An Evaluation of the In-Situ Hydraulic Conductivity of Cement-Bentonite Walls

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by

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This thesis is confidential and cannot be made public until October 31, 2022.

Preface and Acknowledgements

This thesis is the final result of my graduation research performed at Witteveen+Bos B.V. (W+B) in cooperation with Rijkswaterstaat. The thesis is written to fulfill the graduation requirements for the Master of Science program in Geo-Engineering at the faculty of Civil Engineering and Geosciences at Delft University of Technology. The purpose of this research is to provide insight into the in-situ hydraulic conductivity of Cement-Bentonite (CB) walls used in the Netherlands. To do so, I investigated the collected pump data (discharge) for a certain period for several CB wall constructions.

First of all, I would like to express my utmost gratitude towards my graduation committee for their support, guidance and feedback during my research. I would like to thank my supervisor at Witteveen+Bos Ir. Jeroen de Leeuw for his time, the opportunity to work on this thesis and helping me with my data collection. I also really appreciate the ideas and advice he gave me, which were very helpful. I would also like to thank Dr. Ir. Wout Broere and Ir. drs. Richard de Nijs for their valuable comments on this thesis. My thanks also goes to Dr. ir. Gerrit Schoups for helping me with the numerical part of my thesis.

Furthermore, I would like to thank the Witteveen+Bos colleagues who had worked on some of the projects where the CB walls have been installed. They helped me to understand the whole process, from the design stage until the (post) construction stage including the dewatering process. I also received help to develop the numerical groundwater flow model in MODFLOW.

I would also like to thank the people who were willing to share the information I needed from the projects.

Finally, I would like to thank my family and friends for their support. My grateful thanks to my boyfriend for the unending patience, loving support and continuous encouragement throughout my years of study at TU Delft. This accomplishment would not have been possible without him.

Vanisha Ramphal
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Abstract

Cement-Bentonite (CB) walls are low permeability vertical cut-off barriers that are mainly used to prevent groundwater flow and isolate contaminated areas. The hydraulic performance of the CB walls depends on the flow rate (discharge) through the wall. Therefore, the walls must achieve very low hydraulic conductivity. Poor in-situ hydraulic performance of these walls due to construction and post-construction defects may lead to surface settlements, groundwater contamination, and instability of the construction. This thesis investigates the range of in-situ hydraulic conductivity values of CB walls installed within the Netherlands.
To achieve this, pump data for the various projects (Westerschelde Tunnel, A2 Motorway at Best, Motorway A4 Delft-Schiedam, Griftpark Utrecht, and Richard Hageman Akwadukt) were analyzed to determine the discharge through the walls. The in-situ hydraulic conductivity of the walls was calculated by Darcy's law using groundwater level data and dimensions of the walls. The CB walls must be "keyed" into an underlying low permeable layer (aquitard), so that seepage of water through the aquitard is prevented.
It was difficult to compute the in-situ hydraulic conductivity of the CB walls for Motorway A4 Delft-Schiedam and Griftpark Utrecht. The reason was that the walls in these projects were embedded in a permeable aquitard, which affected the total discharge value. The calculated in-situ hydraulic conductivity values were compared with the required hydraulic conductivity values and laboratory test results. In most of the cases, the in-situ hydraulic conductivity values of the walls were larger than the values acquired from the laboratory samples. The reason is that the estimation of the hydraulic conductivity of the CB walls from laboratory tests was based on small sample areas. This remains unreliable to evaluate the field performance of the CB walls. The average hydraulic conductivity of the CB walls at Richard Hageman Akwadukt was required to be less than or equal to $1 \cdot 10^{-9}$ m/s. The calculated hydraulic conductivity values of the CB walls for the northern and southern polders were approximately $2.5 \cdot 10^{-9}$ m/s and $2 \cdot 10^{-8}$ m/s, respectively. This study also shows that the hydraulic performance of the CB walls is mainly affected by insufficient connections between the panels.

Also, the impact of the defects on the discharge through the wall has been investigated by developing a three-dimensional numerical groundwater flow model using MODFLOW. Simulations were performed for different types of defects, such as fully and partially penetrating windows, insufficient embedment, and connection between the panels of the CB walls. The results of the simulations indicated that fully penetrating windows have more impact on the discharge through the wall compared to partially penetrating windows. Partially penetrating windows with a hydraulic conductivity lower than $1 \cdot 10^{-6}$ m/s are often insignificant. The size of a fully penetrating window also plays an important role. The difference in discharge (ΔQ) was calculated by subtracting the discharge through a perfect wall and imperfect wall ($Q_{imperfect} - Q_{perfect}$). The ($\Delta Q$) through a CB wall with a window whose area is equal to 1 m^2 can increase by a factor of 10 compared to a window whose area is equal to 0.1 m^2. The location of the defects has no impact on the discharge through the wall. The simulations also show that the flow rate is unaffected by the embedment depth of the wall, but it must be ensured that the wall is in direct contact with the aquitard (low permeability soil layer). The vertical deviation of panels also affects the discharge through the wall. The MODFLOW results can be used to get an indication of the increase in discharge caused by various types of defects. From this, the possible defects for a particular project can be determined.

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List of Abbreviations

CB Cement-Bentonite

N/A Not Applicable

Q Discharge

K$_h$ Horizontal hydraulic conductivity

K$_v$ Vertical hydraulic conductivity

K$_a$ Horizontal hydraulic conductivity of the aquifer

K$_c$ Horizontal hydraulic conductivity of the aquitard

K Hydraulic conductivity

c Hydraulic resistance

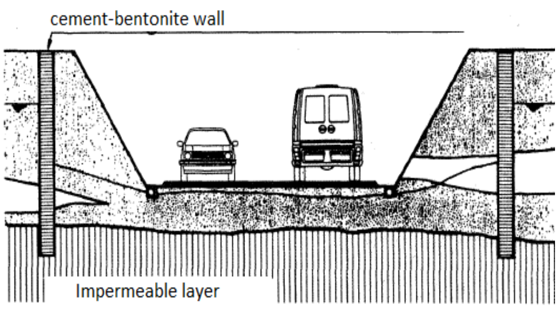
HDPE High-density polyethylene

1
Introduction

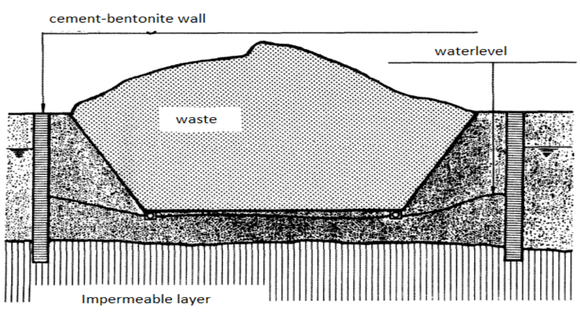
1.1 Motivation

Slurry walls are self-supporting, low permeability, vertical cutoff walls widely used since the early 1970s to restrain groundwater flow, isolate waste or contaminated areas (see Figure 1.1) (Xanthakos et al., 1994; Jefferis, 1997). The most frequently used slurry walls are soil-bentonite (SB), cement-bentonite (CB), and soil-cement-bentonite (SCB) (Ruffing and Evans, 2014). This work focuses on the hydraulic conductivity of CB walls within the Netherlands.

The hydraulic performance of the CB wall depends on the rate of flow through the wall. Therefore the hydraulic conductivity of the wall must be very low. According to CUR 189 the hydraulic conductivity of hardened CB wall lies in the range of $1 \cdot 10^{-8}$ m/s and $1 \cdot 10^{-9}$ m/s at a hydraulic gradient of i = 30. The thickness, CB slurry composition, homogeneity, and continuity of the wall determine the hydraulic conductivity of the wall. The in-situ hydraulic conductivity may vary because of heterogeneities. The construction of CB walls under the water table can lead to several complications resulting in leakages of the wall.



(a) Groundwater control



(b) Waste containment

Figure 1.1: CB wall used to restrain groundwater (left) and isolate waste (right)

The main factors that contribute to leakages of the CB wall are:

- inaccurate ratio of cement-bentonite;
- insufficient base sealing;
- insufficient connection between the panels;
- unstable retaining wall;
- occurrence of soil inclusions in the CB wall due to instability of the excavated trench before or after the hardening process;
- deformation of the hardened wall.

Due to the factors mentioned above the permeability of the CB wall becomes uncertain, because the defects can affect the flow rate past the wall.

Under performance of retaining (CB) walls can lead to:

- high groundwater inflow, causing wet working conditions and thus resulting in instability of the construction and high pumping costs
- damage to the adjacent structures due to settlement or piping

Griftpark (Utrecht), 3e Merwedehaven (Dordrecht), Bouwdok Barendrecht and Richard Hageman aqueduct are examples within Netherlands where CB walls have been used. The most common techniques to determine the permeability of CB walls are:

- conducting hydraulic conductivity tests on samples taken from the completed wall in the laboratory
- performing pump tests after the wall has hardened (monitoring groundwater level inside and outside the wall)

Some difficulties arise by the second method because groundwater cannot only flow through the wall but also the underlying sealing bottom layer. Until now no detailed study has been performed on the actual performance of CB walls. Proper knowledge of the hydraulic conductivity value is necessary, for the design of effective CB walls. By evaluating the different construction methods for the various projects and the pump data for a certain time range the hydraulic conductivity of the wall can be determined. Possible leakages can also be determined by analyzing the pump data.

With the use of hydrological flow models, the flow of groundwater through an intact (no defects) CB wall or defect CB wall can be simulated.

1.2 Problem statement

Cement-bentonite (CB) walls are one of the most common slurry trench cutoff wall types used in the Netherlands. A very low hydraulic conductivity is one of the most important requirements for the CB walls, mainly for groundwater control and contaminant containment. The evaluation of the hydraulic conductivity based on the samples taken during or after construction leads to the calculation of hydraulic conductivity for small scale test areas, which is not appropriate to assess the performance in the field. The hydraulic conductivity of the walls can be influenced by the presence of defects. The defects can occur due to design errors, construction defects, and post-construction property changes. Identification of possible defects in the walls that are likely to exist is therefore very important for the in-situ hydraulic conductivity. The flow rates through the wall due to the defects can increase significantly. This can result in the drawdown of local water tables, surface settlements, and cracks of surrounding buildings. More insight into the in-situ hydraulic conductivity of CB walls is required to get a better understanding of the performance of the walls.

1.3 Research question:

The main research question will act as a guide to achieve the project goals. Several investigations have been conducted to derive hydraulic conductivity of the CB walls in the laboratory. These measurements only indicate the approximate hydraulic conductivity from a part of the wall. Extensive research on the post-construction hydraulic conductivity of the CB wall has not been performed yet. It is therefore crucial to investigate the in-situ hydraulic conductivity of the walls including defects.

What range of in-situ hydraulic conductivity values can be expected for Cement-Bentonite (CB) walls used in the Netherlands?

Sub questions:

- What are the possible factors that potentially impact the hydraulic performance of the CB Walls?
- What are the hydraulic conductivities of the CB wall at different stages of the projects such as design stage, construction stage, and post-construction (in-situ) stage and measured in the laboratory?
- To what extent does the hydraulic conductivity of CB walls vary for various construction techniques?
- How do defects of various sizes, position, and the depth of penetration affect the flow rates past CB walls?
- What are the consequences of walls that have higher hydraulic conductivity than desired?

1.4 Objectives

The main objective of this study is to get a better understanding of the hydraulic performance of CB walls used at various projects within the Netherlands. To achieve this main objective, some sub-objectives can be formulated:

- To analyze pump data for various project locations to determine the flow rate past the walls.
- To develop a model to determine the in-situ hydraulic conductivity of CB walls.
- To validate the model with the use of data available from the projects.
- To compile recommendations to achieve the desired hydraulic conductivity for CB walls in the future.

1.5 Scope and limitations

This study will focus on the in-situ hydraulic conductivity of CB walls for various projects, which is important to evaluate the hydraulic performance of the wall. However, due to insufficient data, assumptions are made to calculate the in-situ hydraulic conductivity of the CB walls. The assumptions include groundwater level data and hydraulic conductivity data of the aquitard and other types of hydraulic barriers, such as HDPE foil and sheet piles. The model developed in MODFLOW consists of two soil layers.

1.6 Thesis structure

The aim of this research is to get a better understanding of the hydraulic performance of CB walls used at various projects within the Netherlands by determining the in-situ hydraulic conductivity of these walls. This thesis consists of eight chapters:

- **Chapter 1: Introduction**
  This chapter gives an introduction to the research by describing the motivation, problem statement, the research questions, objectives and the scope and limitations of the study.

- **Chapter 2: Literature Review**
  This chapter explains the construction techniques and specifications of the CB wall. Also, the reasons behind the occurrence of leakages are presented based on literature and project information.

- **Chapter 3: Analytical Model**
  In this chapter analytical models are presented, which are based on Darcy's law. These models will be used to calculate the in-situ hydraulic conductivity of the CB wall.

- **Chapter 4: General overview of projects within Netherlands**
  In this chapter four projects are presented where CB walls have been installed. First, each project will be briefly described. After that, the CB wall installation and specifications will be explained. Finally, the hydraulic conductivity values and discharge through the walls for the design, construction and post-construction stage will be presented.

- **Chapter 5: Richard Hageman Akwadukt**
  This chapter presents a detailed overview of the Richard Hageman Akwadukt. The chapter discusses the project, CB wall installation and specifications, dewatering system, allowed discharge, collected data, and results of the in-situ hydraulic conductivity of the CB walls.

- **Chapter 6: MODFLOW Model**
  In this chapter the impact on the hydraulic performance of the CB walls due to the presence of defects will be investigated. To do so, a three-dimensional groundwater flow model will be developed using MODFLOW.

- **Chapter 7: Discussion and Conclusions**
  This chapter includes the discussion and conclusions that are drawn from the findings of the study.

- **Chapter 8: Recommendations**
  This is the final chapter and presents recommendations regarding further study.

2 Literature Review

CB walls are being used with increasing frequency to create impermeable barriers in many geotechnical engineering and environmental engineering works. This chapter provides an overview of the CB wall technique. In the first section, the construction technique for the CB wall is described. The second section gives an overview of the CB wall specifications (requirements) that are mandatory for optimum performance focussing mainly on permeability. After that, the possibility of leakages is presented based on literature and projects in the past. The last section explains how the permeability through a water retaining wall can be determined.

2.1 Construction of CB walls

There are several methods for installing a CB wall. For every method, specific aspects need to be considered. Before the excavation takes place, guidewalls are installed in order to ensure:

- proper guidance of the hydromill or clamshell excavator
- proper alignment of the panels
- the stability of the top of the trench
- that erosion does not take place as a result of fluctuation in fluid levels during excavation

CB walls are constructed by excavating a trench using hydromills or clamshell excavators. The standard width of a panel is 2.8m. The distance between the guidwalls are 50mm larger than the thickness of the hydromill or clamshell excavator in order to prevent jamming.

Construction sequence

The excavation can take place according to the:

- Alternating excavation method: at first primary panels will be excavated. After that, the secondary panels will be excavated, which lie in between the primary panels. The sizes of the primary and secondary panels are therefore different (see Fig. 2.1).
- Continuous excavation method: the panels are excavated in one continuous process and have the same size.

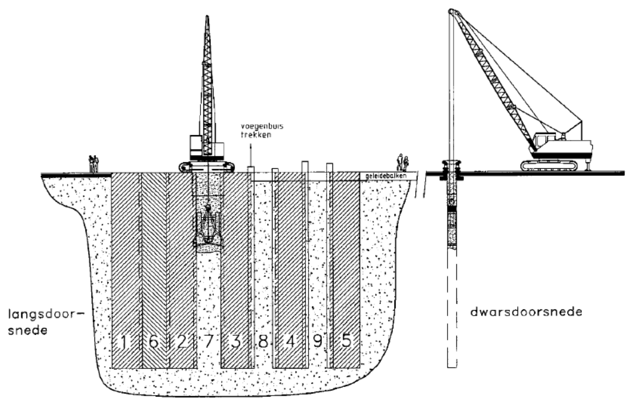


Figure 2.1: Alternating excavation method

Construction technique

The CB walls can be constructed according to the single phase or two phase technique:

- Single-phase technique: a self-hardening CB suspension is used during the excavation and remains in the trench.
- Two-phase technique: in this case the support fluid (mainly bentonite suspension) that is used during the excavation is pumped out of the trench and replaced by the final CB suspension (higher unit weight) after the final depth has been reached. (TEC)

2.2 Specifications of CB slurry

The permeability of the wall is the most important aspect of the design. Other additional aspects have to be considered as well for the design of CB walls (see Figure 2.2).

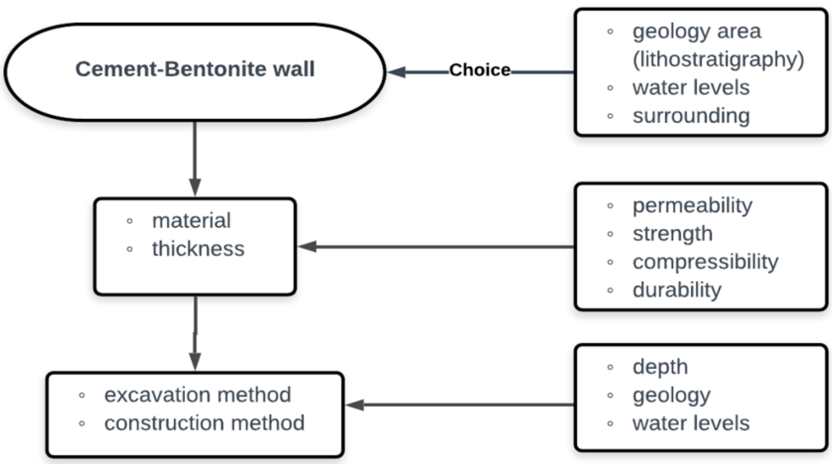


Figure 2.2: Flowchart for the design of CB walls (CUR, 1997)

For the preparation of the CB slurry, at first water is pumped into a colloidal mixer and then a specific amount of bentonite that is required is added to the mixer. The mixing of water and bentonite starts until a homogeneous suspension is produced. This suspension is then left to hydrate (swell) for hours before cement is added. Proper hydration decreases the permeability of the water-bentonite suspension. Cement is then added to the bentonite slurry, the mixing is continued and hydration of cement takes place (Visudmedanukul, 2004). The main types of cement that are used in the Netherlands are Portland cement and hoogoven cement. By replacing a portion of cement with granulated blast furnace slag (GGBFS) slag cement is formed. Studies have shown that the hydraulic conductivity of CB mixtures tend to decrease drastically when slag replacement increases from 70-80 % (Opdyke and Evans, 2005; Evans and Dawson, 1999). The quality of the cement-bentonite slurry depends on the type of cement and the quantity of bentonite that is added.

According to Rijkswaterstaat for the CB slurry mixture, the following conditions apply:

- the suspension should contain for every m^3 at least 35 kg bentonite and 200 kg blast furnace slag cement with a slag replacement of at least 70 %;
- the suspension should not contain any toxic substances;
- the materials used for the slurry should meet the relevant product standards;
- various additions to test methods for correct quality control.

(de Vries, 1992)

2.3 Permeability

One of the most important characteristics of a CB wall is permeability, because the main function of a CB wall is to restrain water.

It is therefore necessary that the wall has:

- a very low permeability
- good horizontal and vertical continuity and integrity
- sufficient bottom connection with the aquitard

The coefficient of permeability (k) of most CB walls varies from $1 \cdot 10^{-8}$ m/s to $1 \cdot 10^{-9}$ m/s for a hydraulic gradient of 30 (CUR, 1997).

2.3.1 The occurrence of leakages

There are several reasons that can lead to leakages of the wall. The most important reasons that will be focused on are described below.

Connection panels

There should be sufficient connection between the panels of the CB wall to prevent the formation of cold joints or windows. Sometimes a retarder can be added to the CB slurry to prevent immediate hardening of the slurry and cracking, therefore providing positive contact between the adjoining panels. The single-stage method has a lower risk of having joints. The presence of joints can lead to an increase in the hydraulic conductivity of the wall(David et al., 1992). The overlap should also be big enough to compensate for the tolerances of the excavator (CUR, 1997).

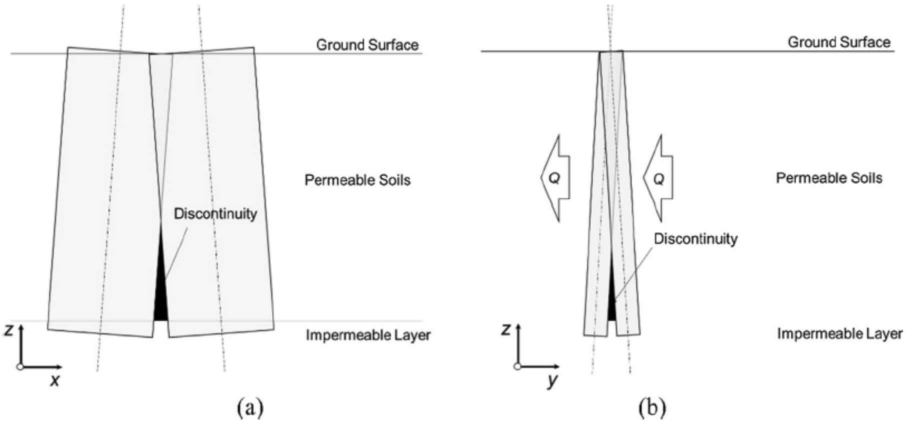


Figure 2.3: Possible seepage passages for insufficient panel connection, (a) deviation in the wall plane (x-z-plane); (b) deviation in the out of wall plane (y-z plane). (Pan and Fu, 2020)

Bottom seal

The CB wall must be ”keyed” properly into the underlying low permeable layer (mostly clay layer) to prevent horizontal and vertical groundwater flow (Powers et al., 2007). The depth of the embedment of the wall into the low permeable layer should be at least 1 - 1.5 m. Extensive geologic surveys in combination with geo-electric surveys, cone penetration tests and borings are carried out to gather information about the occurrence and depth of the aquitard (CUR, 1997).

Leakages can be determined by geophysical techniques and hydrolgeological techniques.

Geophysical techniques include:

- ground-penetrating radar;
- multi sensor survey system (Electrical Chemical Respons, ECR) with application of spatially targeted electrical impulses (Electric Flux Tracking, EFT);
- seismic survey;
- acoustic emission
- temperature sensors;
- optical fibre ;
- gas injection

(Lambert, 2000)

Hydrogeological techniques include monitoring of pumping rate and piezometric head data on both sides of the CB wall.

3
Analytical Model

3.1 Estimation of the in-situ hydraulic conductivity of CB walls

Analytical models are faster to solve, numerically exact, and continuous in time and space. Analytical solutions can be used to validate numerical solutions (Anderson et al., 2015). The performance of the CB wall can be estimated by at least knowing the hydraulic head on both sides of the wall, the thickness of the wall and the discharge. From the pump data, the discharge of water volumes (Q_{total}) for a certain time range can be determined. The data will be collected for specific project locations where CB walls are applied. Precipitation data can also be of great importance as it may influence the total discharge rate. Precipitation data can be retrieved from KNMI (Royal Netherlands Meteorological Institute). Information about the soil layers can be achieved from available CPT's and borings as well as geological and geohydrological data.

Data analysis

First, the data (raw) from the pumps will be validated to make sure that the data collection was done correctly. Errors and outliers that are present in the data will be identified and removed. By analyzing rainfall data a distinction can be made between dry and wet periods. The dry periods indicate a steady-state situation. After that, monthly visualizations of the data for the dry periods will be generated to get a better insight into the discharge rates of the pumps. Data of the water levels on both sides of the wall will also be analyzed.

General analytical approach

The in-situ hydraulic conductivity of a wall assuming steady flow can be calculated using Darcy's law, which describes the groundwater flow from high to low potential energy. (Ruffing and Evans, 2014):

$$Q = k \cdot i \cdot A \tag{1}$$

Where Q = the discharge/flowrate $[\frac{L^3}{T}]$, k = hydraulic conductivity $[\frac{L}{T}]$, i = hydraulic gradient $(\frac{dh}{dl})$ and A = cross sectional area perpendicular to the direction of the flow [L].

3.2 Formulas for ground(water) inflow

- Groundwater inflow through the vertical barrier (CB wall):

$$Q = k \cdot \frac{(h_{inside} - h_{outside})}{D} \cdot A \quad (2)$$

  Where:
  Q = the discharge/flowrate ($\frac{m^3}{d}$);
  h_{inside} = hydraulic head inside the CB wall in the first aquifer (m);
  $h_{outside}$ = hydraulic head outside the CB wall in the first aquifer (m);
  A = area of the CB wall (m^2);
  D = thickness of the wall (m) k = hydraulic conductivity of the wall (m/d);

- Groundwater inflow through the aquitard (sealing layer):

$$Q = k \cdot \frac{(h_{inside1} - h_{inside2})}{D} \cdot A \quad (3)$$

  Where:
  Q = the discharge/flowrate ($\frac{m^3}{d}$);
  $h_{inside1}$ = hydraulic head inside the CB wall in the first aquifer (m);
  $h_{inside2}$ = hydraulic head inside the CB wall in the second aquifer (m);
  A = area of the aquitard inside the CB wall (m^2);
  D = thickness of the aquitard (m);
  k = hydraulic conductivity of the aquitard (m/d);

- Groundwater inflow through permeable windows:

$$Q = k \cdot \frac{(h_{inside1} - h_{inside2})}{D} \cdot A \quad (4)$$

  Where:
  Q = the discharge/flowrate ($\frac{m^3}{d}$);
  $h_{inside1}$ = hydraulic head inside the CB wall in the first aquifer (m);
  $h_{inside2}$ = hydraulic head inside the CB wall in the second aquifer (m);
  A = area of the permeable windows inside the aquitard (m^2);
  D = thickness of the permeable windows (m);
  k = hydraulic conductivity of the permeable windows (m/d);

- Rainwater infiltration:

$$Q = d \cdot A \quad (5)$$

  Where:
  Q = the discharge/flowrate ($\frac{m^3}{d}$);
  A = catchment area (m^2);
  d = precipitation surplus (m/day);

- Groundwater inflow through windows between panels (insufficient connection):

$$Q = A \cdot \frac{(h_{inside} - h_{outside})}{D} \cdot (\frac{1}{c_{leak}} + \frac{a'}{c_{wall}}) \tag{6}$$

Where:
Q = the discharge/flowrate ($\frac{m^3}{d}$);
A = area of the CB wall (m^2);
h_{inside} = hydraulic head inside the CB wall in the first aquifer (m);
$h_{outside}$ = hydraulic head outside the CB wall in the first aquifer (m);
c_{leak} = hydraulic resistance of surrounding material inside windows (days);
c_{wall} = hydraulic resistance of the wall (d). The hydraulic resistance can be calculated from: c= D/k
a' = area of the CB wall minus windows;

3.3 Leakage through a homogeneous wall (analytical method)

- The leakage through a homogeneous wall (CB wall) can be calculated according the following formula:

$$Q = c \cdot H \cdot \left(\frac{H}{2} + h\right) \tag{7}$$

Where:
Q = the discharge/flowrate ($\frac{m^3}{d}$)
H =head difference over the wall (m)
h= distance from the top of the water table to the top of the aquitard inside the construction (m)
c = hydraulic resistance of the wall (d)
D = thickness of the wall (m)
k = hydraulic conductivity of the wall (m/d)
(Lambert, 2000)

- Using the least squares method, the leakage of a deep excavation can be determined by adding up the individual discharge rates (see Fig. 2.3) (Elprama et al., 2007):

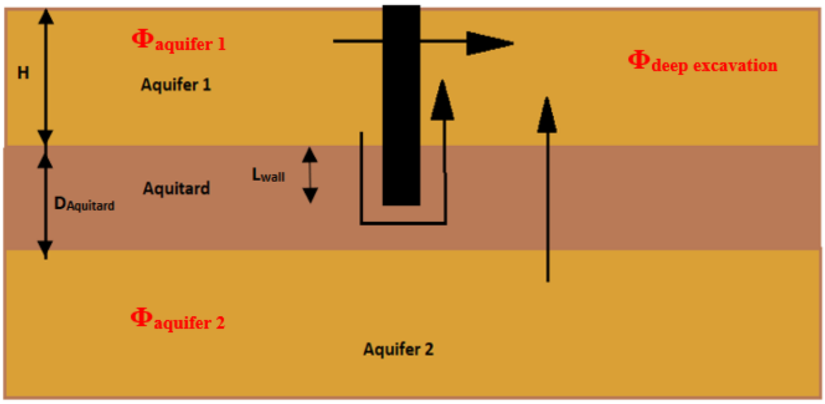


Figure 3.1: Leakage calculation model with $Q_{C-B\,wall}$, $Q_{under\,C-B\,wall}$ and $Q_{aquitard}$

$$\mathrm{Q_{total}} = \mathrm{Q_{C\text{-}B\ wall}} + \mathrm{Q_{under\ C\text{-}B\ wall}} + \mathrm{Q_{aquitard}} \tag{8}$$

$$\mathrm{Q_{C\text{-}B\ wall}} = 2 \cdot (\mathrm{B} + \mathrm{L}) \cdot \mathrm{H} \cdot \frac{\phi_{\text{aquifer 1}} - \phi_{\text{deep excavation}}}{\mathrm{c_{C\text{-}B\ wall}}} \tag{9}$$

$$\mathrm{Q_{under\ C\text{-}B\ wall}} = 2 \cdot (\mathrm{B} + \mathrm{L}) \cdot \frac{\mathrm{D_{aquitard}}}{\mathrm{c_{aquitard}}} \cdot \frac{\mathrm{K_f(1-b)}}{\mathrm{K_f(b)}} \cdot \frac{\phi_{\text{aquifer 1}} - \phi_{\text{deep excavation}}}{2} \tag{10}$$

$$\mathrm{Q_{aquitard}} = \mathrm{B} \cdot \mathrm{L} \cdot \frac{\phi_{\text{aquifer 2}} - \phi_{\text{deep excavation}}}{\mathrm{c_{aquitard}}} \tag{11}$$

$$\mathrm{K_f(m)} = \int_0^{0.5\cdot\pi} \frac{\mathrm{d}\theta}{\sqrt{1 - \mathrm{m} \cdot \sin(\theta)^2}} \tag{12}$$

$$\mathrm{b} = \sin\left(\frac{\pi \cdot \mathrm{L_{wall}}}{2 \cdot \mathrm{D_{aquitard}}}\right)^2 \tag{13}$$

where:
B = width of the deep excavation $[\mathrm{m}]$
L = length of the deep excavation $[\mathrm{m}]$
H = thickness of the aquifer 1 $[\mathrm{m}]$
$\mathrm{D_{aquitard}}$ = thickness of the aquitard $[\mathrm{m}]$
$\mathrm{L_{wall}}$ = embedment depth of the C-B wall into the aquitard $[\mathrm{m}]$
$\phi_{\text{aquifer 1}}$ =hydraulic head aquifer 1 $[\mathrm{m}]$
$\phi_{\text{aquifer 2}}$ = hydraulic head aquifer 2 $[\mathrm{m}]$
$\phi_{\text{deep excavation}}$ = hydraulic head in the deep excavation (the required drawdown) $[\mathrm{m}]$

4

General overview of projects within Netherlands

In the Netherlands, CB wall technology has been used for the construction of low permeability barriers for years. This technology is cost-effective, can reach larger depths, and achieves low hydraulic conductivities. In this chapter a few projects are discussed where CB walls have been installed. Also, the hydraulic conductivity and discharge through the walls for the design and construction stage will be presented. This can be used to compare with the results of the post-construction (in-situ) stage.

