Mitigating the Impact of Boreholes on the Groundwater Quality

Appropriate Sealing Agents and Associated Regulations for Cone Penetration Tests within Groundwater Extraction Areas

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Abstract

Cone penetration tests within environmental protection areas are inevitable and the potential consequences of incorrect sealing procedures can significantly affect the quality of the groundwater. This research investigates the regulations associated with the protection of the groundwater in these areas and assesses the hiatuses in the Provincial Environmental Regulation South Holland (PERSH). In addition, the sealing capacity of clays within the area of Oasen is assessed in order to conclude on the self-restoring capacity of Dutch clays. Furthermore, this paper summarises the available sealing agents within the Netherlands, divided into clay pellets, clay bars and clay suspensions. Three main producers of these agents are discussed: DantoPlug, Cebo, and Mikolit®. The products associated with these brands are extensively discussed and a comparison has been made for the pellets on the dimensions, sinking velocity in water, bulk density, swelling delay, swelling capacity, permeability, water absorption capacity, montmorillonite content, and the swelling pressure. The paper also compares the various forms of application of these products. In conclusion, this research found that clay pellets and bars are inapplicable in small-diameter boreholes. Instead, it advocates the use of Baroid drill-grout or similar bentonite suspensions in small-diameter boreholes. The clays in the area of Oasen contain a certain set of minerals to exert a self-restoring behaviour. However, the swelling rates are unknown and hence the micro bacteriological safety of the groundwater cannot be assured in open boreholes. . The recommendations in this paper include an implementation of a minimal sealing agent permeability of 10^{-9} m/s into the PERSH along with an implementation of bentonite suspensions as the appropriate sealing agents in small-diameter boreholes. Finally, the absence of experimental results regarding the self-restoring capacity of the clays in the area of Oasen highlights the shortcomings regarding this part in the conclusion. This paper establishes that further research is required on the subject and, therefore, includes a set-up for such research.

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List of Abbreviations

DFZ = Drilling-Free Zone
GPZ = Groundwater Protection Zone
GEZ = Groundwater Extraction Zone
SPT = Standard Penetration Test
CPT = Cone Penetration Test
QMRA = Quantitative Microbiological Risk Assessment
PERSH = Provincial Environmental Regulation South Holland
HES = Haaglanden Environmental Service
CMM = Coordinate Measuring Machines
NEN = Nederlandse Norm
BRL = Boorrichtlijnen
GWT = Groundwater Table
EPA = Environmental Protection Area

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Introduction

Drinking water companies are responsible for the production of drinking water. The quality of the product is of paramount concern and therefore, elimination of the risks of microbiological or chemical pollution during extraction is actively pursued.

This research is performed at the request of drinking water company *Oasen drinkwater*, which extracts groundwater as a source for high-quality drinking water in the Netherlands, alongside nine other drinking water companies (see Appendix A1). Within the distribution area of Oasen, the company currently has seven active treatment plants, each with its own extraction wells. Together, the plants produce approximately 48 billion litres of drinking water each year for about 750,000 people and 7,200 companies (Oasen, 2014). In order to safeguard the good quality and healthiness of this drinking water, it is key to protect in particular the areas closest to the extraction wells from potential pollutants.

While pollution can enter the aquifers through multiple processes, this paper only addresses the piercing of the impermeable clay layers by drilling into the subsoil with the purpose of acquiring subsurface information (hereafter referred to as "geotechnical testing"). This, however, may potentially lead to short-circuit flow, which means that water can infiltrate into the pumped aquifers within less than the minimum acceptable residence time of 110 days, as established by Medema et al. (2008). As a result, the extracted water may potentially be microbiologically contaminated and the predefined purification process will not suffice to guarantee clean and healthy drinking water. In conclusion, Oasen is concerned about the occurrence of short-circuit flow in drilling projects.

In order to avoid recharging aquifers with polluted water, vulnerable areas throughout the Netherlands are marked as Environmental Protection Areas (EPAs), which in turn are subdivided into "Groundwater Extraction Zones" (GEZs), "Groundwater Protection Zones" (GPZs) and "Drilling-Free Zones" (DFZs), located in bands around extraction wells (see Appendix A2). Activities regarding disturbance of the subsoil in these areas are associated with regulations implemented by the government. However, in reality these sets of rules often contain hiatuses and/or lack enforcement mechanisms. This may lead to conflicts between the involved parties and may thus endanger the quality of the water supply.

Penetration of the impermeable clay layer(s) remains a vulnerable subject to drinking water companies and although most aspects are well-covered by existing regulations (BRLs[1] and NEN Standards[2]), recurrent questions remain unanswered, especially those regarding cone penetration tests, which are excluded from the BRLs and are achieved with relatively small-diameter drillings. Incorrect or partial sealing after such projects may result in the occurrence of short-circuit flow. Hence, drinking water companies advocate the use of bentonite-mixtures as artificial sealing agents after drilling. These mixtures should safely restore the penetrated clay layer, which acts as a natural bacteriological filter for water. According to contractors, however, the current diversity in sealing agents is large and therefore unclear. In addition, the overall applicability of clay is said to be questionable. Contractors claim that afterwards, the soil recovers in a natural way by the swelling of in situ clays, which restore the impermeable boundaries and make the use of bentonite redundant.

The aforementioned dilemmas led to the following research questions:

- *Do small-diameter boreholes restore over time without artificial sealing due to in situ swelling of clay?*
- *What types of sealing agents are available in the Netherlands and in what forms of application?*
- *Which sealing agent(s) is/are most adequate in the sealing procedure taken into account the demands stated in the Provincial Environmental Regulation South Holland (PERSH) and by Oasen?*

In order to answer these questions, one must first gain insight into the behaviour and physical properties of clay. In addition, it is of vital importance to review different geotechnical tests, their purposes, and their interaction with the governmental regulations. Combined with a review on the geological and hydrological conditions, these aspects form crucial background information aiding in the understanding of the second part of this research, which includes an analysis of the main clay suppliers in the Netherlands and their currently available products. This overview will provide all information necessary to conclude on the recurrent question regarding the relatively best sealing agent(s) currently available. Furthermore, the second part analyses current regulations and legislation concerning geotechnical testing. Finally, the research questions are answered in the form of a brief conclusion containing recommendations for all parties involved, regarding the issues with sealing agents as well as the set of rules and their implementation and implications.

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[1] BRLs are guidelines on methods and procedures regarding mechanical drillings, established and agreed upon by all involved parties and written/published by the SIKB

[2] NEN Standards are general standards for certain procedures and methods in the Netherlands. This paper only features the NEN Standards relevant for geotechnical testing (further explained in Chapter 1.4).

Chapter 1 Review

This research is based on existing experiments and published articles concerning specific scientific aspects referred to as basic knowledge in this research. The background literature required to understand the set-up will be extensively elaborated in this chapter.

1.1 Site Description and Key Concept

As mentioned in the introduction, Oasen extracts groundwater for the production of drinking water. This extraction is performed in sand layers at a relatively shallow depth ranging from approximately 15 metres to 100 metres into the ground. The composition of the subsurface along with the hydrological situation is discussed in this chapter. Finally, a brief explanation on the key concepts is presented, which highlights the significance of this research.

1.1.1 Geological History

In order to understand the risks of leakage through boreholes, one must first acquire knowledge of the local geology within the supply area of Oasen. The focus lies on the sediments in the top layers of the Dutch subsurface in particular. The deeper geology (deeper than 100 metres) is not discussed here, as the groundwater is brackish or salt on those depths and, therefore, useless to Oasen for purification at this point in time[3].

The first relevant layer for this research in the Dutch subsurface is situated at a depth of 100 metres as a thick layer of impermeable clay: The Maassluis Formation (see Figure 1.1). According to Berendsen (2008a) this clay has been deposited during the early Pleistocene as marine sediment. The Netherlands was located entirely below sea level, resulting in sedimentation of the finest particles. As the Pleistocene period progressed, ice caps and glaciers began to form, which resulted in a lowering of the sea level. This resulted in a westward shift of marine clay deposition. The newly exposed land areas developed a large number of braided rivers, which started the sedimentation on land. A closer look at the area of interest, the Rhine basin (indicated in Figure 1.2), reveals that this sedimentation over time formed the formations now known as the formation of Peize, Waalre and Sterksel (see Figure 1.1). These formations are defined as the second aquifer and are moderately permeable because of their alternating characteristics of clay with a low permeability and highly permeable sand.

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[3] Oasen is actively replacing conventional purification methods with reverse osmosis technology. This implies that even brackish or salt water will become available as a source for extraction in the future

Later during the Pleistocene period, the climate was dominated by an alternating series of ice ages and interglacial periods. During these ice ages, rivers expressed a braided structure, resulting in the deposition of coarser sediments. The Rhine sediments deposited during these periods are now known as the Urk and Kreftenheye formations (see Figure 1.1). The coarse nature of these formations implies a high permeability, which makes them ideal for water storage. Moreover, the aquifer is a confined aquifer, which implies the presence of a confining layer on top. This confining layer consists of clay and peat deposits dating from the Holocene.

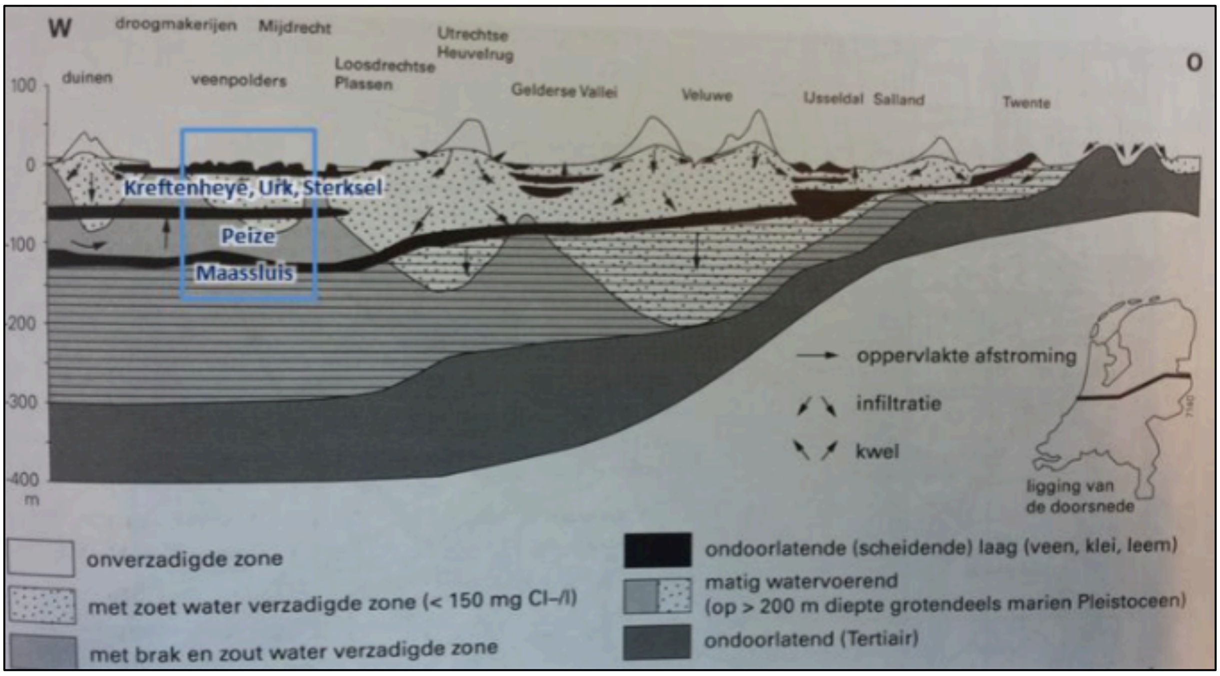

Figure 1.1. A cross-section of the Netherlands illustrating the geohydrology. The area boxed in blue indicates the location of the Lek River, where Oasen extracts most of its water. The fresh-water-bearing layers are shown in white, while the light grey areas contain brackish or salt water. The dark grey area consists of impermeable Tertiair deposits. The arrows in the figure indicate the flow direction of subsoil water.

According to Berendsen (2008a), the clay and peat deposits were a direct consequence of sea level rise combined with a subsiding Dutch subsurface. Clay was deposited due to inundating processes and peat deposits had formed in places with locally favourable water conditions. Consolidation of these layers over time led to highly impermeable behaviour of this confining layer.

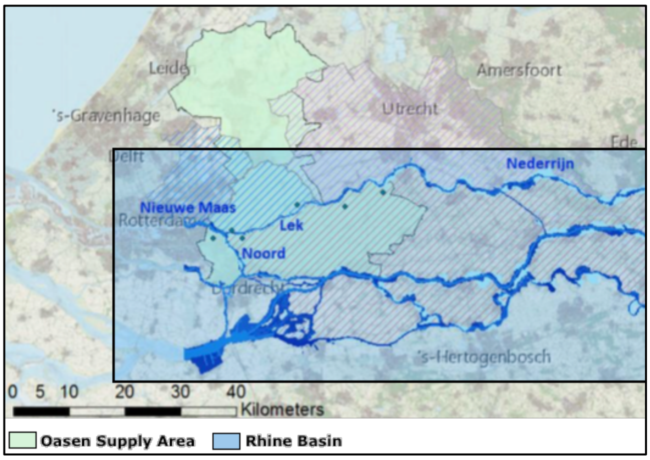

Figure 1.2. A map of the Netherlands indicating approximately the Rhine basin.

In conclusion, the aforementioned characteristics regarding the first aquifer are relatively advantageous with respect to the drinking water production process. Nevertheless, it is not ideal as extraction leads to accelerated compaction of the layers and increased salt water intrusion, among other things. As people need drinking water, however, Oasen extracts its groundwater mainly[4] from this first aquifer, extending to a depth of approximately 50 metres according to Figure 1.1.

1.1.2 Hydrological Situation

As mentioned in the previous section, the subsurface subsided and the sea level rose throughout the Pleistocene and Holocene. Nevertheless, Heij (1989) states that the land surface was higher than the water level in the rivers at that time. This implies that rivers were recharged with groundwater.

However, above-mentioned relation changed significantly when the land was drained for land reclamation purposes, which resulted in compaction of the Holocene clay and oxidation of the existing peat layers. Combined with peat digging, these human activities led to subsidence of the surface level and had a large impact on the hydrological conditions in this area. Flooding of the reclaimed lands now became a risk and prevention was implemented in the form of diked rivers and artificial drainage of the polder areas. Today, this has resulted in an elevated river level, peaking above the surrounding land. Consequently, the surrounding area is now being recharged by the rivers.

In general, these hydrological conditions would imply an overpressure throughout the area according to the law of Darcy, which defines a flow from high energy to low energy and is governed by the hydraulic head (h) (see Appendix A3). However, the geomorphological conditions in the area of interest are more complex than mentioned in the last paragraph. In this paragraph, a north-west/south-east cross-section is shown according to the line drawn through the area from A to B in Figure 1.3. The obtained cross-section will respectively cross two rivers in the area: *the Hollandse IJssel* River and *the Lek River*. The elevation along the line gradually increases from point A to point B, implying spatial differences in hydraulic head levels, which have

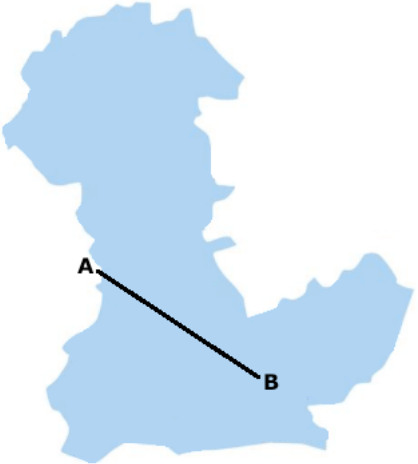

Figure 1.3. Location of the cross-section

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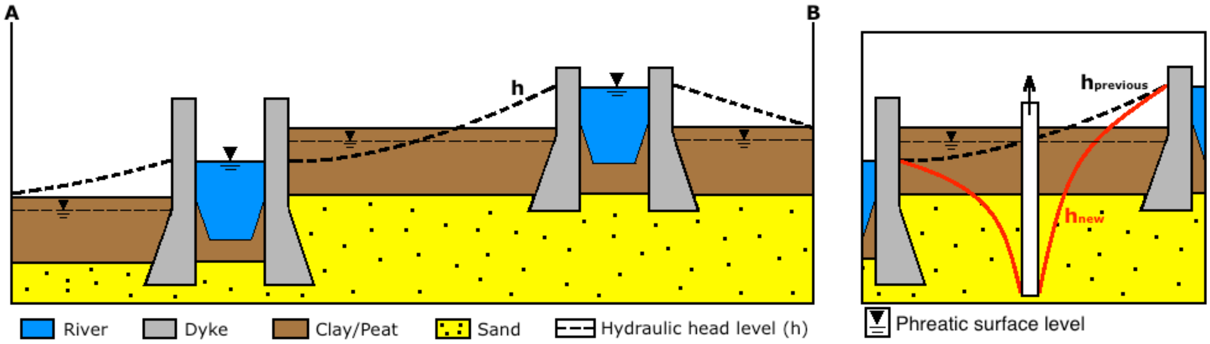
[4] A relatively small volume is also extracted from the second aquifer at greater depths

been illustrated in Figure 1.4 and can be split into two main groups: *infiltration areas* and *seepage areas (Figures 1.5 and 1.6).*

Figure 1.4a illustrates these distinctively different areas with a hydraulic head distribution curve. At any place along this curve, if the curve is situated above the phreatic surface, it defines a seepage area. Similarly, if the curve is situated below the phreatic surface, that specific area is defined as an infiltration area. Figure 1.4b illustrates the effect of extraction wells on the hydraulic head. This is indicated by $h_{previous}$ (the undisturbed head distribution curve) and h_{new} (the head distribution curve influenced by a well).



Figures 1.4a & b. Hydrological situation on the location of the cross-section[5]*. The figure on the left (a) shows the entire cross-section, while the figure on the right (b) zooms in on the area between the two rivers. Figure b illustrates the induced differences in hydraulic head due to installed wells.*

While Figure 1.4 has been approximated for a predefined location, Figure 1.5 shows a complete infiltration/seepage map for the Netherlands according to Veldkamp & Wiertz (1997). The yellow/orange colours define infiltration while the blue colours define seepage, both indicated in millimetres per day. The generally observed pattern in this map mainly indicates seepage areas in the north-western part of the country, while the south-eastern part is dominated by infiltration areas[6]. Typically, the lower parts of the Netherlands are more prone to seepage.

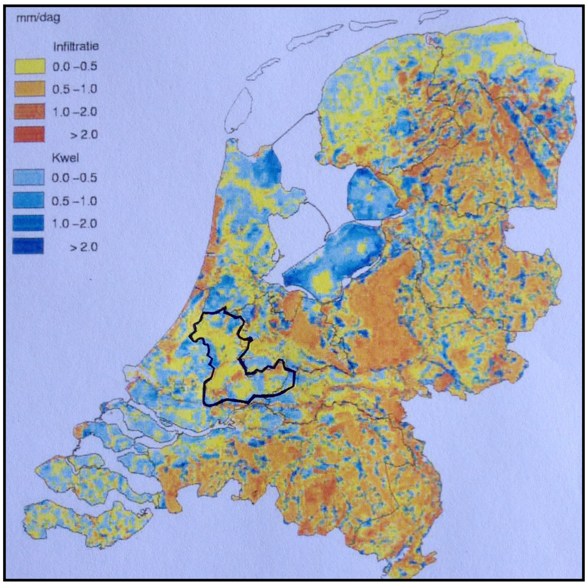


Figure 1.5. Infiltration/seepage map of the Netherlands. Values are given in mm/day while yellow/orange colours indicate infiltration and blue colours indicate seepage.

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[5] Figure is not on scale. Dimensions have been exaggerated and drawn out of proportion solely for the purpose of illustrating the hydraulic head distribution.

[6] The dunes on the western shore are an exception to this pattern, due to their elevation.

In the area of Oasen (see Figure 1.6), however, the land is dominated by infiltration. A closer look reveals several spots with significant infiltration (>2.0 mm/day) in the lower part of the area. By adding the river to the figure, it becomes clear that these spots are located along the Lek River, where the majority of the extraction wells belonging to Oasen are located, as illustrated in figure 1.6.

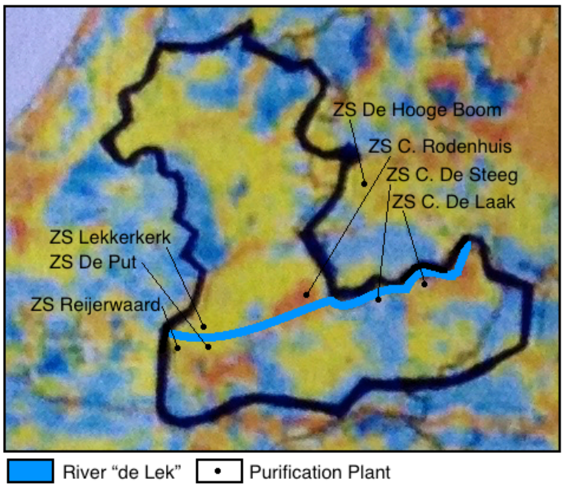

Figure 1.6. Isolated area of interest from Figure 1.5 showing the infiltration/seepage patterns relevant for this research.

The relation between these wells and the significant infiltration rate is explained by Figure 1.4b. The extraction of water through wells induces drawdown in a cone around the well, resulting in a lowering of the hydraulic head and thus drastically changing the local hydrological conditions, turning seepage areas into infiltration areas and further increasing the infiltration rate in existing infiltration areas. These are the areas this paper focuses on.

