EXPERIMENTAL VALIDATION OF A MATHEMATICAL MODEL SIMULATING UNSATURATED FLOW THROUGH A SOIL SAMPLE EXPOSED TO CENTRIFUGAL FORCES

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An interesting project stimulated me to give more than my best to deliver a fine work.

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Arvid Jacobs, June 2012
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Summary

In this thesis research was carried out to experimentally validate a mathematical model simulating unsaturated flow through a soil sample exposed to centrifugal forces. The mathematical model is based on the van Genuchten-Mualem approach. The model is developed at the Department of Mathematical Analyses at Ghent University in cooperation with the Comenius University of Bratislava, Slovakia. Saturated flow, drainage and imbibition are tested on Mol sand, a kaolin clay and a mixture of both. Orders of magnitude concerning the tests are concluded as well as accuracies of the measurement procedures, measuring equipment and dimensions of the soil recipients. Recommendations are formulated for further research.

Keywords

Unsaturated conductivity, centrifuge, imbibition, drainage, retention curve.
Experimental Validation of a Mathematical Model Simulating Unsaturated Flow Through a Soil Sample Exposed to Centrifugal Forces

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Abstract — The aim of this thesis research is to validate a mathematical model simulating unsaturated flow through a soil sample exposed to centrifugal forces. This is done by static falling head tests and centrifuge experiments.

Keywords — centrifuge, imbibition, drainage unsaturated conductivity, retention curve

I. INTRODUCTION

A. Unsaturated flow

The saturated conductivity of soils is easy to test and to model. Also the mathematical model related to this work simulates this flow well. Unsaturated flow is more difficult to determine since it is a function of the water content. A different flow for imbibition and drainage gives rise to a hysteresis effect in the retention curve. Current test methods are complicated, require a lot of samples or a long testing time. Many of them are not suited for testing in situ soil samples. The importance of quantifying unsaturated flow is mainly found in the practice of landfills and infiltration areas.

B. Aims and scope of research

The ultimate aim is to develop a testing setup that makes it possible to test manually in situ taken soil samples in a relatively fast time and with a simple testing procedure, together with an accompanying validated mathematical model. Pressure is applied using centrifugal forces to speed the test. The aim is to develop a centrifuge capable of performing several in-flight measurements. The mathematical model that is developed simultaneous with this research is based on the van Genuchten-Mualem approach. The model is developed at the Department of Mathematical Analyses at Ghent University in cooperation with the Comenius University of Bratislava, Slovakia. The focus of this research is the validation of the mathematical model using tests carried out with a bench-scale centrifuge. Orders of magnitude concerning the tests are concluded as well as accuracies of the measurement procedures, measuring equipment and dimensions of the soil recipients. The required data is determined for the development of a new centrifuge. This research will not focus on the development of this new centrifuge itself.

II. RESEARCH

A. Saturated flow

First a validation of the model and setups is done by testing saturated flow. For static falling head tests the total conductivity $k_t$ is given by following formula.

$$k_t = \frac{L}{t} \ln \left( \frac{h_1 + L}{h_2 + L} \right)$$

With $L$ = the length of the filter or soil, $t$ = the time, $h_1$ and $h_2$ the height of the water on top of the filter (or soil) respectively at the beginning and at the end of a test. For tests on the filter $k_t$ is equal to the conductivity of the filter $k_f$.

For tests on soil samples the conductivity of the soil $k_s$ is given [1] by

$$k_s = \frac{t_s}{\frac{t_f + t_s}{k_i} + \frac{t_f}{k_i}}$$

with $t_s$ the thickness of the soil and $t_f$ the thickness of the filter.

When the sample is exposed to centrifugal forces the total conductivity is given [2] by $k_{cen, s}$ below

$$k_{cen, s} = \frac{L}{N t} \ln \left( \frac{h_1 + L(2R - h_2)}{h_2 + L(2R - h_1)} \right)$$

with $N$ the amount of gravitational force and $R$ the distance from the rotational axis to the centre of gravity of the soil sample. This formula is also applicable for tests on only filters. Note that this formula does not consider an acceleration or deceleration curve.

As well static falling head tests as centrifuge tests were performed and both types on samples...
that were either pre-consolidated in the centrifuge or with weights outside the centrifuge.

B. Unsaturated flow

For non steady-state situations Richard’s continuity equations are solved using the Levenberg-Marquardt algorithm. This is an iterative process where the differences between the results from the model with multiple parameters and the measurements are minimized.

Both drainage and imbibition were tested with Mol sand, a kaolin clay and mixtures of both. For drainage it is important to have a saturated boundary condition at outflow side. A free outflow boundary starting with a saturated sample is not sufficient. A water level at outflow side keeping the filter saturated is a minimum.

C. Results and discussion

The obtained saturated conductivities for different types of tests and pre-consolidation methods are shown in figure 1 for kaolin clay samples. Main reasons for the obtained differences are the formation of drops at the bottom of the filter during static tests and the enlarged effect of incorrect inside diameters of the tubes that were used. The causes for the latter are the practical difficulties to measure these dimensions. For short centrifuge tests the acceleration and deceleration curves have also an effect.

Drainage of a saturated clay is impossible due to high capillary forces. It was possible to drain mixtures with saturated conductivities up to $6.12 \times 10^{-6}$ m/s sufficiently (± 80%) to obtain practically interesting parts of the retention curve.

Imbibition is advised to perform with water added on top of the sample. For accurate measurements this can only be carried out with a centrifuge test and in-flight measurements. Since this was not available only accurate results were obtained for a static test with imbibition from the bottom of the tube upwards. Results of the movement of the centre of gravity of the inflow water are shown in figure 2. These results can be simulated with the model but note that this is a different type of imbibition. Less air will get enclosed in the soil with this testing procedure.

Drainage of a saturated clay is impossible due to high capillary forces. It was possible to drain mixtures with saturated conductivities up to $6.12 \times 10^{-6}$ m/s sufficiently (± 80%) to obtain practically interesting parts of the retention curve.

III. Conclusions

Orders of magnitude concerning the tests are concluded as well as accuracies of the measurement procedures, measuring equipment and dimensions of the soil recipients. The required data is determined for the development of a new centrifuge.

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"The Book of Nature is written in the language of mathematics."

Galileo Galilei

1.1 Unsaturated groundwater flow

The laws for saturated flow through a soil sample are well known and easy to model. When the effective saturation degree is lower than 100 % and the water content is lower than the saturated water content the flow is referred to as unsaturated flow. The magnitude of unsaturated flow is a lot less known and much more difficult to determine since it is a function of the water content. There is also a difference between draining and imbibition of a sample due to different phenomena (ink pattern, rain drop effect) causing a hysteresis effect in the retention curve. This retention curve classically gives the matric suction head in function of the volumetric water content. Current test methods are complicated, require a lot of samples or a lot of time crf. paragraph 2.5 Many of them are not suited for testing in situ soil samples.

The importance of quantifying unsaturated flow is mainly found in the practice of landfills and infiltration areas. For landfills liners and covers with low conductivity are used to control the pollution in the surroundings of these landfills. Liner materials and their application are expensive. Because of the high public interest to restrict pollution rigorous standards are used now since the flow is not known accurately. A better prediction of unsaturated flow can therefore lead to more accurate and economically justified standards. Infiltration areas are
used to allow rainwater to infiltrate the soil and recharge the groundwater supply, delay the
water flow off towards ditches, channels, rivers etc. Often it is required for infiltration areas
to dimension them to handle large amounts of water with short time intervals. A correct
dimensioning without over-dimensioning in order to limit the costs is therefore of importance.
In both cases it is mainly imbibition that is of importance. Knowing the drainage curve is less
important but still interesting for some applications and for scientific research when it can also
be determined.

Some agronomists are also interested in connection with the analysis of plant-soil interaction,
the availability of water and the transport of nutrients. In petroleum engineering an accurate
science on flow is also desirable for oil reservoir characterizations but this flow differs a lot
from the flow of water through soils with low conductivities. It consists mainly of flow through
porous rock samples of a highly viscous liquid. For this type of research some set-ups have
been developed quite extensively.

1.2 Aims and scope of research

The ultimate aim is to develop a testing set-up that makes it possible to manually test in
situ taken soil samples in a relatively fast time and with a simple testing procedure, together
with an accompanying validated mathematical model. Conductivity tests on soils with low
conductivity obviously require a (very) long time. Applying pressure is one way to speed up the
test but another classical method is using centrifugal forces, as used in this work. The ultimate
aim of this research is the development of a centrifuge capable of performing several in-flight
measurements. The mathematical model that is developed simultaneously with this research
is based on the van Genuchten-Mualem approach. The model is developed at the Department
of Mathematical Analyses at Ghent University in cooperation with the Comenius University
of Bratislava, Slovakia. The focus of this research is the validation of a mathematical model
using tests carried out with a fairly basic bench-scale centrifuge that was available. Orders
of magnitude concerning the tests are concluded as well as accuracies of the measurement
procedures, measuring equipment and dimensions of the soil recipients. The required data
is determined for the development of a new centrifuge. This research will not focus on the
development of this new centrifuge itself.

1.3 Outline of this masters dissertation

In the second chapter of this work a literature study is made of several topics. The application
of landfills and infiltration areas, some soil mechanical aspects concerning unsaturated soil,
existing centrifuge and other testing set-ups for unsaturated flow through a soil sample, a brief
description of the mathematical model and some properties and characteristics of the tested
soils in this work (Mol sand, a kaolin clay and mixtures of both) are treated.
1.3. **OUTLINE OF THIS MASTERS DISSERTATION**

In the third chapter an overview is given of the sample preparations and the equipment used.

Chapter four concerns the tests that were carried out. Different procedures and main results are discussed and preliminary as well as more formal conclusions are made. In this chapter often references are made to more detailed data and graphs, added in the appendix.

The previous chapters start with a general introduction and end with the most important conclusions. All conclusions are summed up in chapter five.

Some possibilities for further research are mentioned in chapter six.

Chapter seven contains the appendices.

The testing procedures, sample preparations, results and the experience resulting from working with the equipment is described as complete and accurately as possible. This was done to help successors in this research to get started more easily, to prevent tests leading to bad results and to get an as clear as possible view on the work that was carried out.

This thesis was written in (British) English, which is not the author’s first language. The author would like to apologise for any linguistic inaccuracies.

The text was written using \LaTeX\, a free document preparation system.
2.1 Introduction

This chapter contains the results of a literature study. First more information is given about the main application fields of this research, i.e. landfills and infiltration areas.

In the next section some soil mechanical aspects are listed necessary for a good understanding of this work. It concerns capillarity, suction potential, the retention curve, the concept of unsaturated hydraulic conductivity and also something about mass transport in soils with low conductivities.

Existing set-ups to determine unsaturated hydraulic conductivity are discussed in the fourth section.

A description of the mathematical model that needs validation through this work is given in section five.

At last some characteristics are mentioned of the types of soil used in this work.

2.2 Landfills

There are several types of landfills (for municipal solid waste). A first type consists in excavating a large volume of soil. This volume will then be filled with waste. A second type consists of creating a volume that can be filled by building walls or dikes of soil enclosing a given volume. A combination of excavation and using the excavated soil to construct dikes around the well can also be used to create large volumes with low soil transport.
Landfills consist basically of a bottom liner (hydraulic barrier), a cover and a leachate (this is the liquid that seeps from the landfill, see figure 2.1) collection and removal system. A bio-gas ventilation system is often used as well. The main reason for using a bottom liner is to slow down the outflow of pollutants into the soil and groundwater. The cover reduces the inflow of rainwater to a minimum. The leachate is collected through pipes into a drainage layer and removed to be purified. A general sketch is given in figure 2.2.

### 2.2.1 Liners

There are different systems to create a liner or hydraulic barrier. According to the number of layers, a distinction is made between singular and composite types. Singular systems can consist of syntactical (geo-membrane) or mineral (clay) barriers. A composite layer is a combination of one or more layers of a singular system. Mineral liners can be subdivided in three types:

- **In situ clay liners (or natural liners).** This means using a natural soil layer of sufficient thickness and low conductivity as a liner.
- **Compacted clay liners (CCL).** These consist of compacted, constructed liners of natural or improved natural materials that are transported to the construction site.
- **Geosynthetic clay liners (GCL).** Here a synthetic structure is used to strengthen a material with very low conductivity such as bentonite. Together they assure the hydraulic barrier.

![Figure 2.1: Illustration of leachate, UK Groundwater forum.](image)

To accomplish the often required standard of $10^{-9} \text{ m/s}$ for the hydraulic conductivity of the liner the following minimal standards are required of the material [2], listed in table 2.1.

At present, composite layers are almost always used. The combination of a thin geosynthetic membrane with a thick layer of (improved) clay gives very low probabilities of leachate as well as low quantities of leachate. The possibility that a leak in the synthetical layer as well as a tear for example in the natural layer should occur at the same horizontal location, is very low.
2.2. LANDFILLS

Figure 2.2: Scheme of a landfill for municipal waste [9].

Table 2.1: Minimal standards for liner material for municipal soil waste [2].

| Percentage of particles $\leq 2 \mu m$ | $\geq 30\%$ |
| Plasticity index $I_P$ | $20\% \leq I_P \leq 30\%$ |
| Percentage of sand | $\leq 30\%$ |
| Maximum particle size | 25-50 mm |
| Water content $w$ after compaction | $18\% \leq w \leq 20\%$ |

Often bentonite is used between two geotextiles or bentonite is glued onto a geomembrane. Some countries prefer to use even more than one layer of each material, mainly when the waste is highly toxic. In that case a double system with a second leachate collection and removal system between two composite layers is used. The hydraulic conductivity of clay liners is strongly dependent on the method of compaction and the energy of compaction (Daniel, 1993). Due to the great thickness of the natural layers, they are constructed in multiple smaller layers that are preferably all compacted equally.

2.2.2 Contaminants

A lot of contaminants are present at waste sites. In general the following groups can be distinguished:

- Inorganic cations and metals.
- Inorganic anions and non-metals.
- Synthetic organic chemicals.
- Hydrocarbons.
- Radionuclides.
- Pathogens.
2.3 INFILTRATION FACILITIES

The origin of all these materials is to variable to mention. The important point is how easily they are solvable and what the effect is on each other and on the (clay)liners. These matters will however not be discussed in this work.

2.2.3 European guideline 1991/31/EG

In the European guideline of 26th of April 1999 a set of prescriptions for waste sites is given in order to prevent any negative effects of these sites on the environment. This work is expected to lead to a better dimensioning of the liners and their thickness.

The geological barrier is determined by the geological and hydro-geological condition in the aria of the waste site. Potential danger for the soil and the groundwater must be prevented.

Bottom and sides of the landfill must consist of a mineral layer that meets certain criteria, depending on the type of waste. In table 2.2 a summary is given of the properties of the layers as a function of the type of waste. Layers must have a protection degree equivalent to the one mentioned.

<table>
<thead>
<tr>
<th>Use of the landfill</th>
<th>conductivity [m/s]</th>
<th>layer thickness [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dangerous waste</td>
<td>$1 \times 10^{-9}$</td>
<td>5</td>
</tr>
<tr>
<td>Non dangerous waste</td>
<td>$1 \times 10^{-9}$</td>
<td>1</td>
</tr>
<tr>
<td>Inert waste</td>
<td>$1 \times 10^{-7}$</td>
<td>1</td>
</tr>
</tbody>
</table>

If no natural or an insufficient barrier is present a synthetic one must be provided with minimum thickness of 0.5 m. A leachate reception system and a system to seal off the waste site at the top is necessary in every circumstance.

2.3 Infiltration facilities

In an urbanized region as Flanders a lot of the surface is paved. The rainwater is sent through sewers to water treatment plants. Also a lot of large areas are drained for agricultural purposes. The water travels through canals to rivers and is not given the time to infiltrate. Groundwater, especially the groundwater at large depths, is used in large quantities to be processed into drinking water. This combination is not sustainable because the demand for groundwater is bigger than its natural replenishment. To spare the water treatment plants and to refill the groundwater level - or at least to prevent further decrease - a trend is set to try to infiltrate more rainwater into the soil.
2.3. INFILTRATION FACILITIES

The VMM (Vlaamse Milieumaatschappij - Flemish Environmental Society) has provided a method to determine the requirements for rainwater wells and infiltration facilities in a code of good practice [3]. Requirements for infiltration facilities are obviously determined by the surface and the conductivity of the soil. Two conditions for the placement of an infiltration facility are

- The groundwater level should be at least one meter under the infiltration facility.
- The conductivity of the soil should be high enough. This will be determined by the infiltration capacity of the soil.

The VMM gives in its code of good practice [3] an extensive method to determine the buffering volume for an infiltration facility. The most important elements will be repeated in the following part.

The discharge rate is given by following formula:

\[
\text{discharge rate} = \frac{\text{infiltration capacity}}{\text{supplying paved surface}} \times \frac{\text{infiltration surface}}{\text{supplying paved surface}}
\]  

(2.1)

Discharge rate and infiltration capacity are usually expressed in \(cm/h\) and the surfaces in \(m^2\).

The infiltration capacity is determined by using the infiltration speed \(K_v\) according to values in table 2.3. The infiltration speed can be determined by one of the following tests.

- A ring test
- A double ring test
- A well test

All tests are based on the principle of measuring the time a given volume of water takes to flow into the soil. The ring tests use a constant head while the well test is based on a falling head test with variable head. The double ring test is used to measure only vertical flow. More detailed information about these tests can be found on the website of the VMM (www.vmm.be) or in their code of good practice [3]. More information about the rain intensity as a function of the duration of a rain shower and the return period of a rain shower can also be found there, as well as extensive information about inflow rates, discharge coefficients of different surfaces, the distribution coefficient of Frühling and design hyetographs. This matter is also dealt with in the course book ”Water Transport” by Prof. R. Verhoeven at Ghent University.

The rules above are valid for discharge surfaces smaller then 1000 \(m^2\). For surfaces over 1000 \(m^2\) other requirements must be followed.
Table 2.3: Infiltration capacity in function of the speed of infiltration.

<table>
<thead>
<tr>
<th>Average $K_v$ $(cm/h)$</th>
<th>Infiltration capacity $(l/h/m^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_v \geq 15$</td>
<td>2.1</td>
</tr>
<tr>
<td>$10 \leq K_v &lt; 15$</td>
<td>1.67</td>
</tr>
<tr>
<td>$5 \leq K_v &lt; 10$</td>
<td>1.25</td>
</tr>
<tr>
<td>$3.5 \leq K_v &lt; 5$</td>
<td>0.85</td>
</tr>
<tr>
<td>$2.5 \leq K_v &lt; 3.5$</td>
<td>0.62</td>
</tr>
<tr>
<td>$0.5 \leq K_v &lt; 2.5$</td>
<td>0.41</td>
</tr>
<tr>
<td>$K_v &lt; 0.5$</td>
<td>No infiltration possible</td>
</tr>
</tbody>
</table>

2.4 Soil mechanical aspects of unsaturated flow

The water content in soils is influenced by a diversity of factors such as pore structure, vegetation, contaminants, temperature, etc. In 1979 Bear made a distinction between the following types of water in the soil (cf. figure 2.3).

- Pendular water. At low saturation degrees there is only water at the contact points between soil particles. No flow is therefore possible.

- Funicular water. When the saturation degree increases a continuous phase of water will form at the sides of the soil particles, allowing flow. In this phase there will still be air present, also in a continuous phase.

- Insular water. When the water content increases further the continuous phase of the water will grow and shut down the continuous phase of the air. Separate air bubbles remain entrapped between soil and water.

![Types of water in the soil as defined by Bear, 1979.](image-url)
2.4.1 Capillarity

The bases of the capillarity phenomenon are the attractive forces between molecules that result in surface tensions at the sides of materials. These surface tensions can easily be explained starting with an everyday example. The liquid inside a glass or cup will rise slightly at the sides due to contact forces called surface tension. Another example is the fact that a small drop of water doesn’t fall from an object in spite of gravity forces. The surface tensions are high enough to compensate the gravitational forces entirely.

Molecules exercise forces on one another. This attraction is called cohesion when the molecules belong to the same material and adhesion if the molecules are of a different nature. These forces only act within the immediate distance of a molecule ($10^{-8} \text{ m}$ [5]). When a molecule is completely surrounded by other molecules in for example a liquid, the attractive forces neutralize one another. For a molecule at the side of the liquid other attractive forces are required to neutralize the attraction forces of this molecule (from for example air at the other side of the interface). When this other fluid does not provide enough neutralizing forces the molecules at the side of the liquid are pushed against each other causing them to be more bound, less free. This phenomenon causes the molecules at the side of the liquid to act as a weak membrane. A drop of water does not fall from an object if this membrane of molecules at the sides is strong enough to support the weight of the entire drop, together with the attractive forces exerted by this other object. When the drop becomes too heavy the membrane will break and the drop will be divided into two parts. Water that rises at the insides of a filled glass can be explained by larger neutralizing forces exerted by the glass then by the water. At normal atmospheric pressure and 20°C the surface tension between water and air is 0.073 N/m [5].

In a fine grained soil the pores are very small. The effect can be simulated by putting a very small tube in a volume of water. The water inside the tube will rise to a substantial level. Also at the sides a meniscus shape will be present. This capillarity can cause an important rise of the apparent groundwater table. The pore water at a higher level than the original level is under a negative pressure due to the surface tensions. This is called capillary or matric potential. It is function of the water content of the soil and strongly dependent on the relative humidity. The higher the water content, the higher (less negative with atmospheric pressure as a reference) the value of the water pressure. A high water content thus means a low capillary pressure (cf. paragraph 2.4.2).

We assume for this reasoning a moistening liquid such as water. These liquids have a contact angle $\beta$ smaller than 90°C with the tube as shown in figure 2.4. This angle and also the rise of the water level depend on the chemical properties, including impurities, of the solids, liquid and gas. The capillary suction head is derived from equilibrium (2.2). This equilibrium expresses at the left side the force due to surface tensions, in the middle the force due to capillary tensions (matric potential) and at the right side the potential energy is given of the volume of water.
that has risen above the original water level.

\[ \sigma_{lw} 2 \pi r \cos \beta = p_c \pi r^2 \rho_w g \]  

(2.2)

With:
- \( \sigma_{lw} \) = surface tension at the interface air-water \([N/m]\),
- \( r \) = the radius of the glass tube \([m]\),
- \( \beta \) = the contact angle,
- \( p_c \) = the matric potential or capillary pressure \([N/m^2]\),
- \( h_c \) = the capillary suction head \([m]\),
- \( \rho_w \) = the density of the liquid \([kg/m^3]\) and
- \( g \) = the gravitational force \([m/s^2]\).

Solving this equation (2.2) to the capillary suction head \( h_c \) gives

\[ h_c = \frac{2 \sigma_{lw} \cos \beta}{\rho_w g r} = \frac{2 \sigma_{lw}}{\rho_w g r m} \]  

(2.3)

With:
- \( r_m = \frac{r}{\cos \beta} \) = the radius of the meniscus.

The suction head will be maximal when \( \beta \) is zero.

In the soil the radius of the pore canals is not constant but is characterized by a certain distribution. This distribution however is difficult to quantify. Table 2.4 gives an indication of the capillary suction head for different types of soil.

**Table 2.4:** Indication of capillary suction head for different types of soil, Beskow (1930) and Hansbo (1960).

<table>
<thead>
<tr>
<th>Type of soil</th>
<th>Capillary suction head [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse grained sand</td>
<td>0.03 – 0.15</td>
</tr>
<tr>
<td>Average grained sand</td>
<td>0.12 – 0.50</td>
</tr>
<tr>
<td>Fine grained sand</td>
<td>0.30 – 3.50</td>
</tr>
<tr>
<td>Loam</td>
<td>1.5 – 12</td>
</tr>
<tr>
<td>Clay</td>
<td>&gt; 10</td>
</tr>
</tbody>
</table>

The assumption of a moistening liquid (called also hydrophilic liquid) was mentioned with a contact angle \( \beta \) smaller than 90°C. The other type of liquid is a repellent liquid (called also hydrophobic liquid), for example mercury, with a contact angle larger than 90°C.

The capillary rise will depend on the soil being either moistened or drained. Figure 2.6 (a) illustrates the difference between the two, often described as the ink pattern.
2.4. SOIL MECHANICAL ASPECTS OF UNSATURATED FLOW

Figure 2.4: Principle of capillarity [9].

This phenomenon is also described by the raingroup effect, illustrated in figure 2.6 (b).

The surface tension is also dependent on the temperature. For water the relation is shown in figure 2.5 as given by Fredlund (1993).

Figure 2.5: Surface tension of water in function of temperature, Fredlund (1993).

Figure 2.6: (a): Ink pattern with (left) drainage and (right) re-moistening [9]. (b): Raingroup effect with contact angles $\alpha_1$ and $\alpha_2$ [9].
2.4. SOIL MECHANICAL ASPECTS OF UNSATURATED FLOW

2.4.2 Suction potential

In case of salts in the soil there can also be another suction that enforces the capillary or matric potential, called osmotic potential. Binding of the negatively loaded clay particles to the positively loaded salt ions results in a barrier that slows down the flow of water. Electrochemical potential is almost always a minor component. Together with the gravitational potential this is called the total soil-moisture potential.

The matric potential is equal to the difference between the air pressure $u_a$ and the water pressure $u_w$ relative to the atmospheric pressure. When the air pressure is equal to the atmospheric pressure the matric potential is thus equal to $-u_w$ since the water pressure of the capillary water is negative, conform with figure 2.4.

The relationship between matric potential and capillary rise is thus

$$ (u_a - u_w) = \rho_w \ g \ h_c $$

or in case the air pressure is equal to the atmospheric pressure equation (2.4) becomes

$$ -u_w = \rho_w \ g \ h_c $$

Osmotic potential is almost completely independent of the water content and originates from the lowering of the relative humidity caused by the presence of salts in the water. When no considerable amount of salts is present the osmotic potential is usually neglected. The matric potential on the other hand is strongly dependent on the water content and increases considerably with decreasing water content.

When neglecting the osmotic pressure and electrochemical potentials (gradient equal to zero), the total soil moisture potential $\phi$ can be written as the sum of matric potential $\psi$ (as a function of the saturation degree $\theta$) and the gravitational potential $z$.

$$ \phi = \psi(\theta) + z $$

Expressed in terms of energy equation (2.6) becomes

$$ \phi = p_c + \rho_w \ g \ z $$

or in terms of length of water table equation (2.6) becomes

$$ \phi = \frac{p_c}{\rho_w} g + z $$
2.4.3 Retention curve

The retention curve is dependent on the soil and expresses the relation between matric suction and the volumetric water content \( \theta \). This volumetric water content is defined as

\[
\theta = \frac{V_w}{V_t} = \frac{W_w}{\rho_w V_t} = \frac{W_t - W_s}{\rho_w V_t}
\]  

(2.9)

With:
- \( V_w \) = the volume of water,
- \( V_t \) = the total volume,
- \( W_w \) = the weight of the water,
- \( W_t \) = the total weight,
- \( W_s \) = the dry weight of the soil and
- \( \rho_w \) = the density of water.

Matric suction expresses the capillary forces by the amount of water that remains in the soil in the unsaturated zone. A different suction potential, caused for example by compaction due to a supplementary force, will create a different water content in the unsaturated zone. Figure 2.7 illustrates the principle of the retention curve. The bubbling pressure is the critical pressure when the first amount of air enters a saturated soil (with initial volumetric water content \( \theta_s \)) that is being drained. Expressed as matric suction potential this pressure is written as \( h_b \).

![Retention curve](image)

**Figure 2.7:** Retention curve: matric suction potential \( h_c \) as a function of the volumetric water content \( \theta \) [9].

A soil that is being drained will always have a residual amount of pendular water (paragraph 2.4, figure 2.3) that can only be removed by heating and evaporation. The minimal water
content is indicated by $\theta_r$. The matric suction potential approaches infinity for this water content.

In paragraph 2.4.1 the difference between drainage and imbibition of a soil was mentioned concerning capillary forces. Also air that gets trapped and swelling or shrinkage of soil can cause a difference between imbibition and drainage. This difference results in a hysteresis effect in the retention curve, illustrated in figure 2.8. When switching from draining to imbibition or conversely intermediate lines are obtained. The modelling of these lines however is not easy. Figure 2.8 shows that the maximum water content for the imbibition retention curve is lower then for the draining retention curve. Entrapment of air when a drained sample is re-moistened is the cause of this difference. When then drained again more or less the same bubbling pressure exists.

![Diagram](image_url)

**Figure 2.8:** Hysteresis effect in the retention curve [9].

### 2.4.4 Unsaturated hydraulic conductivity

The hydraulic conductivity of an unsaturated soil is always different from the conductivity of a saturated soil. The pores filled with air are not able to facilitate the transport of water. The capillary forces too will be different for different water contents. The difference in capillary forces can be very large especially for very fine grained soils such as clay. Figure 2.9 is an illustration of the results of the conductivity in function of the volumetric water content $K(\theta)$ of some soils tested with the UFA method (cfr. paragraph 2.5.2). The difference for these very fine grained soils can reach a factor $10^6$.

Figure 2.10 illustrates the results of tests by Liakopoulos (1965) on a sandy soil. The difference between saturated and unsaturated conductivity for this coarser grained soil (relative to clay) is of a factor 50.
2.4. **SOIL MECHANICAL ASPECTS OF UNSATURATED FLOW**

These large differences indicate the importance of well known values of \( K(\theta) \).

The slope of the retention curves depends on the grain size distribution. A homogeneously grained soil such as Mol sand will have a more gradual change in conductivity in function of the water content. A soil with a heterogeneous grain size distribution with a lot of large as well as small pores will have a fast decrease in conductivity when drained. The end of the curve will then be a lot flatter.

The conductivity \( K \) as well as the matric suction potential \( \psi \) are a function of the volumetric water content \( \theta \). This means the conductivity can be written in function of the matric suction potential:

\[
K = f(\psi)
\] (2.10)

Buckingham (1907) wrote down the unsaturated flow in function of the matric potential. In
2.4. **SOIL MECHANICAL ASPECTS OF UNSATURATED FLOW**

vector notation this is

\[ q = -K(\psi) \cdot \nabla(\phi) \] (2.11)

With: \( q \) = the flow \( \left[ \frac{m^3}{m^2 \cdot s} \right] \),

\( K(\psi) \) = the conductivity in function of the matric potential \( \psi \),

\( \nabla(\phi) \) = the gradient of the total soil-moisture potential (as defined by formula (2.6)).

The continuity equation for the water content in an elementary volume can be described as

\[ \frac{\partial \theta}{\partial t} = - \left( \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right) \] (2.12)

or also in vector notation as

\[ \frac{\partial \theta}{\partial t} = -\nabla \cdot q \] (2.13)

Substitution of formula (2.11) in formula (2.13) gives the general form of Richards equation (1931):

\[ \frac{\partial \theta}{\partial t} = \nabla [K(\psi) \cdot \nabla (\phi)] \] (2.14)

For one-dimensional flow this will be

\[ \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[ K(\psi) \cdot \left( \frac{\partial \psi}{\partial x} + \frac{\partial Z}{\partial x} \right) \right] = \frac{\partial}{\partial x} \left[ K(\psi) \cdot \left( \frac{\partial \psi}{\partial x} + \cos \alpha \right) \right] \quad x \in (0, L) \] (2.15)

With: \( \alpha \) = the angle between the direction of flow (x) and the direction of gravity (z),

\( \frac{\partial \psi}{\partial x} \) = the gradient caused by the total suction head.