4.1 Westerschelde Tunnel

The Westerschelde Tunnel is a 6.6 kilometers bored tunnel beneath the Westerschelde, which runs from Ellewoutsdijk (Zuid-Beveland) to Terneuzen (Zeeuwsch-Vlaanderen) (see Figure 4.1). The soil around the tunnel consists of a layer of very stiff and impermeable clay, the so-called Boom clay. The soil deposits on the northern and southern side of the tunnel differ from each other. Therefore, the access ramp on both sides have been constructed in different ways. The access ramp on the southern side was constructed in an artificial polder consisting of CB walls. On the other hand, for the access ramp on the northern side, a pneumatically immersed caisson was used. The focus will be placed on the southern access ramp, due to the presence of CB walls.

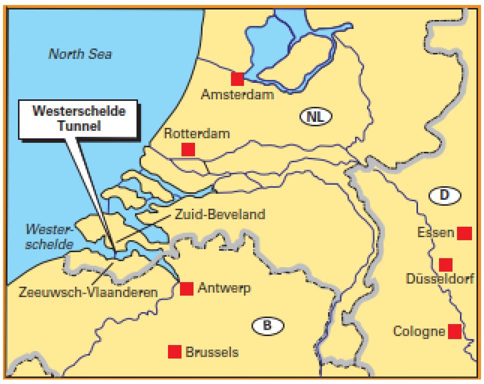


Figure 4.1: Location of the Westerschelde Tunnel in the Netherlands (Heijboer et al., 2003)

4.1.1 CB wall installation & specifications of the southern access ramp

For the southern access ramp, a polder had been constructed, consisting of CB walls, which were installed, from the surface level into the Boom clay layer (see Figure 4.2). The Boom clay layer lies at a depth of approximately NAP -25 m. The CB walls have a thickness of 600 mm and are approximately inserted 1500 mm into the clay layer to assure a watertight polder construction. Inside the CB walls, light sheet piling had been included, to decrease the permeability even more. The circular-shaped CB wall on top of the construction pit had not been provided with sheet piling because the tunnel boring machines had to bore through it. The construction of the CB wall started at the designed level of NAP 1.4 m. Around the polder embankments with a height of NAP 6.5 m were constructed, to prevent the polder area from flooding (Heijboer et al., 2003). The hydraulic conductivity of the hardened CB wall for this case was required to be equal to or below $1 \cdot 10^{-9}$ m/s with a hydraulic gradient (i) of 30. Hydraulic conductivity tests were performed on the hardened CB slurry samples to make sure the slurry met the requirements. The tests resulted in a mean hydraulic conductivity of $4.2 \cdot 10^{-10}$ m/s with a standard deviation of $1.26 \cdot 10^{-9}$ m/s (Collignon, 1998).

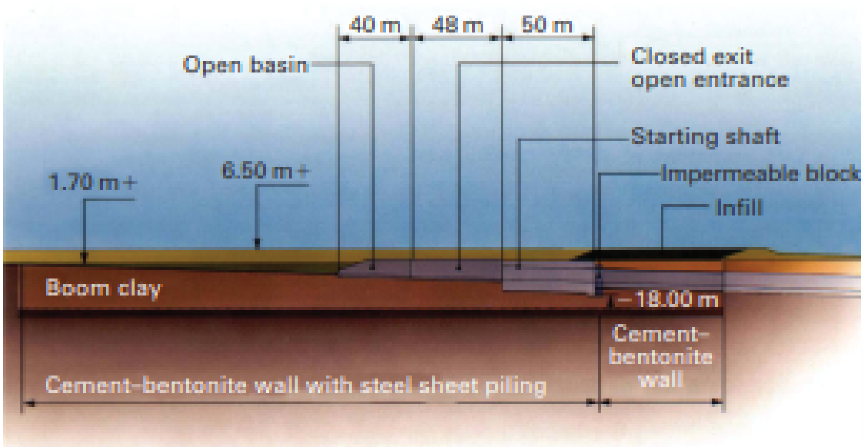


Figure 4.2: Design access ramp south (Heijboer et al., 2003)

4.1.2 Allowed and post-construction discharge

Allowed discharge

A drainage system is installed inside the polder construction to keep the groundwater level at NAP -6 m during its lifetime. Based on calculations, according to Darcy's law (1), the allowed discharge through the CB walls and the Boom clay is approximately 2.33 m^3/day and $8.4 \cdot 10^{-3}$ m^3/day. The groundwater discharge calculation through the Boom clay layer is based on the following assumption: no difference in hydraulic head between the different aquifers. The hydraulic conductivity of the Boom clay is very low, which means that the amount of groundwater flowing through this layer is very low. The various parameters used for these calculations and their values are given, in Table 4.1.

Post-construction discharge

The groundwater discharge through the CB walls (including the sheet piles) and the Boom clay layer is collected in a water cellar. The amount of water from the years 2017 until 2019 is given in Figure 4.3. It is notable that in 2018 more water is pumped from the polder, even though the total amount of rainfall in 2018 was lower, compared to 2017 and 2019. In April, June, and July 2019, there was less rainfall (see Figure 4.4).

Table 4.1: Overview of the parameters used and their values

Parameters	**Value**	**Reference**
Total area CB wall	$\approx 21589\ m^2$	Appendix A.1
Total area Boom clay (inside the CB wall construction)	$\approx 33856\ m^2$	Appendix A.1
Horizontal hydraulic conductivity Boom clay	$5 \cdot 10^{-12}$ m/s	(Ma et al., 2016)
Horizontal hydraulic conductivity CB wall + sheet pile wall	10^{-10} m/s	Arbitrary chosen
Hydraulic head inside polder	$\approx$ NAP -6 m	Appendix A.2
Hydraulic head outside polder	$\approx$ NAP 1.5 m	Appendix A.2
Thickness CB wall	0.6 m	Appendix A.1
Thickness Boom clay	≈ 13 m	Appendix A.3

In Figure 4.3 can be seen that in these months, the amount of water in the cellar is also low. These amounts are used to calculate the hydraulic conductivity of the CB wall (including the sheet piles).

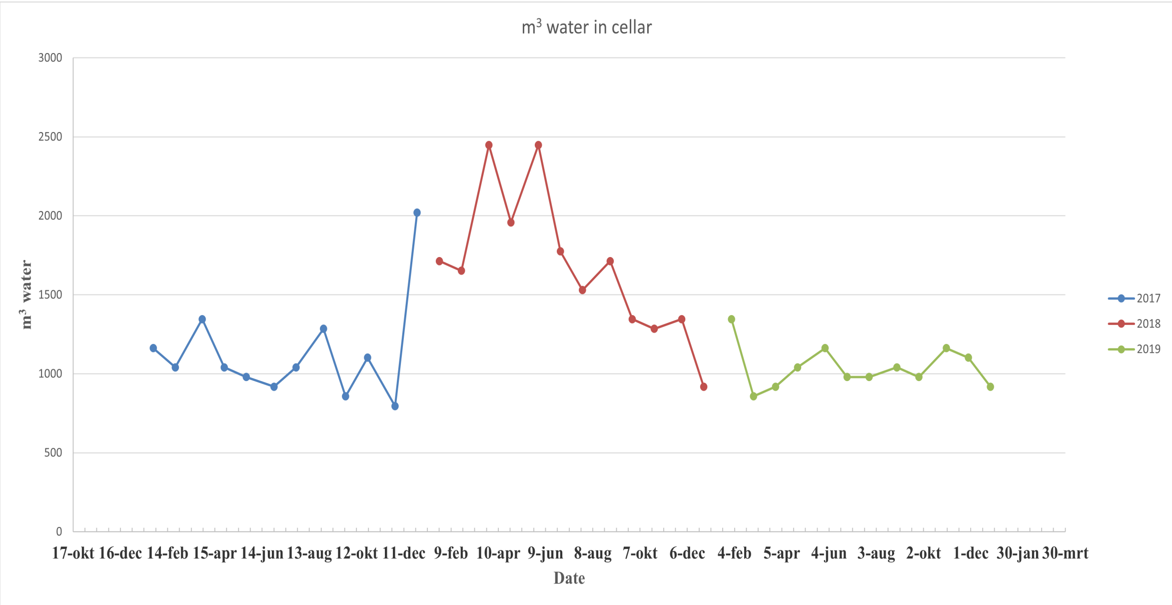


Figure 4.3: m^3 water in cellar

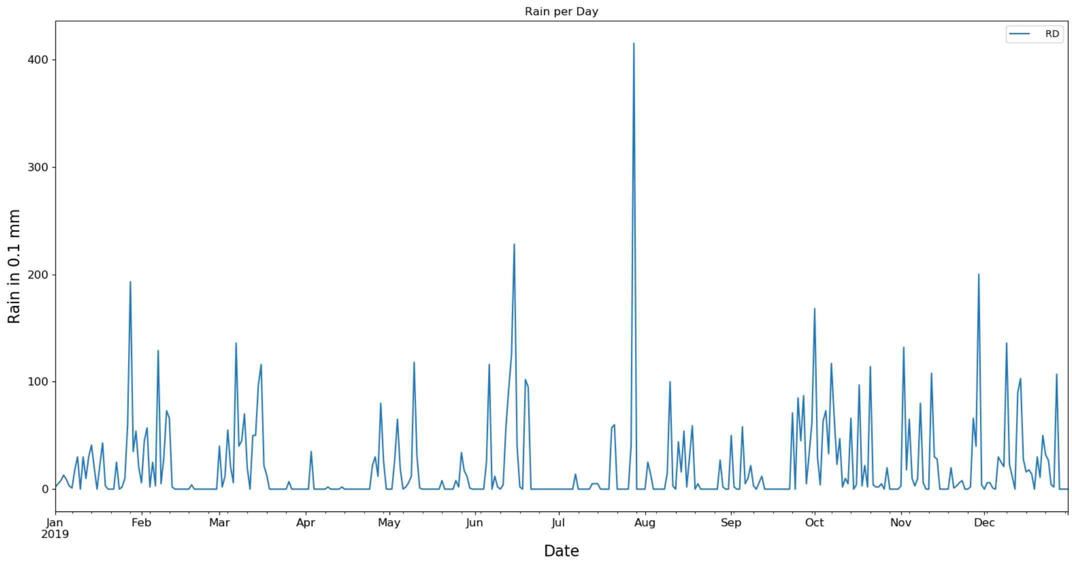


Figure 4.4: Rainfall in Terneuzen for 2019 (KNMI)

The parameters used for the calculation of the hydraulic conductivity of the CB wall (including the sheet piles) and their values are given, in Table 4.2. The measured discharge is higher compared to the total calculated allowed discharge of 2.34 m^3/day ($2.71 \cdot 10^{-5} m^3/s$). The possible reasons for this deviation can be:

- That the hydraulic conductivity that is chosen for the CB wall (including the sheet piles) is incorrect (can be higher or lower)
- The hydraulic conductivity of the Boom clay is higher
- The discharge through the walls is higher than expected

The calculated hydraulic conductivity of the CB wall (including the sheet piles) is approximately $1.31 \cdot 10^{-9}$ m/s.

Table 4.2: Overview of the parameters used and their values for the hydraulic conductivity calculation

Parameters	**Value**	**Reference**
Total area CB wall	$\approx 21589\ m^2$	Appendix A.1
Hydraulic head inside polder (June/July 2019)	$\approx$ NAP -6.19 m	Appendix A.2
Hydraulic head outside polder (June/July 2019)	$\approx$ NAP 1.81 m	Appendix A.2
Thickness CB wall	0.6 m	Appendix A.1
Total measured discharge (June/July 2019)	$3.78 \cdot 10^{-4} m^3/s$	see Figure 4.3

4.2 A2 Motorway at Best

The A2 motorway is highway in the Netherlands which connects the city of Amsterdam, close to the Amstel interchange with the Belgian border, near Maastricht (NL) and Liège (B), and the Belgian A25 road. The sunken part of the A2 motorway (see Figure 4.5) has a length of approximately 1912 m (km 54.886 - km 56.798). This part was constructed in a polder to reduce the groundwater inflow. The polder was divided into three compartments, from km 54.886 to km 55.500 (northern compartment), from km 55.500 to km 56.345 (middle compartment) and from km 56.345 to 56.798 (southern compartment).

Figure 4.5: Sunken part of the A2 motorway at Best (red line)

4.2.1 CB wall installation & specifications

For the construction of the polder, CB walls were installed, until approximately NAP -20 m. Sheet pile walls were installed inside the CB walls to decrease the permeability and retain earth. The single-phase technique and the continuous excavation method were used to construct the CB wall. Each CB panel has a width of nearly 10 m and a thickness of 0.6 m. Inside the polder, two CB partition walls were constructed, to divide the polder into three compartments. At the end of 2011, the construction of the third lane began. Installation of sheet piles between the new road and the existing CB was necessary to serve as a foundation for the noise barriers. Because of this, the groundwater level between the sheet pile wall and the CB wall can rise up to the ”normal” water level. To prevent this, after every 10 sheet pile walls installations, one sheet pile was not installed. Thus, an opening of 10% was created (Haveman, 2012).

The CB slurry had to meet the following requirements:

- The CB slurry should contain at least 35 kg cement-stable bentonite CV 15 and 200 kg blast furnace slag cement (minimal 65% slag replacement) per 1000 liter water;
- The slurry must not contain any toxic substances;
- The pH value must be between 9 and 12.

The CB slurry should meet the following requirements after curing for 28 days in the trench.

- The hydraulic conductivity according to Darcy for a hydraulic gradient (i) of 30, should not be greater than $1 \cdot 10^{-8}$ m/s;
- The compressive strength should be at least 0.5 N/mm^2;
- The elastic modulus should be approximately 10 MN/m^2 at a strain of 1 to 1.5 %.

Hydraulic conductivity tests performed on samples after curing for 28 days provided the following results: for the mean hydraulic conductivity:

- At a temperature of $10°$ C, the mean hydraulic conductivity is equal to $1 \cdot 10^{-8}$ m/s
- At a temperature of $15°$ C, the mean hydraulic conductivity is equal to $0.5 \cdot 10^{-8}$ m/s

4.2.2 Allowed discharge & post-construction discharge

Allowed discharge

Three water cellars are built underneath each compartment. On a yearly basis, 0.8 million m^3 water was collected by the drainage system (Haveman, 2012). The allowed discharge through the northern compartment is calculated using Darcy's law and the parameters given in table 4.3. The discharge through the wall is $\approx$ 1 m^3/day. The average discharge through the clay layer is $\approx$ 77.1 m^3/day.

Table 4.3: Overview of the parameters used and their values (North)

Parameters North	Value	Reference
Total area CB wall+sheet pile wall/HDPE foil	$\approx 31311.68\ m^2$	Appendix B.1
Total area CB wall	$\approx 614\ m^2$	Appendix B.1
Total area clay (inside the CB wall construction)	$\approx 36287.4\ m^2$	Appendix B.1
Vertical hydraulic conductivity clay (min)	$1 \cdot 10^{-3}$ m/d	Appendix B.6
Vertical hydraulic conductivity clay (mean)	$3 \cdot 10^{-3}$ m/d	Appendix B.6
Vertical hydraulic conductivity clay (max)	$5 \cdot 10^{-3}$m/d	Appendix B.6
Horizontal hydraulic conductivity CB wall + sheet pile wall	10^{-10} m/s	Arbitrary chosen
Horizontal hydraulic conductivity CB wall + HDPE foil	10^{-12} m/s	Arbitrary chosen
Horizontal hydraulic conductivity CB wall	10^{-9} m/s	Arbitrary chosen
Hydraulic head inside polder	$\approx$ NAP 8.75 m	Appendix B.1
Hydraulic head outside polder	$\approx$ NAP 13 m	Appendix B.1
Thickness CB wall	0.6 m	Appendix B.1
Thickness clay	≈ 6 m	Appendix B.1

For the middle and southern compartment, the same calculations were performed using the parameters in the tables 4.4 & 4.5. The calculated discharges through the wall and clay layer for the middle compartment are 4.12 m^3/day and 139 m^3/day. Lastly, the discharges through the wall and clay layer for the southern compartment are 1.81 m^3/day and 72.3 m^3/day. The total allowed discharged is approximately 300 m^3/day and relatively low compared to the measured discharge of 0.8 million $m^3/year$ ($\approx$ 2191 m^3/day).

Table 4.4: Overview of the parameters used and their values (Middle)

Parameters Middle	**Value**	**Reference**
Total area CB wall+sheet pile wall	$\approx 43112.46\ m^2$	Appendix B.2
Total area CB wall	$\approx 845\ m^2$	Appendix B.2
Total area clay (inside the CB wall construction)	$\approx 49939.5\ m^2$	Appendix B.2
Vertical hydraulic conductivity clay (min)	$1 \cdot 10^{-3}$ m/d	Appendix B.6
Vertical hydraulic conductivity clay (mean)	$3 \cdot 10^{-3}$ m/d	Appendix B.6
Vertical hydraulic conductivity clay (max)	$5 \cdot 10^{-3}$ m/d	Appendix B.6
Horizontal hydraulic conductivity CB wall + sheet pile wall	10^{-10} m/s	Arbitrary chosen
Horizontal hydraulic conductivity CB wall	10^{-9} m/s	Arbitrary chosen
Hydraulic head inside polder	$\approx$ NAP 8.75 m	Appendix B.2
Hydraulic head outside polder	$\approx$ NAP 14.3 m	Appendix B.2
Thickness CB wall	0.6 m	Appendix B.2
Thickness clay	≈ 6 m	Appendix B.2

Table 4.5: Overview of the parameters used and their values (South)

Parameters South	**Value**	**Reference**
Total area CB wall+sheet pile wall	$\approx 19466.8\ m^2$	Appendix B.3
Total area CB wall	$\approx 453\ m^2$	Appendix B.3
Total area clay (inside the CB wall construction)	$\approx 26772.3\ m^2$	Appendix B.3
Vertical hydraulic conductivity clay (min)	$1 \cdot 10^{-3}$ m/d	Appendix B.6
Vertical hydraulic conductivity clay (mean)	$3 \cdot 10^{-3}$ m/d	Appendix B.6
Vertical hydraulic conductivity clay (max)	$5 \cdot 10^{-3}$ m/d	Appendix B.6
Horizontal hydraulic conductivity CB wall + sheet pile wall	10^{-10} m/s	Arbitrary chosen
Horizontal hydraulic conductivity CB wall	10^{-9} m/s	Arbitrary chosen
Hydraulic head inside polder	$\approx$ NAP 10.2 m	Appendix B.3
Hydraulic head outside polder	$\approx$ NAP 15.6 m	Appendix B.3
Thickness CB wall	0.6 m	Appendix B.3
Thickness clay	≈ 6 m	Appendix B.3

Post-construction discharge

Each water cellar has three pumps, and the data per minute for every pump is available. After analyzing the pumping and rainfall data for the years 2016, 2017, 2018, and 2019 the data of July 2018 is used for this study to avoid rainwater infiltration (see Figure 4.6). The data for the first five days of July 2018 is displayed in Figure 4.7. The blue line is the water level in the cellar, and the other three lines indicate the current of the pumps in ampere. The pumping stops when the water level in the cellar is equal to NAP 0.3 m. Pumps 2 and 3 are operating more than 12 hours in a day, which means that large volumes of water enter the cellar (B.4). The pumps in the northern cellar operate approximately 6 hours in a day (see Figure 4.8). Sheet pile walls and HDPE foil are inserted in the CB walls for the whole construction (three compartments), which makes the construction extra watertight. The calculated discharge for the middle compartment is ≈ 480 m^3/day (see Appendix B.4). The discharge is used to calculate the in-situ hydraulic conductivity of the CB wall, which is approximately $5 \cdot 10^{-7}$ m/s (see Appendix B.8 & B.9). This value indicates that the CB walls are more permeable than expected. It can be seen in the subsurface model of the sunken part of A2 Best in Appendix B.5 that the clay layer is missing nearby kilometer 140.000, which is a part of the middle compartment. Thus, a large amount of groundwater is mainly seeping through the clay layer. Due to insufficient information on the area of the missing clay layer, it is difficult to indicate the discharge through the clay layer and the window (gap). This means that the hydraulic conductivity value of the CB walls is probably lower than calculated.

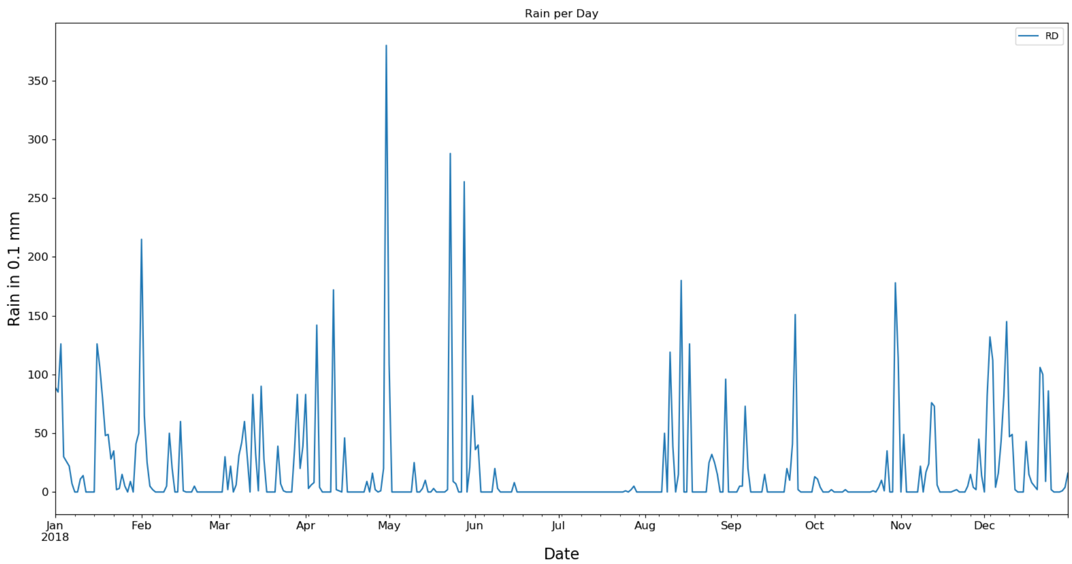


Figure 4.6: Rainfall in Eindhoven for 2018 (KNMI)

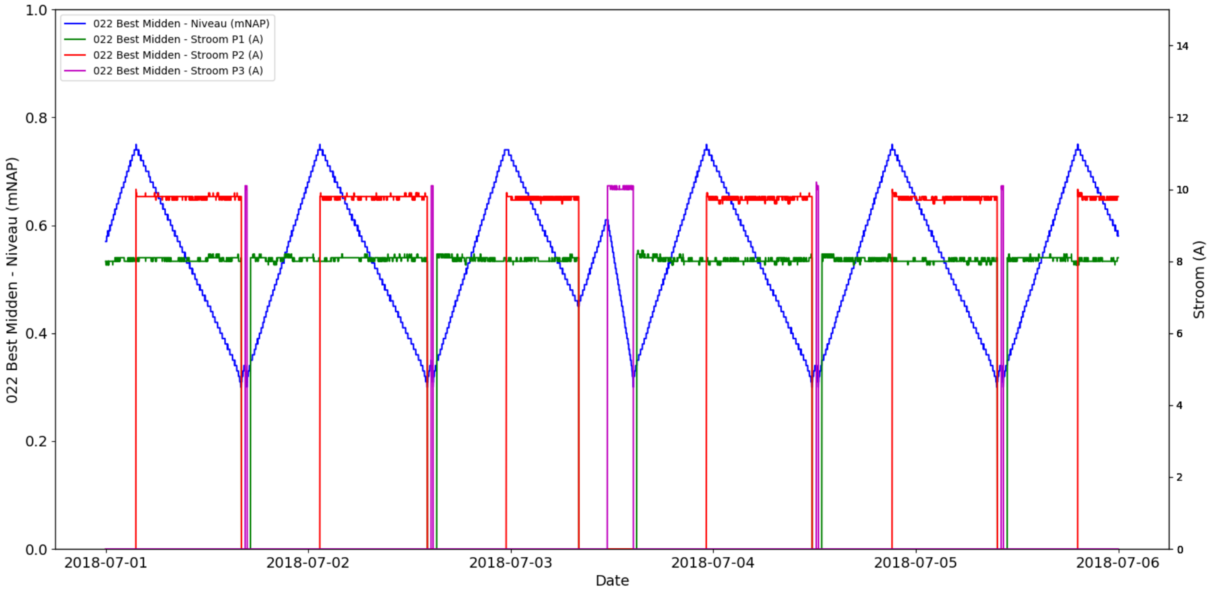


Figure 4.7: Pump data for the middle compartment (July 2018)

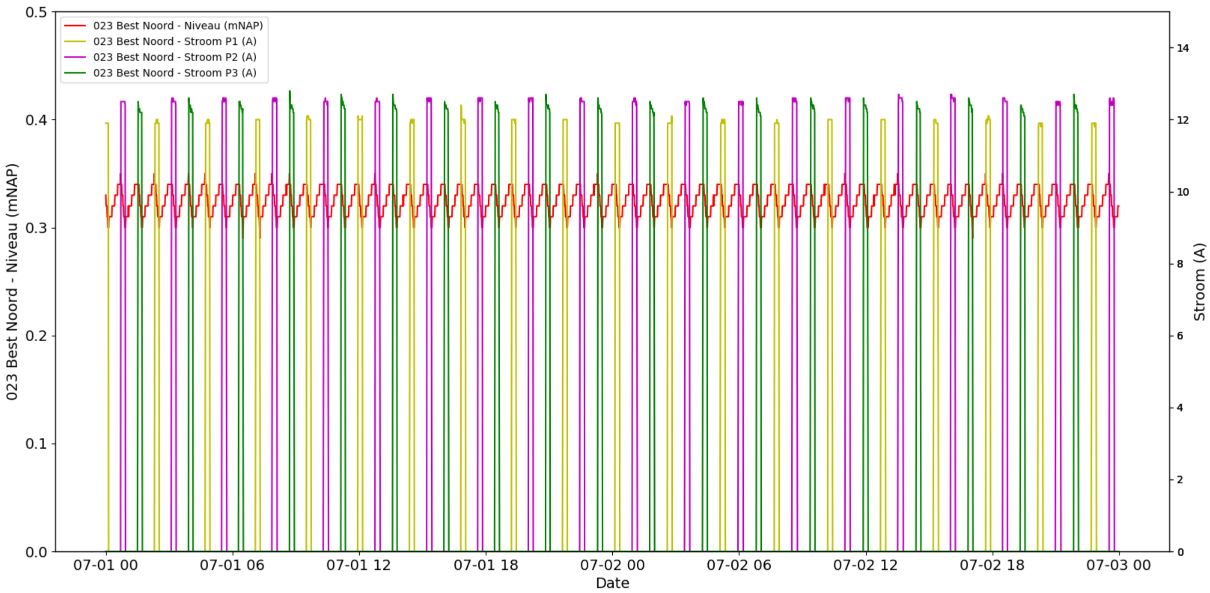


Figure 4.8: Pump data for the northern compartment (July 2018)

4.3 Motorway A4 Delft - Schiedam

The motorway A4 Delft - Schiedam was constructed to enhance the accessibility between The Hague and Rotterdam and to reduce the traffic congestion on the Delft, Midden-Delfland, Lansingerland, and Westland freeway (A13). The motorway is 7 kilometres long and consists of:

- a semi-sunken part of 2.6 kilometres
- a sunken part of 1.4 kilometres
- a tunnel of 2 kilometres long
- the Kethelplein junction, which crosses the A4 and is connected to the existing A4 leading to the Benelux Tunnel and the A20.

The semi-sunken and sunken motorway, are divided into 15 compartments.

Figure 4.9: Location of the semi-sunken (halfverdiepte ligging) and sunken part (verdiepte ligging) of the motorway A4 Delft - Schiedam

4.3.1 CB wall installation & specifications

Semi-sunken part

The semi-sunken part (see Figure 4.10) is divided into nine compartments and is constructed in an artificial polder, consisting of CB walls (vertical barrier) embedded in the Holocene peat and clay layers (horizontal barrier). On the south side of this part, the CB walls are installed, at a depth of NAP -7.5 m. On the contrary, the CB walls on the north side also contain HDPE foil to increase the water tightness and reach down to a depth of NAP -19 m.