1.1.3 Travel Time and Water Quality

The previous chapter states that the extraction areas of Oasen are mainly located around the Lek River. According to Phernambucq (2015), the surrounding areas are situated at a lower elevation than the diked river, which means that the Lek is an infiltrating river and riverbank groundwater is always readily available for extraction. Furthermore, riverbank groundwater has a relatively constant temperature and quality due to the fact that it is being filtered through natural processes (Van der Kooij, (1985). As a result, the extraction of riverbank groundwater by Oasen has proven to be very advantageous.

Natural filtration is one of the most important processes for making groundwater bacteriologically reliable. Van der Kooij (1985) states that bacteria are removed relatively quickly from the water, which according to Medema et al. (2008) corresponds to the value of 110 days. As Phernambucq (2015) explains, the water infiltrating from the river towards the first aquifer has a travel time that largely depends on the vertical hydraulic resistance of two layers: the resistance of the riverbed and the resistance of the (in)complete confining layer.

To illustrate the importance of the natural filtration process, Van der Kooij (1985) mentions that during retardation of the infiltrating water several processes take place which affect the organic material, inorganic substances and microbiology of the water. These aspects are the main actors in the definition of water quality and during the infiltration they are affected by:

- Filtration of suspended material
- Ammonium nitrification
- Mineralisation of organic matter
- Precipitation of sulphide
- Dissolution of inorganic substances
- Exchange of cations and anions

The direct relation of these aspects with the magnitude of the travel time implies that a longer path through the confining layer results in more available time and space for these reactions to take place and, thus, increases the water quality. Oasen concludes on the water quality with a so-called Quantitative Microbiological Risk Assessment (QMRA) on the removal of viruses. This method is based on the fact that virus particles barely adsorb to soil particles, especially in anoxic conditions. A QMRA evaluates the risk of infection; this risk should be lower than 1 on 10,000 persons per year to be acceptable.

1.1.4 Environmental Protection Areas

As mentioned in the introduction, the province distinguishes several zones within Environmental Protection Areas with respectively increasing risks and, therefore, stricter regulations:

- Drilling-Free Zones (DFZs)
- Groundwater Protection Zones (GPZs)
- Groundwater Extraction Zones (GEZs)

Figure 1.7 provides a geographical overview of these areas in different colours. Three main colours can be distinguished within these zones: green, yellow and brown, respectively indicating the DFZs, GPZs and GEZs. The GEZs are hardly visible, but are located in bands within the GPZs. Purification plant “De Hoge Boom” is indicated separately because it is situated outside of the indicated area (in the northern part of the supply area).

The area boundaries are established through travel time calculations. According to Oasen (2014), a DFZ is defined as a zone in which a single droplet of water travelling through the water-bearing layer can reach the extraction well in less than 50 years. Hence, it covers the horizontal dimension of displacement. In contrast, a GPZ is defined as a zone in which a single droplet of water traveling from the mowing field downwards can reach the extraction well in less than 50 years. As a result, this covers the vertical dimension of displacement. Lastly, the definition of a GEZ is similar to that of a GPZ, but instead of 50 years the travel time boundary is set to 60-110 days (Oasen, 2014).

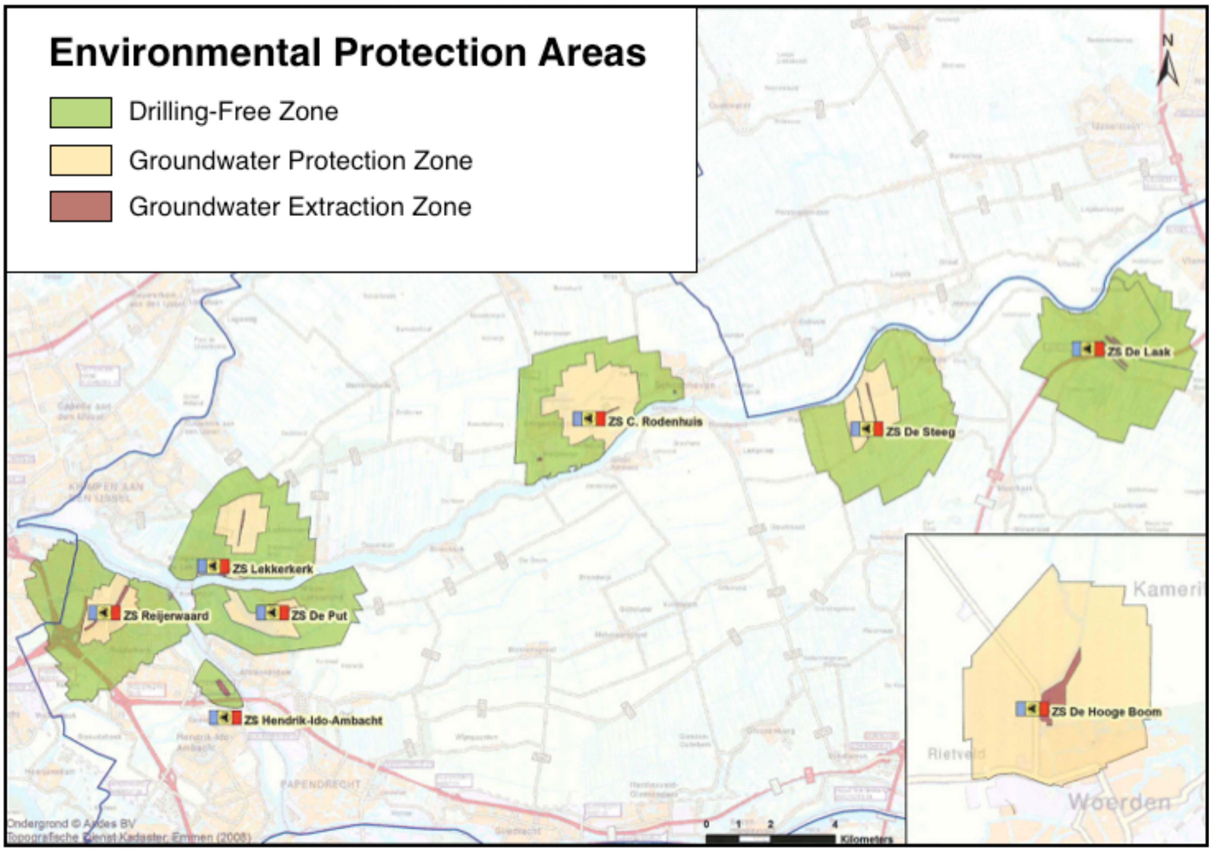

Figure 1.7. A geographical map indicating the locations of the environmental protection areas in the supply area of Oasen, as well as their subdivision into DFZs, GPZs and GEZs.

1.2 Subsurface Disturbance and Associated Risks

Altering the integrity of the protecting Holocene clay layer can exert a significant impact on the quality of the water-bearing layers situated directly below. This chapter discusses different methods affecting the subsurface configuration, and their purposes. Finally, it will shed a light on the occurrence of preferential pathways: the main risk of geotechnical testing in this research.

1.2.1 Geotechnical Testing

The last decades saw an increase in the use of the Dutch subsurface for various purposes, e.g. groundwater extraction, geothermal energy, sewage, transportation pipes, and electricity. As all these pose potential threats to the water quality, however, Oasen mainly concerns itself with geotechnical testing, due to the fact that these drilling projects extend to greater depths and certain aspects are excluded from legal documents, making it a vulnerable topic for negligence. As mentioned earlier, there are recurrent questions regarding the execution and the involved risks of geotechnical tests.

Geotechnical testing is the definition of a subsurface investigation conducted in order to obtain information on the subsurface stratigraphy and the physical properties of soil and rock around a site (Geotechdata, 2016). This information is acquired for the construction of proposed structures which require specific earth works or foundations. According to VertekCPT (2014), there are four different categories into which the currently available geotechnical tests are split:

- Test Pits
- Trenching
- Boring
- In Situ Testing

The first two are based on the same principles. A test pit is a manually or mechanically dug pit to a predefined depth in order to reveal subsurface conditions. Much like a test pit, trenching follows the same principles but extended to a certain length with the purpose of establishing spatial variations of subsurface conditions (VertekCPT, 2014). In contrast, boring is a method used for the physical removal of soil or rock samples, which can then be analysed in the lab. According to VertekCPT (2014), the advantage of this method is that composition and structures of normally inaccessible soil and rock become visible to the naked eye. It allows for ‘vision’ on the actual material normally located at unreachable depths. However, VertekCPT (2014) also mentions the downside of boring. The soil is (partly) disturbed by the sliding movement of the casing, resulting in disturbed or completely useless samples. Moreover, when a sample is removed from a certain depth and out of the casing, the in situ stresses of the sample will be lost, resulting in samples which do no longer represent the in situ conditions. This needs to be kept in mind when the boring method is used for a geotechnical test.

Finally, in situ testing is an expression for various penetration tests performed on-site. These include standard penetration tests (SPTs) and various cone penetration tests (CPTs) for relatively deep subsurface investigation, and manual cone penetration tests for relatively shallow subsurface investigation. According to Bakker (n.d.), SPTs and CPTs are capable of reaching depths of up to approximately 60 metres, while manual CPTs are applied up to a maximum depth of approximately 3 metres (PastoorsBouw, 2014).

According to VertekCPT (2014), the difference between an SPT and a CPT is indicated by means of soil penetration. In a SPT, a thick sample tube is pressed into the ground at the bottom of a borehole. This pressing motion is performed with the struck of a slide hammer, which repeatedly presses the tube deeper into the ground while measuring the number of blows (VertekCPT, 2014). These blows are then correlated to the displacement of the tube into the ground, which can in turn be correlated to the matrix type at a certain depth. The test requires only a tube and a slide hammer, making it a relatively inexpensive and simple testing method.

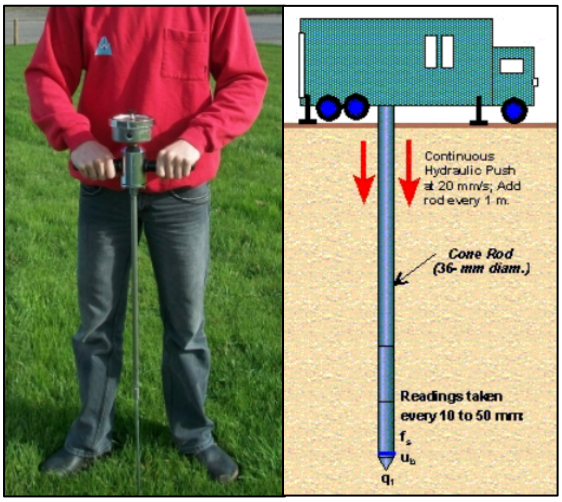

Figure 1.8. Illustration of a manual CPT (left) (Wiertsema & Partners, 2010) and an automatic CPT (right) (Geotechdata, 2016).

However, the drawbacks are significant. According to VertekCPT (2014), a SPT is relatively inaccurate when compared to a CPT, which relies on penetration of a cone into the ground through direct push (see Figure 1.8 (right)). The surface of the cone is subjected to a varying resistance of the matrix, which is then correlated to the type of matrix. A manual CPT is similar to an automatic CPT, with the difference that the cone is pressed into the ground manually (without the use of machines), as illustrated in Figure 1.8 (left). As a consequence, manual CPTs are less accurate, but at the same time less expensive. Either way, both tests result in small-diameter boreholes, which require sealing. In the following chapters, CPT refers to the mechanical variant unless specified otherwise.

All methods are executed with the aim of directly acquiring the physical properties of the subsurface soil without removing of in situ material. According to Vertek CPT (2014), this provides the advantages of generating a more accurate reflection of the underground conditions as well as avoiding the necessity of involving a third party for the analysis of samples. However, CPTs are significantly more accurate than SPTs and are therefore applied more frequently. CPTs are applied in vast numbers throughout the Netherlands and recurrent questions exist regarding the afterward sealing of the boreholes. Hence, this paper highlights the importance of CPTs and will further disregard SPTs, implying that within this research cone penetration tests are taken as the potential cause for pollution of the water bearing layers. For this reason, trenching, test pits and boring are also excluded from this research.

1.2.2 Cone Penetration Tests

Geo-consultancy companies have different methods to apply a cone penetration test as well as different types of cones. The choice depends on the accuracy and parameters desired to be measured and the maximum depth. The available tests are the electrical-, piezo- and mechanical cone penetration tests. Today most of the commercially available cone penetration tests use an electronic- or piezo friction cone, according to Rogers (n.d.).

A regular cone penetration test measures the time (t), depth (d), cone resistance (q_c), and sleeve friction (f_s)[7] (EMABS, 2011). These parameters are afterwards linked to a certain matrix type. As mentioned by Rogers (n.d.), the electrical cone penetration test yields significantly more accurate results than the mechanical cone penetration test, which inevitably results in a relatively higher application of the electrical variant. VertekCPT (2015) states that the range in diameter of CPTs is situated between 35.3 and 44.0 millimetres, with the most commonly applied cone having a diameter of 35.7 millimetres.

According to Edelman (2015), cone penetration tests are forced into the ground either with a constant force or with a constant displacement, squeezing soil particles to the sides as the pipe progresses. The cone at the end of the pipe is constantly subjected to a resisting force from the compressed soil particles. During the process, a monitoring system directly above the borehole receives constant information regarding this resistance. Depending on the interests, a different cone can be chosen in order to achieve additional information of the local subsurface like the pore water pressure, the conductivity of the ground, or the local subsurface temperature.

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[7] Generally a CPT also lists the friction number (R_f), which is not directly measured but instead calculated. It is equal to the sleeve friction (f_s) divided by the cone resistance (q_c).

Edelman (2015) also states that the resistance of the compressed matrix relies on multiple aspects: the water content, grain size, grain size distribution, void volume, presence of organic particles, presence of minerals, and the degree of layer consolidation.

Figure 1.9 is a graph showing the data acquired during a cone penetration test. This data is afterwards analysed and interpreted by a geo-engineer. In addition to the parameters mentioned previously, this example also lists the pore water pressure (u). The coloured legend on the left is an example of the interpretation of soil matrix type corresponding to the measured data.

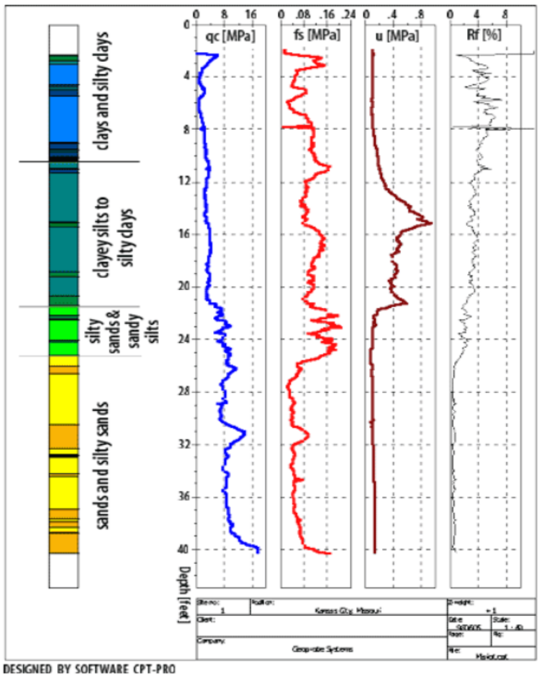

Figure 1.9. An example of the data acquired during a CPT, including the afterward interpretation.

1.2.3 Preferential Pathways

Throughout this research, several processes are discussed regarding the penetration of the subsurface, from which cone penetration tests have been isolated in this research. For water companies like Oasen, the main risk of cone penetration tests is the development of preferential pathways, which will be discussed below.

Preferential pathways introduce a possibility for water to move in an accelerated fashion through the subsurface. In general, it is explained as the path of least resistance for fluid flow, implying migration through a more permeable feature in comparison to the surrounding materials (Daniels & Easterly, 2011). These water shortcuts may extend vertically as well as horizontally – either formed by nature or man-made – and are generally extensive in length. Figure 1.10 illustrates the appearance of preferential flow paths in a soil. The arrows in the left image illustrate the locations of accelerated flow whereas the vertically extending red paths in the right image indicate the preferential pathways.

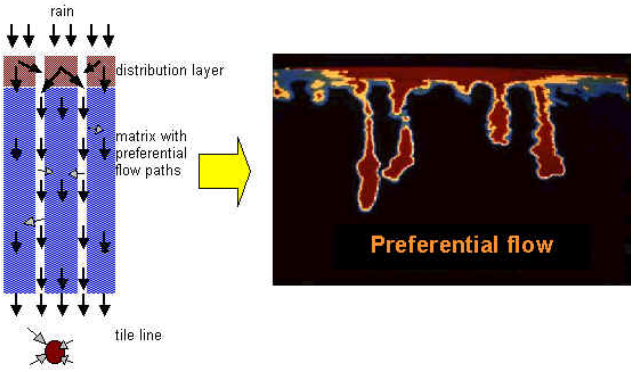

Figure 1.10. An example of preferential pathways in the subsurface (Peranginangin, 2002).

A volume flux through these features can result in a flow deviating from its intended travel direction or path according to Daniels & Easterly (2011). As an example, Daniels & Easterly (2011) list multiple causes for the occurrence of preferential pathways, which include buried stream channels, fractured or dissolved bedrock, desiccation fractures in sediments, improperly sealed wells, field tiles, buried utility lines, and building foundations.

In addition to the examples, any way of subsurface penetration also carries the risk for the development of preferential pathways. To illustrate the process, an example of the subsurface located in Ridderkerk is reviewed in Figure 1.11. Oasen has multiple extraction wells in this area and for the purpose of illustration the figure shows an extraction well with two filters, extracting water from the first sand layer as well as from the second. The wells are always installed at locations where the extracted water has travelled through the subsurface at least 110 days, which is assumed to be adequate to guarantee the absence of microbiological contamination.

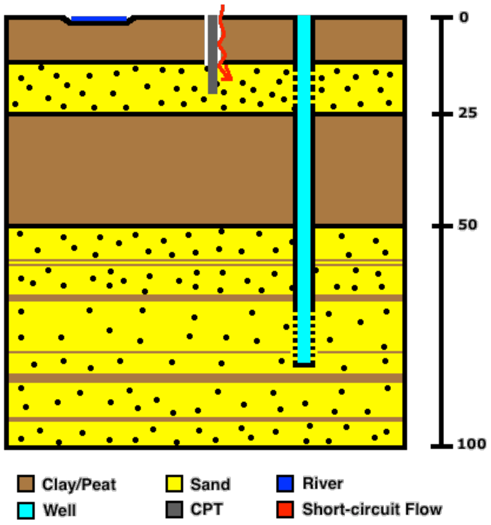

Figure 1.11. Simplified approximation of the subsoil within the extraction areas of Oasen, indicating the issue with an incorrectly sealed or open borehole after a CPT.

Figure 1.11 shows the consequence of a potential penetration test in the vicinity of a well in an approximated subsurface configuration. By piercing the confining clay layer and removing the equipment afterwards, the abandoned hole remains filled with either air, water (due to seepage) or collapsed sediments from the borehole walls. In either case, the hole has a higher permeability than the surrounding compressed clay layer, implying that water in the vicinity of the mentioned borehole will choose to migrate through the hole. Rainwater, for instance, will inevitably be transported faster to the water-bearing layer, introducing the risk of microbiologically polluted water to be mixed with the clean aquifer water[8]. The phenomenon of water flowing through a preferential pathway is also known as short-circuit flow.

According to Oasen, some years ago an execution of a small-diameter drilling went wrong due to the usage of polluted water from a local ditch during the process. This

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[8] The composition of the water will also be different due to the significantly shorter timescale on which the chemical processes in the soil will act.

water was found within days in the closest purification plant of Oasen and resulted in the closure of the plant for several months. This event highlights the significance of correct sealing after the execution of CPTs in order to avoid the occurrence of short-circuit flow and the consequences thereof.

Fortunately, for mechanical drillings the risks are recognised and therefore lawfully anchored in BRL 2100 and Protocol 2101. However, for penetration tests the opposite is true. There are guidelines and best practices available as documents, but they are by no means enforceable. Hence, the company carries the responsibility of understanding the potential risks and acting accordingly. Further information on the regulations regarding cone penetration tests is discussed in Chapter 1.4.

1.3 The Self-Sealing Capacity of Clays

The favourable properties of clays are numerous. For example, it can be used for waste storage due to its chemical binding behaviour with radioactive substances, it behaves as a bacteriological filter for water due to its impermeable character and, moreover, clays exert a plastic behaviour, meaning that they can recover their original structure (EURIDICE, n.d.). This means that fractures or cracks close up over time. Plastic behaviour is the main focus of this chapter. Understanding the plastic behaviour of clays requires knowledge of the general composition and structure of clays, which is extensively discussed below. The chapter is concluded with an elaborate explanation of swelling behaviour and an analysis of the clays found in the area of Oasen.

1.3.1 Chemical Composition and Structure

Clay minerals are defined as aluminosilicates. Their structure mainly consists of the elements aluminium (Al), silicon (Si) and oxygen (O). However, aluminosilicates also contain other elements in variable proportions, such as sodium (Na), potassium (K), calcium (Ca), magnesium (Mg) or iron (Fe).

