Scour holes in tidal rivers with heterogeneous subsoil under anthropogenic influence
Scour holes in tidal rivers with heterogeneous subsoil under anthropogenic influence

Thesis report

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Preface

This research thesis is the final part of my master in Hydraulic Engineering at Delft University of Technology. The research focuses on the development of scour holes in the Rhine-Meuse delta in the Netherlands and was carried out in cooperation with Deltares.

First I would like to thank my graduation committee for guiding me through the last part of my master and to help me with the questions I faced. Wim Uijttewaal was very involved especially in the experimental part of the research and was of great help with carrying out the experiments and analyzing our observations. Erik Mosselman was always available for questions, was of great help with setting up the structure of the report and his honesty on what was expected of me during the entire period is much appreciated. Kees Sloff his enthusiastic response on my work and suggestions on what to investigate further was appreciated especially since most of the time he was abroad. Yorick Broekema, although not officially in my graduation committee, was of help since he was investigating a similar topic and gave good suggestions on what I could do to improve my report. But most of all, my appreciation goes out to my daily supervisor, Ymke Huismans. She was always available for help on every level and puts a lot of her own time in guiding students through their research. Her perfectionism and will to get the most out of my capacities tilted this research to a higher level and made me learn a lot about how to perform a research but more importantly, about myself as a person and my capabilities.

The technical staff of the Waterlab consisting of Sander de Vree, Hans Tas, Frank Kalkman, Arno Doorn and Jaap van Duin, was of great help constructing and preparing the water flume for use. When the experiments started they continued helping were necessary and made the whole process a lot quicker and easier than it would have been otherwise. Although it was short, I had a great time in the Waterlab thanks to the staff.

Rijkswaterstaat is responsible for the gathering of a large amount of data I used in my analysis. Special thanks goes out to Aad Fioole who was responsible for providing me with this data and his opinion on my methods an interpretations is much appreciated.

From Deltares I would like to thank Olav van Duijn and Gijs Hoffmans. Olav van Duijn helped me to use the required software to perform my analysis. Gijs Hoffmans spend a large amount of his time guiding me through all there is to know about scour and encouraged me to add my knowledge and observations to what was already known.

Last I would like to thank my family and friends for their unconditional support. Special thanks goes out to Joost Stenfert, Sam Bom, Gerben Postema, Hugo van Es and Sebastiaan Klaver for reading parts of my report and Hilde Keizer for her creative advice. Moreover, the group of the Deltares students became good friends who were of great help and offered some distraction during these seven months. Finally I would like to thank my parents for their ”good luck”-messages almost every day in the last couple of weeks.

Hilde Koopmans
Delft, April 2017
Abstract

Over one hundred scour holes are located in the Rhine-Meuse delta. These scour holes have relatively large depths and steep slopes and could pose a risk to the stability of river banks and hydraulic structures, especially since some scour holes are still growing. Scour holes develop at locations where either the hydrodynamics or the erodibility of the soil varies locally. In the Rhine Meuse delta, the subsoil stratigraphy is believed to play a large role (Huismans et al., 2016; Sloff et al., 2013), as it is composed of alternating layers of poorly erodible clay and peat and highly erodible sand (Berendsen and Stouthamer, 2001; Hijma, 2009; Wiersma, 2015). Local and large scale erosion are therefore not evenly distributed over the river bed and at locations where a top layer of clay or peat becomes too thin, exposure of an underlying layer of sand can result in a scour hole. Anthropogenic activities also have a large impact on the development of scour holes, such as the presence of hydraulic structures (e.g. groynes, bridge piers) and changes in geometry, which cause local changes in hydrodynamics. Moreover, deepening of river beds by dredging may have removed protective clay layers exposing underlying sand bodies. Finally, the closure of the Haringvliet caused higher flow velocities and therefore erosion in the connecting branches in the central part of the delta (Huismans et al., 2016; Sloff et al., 2011, 2013).

In order to judge the potential risk, understanding is needed on the behaviour of scour holes in the Rhine-Meuse delta. A thorough data analysis is therefore performed on a large set of bed topography data. By performing experiments in a scale model more knowledge is obtained on the detailed physical processes influencing scour hole development. In order to predict future scour hole development the applicability of the method of Breusers (1965) is tested that predicts the depth and slopes of scour holes behind bed protections.

As a first step in this research an attempt is made to develop an objective and generic identification method in order to identify scour holes in the future or in other river branches. Although a method based on the statistical characteristics of the river bed results in a good first approximation to indicate scour zones, the analysis shows that bed irregularities and large variations in scour hole shapes and sizes complicates this method. It is therefore advised to always study scour holes in more detail individually.

As the closure of the Haringvliet in 1970 led to erosion in the connecting branches, it is likely that this also influenced the growth of scour holes in that area. After relating the current growth of the scour holes in the delta to the current bed level trends, it is seen that despite these degrading bed levels, the scour holes in the connecting branches do not show the largest growth. This is explained by studying the evolution of scour hole growth over the last five decades in two connecting branches (Oude Maas and Dordtsche Kil). It shows that most scour holes in the area already exist for decades and have reached a stable state. Most of the scour holes show a large growth after 1970 which is likely related to enhanced flow velocities caused by the Haringvliet closure. However, the analysis furthermore shows that only few scour holes developed just after 1970 of which some are expected to have been caused by dredging activities (Huismans and Duin, 2016). The influence of the Haringvliet closure on the development of new scour holes seems therefore limited.
The analysis of long term evolution of scour holes in the Oude Maas and Dordtsche Kil furthermore shows that the scour hole behaviour varies strongly and does not show similar trends, not even when they are located in the same river reach. This is likely related to the large variations in local conditions such as changes in geometry, the presence of structures, such as bridges and groynes, and the composition of the subsoil.

When applying the theory of Breurers (1965) on the scour holes in the delta, the flow velocity needs to be corrected for the tide. For this a factor of 0.73 has been derived. Even by using this factor, Breurers’ theory overestimates the scour hole depth as observed in the field and the slopes of the scour holes vary strongly from what is expected. The most important explanation is that Breurers’ theory is based scour behind a non-erodible bed protection, whereas scour holes in the Rhine-Meuse delta are surrounded by poorly-erodible layers due to the heterogeneous subsoil. These layers limit scour hole growth and can cause very steep slopes. Moreover, Breurers’ theory is based on clear-water conditions, while the scour holes in the delta are expected to be subjected to live-bed conditions, where there is an inflow of sediment decreasing the maximum scour hole depth.

Scale model experiments simulating 3D scour hole development under a poorly erodible top layer showed an increase in scour hole depth compared to experiments which were performed under quasi-2D conditions (Zuylen and Sloff, 2015). This verifies the expectation that 3D effects can enhance scour hole development (Mosselman and Sloff, 2002). Moreover, an attempt was made to simulate a poorly erodible layer as observed in the delta. Although it gives insight in the behaviour of a scour hole when it is not limited in width and length, scaling mechanisms challenge the correct failure behaviour of the poorly erodible layer in the scale model. The experiments did show that scour hole growth is slower, when limited in the downstream direction by a poorly erodible layer.

It is recommended that the growth of scour holes in width is studied as the sideways growth of scour holes can cause potential risk to the stability of the river banks. Moreover, as the subsoil stratigraphy is of large influence on scour hole development in the Rhine-Meuse delta, more geological research should be done on the levels of the varying soil layers, the locations of channel belts and the stability the scour hole slopes.

In order to obtain more knowledge on the processes of scour hole development in the Rhine-Meuse delta more scale model experiments need to be performed. An attempt can be made by finding material that shows more agreement with the clay layer in the field. To study the 3D effects in more detail, the flow velocities in and around the scour hole need to be measured during the experiments. Other aspects also need to be considered, such as the sideways growth of scour holes and variations in scour hole shapes, flow velocities, bed roughnesses and local water depths. These experiments will provide useful information to improve the relations that predict future scour hole development. This knowledge will also help to determine the protection measures that need to be taken in order to reduce the risks of scour holes in the Rhine-Meuse delta.
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<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$</td>
<td>m</td>
<td>Width of the waterway</td>
</tr>
<tr>
<td>$C$</td>
<td>m$^{1/2}$/s</td>
<td>Chézy coefficient</td>
</tr>
<tr>
<td>$C_0$</td>
<td>m$^{1/2}$/s</td>
<td></td>
</tr>
<tr>
<td>$D$</td>
<td>m</td>
<td>Height of a sill</td>
</tr>
<tr>
<td>$d$</td>
<td>m</td>
<td>Grain size</td>
</tr>
<tr>
<td>$d_n$</td>
<td>m</td>
<td>Nominal grain diameter</td>
</tr>
<tr>
<td>$d_{50n}$</td>
<td>m</td>
<td>Median nominal grain diameter</td>
</tr>
<tr>
<td>$f_c$</td>
<td>-</td>
<td>Roughness factor, $f_c = C/C_0$, with a minimum of $f_c = 1$</td>
</tr>
<tr>
<td>$g$</td>
<td>m$/s^2$</td>
<td>Gravitational constant/Acceleration of gravity</td>
</tr>
<tr>
<td>$h_0$</td>
<td>m</td>
<td>Local water depth</td>
</tr>
<tr>
<td>$i$</td>
<td>-</td>
<td>Slope in water level $dz/dx$</td>
</tr>
<tr>
<td>$K$</td>
<td>m$^{2.3}/s^{3.3}$</td>
<td>Calibration coefficient for the characteristic time scale, $t_1$</td>
</tr>
<tr>
<td>$k_s$</td>
<td>m</td>
<td>Equivalent Nikuradse roughness</td>
</tr>
<tr>
<td>$L$</td>
<td>m</td>
<td>Length of a bed protection</td>
</tr>
<tr>
<td>$M_s$</td>
<td>kg</td>
<td>Grain mass</td>
</tr>
<tr>
<td>$R$</td>
<td>m</td>
<td>Hydraulic radius $R = \frac{bh_0}{2b^2 + h_0}$</td>
</tr>
<tr>
<td>$r_0$</td>
<td>-</td>
<td>Relative turbulence intensity</td>
</tr>
<tr>
<td>$S$</td>
<td>m$^2$/s</td>
<td>Sediment transport per unit of time and width</td>
</tr>
<tr>
<td>$T$</td>
<td>h</td>
<td>$t_b - t_a$ half tidal period where $\alpha \bar{u} &gt; u_c$</td>
</tr>
<tr>
<td>$t$</td>
<td>h</td>
<td>Time</td>
</tr>
<tr>
<td>$t_1$</td>
<td>h</td>
<td>Characteristic time at which $y_m = \lambda$</td>
</tr>
<tr>
<td>$t_a$</td>
<td>h</td>
<td>Time at which $\alpha \bar{u}$ first exceeds $u_c$ during flood tide</td>
</tr>
<tr>
<td>$t_b$</td>
<td>h</td>
<td>Time at which $\alpha \bar{u}$ drops below $u_c$ during ebb tide</td>
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<tr>
<td>$u$</td>
<td>m$/s$</td>
<td>Flow velocity</td>
</tr>
<tr>
<td>$\bar{u}$</td>
<td>m$/s$</td>
<td>Depth averaged flow velocity in front of the scour hole</td>
</tr>
<tr>
<td>$\bar{u}_c$</td>
<td>m$/s$</td>
<td>Mean critical flow velocity</td>
</tr>
<tr>
<td>$u_{*c}$</td>
<td>m$/s$</td>
<td>Critical bed shear velocity</td>
</tr>
<tr>
<td>$u_d$</td>
<td>m$/s$</td>
<td>Characteristic depth averaged flow velocity</td>
</tr>
<tr>
<td>$u_{max}$</td>
<td>m$/s$</td>
<td>Maximum flow velocity</td>
</tr>
<tr>
<td>$</td>
<td>u(m + 1)</td>
<td>$</td>
</tr>
<tr>
<td>$V_s$</td>
<td>m$^3$</td>
<td>Grain volume</td>
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<tr>
<td>$x$</td>
<td>m</td>
<td>Coordinate along horizontal axis</td>
</tr>
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<td>$y_m$</td>
<td>m</td>
<td>Maximum scour depth</td>
</tr>
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<td>$y_{m,e}$</td>
<td>m</td>
<td>Equilibrium scour depth</td>
</tr>
<tr>
<td>$y_m(m)$</td>
<td>m</td>
<td>Scour depth at time step m</td>
</tr>
<tr>
<td>$y_m(m + 1)$</td>
<td>m</td>
<td>Scour depth at time step m+1</td>
</tr>
<tr>
<td>$z$</td>
<td>m</td>
<td>Height in the water column with respect to the bed level</td>
</tr>
<tr>
<td>$z_0$</td>
<td>m</td>
<td>Roughness height</td>
</tr>
<tr>
<td>$z_b$</td>
<td>m</td>
<td>Bed level with respect to NAP</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
<td>Units</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>α</td>
<td>Amplification factor for flow velocity</td>
<td></td>
</tr>
<tr>
<td>β</td>
<td>Upstream slope angle</td>
<td>°</td>
</tr>
<tr>
<td>γ</td>
<td>Exponent in the scour hole development in time equation</td>
<td></td>
</tr>
<tr>
<td>Δ</td>
<td>Relative density $\frac{\rho_s - \rho_w}{\rho_s}$</td>
<td></td>
</tr>
<tr>
<td>η</td>
<td>Tidal flow reduction factor</td>
<td></td>
</tr>
<tr>
<td>κ</td>
<td>Constant of Karman $\kappa = 0.4$</td>
<td></td>
</tr>
<tr>
<td>λ</td>
<td>Characteristic length scale</td>
<td>m</td>
</tr>
<tr>
<td>ν</td>
<td>Kinematic viscosity</td>
<td>(m²/s)</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>Density of sediment</td>
<td>kg/m³</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>Density of water</td>
<td>kg/m³</td>
</tr>
<tr>
<td>$\tau_c$</td>
<td>Critical shear stress</td>
<td>N/m²</td>
</tr>
<tr>
<td>$\psi_c$</td>
<td>Critical mobility parameter</td>
<td></td>
</tr>
<tr>
<td>$\omega$</td>
<td>Turbulence coefficient</td>
<td></td>
</tr>
</tbody>
</table>

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Chapter 1

Introduction

1.1 Background

The Rhine-Meuse delta, shown in figure 1.1, is located in the most used and densely populated part of the Netherlands. At the moment there are over one hundred identified scour holes located in the river branches of the delta, see figure 1.2. These holes and their steep slopes may pose a risk to the stability of riverbanks, dikes, hydraulic structures and also to underlying cables and tunnels. Especially since most of the scour holes still show growth in depth or extent. To guarantee safety and navigability of the rivers it is of great importance that the dynamics of those scour holes are closely monitored and understood where possible.

Scour holes develop at locations where there is local erosion of the river bed, which can result in a significant local deepening of the river bed. Erosion is influenced by the hydrodynamic conditions of the river flow and the geological conditions of the river bed. The local hydrodynamic conditions of a river are influenced by local changes in geometry which influence the flow velocity. This can be of a more natural kind (e.g. in bends, confluences), but can also occur around hydraulic structures (e.g. bridges, groynes). The geological conditions of the river bed are influenced by the heterogeneity of the subsoil in the Rhine-Meuse Delta. The delta is located in a tidal area and due to the inflow of sediment from the rivers and the sea, the subsoil is composed of alternating layers of poorly erodible clay and peat and highly erodible sand (Berendsen and Stouthamer, 2001; Hijma, 2009; Wiersma, 2015). Local and large scale erosion are therefore not evenly distributed over the river bed and local incision of sand patches underneath poorly erodible layers could result in deep scour holes. Another important fact that influences the development of scour holes in the Rhine-Meuse delta is presumed to be the closure of the Haringvliet estuary in 1970 which is situated in the south of the delta (Sloff et al., 2013). The Haringvliet sluices are separating the estuary from the sea, allowing tidal flows to enter the delta only from the northern part of
CHAPTER 1. INTRODUCTION

the delta. The rivers that connect the tidal inlet with the estuary are consequently subjected to higher flows and experience erosion since 1970. It is therefore expected that the Haringvliet closure enhanced scour hole development. Moreover, as ship sizes have increased over time, several rivers have been deepened by dredging works to provide sufficient water depth (Sloff et al., 2011). It is possible that by dredging the river beds, protective clay layers have been removed, exposing underlying sand layers in which scour holes can form (Huismans et al., 2016).

