau, Universität Essen, Braunsweig/Essen, November 2001

Impact of weathering on erosion resistance of cohesive soil.
8th Int. IAEG Congres
Balkema, Rotterdam, pp 4299 - 4306
Appendix 1: Information University of Essen

<table>
<thead>
<tr>
<th>classification test</th>
<th>EG 9.0</th>
<th>EG 3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>particle size distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 2 µm</td>
<td>20</td>
<td>35</td>
</tr>
<tr>
<td>&gt; 2 µm and &lt; 63 µm</td>
<td>45</td>
<td>53</td>
</tr>
<tr>
<td>&gt; 63 µm</td>
<td>35</td>
<td>12</td>
</tr>
<tr>
<td>water content in-situ [%]</td>
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<td>40-50</td>
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<tr>
<td>Atterberg limits</td>
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<tr>
<td>shrinkage ratio [%]</td>
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<td>shrinkage limit [%]</td>
<td>16.43</td>
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<td>plastic limit [%]</td>
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<td>liquid limit [%]</td>
<td>41.20</td>
<td>77.00</td>
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<td>plasticity index [%]</td>
<td>20.76</td>
<td>45.00</td>
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<td>consistency index [-]</td>
<td>0.73-0.92</td>
<td>0.60-0.82</td>
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<td>optimal water content [%]</td>
<td>18.5</td>
<td>25.9</td>
</tr>
<tr>
<td>maximum dry proctor density [g/cc]</td>
<td>1.643</td>
<td>1.458</td>
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<tr>
<td>permeability [m/s]</td>
<td>1.22E-08</td>
<td>1.37E-9</td>
</tr>
<tr>
<td>time to disintegration t30% [s]</td>
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<td></td>
</tr>
<tr>
<td>undrained shear strength [kN/m2]</td>
<td>18.64-40.0</td>
<td>22.55-70.68</td>
</tr>
<tr>
<td>water absorption capacity [-]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A: Results classification tests University of Essen

Description of sampling, transport and treatment of clay types
1 sampling with 1.5 m³ excavator
2 transport per lorry to Hannover
3 unloading and storage (for about 6 months?) in a hall without rain and sun influences (covered?)
4 taking sub-samples by shovel, packing in plastic and in a carton box and transportation to Delft
5 storage in that packing at GeoDelft during approximately 1 year
Appendix 2: Graphical results of erosion tests
Erosion tests on Hannover clay
EROSIEPROEVEN OP KLEI HANNOVERPROEF
ELISABETHGRODEN KM 9.0
PROEfstuk 1 Test 2 w=19.35% P=2.034 t/m3

Date: June 2003
Erosion tests on Hannover clay
appendix 2
Date: June 2003

Erosion tests on Hannover clay

appendix 2
EROSIEPROEVEN OP KLEI HANNOVERPROEF
CALICIENGRODEN
PROEFSTUK 3 TEST 2 W=42.38% P1=1.871 t/m³

Date: June 2003
Erosion tests on Hannover clay

appendix 2
EROSIEPROEVEN OP KLEI HANNOVERPROEF
CALICIENGRODEN
PROEFSTUK 3 TEST 4 W=44.11% P=1.708 t/m³

17 Feb 2003
CO-730202
Appendix 3: Graphs of particle size distributions
erosion tests on hannover clay appendix 3
Erosion tests on Hannover clay

**Appendix 3**

Date: June 2003

Erosion tests on Hannover clay
Erosion tests on Hannover clay

Appendix 3
Appendix 4: Proctor curves