In general, the elements appear in a common structure. According to Jordán (2014), the complex configuration of silicates consists of certain structural units, Si-O tetrahedrons, which are connected to Mg-O/Al-O octahedrons[9]. The tetrahedrons are built up in a pyramid shape with an oxygen atom on each corner, bound to a common silicon atom in the centre of the pyramidal space (see Figure 1.12). However, the total of four oxygen atoms bound to one silicon atom generates a strong negatively charged tetrahedron ($(SiO_4)^{4-}$). In an attempt to neutralise this, the oxygen atoms bind to other cations. The number of oxygen atoms binding to cations other than silicon determine the formation of different minerals between multiple tetrahedral groups (Jordán, 2014). The octahedrons have a similar setup, with the mid atom existing of magnesium or aluminium and being surrounded by six oxygen atoms.

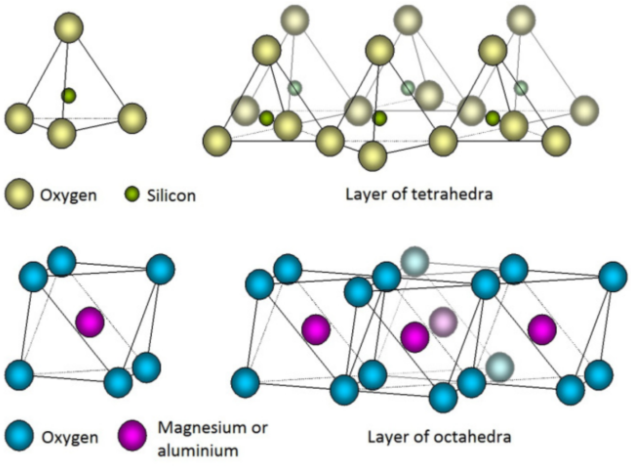

Figure 1.12. Illustration of Tetrahedrons and Octahedrons along with the layer configuration.

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[9] In clays the tetrahedrons are always connected to octahedrons. In other cases, the tetrahedrons are not necessarily always bound to octahedrons.

The above-mentioned tetrahedrons are interconnected and the number of shared oxygen atoms (either zero, one, two, three, or all four) determine the total structure of the tetrahedral layer. Jordán (2014) states that depending on the number of shared oxygen atoms, large groups of silicates can form the following shapes (see Appendix A4 for a few examples):

- No oxygens shared: Isolated molecules (nesosilicates or orthosilicates)
- One oxygen shared: Pairs (sorosilicates)
- Two oxygens shared: Rings (cyclosilicates)
- Two-three oxygens shared: Chains (inosilicates)
- Three oxygens shared: Planes (phyllosilicates)
- Four oxygens shared: Tridimensional structures (tectosilicates)

According to Jordán (2014), phyllosilicates are the most significant in soils (see Figure 1.13). As mentioned by Jordán (2014), phyllosilicates are characterised by three shared vertices, while the fourth vertex is bound to the central cation of an octahedron. This implies that the structure of clay minerals consists of a stack of layers of tetrahedra and octahedra, resulting in a lamellar structure with shared oxygen atoms within the individual layers. Depending on the way that the sheets are packaged into layers, clays can be categorised as 1:1 or 2:1 clays. This means that a layer consists of one tetrahedral sheet connected to one octahedral sheet, or two tetrahedral sheets enclosing one octahedral sheet respectively. The central positions within the tetrahedral and octahedral units are generally occupied by silicon, magnesium or aluminium.

Phyllosilicate (apophyllite).

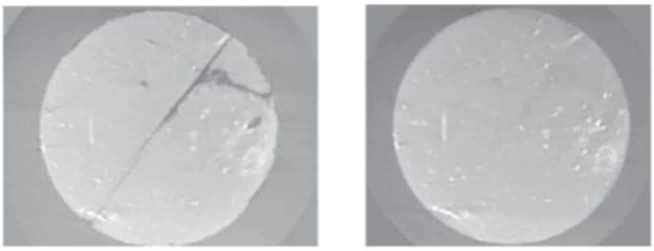
Figure 1.13. The orientation of the tetrahedra in a specific group of Phyllosilicates: apophyllite.

However, Jordán (2014) explains that these cations can be substituted in natural processes by other cations, resulting in changes of volume and global charge. The spatial variability in these cations results in the appearance of different mineral species, which can be split into several groups according to Jordán (2014) (with their layer type added between brackets):

- Kaolinite-Serpentine (1:1)
- Pyrophyllite-talc (2:1)
- Smectite (2:1)
- Vermiculite (2:1)
- Mica (2:1)
- Chlorite (2:1)
- Sepiolite-Palygorskite (2:1)
- Mixed-layer (variable)

1.3.2 The Plastic Behaviour of Clays

A study performed by EURIDICE (n.d.) in the HADES underground research laboratory revealed that boreholes with a diameter of 10 centimetres closed up entirely after several days. The clay samples were brought to the lab and opened in order to track the process of fracturing. Figures 1.14a and 1.14b show the samples after fracturing and after self-sealing. The samples were fully saturated and the fractures disappeared within several days, allowing the sample to fully restore its original structure. However, this study only tested so-called "Boom Clay"[10].



Figures 1.14a & b. The left image (a) shows the clay sample after retrieving the sample and the fracturing process. The right image (b) shows the self-restored state of the clay sample after several days.

The above-mentioned test performed by EURIDICE (n.d.) introduces the plastic behaviour of clays. Like the Boom clay, many types of clay tend to exert this self-restoring process due to their expansive behaviour. In order to understand this complex interaction, one must understand the environment in the interlayer spaces. As mentioned earlier, clays consist of a succession of negatively charged aluminosilicates layers, bound as a whole by interlayer cations (Hensen & Smit, 2002). However, the most characteristic property of clays is the potential water adsorption between the layers. According to Hensen & Smit, this ability results in strong repulsive forces and thus, in expansion of the total structure. Figure 1.15 illustrates this interlayer in a 2:1-orientated clay (in this case, "sodium montmorillonite").

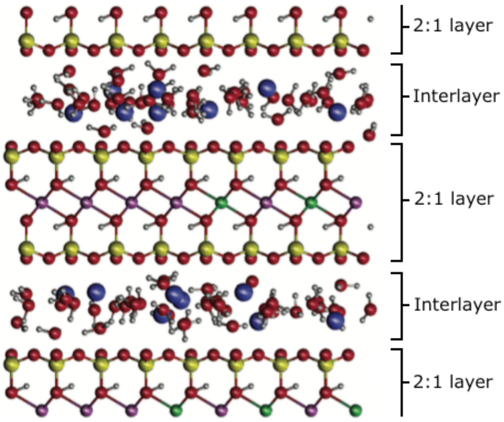


Figure 1.15. Atomistic model of sodium montmorillonite. (O: red, H: white, Si: yellow, Na: blue, Al: purple, and Mg: green)

On the microscopic scale of clay layers, the properties of a liquid are different from those of a bulk liquid. Hence, the swelling behaviour in this regime strongly depends on the molecular packing of intercalated water (Hensen & Smit, 2002). The swelling procedure for microscopic or crystalline swelling occurs in multiple steps. According to Hensen & Smit (2002), within the clay interlayer the counterions can be hydrated in three discrete steps. These steps are illustrated in a theoretical experiment executed

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[10] A specific type of clay found in the subsurface of Belgium.

by Hensen & Smit (2002), which imitated the commonly applied water adsorption/desorption experiment with the use of molecular dynamic algorithms and configurational-biased methods[11]. The simulation results yielded a layer spacing value of d_0=12.3 Å[12]. According to Hensen & Smit (2002), previously acquired experimental results on one-layer hydrate of sodium montmorillonite yielded similar values, which verify the algorithms.

Consequently, the swelling curves were simulated for sodium-montmorillonite (see Figure 1.16), which is a type of clay in the smectite group with a significantly high swelling rate. The difference between the full line (■), dashed line-short (▲) and dashed line-long (**x**) is the result of different starting values for the number of water molecules per simulation super cell (N_0), respectively 50, 100 and 150 and the different starting values for the layer spacing (d_0), respectively 12.5 Å, 15 Å and 17.5 Å.

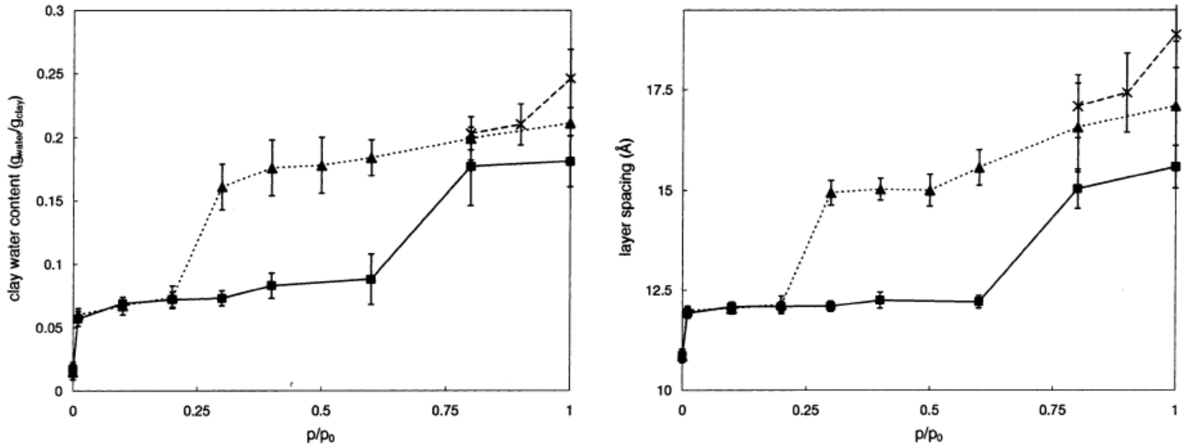

Figure 1.16. Sodium montmorillonite swelling curves. Left: clay water content (g_{water}/g_{clay}) as a function of the water vapour pressure (p/p_0). Right: Layer spacing (Å) as a function of the water vapour pressure (p/p_0).

One may observe that there are three significant increments in layer spacing along the curves. The first distinguishable point in the graph is located at d=10.3 Å, which corresponds to the dehydrated state of the clay. This is followed by two well-defined hydrated states; a one-layer hydrate situated at d=12.3 Å and a two-layer hydrate situated at d=15.2 Å, and finally there is a less-defined state at the highest vapour pressure, situated at d=16-18 Å. According to Hensen & Smit (2002), these observed values for layer spacing are in agreement with the experimentally obtained values for dehydrated clay (d=10-10.4 Å), a one-layer hydrate (d=12-12.5 Å), a two-layer hydrate (d=15 Å), and a three-layer hydrate (d=18-19 Å). As a result, the curves flawlessly illustrate the stepwise nature of the swelling behaviour in sodium montmorillonite. The increase in hydrated states corresponds to individual counterions

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[11] More detailed information on this experiment can be found in the published article of Hensen & Smit (2002); "Why Clays Swell" .

[12] The Ångström or angstrom is a unit of length (Å) equal to 10^{-10} metre or 0.1 nanometre.

(e.g. sodium atoms in this case) becoming fully hydrated step by step through the formation of multiple water layers due to re-coordination of the intercalated water molecules. Hensen & Smit (2002) state that during this hydration, counterions move towards the centre of the interlayer. However, certain types of clay bind counterions stronger depending on their charge (a more negative charge implies a stronger clay tetrahedron-counterion bonding. This directly correlates with the magnitude of swelling, as counterions cannot migrate towards the centre of the interlayer when they are located firmer to the chemical main structure. As a result, the counterions cannot get fully hydrated and thus, the swelling volume is significantly smaller.

Another factor that significantly affects swelling behaviour, is the cation exchange capacity. According to Kodama (2016), certain clays can exchange their interlayer cations easier than others. Under the same conditions, calcium for example is known to replace sodium easier than vice versa. This alters the swelling behaviour as different cations react in different ways with the intercalated water molecules. According to Hensen & Smit (2002), potassium-rich (K^+) clays have a low tendency to swell due to their poor interaction with water molecules, whereas sodium-rich (Na^+) clays swell significantly stronger and lithium-rich (Li^+) clays swell even more[13]. For this research, however, it suffices to conclude that the kaolinite-serpentine clays exhibit little to no swelling on hydration while the smectite group, on the other hand, has the most extreme swelling capacity. The other groups are situated in between these extremes.

1.3.3 Clay in the Dutch Subsurface

The Dutch soil contains a significant amount of clay, deposited in the past by river flooding and by seaward migration of the land. In terms of mineralogy, Dutch clays were originally similar to the mother rock from which they had been eroded through mechanical weathering. During downstream transportation and deposition, however, chemical weathering has altered the mineralogy over time. This has had a significant impact on the relative appearance of the various minerals in the clay, which in turn determines the swelling capacity of the soil. Unfortunately, information on clay mineralogy or swelling capacity on specific locations is scarce. According to Muijs (1984), the total mineralogy at predefined locations may however be established through specific tests, like differential-thermal analyses or an x-ray diffraction tests.

A previously conducted research by Dekker & Kruse (1985) revealed that the mineralogy of natural clay grounds within the Netherlands highly correlates with the local grain size. Overall, they state that the Dutch subsurface includes the following minerals):

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[13] Further details on the relative swelling behavior can be found in the published article of Hensen & Smit (2002).

- Illite (mica)
- Kaolinite
- Montmorillonite (smectite)
- Vermiculite
- Chlorite

From this list, illite has the highest appearance in the Dutch clay grounds (75-80% according to Muijs (1984)). Its structure is characterised by 2:1 layers held together through potassium ions. These specific cations in the interlayer have a large binding energy, implying cation exchange resolving in a significant slow fashion. However, at the locations where potassium ions do get removed, water can be attracted and incorporated into the structure. Inevitably, the clay will swell or may even disintegrate into loose elementary layers, which according to Dekker & Kruse (1985), may result in the formation of montmorillonite particles in a further stadium.

In contrast, kaolinite, appearing for approximately 10-15% in the Dutch clays (Muijs, 1984), has entirely different characteristics. Its 1:1-layer structure is responsible for its firm character due to hydrogen bonding and, as a consequence, the kaolinite group exerts no swelling behaviour.

Lastly, montmorillonite, vermiculite and chlorite appear significantly less in the subsurface. According to Muijs (1984), montmorillonite appears for about 3-5% and no data is available on the occurrence ratio of vermiculite and chlorite. Montmorillonite belongs to the smectite group and is known for its high water intake capacity and significant swelling as a consequence thereof. According to Dekker & Kruse (1985), montmorillonites in the Dutch soil are products of the chemical weathering of illite. However, even further chemical alteration can result in the minerals vermiculite and chlorite, which are virtually similar. Both have a 2:1-layer structure and exert (nearly) no swelling.

Dekker & Kruse (1985) also mention a research performed by the "Nederlandse Grof Keramische Industrie", which established a correlation between lutum content and the presence of montmorillonite. Lutum is the definition for ground particles, which are smaller than two micrometres. This means that across the Netherlands, a higher lutum content of the soil implies higher montmorillonite content. Furthermore, the research established that the presence of montmorillonite in river clays is higher than in sea clays.

1.4 Policy and regulations for EPAs

In order to prevent microbiological or chemical pollution of groundwater sources, legislation and procedures are developed to protect the water bearing aquifers for drinking water. Provincial rules state that in EPAs, the protecting (semi) impermeable clay/peat layer on top of the aquifer should be kept intact. Drilling deeper than 2.5 metres is strictly prohibited. Beyond this predefined point drilling can be allowed, but only on condition that the clay/peat layer is restored. The original lithology– the alteration of sand and clay – should always be repaired. This chapter provides an overview of the rules associated with the correct execution of geotechnical penetration testing procedures.

1.4.1 The PERSH and HES

The PERSH is a provincial regulation associated with the protection and innovation of the environment in the midwestern province of the Netherlands which focuses on the soil and subsurface amongst others. The provincial states have agreed on how this regulation should be implemented and have reviewed it in the document "Beleidsvisie Duurzaamheid en Milieu". The applicable law is clearly defined in the "Provinciale Milieuverordening Zuid-Holland", written by the South Holland provincial executive. During activities in EPAs, companies are obliged to work according to this regulation. Isolating geotechnical testing from other activities in EPAs results in the following legislations being relevant, and hence depicted in the following seven articles:

Article 1

- When stating "drillings regarding geotechnical testing" it excludes drillings exceeding the location (depth) of the fresh-brackish boundary plane. This boundary is defined as the plane on which the chloride concentration of the groundwater is equal to or exceeds the value of 150 milligrams per litre.
- Geotechnical testing does not include any form of seismic investigation.

Article 2

- Any water being used in the project has to be of drinking water quality.

Article 3

- After drilling the borehole has to be restored with annealed sand and at the locations of penetrated clay layers it must be restored with special clay shards/chunks/lumps/pellets, with the purpose of restoring the impermeable properties of the layer.

Article 4

- The application method and type of sealing agent to be used has to be announced to the head of the *Groen, Water en Milieu* department of the province South Holland two weeks before execution.
- The application of the sealing agent in question has to be executed in the presence of the head of the *Groen, Water en Milieu* department of the province South Holland or by an appointed[14] official in his place.

Article 5

- Oil products potentially being used in the drilling installation during the activities have to be carefully transported, refilled, refreshed and disposed without spills in order to avoid the risks of groundwater pollution.

Article 6

- All involved drilling material located within EPAs for drinking water have to be specifically equipped to make sure that the risk of spilling oil or fuel and, consequently, contaminating the groundwater is minimised.

Article 7

- Whenever the subsurface has been, or is in danger of being contaminated due to spills, leakage etc. during the activities, the business owner/drilling master is obligated to inform the head of the *Groen, Water en Milieu* department from the province South Holland and the director of the drinking water company of the situation.
- Whenever the subsurface has been, or is in danger of being contaminated due to spills, leakage etc. during the activities, the business owner/drilling master is obligated to debate with the head of the *Groen, Water en Milieu* department from the province South Holland and the director of the drinking water company and implement any necessary measures in order to either diminish the risk of contamination or neutralise the contamination.

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[14] The official in question has to be appointed by the head of the *Groen, Water en Milieu* department of South Holland

Enforcement of these regulations and the granting of permits is the responsibility of the *Omgevingsdienst Haaglanden*, translated and referred to in this paper as the Haaglanden Environmental Service (HES). The process from initial commission by the client to execution of the project is illustrated in Figure 1.17.

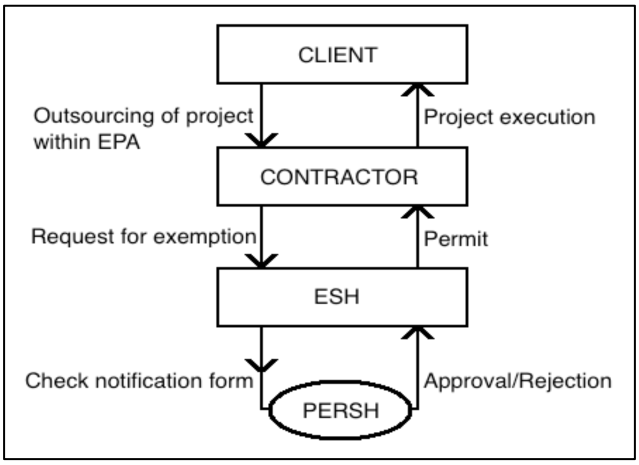

Figure 1.17. Illustration of the process associated with a request for exemption within EPAs.

The initial request for a certain project comes from the client, for example from a municipality for the building of new houses in an Oasen EPA. In this case, information is required concerning the subsurface layer orientations and conditions in order to establish the bearing capacity of the underlying layers, the appropriate type of foundation etc. In order to acquire this information, the municipality contracts a geoconsultancy company to perform CPTs and advise on the subsurface conditions.

If a certain geoconsultancy company decides to take on the project, it is obliged to submit a request for exemption to the HES in order to perform the planned activities at the predefined location. This must be accompanied by an overview of the potential project, the equipment, the number of planned CPTs, the location(s), and the sealing agent to be used. The information is to be submitted in the form of a notification form, provided by the HES. As a result of the necessary specialist expertise, this independent governmental organisation is appointed for the execution of lawful environmental tasks according to the PERSH within the province of South Holland. Furthermore, the ESH is responsible for the issuing of "normal" permits, enforcement of the associated laws and monitoring of all projects in the municipalities Delft, Den Haag, Midden-Delfland, Leidschendam-Voorburg, Pijnacker-Nootdorp, Rijswijk, Wassenaar, Westland and Zoetermeer (ODH, 2016).

The HES then validates the request and checks whether the contractor possesses the required certificates, licenses and equipment to perform the activities. When the request is approved, a permit is issued to the contractor. The HES also provides the contractor and other involved parties with the relevant sections from the PERSH on geotechnical testing (as listed in 1.4.1) and partly performs occasional controls to enforce those regulations. Then the contractor is allowed to initiate the project for the client.

The enforcement is partly performed by the HES and partly by other environmental services in the province of South Holland, depending on the location of the potential project. Figure 1.18 indicates the different environmental services responsible for enforcement throughout the province of South Holland.