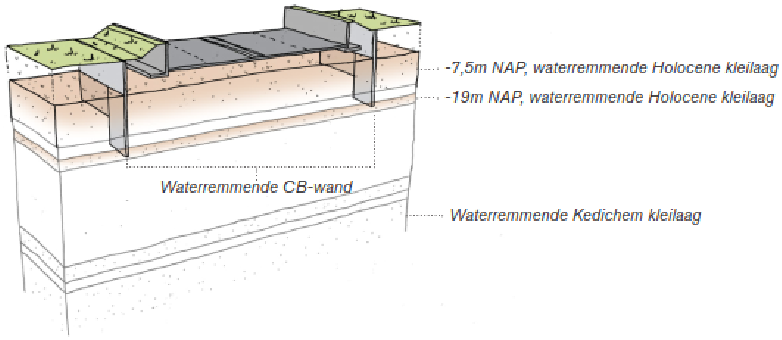


Figure 4.10: Cross-section of the semi-sunken part with CB walls installed at a depth of NAP -7.5 m and NAP -19 m (RWS, 2015)

The following requirements for the hydraulic conductivity apply for the CB walls of the semi-sunken part:

- A target value of $1 \cdot 10^{-9}$ m/s (lab value, based on the mixture composition)
- A target value of $1 \cdot 10^{-11}$ m/s (including foil panels)

Sunken part

The sunken part (see Figure 4.11) is divided into three sections:

- At the northern and southern access ramp, sheet pile walls, are used as a vertical barrier and the low permeable Holocene layers as the horizontal barrier.
- For the middle section of the sunken part, CB walls are installed at depth of approximately NAP -45 m into the Kedichem layer. To increase the water tightness, sheet pile walls are inserted in these walls until NAP -25 m.
- At the location of the Ecoaqueduct and the Oostveense- en Woudweg, the walls are designed as diaphragm wall panels at the same level as the CB walls.

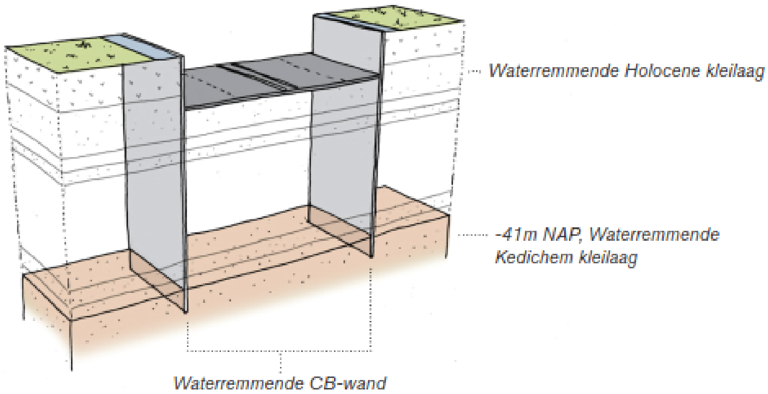


Figure 4.11: Cross-section of the sunken part (RWS, 2015)

4.3.2 Allowed discharge & post-construction discharge

Allowed discharge

A drainage system is installed inside the polder system to keep the road structure dry. The rainwater that is collected by a separate sewage system is returned into the polder system after purification. The total allowed discharge for the semi-sunken part and the sunken part was estimated to be 400 m^3/day. For this estimation, a design value of 1852 days was chosen for the hydraulic resistance for a wall thickness of 0.8 m. The hydraulic conductivity can be calculated using the following formula:

$$c = \frac{D}{k} \tag{1}$$

Where:
c = hydraulic resistance of the wall
D = thickness of the wall (m)
k = hydraulic conductivity of the wall (m/d)

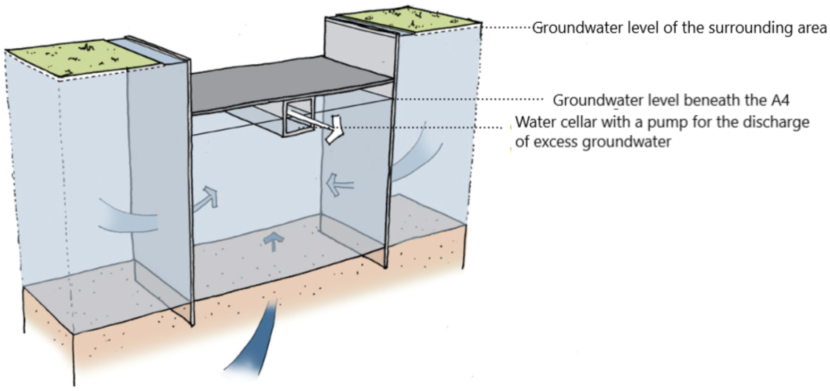


Figure 4.12: Drainage system of the semi-sunken and sunken motorway

Post-construction discharge

The compartments of the semi-sunken and sunken motorway were constructed in phases. After the construction of each compartment, their discharge was measured to establish whether they met the permit requirement. It appeared that the discharge for some of the compartments exceeded. After extensive investigation the defects were detected.

The leakages mainly occured due to:

- insufficient connection between the CB panels
- leaking sand compaction piles
- insufficient embedment into the second Kedichem clay layer
- poor interlocking joints of the sheet piles
- poor connection between the CB wall and the sheet pile wall
- large variation in the hydraulic conductivities of the Kedichem clay and the aquifer
- inhomogeneity of the Kedichem clay layer
- tearing of the HDPE foil

Compartiment	Debiet (m3/dag)	
	Gemeten	IW-eis
1	0.2	10
2	17	20
3a	8	8
3b	- *)	10
4	12	42
5	16	16
6	35	22
7	45	25
8	17	22
Totaal debiet	**160 *)**	**175**

(a) Discharge semi-sunken part

Compartiment	Debiet (m3/dag)	
	Gemeten	IW-eis
9	12	12
10	0,5	26
11	150	40
12	350	42
13	390	65
14	100	10
15	25	30
Totaal debiet	**1028**	**225**

(b) Discharge sunken part

Figure 4.13: Measured (Gemeten) and allowed (IW-eis) discharge for the semi-sunken and sunken part

After reparation of these defects, the discharge was reduced from approximately 2600 m^3/day to 1200 m^3/day (see Figure 4.13). A study had been conducted for the sunken part to determine whether the design values for the hydraulic resistance of the CB wall and the Kedichem clay layer correspond to the values found in practice. The design values for the hydraulic resistance for the CB wall and the clay layer were 1852 days and 14457 days, respectively. The results from the study (Bosman, 2015) showed that the calculated total discharge corresponds to the measured discharge when a hydraulic resistance of 926 days for the CB wall and 1500 days for the Kedichem clay layer was used. The hydraulic resistance of 926 days is approximately equal to a hydraulic conductivity of $1 \cdot 10^{-8}$ m/s. The hydraulic resistance of 1500 days of the Kedichem clay layer was derived from the Randstadrail project in Rotterdam. Thus, the design values for the hydraulic resistance of the CB wall and the Kedichem clay layer were overestimated for this project (Motorway A4 Delft-Schiedam).

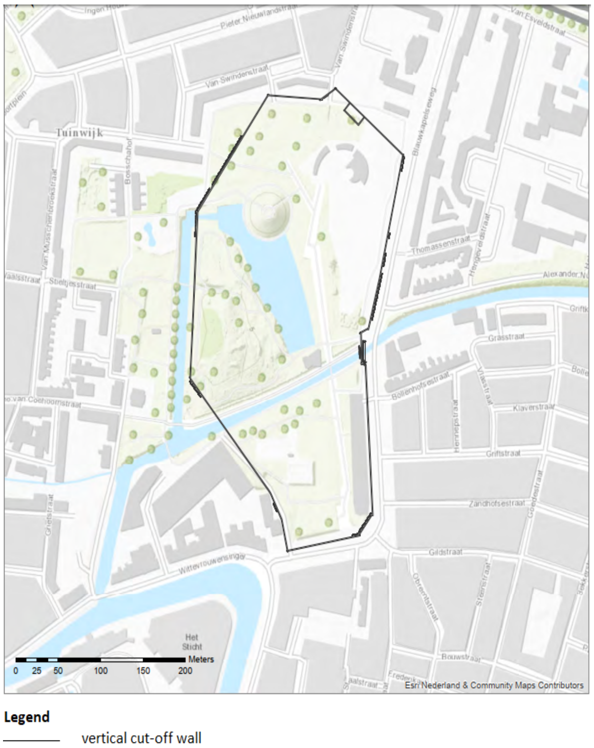
4.4 Griftpark Utrecht

The ”Griftpark” is one of the notable remediation locations in the Netherlands. It has an area of 10 hectares and is located close to the center of the old city of Utrecht. The site has been used for the following activities:

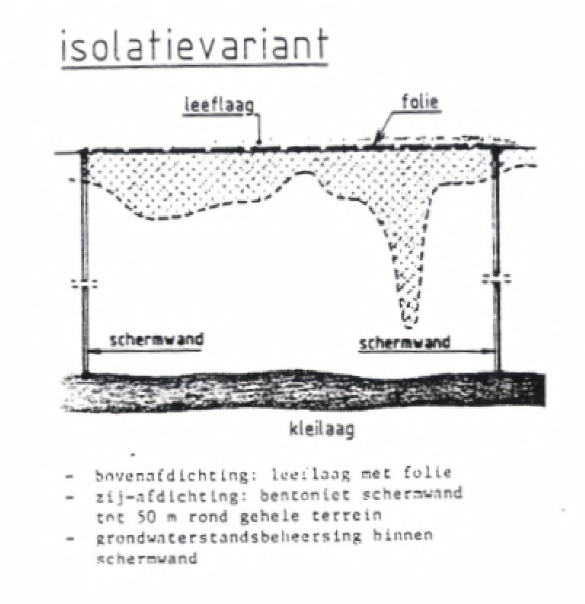
- production of gas and benzene
- landfill
- scrapyard
- dumping of sewage sludge

As a consequence, the site has become extremely polluted with aromatics, PAKs (polycyclic hydrocarbons), phenols, cyanides, and mineral oil. The contamination is leaking into the first groundwater aquifer over more than 50 meters of depth. The gas factory was demolished in 1960. The realization of the new ”park” began in 1977 and halted in 1979 after encountering tars and other contaminations in the upper ground layers. Intensive examinations took place from 1984 up till 1987 and almost a hundred remediation options were studied. The opinions of many parties (such as the municipality, people living nearby the site, the provincial government, ministry of environment, and housing) clashed until 1987. In 1990 all parties concurred with the realization of an Isolation (Isoleren), Control (Beheersen), and Monitoring (Controleren) solution (IBC method). The Isolation, Control, and Monitoring solution (see Figure 4.14) consisted of three phases:

- The construction of a vertical cut-off wall (schermwand);
- Remediation of the Biltsche Grift and peripheral areas;
- Application of an isolation clean top layer (leeflaag), which was also used as a base for the public park.



(a) Location of Griftpark in Utrecht



(b) The IBC method

Figure 4.14: Solution for controlling the spreading of the pollution at Griftpark

4.4.1 CB wall installation & specifications

The purpose of the construction of the CB walls was to isolate the contaminated area and prevent subsidence of the surrounding area during the extraction of polluted water from that area. The walls were embedded into a semi-permeable clay layer (Kedichem layer) and reached a depth of approximately NAP -60 m. The two-phase technique and the alternating excavation method were used to construct the CB wall. The walls have a thickness of 800 mm and a total circumference of 1202 meters. Sheet pile walls were installed within the CB walls at several locations where remediation outside the wall was required. The requirements for the CB wall based on geohydrological analyses were:

- an average hydraulic resistance of 1000 days for the CB wall (whole construction);
- an average hydraulic conductivity of $< 5 \cdot 10^{-9}$ m/s for every panel after 28 days of hardening (hydraulic gradient (i) of 30).

During quality control (QA) tests it appeared that the CB slurry composition for thirteen panels was different from the required composition. These panels were ”rejected”. The results of the hydraulic conductivity tests performed in 1994 on the thirteen panels are shown in Figure 4.15. The expected (K_{Verw}) and average values ($\bar{K}$) for the hydraulic conductivity of each panel were calculated using the following formulas:

$$K_{Verw} = e^{\left(\left(\frac{1}{n}\sum_{i=1}^{n}\ln k_i\right)+\frac{1}{n-1}\sum_{j=1}^{n}\left(1nK_j-\frac{1}{n}\right)\right)} \quad (2)$$

$$\bar{K} = e^{\frac{1}{n}\sum_{i=1}^{n}} \quad (3)$$

According to the tests, the average hydraulic conductivity of every panel met the requirements (Kabos, 1994). The variations in the test results are caused by:

- Incidentally very high viscosities of the coulis (CB suspension);
- Incidentally low densities of the coulis, indicating the presence of less cement (locally).

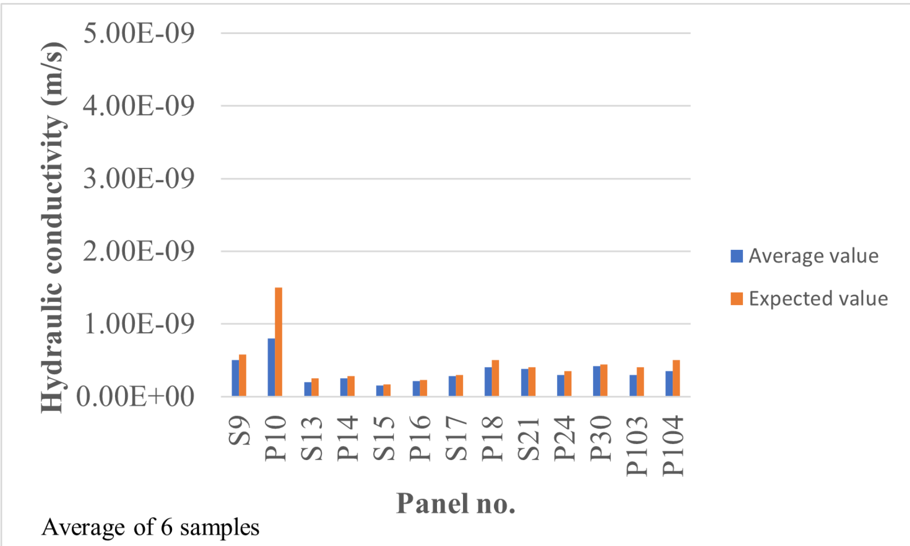


Figure 4.15: Hydraulic conductivity test results

4.4.2 Allowed discharge & post-construction discharge

Allowed discharge

According to calculations performed during the design stage by Heidemij Advies B.V. (Arcadis) for the groundwater management plan, the average and maximum extraction inside the CB wall construction were determined to be $\pm$ 90 m^3/day and 320 m^3/day ($\approx$ 13 $m^3/hour$), respectively. The calculations were based on the following assumptions:

- CB walls without imperfections;
- Precipitation surplus for 70% of the area inside the construction;
- Declining groundwater levels outside the construction ($\approx$ 10 mm/day), requiring higher groundwater extraction inside the construction.

The presence of imperfections in the wall will lead to an increase in the calculated discharge.

Post-construction discharge

Three deep wells are used for the groundwater extraction inside the construction. In the first aquifer, three piezometers are installed inside (LT1, LT2 and LT3) and two outside (LT4 and LT5) the construction. There are also piezometers placed in the second aquifer to measure the hydraulic head. The purple and green lines in Figure 4.16 indicate the water level measurements in the first aquifer inside the CB wall construction. The water level measurements outside the construction, are illustrated by the orange (first aquifer/WVP1) and blue lines (second aquifer/WVP2). Finally, the red line displays the groundwater extraction (discharge) in $m^3/hour$. Figure 4.16 shows that the water levels in the first and second aquifer (inside and outside the construction) increase when the discharge decreases. The discharge through the years is also extremely fluctuating. The only drawback of this case is that the data is available on a quarterly basis due to discontinuous measurements.

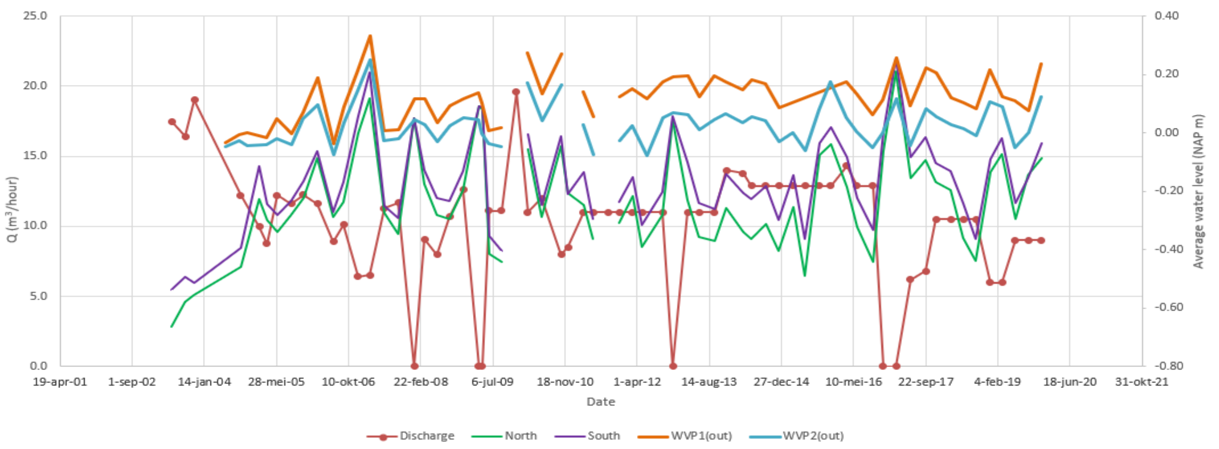


Figure 4.16: Total discharge rate of the deep wells and the water levels in the first and second aquifer on both sides of the construction

The discharge (red), difference in hydraulic head over the wall in the first aquifer (brown, orange, grey, yellow, green, dark-and light blue), and the precipitation surplus (black), are shown in Figure 4.18 for 2019. The difference in hydraulic head over the CB wall in the first aquifer is between 0.10 m - 0.25 m for 2019 (see Figure 4.18). The hydraulic head difference inside the construction between the first and second aquifer is $\approx$ 0.1 m (see Table 4.6, (2)). The groundwater extraction should be at least 9 $m^3/hour$ to achieve this hydraulic head difference. This amount of water is consists of (see Figure 4.17):

- Precipitation surplus ($Q_n - Q_v$) (22%);
- Discharge through the wall (Q_w) (18%);
- Discharge through the semi-permeable clay layer (Q_k) and seepage through the windows in the clay layer (Q_g) (60%).

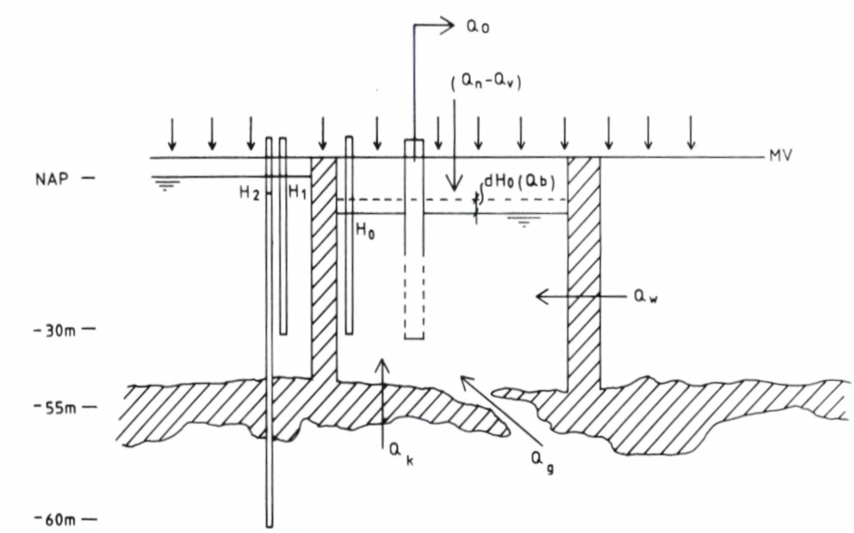


Figure 4.17: Water balance model for Griftpark with the various discharges

Table 4.6: Overview of the preferred hydraulic head difference

	Peilverschil	**max.**	**gem.**	**min.**
1	beheerspijl 1^e pakket binnen wand versus peil 1^e pakket buiten wand	0.8	0.6	0.3
2	beheerspijl 1^e pakket binnen wand versus peil 2^e pakket	0.6	0.4	0.1

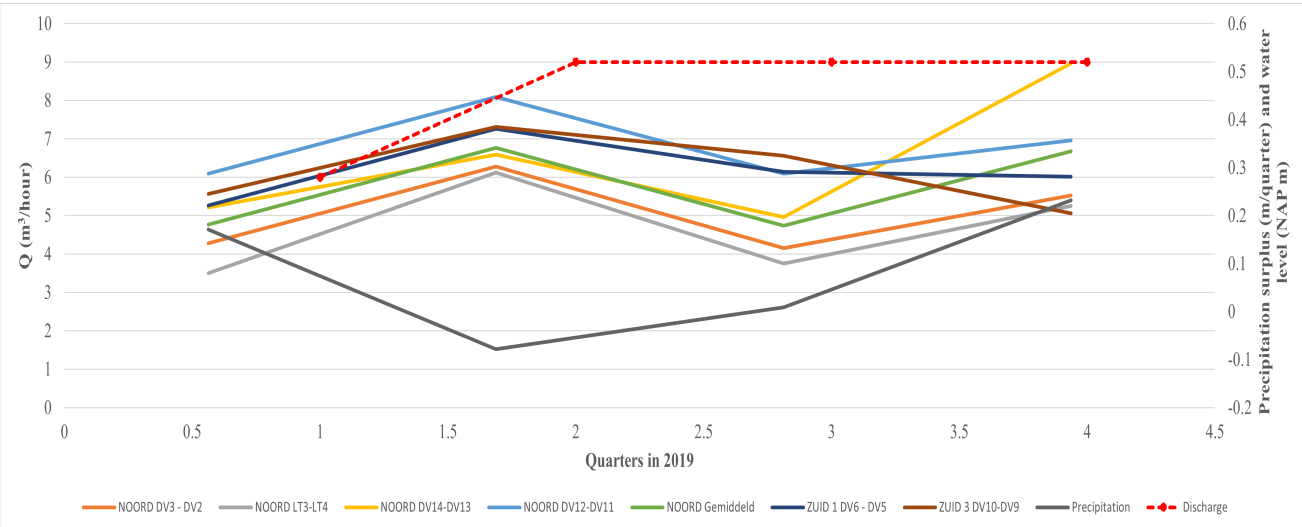


Figure 4.18: Total discharge rate of the deep wells, the difference in hydraulic head over the wall and precipitation surplus for 2019

Figure 4.19 displays the following:

- the hydraulic head difference between the first and second aquifer inside the construction (yellow). Due to this difference, groundwater can flow from the second to the first aquifer;
- the hydraulic head difference over the wall for the first aquifer (orange). Groundwater can flow through the wall;

- the precipitation surplus (purple);
- the discharge rate of the pumps (green);
- the total discharge through the wall and Kedichem layer (grey).

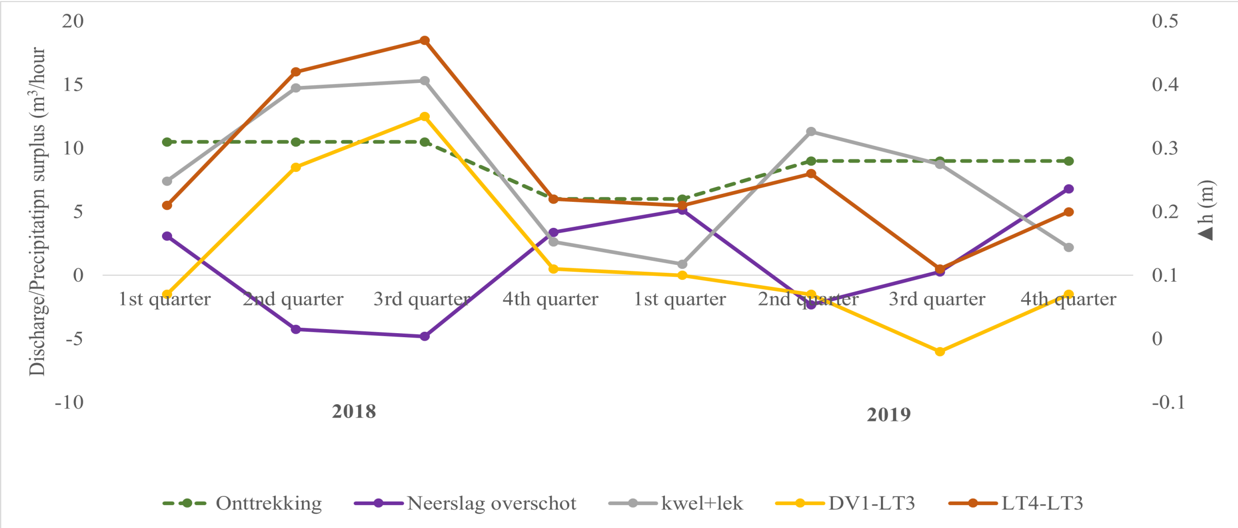


Figure 4.19: Total discharge rate of the deep wells (Onttrekking), discharge through the wall+clay layer, the difference in hydraulic head (first and second aquifer), precipitation surplus for 2018 and 2019

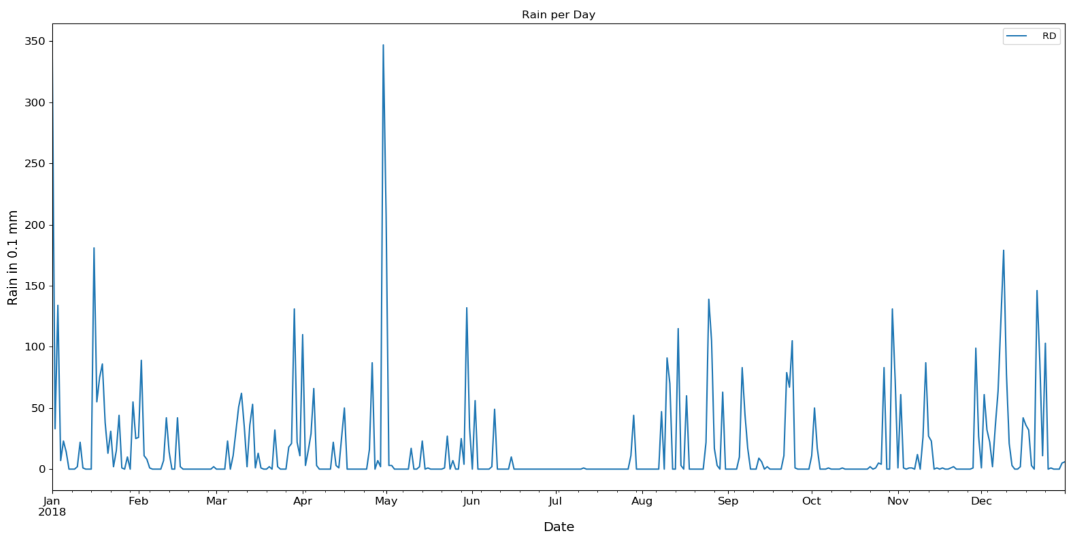


Figure 4.20: Rainfall in de Bilt (Utrecht) for 2018 (KNMI)

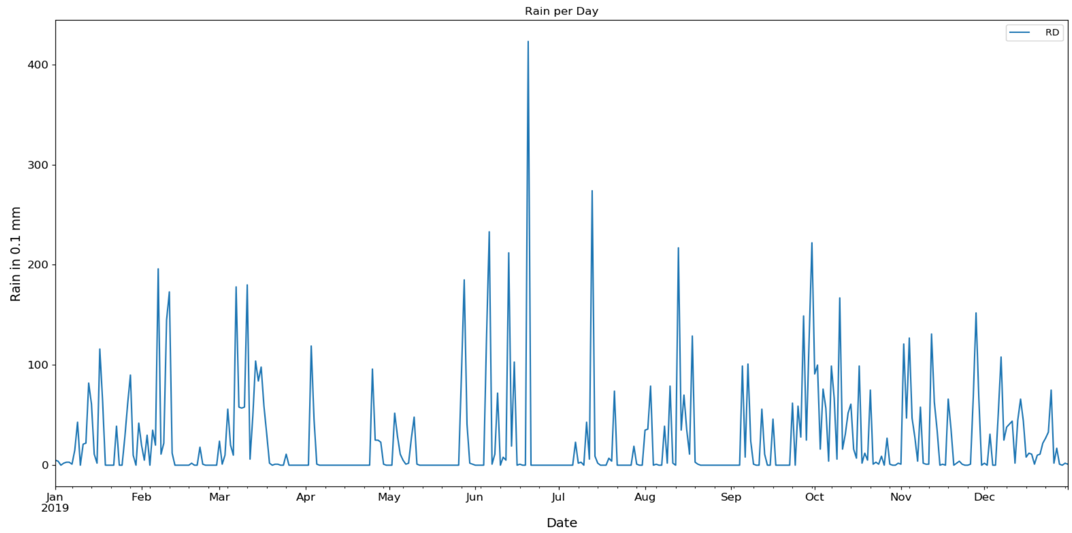


Figure 4.21: Rainfall in de Bilt (Utrecht) for 2019 (KNMI)

For all the four quarters of 2018 and 2019, the discharge through the wall, clay layer and windows is calculated using the hydraulic head difference from Figure 4.19 and the parameters from Table 4.7. The results are shown in Figure 4.22.