1.2 Problem description

More than one hundred scour holes are identified in the Rhine-Meuse delta. However, the process of identifying a scour hole is rather complex due to varying dimensions and locations. Therefore, a generic method to identify scour holes is still missing, which might be of great use to automatically detect new scour holes. In order to predict the moment when scour holes are starting to form a risk for nearby dikes or structures, knowledge is needed on how these scour holes develop in time. Field data analysis so far has been focused on either the recent development (last 5 years) of many scour holes or the longer development (40 years) of a few scour holes. A systematic study of many scour holes over a large period is still missing. Scale model tests have so far been focused on the quasi 2D cases, with non-erodible top layers, which is a very schematised representation of the reality. A more realistic case of a 3D situation with a poorly erodible top layer has not been studied yet. For scour holes behind structures, methods exist to predict their depth and slope development in time (Breusers, 1965). From here on these methods will be referred to as "Breusers’ theory”. An attempt was done to adapt this theory to scour hole development in a tidal area with heterogeneous subsoil by Zuylen and Sloff (2015) based on field data analysis and experiments in a scale model. However, the results do not agree with the predictions based on the theory. It is expected that aspects such as the tidal influence, the heterogeneous subsoil and 3D effects are of great influence. It is therefore required to further investigate those aspects and the significance of their influence on scour hole development.

1.3 Objective

The goal of this research is to obtain a better understanding of scour hole development in the Rhine-Meuse delta. It aims at the identification of scour holes, finding their possible causes and following their development in time. In addition this research intends to contribute to the knowledge on the physical processes around scour hole development and to give insight into the influence of the tide, the heterogeneous subsoil and human interventions.

Main research question

How do scour holes develop in tidal rivers with heterogeneous subsoil under anthropogenic influence?

Sub questions

1. Is it possible to make use of a generic method to identify scour holes?
2. What is the influence of the Haringvliet closure on scour hole development?
3. How does a heterogeneous subsoil influence scour hole growth in depth and extent?
4. Do scour holes show similar behaviour when located in the same river reach?
5. Is Breusers’ theory applicable to scour holes in a heterogeneous subsoil under influence of tidal flow?
6. How does the shape of a scour hole influence the 3D flow pattern around the hole and with this the development of the scour hole with respect to a 2D shaped scour hole?
CHAPTER 1. INTRODUCTION

1.4 Approach and outline of the report

In order to obtain a first understanding of the processes of scour in general and scour hole development in the Rhine-Meuse delta, a review of data, literature and previous studies is performed in Chapter 2. As every scour hole develops in a different way, available field data of a large set of scour holes are analyzed thoroughly in Chapter 3. A suggestion for a generic method is given to identify scour holes in a river branch (subquestion 1). Moreover, an overview is made of all scour holes in the delta based on their current growth related to the possible aspects that cause this growth (subquestions 2, 3). In Chapter 4 the scour hole development in time is studied in two specific river branches. It gives insight into the influence of the heterogeneous subsoil and the Haringvliet closure on scour hole growth and if scour holes show similar behaviour when they are located in the same river reach (subquestion 2, 3, 4). By studying the depth and the slopes of the scour holes the applicability of the theory of scour hole development behind bed protections by Breusers (1965) is tested on scour hole development in the field (Subquestion 5). Finally, scale model experiments are performed to study the relevant hydrodynamic and morphodynamic processes of 3D scour hole development in a heterogeneous subsoil (subquestions 3 and 6). In Chapter 5 the results of the experiments are discussed and the applicability of Breusers’ theory is tested on scour hole development in the scale model as well (Subquestion 5). The conclusions and recommendations regarding this research are presented in Chapter 6.
Chapter 2

Review of data, literature and previous studies

This chapter contains the background information needed for this research on scour hole development in the Rhine-Meuse delta. It starts with a description of the characteristics of the Rhine-Meuse delta and its historical background. Then a schematic overview is given of scour hole development. Along with a short explanation, it indicates all the important processes and aspects which are elaborated further on in this chapter. The principle of sediment transport is explained first, in order to understand the occurrence of scour holes in general. Combining the specific information on the Rhine-Meuse delta with the knowledge on scour it becomes clear why this specific delta contains a large amount of these scour holes.

Once a scour hole starts to grow, it is interesting to follow its growth in time in order to predict future development. A description of scour hole development behind bed protections is therefore introduced, which shows similarities with scour hole development in heterogeneous subsoil. It discusses the processes in and around scour holes and introduces a method to determine the depth and slopes of a scour hole. Finally, the most recent attempt to adapt this method to scour holes in the Rhine-Meuse delta is presented. Since it shows deviations with what is seen in the field, possible solutions and recommendations are treated in order to determine the steps that have to be taken to make the theory more suitable for scour holes in the Rhine-Meuse delta.

2.1 History of the Rhine-Meuse delta

The current shape and location of the Rhine-Meuse delta dates back to about 11,000 years ago, around the end of the Pleistocene. During the Pleistocene, glacial periods caused the sea level to drop, which rose again during warmer periods. This caused sediment inflow from both the sea and the rivers, resulting in a subsoil composed of layers of clay and coarse sand. The last layer formed in the Pleistocene consists of poorly-erodible clay, known as the ‘layer of Wijchen’ which spreads over a large part of the current delta area. At the same time river avulsions and their deposits caused so-called channel belts consisting of medium fine sand to be embedded in the subsoil. Some channel belts intersect the ‘layer of Wijchen’ which causes the erosion resistant layer to be interrupted by a highly erodible sand body. When the last glacial period came to an end, the quick sea level rise caused a landwards movement of the coastline transforming the area in a sedimentation area. It also caused a rising ground water level in the hinterland, resulting in swamps initiating the formation of peat. During later flood events sediments from the river settled on top of the peat layer covering it with a thick clay layer. Throughout history, this has led to a very heterogeneous subsoil stratigraphy composed of alternating poorly erodible clay and peat layers and highly erodible sand layers (Berendsen and Stouthamer, 2001; Cohen et al., 2012; Hijma, 2009; Kleinhans et al., 2013, 2010; Wiersma, 2015). Figure 2.1 illustrates the evolution of

Scour holes in tidal rivers with heterogeneous subsoil under anthropogenic influence
the Rhine-Meuse delta starting from 9000 BC.

Figure 2.1: The evolution of the Rhine-Meuse delta since 9000 BC, the end of the last glacial period (Vos and Vries, 2013). Where in (a) the soil consists of mainly sand; (b) layers of peat (brown) and clay (green) develop; (c) the delta is under anthropogenic influence.

A hypothetical subsoil profile is illustrated in figure 2.2, showing the alternating layers of sand, clay and peat of which some are incised by sandy channel belts.

Figure 2.2: Hypothetical subsoil composition of the Rhine Meuse delta (Huismans and Duin, 2016).

The delta has also been subjected to a long history of anthropogenic influences (Sloff et al., 2011; Vellinga et al., 2014; Vermeer and Mosselman, 2005). In order to improve the infrastructure and navigability of the waterways, changes were made in the course and geometry of river branches and hydraulic structures were constructed. As a reaction to the flood of 1953, the ‘Delta works’ were introduced to protect the delta area from future floods and salt intrusion. In 1970, as part of the ‘Delta works’, the Haringvliet sluices were completed. It closed off the Haringvliet estuary from the sea and consequently also the tide. Now the tidal wave enters the area only through the Nieuwe Waterweg, having a larger tidal prism than before due to larger differences in water level between the northern and southern parts of the delta (Vellinga et al., 2015). Therefore, the rivers that connect the tidal inlet with the estuary are subjected to higher flow velocities. The tide also causes large variations in these flow velocities and even alternates the flow direction in the tidal rivers. On the contrary, since the rivers supply a large amount of sediment to the delta, the northern and southern rivers of the delta are subjected to sedimentation. At those locations the river bed is deepened by dredging to maintain a sufficient navigable water depth for ships. It is possible that clay layers are removed by dredging works, exposing underlying sand layers (Huismans et al., 2016).

### 2.2 The principle of scour hole development

A river flow has a certain capacity to transport sediment which causes some river parts to erode and others to sedimentate. Depending on the hydrodynamics of the river flow and the geological conditions of the river bed, it is possible that local and large scale erosion is not evenly distributed.
over the river bed. If this results in a much larger depth with respect to the surrounding river bed and the dimensions are significantly larger than local bed forms, this can be identified as a scour hole. An example of scour hole development due to variations in subsoil stratigraphy is illustrated in figure 2.3. A detailed explanation of scour hole development, different causes for scour and its related processes is given in the next section.

Figure 2.3: Schematisation of scour hole development in a heterogeneous subsoil.

2.2.1 Sediment transport

The process of sediment transport is different for non-cohesive sediments (e.g. sand) and cohesive sediments (e.g. clay, peat) and is therefore treated separately.

Non-cohesive sediment

The initiation of motion of non-cohesive material in uniform flow is described by Shields (Schiereck, 2012). According to Shields, grains begin to move when the load of the flow that acts upon the river bed exceeds the strength of the river bed. The load of the flow can be seen as a shear stress, acting on the surface of a grain. The strength of non-cohesive material can be seen as the relative weight of a grain. This ratio is expressed as the critical mobility parameter, $\psi_c$, in equation 2.1, assuming a uniform flow and a width that is much larger than the water depth.

$$\psi_c = \frac{\text{load}}{\text{strength}} = \frac{\tau_c d^2}{(\rho_s - \rho_w) g d^3} = \frac{u_{*,c}^2}{\Delta g d} = \frac{\bar{u}_c^2}{C^2 \Delta d}$$  \hspace{1cm} (2.1)

$\psi_c$  \hspace{0.5cm} critical mobility parameter (-)
\tau_c  \hspace{0.5cm} critical shear stress (N/m$^2$)
d  \hspace{0.5cm} grain size (m)
\rho_s  \hspace{0.5cm} density of sediment (kg/m$^3$)
\rho_w  \hspace{0.5cm} density of water (kg/m$^3$)
g  \hspace{0.5cm} Acceleration of gravity (m/s$^2$)
u_{*,c}  \hspace{0.5cm} critical bed shear velocity (m/s)
\Delta  \hspace{0.5cm} relative density $\frac{\rho_s - \rho_w}{\rho_s}$ (-)
\bar{u}_c  \hspace{0.5cm} depth averaged critical flow velocity (m/s)
C  \hspace{0.5cm} Chézy coefficient (m$^{1/2}$/s)

Since a grain is not a smooth sphere, it is common to use the median value of the nominal diameter, $d_{n50}$, instead of the grain diameter $d$. The nominal diameter is simply the side of a cube with the same volume as the grain. This volume is determined based on the mass of the sediment and its density.

$$d_n = \sqrt[3]{V_s} = \sqrt[3]{\frac{M_s}{\rho_s}}$$  \hspace{1cm} (2.2)

$d_n$  \hspace{0.5cm} nominal grain diameter (m)
$V_s$  \hspace{0.5cm} grain volume (m$^3$)
$M_s$  \hspace{0.5cm} grain mass (kg)
\rho_s  \hspace{0.5cm} density of sediment (kg/m$^3$)

The median value, $d_{n50}$, indicates that 50% of all grains is smaller or larger than that value.
CHAPTER 2. REVIEW OF DATA, LITERATURE AND PREVIOUS STUDIES

The Chézy coefficient is calculated with the following relation:

\[ C = 18 \log \left( \frac{12R}{k_s} \right) \]  \hspace{1cm} (2.3)

\( R \) : hydraulic radius \( R = \frac{bh}{2b+h} \) (m)
\( b \) : width of the waterway (m)
\( h \) : local water depth (m)
\( k_s \) : equivalent Nikuradse roughness (m)

Due to irregularities in stones, position, protrusion, the turbulence of the flow and many other aspects, there is no such thing as one critical flow velocity. Therefore, Shields formed a graph which shows a broad belt of grain movement but now divided in several stages, see figure 2.4. The Shields criterion fits stage 6, which is the stage of continuous movement of grains.

![Shields diagram with \( D^* = d_{50} (\Delta g / \nu^2)^{1/3} \) (Hoffmans and Verheij, 1997).](image)

Figure 2.4: Shields diagram, with \( D^* = d_{50} (\Delta g / \nu^2)^{1/3} \) (Hoffmans and Verheij, 1997).

When the width of the flow is large compared to the water depth, the critical flow velocity can be rewritten as shown in equation 2.4, where \( \psi_c \) is based on the stage of grain movement in the Shields diagram.

\[ u_c = 2.5 \sqrt{\psi_c \Delta g d_{50}} \ln(12h_0/k_s) \]  \hspace{1cm} (2.4)

A flow has a certain capacity to transport sediment which is related to the flow characteristics, like velocity and turbulence, and soil properties (Hoffmans and Verheij, 1997). A change in either of the two will cause a gradient in the transport capacity. Depending on the erodibility of the river bed, an increase in transport capacity (a positive gradient), will increase the transport of sediment causing the river bed to erode. On the other hand, when the flow is transporting a certain amount of sediment, a decrease in transport capacity of that flow (a negative gradient) will cause an accretion of the bed. This is summarized in the formula of Exner, equation 2.5. Note that in this equation a 1D situation is considered and the storage of the suspended sediment in the water column is neglected.

\[ \frac{\delta z_b}{\delta t} + \frac{\delta S}{\delta x} = 0 \]  \hspace{1cm} (2.5)

\( z_b \) : bed level with respect to NAP (m)
\( t \) : time (s)
\( S \) : sediment transport (m\(^2\)/s)
\( x \) : coordinate along a horizontal axis (m)

A new equilibrium may eventually be reached when the flow characteristics or soil properties are adjusted through the behaviour of the river bed.
CHAPTER 2. REVIEW OF DATA, LITERATURE AND PREVIOUS STUDIES

Cohesive sediment
Transport of cohesive material is more complex and can occur in two different ways (Hoffmans, 2012; Sloff et al., 2013). The first is abrasive erosion where the grains are slowly scraped off by the flow when the flow exerts a higher shear stress on the bed than the critical shear stress of the material. This type of erosion will cause an overall lowering of the bed level. The second type of erosion is the pulling-off of complete soil fragments by the flow. In general there are no applicable equations for the transport of cohesive sediments in relation to scour hole development, because in literature most equations are related to one specific sediment (Hoffmans and Verheij, 1997). Since the theory for scour hole development requires a critical flow velocity, a first estimate is given by Hoffmans and Verheij (1997) for critical flow velocities. For fairly compacted clay \( u_c = 0.80 \text{ m/s} \) and for stiff clay \( u_c = 1.5 \text{ m/s} \) can be assumed.

2.2.2 A description of scour hole development

When erosion occurs locally, it is known as scour. Scour is a case of sediment transport that can occur under two different types of conditions (Hoffmans and Verheij, 1997; Schiereck, 2012). When the sediment supply to the upstream flow is zero and the upstream does not contain any sediment, it is known as clear-water scour. This is possible due to a non-erodible bed or a flow that is too weak to transport sediment. The scour will reach an equilibrium when the scour hole reaches a depth that slows down the flow in such a way that it drops below the critical value. The second type of scour is live-bed scour. In this case, the upstream flow does contain sediment. Scour occurs when the sediment transport capacity of the flow is locally higher than upstream. The scour will reach its equilibrium when the local sediment transport capacity equals the upstream transport capacity.