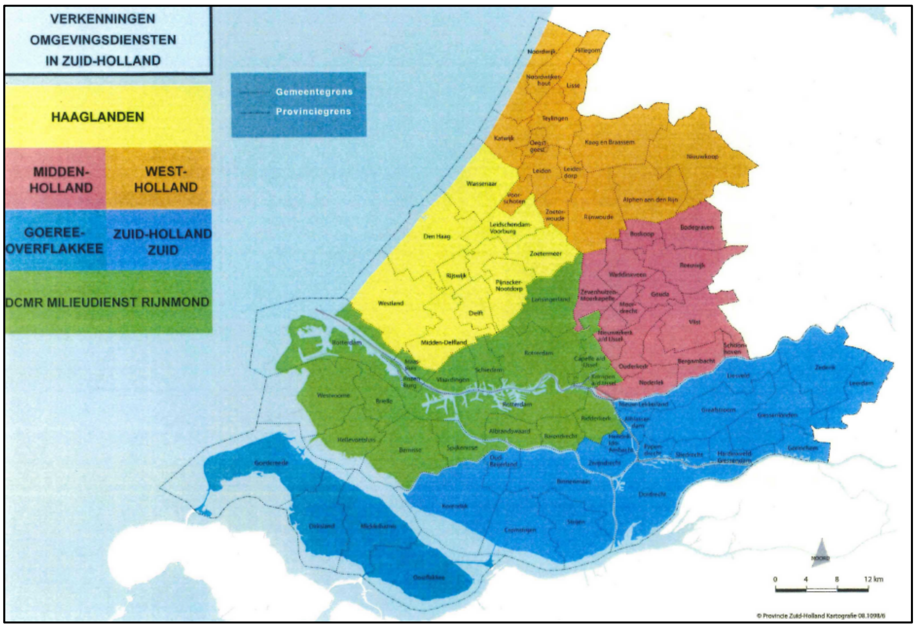

Figure 1.18. An overview of the different environmental services within the province of South Holland (ODH, 2016).

According to geoconsultancy company Inpijn-Blokpoel, the entire process of requests, check and execution takes too long. They state that the process of obtaining a permit for a certain project can take longer than a month. According to the HES, however, recent changes have been implemented into the system which have significantly reduced the total amount of time needed to legalise the project. The maximum time needed for this process is said to have been effectively reduced to 10 working days.

1.4.2 Additional regulations provided by Oasen

in addition to the governmental PERSH regulations, Oasen provides a different set of rules. However, these cannot be enforced unless the contractor is executing a project governed by Oasen, in which case it has signed an agreement regarding the rules to be followed under any circumstances. The following rules apply when performing activities in the vicinity of a water extraction area according to Oasen:

General Rules

Performing activities within the supply area of Oasen requires an arrangement with an Oasen employee in order to establish a work permit. In addition, Oasen has established a safety, health and environmental plan[15], which has to be complied with at all times.

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[15] Available on the website of Oasen: https://www.oasen.nl/Lists/Downloads/Veiligheidsplan.pdf

Furthermore, the company performing the activities (the contractor) has to make sure the nearby purification plant, soil, air, surface water and groundwater are not contaminated. Whenever an incident occurs, the company in question has to prevent and/or mitigate potential contamination.

The contractor has to inform the local representative from Oasen if one or more of the following incidents occur:

- Alarm
- Malfunction
- Calamity
- Fire
- Incident with potential injury or environmental damage
- In general, a hazardous event

If one of these points concerns a leakage, the company in question has to perform direct countermeasures to control the environmental consequences.

The following actions are strictly prohibited:

- Bringing leaking material into the EPAs
- Refreshing oil or chemical products
- Storing more than the required daily fuel volume
- Storing oil, chemical products, manure and other substances, which are a potential threat to the environment
- Burning or burying garbage and other materials
- Urinating in the direct environment
- Disposing rinse water or water used for cleaning the installations in the direct environment
- Usage of oil-based heaters on the working site

Regarding Equipment

When using equipment, the following regulations apply:

- Regular checks on potential leakage (at least once at the beginning of the day and once at the end)
- If possible, store fuel, oil and other chemicals outside the EPA
- If possible, refill abovementioned substances outside the environmental protection area, else carefully without spills above a container or piece of foil
- Repairs to equipment must be discussed with the local representative of Oasen

- If using oil- or petroleum-driven machines, these must be installed above a container
- Chemical toilets are only allowed in agreement with the local representative of Oasen and under the condition that it is fixed to the ground on one location

Regarding the Subsurface

- It is not allowed to dig holes deeper than 2.5 metres into the subsurface without explicit permission and exemption from a hydrologist
- It is not allowed to install and/or remove foundation constructions deeper than 2.5 metres into the subsurface without explicit permission and exemption from a hydrologist
- Water to be used in the activities for any purpose has to be locally produced drinking water; any other type of water with a different composition is illegal
- Planned drilling processes have to be executed with clean materials/tools
- Boreholes have to be sealed with swelling clay after the activities are done to a minimum of 10 metres under the mowing field; Oasen advocates the use of Mikolit® 00 or Mikolit® 300
- Any activities have to be announced with a so-called KLIC-report
- A report has to be delivered to the local representative of Oasen due to cables and pipelines being present in the subsurface

1.4.3 Associated NEN-EN-ISO standards

NEN-EN-ISO is an abbreviation which refers to the "NEN" (the Netherlands Standardization Institute) and the "ISO" (the International Organization for Standardization). The NEN is a Dutch company which concerns itself with the process of normalisation in the Netherlands. Its relevance lies in the occurrence of uncertainties and/or disagreements in different procedures between involved parties. In case of an uncertainty or disagreement, the involved parties can apply a request to create a certain set of rules, a standard, in cooperation and agreement with one another. The NEN is the neutral party, whose task it is to document the agreements and establish a so-called standardised procedure. The NEN expressively highlights[16] that the key in this process is the creation of standards by consensus, implying that a large number of interested parties is the main boundary condition. Furthermore, newly written standards cannot conflict with existing standards.

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[16] This information is retrieved from the homepage of NEN, available on: https://www.nen.nl/Veelgestelde-vragen/Over-normen.htm

Unlike requests for the creation of a standard, the NEN also frequently receives governmental requests regarding the inducement of an investigation to establish whether or not standardisation is possible within a certain sector (and to what degree). Depending on the results, the investigation carried out by the NEN has the potential to become the reason for a new project in which all interested parties can join freely. However, in order to obtain the finalised standard, the interested parties have to pay a fee.

The final standards are by no means part of the law or lawfully enforceable. The documents only include best practices, which indicate empirically established ideal parameter values leading to the best results. While these are not directly related to the law, laws do occasionally refer to certain standards. They are a form of self-regulation and within business agreements, they provide trustworthy guidelines on possibilities regarding equipment and differences between parties.

The following standards apply to geotechnical testing:

- NEN-EN-ISO 22476-1:2012 – Geotechnical investigation and testing – Field testing – Part 1: Electrical cone and piezocone penetration test
- NEN-EN-ISO 22476-2:2005 – Geotechnical investigation and testing – Field testing – Part 2: Dynamic probing
- NEN-EN-ISO 22476-12:2009 – Geotechnical investigation and testing – Field testing – Part 12: Mechanical cone penetration test
- NEN-EN-ISO 10360-7:2011 – Geometrical product specifications – Acceptance and reverification tests for coordinate measuring machines (CMM) – Part 7: CMMs with imaging probing systems

This paper will not elaborate the content of these standards; it suffices to know that there are several methods for performing a penetration test (as explained in Chapter 1.2) and that each of those methods has its own best practices, established in a NEN standard. The last standard describes the verification of the performance of a CMM (used for measuring linear dimensions) with specific acceptance tests. In other words, it concerns the measuring devices used in penetration tests. These four standards form the guidelines for the entire process of penetration tests in geotechnical testing and describe what a well-executed penetration test should measure, how it should measure and what equipment should be used for these measurements.

Chapter 2 Methodology

This chapter provides an overview of the used materials and applied methods. A motivation of choices will be expounded and the limiting conditions will be listed.

This study has been conducted at the headquarters of Oasen in Gouda. It is a literature research, which means that information is mainly retrieved from scientific sources on the internet, published articles, geological maps and data provided by the research department of Oasen. In addition, in-person interviews have been conducted with representatives from the companies involved, to make up for the lack of documented information regarding the experienced shortcomings and the superiority of the involved sealing products.

During this research, multiple companies were visited: Research institute Deltares, geoconsultancy company Inpijn-Blokpoel, Haaglanden Environmental Services (HES), and the network-based organisation SIKB. These companies are located in Nieuwegein, Utrecht/Delft, Den Haag, and Gouda respectively. The visits to the research facilities of Deltares in Utrecht and Delft highlighted the different perspectives within this research and cast a light on the overall problem. In contrast, Inpijn-Blokpoel contributed towards a better understanding of the experienced problems and shortcomings in the process of sealing agent application. Furthermore, the assessment of the PERSH was significantly substantiated through visits to the HES and the network-based SIKB.

The lack of data concerning the swelling capacities of Dutch river clay and sea clay resulted in assumptions based on the mineral content of the clays. These can be verified by future experimental research. In the comparison of the pellet parameters, this research only includes the dimensions in millimetres (mm), the sinking velocity in metres per minute (m/min.), the bulk density in tonnes per cubic metre (t/m^3), the swelling delay in minutes (min.), the swelling capacity as a percentage of the original volume (%), the water absorption capacity as a percentage (%), the permeability in metres per second (m/s), the montmorillonite content as a percentage (%), and the swelling pressure in kilo newton per square metre (kN/m^2). In this process of comparison, several graphs were constructed with Microsoft Office Excel 2010. This program was chosen because of the clean visualisation it provides of the data.

A number of these parameters were further disregarded due to their insignificance in further comparison. This is substantiated by a brief explanation of the gravity of the problem and the direct links between certain parameters, rendering the discussion of certain parameters unnecessary. Also, the parameter data for DantoPlug and Mikolit® has been retrieved from the homepages of the companies, while the data for the Cebo products has been retrieved from product data sheets provided by the Cebo Holland Sales & Services department.

This research also created a set-up for further research. This set-up includes an experiment, which may contribute to the conclusion on the sealing capacity of the Dutch clays in the area of Oasen. The experiments have been validated by the Deltares laboratory, which confirmed the significance of the outcome for further research on this subject. The formulas associated with these experiments have been established with hydrologists at the research facilities of Oasen.

Chapter 3 Results

This chapter introduces fundamental assumptions along with a conclusion on the sealing capacity of the Dutch subsurface. Furthermore, the available sealing agents are compared and explained. Subsequently, the situational applicability and the relative superiority of different forms of application is discussed prior to the introduction of potential future experiments required in order to fully conclude on the different aspects of this research.

3.1 The Natural Sealing Capacity of the Dutch Subsurface

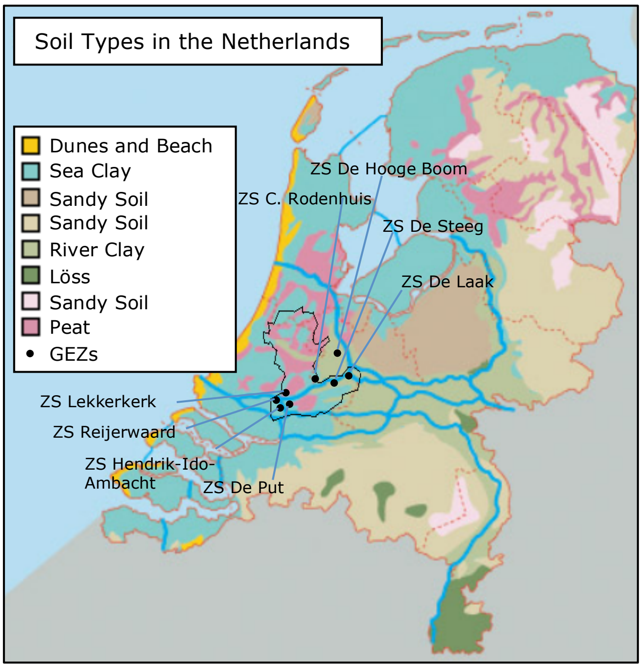

Figure 3.1. An overview of the different soil types in the Netherlands including the GEZs of Oasen. The boundaries of the Oasen area are approximated.

The Dutch subsurface has a high diversity in clay minerals, as depicted in Chapter 1.3.3. Of the discussed appearances, illite is mainly found in sea clay deposits, while river clay contains mica's and smectites among other things (Berendsen, 2008b). As a result, there is a clear division in Dutch soil types, which can be connected to the discussed clay minerals. Figure 3.1 illustrates the zones dominated by dunes/beaches, sea clay, sand, peat, river clay, and löss in the Netherlands (Deltawerken Online, 2004). In addition, the figure lists the Groundwater Extraction Zones (GEZs). Isolating the zone corresponding to Oasen, this research concludes that the area is mainly dominated by peat, sea clay and river clay.

Two zones can be distinguished: a western area including the extraction locations ZS Reijerwaard, ZS Lekkerkerk, ZS De Put, and ZS Hendrik-Ido-Ambacht[17], and an eastern area including the extraction locations ZS C. Rodenhuis, ZS De Steeg,

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[17] This is merely an extraction area, whereas the other locations also include purification plants

ZS De Laak, and ZS De Hooge Boom. According to figure 3.1, the western area is dominated by the over time deposition of sea clay in the subsurface in contrast to the eastern area, which is dominated by over time deposition of river clay. These clays have fundamentally different compositions and hence exert a different swelling behaviour upon disturbance.

Consequently, this research concludes that as a direct result of the higher montmorillonite content in river clays, the GEZs located in river clays exert the self-restoring behaviour to a relatively higher degree than those located in sea clays. This implies that an open borehole in sea clay will restore significantly less compared to an open borehole in river clay, due to the higher swelling capacity of river clay. Hence, the GEZs of ZS Reijerwaard, ZS Lekkerkerk, ZS De Put, and ZS Hendrik-Ido-Ambacht are located in sea clay and therefore exert this self-restoring behaviour significantly less than the GEZs of ZS De Hooge Boom, ZS C. Rodenhuis, ZS De Steeg, and ZS De Laak, which are located in river clay. In conclusion, the GEZs in river clay have a relatively higher self-restoring capacity than the GEZs in sea clay.

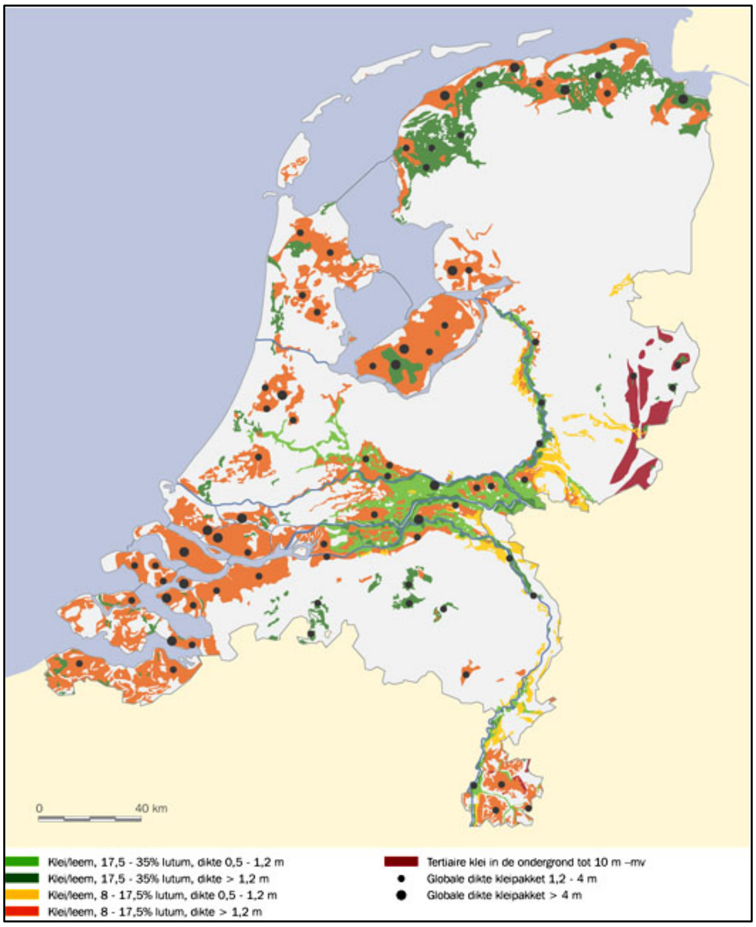

Figure 3.2. An overview of the lutum content in the Dutch subsurface.

Another way to review the self-restoring capacity of a soil is the lutum content. As described in Chapter 1.3, lutum content can be linearly correlated to montmorillonite content. However, no concrete values are given of the relation lutum content to montmorillonite content with respect to the swelling capacity. This implies that only a relative comparison can be made regarding the lutum content.

According to *TNO Bouw en Ondergrond*, Figure 3.2 provides a map of the Netherlands indicating the lutum content in the soil[18]. As visible in the figure, two areas can be distinguished regarding the lutum content: orange areas and green areas. The orange areas indicate soils with a lutum content of 8-17.5% while the green areas show soils with a lutum content of 17.5-35%. The white areas correspond to areas without available data regarding the lutum content.

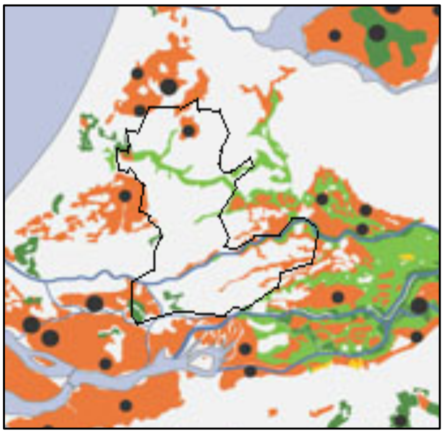

Figure 3.3. An overview of the lutum content in the subsurface within the area of Oasen.

The area relevant for Oasen is isolated in Figure 3.3. By comparing of Figure 3.3 with the locations of Oasen's GEZs (see Figure 3.1) it becomes clear that ZS Reijerwaard, ZS Hendrik-Ido-Ambacht, and ZS De Steeg are located in orange areas. Furthermore, ZS Lekkerkerk, ZS De Put, ZS C. Rodenhuis, and ZS De Laak are located in white areas and ZS De Hooge Boom is located in a green area. An overview of these groups is provided in Table 3.1.

With respect to the lutum content, this research concludes that the subsurface of GEZ ZS De Hooge Boom contains clay with the highest self-restoring capacity compared to ZS Reijerwaard, ZS Hendrik-Ido-Ambacht, and ZS De Steeg. No conclusion can be made regarding the lutum content of the subsurface at ZS Lekkerkerk, ZS De Put, ZS C. Rodenhuis, and ZS De Laak due to the lack of data.

Table 3.1 – An overview of the lutum content corresponding to the soil of the GEZs.

8-17.5% Lutum (Orange)	**No Data (White)**	**17.5-35% Lutum (Green)**
ZS Reijerwaard	ZS Lekkerkerk	ZS De Hooge Boom
ZS Hendrik-Ido-Ambacht	ZS De Put	
ZS De Steeg	ZS C. Rodenhuis	
	ZS De Laak	

As a result, the main conclusion of Chapter 3.1 is that the clays in the soils found in the area of Oasen contain swelling clay minerals. This means that the ground restores naturally, especially thanks to the horizontal ground forces. The rates at which these processes take place, however, remain unknown. This paper therefore concludes that experiments need to be executed in order to establish the exact swelling rates of sea clay and river clay, to conclude on the acceptability of the swelling rates regarding the assurance of microbiologically clean groundwater. High swelling rate results will render

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[18] Figure is available on: http://www.natuurinformatie.nl/ndb.mcp/natuurdatabase.nl/i000328.html

the application of sealing agents redundant while low swelling rate results emphasize the application of sealing agents, with respect to the risks of microbiological pollution. In other words, it has not been proven that boreholes restore adequately fast over time and hence the timescale on which the natural-restoring process works remains unknown.

3.2 Available Sealing Agents

Proper sealing of abandoned boreholes is a procedure, partly bound to rules and partly existing of choices made by the contractor. One of the choices a contractor has to make, is the type of sealing agent to be used. The following sections provide an overview of the significant variability in sealing agents and their relevant properties. Thorough research revealed that there are mainly three brands of sealing agents that are currently used in the Netherlands: *DantoPlug*, *Cebo* and *Mikolit*®. These brands are respectively created by the companies *Dantonit A/S*, *Cebo Holland B.V.*, and *Terratech B.V.* and refer to a product line rather than a single product. All three brands include a standard product, one or several improved version(s) of the standard product with a higher swelling capacity, a traceable magnetite-containing version and a thermal bentonite mixture. However, mixtures with thermal properties for the purpose of heat conduction are disregarded here, as heat conduction is not a significant property in this research.

3.2.1 DantoPlug

Dantonit A/S is a Danish company, specialised in the production of bentonite products. According to Dantonit A/S (2016), the company is the only Scandinavian manufacturer of bentonite products and distributes worldwide – for instance, to AB Veenstra B.V., a Dutch company mainly specialised in the distribution of sand, gravel, thermal grout and bentonite in the Netherlands. The DantoPlug product line has been created for the purpose of sealing small-diameter boreholes with the individual pellets being created from pure Danish bentonite extracted from a bentonite pit on Tåsinge, an island to the east of Denmark (Rotek A/S, 2016). The product line consists of the following products:

- DantoPlug Standard
- DantoPlug Super
- DantoPlug Super M

Dantonit A/S (2016) states that these three products are available in a cylindrical shape (see Figure 3.4) and can be split into two groups. DantoPlug Standard is developed for application in saturated zones while DantoPlug Super/Super M is developed for application in the unsaturated zone.

Figure 3.4. Cylindrical shape of DantoPlug.

The main differences with regard to parameter values includes a further delayed swelling for the Super variant and a difference in swelling capacity and permeability (see Table 3.2). The difference between DantoPlug Super and Super M is the addition of magnetite to the mixture in the Super M variant. This adds the ability to track the restored layer(s) with geophysical methods after application, which is a favourable characteristic for water companies like Oasen, for instance, as it allows them to check whether boreholes are correctly sealed and abandoned. Table 3.2 provides an overview of all DantoPlug parameter data.