Table 4.7: Overview of the parameters used and their values for Griftpark

Parameters	**Value**
Total area CB wall+sheet pile wall	$\approx 64941.30\ m^2$
Total area clay layer without windows	$\approx 74935\ m^2$
Total area windows	$\approx 6225\ m^2$
Total catchment area	$\approx 64789\ m^2$
Hydraulic resistance clay layer	2000 days
Hydraulic resistance CB wall	1000 days
Hydraulic resistance windows	25-100 days
Hydraulic resistance windows (wall)	161 days
a’	0.9999

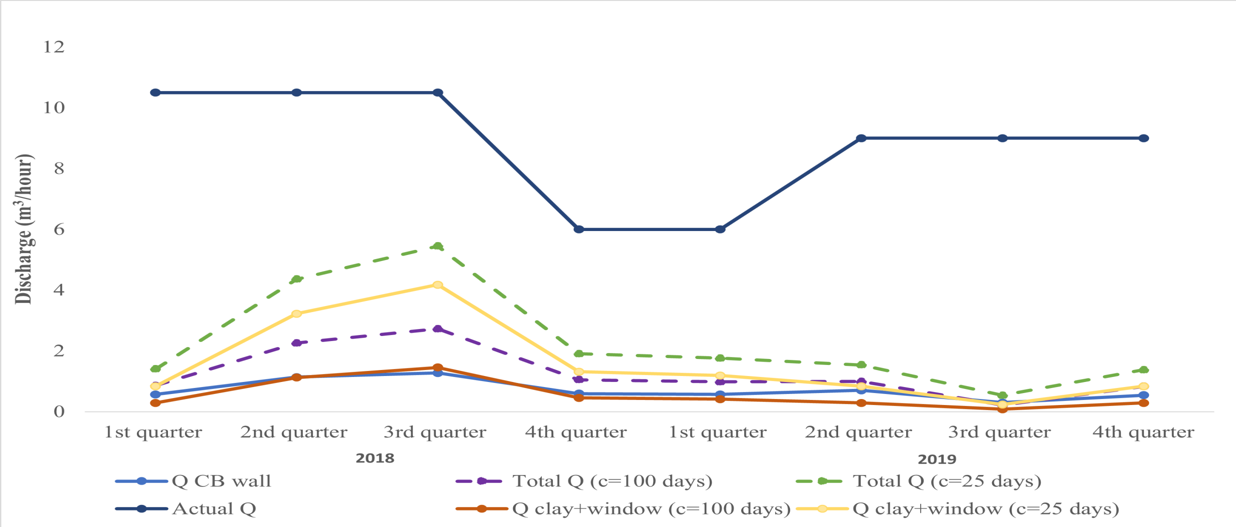


Figure 4.22: Total discharge through CB wall, clay layer and windows for 2018 and 2019

The discharge through the windows in the clay layer is calculated using two values for the hydraulic resistance (c= 25 days and c = 100 days). Remarkably, the difference between the total calculated (purple and green) and actual discharge (blue) is still huge (see Figure 4.22). The discharge through the CB wall (light blue) is almost equal to the total discharge through the (semi-permeable) clay layer and windows, when the windows have a hydraulic resistance of 100 days (orange line). The yellow line illustrates the total discharge through the (semi-permeable) clay layer and windows, when the windows have a hydraulic resistance of 25 days. As noted above, this total discharge (Q_g and Q_k) is almost 60 %. It is possible that the total area of the windows (sand lenses) in the clay layer is higher than expected and the windows have a lower hydraulic resistance. The total discharge through the wall, clay layer, and windows with a hydraulic resistance of 25 days (green) is also lower than the actual discharge. The presence of sand lenses (see Figure 4.17) in the clay layer (Kedichem layer) causes difficulties in the calculation of hydraulic conductivity of the CB wall because of a large volume of water can flow through this "sealing" layer. Groundwater can also enter the construction due to the existence of windows in the wall, causing an increase in the total discharge.
The discharge through the windows in the wall caused by the insufficient connection between the panels is calculated using equation 6. The results are shown in Figure 4.23 (pink and red). The purple and the green lines are the same lines from Figure 4.22. The total calculated discharge (red and pink), which includes the discharge through the windows in the wall is closer to the actual discharge. Thus, the windows in the wall affect the discharge. The hydraulic resistance of the windows (wall) and a' can also differ from the values that are used. The discharge for the second and third quarters of 2018 is higher due to an increase in the hydraulic head difference. The hydraulic head in the first and second aquifer dropped because of the small amount of rainfall (negative precipitation surplus) (see Figure 4.19) and high discharge. It is difficult to tell which amount of water is entering through the various areas. According to Figure 4.19 groundwater extraction of approximately is 9 $m^3/hour$ is sufficient to maintain the hydraulic head difference of approximate 0.3 m across the wall. This value is also lower than the required value calculated in the design phase.

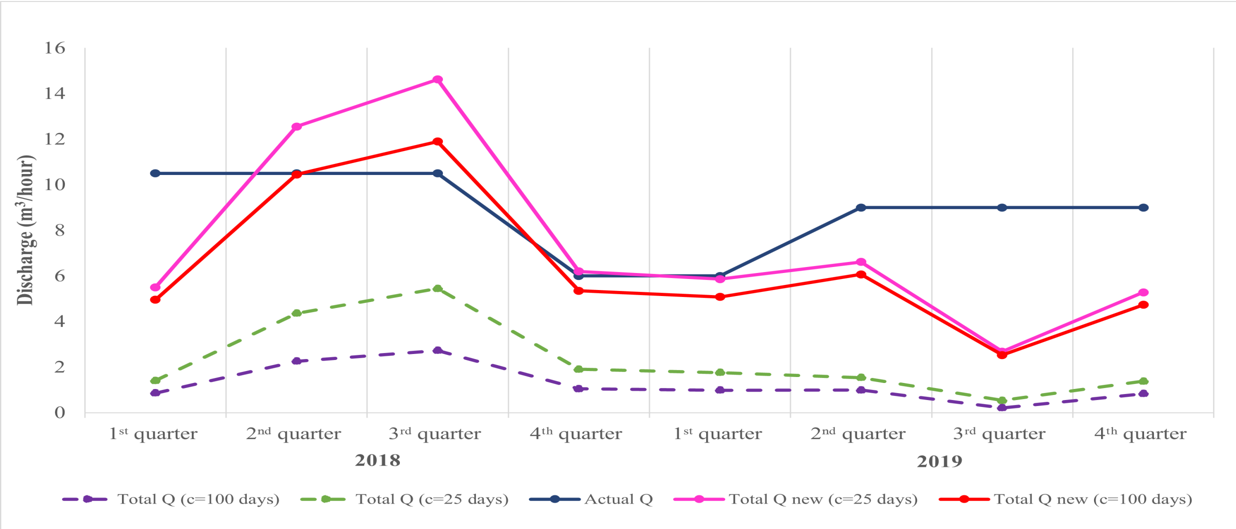


Figure 4.23: Total discharge for 2018 and 2019

4.5 Discussion

This chapter briefly discussed four projects where CB walls have been installed. An evaluation of the hydraulic conductivities of the CB walls for the design stage, construction stage, and post-construction stage will be conducted to identify the potential changes.

- **Westerschelde Tunnel**: the southern access ramp of this tunnel was constructed in an artificial polder created with CB walls and light-sheet piling. The Boom clay layer was used as a horizontal boundary.
  - **design stage**: the hydraulic conductivity of the hardened CB wall for this case was required to be less than or equal to $1 \cdot 10^{-9}$ m/s with a hydraulic gradient (i) of 30. Results of laboratory testing of the CB slurry showed a mean hydraulic conductivity of $4.2 \cdot 10^{-10}$ m/s with a standard deviation of $1.26 \cdot 10^{-9}$ m/s.
  - **post-construction stage**: the hydraulic conductivity was calculated using Darcy's law and the measured discharge, which resulted in a hydraulic conductivity of the CB wall including light-sheet piling of approximately $1.31 \cdot 10^{-9}$ m/s.

  The hydraulic conductivity does not show drastic changes, which means that the overall performance of the wall is good. Note that the calculated hydraulic conductivity is a combination of the hydraulic conductivity of the CB wall and the light sheet piling inside it.

- **A2 Motorway at Best**: the sunken part of this motorway was also constructed in an artificial polder. CB walls and sheet piles were used as a vertical barrier and the Boxtel formation (second clayey unit) as the horizontal barrier.
  - **design stage**: The hydraulic conductivity according to Darcy for a hydraulic gradient (i) of 30, should not be greater than $1 \cdot 10^{-8}$ m/s. Results of laboratory testing of the CB slurry showed mean hydraulic conductivities of $1 \cdot 10^{-10}$ m/s and $0.5 \cdot 10^{-8}$ m/s at temperatures of $10°$ C and $15°$ C, respectively.
  - **post-construction stage**: The calculated hydraulic conductivity of the CB wall for the middle compartment was approximately $5 \cdot 10^{-7}$ m/s. This value seems to be very high compared to the design value.

  High discharges were measured for this project. The presence of the inhomogeneous clay layer leads to an increase in the discharge. It is also possible that the CB walls (including HDPE foil and sheet pile walls) have a higher permeability than assumed. Water level data from piezometers installed in the first and second aquifer, inside and outside the construction, could give a better explanation for the high discharge.

- **Motorway A4 Delft - Schiedam**: for the semi-sunken part of this motorway, CB walls and HDPE foil were used, while for the sunken part of this motorway, CB and sheet pile walls were used. The walls were "keyed" into the Kedichem clay layer.
  - **design stage**: the target value for the hydraulic conductivity based on laboratory test results had to be around $1 \cdot 10^{-9}$ m/s. For the CB walls with HDPE foil, the target value was $1 \cdot 10^{-11}$ m/s.
  - **post-construction stage**: according to a study that had been conducted (Bosman, 2015), the CB walls had a higher hydraulic conductivity ($1 \cdot 10^{-8}$ m/s) than expected.

  The measured discharge was higher than the expected (allowed) discharge. Apparently, the hydraulic conductivity of the CB wall and the Kedichem clay layer was higher than predicted during the design stage. It is also possible that not all defects were detected and repaired.

- **Griftpark Utrecht**: the CB walls have been used to isolate waste and prevent contaminated groundwater flow.
  - **design stage**: the requirement for average hydraulic resistance of the CB wall (whole system) was 1000 days, while the average hydraulic conductivity for every panel after 28 days of hardening had to be less than $5 \cdot 10^{-9}$ m/s (hydraulic gradient (i) of 30).
  - **post-construction stage**: it was difficult to give an indication of the hydraulic conductivity of the CB wall for this case.

  The seepage of groundwater through the clay layer with large windows (sand lenses) was approximately 60%. The maximum required discharge was approximately 320 m^3/day (13 $m^3/hour$). According to the pump data, the discharge in the last three quarters of 2019 was 9 $m^3/hour$, which means that that the CB walls are functioning properly. The minimum hydraulic head difference in the first aquifer across the wall and the hydraulic head difference between the first and second aquifer inside the polder construction was achieved.

5
Richard Hageman Akwadukt

A detailed overview of the Richard Hageman Akwadukt is given in this chapter. This chapter discusses the project, vertical cutoff walls installation, dewatering system, discharge, collected data, and results of the in-situ hydraulic conductivity of the CB walls. The road De Haak om Leeuwarden was constructed to create a connection between A31 at Marsum and the N31 at Hemriksein (Leeuwarden). To cross the Harinxma canal, the Richard Hageman Akwadukt was built in an open polder construction. According to the occurrence of low permeable layers at different depths, shallow and deep polders were constructed on both sides of the canal by using water retaining structures to prevent groundwater inflow (Dijkstra, 2013).

5.1 Project Description

Three different types of polders that were constructed are listed below (see Figure 5.1 & 5.3):

1. Polders on the north of the Van Harinxma canal (Northern polder)

   - Pot clay polder: This polder has a greater excavation depth than the other polders. The polder consists of not only CB walls but also sheet pile walls and Geolock (vertical HDPE barrier) at certain locations. The walls are embedded into the pot clay layer to create a watertight building pit. The pot clay layer is located at a depth of approximately NAP -30 m. The hydraulic resistance (c) is assumed to be 5000 days/m.
   - Loam polder: This is a shallow polder compared to the pot clay polder. Geolock cut off walls are used here as a vertical barriers and the loam layer acts as a horizontal barrier. According to pumping tests, this layer has a hydraulic resistance of 200 days/m. The depth of embedment into the loam layer varies from NAP -14 m until NAP -16 m.

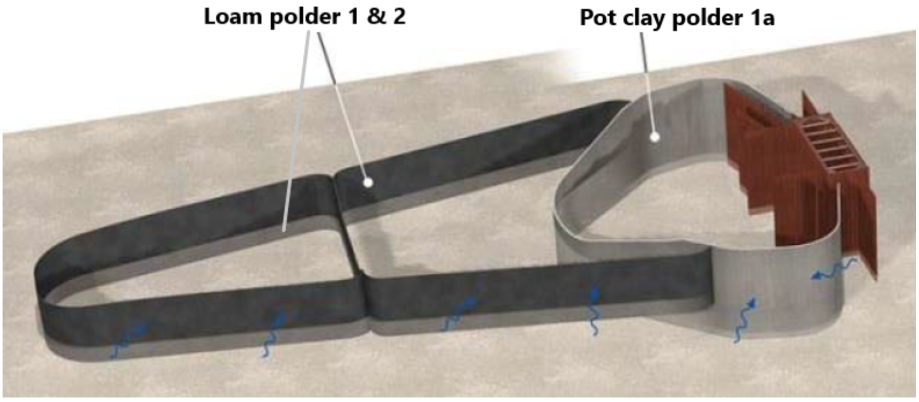


Figure 5.1: Overview pot clay polder 1a and loam polders (1 and 2)

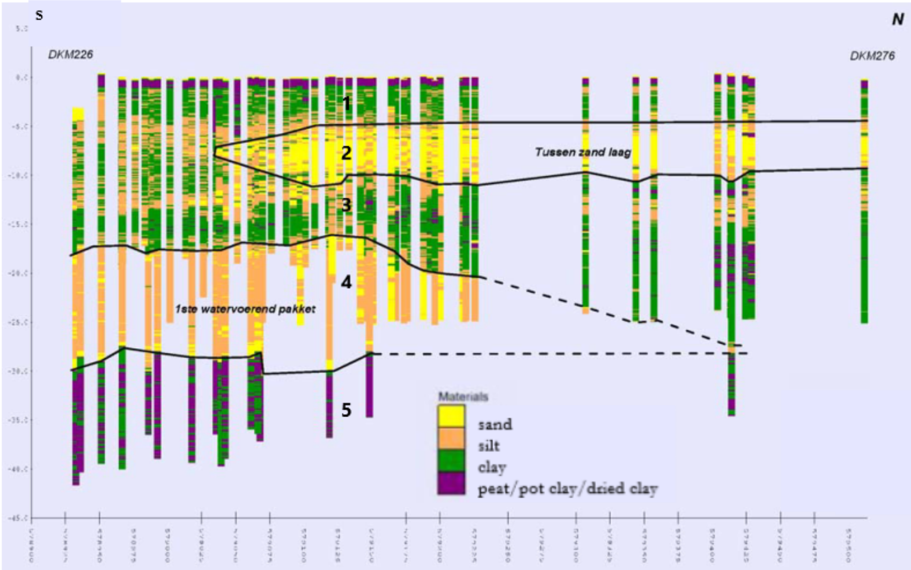


Figure 5.2: Overview of the soil profile on the north of the canal

2. Polders on the south side of the Van Harinxma canal (Southern polder)

- Pot clay polder: This polder is identical to the pot clay polder on the north side.
- Clay polder: This is a shallow polder, where geolock cut off walls are used as vertical barriers and the clay layer acts as a horizontal barrier. The hydraulic resistance was determined by performing in-situ and laboratory permeability tests. The test results indicate a hydraulic resistance of 116 days/m clay. The depth of embedment into the clay layer is approximately NAP -4 m.

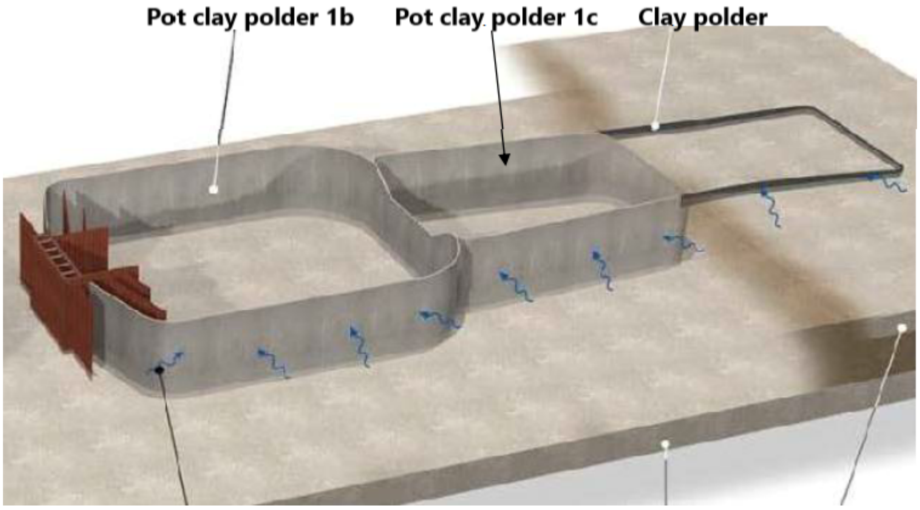


Figure 5.3: Overview pot clay polders 1b and 1c and clay polder

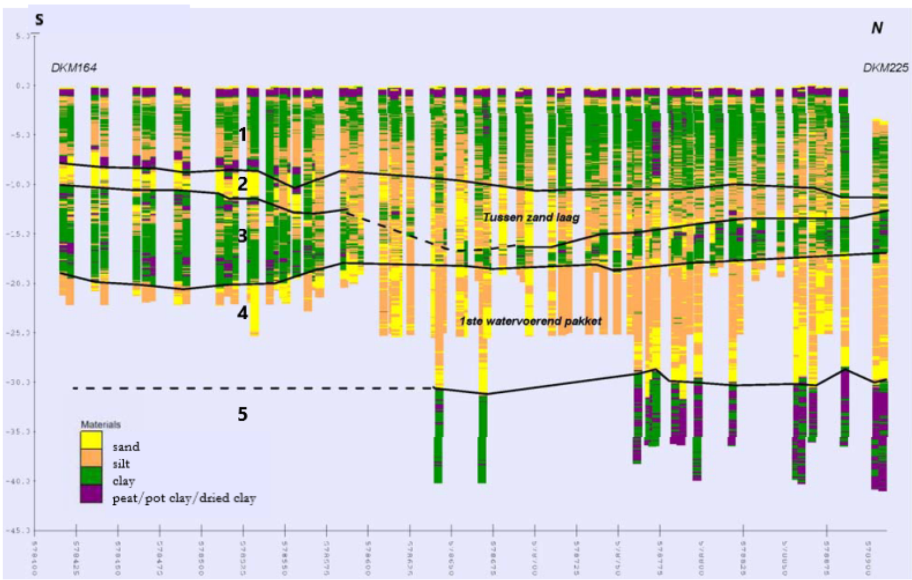


Figure 5.4: Overview of the soil profile on the south side of the canal

5.2 Vertical Cutoff Walls Installation

In this section, an overview of the different types of vertical cutoff walls that were used for this project will be presented. As this study aims to investigate the hydraulic conductivity of the CB walls, the main focus will be on the pot clay polders, where CB walls have been used. At some parts of this construction, sheet pile walls and Geolock were installed within the CB wall.

5.2.1 CB wall installation & specifications

The single-phase technique and the alternating excavation method were used to construct the CB wall. Before the excavation, guide walls were placed. According to this technique, a set of primary panels of 600 mm by 3400 mm were excavated first using clamshell equipment in presence of the CB slurry leaving out the secondary panels. After the setup of the slurry, the secondary panels of 600 mm by 2800 mm were excavated between the primary panels and filled with the slurry ensuring a tight overlap of 300 mm (see Figure 5.5) (Wicherson, 2013).

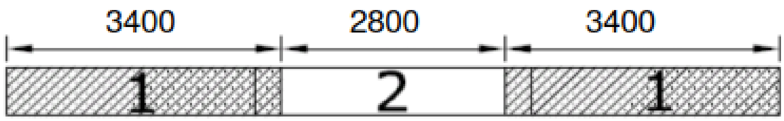


Figure 5.5: Alternate panel excavation technique

At the corners of the construction, the panels were excavated differently to ensure a watertight connection. In Figure 5.6 the different phases of installation are illustrated. In the initial phase (Phase 1), panel A was excavated under CB slurry. After the slurry in panel A was sufficiently hardened, the guide walls were replaced (Phase 2). Finally, Panel B was excavated in the same way as panel A (Phase 3).

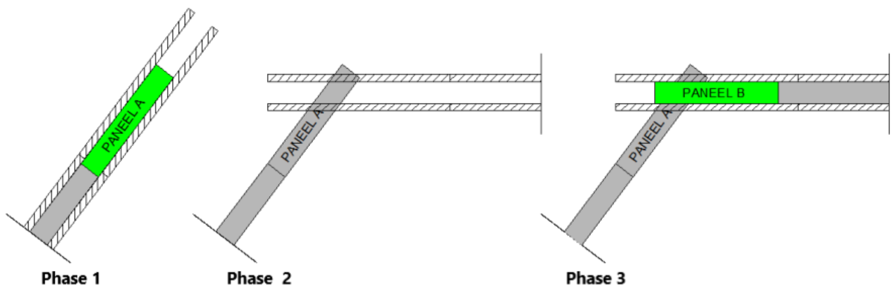


Figure 5.6: Overview of the corner connection

For the CB slurry mixture +/- 210 kg DiWa-mix 210 per m^3 cement/bentonite was used. The engineering properties of hardened CB slurry for this project is given in Table 5.1.

Table 5.1: Properties of the hardened CB slurry

Properties	**Requirements after 28 or 56 days of hardening at 20°**
Compressive strength	$\geqslant$ 800 kPa
E-modulus	$\geqslant$ 100 MPa
Volumetric weight	1170 kg/m^3
Hydraulic conductivity	Average per 8 test samples $\leqslant 10^{-9}$ m/s, 5% of 3 days production is allowed to be $\geqslant 5.10^{-9}$ m/s

Laboratory test were also performed after constructing the panels. Samples were taken at three locations within the wall (top, middle and bottom). The average hydraulic conductivity value for each of the tested panels are given in the Figure 5.7.

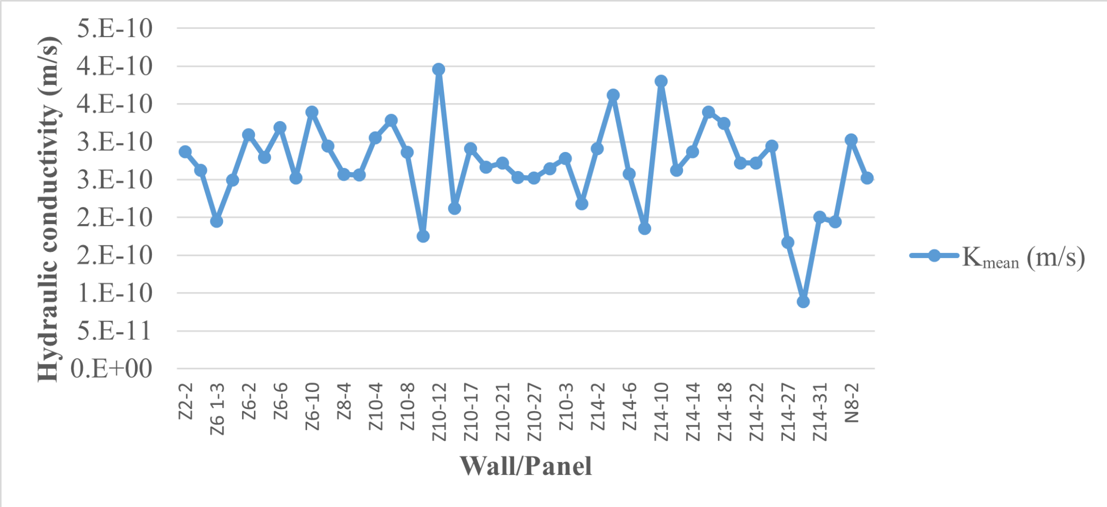


Figure 5.7: Average hydraulic conductivity values of various panels

5.2.2 Sheet pile wall and Geolock installation

The sheet pile wall and Geolock screen installation within the CB walls will be briefly discussed in this section (see Figure 5.8). The CB wall connects on four sides to the sheet pile walls of the aqueduct foundation. The CB trench was excavated directly against the sheet pile walls. After that, a few sheet pile walls were installed in a staggered manner into the CB trench while the CB slurry was still plastic. The Geolock screen was installed in the CB slurry trench by pushing or vibrating it down to the required depth. More detailed information of the installation and connection between the CB wall, sheet pile wall and Geolock screen can be found in Appendix C.2 & C.3.

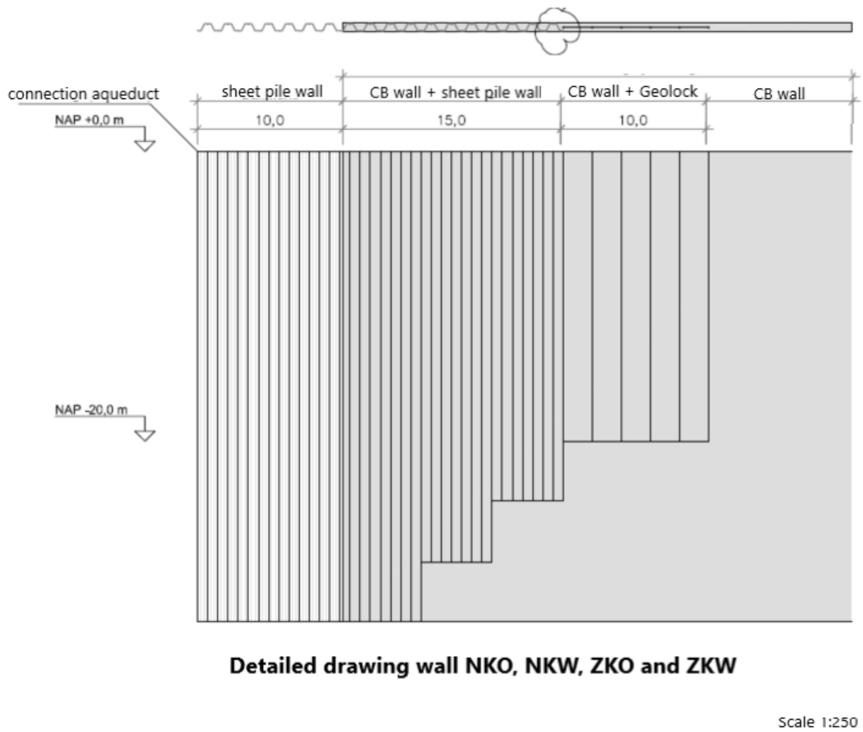


Figure 5.8: Overview of the installation of sheet pile wall and Geolock screen

5.3 Dewatering System

It is essential to understand the dewatering process of Richard Hageman Akwadukt to collect the data necessary to determine the in-situ hydraulic conductivity of the CB walls, for example, the discharge rate.

The purpose of the dewatering system is to remove water that seeps into the polder by:

- Rainwater infiltration
- Groundwater inflow through the aquitard
- Leakage of (ground)water through the vertical barriers (CB Walls, Geolock, Sheet-piles)
- Rainwater runoff through the tunnel

There is a separate dewatering system for the Northern and Southern polder. Further, each of the polders has three different types of drainage systems:

1. ”Deep drainage system”: This is used for the drainage of saline groundwater that can enter the polders through the aquitard and leakages of CB walls. This system ensures sufficient drainage of the water to keep it below the road surface. Two deep wells are installed in pot clay polder (1a) and (1b), each on the east and the west side. Water from the deep wells is pumped into the injection wells outside the polders (see Figure 5.9).

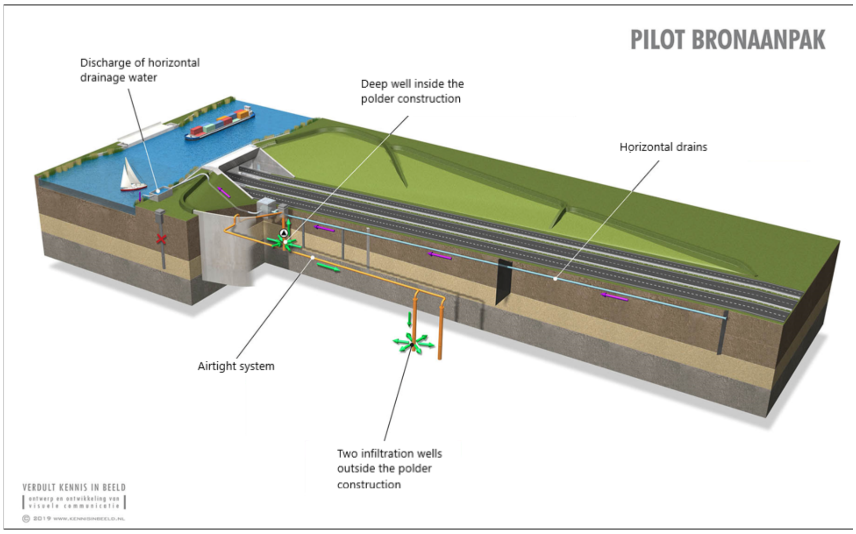
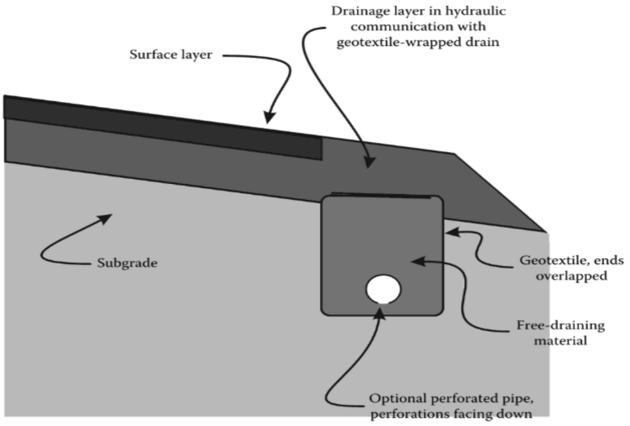
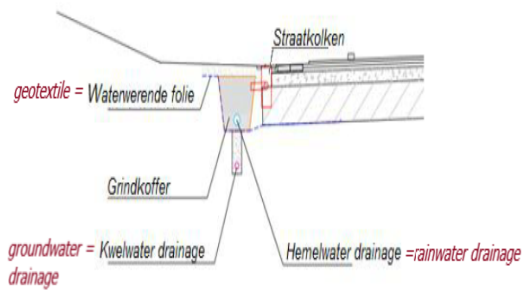


Figure 5.9: Overview of the water drainage system on the North side of the Van Harinxma canal

2. "Shallow drainage system": Trench ("French") drains are installed on both sides of the road to drain rainwater from the road surface and shallow groundwater that flows through the wall (leakage). The drains are usually filled with a highly permeable material such as gravel/sand, wrapped in a geotextile with a perforated tube at the bottom for drainage. The rainwater and groundwater drainage systems are separated from each other by the geotextile (see Figure 5.10).