Since scour holes are common to grow around hydraulic structures and pose a risk to their stability, extensive research has been done on this topic. It resulted in methods to determine equilibrium depths of scour holes around structures and the scour process as a function of time. More specifically, methods were developed to predict scour hole development behind bed protections of sills (Breusers, 1965; Dietz and Wittke, 1969; Hoffmans and Verheij, 1997; Meulen and Vinjé, 1975). A schematisation of the latter is shown in figure 2.5.

![Figure 2.5: Schematisation of a scour hole behind a bed protection in which the following parameters are indicated; waterdepth \( h_0 \), the upstream slope \( \beta \), the maximum scour hole depth \( y_m \), the mean flow velocity \( U \), the length of the bed protection downstream of a sill \( L \), the height of the sill \( D \), the flow discharge \( Q \) and the distance between the end of the bed protection and the maximum scour hole depth \( x_m \) (Hoffmans and Verheij, 1997).](image)

According to Breusers (1965) scour hole development downstream of a bed protection depends on the flow velocity and the turbulence intensity at the transition of the non-erodible and erodible bed. Based on physical model tests at different scales and with different bed materials, relations were derived for the scour hole process as function of time based on a certain length scale, see equation 2.6 (Breusers, 1965; Dietz and Wittke, 1969; Meulen and Vinjé, 1975).
\[
\frac{y_m}{y_{m,e}} = 1 - e^{\ln\left(1 - \frac{\lambda}{y_m}\right)\left(\frac{t}{t_1}\right)\gamma}
\]  
(2.6)

where:
- \(t_1\) is the characteristic time when \(y_m = \lambda\)
- \(y_m\) is the maximum scour depth in meters
- \(y_{m,e}\) is the equilibrium scour depth in meters
- \(\gamma\) is the exponent
- \(\lambda\) is the characteristic length scale in meters

In this equation, \(t_1\) stands for the time that is needed to reach a scour hole depth equal to a certain length scale (\(\lambda\)) and is therefore related to a certain volume of sediment that is eroded. Many definitions of characteristic length scales are found in literature varying from the size of eddies to the size of a hydraulic structure (Hoffmans and Verheij, 1997). Based on extensive analysis of results from scale model tests, different values were found for \(\gamma\), see table 2.1.

Table 2.1: Values for \(\gamma\), empirically determined based on the results of scale model tests.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>(\gamma)</th>
<th>Flow condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breusers (1965)</td>
<td>0.38</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>Mosonyi (1968)</td>
<td>0.27 - 0.35</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>Dietz and Wittke (1969)</td>
<td>0.34 - 0.40</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>Meulen and Vinjé (1975)</td>
<td>0.4 - 0.8</td>
<td>Three-dimensional</td>
</tr>
</tbody>
</table>

Depending on the local hydrodynamics and soil properties, scour holes develop under clear-water or live-bed conditions. In the case of clear-water scour, the depth of a scour approaches an equilibrium depth asymptotically (Hoffmans and Verheij, 1997), see figure 2.6. Since the upstream flow under clear-water conditions does not contain sediment, the flow has a lower upstream velocity than the critical velocity of the upstream river bed. Under the same geological conditions, live-bed scour will occur under a higher flow velocity which is higher than the critical flow velocity of the upstream river bed. It will therefore result in a faster scour hole growth, but it will eventually result in a smaller scour depth than in clear-water scour situations. In the case of live-bed scour, the scour rapidly increases in time and ends up fluctuating about a mean value depending on the passing bed forms.

Figure 2.6: Clear water and live bed scour hole development (Hoffmans and Verheij, 1997).

Four phases were distinguished in the process of clear-water scour, based on experiments simulating scour hole development behind a non-erodible bed protection (Breusers, 1965; Dietz and Wittke, 1969; Zanke, 1978). An illustration of the scour process is shown in figure 2.7 and the four different phases are indicated in the diagram of figure 2.8.
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Figure 2.7: Schematisation of scour behind a (a) sill (b) bed protection (Hoffmans and Verheij, 1997).

Figure 2.8: The four different phases of clear water scour (Hoffmans and Verheij, 1997).

It starts with an initiation phase where the bed material near the upstream scour slope starts to move. It is followed by the development phase where the upstream slope of the hole separates the flow, causing a mixing layer and below that a recirculation zone. At the end of this zone the flow touches the bed again at the so-called reattachment point (Schiereck, 2012). The area near that point and slightly downstream appears to be the point of maximum attack by the flow. The recirculation zone and the reattachment point are illustrated in figures 2.7a and b. In the development phase the erosion is most severe and the scour hole grows mainly in depth. In the recirculation zone the upper part of the upstream slope stays constant due to a balance between the downstream and upstream directed flow. As the scour hole deepens the stabilization phase starts. The transport capacity of the flow decreases due to a decrease in flow velocity. As the reattachment point moves downstream the scour hole keeps growing in longitudinal direction. During the final equilibrium phase the dimensions of the scour hole no longer change significantly.

For scour hole development behind bed protections of sills the characteristic length scale is based on the local water depth, \( h_0 \) (Hoffmans and Verheij, 1997). In this case \( t_1 \) is the time that is needed to reach a scour hole depth equal to the initial water depth. Assuming that the slopes of a scour hole are constant, the length of a scour hole also depends on the scour hole depth. Therefore,
the volume of a scour hole is directly related to a coefficient \( K \), \( h_0^2 \) and the relative density of the sediment with respect to water \( V \approx K h_0^2 \Delta \). The time that is needed to transport this volume is related to the transport capacity of the flow, which is based on the flow velocity and the critical flow velocity. In the development phase \( t < t_1 \), the equation for scour hole development in time can be reduced to equation 2.7, the original scour relation of Breusers (1965).

\[
y_m \frac{h_0}{h_0} = \left( \frac{t}{t_1} \right) \gamma \quad \text{with} \quad t_1 = \frac{K h_0^2 \Delta}{(\alpha \bar{u} - \bar{u}_c)^{4.3}}
\]

\( K \) calibration coefficient for the characteristic time scale, \( t_1 \) \( (m^{2.3}/s^{3.3}) \)

\( \alpha \) amplification factor for the flow velocity \((-)\)

However, equation 2.7 is only representative for the beginning of scour hole development (for \( t < t_1 \)) and shows linear growth after \( t_1 \) instead of reaching an equilibrium state. Moreover, equation 2.6 is only valid for situations where the equilibrium depth, \( y_{me} \), is larger than the local water depth, \( h_0 \), and is therefore not applicable for small flow velocities or less erodible soil types (Hoffmans and Verheij, 1997). Therefore, equation 2.8 is developed by Velzen et al. (2014).

\[
y_m \frac{y_{me}}{y_m, e} = 1 - e^{-\left(\frac{t}{t_1}\right)^\gamma}
\]

In general a value of 330 \( m^{2.3}/s^{3.3} \) is applied for the coefficient \( K \), which was found valid for experiments with a rough bed (Graauw and Pilarczyk, 1981). In equation 2.7 the mean flow velocity is multiplied with a factor, \( \alpha \), that takes the turbulence \( r_0 \) of the flow into account. \( \alpha \) is expressed by equation 2.9 (Jorissen and Vrijling, 1989).

\[
\alpha = 1.5 + 5r_0
\]

\( r_0 \) relative turbulence intensity \((-)\)

A more general relation for the amplification factor is given by Hoffmans and Booij (1993). In this relation the factor \( f_c \) is introduced, which is related to the roughness of the bed protection, causing a higher value for \( \alpha \) for a smoother bed. In the case of a rough protection \( C = 45 \text{ m}^2/\text{s} \) equation 2.10 reduces to equation 2.9.

\[
\alpha = 1.5 + 4.4r_0 f_c \quad \text{with} \quad f_c = \frac{C}{40} \quad (f_c = 1 \text{ for } C \leq 40 \sqrt{\text{m/s}})
\]

\( f_c \) roughness factor, \( f_c = C/C_0 \), with a minimum of \( f_c = 1 \) \((-)\)

\( C_0 \) \( 40 \text{ m}^2/\text{s} \)

Equation 2.11 is deduced for the relative turbulence intensity by Hoffmans and Booij (1993).

\[
r_0 = \sqrt{0.0224 \left( 1 - \frac{D}{h_0} \right)^{-2} \left( \frac{L - 6D}{6.67h_0} + 1 \right)^{-1.08} + 1.45 \frac{\varrho}{C_0^2} \quad \text{for} \quad L > 6D}
\]

\( D \) Height of the sill (m)

\( L \) Length of the bed protection (m)

In case of non-steady flow the characteristic time scale is adapted. In case of a cyclic flow, for example a tidal river, the characteristic time can be represented by equation 2.12 (Hoffmans and Verheij, 1997).
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\[
t_{1, \text{cyclic}} = \frac{K h_0(0) \Delta^{1.7}}{\frac{4}{7} \int_{t_a}^{t_b} \frac{[\alpha \bar{u} - u_c]}{h_0(t)}^{1.3} dt}
\]  
(2.12)

- \( t_a \): time at which \( \alpha \bar{u} \) first exceeds \( u_c \) during flood tide (h)
- \( t_b \): time at which \( \alpha \bar{u} \) drops below \( u_c \) during ebb tide (h)
- \( T \): \( t_b - t_a \) half tidal period where \( \alpha \bar{u} > u_c \) (h)

In a tidal period the average flow velocity is lower than the maximum flow velocity. Therefore, to approximate scour hole growth in a tidal area a factor (\( \eta \)) can be used to determine a characteristic mean flow velocity which is corrected for varying flow velocities. This factor is almost independent of the type of sediment transport (Breusers, 1965). An approximation for the characteristic time scale for varying flow velocities is given in equation 2.13.

\[
t_{1, \text{cyclic}} = \frac{K h_0^2 \Delta^{1.7}}{(\alpha u_d - u_c)^{4.3}} \text{ with } u_d = \eta u_{\text{max}}
\]  
(2.13)

- \( u_d \): characteristic depth averaged flow velocity (m/s)
- \( \eta \): tidal flow reduction factor (-), \( \eta = 0.75 - 0.85 \)
- \( u_{\text{max}} \): maximum flow velocity during a tide (m/s)

In most situations the scour hole development in time is less important than the maximum depth a scour hole can reach. Therefore, the equilibrium scour hole depth is given by equation 2.14 (Dietz and Wittke, 1969).

\[
y_{m,e} = \frac{\omega \bar{u} - \bar{u}_c}{\bar{u}_c} \text{ with } \omega = 1 + 3 r_0
\]  
(2.14)

- \( \omega \): turbulence coefficient (-)

**Upstream slope**

The relation for the upstream slope of a scour hole in non-cohesive material behind a bed protection derived by equation 2.15 (Hoffmans, 1993; Hoffmans and Pilarczyk, 1995).

\[
\beta = \arcsin \left[ 3 \times 10^{-4} \left( \frac{u_0}{\Delta g d_{50}} \right)^2 + (0.11 + 0.75 r_0) f_c \right]
\]  
(2.15)

- \( \beta \): Upstream slope angle (°)

When the slope becomes too steep and reaches the angle of repose \( \phi \) (or its maximum angle of internal friction), it can not withstand the gravitational forces and any shear stress will cause motion of the particles. This is called micro-instability. Four different packings of fine sand and their corresponding possible type of failure due to critical slopes, are listed in figure 2.9 which are determined empirically by Silvis (1988) based on dike failures. For design purposes it is clear that the upstream slope has to be less than the critical value of the natural slope of the sediment in water (Hoffmans and Verheij, 1997). However, these criteria do not consider a scour situation with a bed protection which could cause the upstream slope to be somewhat steeper due to the recirculation zone. Characteristic values for the angles of repose for different materials are listed in figure 2.10 based on stagnant water conditions.

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When the slope becomes unstable it can slide into slopes with different steepnesses depending on the initial packing of the sediment. In case of densely packed sand it will transform to a looser packing. The creation of larger pores causes under pressure and inflow of water. This leads to an increase of effective stress and causes a temporarily stable slope. However, when the inflow of water is too large, breaching occurs. On the other hand, when the initial sand loosely packed, sliding will cause denser packing forcing the water out of the pores. This decreases the contact forces of the grains. Thereby, the shear strength is reduced, causing the sand acting like a thick fluid, called liquefaction. The two processes are illustrated in figure 2.11.

2.2.3 Scour hole development in the Rhine-Meuse delta

The Rhine-Meuse delta contains many structures like groynes and bridge piers. As mentioned in section 2.1, these structures cause local variations in the flow and an increase in turbulence,
causing scour holes to develop. Besides hydraulic structures, more natural aspects of the rivers can also influence local hydrodynamics, for example in bends and confluences. At these locations strong local erosion could occur, causing a scour hole to develop (Hoffmans and Verheij, 1997). An illustration of scour hole development around a structure is given in figure 2.12a.

Figure 2.12: Three different types of scour hole development in the Rhine-Meuse delta.

Besides the hydrodynamic aspects, the soil properties are also of large influence on scour hole development in the delta. As explained in the geological history of the delta in Section 2.1, the subsoil is very heterogeneous and consists of alternating layers of poorly-erodible cohesive clay and peat and highly erodible non-cohesive sand. This causes local and large scale erosion to be not evenly distributed over the river bed. Figure 2.12b shows an example of this process, where the top layer of the river bed consists of the cohesive material clay. There is an eroding trend in the river causing the entire clay layer to gradually degrade. When this layer becomes too thin at a specific location it can tear and a lump of clay is removed at once, exposing an underlying layer of sand. Since sand is more erodible than clay, erosion in that part is enhanced and a scour hole could form. Depending on the thickness and the behaviour of the surrounding clay layer, the scour hole can grow significantly in depth and area (Huismans et al., 2015; Sloff et al., 2013). A different situation occurs when sandy belts are embedded in the subsoil and are exposed to the river flow, illustrated in figure 2.12c. In this situation a scour hole can also develop, but the growth of the scour hole in depth and area is expected to be limited by the size of the channel belt and the thickness of the surrounding clay layer (Huismans et al., 2016).

As mentioned before, a scour hole can reach a stable state when it reaches a depth that slows down the flow in such a way that it drops below the critical value. In the Rhine-Meuse delta, scour hole growth can also slow down when it reaches a poorly-erodible layer deeper in the subsoil (Huismans et al., 2016).

Due to the increasing flow velocities in the tidal rivers due to the closure of the Haringvliet estuary these rivers experienced high erosion trends since 1970. An analysis of bed topography data by Huismans et al. (2016) concluded that the majority of the scour holes were already present before 1970. However, some of them show a strong development since 1970 and also new scour holes developed. The deepening of the non-tidal rivers by dredging could have caused removal of valuable protective clay layers (Huismans et al., 2016). It is expected that this has happened
during the deepening of the Dordtsche Kill in the 70’s and 80’s of the 20th century. Underlying sandy channel belts were exposed in which scour holes have developed.

2.2.4 Application of Breusers’ theory on scour holes in a heterogeneous subsoil under tidal influence

Since non-erodible bed protections show similarities with a poorly erodible clay layer, attempts are done to apply Breusers’ theory to scour holes in the Rhine Meuse delta (Huismans et al., 2015; Zuylen and Sloff, 2015). A first attempt was made by Zuylen and Sloff (2015) to apply the method to a situation of scour hole development in highly erodible sand layers covered by a poorly erodible clay layer, both for field data as for physical scale model tests.