Table 3.2 - Data overview of relevant DantoPlug sealing agents (Dantonit A/S, 2016).

Parameter	Unit	DantoPlug-Standard	-Super	-Super M
Pellet Diagonal Ø	mm	7	7	7
Pellet length	mm	6-12	6-12	6-12
Sinking velocity in water	m/min.	24	24	24
Bulk density	t/m^3	1.1	1.1	1.1
Swelling delay	min.	10	30	30
Swelling capacity	%	No data	No data	No data
Water absorption capacity	%	600	800	800
Permeability	m/s	$3 \cdot 10^{-10}$	$3 \cdot 10^{-11}$	$3 \cdot 10^{-12}$
Montmorillonite content	%	No data	No data	No data
Swelling Pressure	kN/m^2	126	189	189

The dimensions of individual pellets are listed first and second respectively as the diagonal and the grain length in millimetres. The third parameter refers to the process of sole pellets sinking into water-filled boreholes with a certain velocity in metres per minute. A lower velocity increases the risk of bridge-forming, the process of individual pellets cohering both to one another and against the borehole wands or the physical blockage of relatively large pellets, inevitably initiating the swelling procedure before the desired depth is reached. The result is a partly filled borehole containing open spaces, thus significantly (and negatively) affecting the local permeability of the clay layer. The fourth parameter states the bulk density of the pellets, also in tons per metre. The fifth parameter describes the maximum number of minutes in which the sealing agent has not yet gone through volumetric changes. In other words, it indicates the point in time where the clay particles start swelling. The sixth parameter describes the total swelling capacity of the pellets. It is listed as a percentage of the original volume by which it can maximally increase. The seventh parameter indicates the water absorption capacity in percentages, which is directly related to the swelling capacity. A higher capacity to absorb water into the crystal lattice generally implies a higher volumetric expansion. The eight and ninth parameters show the permeability and montmorillonite content, respectively indicating how easily the water flows through the sealing agent in metres per second, and the percentage of montmorillonite content, which is directly related to the swelling capacity of the sealing agent. Higher montmorillonite content yields higher swelling rates. Lastly, the table lists the swelling pressure, the parameter defined as the pressure of the expanding clay against the surrounding matrix.

3.2.2 Cebo

Cebo Holland B.V. is a Dutch company, specialised in the distribution of high-quality industrial minerals and additives. For the purpose of sealing abandoned small-diameter boreholes, the company produced the following compounds:

- Cebogel QSE
- Cebogel QSM
- Cebogel QSL
- Baroid Drill-Grout
- Baroid Drill-Grout Plus

According to Cebo Holland (2016), Cebogel QSE is a compound consisting of 100% sodium bentonite, thus having a high swelling capacity, while Cebogel QSM consists of 100% calcium bentonite, which as a result has a significantly lower swelling capacity. This means that Cebogel QSE is applicable at greater depths due to its higher swelling capacity, which indirectly implies a higher swelling pressure and the ability to guarantee impermeable conditions under higher water and ground pressures present at greater depths. Cebogel QSL is another variant, consisting of 100% natural clay and possessing the ability to delay the swelling process and trigger it on greater depths instead. According to Cebo Holland (2016), however, the swelling capacity is very low, implying the exact opposite. Cebo Holland (2016) recommends to use it only for seals which do not necessarily require more than a light-swelling sealing material – for instance, at the top of a borehole. Like DantoPlug, Cebogel QSE, QSM, and QSL appear as cylindrical pellets.

The main differences regarding the parameter data indicate that the sole pellets have larger dimensions for Cebogel QSL. This results in a higher sinking velocity according to Cebo Holland (2016), compared to Cebogel QSE and QSM. At the same time, Cebogel QSL has a significantly lower swelling capacity than Cebogel QSM, which in turn has a lower swelling capacity than Cebogel QSE (see Table 3.3). According to Cebo Holland (2016), Cebogel QSE has the lowest permeability value of all three.

Besides sealing agents in pellet form, Cebo Holland also offers products in powder form, which must be mixed into a suspension with water before application. Baroid Drill-Grout is the main powder-form sealing agent. According to Cebo Holland (2016), it is a self-settling suspension, used to fill annular spaces or abandoned open boreholes after drilling is completed. The suspension after mixture with water can be effectively pumped into the borehole with a standard centrifugal pump. Cebo Holland (2016) recommends the Baroid Drill-Grout powder to be mixed at a concentration of 160 kilograms per cubic metre, in order to achieve the properties listed in Table 3.3. Baroid Drill-Grout Plus differs in the sense that unlike its standard version (Baroid Drill-Grout), it requires to be mixed at a concentration of double the standard value: 320 kilograms per cubic metre. This results in a significant difference in the total amount of time needed for the suspension to reach total solidification. According to Cebo Holland (2016), this leads to a total solidifying time of one month for the regular Baroid Drill-Grout, whereas the Plus counterpart reaches total solidification in one week.

A total overview of Cebo parameter data is provided in Table 3.3. Certain parameters in the drill-grout variants are listed as not applicable (n/a). This implies that due to the difference in appearance (pellets or suspension), certain parameters do not apply. Furthermore, Baroid Drill-Grout is a relatively new sealing agent, which explains the lack of available data (in the table, “no data”). Also, the montmorillonite content in the drill-grout variants is depicted as “variable”. This means that the montmorillonite content is highly dependent on the relative mixture of the powder with water. As mentioned before, Cebo Holland recommends a predefined ratio of powder to water, but the company responsible for the application can choose to deviate from that ratio at its own discretion.

Table 3.3 - Data overview of relevant Cebo sealing agents[19].

Parameter	Unit	Cebogel-QSE	-QSM	-QSL	-Baroid Drill-Grout	-Baroid Drill-Grout +
Pellet diagonal Ø	mm	*6.5*	*6.5*	*10*	**	**
Pellet length	mm	*5-20*	*5-20*	*5-25*	**	**
Sinking velocity in water	m/min.	*17*	*17*	*23*	*n/a*	*n/a*
Bulk density	t/m^3	*1.1*	*1.1*	*1.1*	$1.11^{\sim}$	$1.11^{\sim}$
Swelling delay[20]	min.	*No data*	*No data*	*No data**	*0*	*0*
Swelling capacity	%	*220*	*150*	*120*	*No data*	*No data*
Water absorption capacity	%	*800*	*230*	*120*	*n/a*	*n/a*
Permeability	m/s	$1 \cdot 10^{-12}$	$1 \cdot 10^{-9}$	$1 \cdot 10^{-9}$	$1 \cdot 10^{-9}$	$1 \cdot 10^{-9}$
Montmorillonite content	%	*80*	*80*	*15*	*No data*	*No data*
Swelling pressure	N/m^2	*18-21*[21]	*No data*	*No data*	*0.15*	*1.88-2.0*

** According to Cebo, QSL has a delayed swelling point; however, no concrete value is presented.*

*** Baroid Drill-Grout is a suspension of powder and water and, therefore, no pellet diagonal/length can be added. The grain size of the powder is 95% through 125 μm.*

~ For Baroid Drill-Grout, the value 1.11 t/m^3 refers to the saturated density because it is applied in suspension.

3.2.3 Mikolit®

Terratech B.V. is a Dutch company specialised exclusively in the production of bentonite pellets for the purpose of restoring penetrated clay layers. This resulted in the production of the Mikolit® product line, existing of the following products:

- Mikolit® 00
- Mikolit® 300
- Mikolit® 300M
- Mikolit® B

Mikolit® 00 is the fundament of the Mikolit® product line (Terratech, 2016a). It is developed focussing on the four essential parameters that define a qualitative sealing agent according to Terratech (2016a). First of all, the swelling capacity. After full swelling in a borehole (the absence of air voids in the restored borehole), Mikolit® 00 has the potential to swell another 30-40%, which means that irregularities as a result of the boring process will also be fully restored. Furthermore, Terratech (2016a) highlights the

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[19] Pdf product data sheets where sent by Mr F. Ooms (Cebo Sales & Services department)
[20] Cebo declared that concrete values of delayed swelling behavior have not (yet) been measured by the company
[21] Derived from experimental results provided by Cebo Holland (see Appendix A5)

importance of preventing dust from sticking to pellets, as dust affects the sinking velocity significantly in a negative fashion. Terratech also states that the more-or-less oval shape of the pellets has shown to result in the best characteristics of the clay. Lastly, the sinking velocity is an important parameter as it directly correlated with the application depth of the pellets in question.

Consequently, Terratech decided to produce 3 alternatives: Mikolit® 300, 300M and B. Mikolit® 300 is a variant produced with the purpose of achieving a higher swelling capacity, approximately 50-70% swelling potential after full swelling. This is the direct result of increasing the montmorillonite content, which, as mentioned before, is a clay mineral responsible for extreme swelling rates. However, Terratech (2016b) does mention that the pellets tend to stick faster to the walls, thus increasing the risk of bridge-forming. The Mikolit® 300M variant is similar to the DantoPlug Super M product. It has an addition of magnetite to its chemical composition, yielding a traceable substance. Another favourable consequence of this magnetite addition is the increase of the bulk density. According to Terratech (2016c), the pellets sink faster into a borehole, increasing their maximum applicable depth. Lastly, the Mikolit® B variant is produced with the highest swelling capacity of all Mikolit® products. This results in a highly impermeable clay layer with high self-sealing capacities due to the significant increase in montmorillonite content.

The mentioned swelling rates are established by laboratory experiments by Terratech and visible in Figure 3.5. The figure also displays the difference in swelling rates between the application of demineralised water versus purified drinking water. The larger swelling rates are associated with the purified drinking water due to the presence of minerals like for example sodium and potassium, which can be adsorbed into the crystal lattice of the clay, implying larger swelling as explained in chapter 1.3. From the Mikolit® products, Mikolit® 00 and 300 have been primarily developed for application in saturated zones (Rotek A/S, 2016). The exact values for the Mikolit® products are presented in Table 3.4.

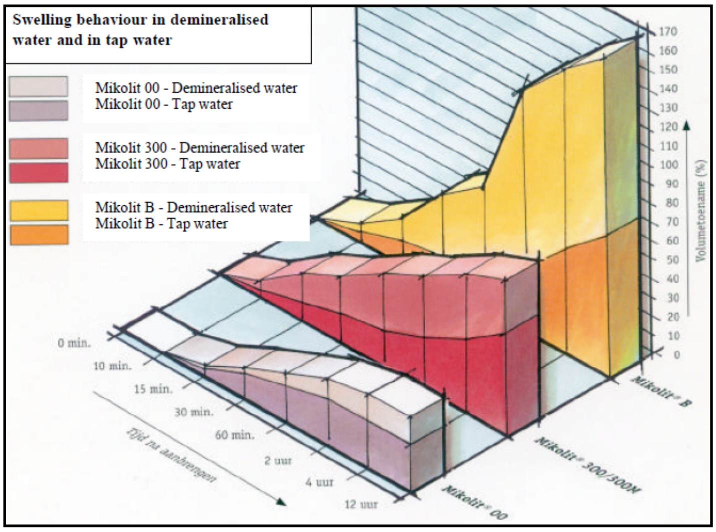

Figure 3.5. Test results on the swelling capacity of Mikolit® 00, 300, 300M and B.

Besides cylindrical pellets, the Dutch company *Van Reekum Materials B.V.* also produces bentonite bars, which are made of Mikolit® 300 (see Figure 3.6). They are recommended for small-diameter boreholes in particular and consist of 100% pure Mikolit® 300 without any additives (VRM, n.d.). Table 3.4 includes the dimensions of the bars along with the mass. Unfortunately, no literature is available on the applicability of the bars.

Table 3.4 – Data overview of relevant Mikolit® sealing agents (Terratech, 2016a, b, c, d).

Parameter	Unit	Mikolit®-00	-300	-300M	-B
Pellet diagonal Ø	mm	8	8	8	8
Pellet length	mm	7-12	7-12	7-12	7-12
Sinking velocity in water	m/min.	21	21	>21*	21
Bulk density	t/m^3	1.1	1.1	1.3	1.0
Swelling delay	min.	15	15	15	12
Swelling capacity	%	30-40	50-70	50-60	180-200
Water absorption capacity	%	100	240	240	800
Permeability	m/s	10^{-10}	10^{-11}	10^{-11}	10^{-12}
Montmorillonite content	%	20-30	35-45	35-45	60-70
Swelling pressure	kN/m^2	3.5	9	6-8	12-15

* Terratech B.V. declared that no individual measurements have been made for the sinking velocity of Mikolit® 300M. Hence, the value is higher than 21 m/min. due to the higher bulk density, but the exact value is not available.

Table 3.5 – Parameter values of Mikolit® 300 Bars

	Unit	Mikolit® 300 Bar
Length	cm	47
Diameter	mm	34
Mass	kg	0.95

Figure 3.6. Mikolit® 300 bars.

3.3 Applicability and Superiority

All products have limitations and relative superiority in certain situations. This chapter contains a comparison of the sealing agents discussed in the previous section. Favourable properties are highlighted and the application shapes of the sealing agents are discussed. At last, the best sealing agent in CPT boreholes will be discussed along with setup for potential further research.

3.3.1 Comparison of the DantoPlug, Cebo and Mikolit®

This research compared the products for each variable separately. Throughout the process, several graphs have been created to organise the results. However, some parameters are left out because they are directly related to other parameters, making it irrelevant to introduce two graphs with essentially identical information. The different available sealing agents, as listed in Chapter 3.2, are shown on the X axis in the graphs and are numbered as follows: 1. DantoPlug Standard, 2. DantoPlug Super, 3. DantoPlug Super M, 4. Cebogel QSE, 5. Cebogel QSM, 6. Cebogel QSL, 7. Mikolit® 00, 8. Mikolit® 300, 9. Mikolit® 300M, 10. Mikolit® B, 11. Baroid Drill-Grout, 12. Baroid Drill-Grout Plus. The different colours of the dots in the graphs, yellow, blue and green, refer to the three main sealing agent brands respectively, DantoPlug, Cebo and Mikolit®. All graphs are based on the data discussed in Chapter 3.2 and assumptions have been made where no data was available. The relative relations and associated assumptions will be discussed in the following paragraphs.

Dimensions

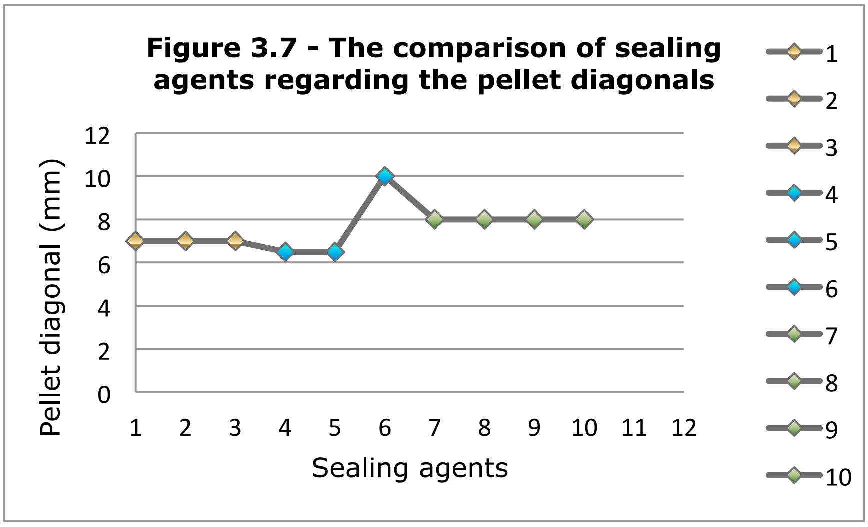
Figure 3.7 - The comparison of sealing agents regarding the pellet diagonals

In this subsection, the dimensions of the individual pellets are being compared. This includes the diagonal as well as the length of the pellets, depicted in Figures 3.7 and 3.8. "Reeks1" in Figure 3.8 shows the minimal length and "Reeks2" shows the maximum length, as reported by the relevant companies. The area between "Reeks1" and "Reeks2" indicates the pellet dimension diversity per sealing agent. A larger area illustrates a higher variability in the size of the pellets per volume unit. The contrary is also true: the smaller the area the greater the present dimensional uniformity per volume unit.

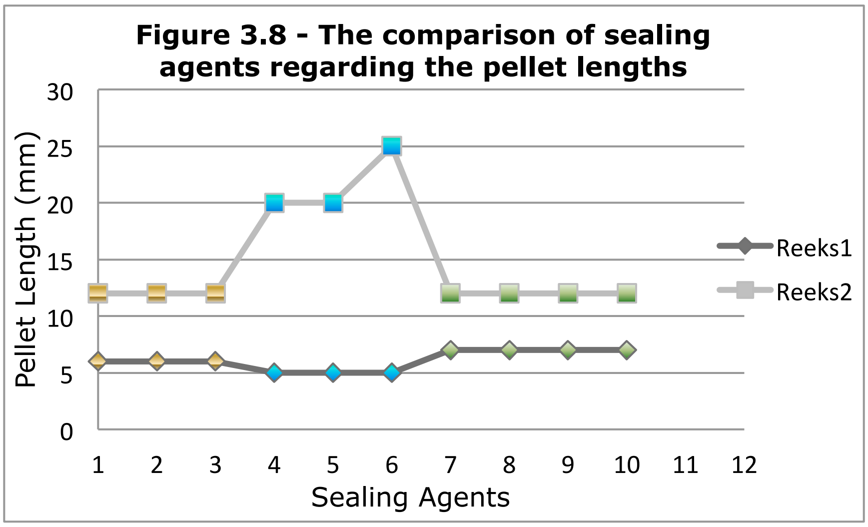

Figure 3.8 - The comparison of sealing agents regarding the pellet lengths

A higher diversity in pellet size results in a reduction of the space not filled with pellets during the process of sealing. This is due to the fact that the individual impermeable clay pellets are assumed to behave in a similar way as individual grains in porous media[22]. In other words, a higher diversity in pellet size (which in porous media is referred to as "poorly sorted") initially results in a less porous sealed borehole due to the relatively smaller pellets filling the spaces occurring between the relatively larger pellets, similar to the behaviour of grains, as illustrated in Figure 3.9 by Engler (2010a).

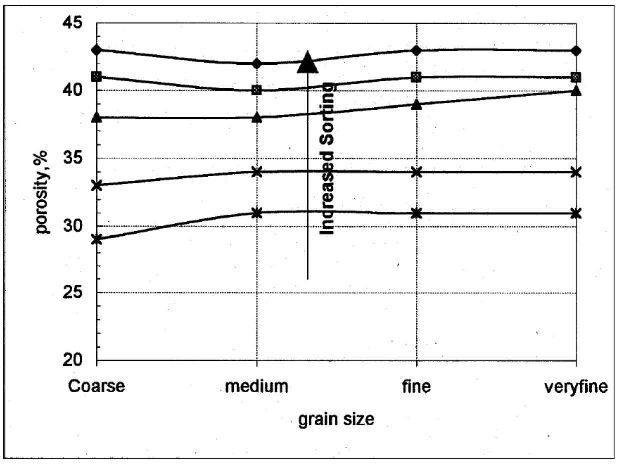

Figure 3.9. The relation between porosity and the degree of sorting in porous media (Engler, 2010a).

As a consequence, the total volume not filled with pellets, after application, will be smaller compared to the application of a sealing agent with uniform pellets. This implies that the pellets will have to swell less to ensure complete sealing, which means they will retain more potential swelling capacity to restore future local subsurface disturbances in order for the long-term impermeable behaviour of the layer to be guaranteed.

Furthermore, the higher variability in pellets size also results in a lower permeability according to Engler (2010b). The effect of sorting on the permeability is illustrated in Figure 3.10. As visible in Figure 3.7, a poor sorted matrix is characterised by a lower permeability.

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[22] The mentioned behavior includes the porosity and permeability. No assumptions are made regarding other factors

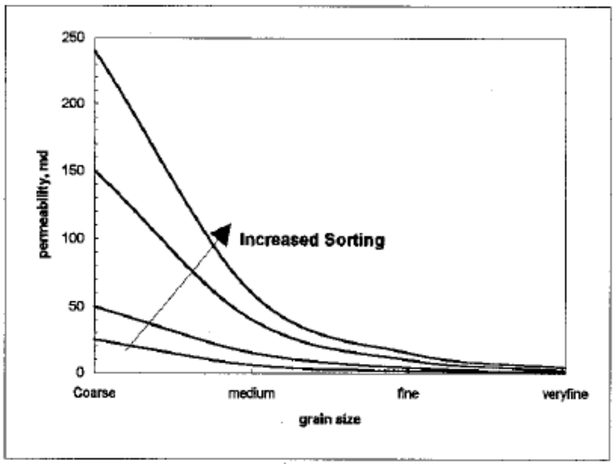


Figure 3.10. The relation between permeability and the degree of sorting in porous media (Engler, 2010b).

The conclusions from Figures 3.7 and 3.8, combined with the information from Figures 3.9 and 3.10, yield that first of all, the differences in the diagonal of individual pellets are negligibly small (in the order of a few millimetres). Hence, it can be assumed that it will not drastically impact the behaviour of the pellets and can thus be further disregarded. However, there is a significant variety in the length of the pellets. Cebo Holland has the highest variety in pellet size with pellets ranging between 5 and 25 millimetres, while DantoPlug and Mikolit are characterised by smaller ranges, with pellet lengths of 6-12 and 7-12 millimetres (resp.). Regarding the length aspect only, larger pellets have a higher risk of bridge-forming to occur, especially with a decreasing borehole diameter according to Terratech B.V.