For saturated conditions the following simplifications are applicable.

- \( \frac{\partial \theta}{\partial t} = 0 \), the soil remains saturated.
- \( K \) is independent of \( \theta \) and shows a constant value: \( K = K_{sat} \).
- \( \psi = 0 \) since there is no matric suction for a saturated soil.

This results in the Darcy law (1856) for saturated flow:

\[ 0 = \frac{\partial}{\partial x} \left[ K_{sat} \cdot \frac{\partial h}{\partial x} \right] \quad x \in (0, L) \] (2.16)
2.5. EXISTING SET-UPS TO DETERMINE UNSATURATED HYDRAULIC CONDUCTIVITY

Previous equations are valid assuming constant temperature, air pressure and a non-deformable soil structure. The water is assumed to be non-compressible and no effect of dissolved substances is considered. The air present in the soil is assumed to have only an effect on the conductivity and not on anything else.

2.4.5 Mass transport

Mass transport is very important in relation to landfills. In principle it can happen in either a liquid or a gas state. The latter is however almost always negligible (C.W. Fetter, 1992) and also difficult to estimate due to unknown pressures. Mass transport in liquid state consists of the following factors.

- Advection, caused by particles transported by the solvent due to a gradient in the hydraulic head.
- Diffusion, caused by a concentration gradient and expressed by Fick’s first and second (when the concentration is changing in time) law.
- Mechanical dispersion, caused by a variety of speed in the pores due to hydraulic aspects.
- A sink/source factor taking into account different possible phenomena such as radio-active and biologic degeneracy.
- Thermo-osmosis, i.e. advective flow induced by a temperature gradient.
- Electro-osmosis, i.e. advective flow induced by an electrical gradient.

Diffusion becomes an important factor when the conductivity of the medium is lower than $10^{-10}[m/s]$. Some disagreement on the estimation of the quantity of diffusion currently exists. Mechanical dispersion for low conductivities is almost negligible.

2.5 Existing set-ups to determine unsaturated hydraulic conductivity

2.5.1 Slicing of the soil sample after centrifugation [19]

A saturated soil sample is centrifuged at a number of rotations per minute in order to drain the sample. After some time the capillary forces will become equal to the centrifugal forces. When this happens the sample is cut into six equal slices in order to determine the water content.

The capillary forces are determined by Corey [20] as

$$p_c \approx \frac{\rho_w \cdot \omega^2}{2} \cdot (R^2 - r^2)$$  \hspace{1cm} (2.17)
with: \( R \) = the radius at the outflow side of the sample,
\( r \) = the distance outward from the center of rotation.

The average Darcy speed is derived from the mass balance resulting into formula (2.18). It can already be stated that this is a very rough approximation because the actual speed is not a constant but will exponentially decrease.

\[
V = \frac{1}{\Delta t} \int_r^R \Delta \theta \, dr 
\]  
(2.18)

When the steady state is reached the following relationship between the volumetric and gravitational water content is valid.

\[
\Delta \theta = \Delta w \cdot \left( \frac{\gamma_s}{\gamma_w} \right) 
\]  
(2.19)

The gradient \( i \) is then equal to

\[
i = \frac{\Delta p_c}{l_s} 
\]  
(2.20)

with: \( l_s \) = the length of the soil sample.

The unsaturated hydraulic conductivity \( k_u \) for a given volumetric water content is then equal to

\[
K(\theta) = k_u = -\frac{V}{i} 
\]  
(2.21)

The test has the advantage of low equipment requirements but it also has several disadvantages:

- In order to obtain a large part of the retention curve a lot of soil samples must be tested.
- The calculations are rough approximations.
- Very high forces must be simulated in order to be able to drain soils with low conductivities (high capillary forces must be overcome).
- The results can not easily be extrapolated to other soils which would require even more tests.
- Slicing of the soil for low and high water contents is not easy to execute accurately. The retention curve can therefore not be determined completely.
2.5. EXISTING SET-UPS TO DETERMINE UNSATURATED HYDRAULIC CONDUCTIVITY

2.5.2 Unsaturated Flow Apparatus (UFA) [18]

The principle of the apparatus, illustrated in figure 2.11, is to obtain an unsaturated steady state condition using a centrifuge. This is done by monitoring the outflow and adjusting the inflow (with an accuracy of 0.001 ml/h) until a steady state is reached. The amount of outflow is measured by strobe light. When the initial water content is known and inflow and outflow are measured the water content is known at any time.

![Unsaturated Flow Apparatus](image)

**Figure 2.11:** Unsaturated Flow Apparatus [18].

Because steady state is reached Darcy’s law can be applied. Submitted to a centrifugal force the law is transformed to formula (2.22) and for more than 300 rotations per minute the law will be by approximation equal to formula (2.23).

It can be remembered that the matric suction potential $\psi$ is a function of the volumetric water content $\theta$ so the conductivity can also be written as a function of the latter.

\[
q = -K(\psi) \left[ \frac{\partial \psi}{\partial r} - \rho \omega^2 r \right] 
\]  
(2.22)

\[
q = K(\psi) \left[ \rho \omega^2 r \right] 
\]  
(2.23)

\[
q = K(\theta) \left[ \rho \omega^2 r \right] 
\]  
(2.24)

The most important disadvantage of this test is that the test has to be repeated for every different water content, requiring a lot of tests in order to determine the retention curve. The water content must namely be measured destructively. This results in a high cost. Another important disadvantage is that the test cannot be carried out at either low or high water contents, making it more difficult to fit the retention curve using a mathematical model.
2.5. EXISTING SET-UPS TO DETERMINE UNSATURATED HYDRAULIC CONDUCTIVITY

2.5.3 Quasi-Steady Centrifuge (QSC) [21]

Similar to the Steady State Centrifuge (SSC) the Quasi-Steady Centrifuge was developed by M.C. Caputo and J.R. Nimmo (2005). The difference is that for the latter no steady state is required. This might however influence the measuring accuracy. When the change of water content in the soil sample is very small, the term quasi-steady state can be used.

Figure 2.12 illustrates the set-up. The ceramic plate should have a conductivity that is high enough to allow free outflow.

![Figure 2.12: Quasi-Steady Centrifuge apparatus [21].](image)

Again an average value of the flow is used to determine the hydraulic conductivity using Darcy’s law for a sample exposed to a centrifugal force.

\[ q = -K(\theta) \left[ \frac{\partial \psi}{\partial r} - \rho \omega^2 r \right] \]  \hspace{1cm} (2.25)

The symbols represent the same characteristics as above in this work.

Again one test only provides one point of the retention curve. A lot of tests and samples are therefore required. Also more advanced measuring equipment is required (for example tensiometers to determine the matric suction potential). In the calculations some simplifications are made. These will have an effect on the accuracy.
2.5.4 The Nuclear Tracer Imaging Centrifuge (NTIC) [22]

This method, in contradiction to any of the former, tries to determine the retention curve in one test. \(^{22}\)NaCl isotopes who emit \(\gamma\)-radiates are added to the water. The \(\gamma\)-radiates are detected by a germanium detector. This equipment allows in flight measurement of the water distribution throughout the soil sample. Every 6 mm a measurement is taken. Every reading corresponds to a different water content and provides a different point on the retention curve. The measurements are only taken when the sample passes the detector. This method does provide more than enough readings. A principle sketch of the set-up is shown in figure 2.13.

![Principle sketch of the NTIC set-up.](image)

After calibration the water content can be calculated using the measurements of intensity of the radiate. The water content \(u\) is linearly proportional to this intensity.

\[
u = \frac{a_i}{a_{i,\text{norm}}} \quad (2.26)
\]

With: \(a_i\) = the measured intensity and \(a_{i,\text{norm}}\) = the measured intensity for a completely saturated sample.

Because multiple points of the retention curve are obtained it is possible to determine the complete retention curve without mathematical model. Fredlund, Xing and Huang provided a possible technique [23]. Using the least-squares method a best-fitting retention curve can be found. Quite accurate results have been obtained with this method.

The only disadvantages of the test are the very expensive equipment and the effect of the salts that must be added. These might have an important effect on the conductivity, especially with clays (cfr. paragraph 2.4.5).
2.5. EXISTING SET-UPS TO DETERMINE UNSATURATED HYDRAULIC CONDUCTIVITY

2.5.5 Parameter optimizing technique for transient flow [26]

Measurements of water content in time and for different numbers of rpm allow to determine some hydraulic properties of a soil sample. These properties are obtained by estimations from numerical inversion of transient experiments.

The test is started with a saturated soil sample. It will therefore only be possible to test soils with low conductivities at high numbers of rpm.

The water content is measured with electrodes that are applied in the sample. The difference in electrical conductivity provides after calibration the required data.

A given amount of salt must be added to the water to ensure the electrical conductivity. For some soils (mainly clays) this can cause important problems since the conductivity can change severely due to the influence of salts.

A mathematical model based on the model of Mualem - van Genuchten is used to find a numerical solution. The non-linear Levenberg - Marquardt algorithm is used to find iteratively the best fit. The mathematical model that is tried to validate in this work also works with these principles, as explained in paragraph 2.6.

2.5.6 Other existing centrifuge set-ups

Different types of centrifuges are and have been used to determine multiple soil parameters. Different set-ups for the soil specimens are used. Only a minority is fit to test soils with a (very) low conductivity. Saturated flow is in principle possible for each type of centrifuge. Only the decrease in time of a test will differ for the different centrifuges. When also soils with low conductivities can be tested it is often the case that no in situ soil specimens can be tested due to the complicated soil specimen set-up. Another often occurring problem is that for the determination of every point on the retention curve a different test is required. This causes long testing times because steady-state is then always required (and this is reached slowly for soils with low conductivities) and/or causes the need to have a lot of soil specimens. For in situ taken soil samples this causes a low accuracy due to differences between the samples.

There are some centrifuges using two liquids with different densities in order to simulate flow. These tests simulate however a completely different flow then the intentions in this work.

Non of the existing centrifuges are able to allow quick and simple tests on in situ taken soil samples in order to determine the retention curve(s) of the soil with only one or two tests. This would be the scope of this work.
2.6 Description of the mathematical model

2.6.1 The van Genuchten-Mualem approach

As seen there are many different methods to try to experimentally validate (mathematical) models predicting unsaturated flow through porous media. There are also many approaches that have been published concerning empirical formulas as well as more complicated models using statistic interpretations of the retention curve to model unsaturated flow. One of the most general methods was described by M. Th. van Genuchten in 1980 [24]. His derivation starts from the approach of Y. Mualem [25]. Mualem considered in his approach the effective saturation degree as defined by formula (2.27).

\[ u = \frac{\theta - \theta_r}{\theta_s - \theta_r} \]  

(2.27)

With:
\( \theta = \) the water content at the considered moment,
\( \theta_r = \) the residual water content and
\( \theta_s = \) the water content at saturated conditions.

The relative permeability \( K_r(u) \) is used instead of the actual permeability \( K(u) \) in order to eliminate some constants present in the estimation formulas for \( K_r(u) \) and \( K_{sat} \) that are difficult to determine.

\[ K_r(u) = \frac{K(u)}{K_{sat}} \]  

(2.28)

With:
\( K_r(u) = \) the relative permeability as a function of the effective saturation degree and
\( K_{sat} = \) the permeability in saturated conditions. This is a constant for each soil with a constant void ratio.

When \( K_r(u) \) is determined \( K(u) \) is known too. Mualem defined \( K_r(u) \) as

\[ K_r(u) = u^\lambda \left[ \frac{\int_0^u \frac{1}{h(x)} \, dx}{\int_0^1 \frac{1}{h(x)} \, dx} \right]^2 \]  

(2.29)

with:
\( h(x) = \) the pressure head as a function of the effective saturation and
\( \lambda = \) a factor depending on the soil.

This factor was estimated at \( \frac{1}{2} \) by Mualem as applicable on most types of soils since with this value the best results were obtained.

The integral in the enumerator expresses the considered situation. The integral in the denominator expresses the saturated condition.
Th. van Genuchten formulated a general equation for the retention curve (pressure head \( h \) in function of the water content \( \theta \)). By combining this equation with the Model defined by Mualem, van Genuchten obtained an analytical expression of the relative hydraulic permeability \( K_r(u) \). The function defined by van Genuchten is

\[
    u = \left[ \frac{1}{1 + (\gamma \cdot h)^n} \right]^m \tag{2.30}
\]

with: \( \gamma, n, m = \) constant empirical soil parameters yet to determine, \( n > 0 \) and \( h > 0 \) if \( \gamma > 0 \).

\[
    \gamma = -\frac{(2^\frac{1}{m} - 1)^{1-m}}{h_b} \quad \text{when} \quad u = \frac{1}{2} \quad \text{and with} \quad h_b = \text{the bubbling pressure as defined in paragraph 2.4.3.}
\]

For clays is \( n \) commonly a little larger than 1 and \( \gamma \) is small since the bubbling pressure for a clay is large.

Combining formula (2.30) with formula (2.27) gives the relationship between \( \theta \) and \( h \) in formula (2.31).

\[
    \theta = \theta_r + \frac{\theta_s - \theta_r}{(1 + (\gamma \cdot h)^n)^m} \tag{2.31}
\]

An example of a retention curve obtained by equation (2.31) is given in figure 2.14.

---

**Figure 2.14:** Example of the theoretical determination of a retention curve using formula (2.31) as defined by M. Th. van Genuchten [24].
2.6. DESCRIPTION OF THE MATHEMATICAL MODEL

The relation expressed by formula (2.32) is assumed by Mualem as well as in the model upon which the experimental data will be referred to in this work.

\[ m = 1 - \frac{1}{n} \]  

(2.32)

Only two unknown constants thus remain in equation (2.30).

When the retention curve is determined by experiments the constant \( m \) can be derived. Using formulas (2.30), (2.32) and eventually formula (2.31) allows the complete determination of the retention curve.

The extended derivation of the formulas as well as the determination of the value \( m \) from test results is given in the original work of M. Th. van Genuchten [24] or in derivative works such as [10].

2.6.2 Determination of parameters

Saturated conductivity

The saturated flow through a soil sample is defined by formula (2.33).

\[ q = -\frac{K}{\mu} \left( \nabla p + \rho g \nabla z - \frac{\omega^2 \rho \nabla r^2}{2} \right) \]  

(2.33)

With:
- \( K = K_{\text{sat}} \) = a Darcy unit of permeability \([m^2]\),
- \( \mu \) = the dynamic viscosity \([kg/m/s]\),
- \( p \) = the pressure in the soil \([kPa]\),
- \( \rho \) = the density of the liquid (i.e. 1 \([kg/dm^3]\) for water),
- \( z \) = the depth in the sample measured from the datum, i.e. the rotating axis \([m]\),
- \( \omega \) = the rotational speed expressed in radians per second,
- \( r \) = the distance from the rotating axis to the centre of gravity of the sample,
- \( \nabla q = 0 \) meaning the inflow is equal to the outflow (saturated flow).

The gravity is neglected (cfr. second term in the brackets) hence a 1-D situation is considered.

Formula (2.33) can therefore be written as

\[ q = -\frac{K \rho g}{\mu} \left( \nabla h - \frac{\omega^2 \nabla r^2}{2g} \right) = -\frac{K \rho g}{\mu} \nabla \left( h - \frac{\omega^2 r^2}{2g} \right) \]  

(2.34)

with: \( h = \frac{p}{\rho g} \),

or also as
2.6. DESCRIPTION OF THE MATHEMATICAL MODEL

\[ q = -k \left( \nabla h - \frac{\omega^2 r^2}{2g} \right) \]  \hfill (2.35)

with: \[ k = \frac{K \rho g}{\mu} \] = the hydraulic conductivity \([\frac{m}{s}]\).

\[ q \bigg|_{r=r_0} = \frac{dH}{dt} \approx \frac{H_2 - H_1}{t_2 - t_1} \] \hfill (2.36)

The flow \( q \) is also defined by formula (2.37).

\[ q = -k \nabla \left( h - \frac{\omega^2 r^2}{2g} \right) \] \hfill (2.37)

Also is \( h \big|_{r=r_0} \) equal to the hydrostatic pressure so

\[ p(r) = \int \rho_w \omega^2 r dr = \frac{\rho_w \omega^2}{2} H (2r_0 - H) \] \hfill (2.38)

with: \[ h = \frac{p}{\rho g}. \]

The elaboration of equation (2.37) is with the combination of formula (2.36) also the following (with some aid of [12] and with the use of formula (2.38) to get from the first to the second line below):

\[ q \bigg|_{r=r_0} = \frac{dH}{dt} = -k \frac{d}{dr} \left( h - \frac{\omega^2 r^2}{2g} \right) \bigg|_{r=r_0} \] \hfill (2.39)

Figure 2.15: Sketch of the notations used in the derivation of the conductivity.

When \( H_1 \) and \( H_2 \) are the water heights corresponding with times \( t_1 \) and \( t_2 \) (with \( t_2 > t_1 \) and \( H_1 > H_2 \) as shown in figure 2.15) and \( t_2 - t_1 \) is small, the following approximation can be assumed.

When \( H_1 \) and \( H_2 \) are the water heights corresponding with times \( t_1 \) and \( t_2 \) (with \( t_2 > t_1 \) and \( H_1 > H_2 \) as shown in figure 2.15) and \( t_2 - t_1 \) is small, the following approximation can be assumed.
2.6. DESCRIPTION OF THE MATHEMATICAL MODEL

\[
\frac{dH}{dt} = - \frac{k \omega^2}{2g} \left( 2(r - r_0) - \frac{H(2r_0 - H)}{L} - L - 2r \right) \tag{2.40}
\]

\[
\frac{dH}{dt} = - \frac{k \omega^2}{L} \frac{2L - 2r_0L - H(2r_0 - H) - L^2 - 2rL}{2g} \tag{2.41}
\]

\[
\frac{dH}{dt} = + \frac{k \omega^2}{L} \frac{((2r_0 + L)L + H(2r_0 - H))}{2g} \tag{2.42}
\]

\[
k = L \frac{1}{(r_0 + L) \frac{\omega^2}{g}} \left. \frac{1}{t_2 - t_1} \ln \frac{H_1 + L}{H_2 + L} \frac{2r_0 + L - H_2}{2r_0 + L - H_1} \right|_{H_1}^{H_2} \tag{2.45}
\]

Considering \( \omega \) not constant formula (2.46) is instead obtained.

\[
k = L \frac{1}{(r_0 + L) \frac{\omega^2}{g}} \int_{t_1}^{t_2} \frac{1}{t_2 - t_1} \ln \left( \frac{H_1 + L}{H_2 + L} \frac{2r_0 + L - H_2}{2r_0 + L - H_1} \right) dt \tag{2.46}
\]

\[
\partial_t \theta = K_s \partial_r \left[ K_r(h) \left( \partial_r h - \frac{\omega(t)^2}{g} r \right) \right], \ h < 0 \tag{2.47}
\]

Again \( L \) is assumed not to be large and at position \( r_0 + L, \ h (r_0 + L) = 0 \).

The formulas derived above are used to inversely determine the expected properties of the tested soil. To solve the necessary equations the correct initial and boundary conditions are needed. These depend on the test that is simulated.

**Unsaturated conductivity**

As inter alia seen in [10] the combination of formulas (2.27), (2.28), (2.29) and (2.32) allows the conversion of \( K_r(u) \) into \( K_r(h) \). The result is given in formula (2.48).

\[
K_r(h) = \frac{1}{(1 + (\gamma \cdot h)^n)^{m/2}} \left[ 1 - \left( \frac{(\gamma \cdot h)^n - 1}{(1 + (\gamma \cdot h)^n)^m} \right)^2 \right] \tag{2.48}
\]

For non steady-state (non linear) situations the equations are solved using the Levenberg-Marquardt algorithm. This is an iterative process where the differences between the results from the model with multiple parameters and the measurements are minimized. It is of importance to choose a correct number of model parameters to obtain a good fit.
2.7 Soils tested

For the tests carried out in this thesis two materials were used. The first is a kaolin clay, the second is Mol sand. Both materials are very equable. For kaolin clay indications are given in table 2.5. For Mol sand more than 90 % of the mass percentage of the grains has dimensions from 0,15 to 0,3 mm. The grain curve of Mol sand is very steep as illustrated by the grain size distribution added in appendix B.

2.7.1 Kaolin clay

The kaolin clay used is a commercial processed clay: Rotoclay HB® (Goonvean, St. Austen, UK). This clay has already been used by many researchers such as Schofield and Worth (1968); Wood (1990); Murthy et al. (1991); Whittle and De Groot (1994). The general characteristics of this clay were given by Mazzieri et al. in 2002 and are listed in table 2.5.

<table>
<thead>
<tr>
<th>Property</th>
<th>Reference</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Product info</td>
<td>Rotoclay HB®</td>
</tr>
<tr>
<td>Main mineral</td>
<td>Product info</td>
<td>Kaolin</td>
</tr>
<tr>
<td>Water content (w)</td>
<td>Lab det.</td>
<td>0.725 %</td>
</tr>
<tr>
<td>Specific density (Gs)</td>
<td>ASTM D854</td>
<td>2.65 g/cm³</td>
</tr>
<tr>
<td>Liquid limit (wL)</td>
<td>ASTM D4318</td>
<td>57.70 %</td>
</tr>
<tr>
<td>Plasticity index (PI)</td>
<td>ASTM D4318</td>
<td>28.60 %</td>
</tr>
<tr>
<td>Silt particles (0.002-0.074)</td>
<td>ASTM D422</td>
<td>59.60 %</td>
</tr>
<tr>
<td>Clay particles (&lt;0.002 mm)</td>
<td>ASTM D422</td>
<td>40.40 %</td>
</tr>
<tr>
<td>Activity</td>
<td>-</td>
<td>0.7</td>
</tr>
<tr>
<td>Maximum dry weight (ρd,max)</td>
<td>ASTM D698 (A)</td>
<td>14.5 kN/m³</td>
</tr>
<tr>
<td>Optimal water content (wopt)</td>
<td>ASTM D698 (A)</td>
<td>28 %</td>
</tr>
<tr>
<td>pH (1:4 extract)</td>
<td>-</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Clay is composed of phyllosilicates. These are silicates with a layered structure. Kaolin exists out of a layer of SiO₄-tetrahedrons bounded to a layer of AL(O,OH)₆- octahedra by dividing oxygen atoms. The minerals are strongly bound by hydrogen links causing a stable structure. Kaolin has therefore a low plasticity and will barely swell or shrink [27].

More (chemical) characteristics of the clay can be found with the producers of the clay.

The one dimensional consolidation theory of Terzaghi gives following relationship:
2.7. SOILS TESTED

\[ k_z = C_v \, m_v \, \gamma_w \]  

(2.49)

With:
- \( k_z \) = the conductivity in the considered direction \([m/s]\),
- \( C_v \) = the coefficient of consolidation \([m^2/s]\),
- \( m_v \) = the coefficient of volumetric compressibility, equal to \( \frac{1}{E_s} \),
- \( E_s = M \) = the oedometer modulus \([N/m^2]\) and
- \( \gamma_w \) = the volumetric weight of water, equal to 10 000 \([N/m^3]\).

Formula (2.49) can therefore be transformed to

\[ k_z = \frac{C_v \, \gamma_w}{E_s} \]  

(2.50)

In [1] values for \( C_v \) and \( E_s \) can be found for the same kaolin clay as a function of consolidation pressure. Figure 2.16 gives the consolidation coefficient of the kaolin clay as a function of the effective vertical tension for following methods:

- Taylor method or \( \sqrt{t} \)-method
- Casagrande method or \( \log(t) \)-method
- Diagnostic curves method (S.K. Singh, 2007), first and second
- Inflection point method (G. Mesri et al., 1999)

For more information about these methods the author of this work would like to refer to the work of P. Pollet [1]. The consolidation pressures in this work will not exceed 100 \( kPa \). For the interval 0 - 100 \( kPa \) the different stated methods give very similar results (see figure 2.16). The method chosen for the values of \( C_v \) is therefore of minor importance. For the mentioned interval in this work, a value of 0,6 \( mm^2/s \) seems appropriate.

The Oedometer modulus can also be found in the work of P. Pollet. In figure 2.17 the red curve gives the required values.

Table 2.6 gives the values of the conductivity \( k_z \) of the kaolin clay for different consolidation pressures. These values will be considered as theoretical reference values later in this work.

<table>
<thead>
<tr>
<th>Consolidation pressure</th>
<th>15 ( kPa )</th>
<th>45 ( kPa )</th>
<th>75 ( kPa )</th>
<th>100 ( kPa )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_v ) [( m^2/s )]</td>
<td>0,6.10^{-6}</td>
<td>0,6.10^{-6}</td>
<td>0,6.10^{-6}</td>
<td>0,6.10^{-6}</td>
</tr>
<tr>
<td>( \gamma_w ) [( N/m^3 )]</td>
<td>10.10^3</td>
<td>10.10^3</td>
<td>10.10^3</td>
<td>10.10^3</td>
</tr>
<tr>
<td>( E_s ) [( Pa )]</td>
<td>750.10^3</td>
<td>1000.10^3</td>
<td>1025.10^3</td>
<td>1050.10^3</td>
</tr>
<tr>
<td>( k_z = \frac{C_v , \gamma_w}{E_s} ) [( m/s )]</td>
<td>8,00.10^{-9}</td>
<td>6,00.10^{-9}</td>
<td>5,85.10^{-9}</td>
<td>5,71.10^{-9}</td>
</tr>
</tbody>
</table>
2.7. SOILS TESTED

Figure 2.16: Consolidation coefficient of the kaolin clay used for this research as a function of the vertical effective tension [1].

Figure 2.17: Oedometer modulus as a function of the vertical effective tension for kaolin clay [1].

2.7.2 Mol sand

Mol sand is also very homogeneous and has been tested by many other scientists, e.g. by De Beer, Ladanyi, De Beer-Vesic and W.F. van Impe. For his PhD research [4] Van Impe has inter alia extensively tested the general characteristics of the sand. Together with the results of the other scientists mentioned, van Impe has summarized the well-known characteristics of the Mol sand. The following description of the sand is based upon his work.
2.8 Conclusion

Geologically Mol sand is part of the Plioceen-tertiair (± 15 million years old) as found in the north east of the Kempen where this sand layer can reach a thickness of 70 m. It is a white pure quartz sand with locally also some lignite. The main property of the sand for this work is the conductivity which depends on the relative packing density $D_r$. The results obtained by van Impe are given in appendix C. For the description of the tests carried out by van Impe to determine the conductivity the author of this work would like to refer to the PhD. paper by van Impe [4]. In short, the samples were first perfused with $CO_2$-gas for 10 minutes in order to replace the air present in the samples with this gas, for this dissolves better in water than in air. This way the sample can be completely saturated. Afterwards a falling head test was carried out with a constant head of 30 mm, relying on the Darcy law of flow. Using picnometer tests the mass density (or specific weight) was determined in order to calculate, together with the volume weights, the pore volumes. That way the relative density $D_r$ can be determined, using the actual pore volume and the minimal and maximum pore volume for the tested soil. For Mol sand van Impe determined following relationship for $D_r$:

$$D_r = \frac{n_{max} - n}{n_{max} - n_{min}} = \frac{47,83 - n}{47,83 - 36,92}$$  \hspace{1cm} (2.51)

The Mol sand used for this work is the same sand, but has been very slightly contaminated. PhD. student ir.-arch. Laure Wils has determined the properties of the sand, now being used in the university lab. The grain size distribution curve of the sand is given in appendix C. The mass density which is important too, was also determined using picnometers with gas, resulting in a value of $G_s = 2,65 \text{ g/cm}^3$. This is the same value as determined by van Impe using water based picnometers [4]. The grain size distribution curves are slightly different but coincide fairly well.

An average compaction of the sand corresponds to a porosity of 40%. With this value a conductivity of $1 \times 10^{-4}$ m/s corresponds ([4], appendix C).

2.8 Conclusion

In this chapter a resume is given of a literature study dealing with the applications of this work, some soil mechanical aspects, related set-ups, a description of the mathematical model that needs validation and the main characteristics of the soils being tested. In the next chapter the sample preparation and the equipment are described to proceed with the tests carried out in this work in chapter four.
3.1 Introduction

In this chapter all sample preparations needed in this work are described as clearly and completely as possible. The soil recipients and the measuring equipment are described first. Then the sample preparation of dry and saturated kaolin clay, Mol sand and mixtures of both are described. The static pre-consolidation set-up, the centrifuge and the development of a simple centre of gravity set-up are described next. The end of the chapter deals with the soil preparation and testing set-up for suction head tests carried out in this work. Chapter four will discuss the tests that were carried out and their results. Chapter five gives a resume of the general conclusions of this research.

3.2 Soil recipients

Figure 3.1 gives an overview of the different elements of the soil recipients. First there is what will be called in this work the *tube*. This tube will contain the soil and is equipped with a VitraPOR©-filter. This is a porous glass filter that is welded solidly in the bottom part of the tube. The porosity can - within limits - be fixed according to the desired requirements of the tests carried out. In order for the filter to have only a little effect on the calculations, the conductivity of the filter should be higher than the conductivity of the tested soil (cf. paragraph 4.2.2). The porosity should however be low enough to prevent any transport of soil through the filter and also to prevent clogging of the filter.

The tubes have almost constant heights. Small irregularities of up to approximately 0.3 mm however occur. That’s why an average of five measurements of all dimensions is always taken. For practical reasons the measurements of the inside diameter are taken at the top of the filter.
3.2. SOIL RECIPIENTS

This inside diameter will however also be different as a function of the length of the tubes. It is practically impossible to measure this accurately with the facilities present in the laboratory. Visual inspection shows that at the level of the thread there is a clear change in dimension of the inside diameter for a lot of tubes. This difference in diameter can also be observed by softly rubbing the inside of the tubes. This rubbing indicates a smaller diameter at the level of the thread. The inside diameter is mainly important for the surface of the filter which is also at the level of the thread. For this value the readings taken will be sufficient. When the height of a water table on top of the soil is calculated using the weight of the water and the inside surface, an error is made as the inside surface is larger in the middle part of the tubes than the value found by measurements at the level of the thread.

A porous glass filter allows the flow of air and water. An alternative option is a ceramic filter which only allows the flow of water and not of air. This is caused by the high capillary forces in a ceramic filter that ensure the filter to remain saturated. Only extreme pressures or drying can cause an unsaturated condition in a ceramic filter. The higher capillary forces are the result of a low porosity but also because of the different material properties (cfr. paragraph 2.4.1). This certainty that a saturated condition is present will be of importance later in this work.

The dimensions of the tubes in use are determined by

- the measurements of the casings inside the centrifuge,
- limiting the possibility of preferential paths trough the sample (rather tall than wide) in a compromise with the influence of the inner surface of the tube,
- the possibility to provide a sufficiently large water table,
- limiting the circular surface of the water level (cfr. paragraph 3.6.1).

The material used for the tubes is glass because this is a very versatile material in which almost any shape can be made to the required dimensions at high accuracy. Another advantage is that it is a transparent material that makes visual inspection possible.