First, the depth of a stable scour hole in the field was studied and compared to the equilibrium depth as predicted by the Breusers’ theory using the hydraulic conditions and soil properties of the field as input parameters. A slightly different equation for determining the equilibrium depth ($y_{m,e}$) was used (Schiereck, 2012).

$$y_{m,e} = \frac{0.5\alpha \bar{u} - \bar{u}_c}{\bar{u}_c} \text{ with } \alpha = 1.5 + 5r_0$$

(2.16)

According to Hijma (2009) the grain size of Pleistocene sand is approximately 350 µm and was assumed to correspond with a critical Shields value of $\psi_c = 0.054$ (critical shear stress $\tau_c = 0.30$ Pa). Zuylen and Sloff (2015) determined the depth averaged flow velocity in the Oude Maas based on measurements in March (year unknown) taken at the Spijkenisse bridge which are received from the Service Desk Data of Rijkswaterstaat. During ebb flow the flow velocity varies between 0.8 and 1.8 m/s and during flood the flow velocity varies between -0.5 and -1.6 m/s. Zuylen and Sloff (2015) chose an average value of 1.5 m/s.

The scour hole is situated in a river with a rough bed, therefore equation 2.10 reduces to equation 2.9. Since this situation does not include a sill, the height is reduced to zero ($D = 0$) and the clay layer can be simplified as a infinitely long non-erodible bed protection ($L = \text{infinite}$). This way, equation 2.11 reduces to equation 2.17.

$$r_0 = 1.21 \frac{\sqrt{gC}}{C}$$

(2.17)

The specific scour hole in the field should reach an equilibrium depth of 1.8 times the water depth when following the theory of Breusers (1965). The real depth of the scour hole was 0.7 times the water depth, which is significantly less deep than expected. Possible explanations for the overestimation by using Breusers’ theory were mentioned by Zuylen and Sloff (2015) and are mentioned below.

- **Tidal influence** - Since the area is situated in a tidal area, several rivers of the Rhine-Meuse delta are subjected to large variations in flow velocity and even reversing flows. This causes a lower average flow velocity than the flow velocity which was used in the calculations. An attempt was made to include the tidal influence by determining a reduction factor for the flow velocity using equations 2.12 and 2.13 for a sinusoidal tide of 12 hours with an amplitude of 1.6 m/s. A reduction factor of $\eta = 0.6$ was found. Moreover, reversing flow can change the shape of the scour hole. According to Breusers (1965), the upstream slope of a scour hole is steeper than the downstream slope. When the direction is reversed, bed load transport can be reduced due to a steeper downstream slope than usual.
- **Poorly erodible downstream top layer** - Since this scour hole is surrounded by a poorly erodible top layer, the growth in length and width is limited in contrast to Breusers’ theory which is based on scour behind a bed protection and is therefore only limited in upstream direction. When the scour hole is not limited in depth, an increase of the scour depth will cause steep slopes, which will reduce the amount of possible bed load.

- **Relative turbulence** - The prediction of the depth of a scour hole behind a bed protection assumes a turbulent eddy just downstream of the upstream edge, see figure 2.7. It causes pressure differences which causes particles to move up and down. An increase in relative turbulence increases the amplification factor for the flow velocity, \( \alpha \), leading to a stronger growth in depth. However, when the upstream slope is not too steep and the curvature around the edge is smooth, the flow does not separate but tends to follow the slope of the scour hole and a smooth flow velocity profile is possible. This reduces the turbulence and therefore the sediment transport. However, a decrease in turbulence also means an increase in local flow velocity which increases the amount of sediment transport. Depending on which aspect is dominant it could lead to a deeper or less deep scour hole.

To investigate the influence of these aspects on scour hole development, scale model experiments were carried out. The set up is shown in figure 2.13. A laboratory flume was used where two steel plates cover a layer of sand. On top of the plates coarse sand was glued to make the surface less smooth. During the experiments the distance between the steel plates was varied as well as the flow velocity. This way the flume simulated a river with a non-erodible bed and a local discontinuity in the top layer exposing an underlying sand layer in which a scour hole could grow. The experiments gave insight into quasi-2D scour hole development with a non-erodible top layer.

![Figure 2.13: Experimental setup in a water flume for scale model tests simulating scour hole development in a sand body (yellow) covered with a non-erodible top layer of steel. The steel plates expose a part of the sand body of x m to the flow which is directed from left to right (Zuylen and Sloff, 2015).](image)

First, experiments were done without a downstream steel plate, similar to the experiments of Breusers (1965). Using equation 2.7, assuming a value for \( \gamma = 0.4 \), similar scour hole development was found in the flume as expected by the theory. After studying the results of the scale model test a value of \( \gamma = 0.37 \) was found. Next, experiments were done with a downstream steel plate leaving a gap of 0.5 m in the middle to study the influence of a non-erodible downstream layer on scour hole growth. The results of the situations with and without a downstream steel plate are shown in figure 2.14.

Figure 2.14 shows that in the scale model the depth development of the scour hole with a downstream bed protection followed similar behaviour as without a bed protection in the first phase. When the scour hole reaches the downstream edge the undermining starts and the scour hole development is slowed down which could be caused by the non-erodible layer reducing the bed load transport. After six hours this results in a decrease in scour hole growth of about 10%. However, in the field it is expected that the undermined top layer will fail. This can occur in at least two ways according to Zuylen and Sloff (2015). First, the layer could crumble down and the scour hole continues to grow in depth and in downstream direction. Second, the top layer could behave as

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a falling apron, protecting the downstream slope. Although this is never observed in the field, it was simulated in a scale model experiment which showed that the undermining was reduced but did not influence the scour hole depth development.

To investigate the influence of reversing flows due to the tide an experiment was performed by Zuylen and Sloff (2015), where a scour hole was made by hand according to the shape as was seen in previous experiments but in an opposite direction by making a steep downstream slope and a mild upstream slope, shown in figure 2.15.

This enabled the flow to act on the scour hole in an opposite direction. The experiment showed that the flow was able to redistribute the sediments back to the expected shape. This could verify the hypothesis that the bed load is reduced by a steeper downstream slope when the flow is reduced which could reduce the scour hole depth.

2.3 Data

- Branch averaged bed level trends between 2000 and 2012 show if a river is subjected to an eroding or sedimentating trend, corrected with the change in bed level done by dredging works, see figure 2.16 (Becker, 2015). The exact magnitude of the trend per river branch can be found in Appendix A. Although these trends are based on a specific period, the last couple of decades show similar trends (Dreumel, 2005; Snippen et al., 2005).

- Surveys by Rijkswaterstaat are performed where the depth was measured of each river branch in the Rhine-Meuse delta. The measurement equipment itself and the way the collected data is processed improved over the years, causing the data to be available in different forms, as listed in table 2.2. Starting in 1967 data from single-beam echosounder measurements is available along each of the river branches of the delta. They consist of strings of data points perpendicular to the river axis and were taken approximately 120 meters apart from each other. Before 1970 the data was made available in drawings and since 1976 data from single-beam echosounder measurements was made digitally available. There is no data available from the period between 1970 and 1976. Between 2000 and 2004 single-beam echosounder measurements were still used but the depth between data points was interpolated.
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Figure 2.16: Current bed level trend of the rivers in the Rhine-Meuse delta (Becker, 2015).

After 2005 multibeam echosounder measurements were performed, provided on a 5 m x 5 m grid and from 2012 onwards on an 1 m x 1 m grid.

Table 2.2: Bed topography data of the Rhine-Meuse delta.

<table>
<thead>
<tr>
<th>Type of data</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-beam echosounder measurements (Maps)</td>
<td>1967 - 1970</td>
</tr>
<tr>
<td>Single-beam echosounder measurements (original data points)</td>
<td>1976 - 1999</td>
</tr>
<tr>
<td>Single-beam echosounder measurements (interpolated 5 m x 5 m)</td>
<td>2000 - 2005</td>
</tr>
<tr>
<td>Multibeam echosounder measurements (5 m x 5 m)</td>
<td>2006 - 2011</td>
</tr>
<tr>
<td>Multibeam echosounder measurements (1 m x 1 m)</td>
<td>2012 - 2015</td>
</tr>
</tbody>
</table>

- Huismans et al. (2015) identified over one hundred scour holes. These scour holes were numbered starting with an abbreviation of the river followed by a number in streamwise direction. Some scour holes consist of multiple sub scour holes, which are assigned an additional letter. For example the third group of scour holes located in the Oude Maas is named OMS 3a - OMS 3e. The identified scour holes were analyzed by Huismans and Duin (2016) based on their location, maximum scour hole depth and the difference in depth and surface area between 2009 and 2014. As example, the results for a part of the scour holes is shown in figure 2.17. Note that information on the current development was not available for a few of the identified scour holes due to a lack of data and are therefore left out of this analysis.

Figure 2.17: A part of the results from the scour hole analysis by Huismans and Duin (2016). A negative difference in depth means a deepening of the scour hole, a positive difference in area means an increase of the surface area of the scour hole.

- Huismans et al. (2015) determined which year the data showed the existence of a scour hole for the first time. It was performed for a select group of scour holes located in the connecting
branches and the Amer and Nieuwe Maas, based on visual inspection of the data from the single-beam echosounding. The results of the analysis of the scour holes in the Oude Maas and Dordtsche Kil are shown in table 2.3. '1967 - 1970' indicates that the scour hole is detected on the historical maps. Figures of the Oude Maas and the Dordtsche Kil and the scour holes that are identified in these rivers can be found in Appendix B.

Table 2.3: The year that data showed identified scour holes for the first time.

<table>
<thead>
<tr>
<th>Scour hole</th>
<th>First identified in data originating from</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMS1</td>
<td>1967-1970</td>
<td></td>
</tr>
<tr>
<td>OMS2</td>
<td>1985?</td>
<td>Not enough resolution</td>
</tr>
<tr>
<td>OMS3a-c</td>
<td>1967 -1970</td>
<td></td>
</tr>
<tr>
<td>OMS4a,b</td>
<td>1989</td>
<td></td>
</tr>
<tr>
<td>OMS5</td>
<td>1967 -1970</td>
<td></td>
</tr>
<tr>
<td>OMS6a,b</td>
<td>1967 - 1970</td>
<td></td>
</tr>
<tr>
<td>OMS7</td>
<td>1987?</td>
<td>Not enough resolution</td>
</tr>
<tr>
<td>OMS8</td>
<td>1967 -1970</td>
<td></td>
</tr>
<tr>
<td>OMS9</td>
<td>1967 -1970</td>
<td></td>
</tr>
<tr>
<td>DKL 1</td>
<td>1978</td>
<td></td>
</tr>
<tr>
<td>DKL 2</td>
<td>1976</td>
<td></td>
</tr>
<tr>
<td>DKL 3</td>
<td>1978</td>
<td></td>
</tr>
<tr>
<td>DKL 4</td>
<td>1979</td>
<td></td>
</tr>
</tbody>
</table>

- Information on the soil stratigraphy of the Rhine-Meuse delta contains the composition of the soil in the delta and the nature and location of the different soil layers (Berendsen and Stouthamer, 2001; Cohen et al., 2012; Wiersma, 2015). To obtain the location and composition of the layers, bore hole data was interpreted, based on geological knowledge and signatures in the river bed topography. This caused a large uncertainty in the exact location of the channel belts and other geological layers. An approximation of the base level of the layer of "Wijchen" and the location of channel belts is available for the whole delta, shown in figure 2.18 and 2.19.

Figure 2.18: An approximation of the depth of the base of the layer of "Wijchen" (Wiersma, 2015).

Figure 2.19: Location of channel belts, 7000 BC (dark green) - 1850 AD (red) (Cohen et al., 2012).

Complete subsoil stratigraphy maps are available for most of the rivers. In those maps the layer of "Wijchen" and the channel belts are also included. An example is shown in figure 2.20 which shows the northern part of the Dordtsche Kil. Finally, with the use of QGIS the depth of the river bed was determined with respect to the suspected level of the base of the layer of Wijchen by Huismans and Duin (2016), see figure 2.21.
• Calculations are carried out by Carine Wesselius (Deltares) with the 1D SOBEK hydrodynamic model of the Rhine-Meuse Delta and determined the flow velocities in 2014 at specific locations in the rivers of the Rhine-Meuse delta. From here on these flow velocities will be referred to as flow velocities from “Sobek 2014”. As an illustration, figure 2.22 shows the flow velocities resulting from the SOBEK calculations in the Oude Maas at approximately 10 km downstream of the confluence of the Oude Maas and the Dordtsche Kil for the beginning of 2014.

Figure 2.20: Subsoil composition of the north part the Dordtsche Kil (Wiersma, 2015)

Figure 2.21: The depth with respect to the layer of “Wijchen” (Huismans and Duin, 2016).

Figure 2.22: Calculated flow velocities by SOBEK at approximately 10 km downstream of the confluence with the Dordtsche Kil in the Oude Maas in 2014.
Chapter 3

Scour hole occurrence in the Rhine-Meuse delta

In order to locate scour holes and recognize future scour hole development, an objective method is required for the identification of scour holes. Previous attempts were done studying the maximum river depth per cross section with respect to a representative bed level as well as studying the maximum slopes in the bed level (Mechelen, 2015). Although these methods have some disadvantages, it results in a good first approximation. An attempt is done to find a complementary method after which the best method is applied to the river branches in the delta. It is expected that this method will at least indicate the scour holes that were identified before by Huismans et al. (2015), but more importantly, also new scour holes should be identified.

By studying the general development of the scour holes all together a better understanding is obtained of scour hole development in the Rhine-Meuse delta. A field data analysis is performed that consists of several phases, starting in this chapter with an overview of the entire delta. In this overview the scour holes are classified based on their growth and their possible causes. First, a relation between the overall bed level trends and scour hole development is investigated. The connecting branches in the central part of the delta show a degrading trend which is expected to be the result of the closing of the Haringvliet in 1970 (Sloff et al., 2013). It is therefore expected that in this area more scour holes developed after 1970 and also show a larger development in growth. Secondly, the possible causes of scour holes and their current growth are studied. As mentioned in Chapter 2, changes in geometry of the river or the presence of hydraulic structures are expected to increase the local load on the river bed causing erosion. Moreover, local erosion and large scale erosion can be enhanced by the heterogeneity of the subsoil stratigraphy and scour holes that develop in channel belts are expected to be more limited in growth than a scour hole that develops in a sand layer covered by the layer of "Wijchen" (Huismans et al., 2016), as described in Section 2.2.3.

To verify these hypotheses the environment of a scour hole is studied and a relation is tried to be found with their current development by treating the following questions.

- Is it possible to make use of a generic method to identify scour holes?
- Is the current scour hole growth related to the corresponding branch averaged bed level trends?
- Which scour holes can be related to the heterogeneity of the subsoil?
- Which scour holes can be related to changes in geometry, hydraulic structures or ship traffic?
- Is there a difference between the influence of the heterogeneous subsoil and changes in geometry or hydraulic structures on scour hole development?
- Is there a difference between the influence of channel belts and the layer of "Wijchen" on the scour hole development?
CHAPTER 3. SCOUR HOLE OCCURRENCE IN THE RHINE-MEUSE DELTA

In the next section the methods are presented which are used to obtain information to answer these questions.