(a) Trench drain



(b) Trench drain at Richard Hageman Akwadukt (Horizontal drainage)

Figure 5.10: Geotextile-wrapped French road edge drain

3. A drainage system for the discharge of rainwater from the aqueduct and between the wing walls.

A detailed overview of the drainage system of the Richard Hageman Akwadukt can be found in Appendix C.1.

Monitoring system

The Geomonitoring system of Mos Grondmechanica registers the following data relevant for this research:

- The discharge of the deep wells at north-east, north-west, south-east and south-west of the pot clay polders (1a) and (1b).
- The injection rate of the injection wells outside the polders at north-east, north-west, south-east and south-west.
- Water levels in the deep wells and injection wells.
- The discharge from the former [1] drainage system (back-up system) (this consists of groundwater discharge from horizontal drains and discharge of remaining groundwater that was not successfully removed by the deep wells. This is also called the remaining discharge).

[1] The former drainage system consisted of relief wells instead of deep wells

5.4 Discharge

When a road is being constructed, significant excavation is often necessary to make the soil suitable for bearing structural loads. In this case, excavation took place within the various polders. The excavation levels for the polders vary from NAP -2.9 m to maximum NAP -11.9 m and are located below the groundwater table. Therefore, dewatering of the polders is necessary in order to work in dry and stable conditions. Post-construction dewatering is significant too, because of the possible leakage through walls and the aquitard.

5.4.1 Allowed discharge

The groundwater levels for soil layer 2 and 4 (see Figure 5.2 & 5.4) for the different polders are presented in Table 5.2.

Table 5.2: Required groundwater levels in the polders

	Polder	**Groundwater level (NAP m)**
North	Loam polder 1	-4.6
	Loam polder 2	-7.5
	pot clay polder (1a)	-11.9
South	pot clay polder (1b)	-11.9
	pot clay polder (1c)	-5.8
	Clay polder	N/A

The polders are allowed to have a global discharge of 1.2 $l/m^2/day$ and a local discharge of 4.8 $l/m^2/day$ over a distance of 10 m. In the design phase of the project, the discharge through the vertical cut off walls and the low permeable layer (aquitard) for each polder was calculated using Darcy's law. The hydraulic conductivity of each water retaining wall used for the calculation is presented in Table 5.3. For the first calculation (1) the groundwater level outside the polder is assumed to be NAP +0.57 m including 50% of sea level rise after 100 years (0.25 m). For the second calculation (2) the groundwater level outside the polder is assumed to be NAP +0.82 m including 100% of sea level rise after 100 years (0.5 m) (see Table 5.4).

Table 5.3: Overview of hydraulic conductivities of water retaining walls

Type of wall	**Hydraulic conductivity k_h (m/s)**	**Reference**
CB wall	10^{-9} m/s	COB, "Bouwen vanaf het maaiveld"
Sheet pile wall	10^{-7*} m/s	"Lekdetectie in waterremmende constructies definitief", GeoDELFT, d.d. mei 2000
Sheet pile wall with interlock sealant	10^{-9*} m/s	"Lekdetectie in waterremmende constructies definitief", GeoDELFT, d.d. mei 2000
CB wall + sheet pile wall	10^{-10} m/s	Arbitrary chosen
Geolock	10^{-13} m/s	Supplier Cofra
* Inverse joint resistance. It is assumed that the c.t.c. distance of the joints is 0.7 m.		

Table 5.4: Total discharge for each polder

	Polder	(1) Discharge (m^3/day)	(2) Discharge (m^3/day)	Allowed discharge $(m^3/day$
North	Loam polders	30.96	32.39	21.09
	pot clay polder (1a)	15.83	16.14	22.16
South	pot clay polders (1b & 1c)	25.87	26.55	50.30
	Clay polder	13.57	14.52	7.41
Total		**86.23**	**89.60**	**100.95**
Maximum local discharge clay polder $10m^1$ $(L/m^2/day)$				3.09
Maximum local discharge loam polder $10m^1$ $(L/m^2/day)$				3.88

5.4.2 Post-construction discharge

After completion of the polder constructions, pumping of groundwater started to keep the water below the road surface level. However, it was noticed that the discharge highly exceeded the allowed discharge limits due to leakages in the polder constructions. After extensive monitoring and research by the contractors, defects were detected. The panels of the CB wall were insufficiently connected at some locations. They decided to construct jet grout columns at these locations (see Appendix C.4 for the exact locations) where the leakages occurred (Klein, 2014). Jet grouting is a ground improvement technique, which creates in-situ columns of grouted soil using very high pressure grout injection.
The remedial works were performed in three phases.

- Phase 1 (mid-July 2014): Jet grout columns were constructed at the pot clay polder (1a) (see Figure 5.11).

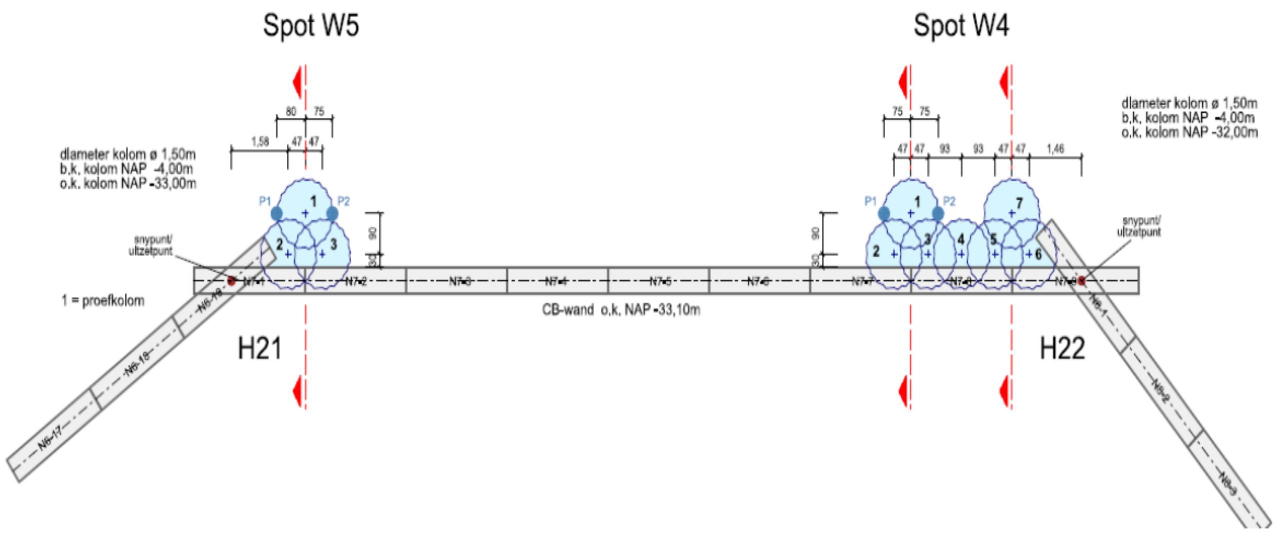


Figure 5.11: Jet grout colums at pot clay polder (1a)

The discharge was measured during phase 1. According to Figure 5.12 more than 50% reduction of the discharged had been achieved.

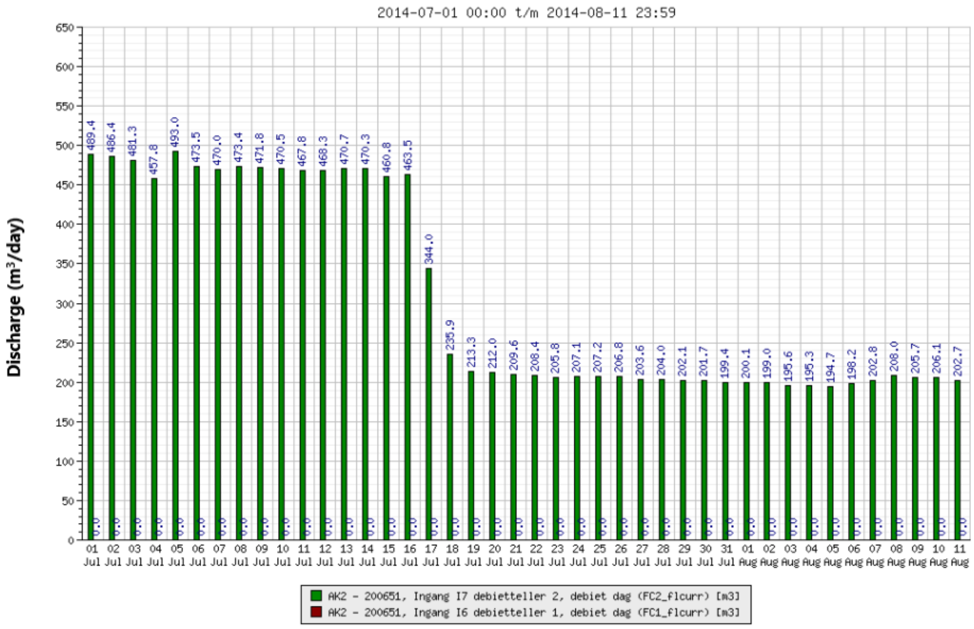


Figure 5.12: The discharge in m^3/day during phase 1

- Phase 2 (mid-September 2014): Jet grout columns were constructed at the pot clay polder (1a) and (1b). The discharge decreased even further for polder construction North (see Figure 5.13).

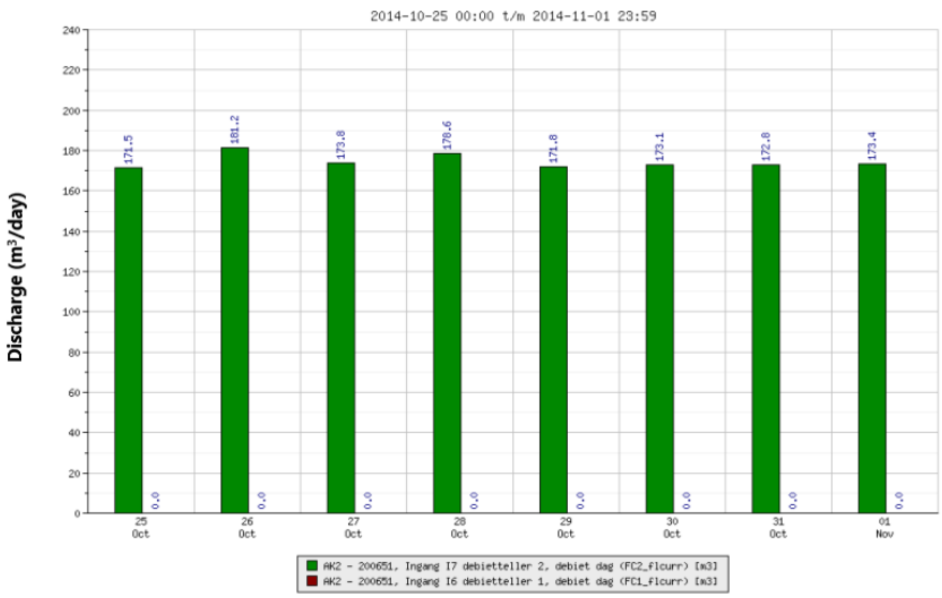


Figure 5.13: The discharge in m^3/day after phase 2 for polder construction North

- Phase 3 (early-November 2014): More jet grout columns were constructed at the pot clay polder (1b). The discharge also decreased enormously for polder construction South.

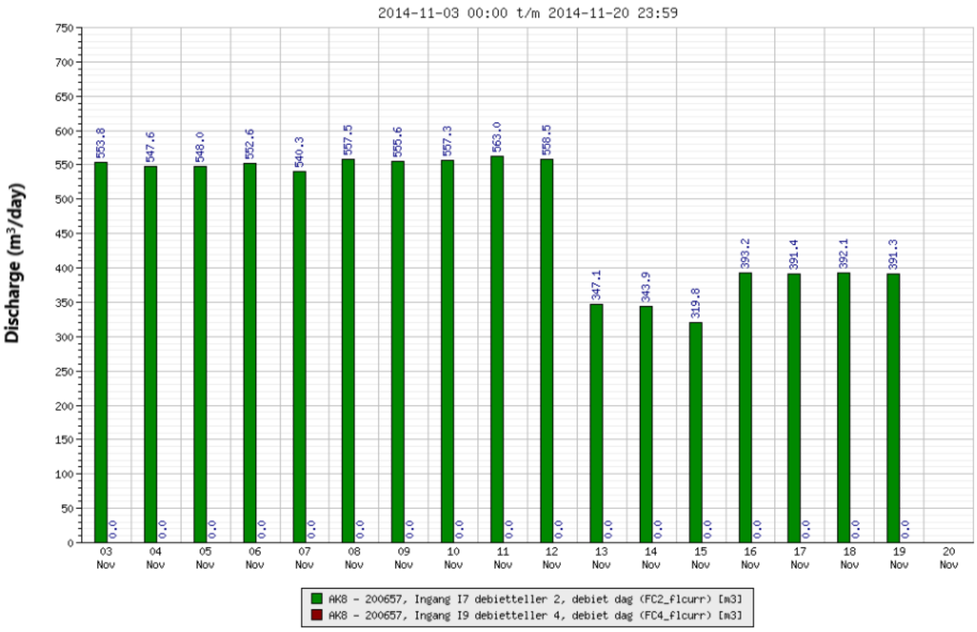


Figure 5.14: The discharge in m^3/day after phase 2 and during phase 3 for polder construction South

After completion of the remedial works, the new requirements for the discharge were determined to be in the order of 25 to 250 m^3/day for polder construction North and 30 to 300 m^3/day for polder construction South. The discharge decreased significantly, but, it was still on the higher side for polder construction South.

5.5 Data

Quality data is essential for this research to obtain an estimate of in-situ hydraulic conductivity of CB walls, the following data is required from all the projects that need be investigated:

- Discharge rate from the dewatering system;
- Water levels on either side of the CB Wall
- Thickness of the wall;
- Surface area of the wall (perpendicular to the direction of flow)
- Surface area of aquitards
- Hydraulic conductivity/hydraulic resistance of the aquitard

This section provides insights noticed while visualizing and analyzing the data. The data for 2019 shall be used for this research. For the southern polder, the discharge measurements after May 2019 remains unreliable due to contamination of the flow meter.

Discharge of the deep wells and the former drainage system

The discharge from the deep wells and the former drainage system gives an indication of the total discharge from the polders. The discharges are measured daily and the unit is m^3/day. Figures 5.15 and 5.16 show the discharge data of the polders and the rainfall that is measured at the KNMI weather station, Leeuwarden.

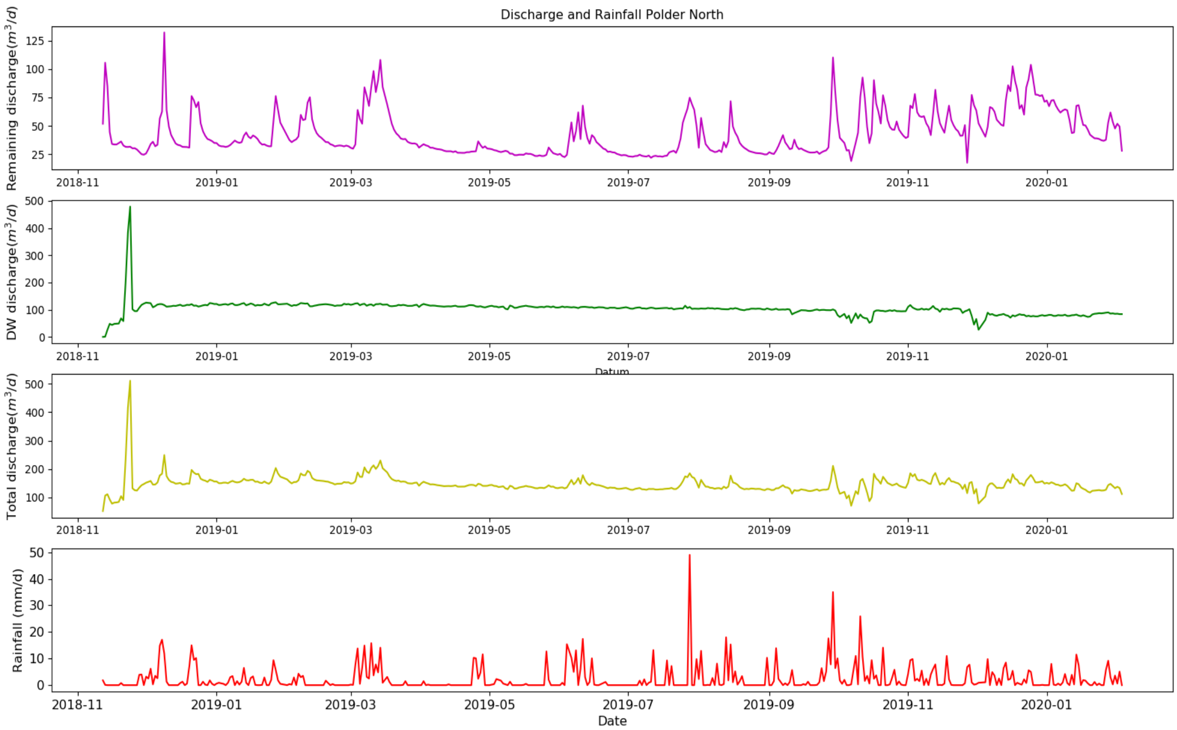


Figure 5.15: Overview of the discharge for Northern polder and the rainfall

Figure 5.16: Overview of the discharge for Southern polder and the rainfall

Notably, the amount of rainfall influences the remaining discharge. Hence, the increase in precipitation leads to increase in discharge. But as discussed in the previous section the discharge of rainwater is separated from the groundwater and there should be no fluctuation in the remaining discharge. On the contrary, there are fluctuations noticed in the data, which can be due to the following reasons:

- Rainwater infiltration into the soil, where the water ends up in the groundwater drainage system.
- Leakage from the rainwater drainage system into the groundwater drainage system (see Figure 5.10).

The monitoring for the polders started at different periods of 2018, therefore the data for 2019 will be considered for this study. The deep well (DW) discharges (green) in the Figures 5.15 and 5.16, are almost constant and they contain the cumulative discharge of both deep wells within the polder. By analyzing data of dry periods, the influence of rainfall can be eliminated. Remarkably, the "remaining discharge" graph for the Southern polder reaches zero after some time, which indicates the presence of errors in the monitoring system. Therefore, only a short period can be analyzed.

Deep wells and injection wells water level monitoring

For the calculation of the hydraulic conductivity, water levels on both sides of the CB walls are required. But unfortunately, there is no piezometer data available. This makes it challenging to retrieve data of the actual water levels on both sides of the walls. Water level data of the deep and injection wells are available. This data will be used instead of the piezometer data, even though this data is only a representation of the actual water levels (see Figure 5.17). The water levels are measured at an interval of 10 minutes and have the unit NAP m. On the contrary, the discharge is measured daily. Therefore, the average daily values for the water levels are calculated. Due to the presence of two injection wells, also the average of the daily values have been calculated. The purple and green lines represent the water level in the deep wells, while the yellow and red lines represent the water levels in the injection wells (see Figure 5.18 and 5.19).

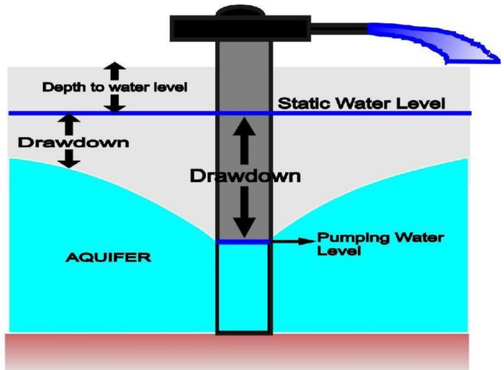


Figure 5.17: Difference in water level in the deep well and groundwater level

Figure 5.18: Overview of water levels in the deep wells and injection wells (Northern polder)

In Figure 5.18 and 5.19, peaks, and troughs are visible. The deep well pumps ensure a constant water level. When the water supply increases, the discharge increases, but the water level stays constant. Remarkably, the peaks of the Southern polder are higher. The water level graphs of the injection wells show a different pattern. The water level, in this case, is influenced by the water supply from the discharge wells. The outliers (peaks)in the deep well water level graphs can affect the calculations and will therefore be ignored.

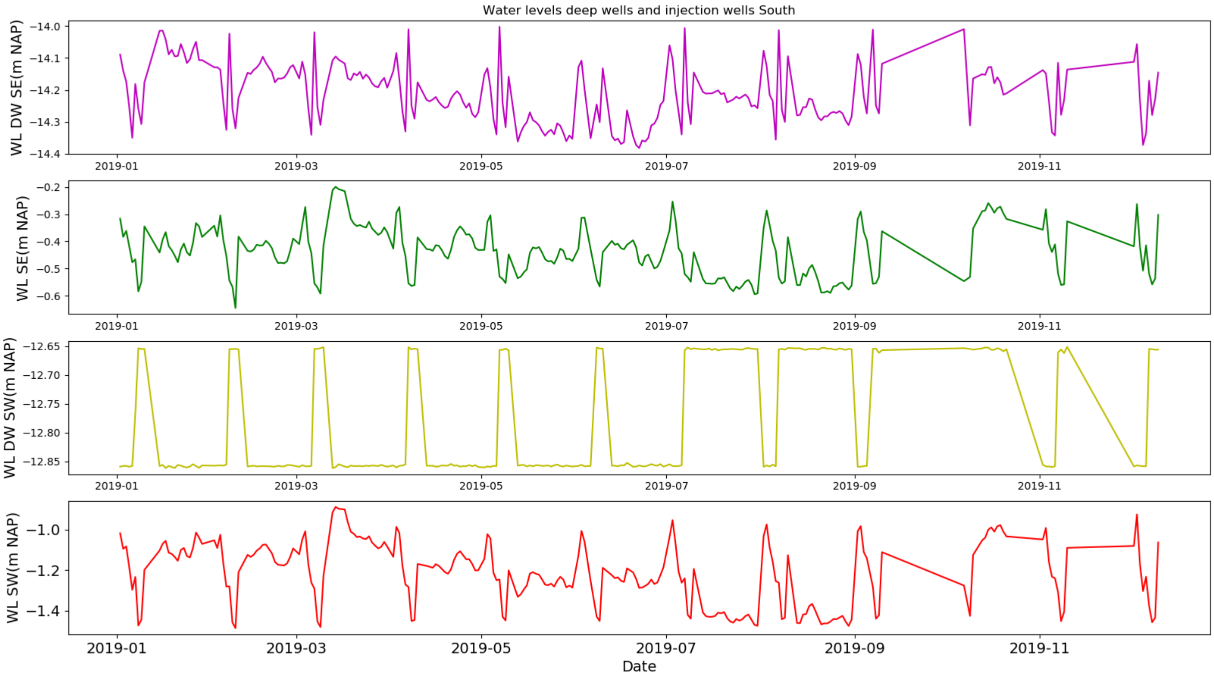


Figure 5.19: Overview of water levels in the deep wells and injection wells (polder construction South)

Thickness and surface area of the vertical barriers

The vertical barriers of the polders (North and South) consist of the following walls/screens:

- CB walls
- Sheet pile walls
- Geolock screens

Sheet pile walls and Geolock screens are inserted inside the CB walls at various places within the construction to ensure a lower hydraulic conductivity. A thickness of 600 mm was chosen for the CB walls. With the thickness and the difference in water level across the wall the hydraulic gradient (Darcy's slope) across the CB wall can be calculated. The surface area for each wall type has been calculated separately. In the table below, the total surface area is presented for each of the polders.

Table 5.5: Total surface area (A)

	Polder	***A* CB wall** (m^2)	***A* sheet-pile wall** (m^2)/ ***A* sheet-pile +CB wall** (m^2)	***A* Geolock** (m^2)/ ***A* Geolock+CB wall** (m^2)
North	loam polders	-	-	7401.3995
	pot clay polder (1a)	7566.0705	526.21 / 297.5	- / 400
South	pot clay polder (1b)	9728.351	521.895/ 295	-/ 400
	pot clay polder (1c)	7977.96	-	-/ 330
	clay polder	-	-	965.868/ -

Thickness, surface area and hydraulic resistance of the aquitards

Different aquitards (loam, clay, pot clay) have been used in this case to prevent groundwater inflow into the polders. However, there is always some seepage of groundwater through the aquitards because they are not impermeable. Therefore, it is mandatory to calculate the discharge through the aquitard. For this calculation it is important to have information about the thickness, surface area and hydraulic resistance of the aquitards. This information can be found in the table below:

Table 5.6: Overview of the thickness, surface area and hydraulic resistance of the aquitards

Aquitard	**Hydraulic resistance** $(days)$	**Surface area** (m^2)	**Thickness** (m)
pot clay (1a)	50000	7980.5	10
pot clay (1b)	50000	15652.5	10
pot clay (1c)	50000	7019.9	10
loam 1 & 2	1600	11922	7
clay	812	4718	7

5.6 Results

In this section the results for the hydraulic conductivity of the CB wall for the northern and southern pot clay polder will be presented. The hydraulic conductivity is calculated analytically according to Darcy's law. The data that is used for this calculation is described in chapter 6. The calculation will be explained step-by-step.

5.6.1 Hydraulic conductivity of the CB wall (northern pot clay polder)

By summing up the discharge through the deep wells and the former drainage system (remaining discharge), an indication can be obtained of the total discharge (Total Q north) through the polders (loam and pot clay). At first, the discharge through the following parts of the northern polder was calculated, because they are a part of the total discharge:

- The discharge through the Geolock walls, the loam layer and the partition wall (N2) of the loam polder;
- The discharge through the sheet pile walls and Geolock wall of the pot clay polder;
- The discharge through the pot clay layer.

The remaining discharge (Rest Q) should be greater or equal to the discharge from the loam polder. The discharge calculations were performed for different values for the hydraulic conductivity of the loam layer ($5.8 \cdot 10^{-8}$ m/s and $3.8 \cdot 10^{-8}$ m/s), to meet this requirement. To get the discharge through the CB wall (Q CB wall north), the three calculated discharges above should be subtracted from Total Q north. Dividing Q CB wall north by the total area of the CB wall and the hydraulic gradient results in the hydraulic conductivity of the CB wall. The rainfall in Leeuwarden is displayed in Figure 5.20. In April and May, the precipitation was low compared to the other months. These months will give a better indication of the calculated hydraulic conductivity because the influence of the rainfall on the discharge is minimal. In Figure 5.21, the remaining discharge (red) is also very low for April and May. Thus, the rainfall has an impact on the remaining discharge. Furthermore, in this figure, the blue line is the measured discharge from the deep wells and the orange line the calculated discharge through the loam polders with a hydraulic conductivity of $5.8 \cdot 10^{-8}$ m/s for the loam layer. The discharge through the loam polder for this case is higher than the remaining discharge, which is not possible. The hydraulic conductivity is fluctuating due to the influence of rainfall (see Figure 5.22). The calculated hydraulic conductivity of the CB wall is approximate $2.5 \cdot 10^{-9}$ m/s. The hydraulic conductivity is fluctuating due to the influence of rainfall.