The second element is the outflow glass together with the large light gray screw. In the middle of this large gray screw there is a smaller red screw in which the tube can be screwed. The reason to provide this outflow glass is obviously to allow us to measure the amount of outflow accurately. There is a second red screw, also called red cap or outflow cap, that can be screwed onto the bottom of the tube. A rubber in this red screw makes it possible to seal off the bottom of the tube. Without the rubber there is the possibility to have a hydraulic head at the bottom part of the tube. Because the surface of the red screw is not horizontal, a water level is possible at the bottom. This water can flow through the thread upto the top of the screw. When flow continues the water will fall down from the red screw into the outflow glass.
In order for the samples to be exposed to a constant atmospheric pressure, hydrodynamic effects in the centrifuge due to the rotation must be avoided. The outflow glass is also useful in this case. For the atmospheric pressure to be the same at the top and bottom of the soil tube, a connection must be made between those two areas. This is achieved by a small gap at the top of the tube. This allows an air flow between the air above the sample towards the air within the outflow glass. Attention must be given to the cap in which the tube is screwed. If a rubber at the top of this cap is present, this might close the small gap and prevent the desired airflow. The connection can simply be checked by a normal falling head test with and without the sealing cap. The time needed for a given volume of water starting from a given level to flow out of the tube should be the same in both cases. If the connection is not complete, a lower air pressure will be created above the sample and will slow down the flow. This means that in the actual tests the same thing would occur and a lower – incorrect – conductivity would be obtained. After removal of the original rubbers a correct connection was realised.
3.3 Measuring equipment

To determine the weights required in this work, a calibrated balance was used with at least 0.01 g accuracy. Heights were measured with a calliper with an accuracy of 0.05 mm. It should be mentioned that these are not the actual accuracies. There might also be human mistakes due to misreading the equipment, writing down incorrect values and entering incorrect values into a digital file (all very occasional) or mistakes caused by the position of the calliper which is limited by the capacities of the human eye.

The soil top is never a straight surface. To limit fluctuations in the values of the heights of the soil as much as possible, dimensions are always taken at the same position of the tube. Concerning the soil height a position for each sample is taken at the start of each test which visually corresponds to the average height of the soil. The distance from the top of the soil to the top of the tube is subtracted from the average value of the total height of the tube. When the bottom of the filter does not coincide with the bottom of the tube, this difference is also taken into account. It is obvious that the accuracy of these measurements is not equal to the accuracy of the measuring device, in this case the calliper.

3.3.1 Visual inspection

The concept visual inspection has been mentioned before. This inspection is a very useful method to help to explain unexpected or inaccurate results or to have a better understanding of some phenomena. It is also useful to describe in a more detailed way some elements in this work. Throughout this work this method will therefore be mentioned several times.

3.4 Sample preparation

Any water used for sample preparation or for the conductivity tests will be purified water to avoid any possible effect from ions present in non purified water.

3.4.1 Dry kaolin clay

Kaolin clay is available at the laboratory in large bags. The clay in these bags has a small water content lower than one percent. This small amount of water causes some of the clay to form chunks, shown at the top of figure 3.3 (a). These chunks though have no different properties from the powder in the bag except for the water content.

To prepare tubes with dry kaolin clay, the soil is first crushed with a mortar (crf. figure 3.3 (a), bottom) to pulverize the larger particles.

The initial water content of less than one percent is not considered to be a problem for the tests that will be carried out in this work, nor is it a problem in the preparation of the samples.
3.4. SAMPLE PREPARATION

Figure 3.3: (a): Kaolin clay as present in the lab with small chunks, water content lower than one percent (top) and mortar used to pulverize the soil (bottom). (b): Prepared tube with dry clay.

Next the crunched soil is inserted into the tubes in three batches and tamped with a cylindrical steel bar with a surface approximately equal to a quarter of the surface of the tube and weight of 90 g. The weight is released to fall free onto the soil from a height of 50 mm. Soil is added after the sample has been tamped 25 times. This procedure was inspired on the procedure of a proctor test to homogeneously compact soil samples. A filter paper is placed at the bottom and top of the soil. Visual inspection of the sides of the tubes shows no irregularities, cf. figure 3.3 (b).

The filter paper at the bottom of the soil, above the filter, is placed there to protect the filter from clogging. The filter paper on top of the soil is used to prevent the water from becoming cloudy so the soil height can be measured more accurately. The filter paper used is a Whatman® quantitative filter paper, medium speed, Grade 589-WH. It has a thickness of 0,10 mm, weighs 0,030 g and absorbs 0,050 g of water. It is advised, despite of the use of the filter paper, to clean the filters regularly by placing the tubes in an ultrasound, also used at the laboratory to clean porous stones.
3.4. SAMPLE PREPARATION

3.4.2 Saturated kaolin clay

In order to obtain a homogeneous mixture of saturated clay a high water content is required. This makes it possible to mix the soil into a homogeneous slurry. This slurry must have a low viscosity in order to fill the soil into the tubes without air bubbles being enclosed. Literature (Fearon, R. E. Coop, M. R., 2000) advises to use at least a water content equal to 1.5 times the liquid limit \(w_L\) to obtain a homogeneously saturated sample. The water must be de-calcified or even better de-mineralized. For the tests in this work de-mineralized water is always used. For most of the tests in this work a water content of twice the liquid limit is used. This was helping the process of filling the soil into the tubes. However the disadvantage of a high water content is the larger decrease of soil height when pre-consolidated. Another disadvantage appears when the samples are pre-consolidated with weights. The slurry is then not capable of supporting the applied weight. When necessary to counteract one or both of the disadvantages mentioned, the minimum value of 1.5 times the liquid limit is sometimes used. The liquid limit of the kaolin clay used is 57.7 % (table 2.5). The water content corresponding to 1.5 respectively 2 times the liquid limit is therefore 86.55 % respectively 115.4 %. These values are an indication for the preparation. The original water content and evaporation will cause the actual water content to be slightly different. Therefore the water content is always measured by drying a soil sample in the oven at 105 °C after the soil is prepared and before the tubes are filled.

The soil is put in a Hobart dough mixer (figure 3.4) and the water is added gradually while the soil is mixed. After the water is added the mixture is being mixed for 15 minutes.

(a) Hobart doughmixer (b) Mixing tool

Figure 3.4: The Hobart dough mixer with mixing tool.

A syringe is used to insert the soil into the tubes (see figure 3.5). The soil is pushed out of the syringe into the tube, starting from the bottom and gradually moving up to the top. A vibratory table is always used in case some air bubbles might have been trapped into the soil. Due to the high water content the soil structure is very loose and the vibrations from the table cause the air bubbles to move upwards and leave the soil. Recording the weight of the tube
before and after the addition of the soil and the water content make it possible to calculate the amount of soil. Together with the dimensions the density, pore volume and other values can be calculated.

The soil height of the sample that is prepared depends on the type of test that will be carried out. For drainage tests a higher soil height is allowed since no water table on top of the soil is required. For imbibition tests and falling head tests a water table on top of the soil is required and thus a lower initial soil height is necessary.

3.4.3 Dry Mol sand

Mol sand is a very homogeneous sand. For dry samples the sand can simply be added into the tube for example with the aid of a funnel. A filter paper on top of the soil is not necessary since the sand will not turbid the water. To protect the filter from clogging it is advised to use a filter paper at the bottom of the soil.

3.4.4 Saturated Mol sand

Procedure

For the preparation of saturated samples a mixture of sand and water can be made. It is however difficult to insert this mixture into the tubes because no slurry can be made. Also air bubbles might get trapped using this method. To ensure that no air bubbles are enclosed an attempt was made to start with a tube and a low water level ($\pm 1 \text{ cm}$). The sand is then added just above the water level using a funnel. The sand trickles into the water very gradually, ensuring no air bubbles are enclosed. By adding sand the water level will increase. If necessary more water is added. The low water level and low dripping height of the sand should ensure that no (important) segregation occurs due to Stokes law. This was checked by performing a slicing test.

Procedure slicing test

A tube prepared according to the procedure above is used for this test. A decapitated syringe is pushed into the soil (in the tube) and pulled out. A cylinder of soil is obtained. The soil cylinder extracted is however longer than the soil sample. The reason is that soil is pushed up into the syringe when this syringe is pushed downwards. The sand cannot be deformed easily causing a volume of soil equal to the volume of the material of the syringe that is pushed into the soil to be pushed upwards. Apparently the way up into the syringe has the lowest resistance. The void ratio is therefore not representative because the soil structure is changed. Since the procedure is the same for all the samples and also the same for one tube, a comparison of the values can however be made. The soil cylinder obtained is then pushed out gradually
and cut into three parts. Dimensions are recorded. The water content will give correct results when using this test, since it is independent of the void ratio.

Results slicing method

Four completely saturated samples were tested, each time divided into three parts. The samples were pre-consolidated in the centrifuge for four times five minutes at 400 rpm. The reason for the four times five minutes is because water must be added on top of the samples. The accuracy of the measurements is not excellent due to the small dimensions. The water content however is measured quite accurately and although lower accuracy of the values a trend in the results should be visible if there are important differences in the samples. The difference between maximum and minimum average water content of all the samples is 1.9%. There is no clear trend (e.g. smaller void ratio at the top because of segregation) in the values of the void ratio, indicating there is not a major influence as a result of the sample preparation. The difference between maximum and minimum average void ratio of all the samples is 2.4%. The saturation degree is calculated as

\[ S = \frac{G_s \ w}{e} \]  

(3.1)

With: \( G_s \) = the specific density of the soil,
\( w \) = the mass water content, i.e. the mass of water divided by the mass of soil and 
\( e \) = the void ratio being the volume of voids divided by the volume of soil.

More detailed results are added in appendix F.32.
3.4. SAMPLE PREPARATION

3.4.5 Mixtures of Mol sand and kaolin clay

Purpose

Sand has the advantage of a quite solid structure that will not allow a lot of deformation when forces are applied. The disadvantage is the high conductivity which makes it more difficult to perform accurate tests, especially in the centrifuge. Clay has the disadvantage of being very deformable. The soil height changes a lot when applying larger forces. Also when lower forces are applied after a period of higher stresses, an important unloading and increase in the soil height will occur. This change in soil height is difficult to model because it changes the void ratio in an unequal way. The advantage of clay is the low conductivity which allows to perform tests inside the centrifuge. To model unsaturated flow of soils with low conductivities is a purpose of this work. In order to combine the advantages of both types of soils and to rule out as much as possible the disadvantages, mixtures of Mol sand and kaolin clay were considered. Literature (Chiu and Shackelford, [6]) shows that by addition of small quantities of clay, 5 to 15 percent, to a sand the conductivity of this sand can easily be decreased ten times. The optimal combination of sand and clay quantities for this type of mixture should result in a solid structure of sand which is less subject to deformations. The pores of the sand are filled with clay causing a much lower conductivity.

Preparation

Preparing a completely saturated mixture of sand and clay in a homogeneous way is very difficult. The best approximation could be made by starting from a dry sample. Using CO$_2$-gas to flow through the sample followed by water flowing through the sample, as described in paragraph 2.7.2, the highest saturation degree within a homogeneous sample can be obtained. In the laboratory no CO$_2$-gas installation is available. In this work the highest saturation degree will thus be obtained by starting from a dry sample and allowing water to flow through the sample until equilibrium is reached. Air bubbles will be enclosed in the sample, but this is on the other hand more representative. The extreme value of total saturation will not be required for practical use. For this reason an attempt to increase the saturation degree with the use of a vacuum chamber, available in the laboratory, is not carried out.

To prepare a dry mixture of clay and sand the following procedure is used. Both clay and sand are dried in the oven at 105 °C for at least 16 hours. In the clay some chunks are left. The mortar does not completely remove the very fine chunks. To solve this problem the dried clay is sieved using a 63 µm sieve. This way a pure powder is obtained without any chunks. Now the clay and the sand can be mixed homogeneously. Since only small quantities are required the mixing is done with a small spoon in a glass cup. The result of a mixture of 90 % Mol sand and 10 % kaolin clay is shown in figure 3.6.
3.5 Static pre-consolidation set-up

In order to pre-consolidate samples the set-up shown in figure 3.7 is used. For consolidation in saturated conditions steel cylinders are used with a perforated bottom at the soil side. These perforations allow the drainage of water. If necessary water can also be added on top of the sample to ensure the saturated condition. The steel tubes fit very tightly into the glass tubes so they are always in a horizontal position. When the weights that are placed on top of these tubes are not perfectly centred, the force will still be equally applied to the soil because the steel tubes are always in a horizontal position.
To obtain exactly the required weights plastic jars with dry kaolin clay are used. They are not completely vertical because of the rough and uneven surface of the metal weights. The steel bars that transfer the weight to the soil however are in a vertical position as mentioned.

For a static conductivity test the same soil recipients as in the centrifuge are used, now placed in a horizontal position. For some time there will be an outflow into the large glass that can be measured accurately. As a check the decrease in weight of the tubes can be measured too.

### 3.6 Centrifuge

The centrifuge available for this work is a Sigma© centrifuge type 3-18. A microprocessor regulates the speed with an accuracy of 1 rpm. The minimum and maximum numbers of rotations per minute are 100 and 4200. The set number of rpm can be chosen with an accuracy of 10 rpm. The centrifuge duration can be set as desired with a minimum of one minute and an accuracy of one minute. If less time time is required the centrifuge can also be stopped manually. Some predefined acceleration curves can be chosen. For this work the steepest curve is chosen so the desired number of rpm is reached as soon as possible.

When the rotating axis is unequally loaded imbalance occurs. When this imbalance is too large the centrifuge will stop automatically. The acceptable degree of imbalance depends on

- the type of centrifuge,
- the strength of the axis,
- the number of rotations per minute,
- the weight of the samples,
- the number of samples and
- the distribution of the weight of the samples as a function of the distance to the rotating axis.
Since the centrifuge is driven by an electronic motor with an automatic gear it will be important to choose a set of parameters that provide a stable gear. If the ideal gear for the centrifuge for a particular set of parameters is difficult to find out and the gear is selected automatically, the motor might switch between two gears. As a result a different number of rotations per minute will be achieved during short periods (10–20 seconds) each time the motor switches gear. This influences the test and thus must be avoided. It is also possible that the set number of rpm is not reached in a rising order but coming down from a higher number of rotations. This happens when the motor has difficulties reaching the desired rpm and therefore switches to a higher gear to subsequently decrease the number of rpm. For the mathematical model the acceleration and deceleration curves are also of importance for a correct simulation and interpretation of the readings. This becomes more important for short tests. To take into account these effects a lot of tests with different configurations were carried out to determine the necessary relationships. Figure 3.9 shows the results for different configurations. In appendix D a more detailed graph is given with a legend. Different weights in the centrifuge, different rotations per minute and different total set times were used to detect possible important differences. Tests were also repeated with the same parameters so as to have an idea of the accuracy of each individual test. The weights used were limited by the limits of the weights that will be used during the actual tests on soil. When the same test is repeated there is a small difference in the curve of rpm in function of the time. A consequent cause for this difference has not been found. It appears however that the probability to reach the maximum rpm is greater when a lighter weight is used. There is no clear difference seen for tests with or without weights (this is better seen in the graph in appendix D with a legend). Practically the best results are reached by making a digital catalogue of all curves of rpm in function of the time and for different weights. Obviously the best method will be to let the centrifuge record the curve followed and to use this actual curve for each test using in-flight, continuous data acquisition and implement these data in the mathematical model.

A small imbalance can cause an automatic shut-down of the centrifuge when the frequency of that imbalance approaches the natural frequency of the system. This causes heavy vibrations and eventually an automatic shut-down of the centrifuge. This is the reason why tests at more than 1200 rotations per minute are avoided. This speed corresponds more or less to the natural frequency. Since there will always be a small difference in the weights and the weight distributions the centrifuge is most likely to get into problems at this number of rpm.

If the natural frequency is surpassed without shut-down the amplitude of the vibrations will decrease again allowing higher speeds. An optimal distribution of weights is therefore possible. This can only be achieved by testing one sample and using one dead weight in order to work quickly. The problem is the manual process. Trial and error is the only possibility because the weight distribution of the tested sample changes during the test. Adjusting the dead weight during the test is therefore a necessity. It is obvious that this can have a (too) large impact on the measurements when short times are used and too many attempts are needed before the optimal weight is found. For this reason speeds higher than 1200 rpm are avoided in this work,
although some tests were carried out at higher speeds when the optimal weight distribution was detected very early.

When higher speeds are applied another limit is applicable. The weakest link of the recipients will limit the speed because it might break. In this work the plastic red cap that is fixed to the large grey cap (see figure 3.1 left) is the weakest link. It broke during a test at 3600 rpm. After that test a limit was set at 2400 rpm since at that speed no problems occurred and not enough recipients were available to find out the actual limit.

![Graph showing rotations per minute as a function of time.](image)

**Figure 3.9:** Actual number of rotations per minute in the centrifuge as a function of weight, set time and set number of rpm.

The centrifuge will cause a horizontal acceleration force on the samples. There will always be one time the gravitational force acting in a vertical direction. The resultant will therefore be inclined. The resulting force will thus be higher than the calculated horizontal acceleration force but will be approximated by the latter at high speeds. A loose axle of the recipient holders is necessary to allow inclination. At rest the holders are already slightly inclined, corresponding to the minimal value of 100 rpm that can be set with the centrifuge.

Evaporation has a small effect on the measurements. This effect will increase with the temperature. At high speeds and long times the temperature inside the centrifuge might increase considerably. It is therefore necessary either to ensure a good ventilation system to fix the temperature or to measure the temperature inside the centrifuge so the effect can be taken into account.
3.6. CENTRIFUGE

3.6.1 Curvature of the water level during centrifugation

An effect caused by centrifugation is the circular (neglecting capillary forces at the edges) water surface that is created. This happens for a free water surface on top of the soil and for a water level in the soil at the outflow side. Equation (3.2), as also described in [12], describes the difference $\delta h$ between the water level at the centre and at a certain distance from the centre. Figure 3.10 gives a sketch of the principle of the water level on top of the soil. The same principle is also valid for a water level at the outflow side.

$\delta h = R \left(1 - \cos(\delta \theta)\right) = R \left[1 - \sqrt{1 - \left(\frac{r}{R}\right)^2}\right] \quad (3.2)$

With:
- $R =$ the radius of the curvature of the water level,
- $\delta \theta =$ the angle as shown in figure 3.10,
- $r =$ the position of the considered point measured from the centre of the water level.

Assuming saturated conditions at the outflow side this decrease of the water level will cause a lower pore-water pressure in the zone where the water table is lowered. This pressure decrease can by approximation be considered to be linear in this area. This has an effect on the conductivity. Since it causes a higher gradient it will cause the conductivity to increase.

For a water table on top of the soil a safe approximation is made when the lowest height of the water table is used. When the average height corresponding with the same volume is used an overestimation is made [12].
These effects caused by the curvature of the water level during centrifugation decrease with increasing distance from the rotating axis (cfr. equation (3.2)).

In this work also tests were carried out with an outflow head. The total volume that represents the decrease in water level due to the centrifugal forces is approximately equal to $150 \text{ mm}^3$. This value is obtained by integration of the variable value $\delta h$ over the surface. The maximal decrease in height $\delta h$ at the centre is for the tests with outflow head approximately equal to 0.46 mm.

### 3.6.2 Forces

The forces acting on a soil sample subjected to centrifugal forces are not easy to describe for all situations. The simplest situation would be a dry soil sample. The pressure distribution in the soil sample for static conditions ($\rho_s g h_s$) must then simply be multiplied by the resulting value of $N$. $N$ being the degree of gravitational force (for example 100 times the gravitational force) corresponding with the weight of the soil sample, the distance of the centre of the soil to the rotating axis and the number of rotations per minute.

Note that this is a large simplification since the centrifugal forces are quadratically increasing with the distance from the rotating axis and that the soil sample is not one unit but a composition of particles. Also for water this reasoning applies. The following derivations are thus only rough indications of the pressures acting on the samples.

**Saturated samples**

In case of a saturated sample with water on top and a sealed bottom of the tube, forces as presented in figure 3.11 are obtained. Sigma represents the total tension and sigma' the effective or soil tension. The water tension is represented by the letter $u$. Indices $s$ and $w$ represent soil and water. Height is obviously represented by the letter $h$. Note that these notations are slightly different than for the description of the mathematical model (paragraph 2.6).

If outflow is possible and an outflow head is present the forces will be as illustrated in figure 3.12. If outflow is possible but no outflow head is provided figure 3.13 is obtained.

Despite the high water content it was assumed no segregation occurred during centrifugation. Remarkable observation is the fact that the effective stress at the top of the soil is always zero.
3.6. CENTRIFUGE

Figure 3.11: Forces acting on a saturated soil sample without outflow and with water on top.

Figure 3.12: Forces acting on a saturated soil sample with outflow, water on top and outflow head.

Figure 3.13: Forces acting on a saturated soil sample with outflow and water on top, no outflow head.
Unsaturated samples

The tensions in unsaturated samples are more difficult to determine. When a water table is added on top of a dry clay sample this water table is subjected to the centrifugal force and exerts a higher pressure as if a larger water table were present. The value of the water tension of the water infiltrating the sample is unknown. A saturated sample that is being drained and has a decreasing water table has the effect of capillarity. The distribution of the suction potential throughout a soil is difficult to determine as mentioned in paragraph 2.4.1. The water tension can therefore not be determined accurately. The effect of the centrifugal force on the remaining water above the water table and its influence on the capillary forces is also unknown.

When a sample is being drained the soil is subjected to the total weight from the moment an effective saturation degree below 100 % is achieved. From that moment the effective stress becomes equal to the total stress. The simplified stress at the base of the sample is then equal to

\[
\int_{r_0}^{r_0+L} (2\pi n)^2 (\rho_w \theta_s + \rho_s (1 - \theta_s)) r \, dr = (2\pi n)^2 \rho_t ((r_0 + L)^2 - r_0^2)
\]

with:
- \( r_0 \) = the distance from the centre of rotation to the top of the soil,
- \( L \) = the thickness of the soil,
- \( n \) = the number of rotations per second,
- \( \rho_w \) = the density of the liquid (water in this research),
- \( \theta_s \) = the saturated volumetric water content, defined by formula (2.9),
- \( \rho_s \) = the density of the soil.

The difference in stresses between the top and the bottom of the sample is very large due to the centrifugal forces. The difference between effective stress in saturated and drainage conditions is also large. These two elements might cause an inhomogeneous porosity in the sample and possible consolidation. It is therefore important to pre-consolidate the sample in such a way that no important consolidation can occur during the drainage phase of tests.

3.7 Centre of gravity set-up

For the mathematical model it is of importance to limit the number of variable parameters. If the centre of gravity (COG) of the water inside the soil can be used as an input in the model, this is useful to limit the number of variable parameters. The centre of gravity of the water present in the soil can be calculated with following formula:

\[
COG_{water} = \frac{M_{total} \, COG_{total} - M_{tube} \, COG_{tube} - M_{soil} \, COG_{soil}}{M_{water}}
\] (3.4)
3.7. CENTRE OF GRAVITY SET-UP

With: \( M = \text{Mass.} \)

\( M_{\text{soil}}, M_{\text{tube}} \) are constant values determined by measurements.

\( COG_{\text{total}} \) is a variable calculated value using measurements.

\( COG_{\text{tube}} \) is a constant calculated value using measurements.

The position of \( COG_{\text{soil}} \) is assumed to be at the middle of the soil height.

(Note that the latter is not completely correct since the inside of the tube is not a perfect cylinder, cf. paragraph 3.2.)

The cog of all the water in the soil and the filter will then be calculated. When the weight of water contained by a saturated filter is known and assuming the centre of gravity of the water in the filter to be in the centre, this can be considered in the calculations so only the cog of the water in the soil is obtained.

To obtain measurements of \( COG_{\text{total}} \) and \( COG_{\text{tube}} \) there are different methods.

- Measuring the moment of rotation. The distance in meter between the centre of rotation and the centre of mass of the rotating mass is given by

\[
 r = \sqrt{\frac{M_{\text{max}}}{m \alpha}} \tag{3.5}
\]

with:

\( \alpha = \frac{d\omega}{dt} = \text{the angular acceleration \([\text{rad/s}^2]\),} \)

\( \omega = \frac{2 \pi n}{60} = \text{the rotational speed \([\text{rad/s}]\),} \)

\( n = \text{the number of rotations per minute,} \)

\( m = \text{the rotating mass and} \)

\( M_{\text{max}} = \text{the moment on the rotating axis. This value needs to be measured.} \)

- Measuring the centrifugal force. The distance in meter between the centre of rotation and the centre of mass of the rotating mass is also given by

\[
 r = \frac{m v^2}{F} = \frac{F}{m \omega^2} \tag{3.6}
\]

with:

\( m = \text{the rotating mass,} \)

\( \omega = \frac{2 \pi n}{60} = \text{the rotational speed \([\text{rad/s}]\),} \)

\( v = \text{the peripheral speed, measured on the turning circle of the centre of mass of the rotating axis \([m/s]\) and} \)

\( F = \text{the centrifugal force. This value needs to be measured perpendicularly to the circular path. It can be done by using load cells or gauges.} \)

- Centrifugation in state of imbalance. Asymmetric loading of the rotating axis will bend the axis. The magnitude of this bending will be determined by the centrifugal force
applying on the axis. After calibration the diversion can be measured and consequently the centrifugal force and the distance from the rotating axis to the centre of mass. This will require an axis with a much higher strength and bearing system.

- Slicing the sample into parts. Theoretically one could cut slices of the sample. By drying these slices the water content of each slice can be calculated. For this work glass tubes were already available. Cutting the glass without disturbing the sample and without changing the water content is practically impossible. An alternative could be to use a different material, a plastic for example, which can be cut more easily. Adding an extra element to the glass tubes might give this method (slicing the sample) a higher chance of success. The soil sticks to the glass but using a thin plastic at the inside of the tubes, one might be able to remove the soil from the glass tubes and slice the sample afterwards. This technique would be similar to the technique used with caissons in offshore structures. A difficulty remains the soil at the filter surface which might not release this surface completely. A kind of cylindrical sock should then be necessary. Deformation of the sample must at all times be avoided. Note that this is a destructive method requiring a lot of samples. For in situ taken samples this will cause poor accuracy due to differences in the samples.

For this work a centrifuge was available. The methods stated above are therefore only useful for further development. Two other methods might be used within the limited capacities of this work.

- Using a pendulum. By measuring the period of the swinging movement the distance \( r \) in meter from the rotating axis to the centre of mass can be calculated. The derivation is not given here, only the result.

\[
T \simeq 2 \pi \sqrt{\frac{T}{g}} \tag{3.7}
\]

With: \( T = \) the period [s].

This formula is only valid for very small angles. Note that the amplitude of the movement is not of importance but for the requirement that it should be small. In order to minimize any mistake in the measurement of the period, the time for a large number of swings should be recorded. It should be noted that the pendulum needs a very low friction resistance because otherwise the pendulum will stop moving before a sufficient number of swings has been reached. Although the experiment is independent of the amplitude, the amplitude has to be constant. No friction is thus acceptable since it will influence the amplitude.
3.7. CENTRE OF GRAVITY SET-UP

- Using a balance. A glass tube with unsaturated soil must for example be placed with one edge on a fixed point and the other edge on a balance. The balance then gives the reaction force at one edge which, in combination with the total weight of the tube and the moment equilibrium, allows the determination of the centre of gravity. Because the total weight is needed, both edges can be placed on different balances. This also provides the possibility for a second check (other momentum equilibrium in case one value was incorrectly read assuming that the weight of the tube is also measured separately). The readings of the balances must then of course be set at zero after the support points are placed on the balances.

The first of both methods was first used in the context of this work. To check the accuracy of the set-up, geometrical objects with known centres of gravity were used. Due to high friction

\[ \text{Figure 3.14: Pendulum method.} \]

\[ \text{Figure 3.15: Principle sketch Centre Of Gravity set-up.} \]
unsatisfactory results were obtained concerning the accuracy. Due to a lack of better equipment this method was not used. Instead the last method above was used for the COG measurements in this work. Figure [3.15] shows an overview of the principle. For this method the accuracy of the set-up was tested using visually perfect cylinders with known centres of gravity (middle of the cylinder). The position of the cylinders was reversed to check possible irregularities in the weight distributions of these cylinders.

For the calculation the distances are needed from one edge to the support points or the distance between the support points. To reduce the time of the measurements (less effect of the tilted position of the tube) it is useful to use a fixed support system so the dimensions have to be measured very accurately only ones. The use of one fixed support system demands a fixed position during the reading. When the position is not fixed, a movement of this support system causes a mistake in the readings. The total value will namely remain the same but a different distribution of the weight will occur.

A first set-up was used as shown in figure [3.16]. Anti-slip pieces were used to avoid displacements of the set-up during the readings. However due to the irregular surface of the supporting half cylinder an incorrect distribution of the weight occurs resulting in incorrect values. This mistake was discovered by a relationship to the mistakes found with different cylinders in relation to the length of those cylinders.

A second set-up was created with a very straight steel element, supported by small anti-slip caps. The set-up was again tested with different cylinders. Because the distances cannot be measured very accurately, they can be derived assuming the set-up is working accurately and assuming the centre of gravity of a cylinder to be exactly in the middle. Using measurements of the inverse position of the cylinder the optimal dimensions can be determined. Figure [3.17] shows a principle sketch of the described set-up. The set-up is not fixed but because of the higher weight of the steel element and the anti-slip support caps, the set-up remains in a fixed position. The dimensions thus have to be measured only once. To be sure about the position it is advised to perform a simple check in the beginning and at the end of each series of tests using a cylinder to check the calibration.

The total centre of gravity is determined by

\[
COG_{total} = \frac{F_1 D_1 + F_2 D_2}{F_{total}}
\]

The reference used is the left side of the supporting bar as illustrated in the figure above. The distance from this point to the bottom of the filter is 30,85 mm. The forces \(F_1\) and \(F_2\) are read from the balances. The centre of gravity of the tubes (filter included) is calculated analogously to the total centre of gravity.

The balances were not calibrated and were of poor quality, but they were the only ones available for this work. For this research phase they were considered to be accurate enough to lead to
3.7. CENTRE OF GRAVITY SET-UP

Figure 3.16: First Centre Of Gravity set-up.

Figure 3.17: Sketch of the second and final centre of gravity set-up.
3.8 SUCTION HEAD TEST

For further development it is advised to use calibrated balances of better quality that can also be positioned horizontally. It would be even better to use in flight measurements of course. For this work the set-up was not fixed to the balances as wanted because no permission was given by the owner. For this reason the calibration had to be repeated multiple times because vibrations in the lab often caused a shift in the position. If for further development a COG set-up is made it is advisable to build one unit that is fixed to the balances.

For correct measurements the balances and supporting bar must be in a horizontal position. If not different values will be obtained when a tube is rotated due to asymmetry in the longitudinal plane. This requirement is not always perfectly fulfilled in this work which resulted in poor accuracy.

3.8 Suction head test

3.8.1 Soil preparation

For a test to determine soil suction (total and matric) - see paragraph 4.6 - cylindrical soil samples must be prepared with different water contents. In order to do this in a representative way the standardized proctor compaction test was used to prepare these samples. The sample preparation will be described in this paragraph, more information about the test itself is given in paragraph 4.6.