3.1 Methods to identify and classify scour holes

Identification
Based on visual inspection of the multibeam echosounder surveys of 2012, Huismans et al. (2015) identified over 100 scour holes. In order to locate scour holes in the future or in other rivers an objective identification method is required. In general, scour holes are characterized by their significant depths and steep slopes with respect to the surrounding bed level. However, the minimum magnitude for those depths and slopes for a scour hole to be defined as scour hole is quite subjective. Moreover, the level of the river bed varies strongly along an entire river branch and scour holes differ in dimensions. It is therefore complex and time consuming to automatically detect scour holes. Previous attempts were therefore made to generate a generic method to identify scour holes in river branches (Mechelen, 2015). The proposed methods were based on:

1. the maximum depth related to a representative bed level. The areas that lie beneath this level were identified as scour holes. The representative bed level could be based on the mean, standard deviation and the median value. These values were determined for the entire river reach but also per 5 km and 1 km intervals. A part of the bed level data was filtered to remove levels above the minimum navigable depth of -5 m to leave the river banks out of the analysis. The outcome for the entire river reach and the 5km intervals appeared to be too high. After using the mean values minus one standard deviation of the 1 km intervals, it showed a better fit;

2. the slopes in the river bed. Images made in QGIS indicate the magnitude of the slopes in the river bed and show maximum slopes around the edges of scour holes. This method provides a good representation of the extent of scour holes and the length of the slope. The disadvantage of this method is that it is hard to find the end of a scour hole when a scour hole has a very mild slope or when there are multiple scours within a scour. Since it requires a more detailed analysis of the entire river branch, method 1 seems a faster method. However, it can be used complementary to method 1;

3. the maximum depth related to the layer of "Wijchen". Since in some cases scour is enhanced by a break through of the layer of "Wijchen" it could make sense to identify locations that lie beneath the layer of "Wijchen" as scour holes. However, the exact level of the layer of "Wijchen" is uncertain. Also some scour holes develop without reaching the layer of "Wijchen" and others grow in channel belts, which can be embedded in the layer of "Wijchen". Moreover, the layer of Wijchen is not present everywhere in the Delta. Therefore, this method is not suitable.

The first method based on the mean minus the standard deviation is applied to rivers in the delta. Moreover, the mode of the bed level data is determined as it could also serve as a representative bed level since it is the most frequent depth value. The mean, standard deviation and the mode are calculated per kilometer river reach with the statistical software SPSS using the available bed topography data from 2014. As an example, figure 3.1 shows how the method is applied on a part of the Oude Maas.

Classification
In this section an attempt is made to find explanations for current scour hole development. Since data is available of the growth in depth and area between 2009 and 2014 of the scour holes previously identified in the delta by Huismans et al. (2015), only these scour holes are taken into account. A classification is made based on their current growth and their possible causes such as current bed level trends, influences of structures, changes in local geometry and the heterogeneity of the subsoil.
To determine the influence of changes in local geometry on scour hole development, the environment of a scour hole is studied by using a combination of the bed topography data imported in QGIS and satellite images from Google. A distinction is made between the more natural changes (e.g. bends, narrow parts, confluences, bifurcations) or man-made changes (e.g. bridges, groynes, tunnels). Scour holes that are located within a distance of 500 m of a confluence or bifurcation are classified as confluence or bifurcation scour, see figure 3.2.

Also, ship traffic has an influence on the local hydrodynamics and at a few locations it is likely that ship traffic may have caused local erosion due to a ferry route or a port entrance which is included in the analysis, see figure 3.3a and b. However, a detailed analysis on the behaviour of general ship traffic and their impact on the area is left out of the scope of this research.

To determine whether scour holes may have formed in channel belts the scour hole locations have been compared to channel belt maps, as illustrated in figure 2.19. Since the exact location of the channel belts is unknown a rule is made that the scour hole is only influenced by a channel belt if it is located in a range of 500 meters of a channel belt, see figure 3.4. For the analysis, only channel belts older than 1000 BC are considered as the younger channel belts are expected to be located higher in the subsoil than the riverbed and are therefore not expected to influence the scour hole growth. Since the depth of all channel belts is unknown, it stays uncertain if a scour hole is actually located in a channel belt.
CHAPTER 3. SCOUR HOLE OCCURRENCE IN THE RHINE-MEUSE DELTA

Figure 3.4: Illustration of a scour hole near a channel belt (dark green).

To determine if scour holes are influenced by the layer of "Wijchen" the depth of the scour hole is studied with respect to the local level of the base of the layer of "Wijchen", see figure 2.21. It shows if the depth of a scour hole has already reached the layer, which could have enhanced the scour hole growth. Some of these scour holes are also located near old channel belts. Since QGIS does not indicate the depth of the channel belts, subsoil stratigraphy maps can give information on the dominance of the two different geological aspects. Especially in the Dordtsche Kil is it clear that channel belts are embedded in the layer of "Wijchen", causing the channel belts to be dominant over the layer of "Wijchen". This can be seen in figure 2.20, where the scour holes are located in the orange channel belts reaching below the pink layer of "Wijchen". However, if scour holes tend to grow deeper than the maximum depth of channel belts, it may still be interesting to know if a scour hole reached beyond the layer of "Wijchen". The subsoil maps are not available for all river branches in the delta, making it impossible to say which geological aspect is dominant for every scour hole.

3.2 Identification of scour holes

To develop an objective method for identifying scour holes a new attempt is done by relating the deepest part of the river to a representative bed level. The mode, mean and standard deviation values are determined per kilometer for the Oude Maas en the Dordtsche Kil based on the bed topography data from 2014. Figure 3.5a and b show the mode and mean minus one standard deviation per kilometer river length in respectively blue and red lines. The maximum depth per cross section in 2014 is indicated in black and the numbers indicate the scour holes as identified by Huismans et al. (2015). The figures show that when using the mode, almost the entire river branch can be identified as a scour zone. In comparison, the mean minus one standard deviation seems to move more parallel to the deepest part of the river and keeps only the significant deeper parts under the line. The difference between the latter and the maximum depth is coloured pink. It shows that the identified scour holes by Huismans et al. (2015) are located in the pink area and are therefore also identified as scour holes by this generic method. However, it also indicates many other areas as scour zones which were not identified before.

Scour holes in tidal rivers with heterogeneous subsoil under anthropogenic influence
3.3 Classification of scour holes

To study the influence of the Haringvliet closure, a distinction is made between the northern, the central and the southern river branches. The northern river branches are the Hollandse IJssel, Lek, Nieuwe Maas and Nieuwe Waterweg. The southern branches are the Nieuwe, Beneden and Boven Merwede, Bergsche Maas and Hollands Diep. The connecting rivers in the center are de Dordtsche Kil, Oude Maas, Spui and Noord. Together with the information on the current growth in depth and area, a classification is made which indicates a possible relation between the branch averaged bed level trends and the location and current growth of the scour holes.

According to the bed level trends shown in figure 2.16 the northern and southern branches are subjected to sedimentation and the central branches are eroding. It is therefore expected that the scour holes in the central branches show larger growth than the scour holes located in the northern or southern branches. Based on the data of Huismans and Duin (2016), figure 3.6a and b show the change in depth and area between 2009 and 2014 for the identified scour holes.
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Figure 3.6: Scour hole growth between 2009 and 2014 based on change in (a) depth and (b) surface area.

It shows that the scour holes in the southern part of the delta do not show significant growth. For the central and northern part it is hard to say based on these figures. To better analyze the growth per area, the scour hole growth is grouped per area (north, center and south) and visualized by the bar plot in figure 3.12. The percentage of the scour holes that show growth is based on the number of scour holes in that area. For example, of the 39 scour holes in the northern branches, 25 show growth in depth, which is 64%.

Figure 3.7: Number of scour holes per river and the growth in depth and area between 2009 and 2014 per area of the delta. The number of scour holes located in each river branch is not totally representative. Some scour holes form a cluster of scour holes which are all numbered separately and at other locations only one scour hole is numbered out of a stretch of scour holes, for example along several groynes.

The largest percentage of scour holes that show growth is found in the northern branches of the delta. Focusing on the magnitude of the growth it can be seen that most of the scour holes in the north show the largest extent of growth in surface area and most of the scour holes in the center show the largest extent of growth in depth. However, the differences between the areas are small.

The results of the categorization of the scour holes on geology, geometry, hydraulic structures and ship traffic are shown in figures 3.8 and 3.9. Figures 3.8a and b show that most of the scour holes are expected to be related to either geometry, hydraulic structures or ship traffic. Figure 3.9 shows that scour holes near channel belts are mostly located in the eastern part of the delta. Scour holes that reached beyond the layer of "Wijchen" are mostly located in the river branches of the Oude Maas and the Nieuwe Waterweg.
CHAPTER 3. SCOUR HOLE OCCURRENCE IN THE RHINE-MEUSE DELTA

Figure 3.8: Categorization based on (a) geometry and (b) structures and ship traffic.

Figure 3.9: Categorization based on geology.

The results from a statistical analysis are shown in the bar plot of figure 3.10. It shows the difference in growth between scour holes related to different possible causes. The first bars indicate the number of scour holes related to a possible cause as a percentage of the total number of scour holes. The other bars show the growth in depth and area as a percentage of the total number of scour holes that are subjected to the same cause.

Figure 3.10: Growth in depth and area of scour holes influenced by geology, geometry and structures on scour hole growth.

The number of scour holes that are only subjected to geology is little (7.5%). Even though these scour holes show the largest growth in depth and area, it is hard to compare since it is such a small number. The largest number of scour holes are located near hydraulic structures or where the geometry changes locally (52%). Scour holes caused by structures and changes in geometry show a larger amount of growth when they are also influenced by geology (difference between light blue and red).
CHAPTER 3. SCOUR HOLE OCCURRENCE IN THE RHINE-MEUSE DELTA

Based on previous data analysis on a few scour holes by Huismans et al. (2016) it is expected that a scour hole in a channel belt is limited in growth due to the dimensions of the channel belt. In this analysis all scour holes of the delta are considered and figure 3.11 illustrates the influence of the layer of "Wijchen" and channel belts on scour hole development as a percentage of all the scour holes. The numbers include the scour holes that are also subjected to geometry and hydraulic structures, hence the difference in percentages with figure 3.10. From the figure it is clear that the layer of "Wijchen" influences the scour hole growth significantly more, both in depth and surface area.

Figure 3.11: Growth in depth and area of scour holes influenced by the layer of "Wijchen" or channel belts.

3.4 Discussion on an identification method for scour holes and general development of all scour holes in the Rhine-Meuse delta

1. The definition of a scour hole based on its depth and slopes is partly subjective and also complex due to large variations in bed levels and scour hole characteristics. To develop a more objective and generic method to identify scour holes, attempts are made by relating the deepest part of the river to a representative bed level. This level is determined according to a method of Mechelen (2015) which uses the mean minus one standard deviation per interval of 1 km and a newly proposed method by using the mode value. Both methods are applied on the Oude Maas en the Dordtsche Kil based on the bed topography data from 2014. When studying the results, it is clear from figures 3.5a and b that the mode is located relatively high. For the entire deepest part of the river, the largest part lies below this level.

A suggestion would be to subtract a representative bed variance based on an experts opinion. To determine more accurate mode values, it is also possible to decrease the interval length to for example 500 m.

The mean minus one standard deviation seems to move more parallel to the deepest part of the river and keeps only the significant deeper parts under the line. Besides the scour holes identified by Huismans et al. (2015) this method detects many other scour zones. To verify whether these are indeed scour holes, the bed topography data of these locations are studied and visualized for three cases in figure 3.12.
CHAPTER 3. SCOUR HOLE OCCURRENCE IN THE RHINE-MEUSE DELTA

Considering the depth of these scour holes and the fact that they are only located in a part of the river, it seems that these areas are indeed possible scour holes. Since this method does indicate scour zones in the river, it is certainly of use as a first approximation for identification of scour holes. Whether those scour holes really pose a risk to river banks or for example structures depends on their growth, maximum depths, slopes and locations which could all be determined if these areas are studied in more detail. Note that the mean and the standard deviation are based on intervals of 1 km. Therefore, their values are highly related to the extent of scour holes in width and length, the number of scour holes in the same interval and finally the location where the interval starts and ends. Since this varies strongly per part of the river and per scour hole, it is in this case recommended to be careful by decreasing the interval length in order to obtain more accurate values. This is in contrast to what was suggested for the method based on the mode which is the most frequent value and is therefore less sensitive for the depth of a scour hole.

2. The natural erosion and sedimentation trends in the Delta are erosion in the rivers located in the central part of the delta and sedimentation in rivers located in the northern and southern part of the Delta. The strong erosion in the central branches is likely to be related to closure of the Haringvliet in 1970, which caused higher flow velocities in these branches (Sloff et al., 2013). It was therefore expected that scour holes located in the central branches also show the largest growth. However, the largest percentage of scour holes that show growth between 2009 and 2014 is found in the northern branches of the delta. What causes this growth has not been investigated, but it is surprising since the overall bed level is subjected to sedimentation. To determine the cause of this scour hole growth, it is suggested to study the development of these scour holes and their environment in more detail. When focusing on the magnitude of the growth, most of the scour holes in the northern branches show the largest growth in surface area and most of the scour holes in the central branches show the largest growth in depth. However, the differences are small. The bed degradation in the central part therefore does not necessarily cause a larger growth in the last five years of the scour holes in that area with respect to the other rivers. A good explanation could be that since scour holes are expected to reach an equilibrium depth according to Breusers (1965), a part of the scour holes already reached a stable state. This is possible since the closure of the Haringvliet occurred more than 40 years ago. Another explanation could be that some scour holes reached a deeper poorly erodible layer. This will be verified later in Chapter 4.

An additional explanation is that the delta is subjected to many anthropogenic influences which can influence scour hole growth such as dredging activities, the increasing amount of ship traffic and constructing works.

3. The analysis of the development of all scour holes between 2009 and 2014 shows that the highest percentage of the scour holes in the Rhine-Meuse delta developed around structures or at locations where the geometry changes locally. They show larger growth between 2009
and 2014 when they are also influenced by the geology. The number of scour holes that are induced by geology alone is significantly smaller and is therefore not necessarily causing the initiation of most scour holes in the Rhine-Meuse delta. They do show the largest growth between 2009 - 2014. An explanation could be that in some parts of the rivers the heterogeneity only becomes influential deeper in the subsoil. For example, a scour hole initiated by a hydraulic structure deepens and reaches deeper in the subsoil. When it reaches a highly erodible sand layer or channel belt it has the ability to grow faster and its development is enhanced.

4. Huismans et al. (2016) studied a few scour holes in the delta of which some were expected to be located in channel belts and others reached the Pleistocene sand below the layer of "Wijchen". The scour holes in the channel belts seemed to be more or less stable, whereas the scour holes under the layer of "Wijchen" were still growing in extent. It was therefore expected that scour holes in a channel belt are limited in growth by the size of the local channel belt. The current analysis on all scour holes in the Rhine-Meuse delta seems to verify this hypothesis by showing that most of the scour holes which reached below the layer of "Wijchen" are growing stronger than the scour holes located in channel belts. However, to be certain more knowledge is needed on the development of the scour hole in time and the location and characteristics of the channel belt and its surrounding soil layers. For example, when a channel belt is significantly wider than the scour hole, it should not have a limiting effect on the scour hole growth. Also, this analysis is only based on the development between 2009 and 2014 and therefore does not take the age of the scour holes into account. It is possible that the scour holes that reached below the layer of "Wijchen" are younger than the scour holes that develop in a channel belt. Finally, as mentioned in Section 3.1 there are large uncertainties in the geological data.