From the perspective of Oasen, the emphasis lies entirely on guaranteeing absolute restoration of the borehole with impermeable clay so that clean groundwater can be guaranteed. Terratech B.V. declared that to achieve this, the main factor lies in the positioning of the pellets. Pellets have to reach the desired depth and the pellets length does in fact significantly affect this process. According to Terratech B.V., smaller pellets tend to stick to the walls more quickly, as they are relatively lightand thus, have a smaller gravitational component. Hence, it is advised not to use smaller pellets in smaller diameters.

Sinking velocity in water

The sinking velocity in water is directly related to the maximum application depth. A higher sinking velocity implies a larger displacement before the clay reaches the critical swelling point, resulting in the downward displacement process being hampered. In other words, if an example clay X reaches its critical swelling point in five minutes, then a sinking velocity of, for example, 20 metres per minute yields a maximum depth of 100 metres before the clay starts sticking to the walls and gradually transforms into a hardened, still plastic formation. Also, the presence of seepage forces may result in pellets being flushed directly out of the borehole.

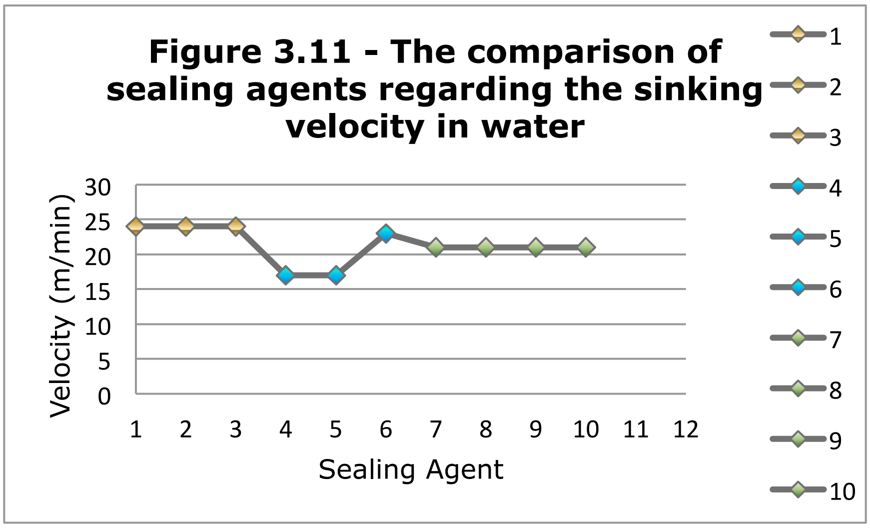


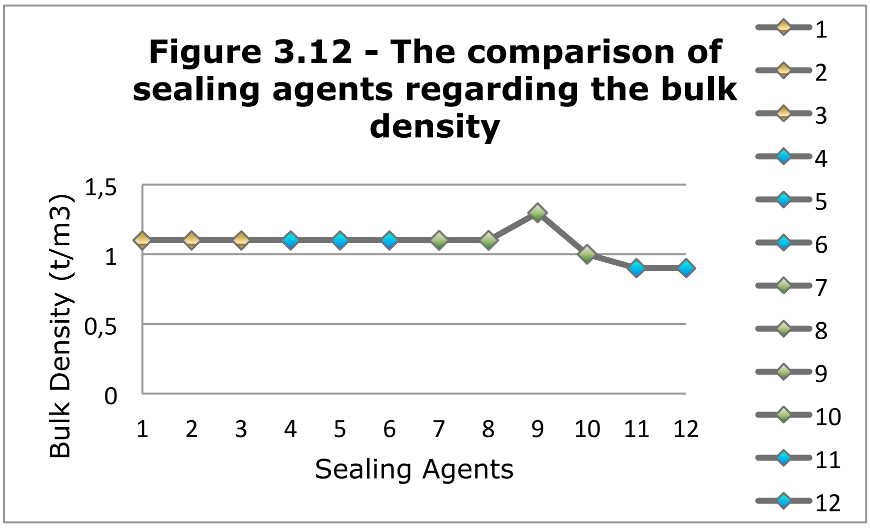
Figure 3.11 - The comparison of sealing agents regarding the sinking velocity in water

However, the application depth does not only depend on the absolute sinking velocity in water. It is also affected by the amount of dust on the pellets and the behaviour of the pellets to stick to the walls. According to Terratech B.V., dust on pellets decreases the above-listed sinking velocities and muddles the water in de borehole. Also, the pellets tend to stick to the walls upon wetting regardless of the swelling procedure, especially when being applied with a high velocity. Dust should be avoided at all times during application of the sealing agents and the pellets should be applied in a stationary gradual way to prevent the pellets from sticking to the wall and hence not reaching the desired depth; also known as bridge-forming.

Figure 3.11 shows a comparison of the sinking velocities of the different sealing agents discussed in this paper. The value corresponding to Mikolit® 300M is determined at 21 metres per minute in Figure 3.11 for lack of exact data. In reality, this value is higher due to the addition of magnetite to the compound. In the argumentations to follow regarding relative sinking velocities, this value is therefore assumed to be higher than 21 metres per minute.

Figure 3.11 yields that DantoPlug is characterised by the highest sinking velocities. All products have the same sinking velocity, namely 24 metres per minute. This is followed by Cebogel QSL with a sinking velocity of 23 metres per minute and then by the Mikolit® products with the exception of the 300M variant (as mentioned in the previous section). The corresponding values are 21 metres per minute for the 00, 300 and B variants, while the correct value for the 300M variant, as provided by Terratech B.V., is >21 metres per minute. Finally, the QSE and QSM pellets of Cebo Holland have the lowest sinking velocities: both 17 metres per minute. As mentioned in section 3.2.2, the grout mixtures of Cebo Holland have no sinking value as they are suspensions, being pumped directly into the borehole.

Bulk density



The bulk density of the sealing agents highlights the extent to which the pellets as a whole fill up the borehole at first (before swelling but after application). This implies that the bulk density indicates the total mass of the sealing agent after application, divided by the total volume of the occupied space, which includes individual particle volume, inter-particle void volume and internal particle volume.
In this case, the volume not occupied by the pellets is dedicated to air. This implies that the bulk density is essentially equal to the particle density in this case according to Graveel & Thien (2002). Hence, a solid block of a certain sealing agent of one cubic metre will have a higher bulk density than its bulk density when appearing as smaller individual particles in the same volume mainly due to the large volume of air trapped between the particles.

In sealing agents, the bulk density refers to the amount of space left between the individual pellets[23] and also directly to the maximum application depth. In general, the pellets have to fill up inter-pellet spaces first before being able to dedicate their swelling potential towards outward expansion. However, this relation can only be established when the dry density is also known for the same sealing agent. This is due to the fact that the difference between dry density and bulk density indicates the volume designated towards water or air between the pellets when being applied. Only then, the value for the difference may be compared to other sealing agents. For Mikolit®, Terratech B.V. (2016a) established this volume to be approximately 45-50%. For DantoPlug and Cebo Holland, the values have not been determined and neither has the dry density. Hence, the inter-pellet space cannot be compared.

However, the bulk density is also directly related to the maximum application depth as mentioned in the previous section. Hence, a comparison between the bulk densities of the sealing agents is made in Figure 3.12. In general, Figure 3.12 yields that

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[23] This holds only true for pellet-form sealing agents

Mikolit® 300B has the highest bulk density; 1.3 t/m^3. This is followed by DantoPlug Standard/Super/Super M, Cebogel QSE/QSM/QSL and Mikolit® 00/300, which have similar bulk densities: 1.1 t/m^3. Then comes Mikolit® 300M with a bulk density of 1.0 t/m^3 followed by the Baroid Drill-Grout mixtures both with a bulk density of 0.9 t/m^3.

Swelling delay

The swelling delay is an important parameter in the process of getting the pellets to the desired depth. The delay is achieved through a special coating around the individual pellets. In general, higher swelling delays correspond to a higher application depth.

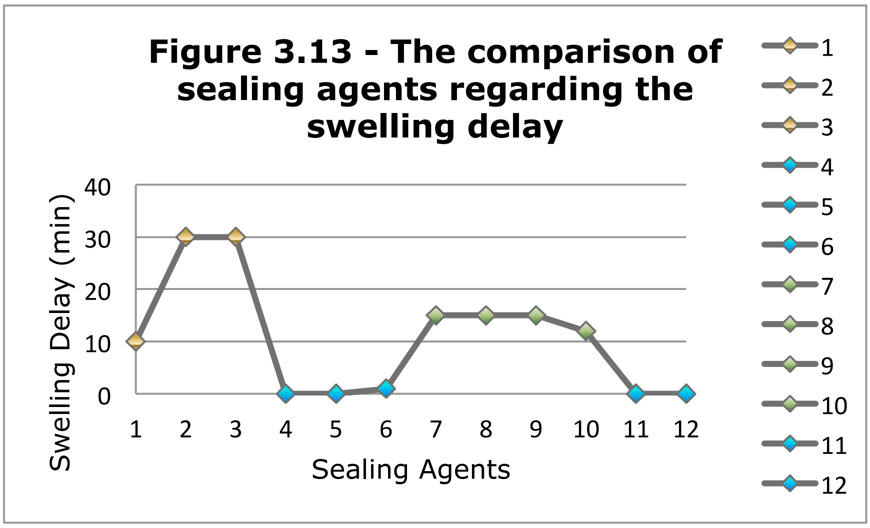


Figure 3.13 - The comparison of sealing agents regarding the swelling delay

In other words, an implemented swelling delay increases the reliability of the pellets to achieve a certain predefined depth. As mentioned before by Terratech B.V., this is one of the main issues in the application of sealing agents. The coating protects the pellets against swelling, which inhibits the pellets from bridge-forming before achieving the depth of the damaged clay layer.

According to the production data sheets of Cebo Holland, the Baroid Drill-Grout compounds are mixed into suspensions, which retain a processability of up to eight hours. However, this does not imply that the swelling procedure is delayed, nor does it list the presence of a substance in the powder with a similar purpose as the protective coating around the pellets. It only validates the point of Baroid Drill-Grout transforming in a more viscous liquid during approximately the following eight hours, after which the viscous fluid is transformed into a hardened, yet still plastic formation. However, the applicability only depends on the available tube length, as the Cebo grout suspensions are added from bottom to top, pressing the existing fluid/suspension out of the borehole and replacing it with the Baroid Drill-Grout suspension. As a result, sealing deeper boreholes requires a greater pipe length, which increases the cost.

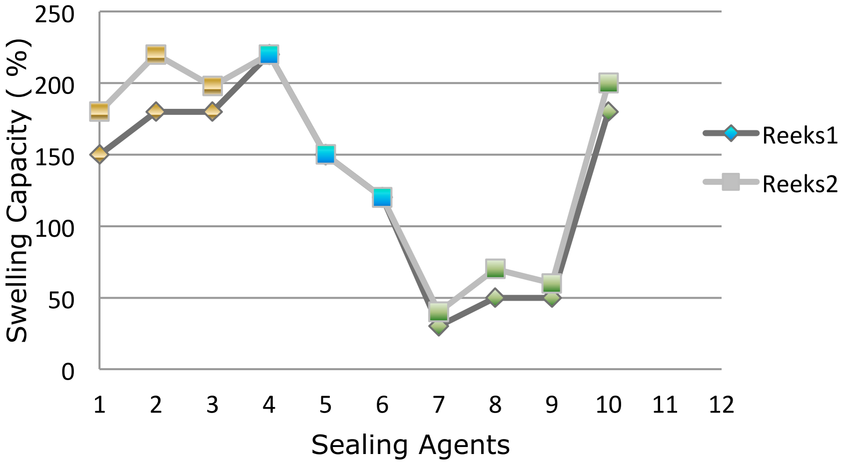
Figure 3.13 illustrates the swelling delay values corresponding to the sealing agents included in this research. The observations include that DantoPlug Super and DantoPlug Super M have the highest swelling delay of 30 minutes. The second highest swelling rates correspond to the Mikolit® product line with 15 minutes for Mikolit® 00, Mikolit® 300, Mikolit 300M, and 12 minutes for Mikolit® B. Finally, DantoPlug Standard is listed with a swelling delay of 10 minutes.

The Baroid Drill-Grouts are assumed in this research to have a swelling delay of zero, as previously argued. According to Cebo Holland, no specific data is acquired through experiments regarding the swelling delays of Cebogel QSE, Cebogel QSM and Cebogel QSL. It is only mentioned that Cebogel QSL has a certain unspecified swelling delay. Due to the lack of specific data, it is assumed in this research that the swelling delay in Cebogel QSE and Cebogel QSM is absent. Also, the swelling delay for Cebogel QSL is estimated at one minute.

Swelling capacity

The swelling capacity is significant as it highlights to what extend a sealing agent is capable of guaranteeing impermeable characteristics and having the ability to adapt and restore occurring annular spaces or other similar local disturbances. In the swelling capacity values for the discussed sealing agents, the space between the pellets is also taken into account. This implies that the listed values are potential swelling capacity values to supplant and restore aforementioned local disturbances.

Figure 3.14 - The comparison of sealing agents regarding the swelling capacity



Terratech B.V. mentions an empirically obtained relation between the swelling capacity and the pellet sizes. The company claims that relatively smaller-sized pellets with a strong swelling character tend to stick to the borehole walls more quickly, before reaching the predefined depth. This results in bridge-forming.

Figure 3.14 compares the swelling capacities of the sealing agents. The DantoPlug swelling capacity values are based on assumptions, as Dantonit does not provide any data regarding the swelling capacity. These assumptions are explained in the next paragraph. In general, the sealing agents with the strongest swelling capacities are Cebogel QSE, DantoPlug Super, Mikolit® B, DantoPlug Super M, and DantoPlug Standard with respective swelling capacities of 220%, 180-220%, 180-200%, 180-198% and 150-180%. The relatively less swelling sealing agents according to Figure 3.14 are Cebogel QSM, Cebogel QSL, Mikolit® 300, Mikolit® 300M, and Mikolit® 00 with respective swelling capacities of 150%, 120%, 50-70%, 50-60%, and 30-40%.

Permeability

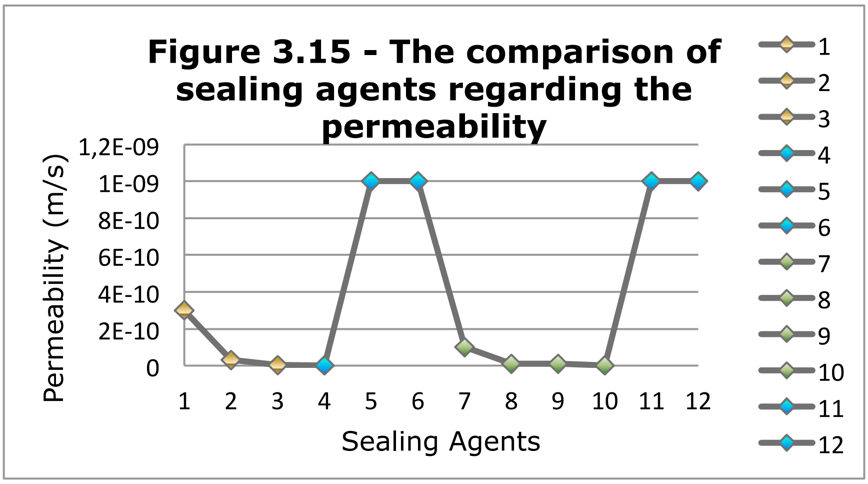


Figure 3.15 - The comparison of sealing agents regarding the permeability

The permeability is the most significant parameter in sealing agents. It refers to the rate at which water can freely pass through a certain layer. Natural clay layers in the Netherlands rarely have a permeability lower than $1\cdot10^{-9}$ m/s (Terratech B.V., 2016e). In order to restore the natural hydrological resistance of the clay-layer, this implies that the permeability of the sealing agent also has to be equal to $1\cdot10^{-9}$ or less. If the permeability of the sealing agent is higher than $1\cdot10^{-9}$, the water will flow through the sealed borehole (path of least resistance) and be transported in an accelerated fashion towards the water-bearing sand layer. In other words, there will be short-circuit flow.

Figure 3.15 compares the permeability of the sealing agents. The main conclusion is that all products have a permeability lower than or equal to the threshold of $1\cdot10^{-9}$ m/s. This implies that all sealing agents satisfy the boundary condition and hence are viable sealing agents regarding the permeability factor.

The lowest permeability values according to Figure 3.15 point to Cebogel QSE and Mikolit® B, both with a permeability of $1\cdot10^{-12}$ m/s, and DantoPlug Super M with a permeability of $3\cdot10^{-12}$ m/s. These are followed, with an increasing permeability, by Mikolit 300 and 300M with $1\cdot10^{-11}$ m/s, DantoPlug Super with $3\cdot10^{-11}$ m/s, Mikolit 00 with $1\cdot10^{-10}$ m/s, DantoPlug Standard with $3\cdot10^{-10}$ m/s, and Cebogel QSM, Cebogel QSL, Baroid Drill-Grout and Baroid Drill-Grout Plus with a similar permeability of $1\cdot10^{-9}$ m/s (resp.).

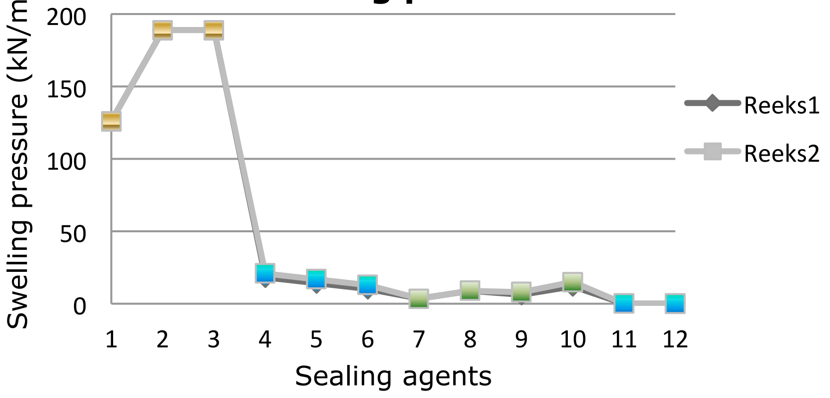
Water absorption capacity and montmorillonite content

Water absorption capacity and montmorillonite content will not be discussed, as both are directly related to the swelling content. A higher montmorillonite content means a higher water absorption capacity, which in turn means a higher ability to absorb water in the crystal lattice and thus expand to a greater extend as explained in Chapter 1.3.

Swelling pressure

The swelling pressure is directly related to the swelling capacity; if a sealing agent has a high swelling capacity, it will exert indisputably a higher force during the expansion. This parameter aids in the determination of the reliability of a sealing agent to assure impermeable behaviour and eliminate the possibility for annular spaces to occur around the artificial clay. This becomes increasingly significant with increasing application depth due to the increase in surrounding water and ground forces. Figure 3.16 illustrates the swelling pressures of the discussed sealing agents and hence highlights the relative relation.

Figure 3.16 - The comparison of sealing agents regarding the swelling pressure



The swelling pressures of Cebogel QSM and QSL are, due to the lack of data, based on assumptions, which will be elaborated in the next paragraph. Figure 3.16 shows that the DantoPlug sealing agents have the highest swelling pressures of 126 kN/m^2 for DantoPlug Standard and 189 kN/m^2 for DantoPlug Super and Super M, as reported by Dantonit (see Table 3.2). This is followed by Cebogel QSE and QSM with swelling pressures of respectively 18-21 kN/m^2 and 14-17 kN/m^2, followed by Mikolit® B with 12-15 kN/m^2, Cebogel QSL with 10-13 kN/m^2, Mikolit® 300 with 9 kN/m^2, Mikolit® 300M with 6-8 kN/m^2, and finally Mikolit® 00 with a swelling pressure of 3.5 kN/m^2.

Finally, the Baroid Drill-Grout powders have relatively low swelling pressure of 0.15 kN/m^2 and 0.00188 kN/m^2, corresponding to Baroid Drill-Grout and Baroid Drill-Grout Plus respectively.

When comparing Figure 3.16 to Figure 3.14, it becomes clear that the curve shows a similar behaviour. When looking at the Mikolit® sealing agents in Figure 3.14 and Table 3.4, for instance, one may conclude that Mikolit® 00 has the lowest swelling capacity of 30-40%, followed by Mikolit® 300 with a higher swelling capacity of 50-60%, followed by Mikolit® 300M with a slightly lower swelling capacity of 50-60% (still higher than Mikolit® 00) and finally Mikolit® B with the highest swelling capacity corresponding to 180-200%. The trend observed yields an increase in swelling capacity from Mikolit® 00 to 300, followed by a decrease from 300 to 300M due to the addition of magnetite and again an increase from 300M to B. When comparing these results from Figure 3.14 to the swelling pressures in Figure 3.16 corresponding to Mikolit®, it is clear that the observed trend line is identical. There is an increase from Mikolit® 00 to 300, followed by a decrease from 300 to 300M and again an increase from 300M to B.