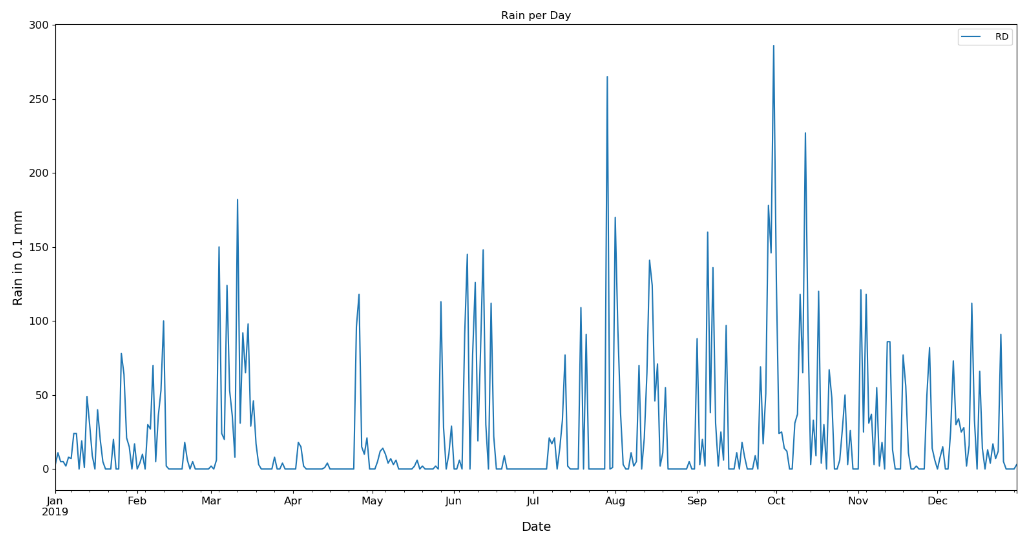


Figure 5.20: Rainfall in Leeuwarden for 2019 (KNMI)

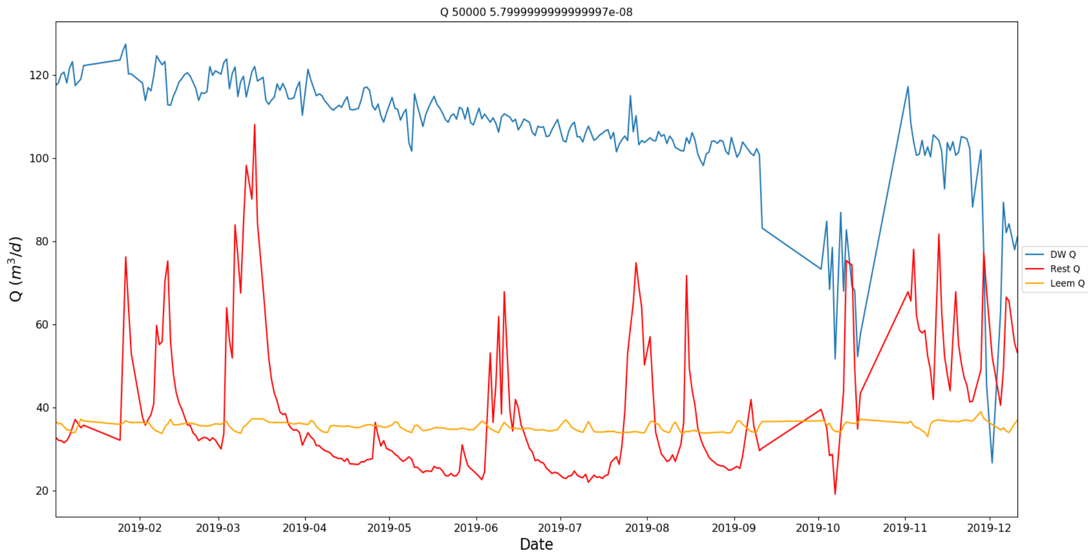


Figure 5.21: Overview of the deep well, remaining and loam polder discharge for $5.8 \cdot 10^{-8}$ m/s

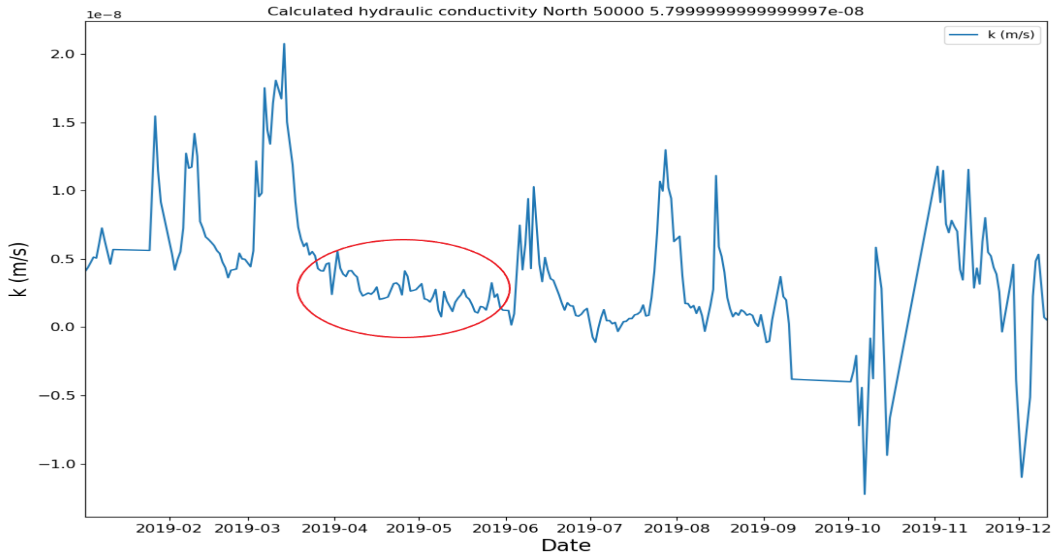


Figure 5.22: Hydraulic conductivity of the CB wall

The discharge through the loam polder (orange) calculated using a hydraulic conductivity of $3.8 \cdot 10^{-8}$ m/s for the loam layer is more reliable (see Figure 5.23). However, the computed hydraulic conductivity for the CB wall using this data is approximate $5 \cdot 10^{-9}$ m/s (see Figure 5.24), which is a small difference. It means that after the remedial works, the performance of the CB wall is improved.

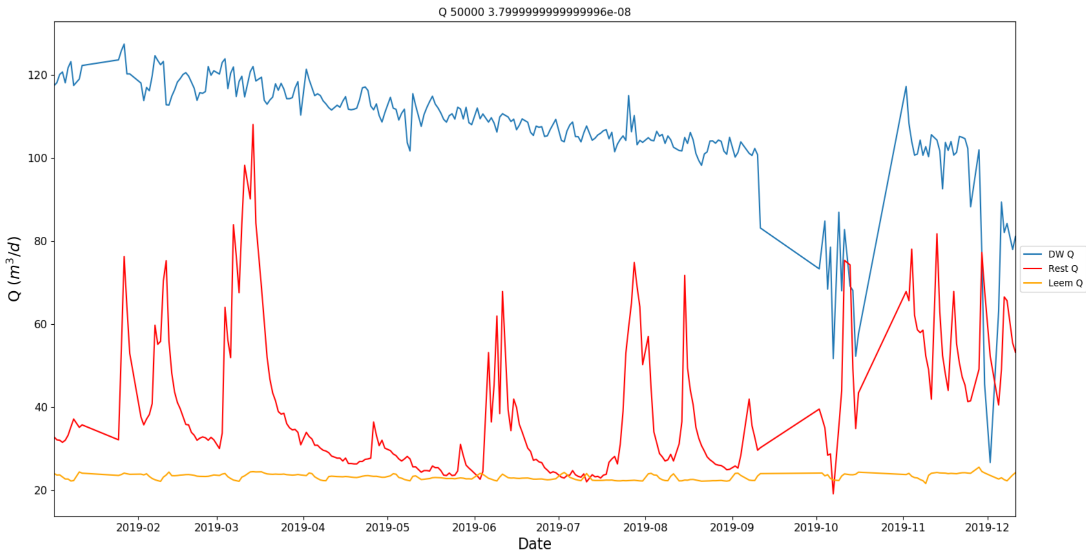


Figure 5.23: Overview of the deep well, remaining and loam polder discharge for $3.8 \cdot 10^{-8}$ m/s

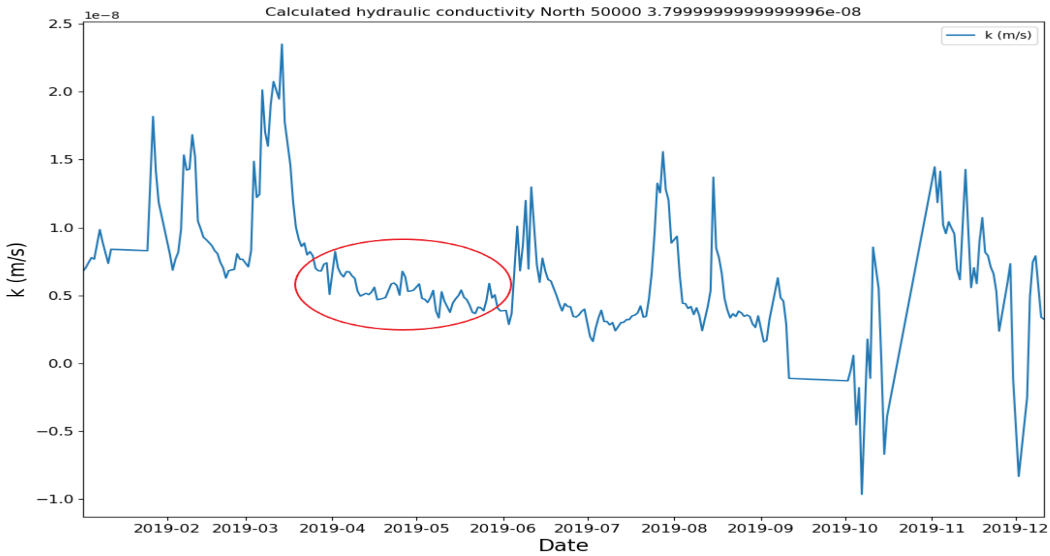


Figure 5.24: Hydraulic conductivity of the CB wall

5.6.2 Hydraulic conductivity of the CB wall (southern pot clay polder)

For the southern pot clay polder, the calculation for the hydraulic conductivity of the CB walls is almost the same as for the northern pot clay polder. The difference for this case is that there is a clay polder instead of a loam polder. The following calculations have to be conducted first:

- The discharge through the Geolock walls and the clay layer of the clay polder;
- The discharge through the partition wall (Z2);
- The discharge through the sheet pile walls and Geolock wall of the pot clay polder 1c;
- The discharge through the sheet pile walls and Geolock wall of the pot clay polder 1b;
- The discharge through the both pot clay layers.

The discharge through the pot clay layers is computed using three different values for the hydraulic resistance of the pot clay layer to observe the impact on the hydraulic conductivity of the CB wall. The various discharges, mentioned above are subtracted, from Total Q south, which gives the discharge through the CB wall (Q CB wall south). Dividing Q CB wall south by the total area of the CB wall and the hydraulic gradient results in the hydraulic conductivity of the CB wall. The results are presented in the Figures 5.25, 5.26 and 5.27. The hydraulic conductivity of the CB wall for all three cases is approximate $2 \cdot 10^{-8}$ m/s, which is higher compared to the hydraulic conductivity of the CB wall for the northern polder. The reason for this is the relatively large total discharge for the southern polder (Total Q south) compared to the northern polder (see Figure 5.19). This indicates the presence of defects within the CB wall construction.

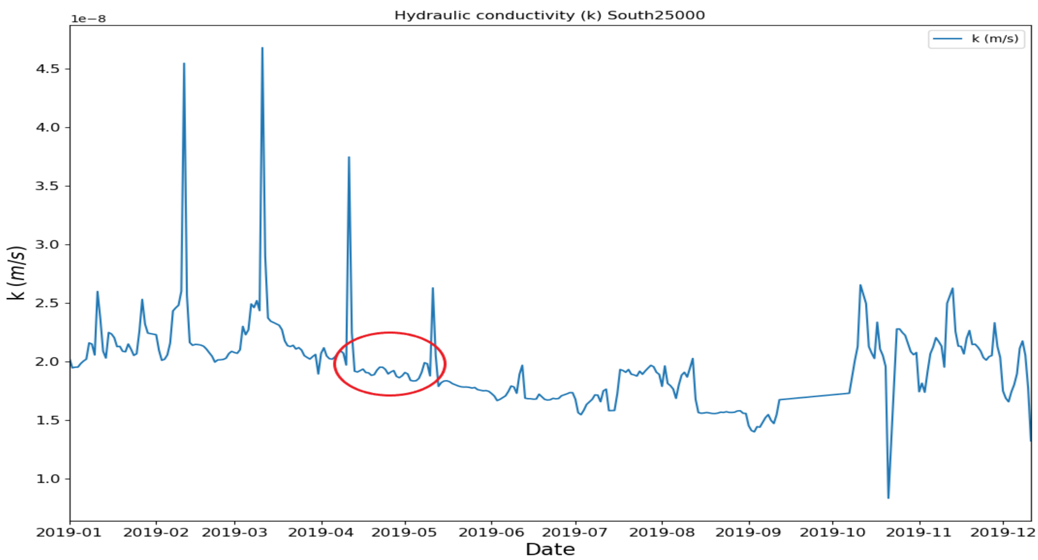


Figure 5.25: Hydraulic conductivity of the CB wall (hydraulic resistance pot clay is 25000 days)

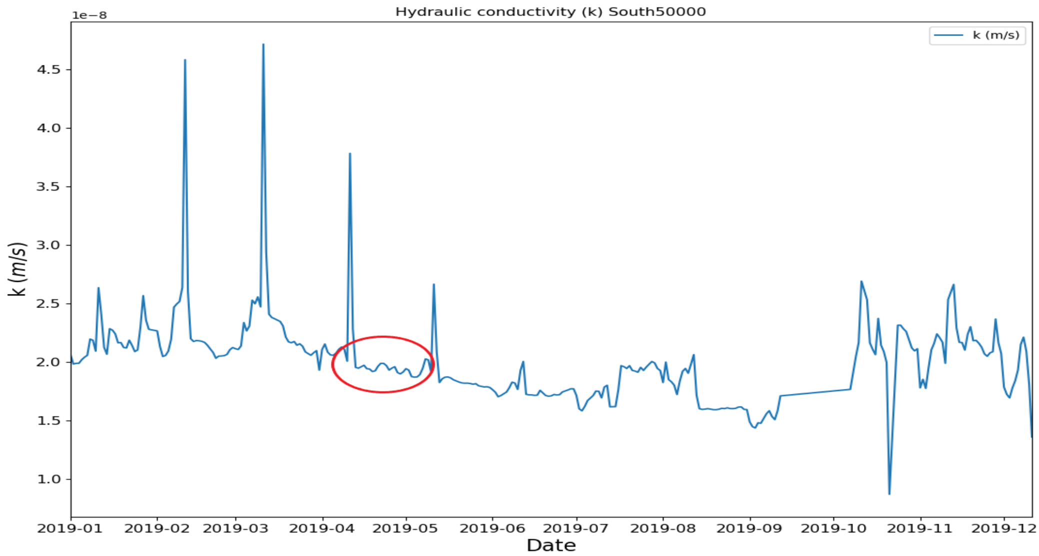


Figure 5.26: Hydraulic conductivity of the CB wall (hydraulic resistance pot clay is 50000 days)

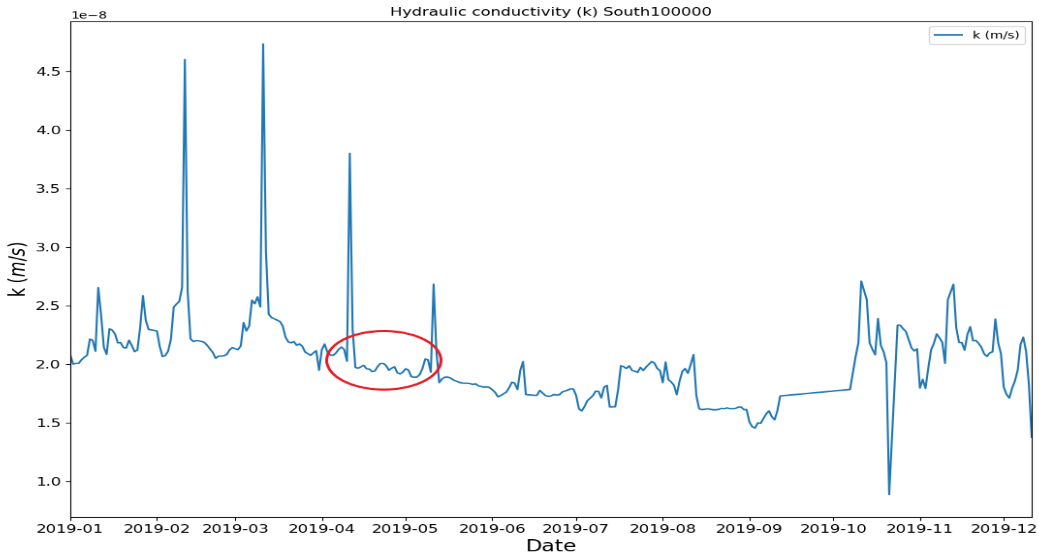


Figure 5.27: Hydraulic conductivity of the CB wall (hydraulic resistance pot clay is 100000 days)

5.7 Discussion

Artificial polders were constructed on both sides (north and south) of the Harinxma canal to build the Richard Hageman Akwadukt. Each polder consisted of shallow and deep polders. For the vertical barrier of the deep polders, Geolock, CB walls and sheet pile wall were used. The pot clay layer was used as a horizontal barrier.

- **design stage**: The average hydraulic conductivity of the CB slurry (8 test samples) after 28 or 56 days of hardening at 20° C had to be $\leqslant 10^{-9}$ m/s.
- **laboratory testing**: According to laboratory test results, the hydraulic conductivity of the CB walls was around $2.7 \cdot 10^{-10}$ m/s.
- **post-construction stage**: The calculated hydraulic conductivity for the northern polder was approximately $2.5 \cdot 10^{-9}$ m/s and for the southern polder $2 \cdot 10^{-8}$.

There is a difference between the calculated hydraulic conductivity of the CB wall in the northern pot clay polder and the CB wall in the southern pot clay polder. The discharge for the southern polder was higher compared to the northern polder. Shortly after the completion of the polder constructions, it was noticed that the measured discharge exceeded the allowed discharge. The defects (the insufficient connection between the panels of the CB wall) at both polders were detected and fixed. However, the discharge for the southern polder remained high. Not all the defects were detected and fixed. The high discharge may be caused by the locally varying thickness and hydraulic conductivity of the wall and small imperfections. The presence of the pot clay layer (very low permeability) indicates that the groundwater is mainly entering the construction through the CB walls.

6
MODFLOW Model

In this chapter the impact on the performance of CB walls due to the presence of defects will be investigated. Defects in CB walls are most likely to occur during construction or due to postconstruction property changes. Some of these defects, such as high hydraulic conductivity windows, can control the flow rate past the CB walls, which influences the performance of these walls. The defects can cause environmental risks and may also have an impact on the groundwater "pump and treat" operations where they are applied. The three-dimensional numerical groundwater flow model MODFLOW will be used to determine the performance of CB walls by simulating various types of defects and monitoring the flow rate (McDonald and Harbaugh, 1988). The flow rate past CB walls can be determined for different hydraulic conductivities. The results of the numerical and the analytical analysis can be compared with each other. This model uses the finite-difference method to divide the groundwater flow model domain into a series of rows, columns, and layers, which defines a unique set of grid blocks (i.e. model cells) to represent the distribution of hydrogeologic properties and hydrologic boundaries within the model domain. The three-dimensional movement of groundwater of constant density through porous earth material is described by Darcy's Law:

$$\mathbf{q} = -\mathbf{K}\nabla h = -\begin{pmatrix} K_{xx} & 0 & 0 \\ 0 & K_{yy} & 0 \\ 0 & 0 & K_{zz} \end{pmatrix} \nabla h \tag{1}$$

Where:
$\mathbf{q}$ = a vector of specific discharge (LIT), or fluid-flux vector
$\mathbf{K}$ = hydraulic-conductivity tensor $(\mathrm{L/T})$
K_{xx}, K_{yy}, and K_{zz} = values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T)
h = the potentiometric head (L)
∇h = the head-gradient vector.

The governing partial-differential equation used in MODFLOW for transient groundwater flow in a heterogeneous and anisotropic medium:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + Q'_s = SS\frac{\partial h}{\partial t} \tag{2}$$

Where :
Q'_s = volumetric flux per unit volume representing sources and sinks of water, with Q'_s being negative for flow out of the groundwater, and Q'_s being positive for flow into the system $\left(\mathrm{T}^{-1}\right)$
SS = specific storage of the porous material (L-1)
t = time (T).

6.1 Methodology

The MODFLOW model is, based on characteristics from several projects within the Netherlands. The model mainly consists of a 30 m thick unconfined aquifer underlain by a 30 m thick aquitard. In reality, the thickness of the aquitard is not always so large, but a large thickness can reduce boundary effects, which can be caused by a deeper, underlying layer (Tachavises and Benson, 1997a,b). The CB walls are 'keyed" into the aquitard to provide a watertight system. The recharge is assumed to be zero. The hydraulic head outside the CB wall construction is higher than inside, which allows the groundwater to flow towards the CB wall construction. For this model, steady-state conditions are presumed for all the simulations. At various locations of the wall, defects (windows) are modelled to observe the change in flow rate through the wall. The windows can be partially or fully penetrating. The partially penetrating windows create zones of higher hydraulic conductivity within the wall.

The windows can result from (Choi et al., 2015):

- settling of course-grained material
- spalling or collapse of the formation
- imperfect mixing
- construction defects within the CB wall
- insufficient embedment into the aquitard
- postconstruction property changes

6.2 Model setup

The model domain exists of 300 rows and 300 columns (see Figure 6.1). The cells of 299 rows have a width of 1 m, and 1 row has a width of 0.1 m. This row is used for the simulation of various defects (windows) within the wall. The columns also differ in size, 299 columns have a width of 1 m, and 1 column has a width of 0.6 m which, is used to model the CB wall. The hydraulic conductivity of the wall is equal to $1 \cdot 10^{-9}$ m/s. The aquifer consists of 16 layers, varying in thickness. The aquitard consists of 4 layers, where the first three layers indicate the varying embedment depth of the CB wall.

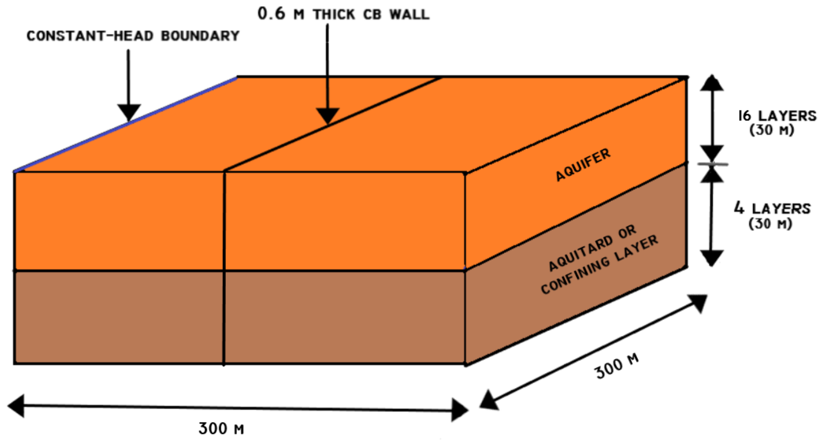


Figure 6.1: Modflow model

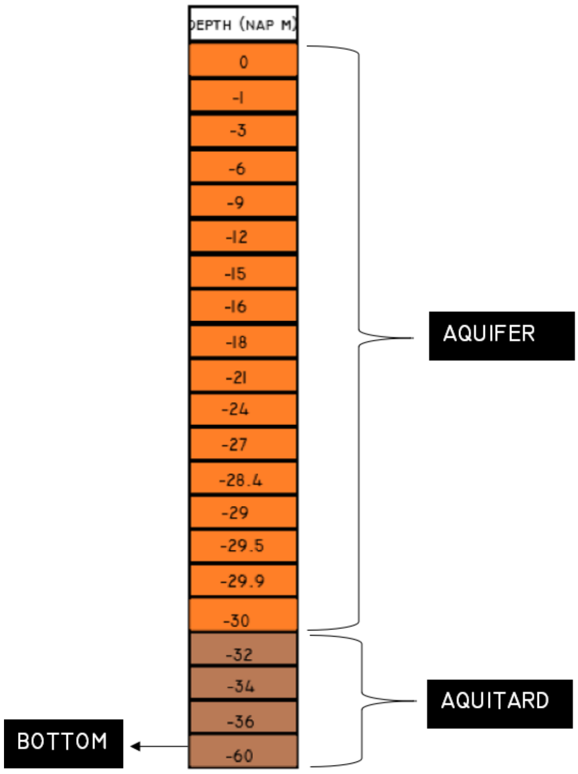


Figure 6.2: Overview of the layers (top elevation)

Constant-head boundary is used for the aquifer on the left side of the model domain. A hydraulic head of NAP -0.5 m is used, which is obtained from the data of Richard Hageman Akwadukt. The hydraulic head inside the CB wall construction is set at NAP -13 m in layer 6 using the drains package. The hydraulic gradient across the wall is approximately 20.8. The hydraulic conductivity of the aquifer (Ka) is set at 15 m/day, falling within the range of coarse sand. The hydraulic conductivity aquitard (Kc) is set at $5 \cdot 10^{-4}$ m/day, which indicates compacted clay, such as pot clay. Various scenarios are simulated to investigate the importance of the embedment depth of the CB wall and the presence of defects (windows) within the wall on the discharge through the wall.

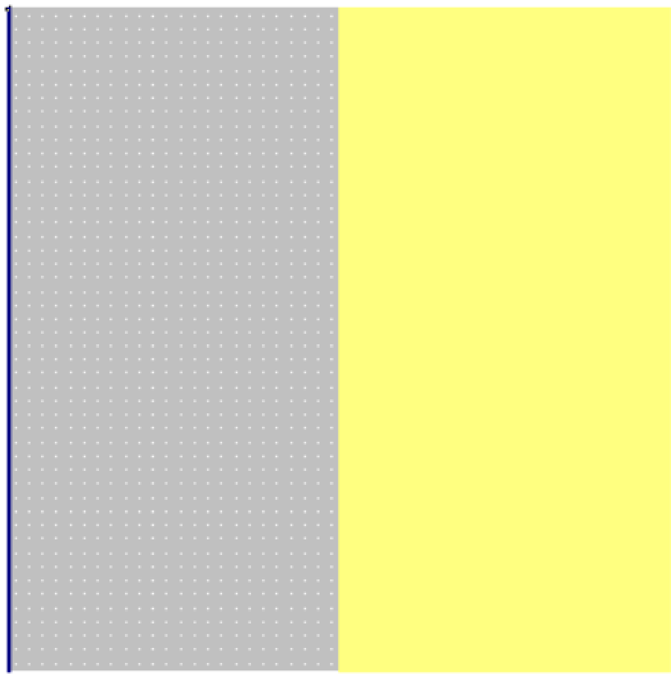


Figure 6.3: Constant-head boundary given in blue (left) and drains (right) in layer 6

6.3 Embedment (key) depth of the CB wall

The embedment of the CB wall into an underlying aquitard is important for obtaining a watertight system. It is also possible that the walls are hanged above the aquitard. In this case, there is a gap between the aquitard and the bottom of the wall. A series of simulations will be performed to determine the significance of the embedment and the embedment depth. The hydraulic conductivity of the aquifer and the aquitard is kept constant for the simulations. The results for the flow rate (discharge) through the intact wall versus embedment depth, are presented in Figure 6.4 below. The embedment depth of zero indicates that the wall is not embedded (keyed) into the aquitard, but is in direct contact with it. The discharge decreases slightly when the embedment depth increases. Due to the small decrement, it can be concluded that the discharge is not affected by the embedment depth. If the wall is installed 0.1 m above the aquitard (hanging wall), the discharge increases extensively to approximately 1402.59 m^3/day. To avoid such a large discharge it is important that the wall is either in direct contact or keyed into the aquitard.

The impact on the discharge through the wall is also investigated for the improper embedment of one panel. The panel has a thickness of 3 m and is placed 0 m, 0.1 m, 0.5 m, and 1 m above the aquitard (see Figure 6.5). The discharge increases as the gap increases. The discharge increases approximately with 750% when a panel is placed 0.5 m above the aquitard, which means that even a small gap can have a large effect on the discharge.

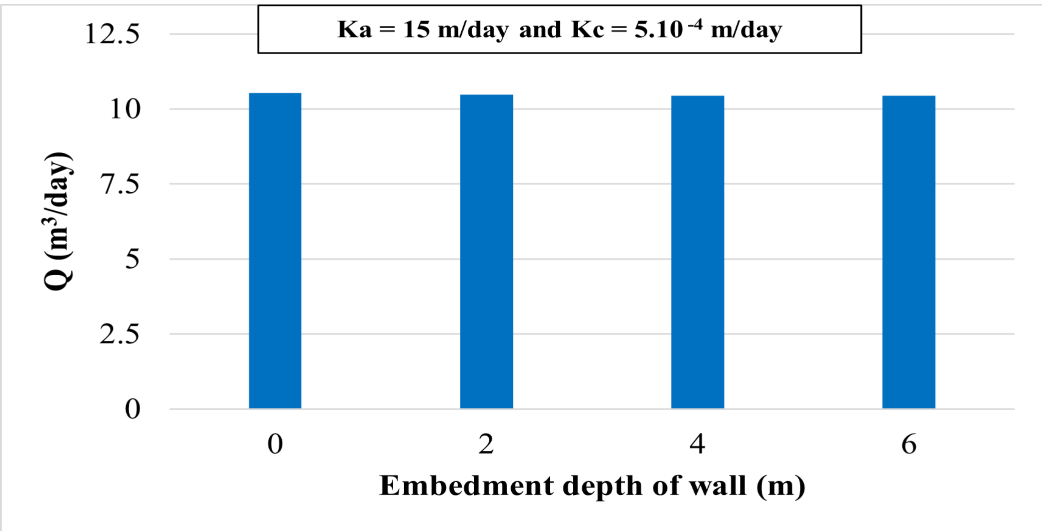


Figure 6.4: The discharge through the CB wall as function of wall embedment depth (m)

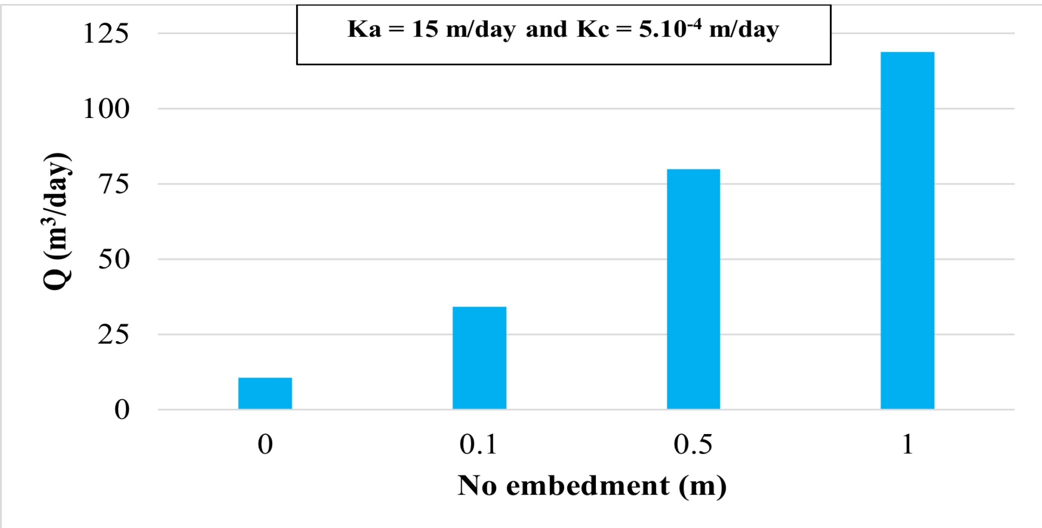


Figure 6.5: The discharge through the CB wall if one panel is not embedded into the aquitard

6.4 Fully penetrating windows (small)

Fully penetrating windows or ”gaps” can also occur within a CB wall. Several simulations are conducted to investigate their impact on the discharge through the wall. The hydraulic conductivity of the CB wall is maintained at $1 \cdot 10^{-9}$ m/s, and the wall is installed 2 m into the underlying aquitard. The windows have a constant width of 0.1 m but vary in length for the various simulations. The maximum area of the window is 0.1 m^2. In MODFLOW the windows, are simulated by changing the (horizontal and vertical) hydraulic conductivity of the CB wall into the hydraulic conductivity of the aquifer for the 0.1 m-wide column. The windows are created in layers 1, 7, 13, 14, 15, and 16. The last three layers have a combined length of 1 m. The results are presented in terms of the difference in discharge (ΔQ). The difference in discharge (ΔQ) was calculated by subtracting the discharge through a perfect wall and imperfect wall ($Q_{imperfect} - Q_{perfect}$). The discharge through the perfect wall is approximately 10.47 m^3/day (see Figure 6.4). In Figure 6.6, the results from the simulations for the fully penetrating windows which are present in the middle and bottom of the wall are displayed. When a window is present in the upper part of the wall (layer 1), the discharge is unaffected, which means that the ΔQ is equal to zero. If the same window is placed at a lower part of the CB wall, the discharge is two times higher than the discharge past the CB wall without windows (perfect wall). The hydraulic gradient across the wall is almost the same at every position, which should result in the same discharge. If the hydraulic heads of the cells of the model are lower than the cell bottom, the cells are identified as dry (inactive) cells in MODFLOW, which causes an error in the calculation. For this model, this is also the case, because the cell bottoms of the first five layers are higher than the drain elevation of NAP -13 m. Thus, the discharge through the wall with windows of the same size should be approximately the same. In Figure 6.7, the results from the simulations for the fully penetrating windows with different areas are displayed. Figure 6.7b shows that the discharge increases linearly with the increasing area of the windows. For every 0.01 m^2 increase of the area, the ΔQ increases with approximately 1 m^3/day (see Figure 6.7a).