The soil is crushed with the mortar (figure 3.3 (a)) until a powder is obtained. A mass of 2,5 kg is appropriate to have sufficient soil to fill the proctor jar. This quantity is also adequate to allow a homogeneous mixture of the soil. First dry soil is mixed and then the previously determined desired amount of water is added slowly to the soil while it is being mixed. After all the water has been added the soil is mixed for 15 minutes. The results of these mixtures is shown in figure 3.20 for different water contents. A proctor test is carried out continuously according to ASTM D 698 with a mechanical set-up, present at the laboratory, with a light weight at low height and in a small mould (figure 3.18 right).

The soil is removed from the proctor jar with the set-up shown at the left in figure 3.19. A disk that fits into a perforated larger disk is used to push the soil out of the jar.

Two rings are then placed around the sample to hold it together as the steel tube is pushed into the soil to extract a suitable sample for the suction head test (middle figure 3.19). The steel tube has an internal diameter of 50,00 mm and a height of 100,00 mm. At one side the edge is sharpened at the outside to facilitate the penetration. The plastic rings allow movement to ensure a correct penetration of the steel tube into the soil. Without any support at all the soil might crumble and with a support system that is too stiff the soil might be pushed incorrectly into the tube destroying the original soil structure. A sufficient amount (± 50 g) of soil from
3.8. SUCTION HEAD TEST

Figure 3.18: Manual (left) and mechanical (right) proctor set-up.

Figure 3.19: Set-up to push the soil out of the proctor jar (left), set-up to push a tube into the soil resulting from the proctor test (middle) and set-up to push the soil out of the tube (right).
the sides of the large sample from the proctor jar is used to determine the water content by
drying it in the oven.

The soil is scraped off at the edges of the tubes until a flat surface is obtained. The weight is
recorded. Together with the weight of the empty tubes and the dimensions of the tube, the
resulting compaction can be calculated. The soil is then pushed out of the steel cylinder (figure
3.19 right). The results of this action is shown in figure 3.21 for different water contents. The
soil is always being handled with latex gloves. The obtained soil cylinder can now be cut into
pieces using a steel wire or a thin kitchen knife.

![Figure 3.20: Kaolin clay after mixing from left to right with increasing water content.](image)

![Figure 3.21: Soil cylinders proctor compacted with increasing water content from left to right.](image)

### 3.8.2 Testing set-up

The procedure of the test is analogous to the one described by ASTM D5298 10. The resulting
sample from the previous paragraph is cut into four pieces with two larger pieces taken from
the centre part of the sample. On top of one slice three filter papers are placed, the middle
one has a slightly smaller diameter and is the one used for the final measurements of matric
suction. The other two serve to protect the middle one from the soil. The second slice is
placed on top of the filter papers and the resulting entity is taped together in the middle with
electrical tape. This entity is placed in a glass recipient. A small pvc-o ring is placed on top of
the soil. (This ring is made out of a syringe out of which cylindrical parts are sawn from. The
edges are smoothened with a knife and sand paper.) A filter paper is placed on top of this ring and will be used for total suction measurements. The recipient is closed and completely sealed off with tape. The recipients are kept in a room where 20°C ± 1°C is maintained at all times. They are placed in an insulating box to reduce the effect of small temperature changes in the room. Latex gloves are used at all times to handle the soil. Tweezers are used to handle the filter papers.

Figure 3.22: Cross section of the soil suction test samples in the recipient.

### 3.9 Conclusion

This chapter discussed all the equipment and sample preparations used. It is important to take into account the rough dimensions of the soil recipients, the acceleration and deceleration curve of the centrifuge and inaccuracies of the simple centre of gravity set-up. The next chapter discusses the tests and their conclusions. Chapter five will give general conclusions of the research.
CHAPTER 4

Tests carried out

4.1 Introduction

In this chapter the different tests that were carried out during this research are described and the results are discussed. General conclusions of the different tests are summed up at the end of each section. Formulas that are required and that were not mentioned before are also given in the relevant sections. Alternative tests that were not carried out for practical reasons are sometimes mentioned.

The first tests determine the saturated conductivity of the filters. Next tests were carried out to determine the saturated conductivity of soils and possible effects between different testing procedures. In sections four and five the most important tests are described. These are drainage and imbibition. The suction head tests and also a drying test are mentioned at the end of this chapter. The tests were not carried out in the same order as mentioned in this paper, but have been summed up here to allow a better overview.

This chapter often refers to graphs and tables added in the appendix. It is strongly advised to read appendix [A] containing some general information about the graphs and tables given in the appendix for a better understanding of these items.
4.2 Determination of the resistance of the filter

4.2.1 Purpose

The output from the tests in the centrifuge is a weight or volume of water. Together with the other parameters of the test a conductivity of the sample can be calculated. This conductivity will be the total conductivity, which means the conductivity of the filter must be taken into account in order to calculate the conductivity of the soil. It can be stated that a thinner filter will result in a smaller effect.

4.2.2 Application

The situation of the flow in the centrifuge is similar to a vertical flow trough different horizontal layers. The relationship of such a system is given by [9]:

\[ k_t = \frac{\sum t_i}{\sum \frac{t_i}{k_i}} \]  

(4.1)

with:
- \( k_t \) = the total conductivity [m/s],
- \( t_i \) = the thickness (in the direction of the flow) of layer i [m].

In the case of the two layered system in the centrifuge with soil and filter, equation (4.1) can be transformed to

\[ k_t = \frac{t_f + t_s}{\frac{t_f}{k_f} + \frac{t_s}{k_s}} \]  

(4.2)

with:
- \( t_f \) = the thickness of the filter [m],
- \( t_s \) = the thickness of the soil [m],
- \( k_f \) = the conductivity of the filter [m/s],
- \( k_s \) = the conductivity of the soil [m/s].

The conductivity of the soil is therefore given by

\[ k_s = \frac{t_s}{\frac{t_s}{k_s} + \frac{t_f}{k_f}} \]  

(4.3)

Equation (4.2) illustrates that the influence of the conductivity of the filter \( k_f \) on the total conductivity \( k_t \) will decrease with higher values of \( k_f \), relative to the conductivity of the soil \( k_s \). Above was stated that a thinner filter will have a smaller effect on the total conductivity. This is now illustrated in equation (4.3). The lower the effect the better for the accuracy of the calculation of the conductivity of the soil. The filter should therefore be as thin as possible with a conductivity clearly higher than the conductivity of the soil but any soil transport in or
4.2. DETERMINATION OF THE RESISTANCE OF THE FILTER

through the filter must be prevented. The use of a filter paper as stated in paragraph 3.2 will be beneficial to this last property.

The conductivity of the filter can easily be measured using a static falling head test. The time [s] required for a given volume [m$^3$] of water to flow through the filter, taking into account the surface [m$^2$] of the filter, results in a value of conductivity [m/s]. The relationship is however not linear because the water level will not decrease in a linear but in a logarithmic way. The changing height of the water level results in a different pressure and a different outflow rate. The correct relationship, as inter alia given by M. Budhu, is

$$k_t = \frac{L}{t} \ln \frac{H_1 + L}{H_2 + L}$$  \hspace{1cm} (4.4)

with: \(L\) = the thickness of the filter or the thickness of the soil [m],
\(t\) = the time [s] required for the water level [m] to decrease from \(H_1\) at the start of the test to \(H_2\) at the end of the test.

This relationship is valid for a section of the filter equal to the section of the soil (and the water on top).

Centrifugation causes the simulation of a larger gravity force. This force is dependent on the rotational speed, the distance to the rotating axis and the mass (cfr. formula (3.6)). Since the conductivity is a material property, the same conductivity should be found using a centrifuge test. For a centrifuge test as stated by [11] formula (4.4) must therefore be adapted to

$$k_{cen} = \frac{L}{N t} \ln \frac{H_1 + L}{H_2 + L}$$  \hspace{1cm} (4.5)

This formula is again valid for a section of the filter (and the soil) equal to the section of the water on top.

The same reasoning as applied in formula (4.4) is also applicable here. The value of \(N\) will not be a constant nor will it change in a linear way. This reasoning is applied by [12] and changes formula (4.5) into

$$k_{cen,e} = \frac{L}{N t} \ln \frac{(H_1 + L)(2R - H_2)}{(H_2 + L)(2R - H_1)}$$  \hspace{1cm} (4.6)

with: \(R\) = the distance [m] from the rotational axis to the centre of gravity of the soil sample; in case of a conductivity test of the filter only, \(R\) equals the distance [m] from the rotational axis to the centre of the filter.

Comparing formula (4.6) to formula (2.45) in paragraph 2.6.2 indicates that the value \(N\) according to the derivation of Sharma should be equal to
4.2. DETERMINATION OF THE RESISTANCE OF THE FILTER

\[ N = (r_0 + L) \frac{\omega^2}{g} \]  \hspace{1cm} (4.7)

with: \[ \omega = 2\pi n = \] the rotational speed of the centrifuge \( \frac{\text{rad}}{\text{s}} \) and \( n = \) the number of rotations per second.

Formula (4.7) indicates the g-level is calculated at the base of the soil sample. It would be more logical to use the g-level calculated for the middle of the soil:

\[ N = (r_0 + \frac{L}{2}) \frac{\omega^2}{g} \]  \hspace{1cm} (4.8)

The notations from figure 2.15 are used. There is however some discussion (Sharma and Samarasekera, 2007) since the pressure at the top of the sample has to be correct. Therefore the g-level should be calculated in the centre of the water layer. Since the water level is not a constant an average value is taken. Sharma and Samarasekera therefore propose formula (4.9) for the calculation of N.

\[ N = (r_0 - \frac{H_1 + H_2}{4}) \frac{\omega^2}{g} \]  \hspace{1cm} (4.9)

Application of formula (4.8) or formula (4.9) will result of course in different values for total and soil conductivities for centrifuge tests on soil samples. For centrifuge tests of the filters and for static falling head tests there is no difference.

N can be considered to be a constant value for large values of R, relative to the value of L [12]. For a particular set of parameters, very representative for those of the actual tests in this work, the relationship of the ratio \( \frac{k_{cen}}{k_{cen,e}} \) as a function of the dimensionless ratio \( \frac{R}{L} \) is given in figure 4.1 for a filter test only and in figure 4.2 for a test on a soil sample. These two graphs should be interpreted differently. Because of the higher value of L in case of a test with a soil sample, a ratio of \( \frac{k_{cen}}{k_{cen,e}} \) is reached at lower values of the ratio \( \frac{R}{L} \). Values for \( \frac{R}{L} \) corresponding to the situations of the tests in this work are 50 for filter tests and 1.6 for soil tests. A ratio of \( \frac{k_{cen}}{k_{cen,e}} \) of respectively 83% and 71% corresponds with these values. This means that with formula (4.5) an important underestimation is reached in comparison to formula (4.6), for tests as well on the filter only as well as on soil samples (+ filter). Formula (4.6) should therefore be used in both cases.

In formula (4.6) the value of N is calculated as a constant value. The second part of the right term of that equation takes the variability of N into account. The constant value of N can be calculated according to formula (4.8) or by formula (4.9).
4.2. DETERMINATION OF THE RESISTANCE OF THE FILTER

Figure 4.1: Relative mistake of formula (4.5) in function of $R/L$ when only the filter is tested.

Figure 4.2: Relative mistake of formula (4.5) in function of $R/L$ when the filter and soil are tested.

4.2.3 Filters with low conductivity

The conductivity of the filter can also be determined by a centrifuge test. Due to the currently unknown influences and possible inaccuracies of tests with a centrifuge, it might seem advisable to determine the conductivity of the filter with a static falling head test. On the other hand it would seem logical to use values obtained by a centrifuge test to calculate the conductivity of the soil. For the calculation of the conductivity of the soil using a centrifuge test the conductivity of the filter must be taken into account. So it will be more representative to use the conductivity of the filter, also determined by a centrifuge test. A comparative test was carried out to find out the differences.
In order to use the most representative values, the values of the conductivity of the filters obtained with static falling head tests will be used in the calculations when a the soil is also tested using a static falling head test. When a soil is tested in the centrifuge the average values of the conductivity of the filters obtained also by centrifuge tests (at different numbers of rpm) are used. To be more exact the value of the conductivity of the filter obtained with the same number of rpm as the test on soil could be used. The difference in the results using the average value or the exact value is however completely negligible due to the very small difference. For this reason the average values of the conductivity of the filters are used for the calculations concerning centrifuge tests on soil, regardless the number of rpm.

Results are given in figure 4.3. The data and calculated values resulting in the displayed values are added in appendix F.1.1. For the calculation of the conductivities of the filters using measurements from static falling head tests formula (4.4) is used. For the calculation of the conductivities of the filters using measurements from centrifuge tests formula (4.6) is used, once in combination with formula (4.9) and once with formula (4.8).

The values obtained by the centrifuge tests are systematically higher than the ones obtained by the static falling head tests. This difference was also found in [10]. The maximum difference is 58.32 % between results obtained by centrifuge tests (and formula (4.9)) and the results from static falling head tests. The effect on the calculated conductivity of the soil (equation (4.3)) is however a lot smaller, because the value of the conductivity of the filter itself has a small effect. The difference in values of the conductivity of the soil corresponding with values of the filter conductivity from centrifuge tests and falling head tests is below 1%.

The values resulting from centrifuge tests and calculated with formula (4.6), regardless of the calculation of \( N \), are higher than those from static falling head tests calculated with formula (4.4). Three main causes have an effect on this difference.

- The first one is the fact that for static tests a drop forms at the bottom of the filter due to surface tensions (cf. paragraph 2.4.1). This drop is prevented from falling down due to the membrane that is formed. This membrane is exposed to tension forces. When the capacity is reached the membrane breaks and the drop falls down. This membrane thus causes the water in the drop to be under pressure. This causes a pressure at the outflow side resulting in a decrease of the flow. The conductivity obtained with formula (4.4) using the results from static tests is therefore lower than the real conductivity.

This effect can be tested by the same static falling head test and forcing the drops to fall sooner. Tests were carried out with filter 17 with a higher conductivity. Three static falling head tests were carried out without removing the drops and three with the drops being removed. Getting rid of the drop was done by placing a small metal bar under the filter causing the drop to fall a lot faster. Results of these tests are added in appendix F.1.1. The conductivity of the filters calculated using measurements from the tests with the drops removed early are on average 18.18 % higher than for tests with the drops still
4.2. DETERMINATION OF THE RESISTANCE OF THE FILTER

Figure 4.3: Comparison of the permeabilities of four clay filters as resulting from centrifuge tests at different numbers of rotations per minute (rpm) and from static falling head tests.

present. The actual effect will be even higher because their will always be some small drops.

This effect will be higher for filters with lower conductivity because the porosity of these filter is lower. The surface of the filter is a lot more level allowing higher attraction forces. Bigger water drops can therefore be formed causing higher pressures at the outflow side. The effect is estimated to cause 25 % lower values.

(This first one and some more causes mentioned later are an explanation for the observed difference. Since further on in this research it will only be of importance to determine the correct conductivity using centrifuge tests it is not considered important to determine the influence for all the different filters. Practically it is also difficult to completely avoid the influence of small drops making it difficult to determine the exact effect.)

- A second effect is the higher inside surface of the tube between the two screw threads (cfr. paragraph 3.2). The water level is calculated on the basis of its weight and the smaller surface measured at the top of the filter. These calculations show the water level as being higher than it actually is causing a higher value for the conductivity. This is the case for static tests and centrifuge tests. The effect is however enlarged in centrifuge tests and contributes to approximately 13 to 19 % of the difference between the two tests.

In appendix F.1.1 results are added in tables F.15 and F.16 resulting from the tests shown in figure 4.3 and for the same tests when using a diameter that is 1 mm larger
4.2. DETERMINATION OF THE RESISTANCE OF THE FILTER

This seems an appropriate assumption. Table F.17 indicates the differences expressed in percentage of the two previous tables compared to the smallest values. The differences are on average 4.7%. In table F.18 the effect of the differences of these two calculations on the difference between static and centrifuge tests are given. On average this contribution is about 16%. In table F.19 the different conductivities for static tests are mentioned using the diameter measured at the level of the thread and using a diameter that is 1 mm larger together with the difference. This difference is about 0.37%.

These results indicate the bigger effect of the incorrect inside diameter for centrifuge tests. They also explain the large impact on the differences between static and centrifuge tests displayed in figure 4.3.

- Formula (4.6) does not consider any acceleration or deceleration curve. Neglecting these moments results in a small underestimation of the conductivity of approximately one percent. In reality a lower $\omega$ is used during acceleration than considered in the calculation. This means in reality a higher value for the conductivity is obtained in comparison with formula (4.6). Tables F.12 and F.13 give results respectively for considering and for not considering the acceleration curves. The calculations were not carried out with the correct thickness’s of the filters, but still indicate the limited effect of maximally 1.45%.

This effect will be important first when the total time of the test is short and also when high numbers of rotations per minute are used. For filters with high conductivity and thus a low centrifugation time this will be important.

The mathematical model considers the acceleration and deceleration curves cf. formula (2.46).

Minor effects are the following:

- The curvature of the water level cf. paragraph 3.6.1. In the calculations the average height corresponding with the actual volume of water on top is used. This causes an overestimation of the conductivity.

- Some of the tubes are damaged at the filter side exposing some of the side surface of the filter. The effect of this can be neglected for further calculations since the effect of the conductivity of the filter itself is very limited.

- During centrifugation the water exercises a force on the tube. Possible openings at the interface of filter and glass might be enlarged causing a higher conductivity for the centrifuge tests.

- The time required to handle the samples and to carry out the measurements has a small influence on the readings.
4.2. DETERMINATION OF THE RESISTANCE OF THE FILTER

- The number of rpm is not always constant after it reached the set number.

- There is often a small imbalance that does not cause heavy vibrations or an automatic shut-down of the centrifuge but causes an unequal oscillation of the centre of rotation. Different amplitudes of this oscillation for different numbers of rpm can cause a different effect on the test that is carried out. This explains different results of the conductivity for the same filter for different numbers of rpm. The centrifuge can have more than one natural frequency explaining fluctuations of the effect for different rpm.

The difference of the inside diameter varies for each tube. This has different effects on the values for the water height and therefore different effects on the calculated values. If a soil is tested for its saturated conductivity the same value should be obtained for each test since conductivity is a material property. Because the incorrect water heights will be different for each tube this will explain different values of conductivity for the tested soils.

Regardless of the formula for \( N \), the mathematical model considers the acceleration and deceleration curves compared to formula (4.6) of Sharma. Not considering this effect causes a small underestimation of approximately one percent as mentioned before. The results obtained with the model coincide very well since only this one effect is different from the calculations. The model as well as formula (4.6) do not consider the curvature of the water level as it are 1D models. No consideration of the curvature of the water level causes an overestimation of the conductivity.

Formulas (4.8) and (4.9) are both approximations. Considering the magnitude of the two main effects (the underestimation for static tests because of drops at the bottom and the overestimation for centrifuge tests because of the enlarged effect of an incorrect inside diameter) the results obtained with formula (4.8) seem to be the best approximation.

Static falling head tests carried out with a water table at outflow side would give more accurate results and would allow a better determination of the effect of the drop at the bottom of the filter. This type of test was not carried out for the determination of the conductivity of the filters because in actual practice it was very difficult to execute this test accurately since the filter itself is very thin.

4.2.4 Filters with high conductivity

The above application for centrifuge tests is only valid for filters with low conductivities. (The first part of the application concerning the flow through a layered system is of course valid for all filters). For filters with a higher conductivity (e.g. \( 1.10^{-4} \)) a centrifuge test is physically impossible because the flow through the filter happens too fast to make accurate measurements possible. With these filters a static falling head test or a constant head test are the only two options for the determination of the conductivity of the filter. A falling head test considers the decrease in height of a water table on top of the filter in a given amount of time. Formula (4.4)
4.2. DETERMINATION OF THE RESISTANCE OF THE FILTER

is then applicable. A constant head test considers the amount of outflow for a given time at constant head. The law of Darcy is then to be applied.

With the filters with high conductivities both tests were carried out. The constant head test however was more difficult to execute without a complicated set-up and so it gives less satisfactory results. The falling head test on the other hand did give satisfactory results. The time for the water level to go from one height to another was measured with a chronometer. Fifteen tests were carried out. The two highest and the two lowest results were ignored. An average of the remaining eleven values was taken. The difference between the maximum and the minimum value (of the eleven remaining values) in relation to the resulting average is ± 1%. The resulting average is therefore considered to be sufficiently accurate.

As mentioned in paragraph 3.2, the inside surface of the tubes is not always a constant. Using the decrease in height of the water table thus results in a small error since the surface of the filter is smaller and the ratio is unknown. The values obtained are slightly lower than the real ones.

Filters with a conductivity of approximately $1.10^{-5} \frac{m}{s}$ were used in this work. The conductivity of these filters were also determined using static tests. As the conductivity was lower it was possible to perform accurate measurements. Only two test were carried out and an average value was taken because the values were very close to each other.

Data, calculated values and results of these different filters with a higher conductivity are added in appendix F.1.2.

4.2.5 Conclusions

When the conductivity of the filters is higher than the conductivity of the soil tested the effect of the filter is very limited. As a considerably different value for the conductivity of the filter has only a very limited effect on the calculated conductivity of the soil, the determination of correct values with good accuracy is possible and advised. For centrifuge tests the acceleration and deceleration curves must be considered to avoid an underestimation of the conductivity. This is mainly important for short tests and high numbers of rpm. Using the correct dimensions of the tubes is very important for the accuracy for centrifuge tests because for these tests the effects are enlarged. For static falling head tests the effect of drops at the bottom of the filter is very important because these drops cause a pressure at the outflow side of the filter and slow down the flow.
4.3 Saturated flow

4.3.1 Kaolin clay

Purpose

A conductivity test in saturated conditions gives the point of maximum (effective) saturation on the drainage retention curve of the soil. The conductivity of the soil can be determined by a normal falling head test or by a centrifuge test. The centrifuge test is a lot faster and is therefore advised. However both tests are initially carried out to compare the results.

Procedure

The mass required to place on top of the soil is determined by the following relationship.

\[ #\text{kg} = \frac{\text{desirable pre-consolidation stress [Pa]} \cdot \text{inside surface of the tube [m}^2\text{]}}{\text{the gravity constant } g \text{ equal to } 9,81 \frac{\text{m}}{\text{s}^2}} \]  

(4.10)

Approximately this results in 1 kg required per 25 kPa that must be simulated.

Because consolidation outside and inside the centrifuge might lead to differences, comparative tests between samples pre-consolidated with weights and pre-consolidated in the centrifuge were also carried out. This was done for static falling head tests and centrifuge tests resulting in four different tests. For the pre-consolidation with weights the same force as created in the centrifuge was simulated. The weights are placed on the samples in saturated conditions (head at the top and at the bottom of the samples) for at least 24 hours.

The testing set-up for static pre-consolidation is described in paragraph 3.5.

The water content at the start of a static consolidation test is known by the preparation of the soil. Using the difference in weight before and after the consolidation the water content at the start of possible further tests is known.

Results

Results of the four tests mentioned are shown in the figures below. Figure 4.4 shows the results where the g-level N is calculated at the middle of the soil according to formula (4.8) for the centrifuge tests. Figure 4.5 shows the results where the g-level N is calculated at the middle of the water according to formula (4.9) for the centrifuge tests. The stress level is dependent on the soil height, the height of the water level and the boundary condition. For the tests carried out for this comparison, stress levels around 45 kPa correspond (± 5 kPa). This difference in stress level has a small impact on the conductivity (cfr. table 2.6).
Data and calculated values that result in the displayed values in figures 4.4 and 4.5 are given in appendix F.2.

**Figure 4.4:** Conductivity of kaolin clay for different types of tests with g-level N calculated at the middle of the soil.

**Figure 4.5:** Conductivity of kaolin clay for different types of tests with g-level N calculated at the middle of the water.

The first observation is that the theoretical value calculated according to paragraph 2.7.1 deviates a lot from the obtained values in this work. This reference value is therefore no longer considered.

It can be remembered that conductivity is a material property and that therefore the conductivity should be the same for each test and all samples. Differences in results for one type of test are mainly caused by different effects caused by the unknown real inside diameter of each tube.
If $N$ is calculated for the middle of the water on top of the soil (formula (4.9)) the results obtained are more logical concerning the differences between static falling head tests and centrifuge tests for the two types of pre-consolidation, i.e. higher results for centrifuge tests. The difference between these values is however larger than for the results obtained with formula (4.8). For this last formula the results obtained for samples pre-consolidated with weights are not logical if higher results are expected for the centrifuge tests. The differences between the static falling head tests and centrifuge tests for samples pre-consolidated inside the centrifuge are smaller and more logical considering the estimated mistakes for both tests. These are an underestimation for static falling head tests of approximately 25 % and an overestimation for centrifuge tests of approximately 4,7 % (cf. paragraph 4.2.3). It can be remembered that formula (4.8) and (4.9) are both approximations. The correct approximation is probably somewhere in between considering the contradicting observations. Because more samples pre-consolidated in the centrifuge were tested, because the results obtained with formula (4.8) coincide better with the expected values considering the two main effects (drop at the bottom during static tests and enlarged effect of an incorrect diameter for centrifuge tests) and because the latter was also observed for tests on filters, formula (4.8) where $N$ is calculated at the middle of the soil, is expected to give the best approximation. For all saturated conductivity tests with the centrifuge carried out later in this work the g-level $N$ is calculated for the middle of the soil but this will not be mentioned explicitly.

For the samples pre-consolidated inside the centrifuge the calculated values (using formula (4.6)) obtained using measurements of centrifuge tests are always higher than those resulting from measurements of static falling head tests (with formula (4.4)). For this kaolin clay with a low conductivity a long time was required for static tests but also for centrifuge tests. The effect of the incorrect $\omega$ in formula (4.6) is therefore very small. The effect of the drop at the bottom of the filter during static tests and the enlarged effect of the incorrect inside diameter for centrifuge tests are the two important effects that cause the resulting difference in values. These differences are analogue to the differences observed in figure 4.3 shown in paragraph 4.2.2.

For the determination of the retention curves it is logical to use the values obtained by the centrifuge test since they will be more representative in relation to any other values of the retention curve obtained by other centrifuge tests.

The mathematical model considers the acceleration and deceleration curves. Only the incorrect diameter has an important effect for centrifuge tests and causes an incorrect output. The real values are somewhere in between the results obtained with static falling head tests and those with centrifuge tests. A boundary of the inaccuracy can be obtained by recalculating the same values with different diameters. It can be remembered that for formula (4.6) and without consideration of acceleration and deceleration curves this effect varies around 16 percent. The values added in figures 4.4 and 4.5 obtained with the mathematical model are average values for two static falling head test and eight centrifuge tests. It is therefore difficult to compare
results but it is clear that the model obtains similar results.

The calculation of the conductivity of the clay for static falling head tests was carried out with the values of the conductivity of the filter obtained by the same test. For the calculation of the conductivity of the clay for centrifuge tests the values were used of the conductivity of the filter also obtained by centrifuge tests were used. This was done in order to work as representatively as possible, although the effect of different values for the conductivity of the filters on the resulting values of the conductivity of the soil are very low, as mentioned before.

### 4.3.2 Mol sand

Testing the conductivity of Mol sand in the centrifuge is only possible at lower speeds (300 rpm). At higher speeds the flow is too fast. If four samples are tested at the same time the accuracy is low, because the time elapsing between preparation and measurements of the first and the last sample causes important inaccuracies. The time the samples are subjected to gravitational forces outside the centrifuge should then be taken into account as well as the acceleration and deceleration in the centrifuge. These factors become important because of the high conductivity. Tests were carried out with one sample in the centrifuge but no accurate measurements were obtained. Static falling head tests are thus more suitable to test soils with a (relatively) high conductivity such as Mol sand. Constant head tests are a possibility too but were not carried out in this study due to less accurate measurements, analogously to paragraph 4.2.4.

It is however possible to pre-consolidate samples briefly inside the centrifuge at low speeds (300 rpm) without taking measurements. Water must then be added at least every five minutes in order to keep the sample saturated.

Note that a centrifuge test is an option when using a centrifuge capable of performing in-flight measurements.

### Results

Static tests were carried out using tubes 7 and 8 (dimensions see table E.3). The procedure was the same as for the filters themselves. The time was measured with a chronometer for the water level to go from one height to another. Fifteen tests were carried out. The two highest and the two lowest were ignored. An average of the remaining eleven values was taken.

The difference between the maximum and minimum values (of the eleven remaining values) is under 1%. The obtained average is therefore considered accurate enough. Data and calculated values of the measurements are added in appendix F.3. The obtained average conductivity of the sand for the tests with tube 7 is $0.99 \times 10^{-4}$ m/s and for the tests with tube 8 it is $1.05 \times 10^{-4}$ m/s. Important is the criterion to use a filter with higher conductivity than the conductivity of the soil. For number 7 this criterion is fulfilled. Tube number 8 has however a filter with a lower
4.3. SATURATED FLOW

conductivity than the conductivity of the sand and should therefore not be used for future tests with pure Mol sand because the influence of the filter is too high. The value of the saturated conductivity of the sand obtained with tube 7 is also considered to be more accurate because of the smaller influence of the filter in the calculation. This value corresponds very well compared to literature, see paragraph 2.7.2 and appendix C.

Note that the obtained values are lower than they really are because of the drops forming at the bottom of the filter. A static falling head test with a water table at outflow side can prevent this error but no accurate set-up was available. Since pure Mol sand will not give satisfactory results further in this research it is not considered of importance to test this characteristic in more detail.

4.3.3 Mixture of Mol sand and kaolin clay

The mixtures used for this work have a conductivity that is sufficiently low to use static falling head tests as well as centrifuge tests in order to determine the saturated conductivity. The pre-consolidation with weights can also be carried out in the same conditions. Analogue to the reasoning mentioned in paragraph 4.2.2 it is more representative for the calculations to use values reached by centrifuge tests.

The mixture used in this work consist of 90% Mol sand and 10% kaolin clay. The sample preparation is described in paragraph 3.4.5.

Water is added on top of the sample in static conditions. When the water front reached the bottom of the sample more water is added and a centrifuge test is started.

Results

The samples were pre-consolidated in dry conditions at 45 kPa. The soil height remained constant during the tests. The saturated conductivity obtained by a centrifuge test is $5,87 \times 10^{-6}$ m/s and when using a static falling head test it is $8,45 \times 10^{-6}$ m/s. Again a higher value is obtained using the centrifuge for the same reasons as mentioned in paragraphs 4.2, 4.3.1 and 4.3.2.

It should be mentioned that the conductivity depends on the pre-consolidation load. For a drainage test (cf. later) a pre-consolidation of 100 kPa was applied. The saturated conductivity in that case was almost half the value of a sample pre-consolidated at 45 kPa, namely $2,54 \times 10^{-6}$ m/s (average value). Data and calculated values resulting in these values of saturated conductivity are added in appendix F.4.