Similar to the observed pattern in the Mikolit® products, the trend line is also visible in the DantoPlug product values, although less well-defined. According to these patterns, and the one value for the swelling pressure of Cebogel QSE (18-21) obtained from Cebo Holland, this research has assumed the values for the swelling pressure of Cebogel QSM and Cebogel QSL to be respectively 14-17 kN/m^2 and 10-13 kN/m^2. These are values determined by observation of the linearity in the swelling capacity decrease going from Cebogel QSE to QSM to QSL (see Figure 3.14) as well as from the fact that the swelling capacities of Cebogel QSE, QSM and QSL remain higher than the Mikolit® 00, 300 and 300M variants. Therefore, the estimated values have to be at least higher than the swelling pressure of 9 kN/m^2 corresponding to Mikolit® 300. Also, the range in swelling pressure for Cebogel QSE is determined by Cebo Holland to be three. The same range between minimum and maximum swelling pressure is assumed for Cebogel QSM and QSL.

3.3.2 Form of application– Bar, pellet and suspension

Due to the large variety in available sealing agents, it remains unclear as to what works best in small-diameter boreholes. Mikkelsen (2002) mentions the difficulties of correct placement and the best practical way of sealing a small-diameter borehole. According to Mikkelsen (2002), it is the avoidance of caving and bridge-forming, which concludes a success or failure in the sealing process. He mentions that the permeability is almost always adequately low if the applied sealing agent is installed on the desired depth(s). Terratech B.V. agrees to this statement and adds that most sealing agents have indubitable structural integrity and sealing capabilities, if correctly installed.

Taking these practical results into account, the gravity of the problem lies in the placement of the sealing agent and as a consequence, multiple parameters being become irrelevant for further discussion here. Hence, the swelling capacity, water absorption capacity, permeability, montmorillonite content, and swelling pressure will be further disregarded. These parameters are relatively insignificant regarding the assurance of pellets reaching a certain pre-defined depth. In contrast, the remaining parameters significantly affect the degree to which a sealing agent is capable of avoiding bridge-forming and the corresponding maximum applicable depth. This includes the dimensions, sinking velocity in water, bulk density, and swelling delay of the pellets. Furthermore, the available forms of application also significantly affect the applicability in small-diameter boreholes.

Form of application – Bars

This research reviewed the bars made of Mikolit® 300 by Van Reekum Materials B.V. The bars are developed with the purpose of overcoming the application problems of pellets in small-diameter boreholes. However, Inpijn-Blokpoel reports that application of sealing agents in bar-form has proven to be complicated if boreholes extend deeper than several metres. The bars need to be pressed into the borehole one by one, but the company encountered problems with the bars getting stuck half-way down due to caving and undesired swelling before reaching the predefined depth. This implies that the bars are only applicable in relatively shallow boreholes. However, CPTs are rarely this shallow. Also, Inpijn-blokpoel reported the advantages of the application of bars in seepage areas over pellets. The application is relatively easy and assures total sealing if the depth and total installed length of the bars is known. In conclusion, bars as a sealing agent are most advantageous in relatively shallow boreholes, which is not the case in CPTs. Hence, the application of bars in CPT boreholes is doubtful, with respect to total sealing.

Form of application – Pellets

If pellets are being applied as a sealing agent in a small-diameter borehole, the pellet dimensions are most significant for the applicability. A higher variety in the pellet dimension results in a layer with a higher certainty of complete closure of the borehole on the long term. This is due to the improved orientation of the grains, implying a lower porosity and permeability. However, this can only be assured when the pellets reach the desired depth. As Terratech B.V. mentions, the pellet size determines the bridge-forming behaviour. Small pellets tend to stick to the walls relatively quickly, while large pellets sink faster and therefore have favourable characteristics for application in small-diameter boreholes. In terms of pellet dimensions, the superiority of Cebogel QSL can be argued, as it has the largest grain size as well as the highest variety in pellet sizes. Nevertheless, an illustration of the dimension relation between a CPT borehole and the different pellets results in Figure 3.17. The maximum dimensions are illustrated here in a minimum diameter CPT borehole of 35 millimetres[24]. Figure 3.17 is drawn on scale, but is reduced in size in this image.

As a result, the main problem with pellets in CPT boreholes is the fact that the dimensions are relatively large compared to the borehole diameter, as shown in Figure 3.17. As mentioned before, Mikkelsen (2002) highlighted the importance of avoiding bridge-forming and caving. In the case of pellets, Figure 3.17 shows that the application of pellets in a small diameters borehole can already result in clogging by applying two pellets for QSM, QSE, and QSL, and three pellets for Mikolit® and DantoPlug. In addition, the application process is based on the gradual application of multiple pellets per predetermined time step. This way, many pellets enter the borehole at the same time, thus increasing the risk of bridge-forming. In other words, this research concludes that pellets are a liability as sealing agents in small-diameter boreholes, due to their relatively large size compared to the borehole diameter of CPTs.

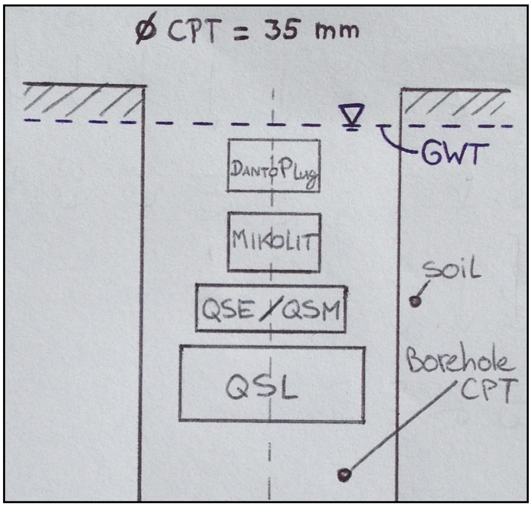


Figure 3.17. An illustration of the relative pellet dimensions in a submerged minimum diameter CPT borehole. The figure is drawn on a 1:1 scale.

Form of application – Suspension

Suspensions have been reported as the most advantageous sealing agents in small-diameter drillings. Mikkelsen (2002) reports that bentonite grout suspensions are the most universally applicable material for successful backfilling. The Baroid drill-grout products are also bentonite grout suspensions. Inpijn-blokpoel reports that the application of Baroid drill-grout goes according to the product data sheet. First the CPT is made, which is then followed by the removal of the pipe and the insertion of a new pipe. This new pipe pumps the pre-mixed suspension into the borehole, replacing the water

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[24] In reality the minimum diameter is equal to 35.3 millimetres, but for illustration purposes, the author took 35 millimetres. This makes the assumptions/conclusions safer due to the fact that in reality the borehole is slightly larger in diameter

column in the borehole entirely with Baroid Drill-Grout while the pipe is slowly removed from bottom to top. This method guarantees total filling of the borehole and the parameter data, which means that the permeability is low enough compared to the permeability of the clay found in the Netherlands: 10^{-9} m/s. This implies that Baroid Drill-Grout and the Plus-variant are the only sealing agents that can guarantee total backfilling of the borehole, and this makes them very advantageous over artificial bars and pellets.

3.3.3 Best sealing agent for CPTs

As a conclusion for Chapter 3.3, the usage of bar-shaped sealing agents is advantageous in shallow CPTs and in groundwater conditions, which describe seepage areas. The bars are effortlessly installed by pushing them into the borehole one by one. At present, only bars consisting of Mikolit® 300 are produced. However, Terratech mentions current developments, leading to the production of Mikolit® 300M bars. Cebo Holland and Dantonit do not produce sealing agents in bar form.

Furthermore, this research strongly states the drawbacks of pellets as sealing agents in small-diameter boreholes. The risk of bridge-forming increases with the application depth, which implies a significant risk for microbiological pollution of the water-bearing layers. If pellets are used, however, larger pellets have favourable characteristics regarding sinking velocity and bulk density, but their relatively large diameter increases the clogging risk. In contrast, small pellets tend to stick to the walls more quickly, thus increasing the risk of bridge-forming. Nevertheless, this research highlights that the risk of clogging due to a large diameter is more significant than the relative difference in sticking behaviour. Hence, it concludes that the relatively small pellets are favourable due to their relatively small size compared to the borehole diameter. In addition, this research advocates the use of magnetite-containing sealing agents when pellets are used, as the magnetite makes potential occurrences of bridge-forming traceable.

As a result, the DantoPlug Super M and Mikolit® 300M variants are the best pellet-form sealing agents. A further comparison regarding the bulk density and the sinking velocity yields that Mikolit® 300M has a higher bulk density whereas the DantoPlug products excel in sinking velocity. In both situations, however, the differences are arguably small.

In contrast, a distinct difference is observed in the swelling delay. DantoPlug Super and Super M have relatively high swelling delays, which is relatively more significant than the observed differences in sinking velocity and bulk density. Also, the addition of traceable magnetite to the Super M variant results in a reliable possibility to check if bridge-forming occurs during application. In conclusion, the best pellet-form sealing agent for small-diameter boreholes discussed in this research is Dantoplug Super M.

The third discussed sealing agent form is the suspension. The advantages of suspensions compared to bars and pellets in small-diameter boreholes are superior. One of the reasons is that the suspension can be pumped effortlessly into the borehole, without posing a risk of bridge-forming. This ensures a total fill-up of the borehole and at the same time, avoids any risks on bridge-forming as it is applied from bottom to top, while gradually removing the tube through which the suspension is transported upwards. This means that all water present in the borehole is replaced by the applied suspension. Also, Inpijn-blokpoel mentions that the second tube, entering the borehole to apply the suspension, is led through the existing hole, thus ensuring that the cone follows the existing borehole path and no new paths are created in the process, in order to achieve total sealing. As mentioned above, this is most important in the sealing process of small-diameter boreholes.

As an overall conclusion, this research advocates the application of suspensions in small-diameter boreholes, in this case, Baroid Drill-Grout and Baroid Drill-Grout Plus from Cebo Holland. A total overview of the aforementioned advantages and drawbacks are illustrated in table 3.6.

Tabel 3.6 - Overview of conclusions regarding the best sealing agent in CPT boreholes.

Bar	**Pellet**	**Suspension**
(+) Effortless application	*(+) Effortless application*	*(+) No bridge-forming*
(+) High swelling rates	*(+) Large variety*	*(+) 100% borehole fill-up*
(+) Result is known afterwards	*(+) Delayed swelling*	*(-) Application requires more effort*
(-) Cannot be applied in deep boreholes	*(-) High risk in deep application*	*(-) Processability time window*

3.4 Further Research

In order to scientifically verify the results and assumptions made in the previous chapters, experiments are indispensable. Unfortunately, no experiments were conducted. Nevertheless, a set-up for potential future experiments regarding this subject has been made and is elaborated in this chapter.

As mentioned before, experimental results have to be obtained in order to verify the conclusions on the sealing behaviour of clays. The following experiment is listed in this research as a potential project regarding this subject, depicted in Figure 3.18.

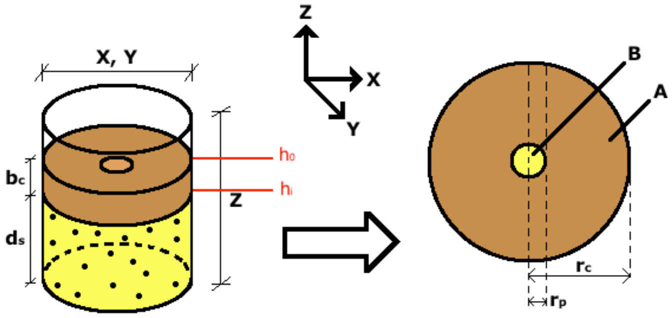

Figure 3.18. Example sample in potential experiment. Sand is illustrated in yellow with black dots and clay in brown.

Two samples have to be taken, one of river clay and one of sea clay, located in the eastern and western area of Oasen respectively. Subsequently, the samples have to be prepared in a preferably transparent container. In Figure 3.18, a cylindrical container is taken as an example; the calculations in this research based on these samples are only applicable for cylindrical containers. The parameters in the figure are b_c, d_s, X, Y, Z, B, A, r_c, and r_p which stand for the thickness of the clay layer, the thickness of the underlying sand, the distance in the X direction, the distance in the Y direction, the total height of the sample, the surface area of the CPT, the surface area of the clay in the sample, the radius of the cylindrical sample, and the radius of the CPT respectively.

Furthermore, a hydraulic potential difference should be applied with an external tube (not shown in the figure) entering the sample at the bottom, indicated by h_0 and h_i. This will induce a flow through the clay layer from bottom to top, which corresponds to a situation with seepage conditions. In reality, the tested clay layer has a thickness of approximately 12 metres, a CPT has a diameter of 35-45 millimetres and the hydraulic head is highly variable, approximated by the value of 0.5 metres from the Oasen database.

With these parameters, the volume flux through the clay layer can be calculated. The associated equations are listed in Figure 3.19, along with approximated values, assumed to represent the geohydrological conditions. Equations (1), (2) and (3) are simple circle-surface calculations, while equation (4) defines the resistance of a layer as a function of the hydraulic conductivity and the thickness of the layer. Equation (5) calculates a total resistance out of the regular clay layer resistance and the open hole resistance in the clay layer. This is achieved as a function of the various involved resistances per surface area within the sample. Finally, equation (6) calculates the volume flux through the sample as a function of the sample area, the hydraulic head difference and the total resistance of the clay layer. When the experiment is conducted, one may afterwards determine whether the found volume flux is measureable.

$$A = \pi r_c^2 - \pi r_s^2 \tag{1}$$

$$B = \pi r_s^2 \tag{2}$$

$$A' = \pi r_c^2 \tag{3}$$

$$c = \frac{1}{k_c} b_c \tag{4}$$

$$c_{total} = \frac{1}{A\frac{1}{c_A} + B\frac{1}{c_B}} \tag{5}$$

$$q = \frac{A'(h_0 - h_i)}{c_{total}} \tag{6}$$

$X = 50$ cm
$Y = 50$ cm
$Z = 50$ cm
$b_c = 12$ cm
$d_s = 18$ cm
$r_c = 25$ cm
$r_s = 0.075$ cm
$h_0 = 0$ cm
$h_i = 0.5$ cm
$k_c = 0.01$ cm/d
$k_{hole} = 100$ cm/d

Figure 3.19. Equations and assumed parameter values associated with the potential experiment.

This research assumed a value of 0.01 cm/d for the hydraulic conductivity through the clay layer and 100 cm/d for the hydraulic conductivity through an open borehole. Furthermore, the thickness of the clay layer is scaled down with 10^{-2}, resulting in the assumed sample value of $b_c = 12$ cm. The same applies to the CPT radius and the hydraulic head, respectively resulting in the values 0.075 centimetre and 0.5 centimetre for r_s and h_i. The calculations with these approximated parameter values yield the following results:

Filling in equations (1), (2) and (3) yields the surface areas of the clay layer, the CPT and the total area:

$$A = \pi \cdot 25^2 - \pi \cdot 0.075^2 = 1963.478 \text{ cm}^2$$
$$B = \pi \cdot 0.075^2 = 0.0177 \text{ cm}^2$$
$$A' = \pi \cdot 25^2 = 1963.495 \text{ cm}^2$$

Furthermore, the resistance of the different surfaces has to be calculated by filling in equation (4) for the two surfaces A and B:

$$c_A = \frac{1}{0.01} \cdot 12 = 1200 \text{ days}$$
$$c_B = \frac{1}{100} \cdot 12 = 0.12 \text{ days}$$

As expected, the resistance of the open hole is significantly lower; a factor 10^{-4} smaller. Combined with the corresponding surface areas, the total resistance of the sample can be calculated by using equation (5):

$$c_{total} = \frac{1}{(1963.478 \cdot \frac{1}{1200}) + (0.0177 \cdot \frac{1}{0.12})}$$
$$= 0.56 \text{ days}$$

Compared to a undisturbed sample with the same composition and with $k_d = 0.01$, the difference is a reduction in the resistance from 1,200 days to 0.56 days. As a consequence, it can be calculated how large the volume flux through the hole will be by using equation (6):

$$q = \frac{1963.495 \cdot (0-0.5)}{0.56}$$
$$= 1753.12 \text{ cm}^3\text{/day}$$
$$= 1.75312 \text{ L/day}$$

The resulting volume flux of q = 1.75 litres per day is a measureable quantity and hence, the experiment will lead to measurable outcomes.

According to the calculations performed, the experiment is feasible. Upon execution, the volume flux has to be monitored each day. The hypothesis is that this volume flux will decrease every day in an exponential way until an asymptotic value is reached. This implies that the sample is restored, which means that the number of days needed for this process can be derived from it. Also, the asymptotic value can be compared to the volume flux through an undisturbed identical sample. If the measured value is higher than the undisturbed sample volume flux, it implies that the borehole in the sample is not recovered to its original state; sand may have flown into the hole or the hole may simply not have had the self-restoring capacity to recover.

Chapter 4 Discussion

First of all, regarding the clay minerals, multiple group categorisations exist with slight differences. This research used a specific source due to the scientific background. However, the main problem lies in the establishment of the mineralogy of river clay and sea clay. Data regarding this mineralogy is diverse and no clear answer is provided. This research assumed that the mineralogy of river clay consists mainly of micas and smectite and that sea clay consists mainly of illite. This is based on information provided by Berendsen (2008a).

Furthermore, regarding the parameter data of the pellets, Dantonit states that DantoPlug Super M contains magnetite in order to make the compound traceable. The addition of magnetite should then result in a higher bulk density and sinking velocity as well, as is the case with Mikolit® 300M, for example. However, this is not the case. The precision of the DantoPlug data can therefore be questioned.

Also, Baroid Drill-Grout Plus data is based on the product data sheet of Cebo Drill-Grout Plus, which, according to Cebo Holland, shows similar characteristics. The reason given for this is the fact that Baroid Drill-Grout Plus is new in the market and the data sheet has yet to be produced.

Regarding the application in bar form, this research only investigated the method of direct application. However, Inpijn-Blokpoel recently reported that a second method is available for the installation of the bars. This method includes the introduction of a casing through which the bars are being applied. This will significantly increase the maximum application depth. However, problems with respect to clogging of the casings have been reported, which highlights that further research is required on this application method.

Another point of discussion lies in the suspensions. This research only investigated Baroid drill-grout and Baroid drill-grout plus, whereas multiple similar suspensions exist. Hence, a conclusion regarding the components of the suspensions and the favourable composition for total sealing of a CPT borehole will yield a more complete conclusion. This will require further research into the currently available suspension sealing agents.

Regarding the potential experiments, the results will only describe the primary swelling of the clay, while expansive soils also exert a so-called secondary swelling. According to Das (2014), this secondary swelling occurs due to flow processes associated with the bimodal pore size distribution in expansive clays. However, this behaviour is not observed in the executed experiments due to the long amount of time needed for this process to occur, which is significantly longer than the timescale required to establish solely the self-restoring process. Despite secondary swelling being significantly less than primary swelling, it will contribute towards a more complete conclusion on the total swelling potential of soils.

In addition, in situ ground forces will not be incorporated in the experiments. The subsurface is under increasing stress as the depth of the CPT increases. These vertical and horizontal stress components have to be defined if the experiment is to be improved. Also, when the experimental CPT-pipe is removed, there is a possibility that the hole will become filled with sand from the underlying layer. This has to be prevented.

Chapter 5 Conclusion

This research has been conducted in order to investigate the impact of cone penetration tests on the groundwater quality in environmental protection zones. The sealing process of these small-diameter boreholes has been extensively discussed and the subsurface clays have been analysed. Consequently, this study set out to answer the three research questions regarding this theme:

- *Do small-diameter boreholes restore over time without artificial sealing due to in situ swelling of clay?*
- *What type of sealing agents are available in the Netherlands and in what forms of application?*
- *Which sealing agent(s) is/are most adequate in the sealing procedure taken into account the demands from the provincial environmental regulation South Holland and Oasen?*

The results include that clays found in the area of Oasen have the mineralogy to exert a swelling behaviour. However, the swelling rates are unknown and thus, the time lapse associated with this self-restoring process is unknown as well. Hence, boreholes have to be sealed at all times. Furthermore, this research found that there are three forms of application in sealing agents: pellets, bars and suspensions. DantoPlug, Cebo and Mikolit® are the main providers of these agents and their products include DantoPlug Standard, DantoPlug Super, DantoPlug Super M, Cebogel QSE, Cebogel QSM, Cebogel QSL, Baroid Drill-Grout, Baroid Drill-Grout Plus, Mikolit® 00, Mikolit® 300, Mikolit® 300M, and Mikolit® B. Comparing these products and their different forms of application showed that pellets and bars are inapplicable as sealing agents in CPT boreholes. As a result, this research advocates the use of Baroid Drill-Grout (Plus) or similar suspensions.

Chapter 6 Recommendations

In addition to the conclusions, this research provides recommendations to the province regarding the regulations, and to Oasen regarding experiments on the swelling rates of clays. The first recommendation focuses on the implementation of a minimum permeability in the PERSH. All sealing agents should have a permeability of 10^{-9} m/s or lower to assure the absence of preferential pathways through a borehole.

Furthermore, sealing agents are defined in the PERSH as “special clay pellets, chips or lumps”. This is outdated and should be replaced by Baroid Drill-Grout or other suspensions with a similar composition, because pellets and bars cannot entirely guarantee total sealing in CPT boreholes due to the shortcomings discussed above. Also, the definition of the “Groen, Water en Milieu” department should be revised, because the current definition is out dated.

As a final recommendation, Oasen should execute the elaborated experiments in this research in order to establish the self-restoring rates of the clay layers in the supply area of Oasen. This will contribute towards a better understanding of a disturbed subsurface.