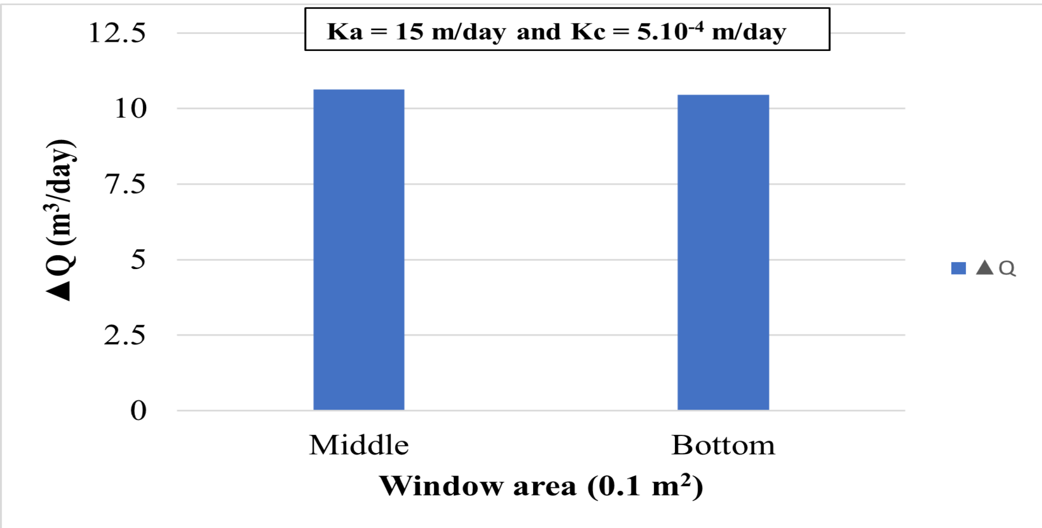
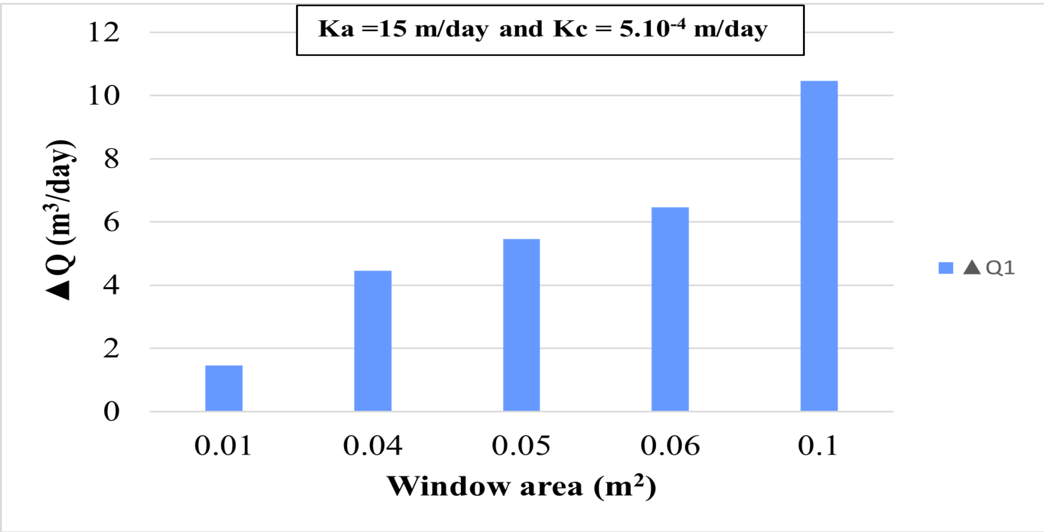
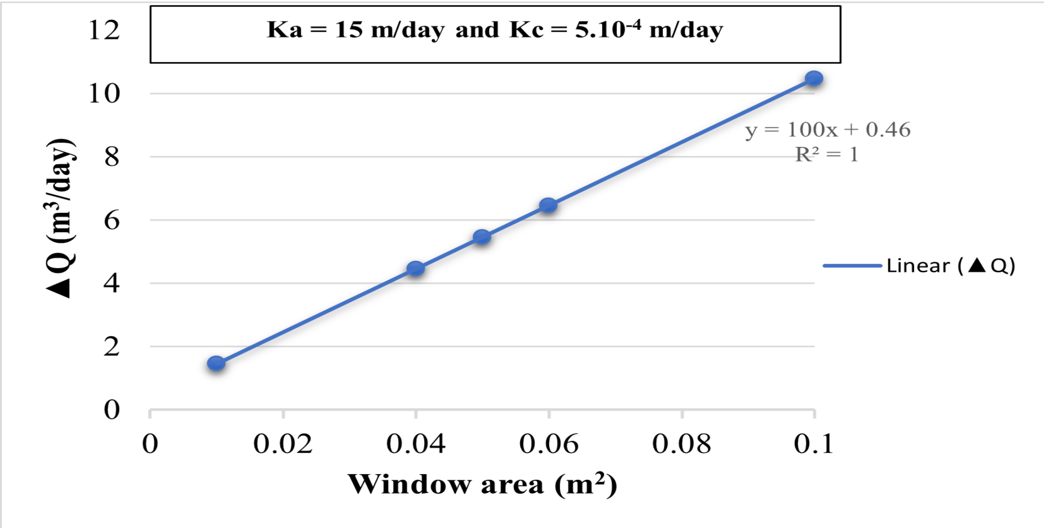


Figure 6.6: Difference in discharge (ΔQ) through the CB wall with fully penetrating small windows at different positions



(a) Fully penetrating small windows with varying sizes



(b) Fully penetrating small windows with varying sizes (linear increase)

Figure 6.7: Difference in discharge (ΔQ) through the CB wall with fully penetrating small windows

Figure 6.8 shows the hydraulic head contours for a perfect wall (no defects) situation. The blue line indicates a fixed-head boundary with a hydraulic head of NAP -0.5 m. On the right side (see Figure 6.3), the hydraulic head is approximately NAP -13 m. The groundwater flows from a high to a low hydraulic head. When a window with an area of 0.1 m^2 is located at a depth of NAP -15 m - NAP -16 m in the center of the CB wall, the hydraulic head pattern is different towards the edges (see Figure 6.9).

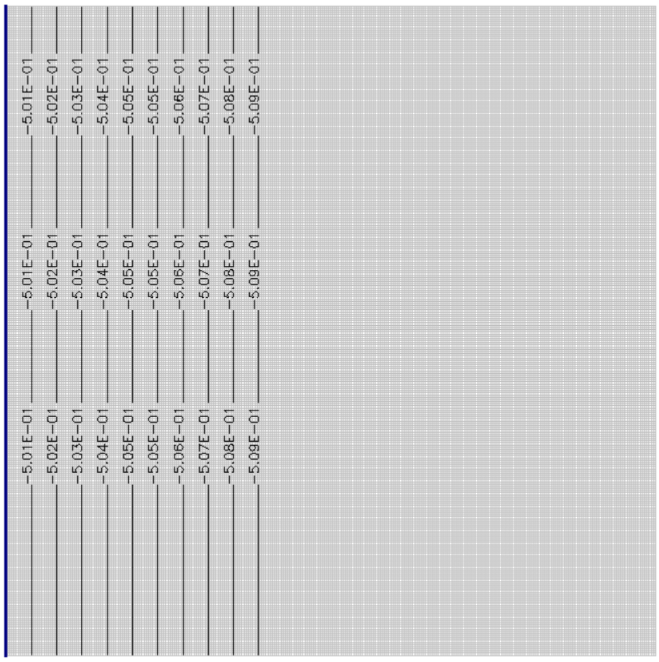


Figure 6.8: 2D visualization of the hydraulic head pattern in layer 7 (NAP -15 m - NAP -16 m) for a perfect wall situation

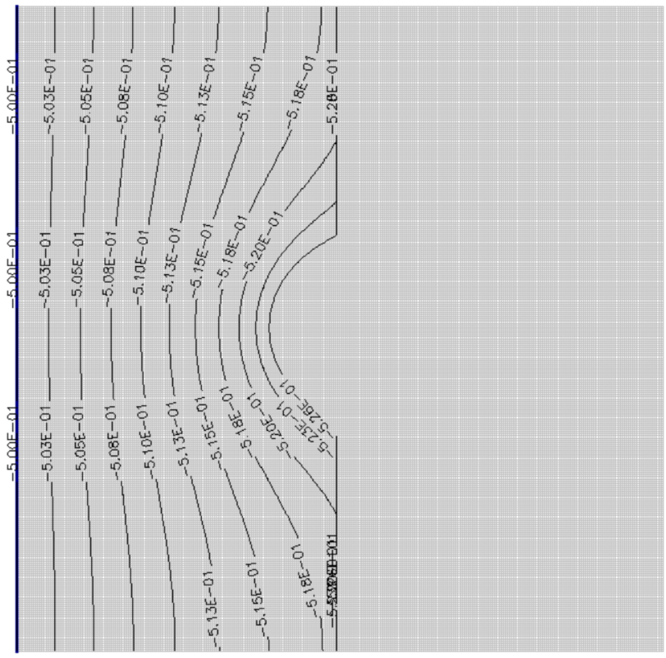
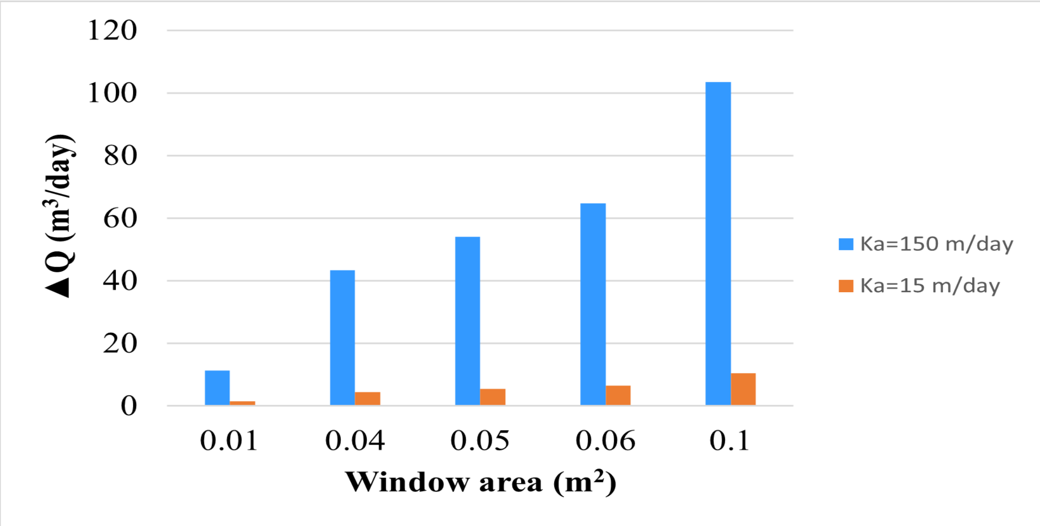


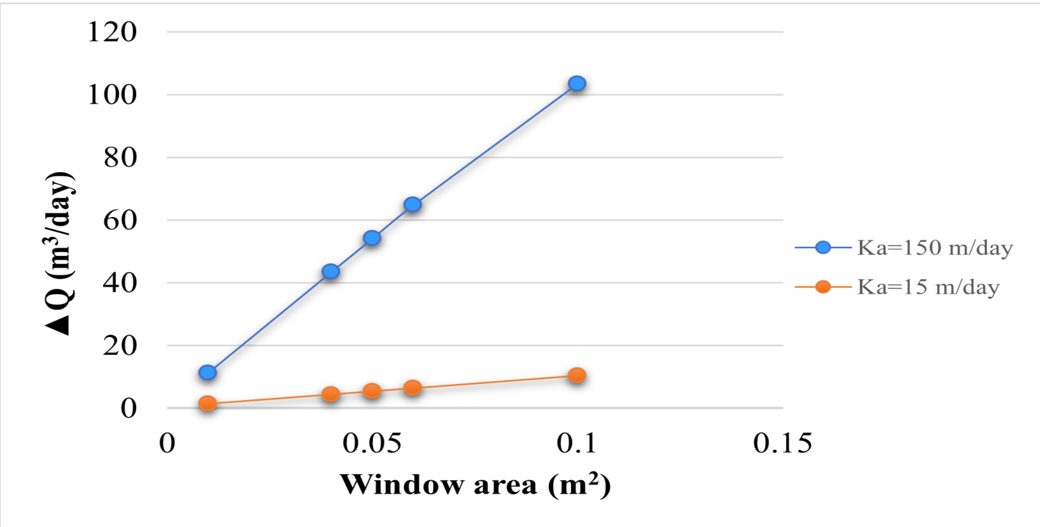
Figure 6.9: 2D visualization of the hydraulic head pattern in layer 7 (NAP -15 m - NAP -16 m) with a window (window area is 0.1 m^2)

6.4.1 Higher aquifer hydraulic conductivity

Figure 6.10 shows the impact of windows for a more permeable aquifer. The hydraulic conductivity of the aquifer (Ka) for this simulation was increased from 15 m/day to 150 m/day, while the horizontal hydraulic conductivity of the aquitard (Kc) was maintained at $5 \cdot 10^{-4}$ m/day. The discharge through a perfect wall remains 10.47 m^3/day. For every 0.01 m^2 increase of the area, the ΔQ increases with approximately 10 m^3/day (see Figure 6.10a). This indicates that an increase of the hydraulic conductivity of the aquifer by a factor of 10, also results in an increment of the ΔQ by a factor of 10. Thus, the discharge through the wall is remarkably affected when fully penetrating windows are present in an aquifer with higher hydraulic conductivity. Figure 6.10b shows a linear relationship between the increase in the window area and the ΔQ.



(a) Fully penetrating small windows with varying sizes



(b) Fully penetrating small windows with varying sizes (linear increase)

Figure 6.10: Difference in discharge (ΔQ) through the CB wall with fully penetrating small windows (Ka= 15 m/day and Ka= 150 m/day)

6.4.2 Varying aquitard hydraulic conductivity

Figure 6.13 & 6.14 show that by decreasing the permeability of the aquitard from $5 \cdot 10^{-4}$ m/day to $5 \cdot 10^{-7}$ m/day or $5 \cdot 10^{-10}$ m/day the ΔQ through the wall with the small fully penetrating windows at the various positions stays unaffected. Figure 6.12 shows the ΔQ past the wall also with the small fully penetrating windows, but for a aquitard with a hydraulic conductivity (Kc) of $5 \cdot 10^{-2}$ m/day instead of $5 \cdot 10^{-4}$ m/day. The ΔQ is similar to the ΔQ of Figure 6.13 & 6.14. However, the discharge past the CB wall is greater when the aquitard has a higher hydraulic conductivity ($5 \cdot 10^{-2}$ m/day), because more water can flow beneath the wall. Thus, the discharge through a perfect wall increases with approximately 650% when the aquitard has a hydraulic conductivity of $5 \cdot 10^{-2}$ m/day instead of $5 \cdot 10^{-4}$ m/day (see Figure 6.11). Note that the hydraulic conductivity of the aquifer for all three simulations is equal to 15 m/day.

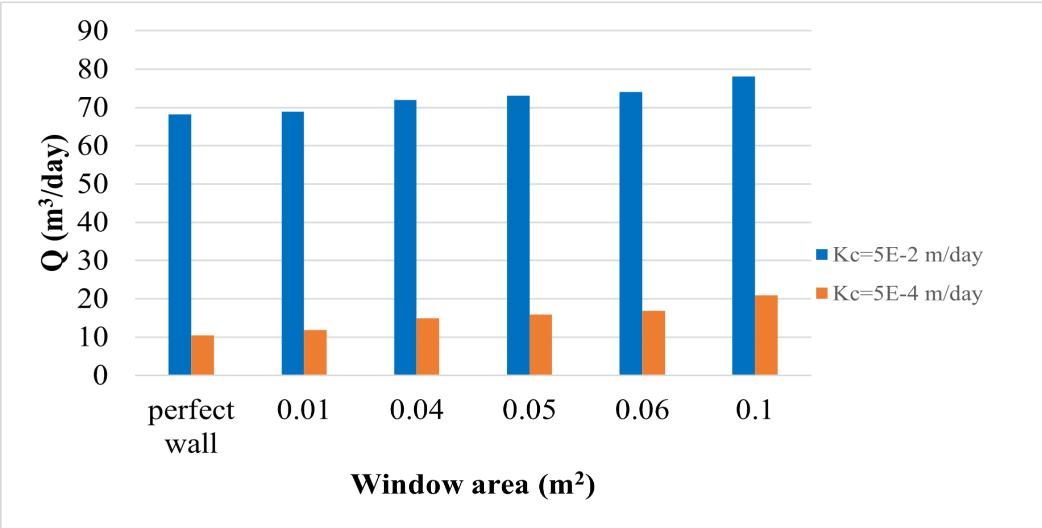


Figure 6.11: The discharge through the CB wall with fully penetrating small windows (Kc= $5 \cdot 10^{-2}$ m/day and Kc= $5 \cdot 10^{-4}$ m/day)

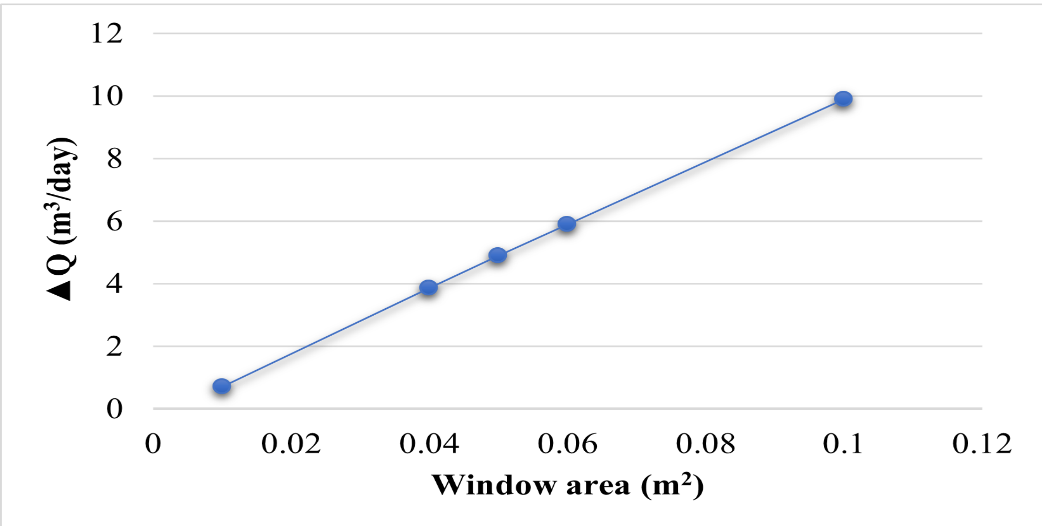


Figure 6.12: Difference in discharge (ΔQ) through the CB wall with fully penetrating small windows (Kc= $5 \cdot 10^{-2}$ m/day)

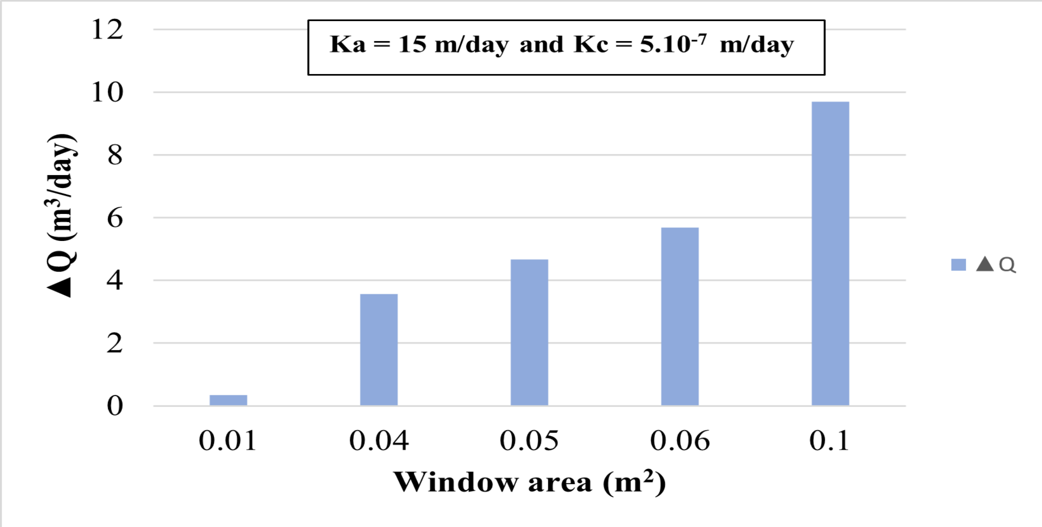


Figure 6.13: Difference in discharge (ΔQ) through the CB wall with fully penetrating small windows (Kc= $5 \cdot 10^{-7}$ m/day)

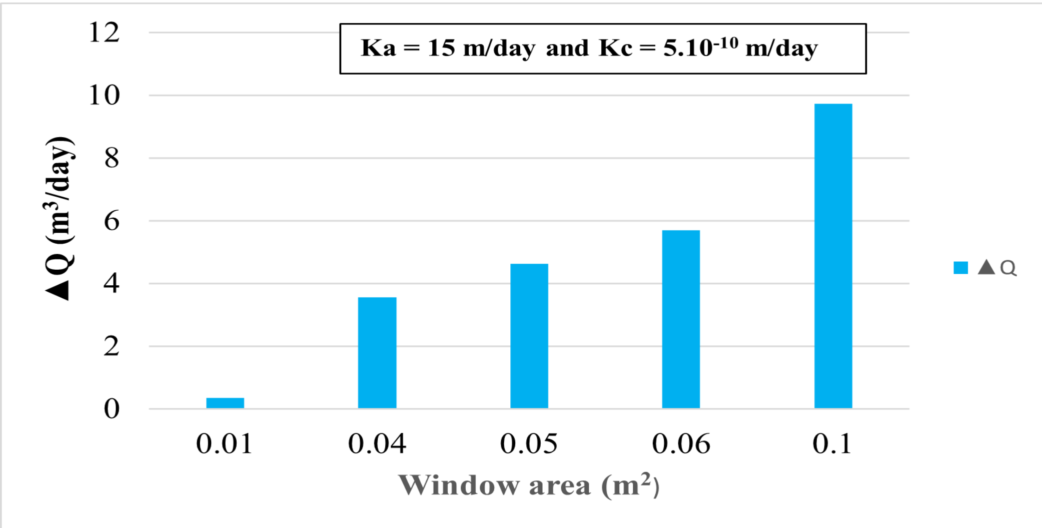


Figure 6.14: Difference in discharge (ΔQ) through the CB wall with fully penetrating small windows (Kc= $5 \cdot 10^{-10}$ m/day)

6.5 Fully penetrating windows (big)

In this case, the area of the fully penetrating windows is increased. The windows are 0.1 m wide and have a variable vertical length. In Figure 6.15, it is noticeable that the ΔQ increased enormously for the three large windows. Thus, the larger the area of the windows, the higher the discharge. Figure 6.16 shows the large difference between the ΔQ of the small (0.1 m^2) and the large (0.6 m^2, 0.8 m^2 and 1 m^2) windows. When the window area is increased by a factor of 10, the ΔQ also increases by a factor of 10.

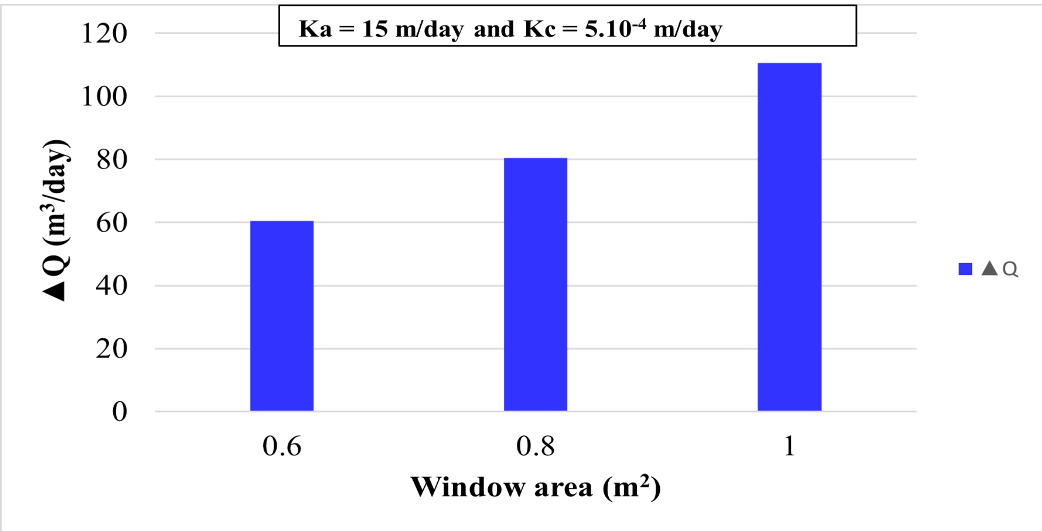


Figure 6.15: Difference in discharge (ΔQ) through the CB wall with fully penetrating big windows

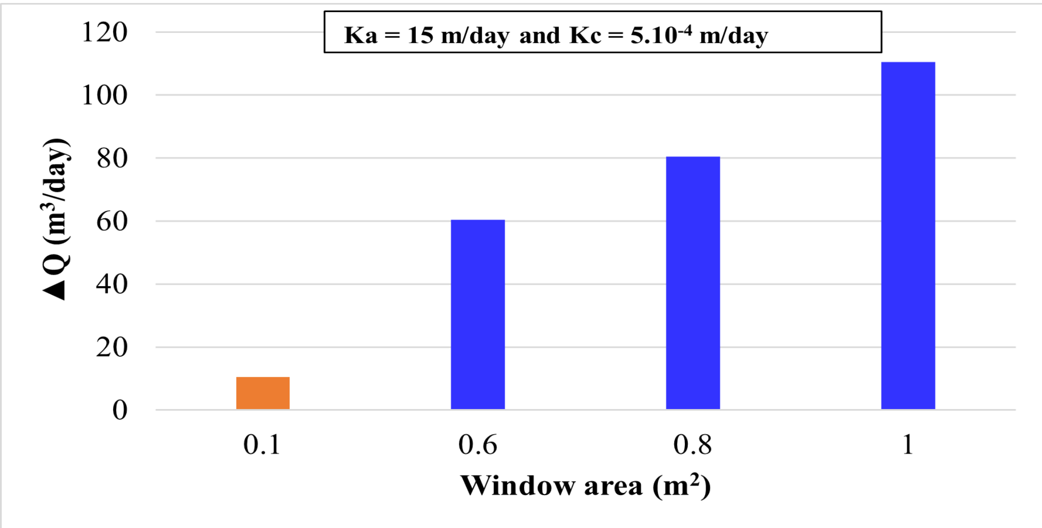


Figure 6.16: Difference in discharge (ΔQ) through the CB wall with fully penetrating small (orange) and big (blue) windows

6.6 Partially penetrating windows

CB walls can also have partially penetrating windows, and their effect on the discharge is also evaluated, by performing simulations. These windows are created by gradually increasing the hydraulic conductivity for a particular area of the wall. The windows are 0.1 m-wide and 1 m long and are placed on the top, middle, and bottom of the wall. The results are shown in Figure 6.17. The increase in permeability of the windows also causes an increment in the discharge. On the contrary, the discharge through the wall for the different hydraulic conductivities remains unchanged for windows that are present at the upper part of the wall. This is not logical and occurs because of dry cells in the layers above NAP -13 m in the MODFLOW model. The presence of partially penetrating windows has minor impact on the discharge through the wall.