Adding 10% of kaolin clay to Mol sand thus decreases the conductivity approximately 10 times for a pre-consolidation load of 45 kPa and even twenty times for a pre-consolidation load of 100 kPa.
4.3.4 Conclusions

The main conclusions concerning saturated flow are the elements that were found to have an important effect on the calculated values of the saturated conductivity. The two main elements are the dimensions of the tubes and the formation of drops at the bottom of the filters during static tests. For short tests the acceleration and deceleration curves are important too. The latter and the effect of the dimensions of the tubes are of importance for imbibition and drainage centrifuge tests. The drops at the bottom of the filter are only of importance during static tests.

In contradiction to the suggestion of Sharma and Samarasekera to calculate the g-level $N$ at the centre of the water on top of the soil, better results are obtained in this work with the calculation of the g-level $N$ at the middle of the soil.

The mathematical model simulates saturated flow accurately with the obtained measurements.

4.4 Imbibition

4.4.1 Kaolin clay

Possible tests

For practical applications only a limited part of the retention curve is necessary. From a research approach it is of course interesting to accurately obtain the complete retention curve. The model can also be optimized better when measurements for all saturation degrees are obtained. For this reason an imbibition test starting from a dry sample is an evident choice. The sample preparation can then be done as mentioned in paragraph 3.4.1. The test can be carried out by adding a water table on top of the soil. Due to the low conductivity of the kaolin clay the imbibition occurs very slowly, despite the large capillary forces. Speeding the experiment in the centrifuge is possible and for accurate measurements also required.

Later will be mentioned that the imbibition of a dry clay causes major volume changes of this clay (shrinkage and swelling). To avoid or reduce this problem the test described above could be carried out on a sample with a small initial water content. To prepare a clay sample in a homogeneous way with a small water content is not possible in the following way. When water is added to dry clay (this looks like a powder) small chunks will be formed binding the small amount of water to some of the clay. The rest of the clay will remain a powder. When more water is added this will cause the formation of larger chunks and eventually a mixture of large and small chunks with a variety of sizes. Adding even more water will allow the formation of a slurry, but then already a water content of 90% is required. The mixture of chunks and powder will not allow a homogeneous sample preparation. Also when this mixture would be moistened preferential paths will originate. This can not be modelled and will differ a lot between different samples. This test is therefore not carried out.
Another possibility to obtain a homogeneous sample with low water content would be to drain the sample. After drainage an imbibition test can then be started. This could work in theory but practically it was not possible in this work because the capillary forces in clay are too high and could not be overcome by the imposed centrifugal forces (cfr. paragraph 4.5.1).

In order to obtain a homogeneous sample with low water content it could be a possibility to dry a sample that was homogeneously made with a higher water content. Drying of a sample was carried out but caused a lot of shrinkage at the sides of the soil. An opening originated between the glass tubes and the soil. It is obvious that adding a water table on top of the soil is useless in order to obtain the desired measurements. Imbibition by providing water at the bottom of the sample would be less problematic. The flow occurs due to the high capillary forces that are possibly be counteracted by centrifuge forces. An opening between the inside surface of the tubes and the soil would than not be a problem. The difficulty would be the measurements of the dimensions of the soil sample. In order to model the flow accurately the correct dimensions must be used. These will be more difficult to measure, as will they change in time. When moistened the soil structure will namely change. This type of flow is also different from in situ flow.

**Tests carried out**

Some possible tests were mentioned in the previous paragraph. The first imbibition tests that were carried out were centrifuge tests with a water table on top of the soil. The tests are started with a dry sample. The sample preparation was mentioned before. A water table is added on top of the soil. One test with four samples at 1000 rpm and one test at 500 rpm, with results of three samples, were carried out. (During the test at 500 rpm an irregularity occurred with one of the samples.)

A colouring liquid, Rhodamine, was used during the test at 500 rpm on sample 2 to obtain a more clear view of the movement of the water front. Measurements of this water front might provide additional useful data. A solution of 20 kg/\text{litre} was used to reduce the influence on the conductivity. The density of the solution was checked with a graduated cylinder and was 1 kg/\text{litre}. No influence on the conductivity was therefore assumed. The use of this colouring liquid however did not work. The clay filtered out the colouring particles causing no colouring inside the sample as desired. Also the outflow water at the end of the test was not coloured indicating the particles had been filtered out of the water. This also indicates that the use of this liquid might have had an influence by clogging the top layer of the soil. This should be considered when interpreting the results. No appendices were added concerning the Rhodamine since it was not used after this first negative test. The water front was also slightly seen without a colouring liquid allowing some rough measurements of the movement of the water front.
Procedure

To reduce the time needed for measurements and therefore reducing the influence of the time the samples are outside of the centrifuge, the tests are preferentially carried out with as little samples as possible. One sample together with a dead weight in the centrifuge is the best possibility in this point of view. To test more samples in the first phase of the research it is considered acceptable to test also four or two samples at once. Before the first test the mistake made was estimated to be small considering the low conductivity and short influencing time in relation to the testing time.

When water is added there occurs an immediate swelling of about 1 mm. Also the water front is immediately visible at the sides of the tubes and varies from three till five millimetres before the start of the test inside the centrifuge. It is not sure if this water movement happens faster at the sides of the tubes but considering the fine particles of the clay it is not assumed. The initial position of the water front should definitely be taken in to account in the modelling. When only one sample would be used these values would be smaller but they would still be important enough to consider.

Again a compromise must be found for the amount of interruptions. To reduce the influence of measurements themselves and the time that the samples are outside the centrifuge (although these moments can be considered in the model), it is wanted to take as few readings as possible. In order to be able to better approximate the curves, more readings are desirable. Also a minimum time in the centrifuge is required for acceleration and deceleration. The dimensions of the tubes limit the amount of water on top of the soil. Therefore the time in between two measurements is also limited in order to be able to refill the water on top of the soil. Otherwise there will be a different type of flow, undesired for this test.

After the samples are removed from the centrifuge, the following procedure is followed for each sample. The weight of the outflow glass is measured. Then the height above the soil is measured. This is done always at the same side of the tube to avoid fluctuations of the values due to irregularities in the soil surface and in a lesser amount of the top surface of the tube.

Then the water on top of the soil is removed using paper to absorb the water. The final amount of water is carefully removed with a tip of paper just above the soil to allow capillary forces to attract the free water on top of the soil. The accuracy of this method is the same as the accuracy of the balance and therefore sufficient. This is illustrated at the end of the imbibition tests were the outflow, the soil height and the weights of the tubes are constant.

After the water on top of the soil was removed and the weight of the tube is measured, the reaction forces $F_1$ and $F_2$ from the COG set-up are taken. After each series of measurements the COG set-up is checked using a perfect cylinder (see paragraph 3.7).

To finish the measurements a new water table is provided on top of the sample and the new
weight of the tube is measured to determine the amount. Now the tube is placed back in to the larger recipient and it is ready to be placed in the centrifuge for the next part of the test.

The time the measurements occupy is approximately five minutes. This period of time is not modelled. Only the time when there is still water on top of the sample, in the beginning and at the end of each test, has a small influence because at those times there will be flow caused by the gravitational force. The period of time when the water on top of the soil is removed, has a much smaller influence since there is no gradient any more. Evaporation is considered to be of the same magnitude outside as inside the centrifuge. Approximately 0.01 g (the accuracy of the balances) evaporates every 10 - 15 minutes.

Results

Results of the tests are added in appendix G.1.

It can be noted that the cog of the water appears (cfr. figure G.6) to be located below the middle of the soil. A correct interpretation should however be made. The values are scaled to the first position of the cog of the water. The soil height is at that moment larger than in the end. Considering a lower soil height at the end of the test makes the results to be expected. There is also a minor effect caused by the filter. Since the conductivity of the filter is always taken larger than the conductivity of the tested soil, the porosity of the filter can be assumed to be larger than the porosity of the soil. Since the water in the soil and the filter is considered and the filter contains more water, the position of the centre of gravity is expected to be below half of the initial position. This will however have a very small contribution compared to the first remark about the change in soil height and also compared to the next. Another important item to be aware of is the reference value. This is the value obtained from the first reading. The water is then not just at the top of the soil but already infiltrated the soil. This makes the value of scaled position of the cog of the water below 0.5 at the end of the test to be expected.

When the values of the cog of the water at the end of the test are compared with the middle of the soil height at the end of the test, it is seen that the differences are between 0.5 and 1.5 mm. When these values are compared only the different porosity of the filter might have an influence. The reason for these differences is caused by the in-homogeneously shrinking, swelling and compaction of the soil during the test. Figure G.7 illustrates the horizontal cracks that formed progressively during the test. Because the flow is so slow the water on top of the soil acts like a weight applying a force on this soil. This causes compression and consolidation. When the centrifuge is stopped this is equal to an unloading of the soil causing tensile stresses. Soil can hardly bare tensile stress causing it to break and cracks are then formed. When the influence of this changing soil structure is dominant the values of the scaled position of the cog will fluctuate around 0.5. This is assumed considering the results of the tests at 1000 rpm and at 500 rpm.

In essence there is only one important difference between the test at 1000 rpm and the test
at 500 rpm. The changes in soil height are smaller but still considerable and they are located more at the top of the soil.

Accuracy of the cog measurements is between 0.34 and 1.95 mm (cfr. table G.1 and G.3). This inaccuracy is mainly caused by the varying inside diameter of the tubes (cfr. paragraph 3.2). In lesser amount it is caused by the relatively low accuracy of the cog set-up itself (cfr. paragraph 3.7) and by the inhomogeneities of the cracks.

The saturation degree at the end of the test is above 90% for all samples (cfr. table G.2). This indicated the complete imbibition retention curve can be found. The difference between 100% saturation and the obtained values is caused by entrapment of air bubbles and air present in the soil structure itself as it was also seen on figure 2.8. The varying inside diameter of the tubes has also here an important influence on the values.

All the measurements for the imbibition tests can be taken accurately. The graphs of the outflow curves and the increasing weight of the tubes are smooth. The only big problem is the changing structure of the soil during the test. If this would show a clear trend it could more or less be taken into account. However it happens in a very irregular way. This causes poor accuracy of the calculated values needed in the model. The most important part of the test is the first one but this is also the part where the changes in soil height are the largest. This test procedure is therefore far from ideal.

Because of the unstable soil structure no other imbibition tests were carried out on clay samples and priority was given to imbibition tests on sand and mixtures.

The tests carried out and discussed above were the ones that were practically possible with the equipment available for this research. With a centrifuge capable of performing in-flight measurements an accurate imbibition test will be possible starting from a dry sample. When a dry sample is pre-consolidated and no interruptions are required for measurements, the soil will remain compressed and only very small changes in soil height can be expected.

### 4.4.2 Mol sand

Imbibition of a Mol sand with a water table on top of the soil happens to fast in order to perform accurate measurements. Even imbibition of Mol sand with an initial water content (lower capillary forces) happens to fast and is coupled with air bubble formation (cfr. later). This is at static conditions. Centrifuge tests are therefore definitely impossible.

A possibility to perform measurement at this fast rate could be optimal imaging. Filming a video of the sample on a balance together with a measuring unit, e.g. a calliper, could provide rough measurements. The weight added each time could be read from the balance. The movement of the water front and the level of the water on top of the soil can roughly be read on of the measuring unit. These distances however will not be accurate due to the
incorrect image of the video material. Not all values can be read horizontally. To do so two cameras are required that can move vertically and level with the movement of the water levels. The test was carried out using one camera in a fixed position, but no useful data were obtained.

In a centrifuge test with water supply at the top of the soil the capillary forces enforce the enlarged gravitational force opposed by the centrifuge. If this situation would cause the water front to move too fast in order carry out measurements accurately, water could be provided at the bottom of the sample. In this case the capillary forces cause a flow upwards and the centrifugal forces would slow these down, resulting in a lower speed. It was not possible within the boundaries of this work to test this set-up in an accurate way. This type of flow would also be different from in situ flow.

A static test with water supply at the bottom was carried out. The water level is kept (approximately) at the top of the filter. The water now has to flow in the opposite direction of the gravitational force causing a flow that is slower than with a water supply at the top. The inflow of water still happened too fast making it impossible taking accurate readings. Furthermore the sample needs to be in a horizontal position for the cog measurements. For a dry sand sample the top of the sand will shift when placed in this horizontal position causing inaccurate measurements.

4.4.3 Mixture of Mol sand and kaolin clay

Imbibition with water on top of a dry mixture happens too fast for tests inside the centrifuge without in-flight measurements. Providing a water table at the bottom might be possible in the centrifuge but is as mentioned not practically possible in this work with accurate results. The test should for that reason also be carried out with in-flight measurements in order to obtain accurate results. An attempt could be made with a static test and video analyses as described in the previous paragraph but accurate equipment is then required.

Imbibition of a drained sample with mass water content around 5% also happens too fast for centrifuge tests. It will not be possible to perform tests with video analyses since the soil to start the test with has already a dark colour. A colouring liquid with no effect on the soil is then required (if available).

A static imbibition test on a drained sample is another possibility. A water table is then provided on top of the soil for 30 or 60 seconds and then removed again. Centre of gravity measurements are then taken at each step to check the movement of the water front. It is obvious that the accuracy of this test is doubtful. One more important problem with this test is the movement of air in the soil when a water table is provided. The intrusion of water in the soil requires a removal of air from the soil in order to have an equilibrium in pressures. Visual inspection showed that air bubbles penetrate the top of the immediately saturated soil. (Figure 4.6 illustrates air bubbles that were formed during imbibition of a drained sand sample with a water table on top of the soil. The same observation was made for the mixtures, although the
impression was that less but larger bubbles were formed.) Apparently the resistance the air
encounters in that procedure is smaller than the resistance to be removed through the filter,
the filter paper and the bottom part of the soil that was exposed to the largest forces. As the
imbibition happens fast, quite large air bubbles get entrapped. These observations indicate
a rupture of the soil structure and an inhomogeneous density throughout the sample height.
A filter with larger porosity did not resolve the problem. The resistance of the necessary
(to prevent loss of soil particles during the drainage process) filter paper and of the bottom
part of the soil was still too large. A set-up where pressure is applied on top of the water
table combined with a spillway to remove the water (subject to the same pressure) might be a
solution. Using the centrifuge to apply this pressure is impossible since the speed of imbibition
and formation of air bubbles is too fast. Filling the sample into its recipient and putting it into
the centrifuge and speeding up all takes time, and by this time air bubbles will already have
penetrated the soil.

![Figure 4.6: Formation of air bubbles during imbibition of a drained Mol sand sample (left) and of a
drained mixture of Mol sand and kaolin clay sample (right) with water on top of the soil.](image)

There are several causes why with imbibition starting from a dry sample no air bubbles are
formed compared to imbibition on a sample with an initial water content, when air bubbles are
formed. A different soil structure of the clay due to the wetting-draining and loading-unloading
cycles is probably not a large problem. The difference between the initial dry flaky structure
and the more layered structure after one imbibition and draining process will have an impact.
The initial amount of water that is present and especially the high water content of the clay
will also have an important impact. With the dry mixture the resistance for air to leave the
sample is low due to the flaky clay structure and the absence of water. Uninterrupted flow
paths are available for the air. For the drained sample with an initial water content this will
no longer be the case or at least in an insufficient measure. The clay can be assumed saturated
causing impermeable layers for air flow but not for the flow of water. When moistened the
air inside is subjected to an increasing pressure. Since the integral structure will aim at an
equilibrium the abundance of air tries to leave the soil and will chose the path with the lowest
resistance. This is the shortest path through the soil for imbibition with a water table on top
of the soil. In the situation with a water supply from the bottom of the sample (for a sample with an initial water content) the formation of air bubbles is also to be expected. The path with the lowest resistance is then less obvious. Larger pressures will be required for bubbles to leave the sample through the top of the soil.

To be representative it is important to consider the situation in reality. If air bubbles will also be created there, it is not important to try to avoid air bubbles in the tested samples. It will however be important to prevent a rupture of the soil by the air bubbles since in situ, at a given depth, this will also be prevented by the load on top of the soil. Considering the reasoning to be representative, one might question the practical reason to test imbibition starting from an oven dried sample. This will never simulate a practical situation. Only for soils with a high conductivity with application in infiltration areas, a very dry soil might be considered after a long warm and dry period. If the flow is too different from the flow through a sample with initial water content it is also impossible to extrapolate results. Only imbibition tests on samples with an initial water content are then of interest. A set-up to prevent air bubbles from destroying the sample is then required.

Note that rupture of the soil by air bubbles is representative for the top part of in situ soil.

Imbibition from the bottom side of the sample requires a new centrifuge test set-up. At outflow side of the sample a water level should be provided. This water level will rise due to capillary forces but will be countered due to the centrifugal forces. Using capillary speed and range known through static calibration tests provides a method to model the results. This set-up however is not possible with the centrifuge used for this work since in-flight measurements would be required as well as more set-up material.

Another option is to carry out a static test (as carried out on Mol sand). The sample is placed in a large basin with (approximately) constant water height for some time. The movement of the water into the soil can be recorded using centre of gravity measurements. The more measurements taken, the larger the inaccuracy will be. The movement of the water in opposite direction to the gravity force will slow down the process which improves the accuracy. When starting from a dry sample no air bubbles are expected. The top of the soil of this pre-consolidated mixture remains fixed when placed in a horizontal position. The problem with this test is the difference with in situ flow. Imbibition with a water table on top of the soil is expected to differ from imbibition with a water supply at the bottom of the soil due to a different meniscus formation and effect of the two phased medium. More air is expected to get enclosed during imbibition with water from the top than from the bottom. The structural changes of the clay when moistened are expected to be low because of the low percentage of clay in the mixture and the more solid structure of the Mol sand. This static test with water supply from the bottom was carried out anyhow and good results were obtained. The position of the centre of gravity of the water in function of time, the cumulative inflow amount of water in function of time and other information about the test is added in appendix G.2. The obtained saturation degree was 85.56 % corresponding with a volumetric water content of 33.98 % or a
mass water content of 21.27 %. The complete imbibition curve can be obtained by this test. The saturated conductivity of this mixture, pre-consolidated at 75 kPa was also determined and is equal to $3.70 \times 10^{-6} \text{ m/s}$. This is a logical result compared to the results from paragraph 4.3.3.

### 4.4.4 Conclusions

The best way to carry out imbibition tests would be to start from a dry sample that is pre-loaded and to apply a water table on top of the soil to represent in situ flow. The centre of gravity of the water moving in the soil must be measured accurately. No static set-up was found that could make this possible. Centrifuge tests without in-flight measurements neither gave satisfactory results because of the interruptions required for the cog measurements. Only for practical reasons a set-up with continuous measurements is thus required. A centrifuge could provide this. High speeds are no necessity since imbibition happens relatively fast.

Different types of tests were carried out to reach the most important conclusion mentioned in the previous paragraph, but also other conclusions were reached. If a soil is tested with an initial water content air bubbles will originate in the soil. At the top of the soil they can cause a rupture of the soil when moving upwards. In order to test imbibition to larger depths longer samples should be tested or a porous weight should be added on top of the soil to get a better simulation of the in situ situation at larger depth. The situation where the soil is ruptured remains also important as it is representative.

For infiltration areas soils with conductivities from two to eight $\text{cm/s}$ or 5.56$\times 10^{-6}$ to 2.22$\times 10^{-5}$ $\text{m/s}$ are common. These conductivities can all be simulated using mixtures of sand and clay with a different ratio or pre-consolidation load. The advantage of these mixtures is that they have a solid sandy structure barely allowing changes in soil length. The other advantage is that these mixtures can be drained (crf. next section) allowing tests on homogeneous samples with an initial water content. In this test air bubbles will be formed but figure 4.6 indicates that this is more limited for mixture samples than for samples with pure sand. The clay present in the mixture will cause some cohesion in the structure and will not allow air bubbles to easily destroy the sample’s structure.

The main practical application for landfills is also imbibition, but soils with lower conductivities are used in those cases. Imbibition can be tested in the same way as explained for the mixtures. Laboratory tests on initially dry samples can be carried out. Homogeneous in situ soil samples with an initial water content that can be extracted from the soil without sample disturbance can also be tested. This type of sample might also be produced in laboratory conditions but might take long equilibrium times concerning the water content.

Imbibition tests on soils that do not have a conductivity that is too high ($> 1.10^{-5} \text{ m/s}$) to test (because the flow is simply too fast) can all be tested with centrifuge tests with in-flight measurements. The mathematical model can be validated by testing mixtures (of for example
Mol sand and kaolin clay) with a wide range of properties (mainly initial water content and pre-consolidation load). Soils with low conductivities ($< 1.10^{-7} \text{ m/s}$) can easily be tested starting from a dry sample. For samples of these soils with an initial water content in situ soil samples can be used or laboratory samples when they are prepared homogeneously and represent the same in situ densities and structures. Proctor compaction for example is only sufficient for a small range of water contents (crf. paragraph 4.6). In order to work with representative samples a soil with cracks might for example be required.

### 4.5 Drainage

#### 4.5.1 Kaolin clay

To determine the drainage retention curve an attempt has been made to drain a sample. As the intention was inter alia the application on soils with low conductivities a first test was carried out on kaolin clay samples.

**Procedure**

The sample preparation is described in paragraph 3.4.2. The samples were pre-consolidated at 1000 rpm (this is the maximum speed at which drainage tests will be carried out afterwards) in saturated conditions (saturated flow) for at least four hours. After this period of time the consolidation is considered to be complete. The water on top of the soil is then removed. The drainage test is then started first with a saturated sample (effective saturation degree equal to 100%). A sample is placed in the centrifuge for a number of time intervals and at a given number of rotations per minute. The time intervals are often quadratic as the most important outflow and height changes occur in the beginning of the test. The height of the soil and the amount of outflow is measured for each time step.

Tests were carried out at 1000 rpm and at the combination of 800 rpm followed by an increase to 1000 rpm. Fours samples were tested in each case. For the first test at 1000 rpm no measurements for the centre of gravity were taken because the set-up was not ready at that time.

**Results**

Graphs of the results are added in appendix H.1.

An important decrease in height occurred during drainage. An important amount of the outflow water is thus the result of consolidation and not of drainage. In order to see the amount of drainage two graphs can be made. The first one represents the volume decrease of the sample. The second graph represents the outflow. When the outflow is higher than the corresponding decrease in height there is drainage. The saturation degree is then decreasing. When the
4.5. DRAINAGE

A decrease in height on the other hand represents the largest volume, the saturation degree is increasing. A graph of the (effective) saturation degree will show this difference. This type of graph was added in appendix H.1.

For the first test at 1000 rpm sample number 5 gives a slightly larger outflow value and also a lower effective saturation degree then the other three samples. The reason is unclear but probably an irregularity in the sample was present causing this difference in results.

Considering the results of sample 5 from this first test to be aberrant, the minimal effective saturation degree obtained was approximately 93%. For the second test when first 800 rpm and later 1000 rpm were run a saturation degree of only 98% is achieved.

Centre of gravity measurements were as mentioned only carried out for the second test and are displayed in figure H.9. First there is a small decrease of the cog of the water that can be explained by the compaction. The second part of the cog curve shows an increase which can not be explained coherent with the assumed boundary conditions. At first insufficient accuracy might explain the results, but with further experiments a different conclusion was made, mentioned in paragraph 4.5.2. “First complement on the conclusion of the drainage tests with clay”.

These saturation degrees can only give the first straight part up of the drainage retention curve (cf. figure 2.7 or 2.8). This test is thus not satisfying. Prolonging the time of the test does not result in any improvement, the outflow has stopped completely. Increasing the number of rotations per minute is only slightly possible. Imbalance due to different weights and different weight distributions makes it very difficult to exceed 1200 rpm. This speed causes heavy vibrations in the centrifuge and is therefore to be avoided.

When flow ceases (equilibrium) the suction distribution obtained is (given by [28])

\[
\psi(z) = \frac{\rho \omega^2}{2} \left[ 2r_0 z - z^2 \right] + \psi_0
\]

(4.11)

with:
- \( z = r - r_0 \),
- \( r \) = the distance from the sample base in the direction towards the centre of rotation,
- \( r_0 \) = the radius from the centre of rotation to the bas of the specimen,
- \( \rho \) = the liquid density,
- \( \omega \) = the rotational speed,
- \( \psi_0 \) = the suction at the bottom boundary of the sample, i.e. zero when only the filter is kept saturated.

It can be remembered that the transition from saturated to unsaturated condition causes large increases in effective stress and also a large difference between the effective stresses throughout the sample (cf. 3.6.2).
4.5. DRAINAGE

The simultaneous consolidation and draining processes are difficult to model, especially for these small outflow values.

**Relation to literature values**

That it is difficult or even impossible to drain a clay sample in the centrifuge used for this work was to be expected. The capillary suction head of clay easily reaches a magnitude of more than 10 meter (cfr. table 2.4). The low water table in the soil at saturated condition of only five centimetres, multiplied by the numeral of gravitational force simulated in the centrifuge, which is around 100, gives only a fictitious water table of five metres. This is insufficient when the capillary forces are more than ten metres. Increasing the number of rotations per minute will increase the draining force but will also compact the sample further, which will lead to an increase of the capillary forces [15].

![Figure 4.7: Suction head in function of relative saturation for kaolin clay and other soils [15].](image)

After saturated flow the water on top of the soil is removed and an attempt is made to drain the sample. Removal of the water on top does however not lead to an increase of effective soil tension. Despite this and the expectation that no drainage would occur, there was still a small amount of water. The decrease in soil height was slower than the outflow but catches up in the end, resulting in a completely saturated sample also at the end of the test. The reason why there was still an outflow is probably because the water content at the start of the drainage is still very high (more than 100%). For such a high water content the capillary forces are very low. A small amount of drainage at the bottom is therefore possible. Possible lower capillary forces (different material and pore structure) of the filter might contribute to this. The small amount that is drained is then exposed to a higher effective soil tension and is then compacted further. Eventually a very small unsaturated layer is created in the filter, also caused by evaporation, with high capillary forces. This layer prevents further drainage.

Other literature ([16] with figure 4.8, [14] with figure 4.9) also shows that extremely high values
are required to drain clay samples. In figure 4.9 the parameter $I$ stands for the pore-interaction term used in the van Genuchten-Mualem function.

**Figure 4.8:** Relation between grain size and degree of saturation after drainage. Curve A (after Zunker 1930) obtained by suction method; curve B (after Lebedeff 1928, [17]) by centrifuge method; curve C by field measurements [16].

**Figure 4.9:** Measured and predicted unsaturated hydraulic conductivities according to [14].
4.5. **DRAINAGE**

4.5.2 **Mol sand**

Since it was not possible to sufficiently drain a clay sample with the centrifuge an attempt was made to drain a sand sample.

**Procedure**

The sample preparation was described in paragraph 3.4.4. It can be remembered that measurements for saturated flow using the centrifuge are not accurate. It is however possible to pre-consolidate the sample briefly inside the centrifuge at low speeds (300 rpm) without taking measurements. Water must then be added at least every five minutes in order to keep the sample saturated. The pre-consolidation is carried out for half an hour. Afterwards the sample is placed vertically until the water on top of the soil flowed through the sample. The test can be carried out accurately as the capillary forces keep the sample saturated and do not allow drainage to start at static conditions. In the centrifuge free outflow is allowed, assuming zero water pressure at the outflow side.

Pre-consolidation at higher speeds is not possible because the flow then becomes too fast. When a sample is being drained, starting from a saturated sample without water on top, this will go on until an equilibrium is reached between the centrifugal forces and the capillary forces. Higher speeds than the pre-consolidation speed are required in order to drain the sample sufficiently. This will cause a supplementary decrease of the sample height which is not desirable.

When a high speed is used immediately to drain the sample the drainage goes on very fast and does not allow sufficient measurements. A gradual increase of the speed is therefore required.

**Results**

Unexpected results were reached. One would expect the centre of gravity to decrease. In the beginning the decrease is expected to happen fast and to go on more slowly in the end. Decreases were obtained alternating with increases. A small increase might only be expected in the end when the water front leaves the sample.

Figures of the results are added in appendix H.2. The first graph shows the different numbers of rpm used for the different time intervals.

The cause for the somehow unexpected results was found through a visual inspection. When the sand is drained a lighter colour is observed. This lighter colour was seen at the top of the sample and increasing in height when the sample was drained, as expected. After a rather short time this light color was also seen just above the filter. Air must have entered the sample through the filter. This does not comply with the assumed boundary condition at outflow side, i.e. a saturated condition with hydraulic head zero. This means the flow lines were interrupted not long after the test was started.
The problem described can be solved by ensuring the saturated condition of the filter. A ceramic filter instead of a porous glass filter can take care of this. The problem is that the conductivity of the filter must be higher than the conductivity of the soil (cfr. paragraph 4.2.2). This will exclude the option of a ceramic filter, especially when testing a sample of sand with a high conductivity. Another option is the use of an outflow head at the filter side. This should ensure the saturated condition and prevent intrusion of air through the filter.

First addition on the conclusion of the drainage tests with clay

The conclusion based on the visual inspection after drainage tests with sand samples is also applicable on the drainage tests with clay samples. It was not visible then because of the high water content and the high saturation degree but the same thing occurred. A slicing test (“Procedure slicing test” cfr. paragraph 3.4.4) was carried out to see the water content in function of the sample height. When a trend would be expected due to the drainage, it would be that the water content at the top of the sample is lower then at the filter side (bottom) of the sample. Results (added in appendix F.4.1) indicate the opposite and therefore affirm the applicability of the conclusions from drainage tests on the Mol sand to the drainage tests on kaolin clay. The assumed boundary condition was thus also for those tests not the same as it was assumed.

4.5.3 New procedure with outflow head

The same red cap as the one screwed into the large gray cap to hold the tube is used as a small outflow reservoir (cfr. figure 3.2). A simple test with a tube filled with water while the red outflow cap is screwed onto the tube shows that the flow of water happens unimpeded. The water can rise through the screw threads. Because of the convex inner surface of the red outflow cap, flow is possible through the filter. Only a small contact surface in the centre of the filter will prevent the flow but since the conductivity of the filter is high enough this does not cause any problem.

To measure the centre of gravity this new procedure causes some small problems. This has to happen when the tube is placed in a horizontal position. This can easily be resolved by using another red cap screwed at the top of the tube. Two red caps were found with exactly the same weight (accuracy 0,01 g). In the calculation for the centre of gravity of the water the caps have to be considered analogously to the other elements as explained in paragraph 3.7. Another problem however is the water in the outflow cap that may not flow out of it when placed horizontally. To prevent this the tube is placed in the horizontal position and only the water that would trickle out is removed. Enough water must remain in the cap to ensure the saturated condition. The weight of removed water is recorded and replaced after the COG measurements. For the calculation the remaining water in the outflow cap must also be considered. Its weight is known but its position is not. An estimation must be made concerning
the position of the centre of gravity of this volume of water. This will cause an inaccuracy even though the amount of water is small ($\pm 1 \, g$).

**Results**

Visual inspection showed a suspicious result after only the first minute of drainage at 500 rpm. Although there was outflow in the large outflow glass, the level of water in the small outflow cap that provides the outflow head was lower than at the start. After two more minutes the water level in the outflow cap even disappeared.