References[25]

Ahrens, H., Trikt, J. van. (n.d.). Rivierkleibodem (Online). Geologie van Nederland, Available on: http://www.geologievannederland.nl/ondergrond/bodems/rivierkleibodem-rivierkleilandschap [Consulted on: 04-05-2016]

Bakker, M. (n.d.). 4.9 Cone penetration tests (CPT) (Online). Leibniz-institute für angewandte geophysik, p. 123-126. Available on: https://www.liag-hannover.de/fileadmin/user_upload/dokumente/Grundwassersysteme/BURVAL/buch/123-126.pdf [Consulted on: 15-06-2016]

Berendsen, H.J.A. (2008a). De vorming van het land. Inleiding in de geologie en de geomorfologie. Van Gorcum.

Berendsen, H.J.A. (2008b). Landschap in delen. Van Gorcum.

Cebo Holland. (2016). Bentonite (Online). Available on: http://www.cebo.com/nederland/en/bentonite/index.html [Consulted on: 25-05-2016]

CETCO. (2016). Bentonite tablets: breaking through the myths and misunderstandings (Online). CETCO, available on http://www.cetco.com/en-us/Case-Studies/Drilling-Products/Environmental-Drilling [Consulted on: 19-05-2016]

Chamley, H. (1989). Clay sedimentology. Springer-Verlag Berlin Heidelberg, p. 61.

Daniels, M. E., Easterly, T. W. (2011). Investigation of manmade preferential pathways for contaminent transport (Online). Indiana department of environmental management, available on: http://www.in.gov/idem/files/remediation_tech_guidance_investigation_mpp.pdf [Consulted on: 13-06-2016]

Dantonit A/S. (2016). Dantoplug datasheet (Online). Available on: http://www.dantonit.dk/PageFiles/304/Data%20Sheet,%20DantoPlug%20Ø6%20mm,%20UK.pdf [Consulted on: 23-05-2016]

Das, J.T. (2014). Evaluation of the rate of secondary swelling in expansive clays using centrifuge technology. Msc thesis, University of Texas, Austin, 144p.

Dekker, J., Kruse, G.A.M. (1985). Kleigrond voor de bekleding van dijken: opmerkingen over het zwellen en krimpen en het ontwikkelen van structuur. Laboratorium voor grondmechanica Delft.

Deltares. (2012). Geologisch en seismisch onderzoek bodem Lek, Langerak-Schoonhovenseveer-Kinderdijk.

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[25] Any date in the references is denoted in the form [DD-MM-YY]

Deltawerken Online. (2004). Geologie van Nederland (Online). Available on: http://www.deltawerken.com/geologie-van-nederland/42.html [Consulted on 23-06-2016]

Edelman, D.H. (2015). Ondergrondinformatie uit sondeergrafieken (Online). Available on: http://www.rvde.nl/pdf/Doorlatendheid%20notitie.pdf [Consulted on: 08-06-2016]

EMABS (Environmental Mechanics AB Sweden). (2011). Cone penetration testing, CPTu. Available on: http://www.envi.se/downloads/manuals/CPT-for-rookies.pdf [Consulted on: 15-06-2016]

Engler, T.W. (2010a). Petroleum Engineering 524 Fluid Flow in Porous Media (Online). New Mexico Institute of Mining and Technology. Available on: http://infohost.nmt.edu/~petro/faculty/Engler524/PET524-porosity-1.pdf [Consulted on: 08-06-2016]

Engler, T.W. (2010b). Petroleum Engineering 524 Fluid Flow in Porous Media (Online). New Mexico Institute of Mining and Technology. Available on: http://infohost.nmt.edu/~petro/faculty/Engler524/PET524-2a-permeability.pdf [Consulted on: 08-06-2016]

European Underground Research Infrastructure for Disposal of nuclear waste In Clay Environment (EURIDICE). (n.d.). Thermo-hydro-mechanical behaviour of clay (Online). Available on: http://www.euridice.be/en/content/thermo-hydro-mechanical-behaviour-clay [Consulted on: 26-04-2016]

Geotechdata. (2016). Cone Penetration Test (Online). Available on: http://www.geotechdata.info/geotest/cone-penetration-test.html [Consulted on: 25-04-2016]

Graveel, J.G., Thien, S.J. (2002). Laboratory manual for soil science; agricultural & environmental principles. McGraw-Hill science/engineering/math; 8th edition, 232 pages.

Heij, G.J. (1989). River-groundwater relationships in the lower parts of the Netherlands. Journal of hydrology 108, p. 35-62.

Hensen, E.J.M., Smit, B. (2002). Why clays swell. The Journal of Physical Chemistry, B, vol. 106, No. 49, p. 12664-12667.

Jordán, A. (2014). Lightening the clay (I) (Online). Soil System Sciences division of the European Geosciences Union (SSS EGU). Available on: http://blogs.egu.eu/divisions/sss/2014/09/05/lightening-the-clay-i/ [Consulted on: 26-04-2016]

Kaempffer, A.T. (2003). Update on Bentonite Chips and Pellets for Sealing Piezometers in Boreholes (Online). Geotechnical Instrumentation News, p. 7-12. Available on: http://www.bitech.ca/pdf/GeoTechNews/2003/GIN_Dec2003rev.pdf [Consulted on: 19-05-2016]

Kodama, H. (2016). Clay mineral rock (Online). Encyclopedia Britannica. Available on: http://www.britannica.com/science/clay-mineral/Chemical-and-physical-properties [Consulted on: 03-05-2016]

Kooij, D. Van der. (1985). Drinkwater uit oevergrondwater: hydrologie, kwaliteit en zuivering. KIWA, Mededeling nr. 89.

Medema, G., Senden, W.J.M.K., Wielen, P.W.J.J. van der. (2008). De microbiologische veiligheid van de 60-dagenzone rond grondwaterwinningen (Online). KIWA. Available on: https://dms.oasen.nl/afd/730000/OZ%20Rapporten/BTO%202008-03%20De%20microbiologische%20veiligheid%20van%20de%2060-dagenzone%20rond%20grondwaterwinningen.pdf [Consulted on: 23-06-2016]

Mikkelsen, P.E. (2002). Cement-Bentonite Grout Backfill for Borehole Instruments (Online). Geotechnical Instrumentation News, available on: http://www.geosense.co.uk/media/BlockAttributeValueFile/129/file/CementBentonitegroutbackfillforboreholeinstruments.pdf [Consulted on: 19-05-2016]

Oasen. (2014). Over Oasen (Online). Available on: https://www.oasen.nl/over-oasen/Paginas/OverOasen-artikel.aspx [Consulted on: 14-03-2016]

Omgevingsdienst Haaglanden (ODH). (2016). Wie zijn wij (Online)? Available on: https://omgevingsdiensthaaglanden.nl/wie-zijn-wij.html [Consulted on:16-06-2016]

Patijn, S. (1993). Wet- en regelgeving provincial milieuverordening Zuid-Holland. Provinciale staten van Zuid-Holland, available on: http://decentrale.regelgeving.overheid.nl/cvdr/XHTMLoutput/Historie/Zuid-Holland/120213/120213_2.html [Consulted on: 01-06-2016]

Peranginangin, N. (2002). Preferential flow. Why is preferential flow so important (Online)? Cornell University, Department of Biological & Environmental Engineering. Available on: http://soilandwater.bee.cornell.edu/Research/pfweb/educators/intro/why.htm [Consulted on: 20-06-2016]

Phernambucq, I.H. (2015). The vertical hydraulic resistance of the Lek river and consequences for travel times. Msc Thesis. Utrecht University, Oasen.

Rogers, J.D. (n.d.). Fundamentals of cone penetrometer test (CPT) soundings (Online). Missouri University of Science & Technology, U.S. Geological Survey, Environmental Engineering Geologists. Available on: http://web.mst.edu/~rogersda/umrcourses/ge441/CPT-Soundings.pdf [Consulted on 01-06-2016]

Rotek A/S. (2016). 4.1 Sealing Materials (Online). Available on: http://www.rotek.eu/e-catalogue/sealing-materials--filter-sand--and-drilling-fluid/sealing-materials.aspx [Consulted on: 23-05-2016]

Terratech. (2016a). Technische gegevens Mikolit 00 (Online). Available on: http://www.mikolit.nl/mikolit+00/technische+gegevens [Consulted on: 25-05-2016]

Terratech. (2016b). Technische gegevens Mikolit 300 (Online). Available on: http://www.mikolit.nl/mikolit+300/technische+gegevens [Consulted on: 25-05-2016]

Terratech. (2016c). Technische gegevens Mikolit 300M (Online). Available on: http://www.mikolit.nl/mikolit+300m/technische+gegevens [Consulted on: 25-05-2016]

Terratech. (2016d). Technische gegevens Mikolit B (Online). Available on: http://www.mikolit.nl/mikolit+b/technische+gegevens [Consulted on: 25-05-2016]

Terratech. (2016e). Vraag en antwoord (Online). Available on: http://www.mikolit.nl/vraag+en+antwoord [Consulted on: 16-06-2016]

Veldkamp, J.G., Wiertz, J. (1997). Schematisatie van bodembedekking en kwel in Nederland voor SMART/MOVE (Online). Rijksinstituut voor volksgezondheid en milieu, rapport nr. 711901021, p. 20. Available on: http://www.pbl.nl/sites/default/files/cms/publicaties/711901021.pdf [Consulted on: 11-04-2016]

Vertek CPT. (2014). 4 types of geotechnical testing: what is the best option for you (Online)? Available on: http://www.vertekcpt.com/blog/geotechnical-testing-types [Consulted on: 25-04-2016]

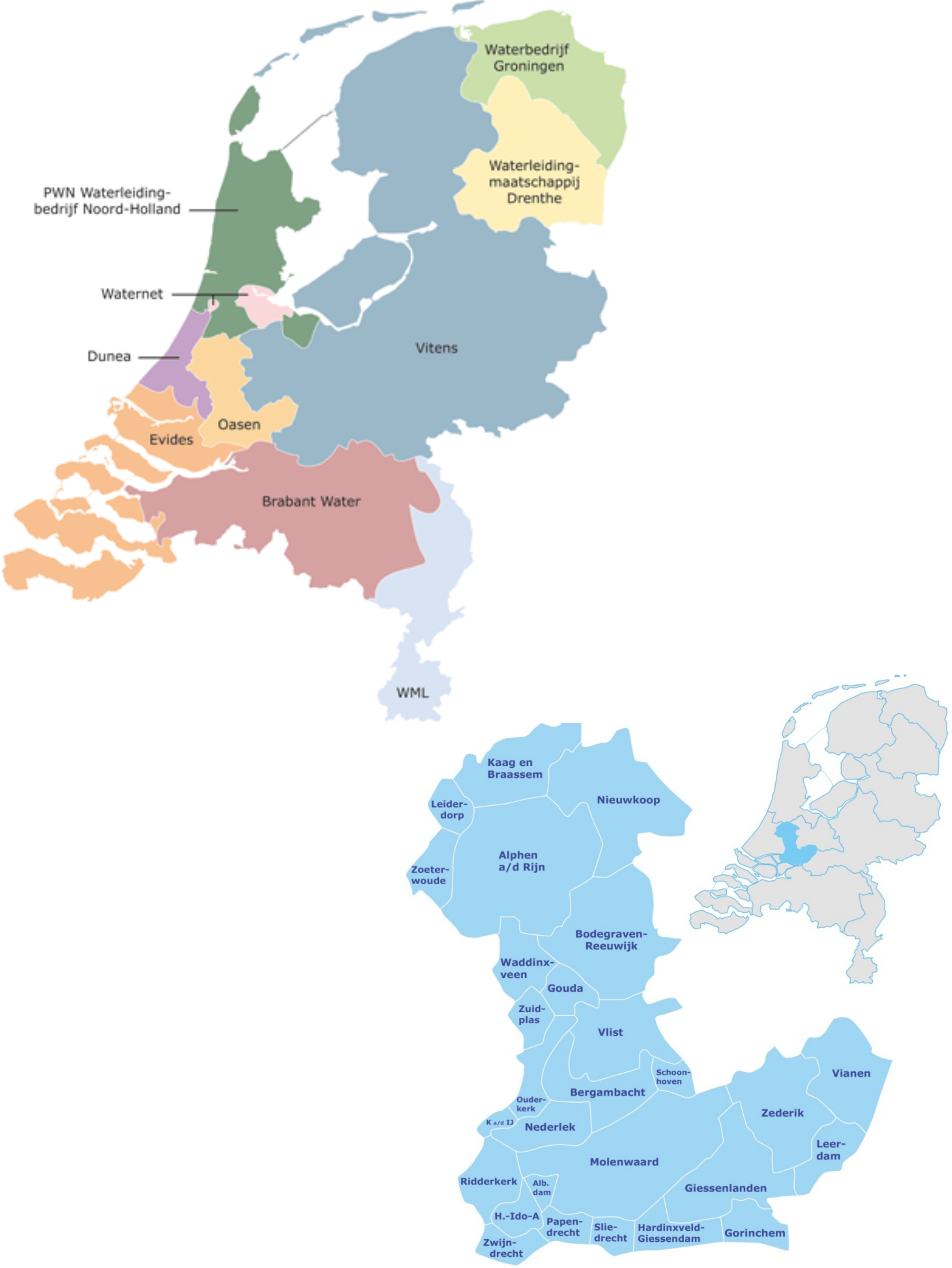
Vertek CPT. (2015). ASTM standard cone penetrometer sizes: which is best for your application (Online)? Available on: http://www.vertekcpt.com/blog/astm-standard-cone-penetrometer-sizes-which-is-best-for-your-application [Consulted on: 15-06-2016]

Van Reekum Materials (VRM). (N.d.). Natuurlijk VRM Kleistaaf (Online). Available on: http://www.vrm.nl/WebRoot/Store2/Shops/VRM/5644/A77B/3D28/AD50/35B0/B903/6B81/F910/INF074.pdf [Consulted on: 26-05-2016]

Wiertsema & Partners. (2010). Handsondeerapparaat (Online). Available on: http://www.wiertsema.nl/?module=materials&cid=1&pid=30&lang=nl [Consulted on: 15-06-2016]

Appendix

A1 Drinking water companies in the Netherlands[26] and the distribution area of oasen



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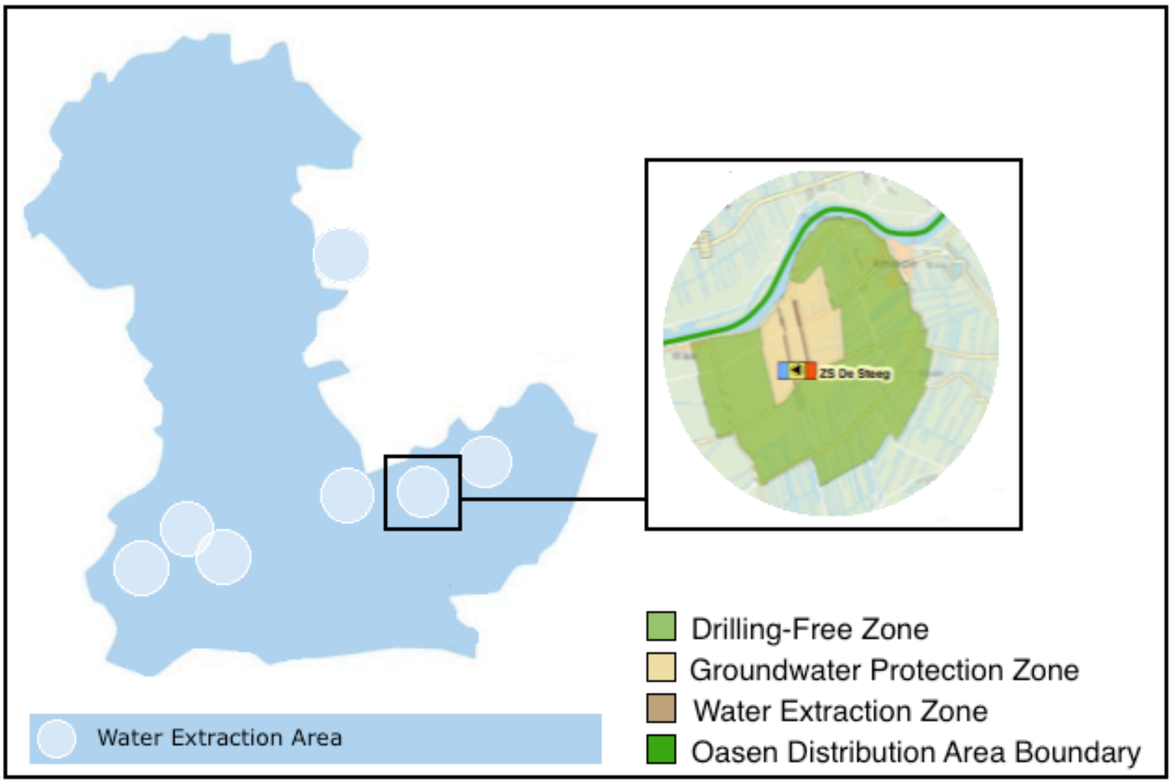
[26] http://www.vewin.nl/SiteCollectionDocuments/Publicaties/Drinkwaterstatistieken%202012/Vewin%20Drinkwaterstatistieken%202012%20lowres.pdf

A2 Indication of the protection zones[27] around water extraction areas



A3 Darcy's Law

$$Q = -k \cdot A \cdot \frac{dh}{dl}$$

Q = Discharge (m^3/d)

k = Permeability (m/d)

A = Area perpendicular to the flow (m^2)

dh = Difference in hydraulic head (m)

dl = Distance being considered (m)

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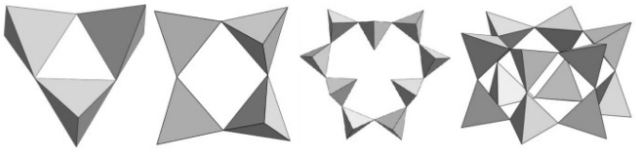
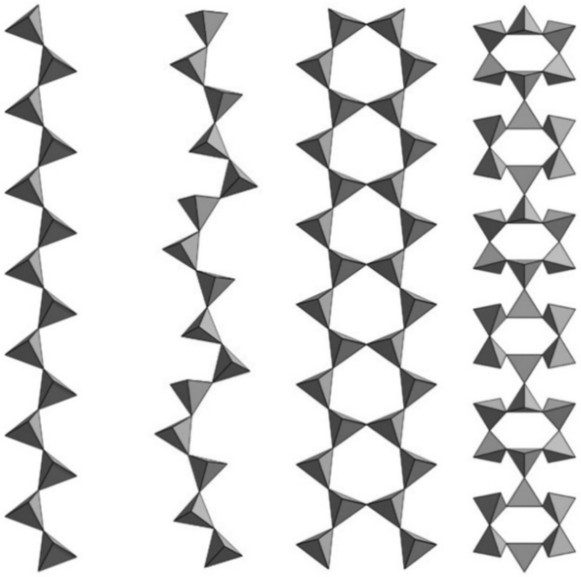
[27] In this case the treatment plant "de Steeg" is taken as an example to highlight the protection zones. The other extraction areas show a similar protection pattern around the wells.

A4 Examples Complex Tetrahedral Layer Structures (Jordán, 2014)

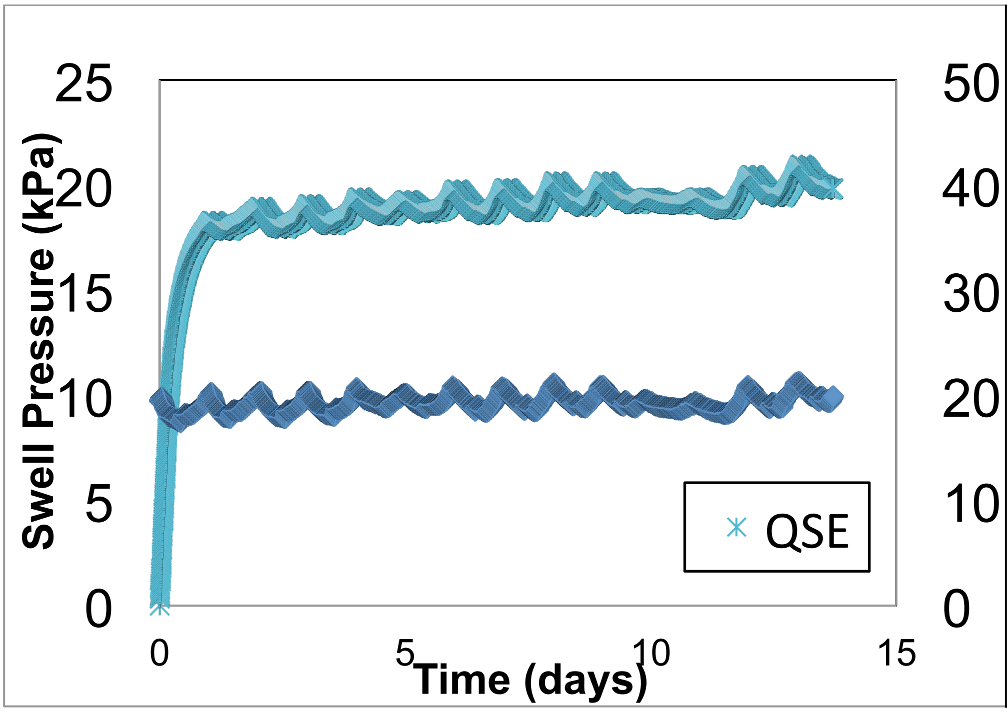


Cyclosilicates. From left to right: benitoite, papagoite, audialyte and milarite.



Inosilicates. From left to right: diopside, rhodonite, tremolite and pellyite.

A5 Experimental data on swelling pressure for Cebo QSE



According to mr.Frank Oo ms, department Sales & Services at Cebo Holland, this data is obtained through an experiment performed by Cebo Holland.