In the next chapter the influences of the Haringvliet closure and the influence of the heterogeneous subsoil will be studied in more detail by following the development of a scour hole over a period of almost 40 years. Breusers’ theory will be tested on scour holes in the field to verify the applicability.
Chapter 4

Scour hole development in time in the Rhine-Meuse delta

To obtain a better understanding of scour hole behaviour in the Rhine-Meuse delta it is interesting to study their development throughout time. This is done by following the development of the deepest points in the river and the development of the deepest point per scour hole. It will show the overall bed development but, more importantly, it gives information on the origin of scour holes and their growth rate. For this study only the scour holes identified by Huismans et al. (2015) are considered. According to Breusers (1965), it is expected that the depth development of a scour hole follows a curve that starts with a fast initial growth and ends in a stable state when the equilibrium depth is reached. By studying long time series of field data of the scour holes it is verified whether similar behaviour can be found. Moreover, the influence of the heterogeneous subsoil and the closure of the Haringvliet will be determined. It is expected that the closure of the Haringvliet or a break through the layer of “Wijchen” enhanced the growth rate. It is therefore decided to study scour holes in two tidal rivers, the Oude Maas and the Dordtsche Kil, which are located in the center of the delta and are expected to be influenced by the heterogeneity of the subsoil stratigraphy. The main difference between these two rivers lies in the subsoil composition. The scour holes of the Dordtsche Kil are expected to have developed in channel belts whereas some of the scour holes in the Oude Maas are growing in the Pleistocene sand below the layer of “Wijchen”, which makes it interesting to study the development of those scour holes. For both of these rivers, it is expected that scour holes that lie in the same river reach show similarities in behaviour since they are more or less subjected to similar hydrodynamics.

To verify the applicability of Breusers’ theory on scour holes in the delta, the dimensions of the scour holes are studied more in detail. As mentioned in Chapter 2, Breusers (1965) developed methods to determine the equilibrium depth, the depth development in time and the upstream slope of scour holes behind bed protections. By applying these equations to the scour holes in the field and using carefully chosen input variables, it becomes clear if Breusers’ theory is suitable to predict scour hole development in the Rhine-Meuse delta.

To determine the influence of the closure of the Haringvliet, the heterogeneous subsoil stratigraphy on scour hole growth and the applicability of Breusers’ theory, the following questions are treated.

- Do scour holes show similar behaviour in growth when they are located in the same river reach?
- What is the scour hole development after the Haringvliet closure in 1970?
- Have scour holes reached a stable state?
- How does a scour hole develop when the layer of “Wijchen” is reached?
Do scour holes show behaviour that corresponds to Breusers’ theory based on their:
– shape of the growth curve;
– equilibrium depth;
– depth development in time;
– slopes.

In the next section the methods are presented which are used to obtain information to answer these questions.

4.1 Methods to determine the development of a scour hole in time

Maximum depth development
To find the answers to the questions mentioned in the previous section, a tool is developed that plots the deepest point per cross-section of the river per year in the period 1976 - 2015. It gives insight into the development of the deepest parts of the entire river branch and will consequently also show the locations of the scour holes, their origin and the development of their deepest points. The tool uses SPSS and Matlab, where SPSS computes the minimum depth per cross-section based on year averaged values and Matlab computes the minimum of those values over a certain distance. These cross-sections are assigned to so-called kmr-values, which is the river chainage value expressed in kilometers. An illustration of a part of the Oude Maas with the corresponding kmr-values is shown in figure 4.1.

![Figure 4.1: A part of the Oude Maas with the single-beam cross-sections and the corresponding kmr-values along the river.](image)

The data from the single-beam echosounder measurements generally consists of cross-sections taken parallel to the kmr-values with varying intervals of between 60m and 150m, indicated with the black lines in figure 4.1. However, between different years the beams can differ in exact location and can be positioned under a different angle than others. Therefore, when the tool selects the minimum depth per kmr it is possible that data points from two different cross-sections are addressed to one specific kmr-value. This way the minimum depth can show significant higher values. To filter out each separate cross section a method is introduced that collects the data points per cross-section by moving to the next when the distance between two data points is more than a specific value. As an illustration, the number of data points per kmr-value are shown in figure 4.2. Every new cross-section corresponds to a step in the line.

The single-beam data from 2000 to 2005 was interpolated between data points covering the entire
River reach which made it possible to introduce bins in which the maximum depth was determined. The length of the bin is set on 100m which was approximately the minimum for which unrealistic high values were still filtered out. For the multibeam data bins are used of 10m. Note that this deepest point per cross-section method does not give insight in the geometry of the scour hole, since the deepest point can be located anywhere across the width of the scour hole. An illustration of the results is shown in figure 4.3, where the years gradually change in colour over time starting with dark blue indicating the year 1976 and ending with dark red indicating the last year of which data was available. Multibeam data since 2006 are indicated with solid continuous lines. The (interpolated) single-beam data from 1976 - 2005 is less accurate and are therefore illustrated with dots and dashed lines. When zooming in on the scour holes identified by Huismans et al. (2015) it is possible to estimate the year of origin is based on the year that the bed level reached below the representative bed level which was determined in Chapter 3. However, this bed level was based on the mean minus one standard deviation per kilometer river length of the bed topography data of 2014. Therefore it does not take into account the overall bed degradation between 1976 and 2015. Moreover, it is likely that the single-beam data underestimate the depth, since the measurements may not be located at the deepest point of the scour hole or even skip the entire scour hole. Determining the year of origin therefore stays subjective and contains a margin of error of a few years where scour holes can be older than it first seems.

Figure 4.3: The development of the deepest bed levels of a part of the Oude Maas in the period 1976 - 2015.  
Figure 4.4: Development of the deepest point of a scour hole in the Oude Maas in the period 1976 - 2015.

A different tool is developed which plots the development of the deepest point per hole per year.
An example of the deepest point development of a scour hole in the Oude Maas is shown in figure 4.4. It shows the growth rate and whether the growth shows a fast initial growth followed by a slower growth towards an equilibrium state. In the resulting figures the base of the layer of "Wijchen" is also indicated. Pink dashed lines indicate the range in the subsoil in which the base of the clay layer is suspected to be. This way the behaviour of the scour hole with respect to the clay layer is visible. The figures do not indicate the thickness of the layer, as for the scour hole growth characteristics it is mainly interesting when the depth has reached the base and incises the Pleistocene sand below. Also, the year (2006) that multibeam echosounder measurements were introduced, which provide very accurate data, is indicated with a blue dashed line. Note that, in contrast to the previous method, this method does not give insight into the origin of the scour hole since a degradation of the deepest point could also be related to the overall bed degradation.

These methods can be applied to all the river branches in the Rhine-Meuse delta. Since the connecting branches in the center of the delta showed surprising behaviour in the previous chapter, it is decided to focus on these branches and their scour holes. The Oude Maas en the Dordtsche Kil were chosen based on their location, but also on the interesting geological aspects of those rivers. In both rivers some scour holes reached beyond the layer of "Wijchen" and others are located near some of the many channel belts that run through the area. Therefore, it might give information on the scour hole behaviour in heterogeneous subsoil.

Method to apply Breusers’ theory on scour holes in the delta
By using Breusers’ theory it is possible to predict the development of the maximum depth in time, the equilibrium depth and the slopes of a scour hole behind a bed protection as mentioned in Chapter 2. By comparing the results to what is observed in the field it is possible to determine the applicability of this theory on scour holes in the Rhine-Meuse delta. In order to define the water depth, the maximum scour hole depth and the slopes of scour holes in the field, longitudinal profiles are taken of each scour hole. These profiles are taken parallel to the streamwise direction over the largest length of the scour hole, including the deepest part of the scour hole. Figure ?? shows examples on how the profiles are taken. Note that by taking a longitudinal profile on a slightly different position or under a different angle it can result differences in bed levels. The longitudinal profiles per scour hole can be found in Appendix C.

The next step is to further investigate the choice of the representative bed level. Chapter 3 already showed the difficulties that arise when an attempt is done finding that level. Figure 4.6 shows the longitudinal profiles of three different scour holes with the dominant flow directed from left to right. Four different possible bed levels are indicated based on the choices made by Mechelen (2015) as well as the values for the mean minus one standard deviation and mode that were computed in chapter 3.

Figure 4.6a shows that the mode would be a good approximation indicating the locations where the slope significantly changes as the edges of the scour hole. However, figure 4.6c shows that
the mode is very shallow compared to the edges of the scour hole. Figure 4.6b is located in an area where the bed gradient is very high, resulting in a large difference between the upstream and downstream edge. Figure 4.6c is a scour hole that grew in an older wider scour hole, therefore a choice has to be made if the larger scour hole is taken or the smaller. Due to the problems that arise when trying to find one generic method, it is decided that it is best to assess the extent of each scour zone individually, resulting in a representative bed level chosen per scour hole.

The start of a scour hole is based on the location where there is a significant change in slope. To rule out local bed level forms, the final level is chosen approximately 1m below. These locations can change between the upstream and downstream edge. This does not cause a problem when determining the slopes, but it does cause a problem when determining the local water depth and the maximum scour depth. To solve this problem the average value is taken of the upstream and downstream edge. For determining the slopes the bottom level is chosen approximately 1m above the deepest point. Figure 4.7 shows two examples where the chosen levels are indicated.

**Figure 4.6:** Examples of longitudinal sections of scour holes in the Oude Maas where the dotted lines indicate the representative bed level in green: the choice by Mechelen (2015) based on mean minus one standard deviation and the maximum slopes in the bed, pink: final choice by Mechelen (2015), red: mean minus one standard deviation, blue: mode.

**Figure 4.7:** Examples of longitudinal section of the scour holes of the Oude Maas where the dotted blue line indicates the level which serves as a base for the water depth and the scour hole depth. The red crosses indicate the start and end of the slopes of a scour hole.

**Calculation of the equilibrium depth**

After performing the analysis as described in the previous section it is clear which scour holes are stable and which are still growing. For the stable scour holes it is possible to compute their equilibrium depth as expected by Breusers (1965), as mentioned in Chapter 2 by using equation 4.1.
CHAPTER 4. SCOUR HOLE DEVELOPMENT IN TIME IN THE RHINE-MEUSE DELTA

\[
\frac{y_{m,e}}{h_0} = \frac{\omega \bar{u} - \bar{u}_c}{\bar{u}_c} \quad \text{with} \quad \omega = 1 + 3r_0 \quad \text{and} \quad r_0 = 1.21\sqrt{\frac{g}{C}} \quad (4.1)
\]

For this calculation certain values for variables are chosen, which are listed in table 5.2 except for the flow velocity and water depth.

Table 4.1: Input variables for Breusers’ equations applied to scour holes in the Oude Maas and Dordtsche Kil.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
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</thead>
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<tr>
<td>Gravitational constant</td>
<td>(g)</td>
<td>9.81</td>
<td>m/s²</td>
<td></td>
</tr>
<tr>
<td>Relative density</td>
<td>(\Delta)</td>
<td>1.65</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Chézy value</td>
<td>(C)</td>
<td>43</td>
<td>(\sqrt{m/s})</td>
<td>Zuylen and Sloff (2015)</td>
</tr>
<tr>
<td>Median nominal grain diameter</td>
<td>(d_{n50})</td>
<td>350</td>
<td>(\mu m)</td>
<td>Hijma (2009)</td>
</tr>
<tr>
<td>Critical Shields parameter</td>
<td>(\psi)</td>
<td>0.054</td>
<td>-</td>
<td>Hijma (2009)</td>
</tr>
<tr>
<td>Mean critical flow velocity</td>
<td>(\bar{u}_c)</td>
<td>0.55</td>
<td>m/s</td>
<td>Followed from equation 2.4</td>
</tr>
</tbody>
</table>

Zuylen and Sloff (2015) analyzed one scour hole in the Oude Maas using a flow velocity of 1.5 m/s for the calculation with Breusers’ theory. It resulted in an equilibrium depth much deeper than the maximum depth of the scour hole in the field. In this analysis all scour holes in the Oude Maas are analyzed using a flow velocity of 1.5 m/s to see if it results in an overestimation of the scour hole depth for all scour holes. Since flow velocities differ along a river branch, especially in the Oude Maas because of the confluences with the Dordtsche Kil and the Spui, new calculations are done with scour hole specific flow velocities, based on SOBEK calculations done for multiple locations along the rivers. The equilibrium depth is assumed to have been caused by maximum flow velocities, however, these maximum flow velocities do not occur that often. Since the duration of the process of scour hole development is relatively long it is better to work with a flow velocity that occurs more often (Huismans et al., 2015). A flow velocity of 0.8 times the maximum flow velocity is chosen to be used as input for the Breusers’ equation and is listed per scour hole in table 4.2.

Table 4.2: Flow velocity at the location of the scour hole based on 0.8\(u_{max}\) resulting from SOBEK calculations for the year 2014.

<table>
<thead>
<tr>
<th>Scour hole</th>
<th>Velocity [m/s]</th>
<th>Scour hole</th>
<th>Velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMS 1</td>
<td>0.70</td>
<td>OMS 7</td>
<td>1.06</td>
</tr>
<tr>
<td>OMS 2</td>
<td>0.66</td>
<td>OMS 8</td>
<td>0.83</td>
</tr>
<tr>
<td>OMS 3a-c</td>
<td>1.16</td>
<td>OMS 9</td>
<td>0.92</td>
</tr>
<tr>
<td>OMS 3d,e</td>
<td>1.18</td>
<td>DKL 1</td>
<td>0.90</td>
</tr>
<tr>
<td>OMS 4a,b</td>
<td>0.84</td>
<td>DKL 2a,b</td>
<td>0.95</td>
</tr>
<tr>
<td>OMS 5</td>
<td>0.84</td>
<td>DKL 3</td>
<td>0.98</td>
</tr>
<tr>
<td>OMS 6a,b</td>
<td>1.10</td>
<td>DKL 4</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Calculation of the depth development in time

The calculation of the depth development in time can be done for scour holes that originated after 1976 of which the growth rate can be determined. The bed topography data that is used in previous sections is averaged per year, although two measurements per year were done after 2006. These datasets are used to determine the growth rate more in detail. For the calculation of the depth development in time equation 4.2 is used with the same input variables mentioned in the previous section and the additional variables listed in table 4.3.

\[
\frac{y_m}{y_{m,e}} = 1 - e^{-\left(\frac{t}{t_1}\right)^\alpha} \quad \text{with} \quad t_1 = \frac{Kh_0^2\Delta^{1.7}}{(\alpha \bar{u} - \bar{u}_c)^{3.3}} \quad \text{and} \quad \alpha = 1.5 + 4.4r_0f_c \quad (4.2)
\]

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Table 4.3: Input variables for Breusers’ equations applied to scour holes in the Oude Maas and Dordtsche Kil.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration coefficient</td>
<td>K</td>
<td>330</td>
<td>m$^2$/s$^3$</td>
<td>Graauw and Pilarczyk (1981)</td>
</tr>
<tr>
<td>Exponent</td>
<td>$\gamma$</td>
<td>0.4 - 0.8</td>
<td>-</td>
<td>Meulen and Vinjé (1975)</td>
</tr>
</tbody>
</table>

Since the development in time is calculated the tide becomes of influence. In Chapter 2 a method was treated to take the tide into account based on a factor $\eta$ times the flow velocity. Zuylen and Sloff (2015) found a value of $\eta$ of 0.6 as a first approximation. A second calculation is done by applying this factor on the flow velocities.

**Calculation of the slopes**

According to Breusers (1965) the upstream slope is the steeper compared to the downstream slope and can be calculated with the following equation 4.3.

\[
\beta = \arcsin \left[ 3 \times 10^{-4} \frac{(u_0)^2}{\Delta g d_{n,50}} + (0.11 + 0.75 r_0) f_c \right] \tag{4.3}
\]

By comparing the outcomes predicted by Breusers’ theory with observations in the field it should become clear if the Breusers’ theory can be applied to predict scour hole development in the delta. Due to the many different input variables and their uncertainties it is important to include a sensitivity analysis.