Even when fresh water is added to the outflow cap regularly the test is useless: this observation does not comply with the desired boundary conditions and the exact conditions (for example centre of gravity) during the test are not known. The explanation for this phenomenon are the capillary forces. When the centrifuge test is stopped there is an unloading of the sample. At that moment the sample can be seen as a sample with a given water level inside and placed in a basin of water. The capillary forces of a fine grained sand such as Mol sand easily reach 30 cm (cfr. table 2.4). This means that at the described static moment the sand sample will absorb the water due to capillary forces and the water level will rise. The conductivity of sand is high causing this rise to occur rapidly.

There is also the contribution of the circular water level during centrifugation that creates a volume of about 150 mm$^3$ (cfr. paragraph 3.6.1). In this volume there is a negative pressure (relative to atmospheric pressure). This volume is insufficient to explain the completely empty outflow cap. The capillary forces dominate this process which explains why the volume mentioned can be neglected for soils with high conductivities. For soils with low conductivities this volume will matter limited.

The speed and range of the capillary forces can be illustrated in two ways. A first is to place a sand sample in a basin of water and see the water level rise in the sample due to the capillary forces. This is typical for the situation observed in the test and gives an indication of the speed and range. A second method that illustrates only the range of the capillary forces is to place a saturated sample in a basin with low water level and to see if and how far it drains. When the sample does not drain this means the capillary forces are at least high enough to cause a suction head equal to the height of the gradient. Both tests indicate as expected that the range easily covers the height of the sample tested. The first test also indicates that the speed is high enough to cause the small volume of water to be absorbed by the sample while the sample is recovered from the centrifuge.

**Second addition on the conclusion of the drainage tests with clay**

If for tests on clay samples the same boundary condition (an outflow head) would be imposed, still no drainage would occur. The filter would remain saturated and the initial water level,
equal to the top of the soil, would start to decrease. As soon as a very small layer is drained very high capillary forces are created in this layer and would prevent further drainage.

4.5.4 Mixture of Mol sand and kaolin clay

A lot of the difficulties mentioned might be solved partially or completely by using a mixture of sand and clay for the following reasons.

- When a mixture is used in such quantities that the clay particles fill the pores of the sand particles, a low soil with low conductivity is simulated with a strong structure that will not (much) be compressed under increasing loading. A soil with a low conductivity is preferable since it is a better simulation of the application in landfills. Changes in height of the samples during tests are unwanted since it is more difficult to model all the effects correctly.

- The capillary forces will be a lot higher for a mixture due to the smaller pores. The lower conductivity however will also cause a very slow speed of the capillary rise. When measurements are taken the mistakes caused by the situation in the centrifuge should therefore be limited. The circular water level will increase the speed slightly but within limits.

- The higher conductivity and lower capillary forces than those of pure clay will allow drainage in the set-up of this work.

- The lower conductivity than the conductivity of pure sand will allow more accurate measurements.

- The same mixture consolidated at different stress levels can provide a range of conductivities to simulate.

Procedure

The same procedure with the outflow cap is used as described in the previous paragraph. A water table is present at the outflow side of the tube. Due to the lower conductivity of the mixture there is not sufficient time for the soil to suck up an important amount of water despite the larger capillary forces. Accurate measurements are therefore possible.

Note that there is now unsaturated flow at the top and saturated flow at the bottom part (below the water level at outflow side) at the same time. This should be modelled the same way. An alternative is to adapt the set-up so only the filter is kept saturated with now supplementary water table.

A first sample was pre-consolidated dry at 45 kPa and then moistened. A saturated conductivity test in the centrifuge was carried out at 600 rpm. Then a drainage test was carried out, also at 600 rpm.
4.5. DRAINAGE

A second test with one sample was carried out to check some limits that could be achieved and some corresponding orders of magnitude. The numbers of rpm used in the test are 600, 1200 and 2400. During the test some difficulties appeared to optimize the mass of the dead weight when attempts were made to reach 1200 and 2400 rpm (cf. paragraph 3.6). This had of course an impact on the measurements taken after short time intervals. At 3600 rpm the red cap of the large grey screw broke. Because it was unknown before the test what the maximum speed would be during the test, an estimated pre-consolidation stress of 100 kPa was applied to the dry soil. That explains why it is to be expected that some consolidation might occur during the test.

A test with a sample pre-consolidated at 75 kPa without intermediate readings was carried out at 2400 rpm to find out if sufficient desaturation is obtained for a soil with lower saturated conductivity.

One test was also carried out with an outflow head keeping only the filter saturated.

Results

Results of the test are added in appendix H.3. The soil height remained constant (46.46 mm) at all times excluding consolidation. For the centre of gravity of the water now results as initially expected are obtained: a continuous decrease, fast in the beginning and slow in the end due to the decreasing gradient. There is a small gradual kink in the curve of the cog of the water. This can be explained by the kink in the retention curve that causes substantially higher suction head values of the soil when a given water content is reached. The obtained average effective saturation degree of the top part of the soil that is being drained is about 50%. The initial volumetric water content was 21.32 % and thus at the end a volumetric water content of 10.66 % was reached.

The speed might be increased in order to obtain lower water contents. Some decrease in soil height and some consolidation might then occur but in limited amounts. A sample pre-consolidated at 75 kPa with saturated conductivity of $6 \times 10^{-6}$ m/s, initial volumetric water content equal to 28.69 % and mass water content equal to 17.96 % was drained at 2400 rpm without intermediate readings. The desaturation in the top part of the soil was 78.43 %. The decrease in soil height was only 0.8 mm.

During the second test a small amount of consolidation occurred as expected. This occurred at each different speed only at the beginning. Some of the outflow water during those first minutes at each different speed is thus contributed by consolidation. A part of the consolidation is assumed to happen after outflow. The actual amount of outflow can be approximated by a fit through the relative outflow during constant sample height and with an initial value of the outflow that is zero.

Except for the two small effects mentioned good results are obtained, added in appendix H.3.
No good results were obtained for the test with an outflow head keeping only the filter saturated. In the red outflow cap holes were drilled to allow outflow of water at the top level of the filter. The cause for the bad results was an insufficient amount of water in the outflow cap. During the interruptions of the centrifuge tests for the measurements the now very small amount of water was absorbed by the soil due to the capillary forces destroying the required boundary condition and allowing intrusion of air in the filter. Drilling the holes higher and not screwing the red cap to the end of the thread would provide more water in the outflow reservoir. Because of small vibrations in the centrifuge the cap turned loose when not screwed tightly to the end of the thread. Other testing equipment or a modification of the existing equipment is required for this type of test.

The dominant structure of the mixture is formed by the sand causing changes in height that are a lot smaller ($< 10\%$) than observed with clay mixtures. The conductivity is sufficiently low for accurate measurements and can also represent a variety of soils using higher pre-consolidation stresses and lower percentages of clay. Drainage of the soil is possible up to any values representing in situ soil properties.

4.5.5 Conclusions

Correct boundary conditions are essential for correct tests and their simulation. Draining a sample with a saturated outflow boundary and head zero requires a saturated filter at all times. The final tests carried out in this work have outflow heads of about two centimetres causing two types of flow, unsaturated in the top part and saturated in the bottom part.

When the capillary forces are not too strong a sample can be drained as a result of the imposed centrifugal forces being larger than the capillary forces. Mixtures of Mol sand and kaolin clay with saturated conductivities up to $6,12 \times 10^{-6} \text{ m s}^{-1}$ can be drained considerably ($78,43 \%$ desaturation) at considerable speeds (2400 rotations per minute) without important changes in sample length.

Pure kaolin clay has capillary forces that are too high to drain the clay with the current set-up. Increasing the number of rpm results in two counteracting elements. The centrifugal forces will increase causing more drainage. A higher force on the sample also causes consolidation and thus a decrease of void ratio. A decrease of void ratio causes an increase in the capillary forces [15] and therefore less drainage. The combination of these two elements in function of the desaturation has an optimum value that corresponds with an effective saturation degree higher than 98 %. It is obvious that this is insufficient to obtain in practice an interesting part of the retention curve. This maximal desaturation was checked with simulations. In these simulations no consolidation was considered and thus a fixed matric suction was used for a given water content. Higher matric suction was obtained by allowing some drainage in the simulation. This drainage then causes an increase of the matric suction. This procedure is an approximation with the result being an overestimation of the desaturation obtained.
4.6 Suction head test

A suction head test as described in paragraph 4.6 was carried out on samples with a volumetric water content of 68.38, 62.63, 55.97, 47.91, 35.48 and 26.90 %. Higher and lower water contents were practically not possible because in that case either too much of a slurry or a too fragile soil structure is obtained. The test was carried out at 20°C but only calibration curves for 25°C were available. The obtained water contents of the filter papers would be larger at 25°C resulting in lower suction values. Using the calibration curves for 25°C for results obtained at 20°C consequently results in higher suction head values. The results are clearly an overestimation. This overestimation can become very large because of the high sensitivity of the results as a function of the water content of the filter papers.

The results are displayed in figure 4.10 using two different calibration curves at 25°C. The difference between these two curves is already an indication of the high sensitivity of the values. The result is anyhow a first indication of the large suction head values of the clay.

![Figure 4.10: Matric suction in function of the volumetric water content for kaolin clay using filter paper tests.](image)

A similar test on the same kaolin clay was carried out by the Cornelis laboratory at Ghent University. No detailed information about the tests was found. The results are shown in figure 4.11 with the full curve on the left and a close-up on the right. It shows that the values for matric suction are a lot smaller then obtained in figure 4.10. The residual volumetric water content $\theta_r$ seems high. A strange curve near the saturated volumetric water content $\theta_s$ is also seen. Because not enough information concerning the test is available no other conclusions are reached with the exception of the indication that clay exercises large matric suction (capillary forces) at low water contents.
Figure 4.11: Results given by the Cornelis laboratory for the matric suction in function of the volumetric water content for kaolin clay (left) and detail (right).

Figure 4.12 shows the retention curves for a sandy soil, a loamy soil and a clayey soil with useful indications for agronomists. The curves are of course dependent on the type of clay and the compaction. It indicates nevertheless that the retention curve of a clay is a curve that differs quite a lot from the classical representation of retention curves (cf. figure 2.7). The research of van Genuchten indicates in [25] that for clayey soils his mathematical representation of the retention curve fits less with test results obtained with these type of soils. Figure 4.12 also indicates larger values for the matric suction than obtained by the Cornelis laboratory, but again not a lot of conclusions can be made since it depends on the type of clay, the compaction and other parameters.

Figure 4.12: Relation between soil matric potential and soil water content in different soils (Scheffer & Schachtschabel, Lehrbuch der Bodenkunde).
4.6.1 Conclusions

The determination of the matric suction of a soil is a delicate procedure. It is advisable to have a specialized laboratory carry out tests to determine these curves. It will also be necessary to obtain this graph for the mixtures used.

For clayey soils this different retention curve must be considered for extrapolations.

4.7 Drying of a sample

An attempt was made to dry a saturated clay sample in multiple steps at 80°C to reduce the water content. After each drying cycle the sample is placed in the centrifuge. First 800 rpm is used until an equilibrium of the water household is reached. Next 1600 rpm is used to create a new equilibrium for the same water content but for higher centrifugal forces. The results of this test should provide extra data which are useful for the mathematical model. In practice there is one critical problem. Small cracks as well vertically as horizontally are created due to shrinkage of the soil. This prevents movement of water in the soil because the flow lines are interrupted. No useful data are obtained because of this. The mathematical implementation of these data in the mathematical model is therefore not included in this work.

4.8 Conclusion

In this chapter all the tests carried out in this research were mentioned and their results discussed. Most important to remember are the successful drainage tests using mixtures of 90 % Mol sand and 10 % kaolin clay with the centrifuge and also the successful static imbibition test of this mixture with a water supply at the bottom of the sample. For drainage tests higher speeds are a necessity to drain soils with lower conductivities sufficiently. The most important conclusion is that a centrifuge with in-flight measurements that leads at least to the accurate calculations of the centre of gravity is required for practical reasons. High speeds are not required for imbibition tests but are expected to cause no harm when the generated forces are not larger than the pre-consolidation load. The next chapter gives a short resume of all the conclusions reached in this work.
In this chapter a summary of the most important conclusions obtained by this research is given. More detailed conclusions are given in the corresponding sections in the previous chapters. This chapter ends with some general conclusions and reflections on the work that was carried out. In the next chapter some recommendations are given for further research.

5.1 Sample preparation and equipment

The sample preparations carried out for this research were always done with high accuracy and great care. The accuracy of the equipment can be improved a lot and an automation of measurements is advised. This will depend on the budget available for further research. It would for example be desirable to have a data acquisition system in combination with sensors measuring water height, the centrifugal force to define the centre of gravity and the amount of outflow. When also the soil height can be measured this will improve the accuracy of the calculated values. A data logging system to obtain the actual number of rotations per minute during the complete test will also improve the accuracy of the simulations. For short tests the consideration of the acceleration and deceleration curves is of importance. Constant and well known dimensions of the soil recipients are also very important. The mistake about the value of saturated conductivity can be upto 25 % when for example an inside diameter of the tubes is used that is 1 \text{mm} smaller than in reality.
5.2 Tests carried out

5.2.1 Saturated conductivity

The saturated conductivity depends on the way a sample was pre-consolidated. A pre-consolidation in static conditions using weights to apply a force on the soil samples represents best in situ samples. If in situ soil samples are tested it is of importance not to load them more than they were loaded in situ. A correct choice of the number of rpm is therefore necessary. Since centrifugal forces do not apply the same linear forces as it is the case in situ, always a number of rpm should be used simulating the in situ soil conditions as closely as possible. Consolidation and changes in soil height and therefore changes in porosity and conductivity are inevitable. Minimizing these changes is necessary for acceptable results.

In this study formula (4.6) as derived by Sharma and Samarasekera was used for centrifuge tests. In contradiction to their work not formula (4.9), calculating the g-level $N$ at the middle of the water on top of the soil, but formula (4.8), calculating the g-level $N$ at the middle of the soil, gave the best results. Higher results were obtained using centrifuge tests (with a maximally observed difference of 58.32 %) compared to the results from static tests. As expected results from the model range in between the two previous results. An inside diameter that is not constant for the complete tube length and drops at the bottom of the filter during static falling head tests are the main causes of these differences. For soils with a high conductivity and for the determination of the conductivities of the filters, the effect of the acceleration and deceleration curves must also be considered as the total testing time is short.

5.2.2 Imbibition

The advise is to perform tests with water added on top of the soil since this simulates the in situ flow best of all. This flow happens relatively fast causing no need to speed the test inside the centrifuge, but for accurate measurements a centrifuge with in-flight measurements is required. For static tests the water on top of the soil has to be removed and replaced before and after each centre of gravity measurement. For centrifuge tests without in-flight measurements the soil structure changes too much due to the interruptions for cog measurements. For soils with low conductivities a water table on top acts like a weight. During centrifugation this will cause loading of the sample. Stopping the centrifuge causes unloading and therefore tensile stresses. Because soil can only support very low tensile stresses horizontal cracks are formed changing the soil structure. Even at low speeds the accuracy of the measurements is poor because still a circuitous measuring procedure must be used.

The only accurate test possible within the limits of this research was an imbibition test with water supply from the bottom of the sample. This test was carried out on a mixture of Mol
sand and kaolin clay and gave results that can be simulated. However this type of flow is different from imbibition with water on top of a soil.

Imbibition of samples with an initial water content is possible according to the same testing procedure described. Air bubbles will originate as it will also be the case in situ. To simulate imbibition at a larger depth an adjustment of the set-up will be required.

5.2.3 Drainage

For successful drainage tests a saturated filter must be guaranteed during the test. For mixtures of Mol sand and kaolin clay good results were obtained with a water table at outflow side and these results coincide well with results from simulations with the mathematical model.

When the matric suction of a soil is too strong no drainage is possible.
CHAPTER 6

Future research

This work was the continuation of a thesis [10] dealing with the same subject in a first phase. Many new tests, conclusions and insights are carried out and reached but still many more tests are required. The application of the centrifuge is narrowed down to certain types of tests and soils and important effects were found which can be considered when new equipment and set-ups are developed.

Following tests to validate the mathematical model concerning drainage are required:

- Changing the ratio of sand and clay in order to test a wider range of soils, characterised by their saturated conductivity.

- Changing the pre-consolidation load for each mixture in order to perform tests at different speeds with as little change in height as possible. This in order to obtain the lowest saturation degree possible at the end of a test for each combination of soil and pre-consolidation load.

- A repetition of tests to find out the repeatability and accuracy of the tests as well as to obtain more data to test and simulate the model.

Imbibition tests with a centrifuge capable of performing in-flight measurements are necessary. These tests can be carried out on samples that are completely dry at the start or on samples with an initial water content. In that case a homogeneous preparation is of importance. Pre-consolidation is necessary. Enough of these tests must be carried out to check the repeatability of the tests and to provide an accurate validation of the model. The results from the research in this work indicate that for these tests accurate results will be obtained.

The effect of multiple parameters can be tested. These are for example temperature and air humidity but also the effects of ions present in the soil or in the water added.
6.1 Suggested modification of the centrifuge

- For imbibition tests it is critical that a parameter that allows the calculation of the centre of gravity is measured in-flight.

- The amount of outflow water must be determined in-flight as well as the height of the water on top of the soil.

- The determination of the soil height during a test will be interesting in a research phase but might not be a necessity in the end if the changes in sample length can be neglected.

- To test more parameters and possible influences it might be interesting to have recipient holders that allow samples with larger dimensions.

- A data acquisition system is of course required.

- The maximal speed of the centrifuge is determined by the drainage tests. More research with stronger recipients is required to find the exact requirement. It will be determined by the optimum of sufficient desaturation that can be reached and a conductivity of the soil as low as possible.

6.2 Suggested modifications of the sample recipients

- Tubes that have more constant and better known dimensions are necessary. Another material is possible. A transparent material will always have the advantage of allowing visual inspections.

- Stronger recipients are required to allow larger speeds.

- Recipients with different and larger dimensions to be able to test more effects.

The current recipients will be sufficient to provide different saturated outflow heads for centrifuge tests with in-flight measurements.
General information about the appendices

The abbreviation cog stands for centre of gravity and rpm stands for rotations per minute, as mentioned before.

The reference top of the filter is considered for a tube placed vertically consequently the bottom of the soil.

When a scaled height of soil is mentioned this means the height of the soil for the different measurements is divided by the original height of soil. This is done to allow a better visual comparison of the different samples.

When a scaled position of cog of water is mentioned this means the cog of the water for the different measurements is divided by the original position. When the soil height changes a lot this will of course also influence the value of the cog of the water. Graphs must therefore always be analysed at the same time.

When time is presented in the abscissa in a logarithmic way, the starting values at time equal to zero are not displayed. For the cog of the water this is obviously not a problem considering imbibition. For drainage tests no logarithmic scale is used. For the graphs displaying the soil height the initial values can be derived from the graphs displaying the scaled soil height where the (not displayed) initial value is 1.

The position of the cog of the water always considers the water inside the soil and inside the filter.

When accuracy of the cog measurements is mentioned two indications are used. The first indication uses the difference between two centre of gravity calculations of the total position of the soil. The first calculation is the calculation reached by formula (3.8) as mentioned in
paragraph 3.7 The second calculation assumes the cog of the soil to be in the measured centre of the soil and also assumes for drainage tests that the cog of the water is in the middle of the measured height of soil and filter.

The second indication is given by the difference between the initial position of the cog of the soil (calculated analogously to formula (3.4) from paragraph 3.7) and the initial midpoint of the soil that is measured.

For both indications the obtained values should coincide for the initial condition as well for drainage tests as imbibition tests since in those cases a homogeneous sample is measured. Both methods are thus an indication of the accuracy, but different aspects are taken into account for the two indications.

The first method comparing positions of the total cog gives an indication on

- the (small) mistake that is made due to the fact that the filter papers are not taken into account,
- the effect of the limited accuracy of the soil height measurements and the uneven soil surface and
- the effect of the inside surface of the tubes that is not constant and causes weight distributions differing from the expected. This is different for each filter and explains sometimes large variations in the accuracy indications for these filters. This effect will also be more important for saturated samples because then it has an effect both on soil and water where for dry samples it only has an effect on the soil.
- the effect of the different porosity of the filter compared to the soil. This effect will however be very small compared to the other ones.

The second method comparing positions of the cog of the soil gives an indication on

- the four elements mentioned for the first method and
- the effect of the inhomogeneous distribution of the water in the soil due to inhomogeneities in the soil. This consolidated soil in the centrifuge has been exposed to varied forces over its height. This caused a different void ratio and therefore a different water distribution in saturated conditions. The changing inside surface over the length of the tubes will enlarge this influence.

The differences of the first indication will be rather small (< 0.25 mm). The differences of the second indication are a lot larger. The most important cause is mentioned in the last item above. This difference will be smaller for samples pre-consolidated with weights.

For a correct interpretation of the graphs it is strongly advised to read the referring texts in chapter 4 simultaneously.
### Mol sand Granulometry

**Grain curve of Mol sand as determined by L. Wils.**

<table>
<thead>
<tr>
<th>Diameter [mm]</th>
<th>Mass percentage on sieve [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>100.00</td>
</tr>
<tr>
<td>10.00</td>
<td>90.00</td>
</tr>
<tr>
<td>20.00</td>
<td>80.00</td>
</tr>
<tr>
<td>30.00</td>
<td>70.00</td>
</tr>
<tr>
<td>40.00</td>
<td>60.00</td>
</tr>
<tr>
<td>50.00</td>
<td>50.00</td>
</tr>
<tr>
<td>60.00</td>
<td>40.00</td>
</tr>
<tr>
<td>70.00</td>
<td>30.00</td>
</tr>
<tr>
<td>80.00</td>
<td>20.00</td>
</tr>
<tr>
<td>90.00</td>
<td>10.00</td>
</tr>
<tr>
<td>100.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Mol sand granulometry**

![Graph of Mol sand granulometry](image_url)
Saturated conductivity of Mol sand as a function of the relative density, determined by W.F. van Impe.
APPENDIX D

Rotations per minute of the centrifuge in function of different parameters.

Values were added to the graphs at constant set speed to obtain a visually more interesting graph where the deceleration paths all end up at the same time.
## General measurements of the tubes and soil recipients

### Table E.1: General values of the soil recipients.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recipient number</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Dry weight of the outflow glass</td>
<td>212,43</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>212,66</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>212,99</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>212,15</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>204,09</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>205,94</td>
<td>g</td>
</tr>
<tr>
<td>Weight large light gray screw with red cap</td>
<td>73,72</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>73,67</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>89,86</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>89,72</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>90,16</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>86,56</td>
<td>g</td>
</tr>
<tr>
<td>Weight of the red outflow cap</td>
<td>17,23</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>17,76</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>17,17</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>17,29</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>17,34</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>17,29</td>
<td>g</td>
</tr>
</tbody>
</table>

### Table E.2: General values of the tubes provided with a filter suitable to test kaolin clay.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube number</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Thickness of the filter</td>
<td>2,90</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>3,05</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>2,90</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>3,00</td>
<td>mm</td>
</tr>
<tr>
<td>Inside diameter of the tube</td>
<td>21,63</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>21,54</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>22,00</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>21,54</td>
<td>mm</td>
</tr>
<tr>
<td>Inside surface of the tube</td>
<td>367,4539</td>
<td>mm²</td>
</tr>
<tr>
<td></td>
<td>364,4024</td>
<td>mm²</td>
</tr>
<tr>
<td></td>
<td>380,1327</td>
<td>mm²</td>
</tr>
<tr>
<td></td>
<td>364,4024</td>
<td>mm²</td>
</tr>
<tr>
<td>Total height of the tube</td>
<td>84,70</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>85,10</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>84,90</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>84,85</td>
<td>mm</td>
</tr>
<tr>
<td>Average height above filter</td>
<td>81,80</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>82,05</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>82,00</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>81,85</td>
<td>mm</td>
</tr>
<tr>
<td>Dry weight of the tubes</td>
<td>53,77</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>53,27</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>50,76</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>52,43</td>
<td>g</td>
</tr>
<tr>
<td>Distance cog of the tube from the top of the filter</td>
<td>38,22</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>37,74</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>38,06</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>38,15</td>
<td>mm</td>
</tr>
</tbody>
</table>
Table E.3: General values of the tubes provided with a filter suitable to test Mol sand.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube number</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Thickness of the filter</td>
<td>3.35</td>
<td>3.88</td>
</tr>
<tr>
<td>Inside diameter of the tube</td>
<td>21.57</td>
<td>21.61</td>
</tr>
<tr>
<td>Inside surface of the tube</td>
<td>365.4182</td>
<td>366.7747</td>
</tr>
<tr>
<td>Total height of the tube</td>
<td>84.40</td>
<td>84.11</td>
</tr>
<tr>
<td>Average height above filter</td>
<td>81.05</td>
<td>80.23</td>
</tr>
<tr>
<td>Dry weight of the tubes</td>
<td>52.57</td>
<td>52.34</td>
</tr>
<tr>
<td>Distance cog of the tube from the top of the filter</td>
<td>37.56</td>
<td>36.69</td>
</tr>
</tbody>
</table>

Table E.4: General values of the tube provided with a filter suitable to test a mixture of 90% Mol sand and 10% kaolin clay.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube number</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>Thickness of the filter</td>
<td>2.84</td>
<td>2.94</td>
</tr>
<tr>
<td>Inside diameter of the tube</td>
<td>21.39</td>
<td>21.58</td>
</tr>
<tr>
<td>Inside surface of the tube</td>
<td>359.3449</td>
<td>365.7571</td>
</tr>
<tr>
<td>Total height of the tube</td>
<td>85.27</td>
<td>85.34</td>
</tr>
<tr>
<td>Average height above filter</td>
<td>82.26</td>
<td>82.05</td>
</tr>
<tr>
<td>Dry weight of the tubes</td>
<td>52.87</td>
<td>51.59</td>
</tr>
<tr>
<td>Distance cog of the tube from the top of the filter</td>
<td>38.76</td>
<td>99.99</td>
</tr>
</tbody>
</table>


Results of saturated tests

F.1 Results of saturated conductivity tests of the filters

F.1.1 Conductivity tests on filters with low conductivity

Table F.1: Data and calculated values of centrifuge tests in order to determine the saturated conductivity of filter number 1 with formula (4.8).

<table>
<thead>
<tr>
<th>Time $s$</th>
<th>rpm</th>
<th>$H_1$ mm</th>
<th>$H_2$ mm</th>
<th>$N$ g</th>
<th>Conductivity filter $10^{-8} \frac{m}{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>400</td>
<td>72,98</td>
<td>37,27</td>
<td>26,26</td>
<td>9,63</td>
</tr>
<tr>
<td>480</td>
<td>500</td>
<td>70,95</td>
<td>41,04</td>
<td>41,03</td>
<td>9,48</td>
</tr>
<tr>
<td>300</td>
<td>600</td>
<td>70,91</td>
<td>42,44</td>
<td>59,08</td>
<td>9,92</td>
</tr>
<tr>
<td>300</td>
<td>700</td>
<td>70,66</td>
<td>36,19</td>
<td>80,41</td>
<td>9,31</td>
</tr>
<tr>
<td>240</td>
<td>800</td>
<td>71,38</td>
<td>36,51</td>
<td>105,03</td>
<td>9,95</td>
</tr>
<tr>
<td>240</td>
<td>900</td>
<td>73,93</td>
<td>30,63</td>
<td>132,92</td>
<td>9,15</td>
</tr>
<tr>
<td>240</td>
<td>1000</td>
<td>71,88</td>
<td>21,47</td>
<td>164,10</td>
<td>9,75</td>
</tr>
</tbody>
</table>
Table F.2: Data and calculated values of centrifuge tests in order to determine the saturated conductivity of filter number 2 with formula (4.8).

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>rpm</th>
<th>$H_1$ (mm)</th>
<th>$H_2$ (mm)</th>
<th>N (g)</th>
<th>$10^{-8}$ m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>400</td>
<td>70,027</td>
<td>42,17</td>
<td>26,24</td>
<td>7,70</td>
</tr>
<tr>
<td>480</td>
<td>500</td>
<td>71,951</td>
<td>47,68</td>
<td>41,01</td>
<td>7,65</td>
</tr>
<tr>
<td>300</td>
<td>600</td>
<td>72,527</td>
<td>49,64</td>
<td>59,05</td>
<td>7,89</td>
</tr>
<tr>
<td>300</td>
<td>700</td>
<td>73,249</td>
<td>44,46</td>
<td>80,37</td>
<td>7,53</td>
</tr>
<tr>
<td>240</td>
<td>800</td>
<td>71,940</td>
<td>43,24</td>
<td>104,97</td>
<td>7,30</td>
</tr>
<tr>
<td>240</td>
<td>900</td>
<td>73,781</td>
<td>38,00</td>
<td>132,86</td>
<td>7,42</td>
</tr>
<tr>
<td>240</td>
<td>1000</td>
<td>73,446</td>
<td>30,75</td>
<td>164,02</td>
<td>7,68</td>
</tr>
</tbody>
</table>

Table F.3: Data and calculated values of centrifuge tests in order to determine the saturated conductivity of filter number 4 with formula (4.8).

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>rpm</th>
<th>$H_1$ (mm)</th>
<th>$H_2$ (mm)</th>
<th>N (g)</th>
<th>$10^{-8}$ m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>400</td>
<td>73,29</td>
<td>44,02</td>
<td>26,26</td>
<td>7,46</td>
</tr>
<tr>
<td>480</td>
<td>500</td>
<td>70,75</td>
<td>46,13</td>
<td>41,03</td>
<td>7,52</td>
</tr>
<tr>
<td>300</td>
<td>600</td>
<td>71,02</td>
<td>47,69</td>
<td>59,05</td>
<td>7,81</td>
</tr>
<tr>
<td>300</td>
<td>700</td>
<td>71,47</td>
<td>42,07</td>
<td>80,37</td>
<td>7,53</td>
</tr>
<tr>
<td>240</td>
<td>800</td>
<td>71,63</td>
<td>42,35</td>
<td>105,97</td>
<td>7,15</td>
</tr>
<tr>
<td>240</td>
<td>900</td>
<td>71,16</td>
<td>35,20</td>
<td>132,86</td>
<td>7,39</td>
</tr>
<tr>
<td>240</td>
<td>1000</td>
<td>66,85</td>
<td>26,20</td>
<td>164,02</td>
<td>7,64</td>
</tr>
</tbody>
</table>
### Table F.4: Data and calculated values of centrifuge tests in order to determine the saturated conductivity of filter number 5 with formula (4.8).

<table>
<thead>
<tr>
<th>Time s</th>
<th>rpm</th>
<th>H1 mm</th>
<th>H2 mm</th>
<th>N #g</th>
<th>Conductivity filter $10^{-8} \text{ m s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>400</td>
<td>73,55</td>
<td>49,14</td>
<td>26,25</td>
<td>6,20</td>
</tr>
<tr>
<td>480</td>
<td>500</td>
<td>74,95</td>
<td>53,50</td>
<td>41,01</td>
<td>6,31</td>
</tr>
<tr>
<td>300</td>
<td>600</td>
<td>72,02</td>
<td>52,66</td>
<td>59,06</td>
<td>6,45</td>
</tr>
<tr>
<td>300</td>
<td>700</td>
<td>77,39</td>
<td>51,18</td>
<td>80,38</td>
<td>6,32</td>
</tr>
<tr>
<td>240</td>
<td>800</td>
<td>74,48</td>
<td>48,88</td>
<td>104,99</td>
<td>6,08</td>
</tr>
<tr>
<td>240</td>
<td>900</td>
<td>72,30</td>
<td>41,02</td>
<td>132,88</td>
<td>6,28</td>
</tr>
<tr>
<td>240</td>
<td>1000</td>
<td>76,51</td>
<td>37,50</td>
<td>164,05</td>
<td>6,38</td>
</tr>
</tbody>
</table>

### Table F.5: Average conductivities of filters 1, 2, 4 and 5 obtained by centrifuge tests at different numbers of rpm with formula (4.8).