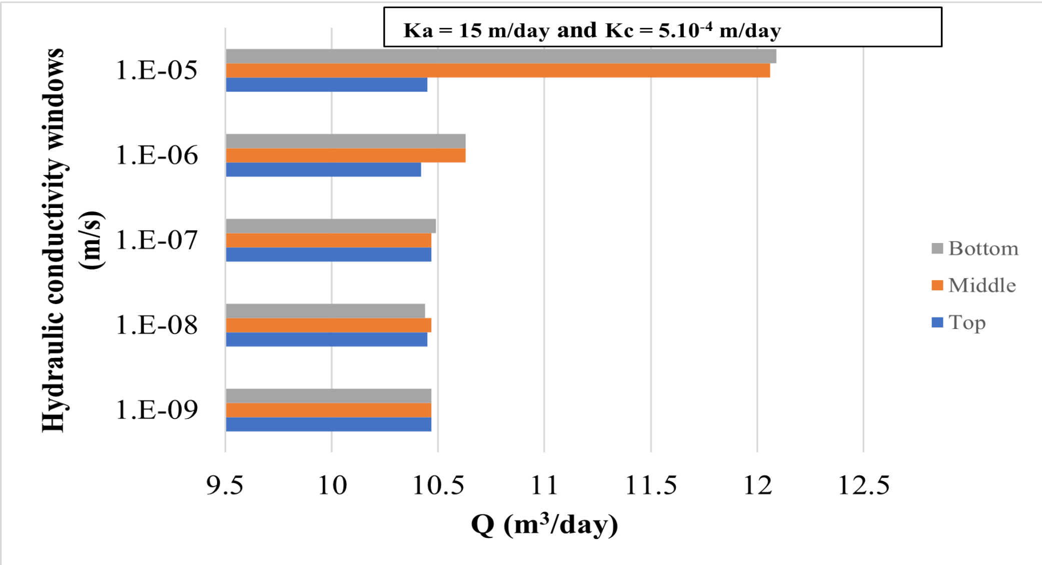


Figure 6.17: The discharge through the CB wall having partially penetrating windows with different hydraulic conductivities

The importance of window size was also investigated for partially penetrating windows. The results are shown in Figure 6.18. The impact on the discharge through the CB wall is noticeable when the hydraulic conductivity of the windows becomes larger than $1 \cdot 10^{-6}$ m/s. But, also the size of the windows is relevant. For example, the discharge can increase by a factor of 5 when a window has a hydraulic conductivity of $1 \cdot 10^{-5}$ m/s and an area of 3 m^2. In this case, if the hydraulic conductivity of the window becomes larger than $1 \cdot 10^{-5}$ m/s, they are identified as fully penetrating windows instead of partially penetrating windows. The reason is that the hydraulic conductivity of the window and the aquifer are almost equal.

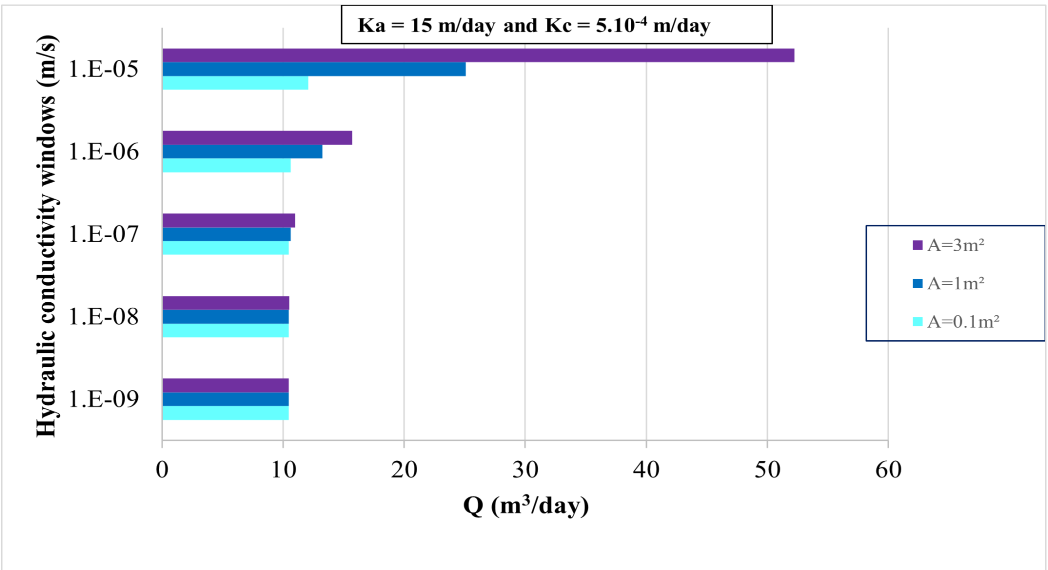


Figure 6.18: The discharge through the CB wall having partially penetrating windows with different hydraulic conductivities and window area (A)

6.7 Vertical deviation of the panels

Leakages and discontinuities in the CB wall panels can be caused by vertical deviations during the excavation. The excavated trench must be as vertical as possible within an acceptable vertical deviation of almost $0.5-1\%$ to provide sufficient connection. An overlap of 300 mm (d) must be achieved between the primary and secondary panel (see Figure 6.20). For a panel length of 30 m, the allowable deviation is 0.30 m. If two adjacent panels deviate in opposite directions, a large window is formed between them (see Figure 6.20). This situation will be modeled in MODFLOW to study the impact on the discharge through the wall. In the model, the hydraulic conductivity of the overlapping part is increased gradually until there is no overlap at all (see Table 6.1). The hydraulic conductivity of the wall and aquifer are identical for the last two layers. By doing this, a window is formed between the panels. The discharge increases from 10.47 m^3/day to 44.57 m^3/day, when the two panels deviate 1% in the opposite direction. If the vertical deviation is larger than 1 %, the discharge will increase more because the window between the panels will become larger.

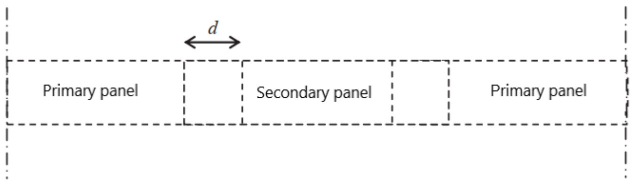


Figure 6.19: Connection between the adjacent panels

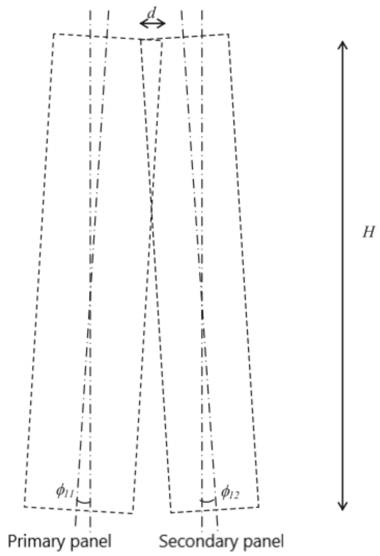


Figure 6.20: Vertical deviation of the panels

Table 6.1: Overview of the increasing hydraulic conductivity for the layers

Layer	**Hydraulic conductivity (m/d)**
10	$8.64 \cdot 10^{-3}$
11	$8.64 \cdot 10^{-2}$
12	$8.64 \cdot 10^{-1}$
13	8.64
14	15
15	15
16	15

6.8 Increasing aquitard hydraulic conductivity

Figure 6.21 shows that the hydraulic conductivity of the aquitard affects the flow rate past the wall. The discharge increases drastically when the vertical hydraulic conductivity of the aquitard is $5 \cdot 10^{-3}$ m/day instead of $5 \cdot 10^{-4}$ m/day or $5 \cdot 10^{-5}$ m/day. The vertical hydraulic conductivity of clay loam and sandy clay is mainly around $5 \cdot 10^{-3}$ m/day and of pot clay between $5 \cdot 10^{-4}$ m/day or $5 \cdot 10^{-5}$ (Biron, 2004). Therefore, it is very important to ensure that the aquitard has low hydraulic conductivity. The vertical hydraulic conductivity is $1/10^{th}$ of the horizontal hydraulic conductivity. The horizontal hydraulic conductivity of the aquifer is maintained at 15 m/day.

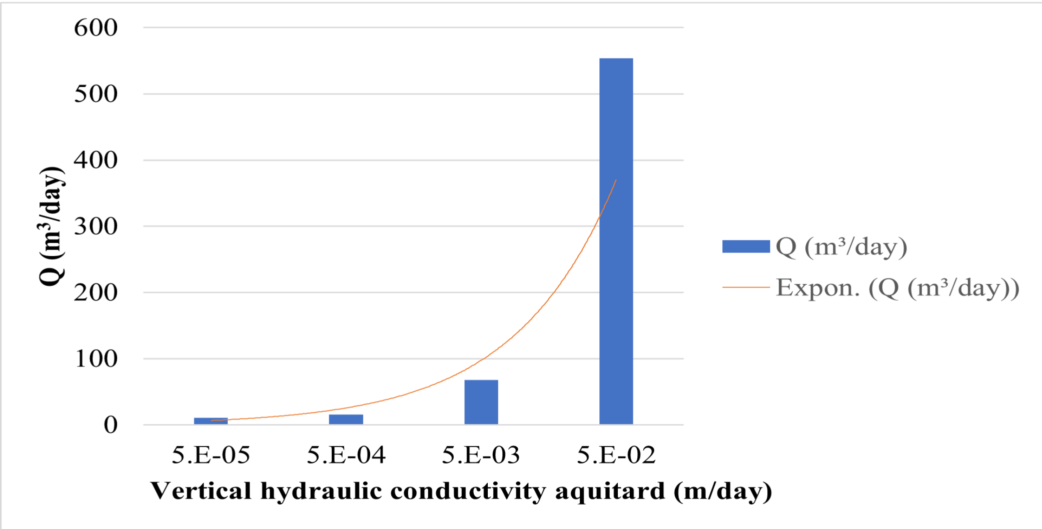


Figure 6.21: The discharge through CB wall (no defects) for different hydraulic conductivities of the aquitard

6.9 Discussion

A series of simulations were performed to evaluate how defects of various sizes, positions, and embedment depth affect the discharge past CB walls. The results from these simulations illustrate that:

- It is important that the wall is embedded or in contact with the aquitard. However, an embedment depth of 1 - 1.5 m is required to ensure that no gap exists between the wall and the aquitard. A small gap of 0.1 m between the bottom of the one panel (3 m) and the aquitard can increase the discharge through the wall by a factor of 3 (see Figure 6.5), which makes the wall ineffective.

- The occurrence of windows in the wall also plays an important role. The discharge through the CB wall increases significantly when small fully penetrating windows exist in a more permeable aquifer or aquitard. The horizontal flow in the aquifer increases when the aquifer has a higher hydraulic conductivity. The discharge increases linearly with increasing area of the windows (see Figure 6.7b). The presence of large fully penetrating windows in the wall also has an enormous impact on the discharge. For example, a window whose area is 1 m^2 leads to an increase of the discharge by a factor of approximately 11. There is a linear relationship between the increment in the window area and the discharge. Note that the area of the windows is less than 1% of the area of the wall. Thus, even small windows can affect the discharge past the CB wall. On the contrary, small windows in the CB wall have less influence on the discharge past the CB wall when the horizontal hydraulic conductivity of the aquitard decreases from $5 \cdot 10^{-4}$ m/day to $5 \cdot 10^{-7}$ m/day or $5 \cdot 10^{-10}$ m/day.

- The vertical deviation of two panels situated next to each other in the opposite direction also has an impact on the discharge. According to the calculation, the discharge can approximately increase by a factor of 4. The maximum allowed vertical deviation during the excavation of the trench is 1%.

- The discharge past the CB wall is less affected by partially penetrating windows and windows existing in a less permeable aquitard. The position of the windows is also insignificant.

- The hydraulic conductivity of the horizontal barrier (aquitard) is also crucial. The higher the hydraulic conductivity, the higher the seepage of water through the aquitard. The presence of gaps inside the high permeable aquitard can lead to even higher discharges.

When constructing a CB wall, it must be ensured that there are no defects in the wall. This chapter revealed which defects are critical and should be avoided.

7
Discussion and Conclusions

7.1 Discussion

In this research, five projects have been investigated to achieve better understanding of the in-situ hydraulic conductivity of the CB walls. Limited information was available for A2 motorway at Best, Motorway A4 Delft-Schiedam and Griftpark Utrecht, which affected the accurate estimation of the in-situ hydraulic conductivity of the CB walls. Darcy's law is applied to estimate the discharge and hydraulic conductivity. It is also notable that CB walls are used in combination with other types of vertical barriers such as sheet pile and HDPE foil. Each project will be discussed separately below:

- **Westerschelde Tunnel**: For the polder construction at the southern access ramp of the Westerschelde Tunnel, CB walls were used in combination with sheet piles. Thus, the calculated in-situ hydraulic conductivity involves the combined hydraulic conductivity of both walls, which was close to the required hydraulic conductivity. Further, the Boom clay layer formed an excellent horizontal barrier due to its low permeability.

- **A2 Motorway at Best**: Sheet piles and HDPE foil were also inserted inside the entire CB wall construction around the sunken part of the A2 motorway at Best. The whole construction was divided into three compartments (north, middle, and south). According to a study performed in 2011 (Haveman, 2012), the yearly discharge (for all three compartments) was 0.8 million m^3. The calculated discharge for July 2018 for the middle compartment was also found to be very high, which indicates the presence of imperfections (defects) or the occurrence of a high permeable horizontal barrier. There was no hydraulic head data available of the aquifers inside and outside the construction, which could explain the high discharge. Therefore, finding the exact reason responsible for the high groundwater inflow is difficult due to insufficient data (piezometer data).

- **Motorway A4 Delft-Schiedam**: The in-situ hydraulic conductivity of the CB wall for the semi-sunken and sunken part of the motorway A4 Delft-Schiedam is based on a study performed in 2015 (Bosman, 2015). There were several defects detected that caused the high discharge. After reparation of the defects, the monitored discharge remained higher compared to the expected discharge (calculated during the concept/design stage). According to this study (see Chapter 4.3), the hydraulic resistance of 926 days of the CB wall is more realistic than 1852 days. The hydraulic resistance of the Kedichem clay layer was also overestimated (horizontal barrier).

- **Griftpark Utrecht**: At some locations within the CB wall construction of Griftpark Utrecht, sheet pile walls were installed to provide stability. The main concern in this project was the occurrence of sand lenses within the clay layer, which contributed to a high groundwater inflow. According to calculations conducted during the design stage, approximately 60% of the groundwater could enter the construction through the clay layer. The collected data, which was available for every quarter, showed that the discharge was highly fluctuating throughout the years. However, the discharge for the last three quarters of 2019 was stable (9 $m^3/hour$). The maximum expected discharge determined during the design stage was approximately 13 $m^3/hour$. This established the expected functioning of the wall.

- **Richard Hageman Akwadukt**: In this project, Geolock and sheet piles were placed at certain locations inside the CB wall. Based on the available data and application of Darcy's law, the hydraulic conductivity of the CB wall for every polder was calculated. The hydraulic conductivities of the CB walls for the northern and southern polder were approximated to be $2.5 \cdot 10^{-9}$ m/s and $2 \cdot 10^{-8}$, respectively. Just after the realization of the polders, high discharges were measured for both polders, which indicated the presence of defects. The pot clay layer has very low permeability and was used as a horizontal barrier, which implies that the defects exist in the walls. Unfortunately, not all the defects were detected and repaired, especially at the southern polder. This resulted in the higher hydraulic conductivity of the CB wall for the southern polder.

The results of the MODFLOW simulation showed that small defects (windows) in the wall can lead to an increase in the discharge past the wall. To achieve a watertight system it is necessary that the vertical barrier (CB wall) is "keyed" into the horizontal barrier (aquitard/mainly clay layer) and the hydraulic conductivities of both barriers are very low. The clay layers that have been used as a horizontal barrier for motorway A2 Best, motorway A4 Delft-Schiedam and the Griftpark Utrecht have a higher hydraulic conductivity compared to the Boom clay layer of the Westerschelde tunnel and the pot clay layer of the Richard Hageman Akwadukt. It was also difficult to determine the hydraulic conductivity of the CB walls for these projects, because the exact amount of water discharge through the aquitard was uncertain. The increase in discharge due to the presence of a high permeable aquitard is shown in Figure 6.15. The presence of sand lenses in the clay layer at Griftpark Utrecht could have caused insufficient embedment of the CB wall panel(s). Figure 6.5 shows that a small gap between the bottom of the wall and the aquitard can cause high discharges. Defects were mainly present in the CB walls of the northern and southern polders of the Richard Hageman Akwadukt. MODFLOW simulations that were conducted for defects in the wall illustrated that the discharge increased significantly when fully penetrating small windows exist in a high permeable aquifer (see Figure 6.7) and when fully penetrating big windows are present in a low permeable aquifer (see Figure 6.11).

7.2 Conclusions

The main objective of this study is to get a better understanding of the hydraulic performance of CB walls used at various projects within the Netherlands. The main research question will be answered after answering the sub questions.

Sub questions:

What are the possible factors that potentially impact the hydraulic performance of the CB Walls?

The hydraulic performance of the CB walls is mainly affected by the presence of other types of vertical cutoff walls (sheet pile walls, HDPE foil) inside the CB walls. The performance of the walls is also affected by the occurrence of defects. Leakages (imperfections) were identified during the investigation of the projects and were caused by:

- Insufficient connection between the panels: this was encountered at motorway A4 Delft-Schiedam (see Chapter 4.3.2) and Richard Hageman Akwadukt (see Chapter 5.4.2). High discharges were measured right after the realization of the constructions. Jet grout columns were used to prevent seepage of groundwater through the space between the panels.
- Variable cement-bentonite ratio (inhomogeneity): laboratory tests performed on samples from different CB wall panels at Griftpark Utrecht showed that the expected and average hydraulic conductivity values can vary for each panel (see Figure 4.15). Variation in the cement-bentonite content can lead to different viscosities and densities of the coulis (CB suspension).
- The presence of windows in the wall: the MODFLOW simulations for the fully penetrating and partially penetrating windows showed that windows, regardless of their size can lead to an increase of the discharge past the CB wall. For example, the discharge is doubled when a fully penetrating window whose area is 0.1 m^2 exists in the wall (see Figure 6.6).

What are the hydraulic conductivities of the CB wall at different stages of the projects such as design stage, construction, and post-construction (in-situ) and measured in the laboratory?

The hydraulic conductivities of the CB wall are different for each project. An overview of the hydraulic conductivities for each project will be given below:

- Westerschelde Tunnel
  - **design stage**: the hydraulic conductivity of the hardened CB wall for this case was required to be less than or equal to $1 \cdot 10^{-9}$ m/s with a hydraulic gradient (i) of 30.
  - **laboratory testing**: test results of the CB slurry showed a mean hydraulic conductivity of $4.2 \cdot 10^{-10}$ m/s with a standard deviation of $1.26 \cdot 10^{-9}$ m/s.
  - **post-construction stage**: the hydraulic conductivity of the CB wall including sheet piles was approximately $1.31 \cdot 10^{-9}$ m/s.
- Motorway A2 at Best
  - **design stage**: the hydraulic conductivity according to Darcy for a hydraulic gradient (i) of 30, should not be greater than $1 \cdot 10^{-8}$ m/s.
  - **laboratory testing**: test results of the CB slurry showed mean hydraulic conductivities of $1 \cdot 10^{-10}$ m/s and $0.5 \cdot 10^{-8}$ m/s at temperatures of $10°$ C and $15°$ C, respectively.
  - **post-construction stage**: The calculated hydraulic conductivity of the CB wall was around $5 \cdot 10^{-7}$ m/s due to the high discharge. The measured discharge exceeded the allowed discharge, which was probably caused by the missing clay layer (horizontal barrier) in the middle compartment of the CB wall construction. Thus, the exact amount of groundwater inflow through the horizontal barrier could not be estimated.

- Motorway A4 Delft-Schiedam
  - **laboratory testing**: the target value for the hydraulic conductivity based on laboratory test results had to be $1 \cdot 10^{-9}$ m/s. For CB walls with HDPE foil the target value was $1 \cdot 10^{-11}$ m/s.
  - **post-construction stage**: according to a study (Bosman, 2015), the hydraulic conductivity of the CB wall had to be around $1 \cdot 10^{-8}$ m/s.
- Griftpark Utrecht
  - **design stage**: the requirement for the average hydraulic resistance of the CB wall (whole construction) was 1000 days.
  - **laboratory testing**: the average hydraulic conductivity for every panel after 28 days of hardening had to be $< 5 \cdot 10^{-9}$ m/s (hydraulic gradient (i) of 30).
  - **post-construction stage**: it was difficult to indicate the hydraulic conductivity of the CB wall because of the uncertainty of the amount of groundwater inflow through the horizontal barrier (including sand lenses).
- Richard Hageman Akwadukt
  - **concept/design stage**: the average hydraulic conductivity of the CB slurry (8 test samples) after 28 or 56 days of hardening at $20°$ C had to be $\leqslant 10^{-9}$ m/s
  - **post-construction stage**: the calculated hydraulic conductivities of the CB walls for the northern and southern polder were approximately $\approx 2.5 \cdot 10^{-9}$ m/s and $2 \cdot 10^{-8}$, respectively.

The hydraulic conductivity test results for the construction stage of every project was not available. For Griftpark Utrecht, the test results are shown in Figure 4.15.

To what extent does the hydraulic conductivity of CB walls vary for various construction techniques?

The CB walls are constructed in two phases: excavation and backfill. The alternating method and the continuous method can be distinguished for excavation, and a distinction can be made between the single and two-phase technique for the backfill. The construction techniques of the CB walls and their hydraulic conductivities for the projects are given below:

- Motorway A2 at Best: the single-phase technique and the continuous excavation method were used here.
- Griftpark Utrecht: for this project, the two-phase technique and the alternating excavation method were used. As stated earlier in this chapter (see Chapter 7.2), it was complicated to compute the in-situ hydraulic conductivities of the walls for these two projects due to insufficient information on the horizontal barrier.
- Richard Hageman Akwadukt: the single-phase technique and the alternating excavation method was applied here. The calculated hydraulic conductivities for the northern polder and southern polder are approximately $2.5 \cdot 10^{-9}$ m/s and $2 \cdot 10^{-8}$ m/s, respectively.

It was difficult to assess the construction methods for the other two projects (motorway A4 Delft-Schiedam and Westerschelde Tunnel) due to the lack of information. It was hard to explain if there is a connection between a particular construction technique and the hydraulic conductivity.

How do defects of various sizes, position, and the depth of penetration affect the flow rates past CB walls?

In Chapter 6, this question is answered by conducting MODFLOW simulations. The CB wall in the simulation is 0.6 m thick and has a hydraulic conductivity of $1 \cdot 10^{-9}$ m/s.

- **Embedment (key) depth of the wall**: the discharge through the wall is not affected by the embedment depth, but the wall must be in direct contact with the aquitard (properly connected). According to the literature, an embedment depth of 1 - 1.5 m is required to ensure that no gap exists between the wall and the aquitard. A small gap of 0.1 m can lead to an increase in the discharge past the wall by a factor of 3 (see Figure 6.5), which makes the wall ineffective.
- **Fully penetrating windows**: fully penetrating windows can also affect the flow rate. The discharge through the CB wall increases significantly when small fully penetrating windows exist in a more permeable aquifer

or aquitard. The CB wall with a window whose area is 0.1 m^2 has a discharge of approximately 117 m^3/day instead of 20 m^3/day when the hydraulic conductivity of the aquifer is increased by a factor of 10. A large window whose area is 1 m^2 leads to an increase of the discharge by a factor of approximately 11. On the other hand, the position of the windows have minimal effect on the discharge past the wall.

- **Partially penetrating windows**: the discharge past the CB wall is less affected by partially penetrating windows. However, if the size of the window increases, the discharge can be affected.
- **Vertical deviation of the panel**: vertical deviation (1%) of two panels in the opposite direction should be avoided, because it can lead to an increase of the discharge of approximately 35 m^3/day. The length of the panel is also important. The longer the panel, the larger the deviation.
- **Increasing aquitard hydraulic conductivity**: the hydraulic conductivity of the horizontal barrier (aquitard) is also crucial. The higher the hydraulic conductivity, the higher the seepage of water through the aquitard.

What are the consequences of walls that have higher hydraulic conductivity than desired?

The discharge through a CB wall with a higher hydraulic conductivity is higher compared to a wall with lower hydraulic conductivity. This can lead to an increase in groundwater level and thus, also an increase of dewatering inside the construction. High hydraulic conductivity walls can cause a wide range of negative consequences such as flooding, sinkholes, bottom instability, and damage of adjacent structures due to surface settlements (decrease in groundwater level outside the construction). The CB wall around Griftpark Utrecht is designed and constructed for the control of contaminant migration. If these walls have a higher hydraulic conductivity than desired, the spread of contaminated groundwater can no longer be prevented.

Combining the answers of the sub questions, the main question can be answered as follows:

What range of in-situ hydraulic conductivity values can be expected for Cement-Bentonite (CB) walls used in the Netherlands?

For the determination of the in-situ hydraulic conductivity of the CB wall, the availability and quality of data are of great importance. Also, the occurrence of a low permeable homogeneous layer is necessary to minimize the groundwater inflow. According to the projects that are investigated, the hydraulic conductivity of the CB walls is within the range of $1 \cdot 10^{-9}$ m/s to $2 \cdot 10^{-8}$ m/s. For example, the calculated hydraulic conductivities of the CB walls at the northern and southern polder of Richard Hageman Akwadukt are $2.5 \cdot 10^{-9}$ m/s and $2 \cdot 10^{-8}$ m/s, respectively. According to the literature, the hydraulic conductivity of the CB walls varies from $1 \cdot 10^{-9}$ m/s to $1 \cdot 10^{-8}$ m/s. Although defects were detected in the CB walls for this project, the hydraulic conductivity did not show large deviations. It is crucial to keep in mind that sometimes sheet pile and HDPE foil, or both are installed inside the whole CB wall construction, which influences the hydraulic conductivity of the wall. The hydraulic conductivity of the wall, including sheet piles and HDPE foil, can decrease by a factor of approximately 10 to 1000. However, laboratory test results often indicate lower hydraulic conductivity values compared to the required values. The estimation of the hydraulic conductivity of CB walls based on samples leads to the calculation of hydraulic conductivity for small scale test areas and is not suitable to estimate their performance in the field. The presence of uncertainties for each project influences computation of the in-situ hydraulic conductivity of CB walls. The design hydraulic conductivity of the wall should be lower than $1 \cdot 10^{-9}$ m/s to compensate for possible defects that could occur in the wall during the construction and post-construction stage.

Relation between the results of MODFLOW and Richard Hageman Akwadukt

The total allowed discharge according to the literature for the polders at Richard Hageman Akwadukt was approximately 100 m^3/day (see Table 5.4). The groundwater dewatering process inside the construction started right after the realization of the polder constructions. The total discharge was more than 1100 m^3/day, which indicated that the total allowed discharge was highly exceeded. After extensive monitoring and research, the defects in the CB walls were detected and repaired. This resulted in a discharge of approximately 600 m^3/day, which was still higher than expected. Therefore, new discharge requirements were introduced. The discharge of the northern and southern polder had to be in the range of 25 to 250 m^3/day and 30 to 300 m^3/day, respectively.

The average measured discharges for 2019 for the northern polder and southern polder were approximately 150 m^3/day and 400 m^3/day. There is still a difference between the total allowed discharge (design phase) and the measured discharge, which means that the hydraulic conductivity of the system is higher than expected. The increase in hydraulic conductivity can be explained by the presence of defects in the wall.

In Chapter 6, simulations were performed for various types of defects that are likely to exist in a CB wall. The defects that could have caused the high discharge are improper embedment of the panels, the occurrence of fully or partially penetrating windows, and the vertical deviation of the panels. However, partially penetrating windows have a smaller impact on the discharge than the other defects. The quantity, the area, and the combination of these defects determine the increase in discharge. For example, four windows within the CB wall (random locations) with an area of 1 m^2 or improper embedment of four panels (3 m) 50 cm above the top of the aquitard (see Figure 6.5) can lead to an increase in the discharge of approximately 400-500 m^3/day. Leakage of groundwater through the aquitard is excluded, because the CB walls are installed in the pot clay layer (aquitard). This clay layer has a very low vertical hydraulic conductivity ($<$ 0.0005 m/day) and a thickness of approximately 10 m.

The difference between the total allowed discharge and the measured discharge for Richard Hageman Akwadukt is approximately 450 m^3/day. Thus, four windows within the CB wall (random locations) with an area of 1 m^2 or improper embedment of four panels (3 m) 50 cm above the top of the aquitard can cause this amount of discharge.

8
Recommendations

Data
For certain projects, not all the data that was necessary for the calculation of the in-situ hydraulic conductivity was available. The following data is important for the analytical calculation:

- Long term groundwater monitoring: Piezometers should not only be used during the construction, but also after the construction. They have to be installed in the first and second aquifer inside and outside the construction to monitor the water levels during all stages of the project. The water level data can indicate the presence and location of defects. For motorway A2 at Best, the water level data was missing, which made it difficult to find the cause of the high groundwater inflow. Observation wells can also be installed to monitor the groundwater fluctuations by time.

- Subsurface data: Extensive geotechnical site investigation needs to be performed to get a better idea of the subsurface. For example, more CPT tests inside the construction. It is very crucial to gather detailed information (characterize geomechanical properties) of the underlying soil or rock, especially the clay layer, which will be used as a horizontal barrier. Lack of data can cause overestimation or underestimation of the allowed discharge, which was the case for motorway A4 Delft-Schiedam. It is also better to use very low permeable layers (horizontal hydraulic conductivity < 0.0005 m/day) as horizontal barriers to prevent seepage through the layer.

Analytical model
The different types of data sources made it difficult to develop a model to determine the in-situ hydraulic conductivity of CB walls. For different data sources, the data processing will be different. The discharge data is not always available. Most of the times, the discharge needs to be calculated from the pump operating hours.

Numerical model
Groundwater flow simulations should be performed for each project to get a better understanding of the expected discharge and to compare the analytical and numerical results with each other.

CPTU test
Implementation of the piezocone penetration test (CPTU) as an on-site quality control/quality assurance (QC/QA) method for constructed CB walls can provide a profile of in-situ hydraulic conductivity versus depth. To estimate the hydraulic conductivity, the cone is pushed into the center of the wall. The excess pore pressure dissipation at the shoulder of the cone (u_2) is also recorded with time. By observing the excess pore pressure measurements during penetration, high hydraulic conductivity zones can be detected in an early stage. It is also important that the piezocone has an inclinometer to ensure that the device stays in the wall. The test should not be performed on older walls, because cracks can occur in the wall.

Slurry
It must be ensured that the slurry composition is according to the requirements in the contracts. The slurry should be mixed properly, and the cement content should not be lower than required. The slurry should be tested in the laboratory before placing it in the trench to guarantee that all required properties are met. The high density of the slurry can indicate the presence of excess solids. Excess solids need to be removed to ensure that they do not settle to the bottom of the trench. This can lead to high hydraulic conductivity areas within the wall.

Verticality
Verticality of the excavated trench is also an important factor. Inclinometers can be used to avoid vertical deviation of the panels. The maximum allowed vertical deviation is in the range of 0.5% - 1%.

Inspections
Frequent (annually) inspection of the monitoring or observation wells, the walls and pumping systems can help to detect defects in an early stage.

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