4.2 Development of scour holes located in the Oude Maas and Dordtsche Kil

The scour hole development in time was studied for the Oude Maas en the Dordtsche Kil in order to relate the scour hole development to the influence of the Haringvliet closure, the influence of the heterogeneous subsoil and Breusers’ theory. After a scour hole has started to develop, which could be before or after 1970, a fast initial growth is expected followed by a slower growth ending in a stable state after some time. Around the layer of “Wijchen” it is expected that the growth first decreases and after the scour hole breaks to the layer, the growth increases again. Finally it is expected that scour holes that are located in the same river reach show similarities in behaviour due to similarities in hydrodynamic conditions.

**Oude Maas**

The development of the deepest part of the Oude Maas between 1976 and 2015 is shown in figure 4.8a. The dominant river flow in the Oude Maas is directed from left to right, thus the lowest kmr value is at the upstream end of the river branch. It was decided to leave some years out of this analysis for different reasons. Data from 1978 and 1986 was unavailable, 2001 and 2005 only had a few data points and 1997 was only measured for half of the length and half of the width of the river branch resulting higher values for the deepest points than in reality. Also, in 1977 and 1980 only the first part of the river was measured, but they have been included as they were taken over the full width of the river. The labels 1-9 indicate the scour holes as they were identified by Huismans et al. (2015). Note that the x-axis is in kilometers and the y-axis is in meters.

The profiles show in most parts an overall lowering of the deepest part of the bed between 1976 and 2015, especially in the west half of the river, with some very deep parts of which most correspond with previously identified scour holes by Huismans et al. (2015).
**Dordtsche Kil**

The development of the deepest part of the Dordtsche Kil between 1976 and 2014 is shown in figure 4.8b. The left of the plot corresponds with the north side of the river and the right side indicates the south. The flow in the Dordtsche Kil is dominantly directed from south to north, but there is not a large difference between the flow velocities directing north and south.

Figure 4.8: Maximum depth per kmr for (a) the Oude Maas in the period 1976 - 2015 and for (b) the Dordtsche Kil in the period 1976 - 2014 (in Appendix D larger versions can be found).
However, the flow velocity directed to the north is slightly higher and also has a longer duration and is therefore chosen to be dominant. Again it was decided to leave some years out of the analysis. Data from 1978 and 1986 was also in this case not available and the data set from 1999 only consisted of a few data points. The labels 1-4 indicate the scour holes as they were identified by Huismans et al. (2015).

Similar to the Oude Maas, the maximum depth profile shows an overall lowering of the bed. However, the southern part of the river bed is situated completely within a sand layer, causing faster and more homogeneous erosion than the northern part that has a clay top layer which is also visible in figure 2.20. In the northern part the top layer slowly erodes but old channel belts consisting of highly erodible sand are embedded in this top layer. These channel belts enhanced the erosion, causing scour holes to develop. These deep parts in the profile correspond to the identified scour holes by Huismans et al. (2015), however as mentioned in Chapter 3 it seems that there is an extra hole between DKL 2 and 3.

When zooming in on the identified scour holes in figures 4.8a and b it was possible to see the development of a scour hole in time and in some cases also the year of origin. Combining these plots with the development of the deepest point in time per hole, the behaviour can be studied in detail. Figure 4.9a shows a 3D top view image of one of the scour holes in the Oude Maas in 2014. Figure 4.9b shows the deepest points per cross-section at the location of the scour hole and figure 4.9c shows the development the deepest point of a scour hole. As mentioned in Section 4.1, pink lines illustrate the range in which the base of the layer of “Wijchen” is suspected to be and the blue line indicate the year 2006 from when the data started to get more accurate due to the multibeam echosounder measurements.

Figure 4.9: Scour hole in the Oude Maas "OMS 6a" showing (a) a QGIS image based on bed topography data from the scour hole in 2014, (b) the deepest points per cross-sections at the location of the scour hole in 1976 - 2015, (c) the deepest point per scour hole in the period 1976 - 2015. The legends of the figures are shown below the corresponding figure.
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All three figures were made for all scour holes in the Oude Maas and the Dordtsche Kil and can be found in Appendix E. The layer of “Wijchen” is also indicated in the figures of the scour holes in the Dordtsche Kil although the scour holes are suspected to be located in a channel belt.

As mentioned before, scour holes that are located in the same part of the river are expected to show similarities in behaviour due to the more or less equal hydrodynamic conditions. Therefore, the scour holes were grouped per part of the river. The Oude Maas can be separated in three parts: an eastern, center and western part. The eastern part is upstream of the confluence with the Dordtsche Kil, the western part is the part downstream of the confluence with the Spui and the center part lies in between. This is also visible in figure 4.8a. The entire Dordtsche Kil is considered to consist of only one part. Figures 4.10 and 4.11 show the development of the deepest point per hole of the scour holes located in the Oude Maas and the Dordtsche Kil.

Figure 4.10: The development of the maximum depth of the scour holes in time in the (left) eastern, (center) central and (right) western part of the Oude Maas.

When studying the scour holes per part of the river, it can be seen that scour hole development varies strongly between the scour holes. Some scour holes already exist for a long time, others developed more recently. Also in most cases, their growth rates are not always similar and their current behaviour varies between eroding, sedimentating and stable behaviour. In the Oude Maas, the overall range of the current maximum depths increases when the scour holes are located more downstream. For all scour holes, it seems that the begin state and the end state are in the same range of depth. Based on the representative bed level determined in Chapter 3, it is clear that most of the holes in the Oude Maas already existed in 1976 (OMS 1, 2, 3a,b,c,e, 5, 8, 9). Some developed later (OMS 4ab, 6ab 7), and in some older holes smaller ones developed (OMS 4a, 6a). Almost all of the holes that originate from before 1976 reached a stable situation in the last decade or are even sedimentating (OMS 1, 2, 3a-e, 5, 6b, 9). Most of them show a large growth in the period after 1976 (OMS 1, 2, 3a-e, 9). Only a few of the new and older scour holes are still growing OMS 4a, 6a, 8. Finally, it is interesting that some scour holes located downstream of each other are showing opposite behaviour (OMS 4a is currently eroding, while OMS 4b is...
CHAPTER 4. SCOUR HOLE DEVELOPMENT IN TIME IN THE RHINE-MEUSE DELTA

Figure 4.11: The development of the maximum depth of the scour holes in time per part of the Dordtsche Kil in the period (a) 1976 - 2014 and (b) 2006 - 2014.

Figure 4.11: The development of the maximum depth of the scour holes in time per part of the Dordtsche Kil in the period (a) 1976 - 2014 and (b) 2006 - 2014.

sedimentating and the same is observed for OMS 1 and OMS 2. The figures of the Dordtsche Kil show that it is likely that the scour holes already existed in 1976 (DKL 2b, 3, 4) or developed just after (DKL 1, 2a). They all show a sedimentation trend after around 2000 which for most scour holes followed after an eroding trend. In the last few years all of the scour holes in the Dordtsche Kil are more or less stable in depth.

Most of the scour holes in the Oude Maas and Dordtsche Kil reached below the layer of "Wijchen" all except for OMS 9. However, a part of the scour holes are suspected to have developed in a channel belt (OMS 1, 3a-e and DKL 1-3). Some of the scour holes that are not located near a channel belt but did reach below the layer of "Wijchen" already reached below that layer in 1976 (OMS 2, 5, 8 and DKL 4). The moment that they broke through the layer is therefore not visible. The growth rate of some scour holes that did reach below the layer of "Wijchen" after 1976, seemed to increase when the scour hole reached a level below the suspected level of the layer of "Wijchen" (OMS 4a, 4b, 6a, 6b). Finally, some scour holes show high peaks indicating sedimentation where it is not expected. The most important observation is that scour hole development varies greatly between the scour holes.

4.3 Application of the Breusers’ theory on the scour holes in the field

In this section the equilibrium depth, depth development in time and the slopes of scour holes are determined based on the data in the field and compared with calculations based on the theory of Breusers (1965).

4.3.1 Equilibrium depth

This analysis is only done for the scour holes that are assumed to be currently stable in depth. The maximum depth of the scour holes located in the Oude Maas and the Dordtsche Kil based on the field data of 2014 is shown in figure 4.12 indicated with the purple dots. The same figure indicates the calculated equilibrium depths for two different flow velocities by using equation 4.1. The blue diamonds indicate the calculated equilibrium depth for the Oude Maas with a flow velocity of 1.5 m/s based on the research of Zuylen and Sloff (2015). This study did not include the scour holes in the Dordtsche Kil and are therefore not indicated in the figure. The green triangles indicate the results based on the flow velocity calculated by SOBEK shown in table 4.2.

It shows that there is a huge difference between the field and the calculated values based on a flow velocity of 1.5 m/s. This difference has a maximum of almost 40 m and a minimum of 17 m. By using the location specific flow velocities derived from SOBEK it results in a smaller scour hole...
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Figure 4.12: Maximum depths per scour hole based on field data from 2014 and the equilibrium depths based on calculations with Breusers’ theory using flow velocities of 1.5 m/s (Zuylen and Sloff, 2015) and $0.8u_{\text{max}}$ calculated with SOBEK.

depth, reducing the difference with the field data to a maximum of almost 23 m and a minimum of 0 m. For some scour holes this difference is significantly reduced, others still show a large difference. Based on table 4.2 the scour holes that are located at a location where higher flow velocities are expected also show the largest differences between the calculated equilibrium depth and maximum data observed in the field.

Sensitivity analysis for the variables used for determining the equilibrium depth

The calculations done by using Breusers’ theory are based on several variables for which certain values are assumed. However, these values contain uncertainties which could influence the eventual outcome of the calculations. The variables for calculating the equilibrium depth that can contain uncertainty are the local water depth, $h_0$, the mean flow velocity, $\bar{u}$, the mean critical flow velocity of the sediment, $u_{c}$, and the roughness of the river bed, $C$. Moreover, the definition of the maximum scour hole depth in the field contains uncertainties. The significance of their influence on the calculation of the maximum scour hole depth are further elaborated below.

Mean average flow velocity, $\bar{u}$

The flow velocities followed from SOBEK are calculated for specific locations in the river. Since these locations are not exactly at the same location as the scour hole, it could cause a difference in flow velocity as for example the local geometry plays a role. Moreover, a representative flow velocity of 0.8 times the maximum flow velocity was assumed to cancel out rare peak flow velocities. This reduced flow velocity still happens rarely, especially when the tide is considered. Zuylen and Sloff (2015) proposed a reduction factor, $\eta$, of 0.6 to correct the velocity for the tide when computing the scour development in time. Although in this calculation the equilibrium depth is considered, it is possible that this is a good first approximation. The influence of a factor of 0.6 is studied and shown in figure 4.13 as even lower factors than 0.6 would result in flow velocities lower than the critical flow velocity.

Figure 4.13: Maximum depths per scour hole based on field data from 2014 and the equilibrium depths based on calculations with Breusers’ theory by using two flow velocities: 0.8 and 0.6 times the maximum flow velocity resulting from SOBEK calculations.
The figure shows that in most the cases the difference between calculated depths and the depths observed in the field significantly reduces or even becomes negative when using a reduction factor of 0.6. The larger differences still occur for the scour holes where the flow velocities or the local water depth are the highest.

**Local water depth, $h_0$, and maximum scour hole depth in the field**

As explained in Section 4.1, it was chosen to use a level of 1 m below the location where the slope of the bed significantly changes. If that 1 m was not used, the maximum scour hole depth would increase with 1 m, and the local water depth would decrease with 1 m. In figure 4.14 the ratio according to equation 4.1 between the maximum depth and the local water depth, $y_{m,e}/h_0$, is shown based on Breusers’ theory by using the flow velocities from the SOBEK calculations. A maximum ratio of 1.7 is found when using flow velocities of 0.8 times the maximum flow velocity. This ratio times the decrease of 1 m in water depth decreases the calculated maximum depth with 1.7 m and the maximum scour depth as observed in the field increases with 1 m. This consequently decreases the difference between Breusers’ calculations and the field with a maximum of 2.7 m. Although the ratio for other scour holes is smaller than 1.7, it can decrease the difference significantly. When using the 0.6 times the maximum flow velocities this ratio has a maximum of 1 which could result in a maximum decrease in difference between the calculations and the field of 2 m. When looking back at figure 4.13 this decrease in difference is still significant.

![Figure 4.14: Maximum scour depth with respect to the water depth based on calculations with Breusers’ theory by using two flow velocities: 0.8 and 0.6 times the maximum flow velocity resulting from SOBEK calculations.](image)

**Roughness of the river bed, $C$**

The bed roughness is of influence on the relative turbulence of the flow and according to Zuylen and Sloff (2015) is based on a visual inspection on the bed forms visible in the bed topography data of the rivers imported in QGIS. Zuylen and Sloff (2015) estimated a dune height of 0.27 m which resulted in a roughness with a Chézy value of $43 \sqrt{m/s}$. Since some parts of the rivers are expected to be less rough due to the clay top layer this may result in a higher Chézy value. However, by using the equation 2.10 this will not have any influence on the depth calculation. This will be later explained in Section 5.5. On the contrary, a rougher bed would cause a large scour hole depth, but since higher Chézy values are not expected and even larger scour hole depths are even more unrealistic this is not further investigated.

**Critical flow velocity, $\bar{u}_c$**

The critical flow velocity of the Pleistocene sand according to Huismans et al. (2015) in the Dordtsche Kil is 0.4 m/s and in the Oude Maas 0.5 m/s. As this is lower than the value that was used, this would result in an even stronger scour hole growth.

### 4.3.2 Depth development in time

Most of the scour holes already existed before 1970. It is therefore not possible to determine the year of origin and the initial development up until 1976. This makes it difficult to relate the growth rate of these scour holes to what is expected by using Breusers’ theory. However, there
are a few scour holes in the Oude Maas that have developed after 1976. But since the single-beam data dating from before 2005 is not always accurate it is also for these scour holes hard to study their detailed development. Fortunately, there is one scour hole (OMS 4a) that developed a second hole in the wider original hole around the year 2008, see figure E.2k in Appendix E. This hole is expected to have developed after it broke through the layer of "Wijchen" and therefore seems suitable to compare its development with Breusers’ theory. The bed topography data contains depth measurements from May 2008 up until April 2014 with approximately two data sets per year. Longitudinal sections of the scour hole based on each data set is shown in figure 4.15a. The development of the maximum depth is shown in figure 4.15b. The exact values can be found in Appendix F. Note that the growth in depth per month is indicated in cm.

![Figure 4.15: (a) Longitudinal sections; and (b) the development of the maximum depth of a scour hole in the Oude Maas (OMS 4a) based on bed topography data from 05/2008 - 04/2014.](image)

The scour hole development as found in the field compared to the calculations based on Breusers’ theory are shown in figure 4.16. A flow velocity of 0.8 times the maximum flow velocity according to the SOBEK calculations is used and as a first approximation a value for $\gamma$ of 0.6 is used since for 3D-flow the $\gamma$ value varies between 0.4 - 0.8, see Chapter 2. In the previous section the reduction factor for the tide was introduced and its applicability was tested. It showed it is likely to work with a factor of similar magnitude and since in this case the development in time is considered this factor becomes of even more importance. Figure 4.16 also shows the depth development calculated with Breusers’ theory when this factor is applied.

![Figure 4.16: Depth development in time based on field data and calculations with Breusers’ theory using flow velocities of 0.8 and 0.6 times $u_{\text{max}}$ (SOBEK) and a value for $\gamma$ of 0.6.](image)
The figure shows a large overestimation of the scour hole depth when calculating the depth development by using a flow velocity of 0.8 times $u_{\text{max}}$. When the tide is taken into account by using a factor of 0.6, the depth development results in even lower values than as seen in the field. When focusing on the shape of the growth curve of the scour hole in the field, it can be seen that it does not necessarily show a curve as expected, but the growth rate alternately increases and decreases again.