<table>
<thead>
<tr>
<th>Tube number</th>
<th>Average Conductivity $10^{-8} \text{ m s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9,45</td>
</tr>
<tr>
<td>2</td>
<td>7,60</td>
</tr>
<tr>
<td>4</td>
<td>7,50</td>
</tr>
<tr>
<td>5</td>
<td>6,29</td>
</tr>
</tbody>
</table>

### Table F.6: Data and calculated values of centrifuge tests in order to determine the saturated conductivity of filter number 1 with formula (4.9).

<table>
<thead>
<tr>
<th>Time s</th>
<th>rpm</th>
<th>H1 mm</th>
<th>H2 mm</th>
<th>N #g</th>
<th>Conductivity filter $10^{-7} \text{ m s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>400</td>
<td>72,98</td>
<td>37,27</td>
<td>21,07</td>
<td>1,20</td>
</tr>
<tr>
<td>480</td>
<td>500</td>
<td>70,95</td>
<td>41,04</td>
<td>32,80</td>
<td>1,19</td>
</tr>
<tr>
<td>300</td>
<td>600</td>
<td>70,91</td>
<td>42,44</td>
<td>47,09</td>
<td>1,24</td>
</tr>
<tr>
<td>300</td>
<td>700</td>
<td>70,66</td>
<td>36,19</td>
<td>64,98</td>
<td>1,15</td>
</tr>
<tr>
<td>240</td>
<td>800</td>
<td>71,38</td>
<td>36,51</td>
<td>84,69</td>
<td>1,11</td>
</tr>
<tr>
<td>240</td>
<td>900</td>
<td>73,93</td>
<td>30,63</td>
<td>107,94</td>
<td>1,13</td>
</tr>
<tr>
<td>240</td>
<td>1000</td>
<td>71,88</td>
<td>21,47</td>
<td>136,39</td>
<td>1,17</td>
</tr>
</tbody>
</table>
F.1. **RESULTS OF SATURATED CONDUCTIVITY TESTS OF THE FILTERS**

Table F.7: Data and calculated values of centrifuge tests in order to determine the saturated conductivity of filter number 2 with formula $4.9$.

<table>
<thead>
<tr>
<th>Time $s$</th>
<th>rpm</th>
<th>$H_1$ mm</th>
<th>$H_2$ mm</th>
<th>N #g</th>
<th>Conductivity filter $10^{-8}$ m s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>400</td>
<td>70,027</td>
<td>42,17</td>
<td>20,95</td>
<td>9,64</td>
</tr>
<tr>
<td>480</td>
<td>500</td>
<td>71,951</td>
<td>47,68</td>
<td>32,22</td>
<td>9,74</td>
</tr>
<tr>
<td>300</td>
<td>600</td>
<td>72,527</td>
<td>49,64</td>
<td>46,14</td>
<td>10,09</td>
</tr>
<tr>
<td>300</td>
<td>700</td>
<td>73,249</td>
<td>44,46</td>
<td>63,42</td>
<td>9,54</td>
</tr>
<tr>
<td>240</td>
<td>800</td>
<td>71,940</td>
<td>43,24</td>
<td>83,28</td>
<td>9,20</td>
</tr>
<tr>
<td>240</td>
<td>900</td>
<td>73,781</td>
<td>38,00</td>
<td>106,17</td>
<td>9,29</td>
</tr>
<tr>
<td>240</td>
<td>1000</td>
<td>73,446</td>
<td>30,75</td>
<td>133,19</td>
<td>9,46</td>
</tr>
</tbody>
</table>

Table F.8: Data and calculated values of centrifuge tests in order to determine the saturated conductivity of filter number 4 with formula $4.9$.

<table>
<thead>
<tr>
<th>Time $s$</th>
<th>rpm</th>
<th>$H_1$ mm</th>
<th>$H_2$ mm</th>
<th>N #g</th>
<th>Conductivity filter $10^{-8}$ m s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>400</td>
<td>73,29</td>
<td>44,02</td>
<td>20,75</td>
<td>9,44</td>
</tr>
<tr>
<td>480</td>
<td>500</td>
<td>70,75</td>
<td>46,13</td>
<td>32,45</td>
<td>9,50</td>
</tr>
<tr>
<td>300</td>
<td>600</td>
<td>71,02</td>
<td>47,69</td>
<td>46,55</td>
<td>9,92</td>
</tr>
<tr>
<td>300</td>
<td>700</td>
<td>71,47</td>
<td>42,07</td>
<td>64,07</td>
<td>9,44</td>
</tr>
<tr>
<td>240</td>
<td>800</td>
<td>71,63</td>
<td>42,35</td>
<td>83,60</td>
<td>8,98</td>
</tr>
<tr>
<td>240</td>
<td>900</td>
<td>71,16</td>
<td>35,20</td>
<td>107,53</td>
<td>9,13</td>
</tr>
<tr>
<td>240</td>
<td>1000</td>
<td>66,85</td>
<td>26,20</td>
<td>136,48</td>
<td>9,18</td>
</tr>
</tbody>
</table>
Table F.9: Data and calculated values of centrifuge tests in order to determine the saturated conductivity of filter number 5 with formula (4.9).

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>rpm</th>
<th>(H_1) (mm)</th>
<th>(H_2) (mm)</th>
<th>(N) (g)</th>
<th>Conductivity filter ((10^{-8} \text{ m s}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>400</td>
<td>73.55</td>
<td>49.14</td>
<td>20.49</td>
<td>7.94</td>
</tr>
<tr>
<td>480</td>
<td>500</td>
<td>74.95</td>
<td>53.50</td>
<td>31.62</td>
<td>8.19</td>
</tr>
<tr>
<td>300</td>
<td>600</td>
<td>72.02</td>
<td>52.66</td>
<td>45.91</td>
<td>8.30</td>
</tr>
<tr>
<td>300</td>
<td>700</td>
<td>77.39</td>
<td>51.18</td>
<td>61.96</td>
<td>8.19</td>
</tr>
<tr>
<td>240</td>
<td>800</td>
<td>74.48</td>
<td>48.88</td>
<td>81.85</td>
<td>7.79</td>
</tr>
<tr>
<td>240</td>
<td>900</td>
<td>72.30</td>
<td>41.02</td>
<td>105.87</td>
<td>7.88</td>
</tr>
<tr>
<td>240</td>
<td>1000</td>
<td>76.51</td>
<td>37.50</td>
<td>136.51</td>
<td>8.03</td>
</tr>
</tbody>
</table>

Table F.10: Average conductivities of filters 1, 2, 4 and 5 obtained by centrifuge tests at different numbers of rpm with formula (4.9).

<table>
<thead>
<tr>
<th>Tube number</th>
<th>Average Conductivity ((10^{-8} \text{ m s}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.70</td>
</tr>
<tr>
<td>2</td>
<td>9.57</td>
</tr>
<tr>
<td>4</td>
<td>9.37</td>
</tr>
<tr>
<td>5</td>
<td>8.05</td>
</tr>
</tbody>
</table>

Table F.11: Data and calculated values for the conductivities of filters 1, 2, 4 and 5 obtained by static falling head tests.

<table>
<thead>
<tr>
<th>Tube nr.</th>
<th>Time (s)</th>
<th>(H_1) (mm)</th>
<th>(H_2) (mm)</th>
<th>Conductivity filter ((10^{-8} \text{ m s}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3600</td>
<td>72.06</td>
<td>65.08</td>
<td>7.88</td>
</tr>
<tr>
<td>2</td>
<td>3600</td>
<td>75.32</td>
<td>69.60</td>
<td>6.42</td>
</tr>
<tr>
<td>4</td>
<td>3600</td>
<td>72.46</td>
<td>66.75</td>
<td>6.35</td>
</tr>
<tr>
<td>5</td>
<td>3600</td>
<td>77.37</td>
<td>72.38</td>
<td>5.34</td>
</tr>
</tbody>
</table>
### F.1. RESULTS OF SATURATED CONDUCTIVITY TESTS OF THE FILTERS

Table F.12: Results for the saturated conductivities of filters 1, 2, 4 and 5 obtained by the mathematical model calculated with measurements from centrifuge tests and considering acceleration.

<table>
<thead>
<tr>
<th>rpm</th>
<th>filter 1</th>
<th>filter 2</th>
<th>filter 4</th>
<th>filter 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>9.43.10⁻⁸</td>
<td>6.41.10⁻⁸</td>
<td>7.43.10⁻⁸</td>
<td>5.61.10⁻⁸</td>
</tr>
<tr>
<td>500</td>
<td>9.31.10⁻⁸</td>
<td>6.38.10⁻⁸</td>
<td>7.51.10⁻⁸</td>
<td>5.73.10⁻⁸</td>
</tr>
<tr>
<td>600</td>
<td>9.79.10⁻⁸</td>
<td>6.60.10⁻⁸</td>
<td>7.84.10⁻⁸</td>
<td>5.89.10⁻⁸</td>
</tr>
<tr>
<td>700</td>
<td>9.19.10⁻⁸</td>
<td>6.30.10⁻⁸</td>
<td>7.55.10⁻⁸</td>
<td>5.76.10⁻⁸</td>
</tr>
<tr>
<td>800</td>
<td>8.86.10⁻⁸</td>
<td>6.13.10⁻⁸</td>
<td>7.19.10⁻⁸</td>
<td>5.56.10⁻⁸</td>
</tr>
<tr>
<td>900</td>
<td>9.06.10⁻⁸</td>
<td>6.24.10⁻⁸</td>
<td>7.44.10⁻⁸</td>
<td>5.75.10⁻⁸</td>
</tr>
<tr>
<td>1000</td>
<td>9.65.10⁻⁸</td>
<td>6.47.10⁻⁸</td>
<td>7.69.10⁻⁸</td>
<td>5.85.10⁻⁸</td>
</tr>
</tbody>
</table>

Table F.13: Results for the saturated conductivities of filters 1, 2, 4 and 5 obtained by the mathematical model calculated with measurements from centrifuge tests without considering acceleration.

<table>
<thead>
<tr>
<th>rpm</th>
<th>filter 1</th>
<th>filter 2</th>
<th>filter 4</th>
<th>filter 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>9.39.10⁻⁸</td>
<td>6.38.10⁻⁸</td>
<td>7.40.10⁻⁸</td>
<td>5.59.10⁻⁸</td>
</tr>
<tr>
<td>500</td>
<td>9.24.10⁻⁸</td>
<td>6.33.10⁻⁸</td>
<td>7.45.10⁻⁸</td>
<td>5.69.10⁻⁸</td>
</tr>
<tr>
<td>600</td>
<td>9.67.10⁻⁸</td>
<td>6.52.10⁻⁸</td>
<td>7.75.10⁻⁸</td>
<td>5.82.10⁻⁸</td>
</tr>
<tr>
<td>700</td>
<td>9.08.10⁻⁸</td>
<td>6.23.10⁻⁸</td>
<td>7.46.10⁻⁸</td>
<td>5.69.10⁻⁸</td>
</tr>
<tr>
<td>800</td>
<td>8.73.10⁻⁸</td>
<td>6.04.10⁻⁸</td>
<td>7.09.10⁻⁸</td>
<td>5.48.10⁻⁸</td>
</tr>
<tr>
<td>900</td>
<td>8.93.10⁻⁸</td>
<td>6.15.10⁻⁸</td>
<td>7.33.10⁻⁸</td>
<td>5.67.10⁻⁸</td>
</tr>
<tr>
<td>1000</td>
<td>9.51.10⁻⁸</td>
<td>6.38.10⁻⁸</td>
<td>7.58.10⁻⁸</td>
<td>5.77.10⁻⁸</td>
</tr>
</tbody>
</table>
Effect of the drop at the bottom of the filter on the conductivity during static falling head tests

Table F.14: Data and calculated values of two static falling head tests with tube 17 to determine the effect of a drop at the bottom of the tube.

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Time</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>Conductivity filter $10^{-5} \text{ m s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>With drops</td>
<td>300</td>
<td>65.73</td>
<td>19.77</td>
<td>1.08</td>
</tr>
<tr>
<td>With drops</td>
<td>300</td>
<td>68.05</td>
<td>21.27</td>
<td>1.05</td>
</tr>
<tr>
<td>With drops</td>
<td>300</td>
<td>66.33</td>
<td>19.90</td>
<td>1.09</td>
</tr>
<tr>
<td>Without drops</td>
<td>300</td>
<td>67.70</td>
<td>16.51</td>
<td>1.26</td>
</tr>
<tr>
<td>Without drops</td>
<td>300</td>
<td>70.95</td>
<td>17.31</td>
<td>1.27</td>
</tr>
<tr>
<td>Without drops</td>
<td>300</td>
<td>70.29</td>
<td>16.90</td>
<td>1.28</td>
</tr>
</tbody>
</table>

Effects of the inside diameter on the conductivity

Table F.15: Resume of the conductivity of the filters 1, 2, 4 and 5 as calculated in tables F.6, F.7 and F.8.

<table>
<thead>
<tr>
<th>Filter number</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, $20.10^{-7}$</td>
<td>9, 64.10$^{-8}$</td>
<td>9, 44.10$^{-8}$</td>
<td>7, 94.10$^{-8}$</td>
<td></td>
</tr>
<tr>
<td>1, $19.10^{-7}$</td>
<td>9, 74.10$^{-8}$</td>
<td>9, 50.10$^{-8}$</td>
<td>8, 19.10$^{-8}$</td>
<td></td>
</tr>
<tr>
<td>1, $24.10^{-7}$</td>
<td>1, 01.10$^{-8}$</td>
<td>9, 92.10$^{-8}$</td>
<td>8, 30.10$^{-8}$</td>
<td></td>
</tr>
<tr>
<td>1, $15.10^{-7}$</td>
<td>9, 54.10$^{-8}$</td>
<td>9, 44.10$^{-8}$</td>
<td>8, 19.10$^{-8}$</td>
<td></td>
</tr>
<tr>
<td>1, $11.10^{-7}$</td>
<td>9, 20.10$^{-8}$</td>
<td>8, 98.10$^{-8}$</td>
<td>7, 79.10$^{-8}$</td>
<td></td>
</tr>
<tr>
<td>1, $13.10^{-7}$</td>
<td>9, 29.10$^{-8}$</td>
<td>9, 13.10$^{-8}$</td>
<td>7, 88.10$^{-8}$</td>
<td></td>
</tr>
<tr>
<td>1, $17.10^{-7}$</td>
<td>9, 46.10$^{-8}$</td>
<td>9, 18.10$^{-8}$</td>
<td>8, 03.10$^{-8}$</td>
<td></td>
</tr>
</tbody>
</table>
Table F.16: Resume of the conductivity of the filters 1, 2, 4 and 5 as calculated in tables F.6, F.7, F.8 and F.9 but with an inside diameter enlarged by 1 mm.

<table>
<thead>
<tr>
<th>Filter number</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 15.10^{-7}</td>
<td>9,231.10^{-8}</td>
<td>9,031.10^{-8}</td>
<td>7,571.10^{-8}</td>
<td></td>
</tr>
<tr>
<td>1, 14.10^{-7}</td>
<td>9,301.10^{-8}</td>
<td>9,091.10^{-8}</td>
<td>7,791.10^{-8}</td>
<td></td>
</tr>
<tr>
<td>1, 19.10^{-7}</td>
<td>9,631.10^{-8}</td>
<td>9,481.10^{-8}</td>
<td>7,911.10^{-8}</td>
<td></td>
</tr>
<tr>
<td>1, 11.10^{-7}</td>
<td>9,121.10^{-8}</td>
<td>9,051.10^{-8}</td>
<td>7,801.10^{-8}</td>
<td></td>
</tr>
<tr>
<td>1, 06.10^{-7}</td>
<td>8,801.10^{-8}</td>
<td>8,611.10^{-8}</td>
<td>7,431.10^{-8}</td>
<td></td>
</tr>
<tr>
<td>1, 08.10^{-7}</td>
<td>8,901.10^{-8}</td>
<td>8,781.10^{-8}</td>
<td>7,541.10^{-8}</td>
<td></td>
</tr>
<tr>
<td>1, 13.10^{-7}</td>
<td>9,091.10^{-8}</td>
<td>8,861.10^{-8}</td>
<td>7,681.10^{-8}</td>
<td></td>
</tr>
</tbody>
</table>

Table F.17: Difference in conductivity between tables F.15 and F.16 expressed in percentages relative to the values of table F.15.

<table>
<thead>
<tr>
<th>Filter number</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>4,54</td>
<td>4,68</td>
<td>4,76</td>
<td>5,11</td>
<td></td>
</tr>
<tr>
<td>4,61</td>
<td>4,99</td>
<td>4,75</td>
<td>5,36</td>
<td></td>
</tr>
<tr>
<td>4,67</td>
<td>5,10</td>
<td>4,83</td>
<td>5,20</td>
<td></td>
</tr>
<tr>
<td>4,40</td>
<td>4,90</td>
<td>4,61</td>
<td>5,37</td>
<td></td>
</tr>
<tr>
<td>4,44</td>
<td>4,80</td>
<td>4,63</td>
<td>5,14</td>
<td></td>
</tr>
<tr>
<td>4,30</td>
<td>4,65</td>
<td>4,32</td>
<td>4,71</td>
<td></td>
</tr>
<tr>
<td>3,89</td>
<td>4,35</td>
<td>3,82</td>
<td>4,73</td>
<td></td>
</tr>
</tbody>
</table>

Table F.18: Contributions expressed in percentages of the values in table F.17 to the differences between the average conductivities obtained by static and centrifuge tests.

<table>
<thead>
<tr>
<th>Filter number</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>16,22</td>
<td>16,55</td>
<td>17,05</td>
<td>17,41</td>
<td></td>
</tr>
<tr>
<td>16,31</td>
<td>17,83</td>
<td>17,11</td>
<td>18,85</td>
<td></td>
</tr>
<tr>
<td>17,32</td>
<td>18,89</td>
<td>18,15</td>
<td>18,53</td>
<td></td>
</tr>
<tr>
<td>15,12</td>
<td>17,17</td>
<td>16,51</td>
<td>18,88</td>
<td></td>
</tr>
<tr>
<td>14,69</td>
<td>16,20</td>
<td>15,76</td>
<td>17,18</td>
<td></td>
</tr>
<tr>
<td>14,46</td>
<td>15,85</td>
<td>14,95</td>
<td>15,92</td>
<td></td>
</tr>
<tr>
<td>13,58</td>
<td>15,08</td>
<td>13,31</td>
<td>16,29</td>
<td></td>
</tr>
</tbody>
</table>
F.1. RESULTS OF SATURATED CONDUCTIVITY TESTS OF THE FILTERS

Table F.19: Effect of a different inside diameter on the calculations for static falling head tests.

<table>
<thead>
<tr>
<th>Filter number</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>With diameter at level thread</td>
<td>7,88.10^{-8}</td>
<td>6,42.10^{-8}</td>
<td>6,35.10^{-8}</td>
<td>5,34.10^{-8}</td>
</tr>
<tr>
<td>With diameter at level thread + 1 mm</td>
<td>7,85.10^{-8}</td>
<td>6,40.10^{-8}</td>
<td>6,32.10^{-8}</td>
<td>5,32.10^{-8}</td>
</tr>
<tr>
<td>Difference [%]</td>
<td>0,38</td>
<td>0,38</td>
<td>0,37</td>
<td>0,36</td>
</tr>
</tbody>
</table>

F.1.2 Conductivity tests of filters with high conductivity

Table F.20: Data and calculated values for the conductivity of filter 7 obtained by static falling head tests.

<table>
<thead>
<tr>
<th>Time ordered</th>
<th>Time ordered</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>Conductivity filter $10^{-4} m/s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18,66</td>
<td>17,80</td>
<td>48.20</td>
<td>19.33</td>
<td>1.55</td>
</tr>
<tr>
<td>17,80</td>
<td>17,92</td>
<td>48.20</td>
<td>19.33</td>
<td>1.53</td>
</tr>
<tr>
<td>17,92</td>
<td>18,23</td>
<td>48.20</td>
<td>19.33</td>
<td>1.51</td>
</tr>
<tr>
<td>22,04</td>
<td>18,26</td>
<td>48.20</td>
<td>19.33</td>
<td>1.51</td>
</tr>
<tr>
<td>18,26</td>
<td>18,26</td>
<td>48.20</td>
<td>19.33</td>
<td>1.51</td>
</tr>
<tr>
<td>23,61</td>
<td>18,29</td>
<td>48.20</td>
<td>19.33</td>
<td>1.50</td>
</tr>
<tr>
<td>18,26</td>
<td>18,36</td>
<td>48.20</td>
<td>19.33</td>
<td>1.50</td>
</tr>
<tr>
<td>18,36</td>
<td>18,47</td>
<td>48.20</td>
<td>19.33</td>
<td>1.49</td>
</tr>
<tr>
<td>18,29</td>
<td>18,48</td>
<td>48.20</td>
<td>19.33</td>
<td>1.49</td>
</tr>
<tr>
<td>18,23</td>
<td>18,58</td>
<td>48.20</td>
<td>19.33</td>
<td>1.48</td>
</tr>
<tr>
<td>18,64</td>
<td>18,64</td>
<td>48.20</td>
<td>19.33</td>
<td>1.48</td>
</tr>
<tr>
<td>18,69</td>
<td>18,66</td>
<td>48.20</td>
<td>19.33</td>
<td>1.47</td>
</tr>
<tr>
<td>18,48</td>
<td>18,69</td>
<td>48.20</td>
<td>19.33</td>
<td>1.47</td>
</tr>
<tr>
<td>18,47</td>
<td>22,04</td>
<td>48.20</td>
<td>19.33</td>
<td>1.25</td>
</tr>
<tr>
<td>18,58</td>
<td>23,61</td>
<td>48.20</td>
<td>19.33</td>
<td>1.17</td>
</tr>
</tbody>
</table>
### Table F.21: Data and calculated values for the conductivity of filter 8 obtained by static falling head tests.

<table>
<thead>
<tr>
<th>Time $s$</th>
<th>Time ordered $s$</th>
<th>$H_1$ mm</th>
<th>$H_2$ mm</th>
<th>Conductivity filter $10^{-5}$ m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.33</td>
<td>31.85</td>
<td>47.30</td>
<td>19.28</td>
<td>9.66</td>
</tr>
<tr>
<td>31.85</td>
<td>32.23</td>
<td>47.30</td>
<td>19.28</td>
<td>9.55</td>
</tr>
<tr>
<td>32.23</td>
<td>32.33</td>
<td>47.30</td>
<td>19.28</td>
<td>9.52</td>
</tr>
<tr>
<td>34.42</td>
<td>33.72</td>
<td>47.30</td>
<td>19.28</td>
<td>9.12</td>
</tr>
<tr>
<td>33.72</td>
<td>33.80</td>
<td>47.30</td>
<td>19.28</td>
<td>9.10</td>
</tr>
<tr>
<td>34.54</td>
<td>34.10</td>
<td>47.30</td>
<td>19.28</td>
<td>9.02</td>
</tr>
<tr>
<td>33.80</td>
<td>34.23</td>
<td>47.30</td>
<td>19.28</td>
<td>8.99</td>
</tr>
<tr>
<td>34.23</td>
<td>34.30</td>
<td>47.30</td>
<td>19.28</td>
<td>8.97</td>
</tr>
<tr>
<td>34.10</td>
<td>34.42</td>
<td>47.30</td>
<td>19.28</td>
<td>8.94</td>
</tr>
<tr>
<td>34.45</td>
<td>34.45</td>
<td>47.30</td>
<td>19.28</td>
<td>8.93</td>
</tr>
<tr>
<td>35.70</td>
<td>34.54</td>
<td>47.30</td>
<td>19.28</td>
<td>8.91</td>
</tr>
<tr>
<td>34.30</td>
<td>35.70</td>
<td>47.30</td>
<td>19.28</td>
<td>8.62</td>
</tr>
<tr>
<td>36.51</td>
<td>36.51</td>
<td>47.30</td>
<td>19.28</td>
<td>8.43</td>
</tr>
<tr>
<td>36.67</td>
<td>36.67</td>
<td>47.30</td>
<td>19.28</td>
<td>8.39</td>
</tr>
<tr>
<td>36.98</td>
<td>36.98</td>
<td>47.30</td>
<td>19.28</td>
<td>8.32</td>
</tr>
</tbody>
</table>

### Table F.22: Data and calculated values for the conductivity of filters 16 and 17 obtained by static falling head tests.

<table>
<thead>
<tr>
<th>Tube nr</th>
<th>Time $s$</th>
<th>$H_1$ mm</th>
<th>$H_2$ mm</th>
<th>Conductivity filter $10^{-5}$ m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>300</td>
<td>66.15</td>
<td>13.52</td>
<td>1.36</td>
</tr>
<tr>
<td>16</td>
<td>300</td>
<td>74.02</td>
<td>15.83</td>
<td>1.34</td>
</tr>
<tr>
<td>17</td>
<td>300</td>
<td>66.30</td>
<td>19.33</td>
<td>1.11</td>
</tr>
<tr>
<td>17</td>
<td>300</td>
<td>69.86</td>
<td>20.94</td>
<td>1.09</td>
</tr>
</tbody>
</table>
Table F.23: Average conductivities of filters 7, 8, 16 and 17 obtained by static falling head tests.

<table>
<thead>
<tr>
<th>Tube number</th>
<th>Average conductivity $\text{m s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>$1.49 \times 10^{-4}$</td>
</tr>
<tr>
<td>8</td>
<td>$8.96 \times 10^{-5}$</td>
</tr>
<tr>
<td>16</td>
<td>$1.35 \times 10^{-5}$</td>
</tr>
<tr>
<td>17</td>
<td>$1.10 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

F.2 Results of saturated tests of kaolin clay

Table F.24: Data and calculated values of centrifuge tests carried out on kaolin clay pre-consolidated with weights at 45 kPa in order to determine the saturated conductivity. The g-level $N$ was calculated according to formula (4.9).

<table>
<thead>
<tr>
<th>Tube nr.</th>
<th>Time</th>
<th>rpm</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>L</th>
<th>N</th>
<th>Total conductivity $10^{-8} \text{m s}^{-1}$</th>
<th>Conductivity filter $10^{-7} \text{m s}^{-1}$</th>
<th>Conductivity mixture $10^{-8} \text{m s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3600</td>
<td>1000</td>
<td>23.57</td>
<td>19.98</td>
<td>34.40</td>
<td>111.86</td>
<td>2.36</td>
<td>1.64</td>
<td>2.20</td>
</tr>
<tr>
<td>2</td>
<td>3600</td>
<td>1000</td>
<td>25.74</td>
<td>22.34</td>
<td>37.45</td>
<td>107.01</td>
<td>2.36</td>
<td>1.40</td>
<td>2.21</td>
</tr>
</tbody>
</table>

Table F.25: Data and calculated values of centrifuge tests carried out on kaolin clay pre-consolidated with weights at 45 kPa in order to determine the saturated conductivity. The g-level $N$ was calculated according to formula (4.8).

<table>
<thead>
<tr>
<th>Tube nr.</th>
<th>Time</th>
<th>rpm</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>L</th>
<th>N</th>
<th>Total conductivity $10^{-8} \text{m s}^{-1}$</th>
<th>Conductivity filter $10^{-7} \text{m s}^{-1}$</th>
<th>Conductivity mixture $10^{-8} \text{m s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3600</td>
<td>1000</td>
<td>23.57</td>
<td>19.98</td>
<td>34.40</td>
<td>143.25</td>
<td>1.84</td>
<td>1.64</td>
<td>1.71</td>
</tr>
<tr>
<td>2</td>
<td>3600</td>
<td>1000</td>
<td>25.74</td>
<td>22.34</td>
<td>37.45</td>
<td>141.38</td>
<td>1.79</td>
<td>1.40</td>
<td>1.67</td>
</tr>
</tbody>
</table>
## F.2. RESULTS OF SATURATED TESTS OF KAOLIN CLAY

Table F.26: Data and calculated values of centrifuge tests carried out on kaolin clay pre-consolidated in the centrifuge at 1000 rpm in order to determine the saturated conductivity. The g-level $N$ was calculated according to formula (4.9).

<table>
<thead>
<tr>
<th>Tube nr.</th>
<th>Time</th>
<th>rpm</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>L</th>
<th>N</th>
<th>Total conductivity</th>
<th>Conductivity filter</th>
<th>Conductivity mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>s</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>#g</td>
<td>$10^{-8}$ m/s</td>
<td>$10^{-7}$ m/s</td>
<td>$10^{-8}$ m/s</td>
</tr>
<tr>
<td>1</td>
<td>900</td>
<td>1000</td>
<td>12,97</td>
<td>10,71</td>
<td>40,40</td>
<td>110,70</td>
<td>2,22</td>
<td>1,64</td>
<td>2,04</td>
</tr>
<tr>
<td>2</td>
<td>900</td>
<td>1000</td>
<td>10,26</td>
<td>8,14</td>
<td>44,85</td>
<td>107,03</td>
<td>2,32</td>
<td>1,40</td>
<td>2,13</td>
</tr>
<tr>
<td>4</td>
<td>900</td>
<td>1000</td>
<td>14,13</td>
<td>12,00</td>
<td>42,80</td>
<td>107,34</td>
<td>2,18</td>
<td>1,34</td>
<td>2,00</td>
</tr>
<tr>
<td>5</td>
<td>900</td>
<td>1000</td>
<td>11,67</td>
<td>9,50</td>
<td>44,35</td>
<td>106,88</td>
<td>2,33</td>
<td>1,22</td>
<td>2,14</td>
</tr>
</tbody>
</table>

Table F.27: Data and calculated values of centrifuge tests carried out on kaolin clay pre-consolidated in the centrifuge at 1000 rpm in order to determine the saturated conductivity. The g-level $N$ was calculated according to formula (4.8).

<table>
<thead>
<tr>
<th>Tube nr.</th>
<th>Time</th>
<th>rpm</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>L</th>
<th>N</th>
<th>Total conductivity</th>
<th>Conductivity filter</th>
<th>Conductivity mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>s</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>#g</td>
<td>$10^{-8}$ m/s</td>
<td>$10^{-7}$ m/s</td>
<td>$10^{-8}$ m/s</td>
</tr>
<tr>
<td>1</td>
<td>900</td>
<td>1000</td>
<td>12,97</td>
<td>10,71</td>
<td>40,40</td>
<td>139,90</td>
<td>1,73</td>
<td>1,64</td>
<td>1,62</td>
</tr>
<tr>
<td>2</td>
<td>900</td>
<td>1000</td>
<td>10,26</td>
<td>8,14</td>
<td>44,85</td>
<td>137,25</td>
<td>1,78</td>
<td>1,40</td>
<td>1,67</td>
</tr>
<tr>
<td>4</td>
<td>900</td>
<td>1000</td>
<td>14,13</td>
<td>12,00</td>
<td>42,80</td>
<td>138,56</td>
<td>1,66</td>
<td>1,34</td>
<td>1,56</td>
</tr>
<tr>
<td>5</td>
<td>900</td>
<td>1000</td>
<td>11,67</td>
<td>9,50</td>
<td>44,35</td>
<td>137,58</td>
<td>1,78</td>
<td>1,22</td>
<td>1,67</td>
</tr>
</tbody>
</table>

Table F.28: Data and calculated values of a static falling head test carried out on kaolin clay pre-consolidated with weights at 45 kPa in order to determine the saturated conductivity.

<table>
<thead>
<tr>
<th>Tube nr.</th>
<th>Time</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>L</th>
<th>Total Conductivity</th>
<th>Conductivity filter</th>
<th>Conductivity mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>s</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>$10^{-8}$ m/s</td>
<td>$10^{-8}$ m/s</td>
<td>$10^{-8}$ m/s</td>
</tr>
<tr>
<td>4</td>
<td>130300</td>
<td>28,57</td>
<td>24,81</td>
<td>41,10</td>
<td>1,80</td>
<td>6,35</td>
<td>1,71</td>
</tr>
<tr>
<td>5</td>
<td>129900</td>
<td>27,69</td>
<td>23,02</td>
<td>41,85</td>
<td>2,30</td>
<td>5,34</td>
<td>2,21</td>
</tr>
</tbody>
</table>
Table F.29: Data and calculated values of a static falling head test carried out on kaolin clay pre-consolidated in the centrifuge at 1000 rpm in order to determine the saturated conductivity.

<table>
<thead>
<tr>
<th>Tube nr.</th>
<th>Time (s)</th>
<th>$H_1$ (mm)</th>
<th>$H_2$ (mm)</th>
<th>L (mm)</th>
<th>Total conductivity filter $10^{-8}$ m/s</th>
<th>Conductivity mixture $10^{-8}$ m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>406200</td>
<td>35.23</td>
<td>27.02</td>
<td>40.45</td>
<td>1.18</td>
<td>7.88</td>
</tr>
<tr>
<td>2</td>
<td>129900</td>
<td>30.11</td>
<td>22.22</td>
<td>44.80</td>
<td>1.26</td>
<td>6.42</td>
</tr>
<tr>
<td>4</td>
<td>130300</td>
<td>32.52</td>
<td>23.34</td>
<td>42.90</td>
<td>1.41</td>
<td>6.35</td>
</tr>
<tr>
<td>5</td>
<td>129900</td>
<td>31.63</td>
<td>23.20</td>
<td>44.40</td>
<td>1.32</td>
<td>5.34</td>
</tr>
</tbody>
</table>

F.3 Results of saturated tests of Mol sand

Table F.30: Data and calculated values of the static falling head tests carried out with tube 7 to determine the conductivity of Mol sand.

<table>
<thead>
<tr>
<th>Time ordered (s)</th>
<th>Time (s)</th>
<th>$H_1$ (mm)</th>
<th>$H_2$ (mm)</th>
<th>L (mm)</th>
<th>Total conductivity filter $m/s$</th>
<th>Conductivity mixture filter $m/s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>69.54</td>
<td>69.54</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000104</td>
<td>0.000149</td>
</tr>
<tr>
<td>70.61</td>
<td>69.55</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000104</td>
<td>0.000149</td>
</tr>
<tr>
<td>70.45</td>
<td>69.76</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000104</td>
<td>0.000149</td>
</tr>
<tr>
<td>70.00</td>
<td>69.85</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000104</td>
<td>0.000149</td>
</tr>
<tr>
<td>70.27</td>
<td>69.93</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000103</td>
<td>0.000149</td>
</tr>
<tr>
<td>69.55</td>
<td>69.96</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000103</td>
<td>0.000149</td>
</tr>
<tr>
<td>69.93</td>
<td>69.99</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000103</td>
<td>0.000149</td>
</tr>
<tr>
<td>69.76</td>
<td>70.00</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000103</td>
<td>0.000149</td>
</tr>
<tr>
<td>70.35</td>
<td>70.05</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000103</td>
<td>0.000149</td>
</tr>
<tr>
<td>70.15</td>
<td>70.12</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000103</td>
<td>0.000149</td>
</tr>
<tr>
<td>70.05</td>
<td>70.15</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000103</td>
<td>0.000149</td>
</tr>
<tr>
<td>70.12</td>
<td>70.27</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000103</td>
<td>0.000149</td>
</tr>
<tr>
<td>69.85</td>
<td>70.35</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000103</td>
<td>0.000149</td>
</tr>
<tr>
<td>69.96</td>
<td>70.45</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000103</td>
<td>0.000149</td>
</tr>
<tr>
<td>69.99</td>
<td>70.61</td>
<td>56.10</td>
<td>36.38</td>
<td>26.55</td>
<td>0.000102</td>
<td>0.000149</td>
</tr>
</tbody>
</table>
Table F.31: Data and calculated values of the static falling head tests carried out with tube 8 to determine the conductivity of Mol sand.

<table>
<thead>
<tr>
<th>Time ordered</th>
<th>Time</th>
<th>H₁</th>
<th>H₂</th>
<th>L</th>
<th>Total conductivity</th>
<th>Conductivity filter</th>
<th>Conductivity sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>s</td>
<td>s</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>m/s</td>
<td>m/s</td>
<td>m/s</td>
</tr>
<tr>
<td>65.61</td>
<td>65.35</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000102</td>
<td>0.000090</td>
<td>0.000105</td>
</tr>
<tr>
<td>65.62</td>
<td>65.39</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000102</td>
<td>0.000090</td>
<td>0.000105</td>
</tr>
<tr>
<td>65.46</td>
<td>65.46</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000102</td>
<td>0.000090</td>
<td>0.000105</td>
</tr>
<tr>
<td>67.16</td>
<td>65.48</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000102</td>
<td>0.000090</td>
<td>0.000105</td>
</tr>
<tr>
<td>65.56</td>
<td>65.49</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000102</td>
<td>0.000090</td>
<td>0.000105</td>
</tr>
<tr>
<td>65.35</td>
<td>65.51</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000102</td>
<td>0.000090</td>
<td>0.000105</td>
</tr>
<tr>
<td>65.58</td>
<td>65.56</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000102</td>
<td>0.000090</td>
<td>0.000105</td>
</tr>
<tr>
<td>65.72</td>
<td>65.58</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000102</td>
<td>0.000090</td>
<td>0.000105</td>
</tr>
<tr>
<td>65.94</td>
<td>65.60</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000102</td>
<td>0.000090</td>
<td>0.000105</td>
</tr>
<tr>
<td>65.60</td>
<td>65.61</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000102</td>
<td>0.000090</td>
<td>0.000105</td>
</tr>
<tr>
<td>65.48</td>
<td>65.62</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000102</td>
<td>0.000090</td>
<td>0.000105</td>
</tr>
<tr>
<td>65.49</td>
<td>65.72</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000102</td>
<td>0.000090</td>
<td>0.000105</td>
</tr>
<tr>
<td>65.51</td>
<td>65.94</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000101</td>
<td>0.000090</td>
<td>0.000104</td>
</tr>
<tr>
<td>66.44</td>
<td>66.44</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000101</td>
<td>0.000090</td>
<td>0.000103</td>
</tr>
<tr>
<td>65.39</td>
<td>67.16</td>
<td>55.35</td>
<td>35.38</td>
<td>22.56</td>
<td>0.000099</td>
<td>0.000090</td>
<td>0.000102</td>
</tr>
</tbody>
</table>
F.4. RESULTS OF SATURATED TESTS OF 90% MOL SAND + 10% KAOLIN CLAY MIXTURES

F.3.1 Slicing test carried out of Mol sand samples

Table F.32: Results of four slicing tests carried out on saturated Mol sand samples that were exposed to saturated flow in the centrifuge at 400 rpm, ordered from the top of the sample to the bottom of the sample.

<table>
<thead>
<tr>
<th>Sample nr.</th>
<th>Mass of water</th>
<th>Mass of soil</th>
<th>Sample surface</th>
<th>Sample height</th>
<th>Void ratio</th>
<th>Water content</th>
<th>Saturation degree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g</td>
<td>g</td>
<td>mm²</td>
<td>mm</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>1</td>
<td>0.96</td>
<td>4.17</td>
<td>194,8278</td>
<td>14.35</td>
<td>77.67</td>
<td>23.02</td>
<td>78.55</td>
</tr>
<tr>
<td></td>
<td>0.89</td>
<td>3.77</td>
<td>194,8278</td>
<td>12.95</td>
<td>77.35</td>
<td>23.61</td>
<td>80.88</td>
</tr>
<tr>
<td></td>
<td>0.92</td>
<td>3.69</td>
<td>194,8278</td>
<td>13.75</td>
<td>92.39</td>
<td>24.93</td>
<td>71.52</td>
</tr>
<tr>
<td>2</td>
<td>0.92</td>
<td>3.76</td>
<td>194,8278</td>
<td>13.75</td>
<td>88.80</td>
<td>24.47</td>
<td>73.02</td>
</tr>
<tr>
<td></td>
<td>0.89</td>
<td>3.85</td>
<td>194,8278</td>
<td>13.47</td>
<td>80.64</td>
<td>23.12</td>
<td>75.97</td>
</tr>
<tr>
<td></td>
<td>0.91</td>
<td>3.90</td>
<td>194,8278</td>
<td>13.59</td>
<td>79.91</td>
<td>23.33</td>
<td>77.38</td>
</tr>
<tr>
<td>3</td>
<td>0.94</td>
<td>3.90</td>
<td>194,8278</td>
<td>14.15</td>
<td>87.32</td>
<td>24.10</td>
<td>73.15</td>
</tr>
<tr>
<td></td>
<td>0.97</td>
<td>4.10</td>
<td>194,8278</td>
<td>14.45</td>
<td>81.96</td>
<td>23.66</td>
<td>76.49</td>
</tr>
<tr>
<td></td>
<td>0.91</td>
<td>3.79</td>
<td>194,8278</td>
<td>13.75</td>
<td>87.31</td>
<td>24.01</td>
<td>72.88</td>
</tr>
<tr>
<td>4</td>
<td>0.91</td>
<td>3.97</td>
<td>194,8278</td>
<td>13.35</td>
<td>73.62</td>
<td>22.92</td>
<td>82.51</td>
</tr>
<tr>
<td></td>
<td>0.94</td>
<td>4.03</td>
<td>194,8278</td>
<td>14.55</td>
<td>86.40</td>
<td>23.33</td>
<td>71.54</td>
</tr>
<tr>
<td></td>
<td>0.76</td>
<td>3.14</td>
<td>194,8278</td>
<td>11.40</td>
<td>87.44</td>
<td>24.20</td>
<td>73.35</td>
</tr>
</tbody>
</table>

F.4 Results of saturated tests of 90% Mol sand + 10% kaolin clay mixtures

Table F.33: Data and calculated values of a static falling head test carried out with tube 16 to determine the conductivity of a 90% Mol sand + 10% kaolin clay mixture pre-consolidated at 45 kPa.

<table>
<thead>
<tr>
<th>Time</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>L</th>
<th>Total conductivity</th>
<th>Conductivity filter</th>
<th>Conductivity mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>s</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>$10^{-6}$ m s$^{-1}$</td>
<td>$10^{-5}$ m s$^{-1}$</td>
<td>$10^{-6}$ m s$^{-1}$</td>
</tr>
<tr>
<td>1560</td>
<td>20.37</td>
<td>3.84</td>
<td>48.53</td>
<td>8.62</td>
<td>1.35</td>
<td>8.45</td>
</tr>
</tbody>
</table>
F.4. RESULTS OF SATURATED TESTS OF 90% MOL SAND + 10% KAOLIN CLAY MIXTURES

Table F.34: Data and calculated values of a centrifuge test carried out with tube 16 to determine the conductivity of a 90% Mol sand + 10% kaolin clay mixture pre-consolidated at 45 kPa.

<table>
<thead>
<tr>
<th>Time</th>
<th>rpm</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>L</th>
<th>N</th>
<th>Total conductivity</th>
<th>Conductivity filter</th>
<th>Conductivity mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>s</td>
<td></td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>#g</td>
<td>$10^{-6} \text{ m s}^{-1}$</td>
<td>$10^{-5} \text{ m s}^{-1}$</td>
<td>$10^{-6} \text{ m s}^{-1}$</td>
</tr>
<tr>
<td>300</td>
<td>300</td>
<td>28,44</td>
<td>4,04</td>
<td>48,53</td>
<td>12,47</td>
<td>6,08</td>
<td>1,35</td>
<td>5,87</td>
</tr>
</tbody>
</table>

Table F.35: Data and calculated values of a centrifuge test carried out with tube 16 to determine the conductivity of a 90% Mol sand + 10% kaolin clay mixture pre-consolidated at 100 kPa.

<table>
<thead>
<tr>
<th>Time</th>
<th>rpm</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>L</th>
<th>N</th>
<th>Total conductivity</th>
<th>Conductivity filter</th>
<th>Conductivity mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>s</td>
<td></td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>#g</td>
<td>$10^{-6} \text{ m s}^{-1}$</td>
<td>$10^{-5} \text{ m s}^{-1}$</td>
<td>$10^{-6} \text{ m s}^{-1}$</td>
</tr>
<tr>
<td>120</td>
<td>600</td>
<td>21,79</td>
<td>7,01</td>
<td>57,46</td>
<td>46,96</td>
<td>2,64</td>
<td>1,35</td>
<td>2,53</td>
</tr>
<tr>
<td>120</td>
<td>600</td>
<td>19,59</td>
<td>5,04</td>
<td>57,46</td>
<td>46,96</td>
<td>2,66</td>
<td>1,35</td>
<td>2,55</td>
</tr>
</tbody>
</table>

F.4.1 Slicing tests of kaolin clay samples

Table F.36: Results of two slicing tests carried out on kaolin clay samples drained at 1000 rpm, ordered from the top of the sample to the bottom of the sample.

<table>
<thead>
<tr>
<th>Sample nr.</th>
<th>Jar nr.</th>
<th>Weight jar empty</th>
<th>Weight jar + wet soil</th>
<th>Weight jar + dry soil</th>
<th>Water content</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>U05</td>
<td>17,92</td>
<td>21,02</td>
<td>19,91</td>
<td>55,78</td>
</tr>
<tr>
<td></td>
<td>P54</td>
<td>19,09</td>
<td>22,64</td>
<td>21,38</td>
<td>55,02</td>
</tr>
<tr>
<td></td>
<td>P52</td>
<td>19,18</td>
<td>22,58</td>
<td>21,42</td>
<td>51,79</td>
</tr>
<tr>
<td>5</td>
<td>U18</td>
<td>17,74</td>
<td>20,94</td>
<td>19,81</td>
<td>54,59</td>
</tr>
<tr>
<td></td>
<td>U19</td>
<td>17,88</td>
<td>22,42</td>
<td>20,83</td>
<td>53,90</td>
</tr>
<tr>
<td></td>
<td>U15</td>
<td>18,26</td>
<td>20,55</td>
<td>19,75</td>
<td>53,69</td>
</tr>
</tbody>
</table>
G.1 Results of imbibition tests of dry kaolin clay

The following graphs and tables represent the results from imbibition tests on dry kaolin clay at 1000 and 500 rpm as described in paragraph 4.4.1.

G.1.1 Imbibition at 1000 rpm of kaolin clay

Figure G.1: Height of soil in function of time for an imbibition test at 1000 rpm on kaolin clay.
G.1. RESULTS OF IMBIBITION TESTS OF DRY KAOLIN CLAY

**Figure G.2:** Scaled height of soil in function of time for an imbibition test at 1000 rpm on kaolin.

**Figure G.3:** Weight of the samples in function of time for an imbibition test at 1000 rpm on kaolin clay.
G.1. RESULTS OF IMBIBITION TESTS OF DRY KAOLIN CLAY

Figure G.4: Cumulative weight of the outflow water in function of time for an imbibition test at 1000 rpm on kaolin clay.

Figure G.5: Position of the cog of the water in function of time for an imbibition test at 1000 rpm on kaolin clay.
Figure G.6: Scaled position of the cog of the water in function of time for an imbibition test at 1000 rpm on kaolin clay.

Figure G.7: Picture of a clay sample at the end of an imbibition test at 1000 rpm.
Table G.1: Accuracy of the cog measurements at the start of the imbibition test at 1000 rpm on kaolin clay according to the cog of the soil.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube number</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Initial position of cog of the soil</td>
<td>30,29</td>
<td>30,80</td>
</tr>
<tr>
<td>Initial midpoint of the soil</td>
<td>29,95</td>
<td>30,33</td>
</tr>
<tr>
<td>Difference</td>
<td>0,34</td>
<td>0,47</td>
</tr>
</tbody>
</table>

Table G.2: Results after the imbibition test at 1000 rpm on kaolin clay.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube number</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Total volume of soil</td>
<td>17417</td>
<td>16744</td>
</tr>
<tr>
<td>Specific weight</td>
<td>0,00265</td>
<td>0,00265</td>
</tr>
<tr>
<td>Total mass of soil</td>
<td>20,28</td>
<td>19,60</td>
</tr>
<tr>
<td>Volume soil without pores</td>
<td>7653</td>
<td>7396</td>
</tr>
<tr>
<td>Volume of pores</td>
<td>9764</td>
<td>9348</td>
</tr>
<tr>
<td>Void ratio e</td>
<td>127,59</td>
<td>126,39</td>
</tr>
<tr>
<td>Density water</td>
<td>0,001</td>
<td>0,001</td>
</tr>
<tr>
<td>Water in pores at the end</td>
<td>9,28</td>
<td>9,02</td>
</tr>
<tr>
<td>Volume of water in pores</td>
<td>9280</td>
<td>9020</td>
</tr>
<tr>
<td>Water content at the end</td>
<td>45,76</td>
<td>46,02</td>
</tr>
<tr>
<td>Saturation degree at the end</td>
<td>95,04</td>
<td>96,49</td>
</tr>
</tbody>
</table>

G.1.2 Imbibition at 500 rpm of kaolin clay

As mentioned in paragraph 4.4.1 rhodamine was used on sample 2 and no values are added for tube number 1 because of an irregularity in this sample.
G.1. RESULTS OF IMBIBITION TESTS OF DRY KAOLIN CLAY

Figure G.8: Height of soil in function of time for an imbibition test at 500 rpm on kaolin clay.

Figure G.9: Scaled height of soil in function of time for an imbibition test at 500 rpm on kaolin clay.
**G.1. RESULTS OF IMBIBITION TESTS OF DRY KAOLIN CLAY**

![Graph showing weight of samples over time](image)

**Figure G.10:** Weight of the samples in function of time for an imbibition test at 500 rpm on kaolin clay.

![Graph showing cumulative weight of outflow water over time](image)

**Figure G.11:** Cumulative weight of the outflow water in function of time for an imbibition test at 500 rpm on kaolin clay.
G.1. RESULTS OF IMBIBITION TESTS OF DRY KAOLIN CLAY

Figure G.12: Position of the cog of the water in function of time for an imbibition test at 500 rpm on kaolin clay.

Figure G.13: Scaled position of the cog of the water in function of time for an imbibition test at 500 rpm on kaolin clay.
Figure G.14: Picture of a clay sample at the end of an imbibition test at 500 rpm.

Table G.3: Accuracy of the cog measurements at the start of the imbibition test at 500 rpm according to the cog of the soil.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube number</td>
<td>2 4 5</td>
<td>-</td>
</tr>
<tr>
<td>Initial position of cog of the soil</td>
<td>33,14 31,70 34,09</td>
<td>mm</td>
</tr>
<tr>
<td>Initial midpoint of the soil</td>
<td>31,98 30,9 33,68</td>
<td>mm</td>
</tr>
<tr>
<td>Difference</td>
<td>1,17 0,80 0,41</td>
<td>mm</td>
</tr>
</tbody>
</table>
G.2 RESULTS OF AN IMBIBITION TEST OF A DRY MIXTURE OF 90% MOL SAND + 10% KAOLIN CLAY

Table G.4: Results after the imbibition test at 500 rpm on kaolin clay.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube number</td>
<td>2 4 5</td>
<td>-</td>
</tr>
<tr>
<td>Total volume of soil</td>
<td>19860 20128 21135</td>
<td>mm³</td>
</tr>
<tr>
<td>Specific weight</td>
<td>0,00265 0,00265 0,00265</td>
<td>g/mm³</td>
</tr>
<tr>
<td>Total mass of soil</td>
<td>23,00 22,22 23,95</td>
<td>g</td>
</tr>
<tr>
<td>Volume soil without pores</td>
<td>8679 8385 9038</td>
<td>mm³</td>
</tr>
<tr>
<td>Volume of pores</td>
<td>11181 11743 12098</td>
<td>mm³</td>
</tr>
<tr>
<td>Void ratio e</td>
<td>128,82 140,05 133,86</td>
<td>%</td>
</tr>
<tr>
<td>Density water</td>
<td>0,001 0,001 0,001</td>
<td>g/mm³</td>
</tr>
<tr>
<td>Water in pores at the end</td>
<td>11,18 10,99 11,95</td>
<td>g</td>
</tr>
<tr>
<td>Volume of water in pores</td>
<td>11180 10990 11950</td>
<td>mm³</td>
</tr>
<tr>
<td>Water content at the end</td>
<td>0,49 0,49 0,50</td>
<td>%</td>
</tr>
<tr>
<td>Saturation degree at the end</td>
<td>99,99 93,59 98,78</td>
<td>%</td>
</tr>
</tbody>
</table>

G.2 Results of an imbibition test of a dry mixture of 90% Mol sand + 10% kaolin clay

The results in this section are from a static imbibition test. The sample was preconsolidated dry at 75 kPa. A water level was provided at the bottom of the sample reaching to the top of the filter. Filter number 8 was used because it has a large conductivity and therefore has a low effect on the total flow. The length of the soil remained constant during the test.
G.2. RESULTS OF AN IMBIBITION TEST OF A DRY MIXTURE OF 90% MOL SAND + 10% KAOLIN CLAY

Figure G.15: Position of the cog of the water in function of time for a static imbibition test on a mixture with water supply at the bottom.

Figure G.16: Cumulative weight of the inflow water in function of time for a static imbibition test on a mixture with water supply at the bottom.
Table G.5: Main results at the end of a static imbibition test on a mixture with water supply at the bottom.

<table>
<thead>
<tr>
<th>Height of soil (mm)</th>
<th>Mass of soil (g)</th>
<th>Weight of water (g)</th>
<th>Void ratio (%)</th>
<th>Saturation degree (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65.48</td>
<td>38.37</td>
<td>8.16</td>
<td>65.87</td>
<td>85.56</td>
</tr>
</tbody>
</table>

Table G.6: Data and calculated values of centrifuge tests carried out with tube 8 to determine the conductivity of a 90% Mol sand + 10% kaolin clay mixture pre-consolidated at 75 kPa.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>rpm</th>
<th>$h_1$ (mm)</th>
<th>$h_2$ (mm)</th>
<th>L (mm)</th>
<th>$r_N$ (mm)</th>
<th>N</th>
<th>Total conductivity $10^{-6}$ m s^{-1}</th>
<th>Conductivity filter $10^{-5}$ m s^{-1}</th>
<th>Conductivity mixture $10^{-6}$ m s^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>300</td>
<td>9.30</td>
<td>4.63</td>
<td>69.16</td>
<td>73.67</td>
<td>7.41</td>
<td>6.44</td>
<td>8.96</td>
<td>6.10</td>
</tr>
<tr>
<td>120</td>
<td>300</td>
<td>9.08</td>
<td>4.39</td>
<td>69.16</td>
<td>73.78</td>
<td>7.42</td>
<td>6.48</td>
<td>8.96</td>
<td>6.14</td>
</tr>
<tr>
<td>120</td>
<td>300</td>
<td>8.94</td>
<td>4.28</td>
<td>69.16</td>
<td>73.84</td>
<td>7.43</td>
<td>6.44</td>
<td>8.96</td>
<td>6.11</td>
</tr>
</tbody>
</table>
H.1 Results of drainage tests of saturated kaolin clay

As mentioned in paragraph 4.5.1 two drainage tests were carried out on kaolin clay starting from a saturated sample. The first test was carried out at 1000 rpm. No centre of gravity measurements were taken because the set-up was not ready yet. The second test was carried out at 800 rpm and continuously at 1000 rpm. Centre of gravity measurements were taken during this test. The results are displayed in the following graphs and also some table were added with some indications of the obtained accuracy.

H.1.1 Drainage test of kaolin clay at 1000 rpm

![Graph showing the height of soil over time for a drainage test at 1000 rpm on kaolin clay.]

**Figure H.1:** Height of soil in function of time for a drainage test at 1000 rpm on kaolin clay.
**H.1. RESULTS OF DRAINAGE TESTS OF SATURATED KAOLIN CLAY**

![Graph](image)

**Figure H.2:** Scaled height of soil in function of time for a drainage test at 1000 rpm on kaolin clay.

![Graph](image)

**Figure H.3:** Cumulative weight of the outflow water in function of time for a drainage test at 1000 rpm on kaolin clay.
Figure H.4: Effective saturation degree in function of time for a drainage test at 1000 rpm on kaolin clay.
H.1. RESULTS OF DRAINAGE TESTS OF SATURATED KAOLIN CLAY

H.1.2 Drainage test of kaolin clay at 800 and 1000 rpm

Figure H.5: Height of soil in function of time for a drainage test at 800 (top) and 1000 rpm (bottom) on kaolin clay.
H.1. RESULTS OF DRAINAGE TESTS OF SATURATED KAOLIN CLAY

Figure H.6: Scaled height of soil in function of time for a drainage test at 800 (top) and 1000 rpm (bottom) on kaolin clay.
**H.1. RESULTS OF DRAINAGE TESTS OF SATURATED KAOLIN CLAY**

Figure H.7: Cumulative weight of the outflow water in function of time for a drainage test at 800 and 1000 rpm on kaolin clay.

Figure H.8: Effective saturation degree in function of time for a drainage test at 800 and 1000 rpm on kaolin clay.
H.1. RESULTS OF DRAINAGE TESTS OF SATURATED KAOLIN CLAY

Figure H.9: Position of the cog of the water in function of time for a drainage test on kaolin clay at 800 and 1000 rpm.

Table H.1: Accuracy of the cog measurements at the start of the drainage test on kaolin clay at 800 + 1000 rpm according to the total cog.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube number</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Initial position of the total cog with formula (3.8)</td>
<td>32,286 31,978 31,830 32,061</td>
<td>mm</td>
</tr>
<tr>
<td>Initial position of the total cog according to the second method</td>
<td>32,380 31,981 32,009 32,154</td>
<td>mm</td>
</tr>
<tr>
<td>Difference</td>
<td>-0,094 -0,003 -0,179 -0,093</td>
<td>mm</td>
</tr>
</tbody>
</table>

Table H.2: Accuracy of the cog measurements at the start of the drainage test on kaolin clay at 800 + 1000 rpm according to the cog of the soil.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube number</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Initial position of the cog of the soil</td>
<td>17,28 17,16 16,69 17,17</td>
<td>mm</td>
</tr>
<tr>
<td>Initial midpoint of the soil</td>
<td>17,80 17,18 17,65 17,68</td>
<td>mm</td>
</tr>
<tr>
<td>Difference</td>
<td>-0,52 -0,02 -0,96 -0,51</td>
<td>mm</td>
</tr>
</tbody>
</table>
H.2 Results of drainage tests of saturated Mol sand

Figure H.10: Numbers of rpm used in function of time for a drainage test on two saturated Mol sand samples.

Figure H.11: Cumulative weight of the outflow water in function of time for a drainage test on two saturated Mol sand samples.
**Figure H.12:** Height of soil in function of time for a drainage test on two saturated Mol sand samples.

**Figure H.13:** Position of the cog of the water in function of time for a drainage test on two saturated Mol sand samples.
H.3 Results of drainage tests of mixtures of 90% Mol sand + 10% kaolin clay

H.3.1 First test at 600 rpm

Figure H.14: Cumulative weight of the outflow water in function of time for a drainage test on a (dry pre-consolidated at 45 kPa) 90% Mol sand and 10% kaolin mixture at 600 rpm.

Figure H.15: Position of the cog of the water in function of time for a drainage test on a (dry pre-consolidated at 45 kPa) 90% Mol sand and 10% kaolin mixture at 600 rpm.
Table H.3: Accuracy of the cog measurements at the start of the drainage test on a mixture at 600 rpm according to the total cog.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube number</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>Initial position of the total cog with formula (3.8)</td>
<td>34,60</td>
<td>mm</td>
</tr>
<tr>
<td>Initial position of the total cog according to the second method</td>
<td>34,64</td>
<td>mm</td>
</tr>
<tr>
<td>Difference</td>
<td>-0,04</td>
<td>mm</td>
</tr>
</tbody>
</table>

Table H.4: Accuracy of the cog measurements at the start of the drainage test on a mixture at 600 rpm according to the cog of the soil.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube number</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>Initial position of the cog of the soil</td>
<td>23,51</td>
<td>mm</td>
</tr>
<tr>
<td>Initial midpoint of the soil</td>
<td>23,23</td>
<td>mm</td>
</tr>
<tr>
<td>Difference</td>
<td>0,28</td>
<td>mm</td>
</tr>
</tbody>
</table>

**H.3.2 Indicative test at 600, 1200 and 2400 rpm**

**Figure H.16:** Height of soil in function of time for a drainage test on a (dry pre-consolidated at 100 kPa) 90% Mol sand and 10% kaolin mixture at 600, 1200 and 2400 rpm.
H.3. RESULTS OF DRAINAGE TESTS OF MIXTURES OF 90% MOL SAND + 10% KAOLIN CLAY

Figure H.17: Cumulative weight of the outflow water in function of time for a drainage test on a (dry pre-consolidated at 100 kPa) 90% Mol sand and 10% kaolin mixture at 600, 1200 and 2400 rpm.

Figure H.18: Position of the cog of the water in function of time for a drainage test on a (dry pre-consolidated at 100 kPa) 90% Mol sand and 10% kaolin mixture at 600, 1200 and 2400 rpm.
Table H.5: Accuracy of the cog measurements at the start of the drainage test on a mixture at 600 rpm according to the total cog.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube number</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>Initial position of the total cog with formula (3.8)</td>
<td>35,52</td>
<td>mm</td>
</tr>
<tr>
<td>Initial position of the total cog according to the second method</td>
<td>35,76</td>
<td>mm</td>
</tr>
<tr>
<td>Difference</td>
<td>-0,24</td>
<td>mm</td>
</tr>
</tbody>
</table>

Table H.6: Accuracy of the cog measurements at the start of the drainage test on a mixture at 600 rpm according to the cog of the soil.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube number</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>Initial position of the cog of the soil</td>
<td>27,77</td>
<td>mm</td>
</tr>
<tr>
<td>Initial midpoint of the soil</td>
<td>28,65</td>
<td>mm</td>
</tr>
<tr>
<td>Difference</td>
<td>-0,88</td>
<td>mm</td>
</tr>
</tbody>
</table>
References