**Sensitivity analysis for the variables used for determining the depth development in time**

In the previous section the uncertainties of some of the variables is already discussed and the same holds when the scour hole development in time is determined. Since the scour hole development in time is more influenced by fluctuations in the flow velocity, this variable is investigated further. Also, the influence of variances in the exponent $\gamma$ is investigated, which determines the growth rate towards the equilibrium depth. Note that this does not influence the equilibrium scour depth.

**Mean average flow velocity, $\bar{u}$**

The factor $\eta$ of 0.6 as proposed by Zuylen and Sloff (2015) to correct the flow velocity for tidal influences was based on a sinusoidal tide. Since the flow velocities in the Oude Maas and the Dordtsche Kil do not follow a sinusoidal curve an attempt is done with the flow velocities based on the outcome of the SOBEK calculations. These calculations were done per 10 minutes and give a more accurate scour hole development in time. Zuylen and Sloff (2015) adapted equation 2.12 to a forward Euler scheme

$$y_{m+1} = y_m + \left(\frac{t(m+1)}{t_1}\right)^\gamma - \left(\frac{t(m)}{t_1}\right)^\gamma \quad \text{with} \quad t_1 = \frac{K h_0 \Delta \gamma}{(\alpha |u(m+1)| - \bar{u}_c)^{1+\gamma}}$$

(4.4)

The results when using this equation are shown in figure 4.17 together with the depth development observed in the field.

Figure 4.17: Depth development in time based on field data and calculations with Breusers’ theory using flow velocities per 10 minutes (SOBEK) and a value for $\gamma$ of 0.6.
CHAPTER 4. SCOUR HOLE DEVELOPMENT IN TIME IN THE RHINE-MEUSE DELTA

Since figure 4.17 is based on a large set of data containing specific flow velocities per 10 minutes, it is interesting to see which tidal correction factor, $\eta$, can be used on the constant maximum flow velocity to obtain the same depth development in time. This way only one flow velocity can be used. Figure 4.18 shows the scour hole depth in time for a flow velocity of 0.73 times the maximum flow velocity calculated by SOBEK, which shows the same behaviour as figure 4.17.

![Figure 4.18: Depth development in time based on field data and calculations with Breusers’ theory using flow velocity of 0.73 times $u_{max}$ (SOBEK) and a value for $\gamma$ of 0.6.](image)

Both figures 4.17 and 4.18 show that by using the flow velocities per 10 min and a $\gamma$ value of 0.6 the scour hole depth is still overestimated.

Exponent $\gamma$

A value of 0.6 was chosen for $\gamma$. However, since this is a 3D situation the range of possible $\gamma$ values lies between 0.4 and 0.8, see Chapter 2 (Meulen and Vinjé, 1975). Figure 4.19 shows the scour hole development as seen in the previous section by applying different values for $\gamma$ of 0.4, 0.6 and 0.8 compared to the scour hole development as observed in the field.

![Figure 4.19: Depth development based on field data from 2008 - 2014 and calculations with Breusers’ theory by using a flow velocity of 0.95 m/s (SOBEK) and four possible values for $\gamma$ varying from 0.4 - 0.8.](image)

The figure shows that for this case the variance in the value for $\gamma$ results in a maximum difference in depth of approximately 1.8 meters. When using a higher value for $\gamma$ the magnitude of the depth agrees more with reality. However, the shape of the curve still does not agree for any of the $\gamma$ values.

4.3.3 Slopes

The slopes of the scour holes in the Oude Maas and Dordtscbe Kil are determined by using the longitudinal sections. According to Breusers (1965) the upstream slope is expected to be the
steepest. Since these scour holes are located in tidal rivers and the flow reverses, the dominant upstream slope is defined as the upstream slope. The dominant flow in the Oude Maas is directed from east to west and in the Dordtsche Kil from south to north. The dominant upstream and downstream slopes as observed in the field are shown in figure 4.20. The exact values of the upstream, downstream and the maximum slope are listed in Appendix G. In this table $\beta_1$ stands for the dominant upstream slope, $\beta_2$ the dominant downstream slope and $\beta_{\text{max}}$ the maximum slope that is observed on either of the slopes.

Figure 4.20: Dominant upstream and downstream slopes based on field data from 2014.

Figure 4.20 shows that most of the scour holes in the Oude Maas have a steeper slope on the dominant upstream side. There are some scour holes that show the opposite but in those cases the difference between the slopes is very small. In the Dordtsche Kil it is the other way around, the dominant downstream slope is in most cases the steepest except for one scour hole (DKL 3) where the upstream slope is significantly larger. The differences between the slopes are relatively large.

To compare the upstream slope with Breusers’ theory, calculations are done with equation 4.3 by using the two flow velocities based on 0.8 times the maximum flow velocity calculated by SOBEK and taking the tidal influence into account by using a flow velocity of 0.6 times the maximum flow velocity. The results are shown in figure 4.21.

Figure 4.21: Upstream slopes based on field data from 2014 and calculations with Breusers’ theory using flow velocities of 1.5 m/s (Zuylen and Sloff, 2015) and 0.95 m/s (SOBEK).

The upstream slopes in the field range between 1° and 30°. The slopes calculated with Breusers’ theory based on a flow velocity of $0.8u_{\text{max}}$ are lying in a range between 12.5° and 16.5°. Taking the tide into account the slopes slightly milder and lie in a range between 11.5° and 13.5°. It shows that a variance in flow velocity results in relatively small differences in the slopes. Although most scour holes in the field show milder slopes as expected, slopes that are twice as steep are also observed.

When studying the steepest parts of either of the slopes, shown in figure 4.22, it shows that some parts reached the critical slope angle (critical slope angle for fine sand = 24° - 34°, see figure 2.10)
and some are even steeper than the angle of internal friction (angle for internal friction for fine sand = 26°-34°, medium sand = 30°-40°, see figure 2.9).

Figure 4.22: Maximum slopes observed per scour hole on either of the slopes based on the field data from 2014.

From these figures it seems that the slopes of most of the scour holes in the field do not show accordance with what was expected by Breusers (1965). It is decided to not perform a sensitivity analysis on the input variables of Breusers’ equation since it is expected that other aspects are of more influence.

4.4 Discussion on the behaviour of the scour holes in the Oude Maas and the Dordsche Kil and the applicability of Breusers’ theory

Overall scour hole development

1. When studying the scour holes in more detail it becomes more clear that the definition of a scour hole and its dimensions is complex. When basing the edges of a scour hole on the maximum slopes in the river bed problems arise. Since the downstream slope of a scour hole could be very mild, upstream and downstream edges can vary in height and scour holes can grow in larger older scour holes. As mentioned in Chapter 3, defining scour holes stays a complex and partly subjective process. It is therefore recommended to assess the extent of each scour hole individually when determining the scour hole dimensions.

2. Chapter 3 provided that the scour holes in the central branches did not show the largest growth with respect to the northern and southern river branches. This was surprising considering the degrading river bed in the central branches and the sedimentation trends in the northern and southern branches. It was suggested that this could be explained by the possibility that the scour holes in the central branches already reached a stable state. After studying two of these rivers, the Oude Maas and Dordtsche Kil, it was verified that most scour holes already exist for decades and have indeed reached a stable state.

3. Most of the scour holes in the Oude Maas already existed in 1976 and were also detected on the maps from before 1970 by Huismans et al. (2015). Some show a large growth in the period after the Haringvliet closure and most of them have currently reached a stable state, similar to the growth curve that is expected by Breusers (1965). The large growth rates in existing scour holes after 1976 might be related to the closure of the Haringvliet. However, the growth rates from before 1976 are not visible which could have already been high before Haringvliet closure.

Based on a study of the maps by Huismans et al. (2015) and the results from this analysis, the scour holes in the Dordtsche Kil developed between 1970 and 1976 or just after. They do not necessarily show large growth after 1976 except for one. Therefore, the scour holes
originating from before 1976 must have developed fast in the period between 1970 and 1976. In case of the Dordtsche Kil it is possible that the Haringvliet closure caused the scour hole development. However, since no new scour holes developed in the Oude Maas just after 1970 and the scour holes in the Dordtsche Kil developed in a short period it is probably more related to the deepening of the river bed by dredging in the period 1970 - 1985 as expected by Huismans et al. (2016). It may have removed protective clay layers exposing the channel belts to the flow. Although initiated by a different cause, it is still possible that the Haringvliet closure enhanced the scour hole growth.

To get more insight into the influence of the Haringvliet closure on scour hole development in the delta, it is suggested to determine the year of origin of the scour holes in the southern or northern branches and study their depth development just after 1976. If these rivers also show scour hole development after 1970 or if existing scour holes also show large growth after 1976, there could be another explanation for scour hole development besides the Haringvliet closure.

Since most of the older scour holes in both river branches reached a stable state as expected by Breusers (1965), it could be expected that the younger scour holes will also reach their equilibrium in the future.

4. The most important observation when studying scour holes in the same river reach, is that scour hole development varies greatly between the scour holes. They do not necessarily show the same behaviour, even though they are subjected to similar hydrodynamic conditions. This is surprising since a study on two other rivers in the delta by Huismans et al. (2013), the Beneden and Nieuwe Merwede, showed that scour holes in those rivers did show similar scour behaviour in relation to hydrodynamic conditions. During high river discharges scour holes were eroding and during low river discharges sedimentation of the scour holes occurred.

Figure 4.10 shows in the Oude Maas the range of the maximum depth deepens when moving downstream. This can be explained by the natural gradient in the river bed. Moreover, it seems that the begin state and the end state are in the same range of depth. In the Dordtsche Kil the scour holes seem to sedimentate around 2000 after a eroding trend. This may have something to do with the deposition of sediment in the scour holes when maintenance works are carried out in the river. Besides these observations a relation between scour holes is not always clear. As mentioned in Chapter 3, the delta is subjected to many anthropogenic influences which can influence scour hole growth. More specifically, it was observed that a significant part of the scour holes in these rivers is likely to have been caused by local changes in geometry or due to structures. Since scour in bends, at confluences or around bridge piers or groynes show different kinds of scour (Hoffmans and Verheij, 1997), this could be an explanation of the differences in scour behaviour. Moreover, these scour holes are highly influenced by the heterogeneity of the subsoil stratigraphy which could also caused deviant behaviour. It is therefore important to keep studying scour holes individually.

5. It is possible that some scour holes influence each other. For example OMS 4b which is sedimentating is located just downstream of OMS 4a which is eroding. An explanation could be that the material from OMS 4a is ending up in OMS 4b. The same holds for OMS 1 and 2, although these scour holes are located further apart.

6. Of the scour holes that did reach beyond the layer of “Wijchen” after 1976, most seem to show behaviour what corresponds to what was expected when the layer is reached. Their growth seemed to increase when the scour hole reached a level below the suspected level of the base of the layer of “Wijchen”.

7. Some scour holes showed behaviour deviant to Breusers’ theory which could not be explained by the subsoil composition. Moreover, some scour holes show high peaks indicating sedimentation where it is not expected. Some of this surprising behaviour can be explained when studying the location of the data points which in some cases skip the entire scour hole, see figure 4.23a where it is visible that some years do not contain data points at the location of
the scour hole, resulting in very high values in figure 4.23b. Interventions by the government are also of influence in some cases. At the locations of some of the holes measures were taken to prevent further erosion, for example by the deposition of material at the location of the hole, see figure 4.24a and b where the maximum depth of the scour hole moves up and down.

![Figure 4.23: An example of a scour hole were single-beam echosounder measurements skip the entire hole (OMS 2), where (a) shows the maximum depth per cross-section and (b) the maximum depth per scour hole development.](image)

![Figure 4.24: An example of a scour hole where it is likely that deposition of material occurred (OMS 8), where (a) shows the maximum depth per cross-section and (b) the maximum depth per scour hole development.](image)

**Applicability of Breusers’ theory**

In most cases the behaviour of the scour holes in the field differs from what is expected by using the theory of Breusers (1965). The scour hole depth is in most cases overestimated and the slopes do not seem to show a relation with Breusers’ theory. There are several explanations for these differences of which a few are investigated in the sensitivity analysis performed for the computation of the scour depths. Moreover, the equations determined by Breusers (1965) are based on scour in a particular situation, namely scour hole development behind a bed protection. Since this situation is quite different compared to scour hole in the Rhine-Meuse delta, many other aspects...
are influencing the scour hole growth, such as the composition of the subsoil and the inflow of sediments.

1. Figure 4.13 and figure 4.14 show that the choice for a representative flow velocity, local water depth and maximum scour depth is of significant influence on the differences between the calculated scour depth by using Breusers’ theory and the scour depths observed in the field. Even when correcting the velocity for the tide, the scour hole depth is still largely overestimated.

To improve the accuracy of the flow velocity, a suggestion would be to study the environment of a scour hole more in detail, since the locations where the flow velocities were generated by SOBEK differ from the exact scour hole locations. This way it could be determined if there are aspects that can cause changes in local flow velocity. Moreover, the SOBEK output could be generated at the specific locations of the scour holes. A third possibility would be to determine representative flow velocities near scour holes by measuring flow velocities at the location of a scour hole in the field. However, this could be very costly and difficult due to navigation problems and high flows in the rivers.

Figure 4.12 showed that the flow velocity and the definition of the local water depth and scour depth are not the only possible explanation for the overestimation of the scour hole depth. Scour holes which are subjected to higher flow velocities and larger local water depths do not necessarily show larger scour hole depth. Reducing relative small variations in the flow velocity by more accurate computations and measurements would therefore probably not solve the problem.

2. Breusers’ theory is based on scour behind a bed protection and is in this study applied to scour holes in the delta since it could show similarities to scour in an incision of a poorly erodible layer. However, scour behind a bed protection is not limited by a downstream bed protection. It is therefore expected that a large influence on the scour hole development in the delta lies in the composition of the subsoil. When in the field a clay layer is surrounding the scour hole at a certain level it could, depending on the thickness and strength of the clay layer, limit the scour hole growth in area, possibly limit the growth in depth and cause steep slopes. The decrease in depth due to a poorly erodible downstream layer was also verified in the scale model experiments of Zuylen and Sloff (2015). The heterogeneity of the subsoil could also be an explanation for the fact that the depth development of a scour hole does not follow a smooth curve as expected by Breusers (1965), but it shows strong varying growth rates. It was also observed that some of the slopes are steeper as expected and even showing some very steep parts. It is possible that those steep slopes reduce the bed load. This could also cause scour holes to be less deep than expected.

A different explanation for the overestimation of the equilibrium scour hole depth could be that the bottom of the scour holes reached a poorly erodible layer situated deep in the subsoil. Based on the subsurface stratigraphy of the Oude Maas in figure 2.2 in Appendix H and the Dordtsche Kil shown in figure 2.20, it is likely that most of the scour holes are lying in the Pleistocene sand and are therefore not limited by underlying poorly erodible layers.

Breusers’ theory is based on scour under clear-water conditions. Even though the clay layer is said to be poorly erodible, the sediment transport is likely not zero and differs per river branch. By observing the multibeam echosounder measurements it can be seen that sand is transported over the river bed. As mentioned in Chapter 2, live bed scour will cause smaller equilibrium depths than clear-water scour (Hoffmans and Verheij, 1997).

Finally, it was observed in Chapter 3 that scour holes in the delta could be caused by local changes in geometry or due to structures. Scour in bends, at confluences or around bridge piers or groynes could show different behaviour than scour that is expected behind a bed protection (Hoffmans and Verheij, 1997). It is therefore suggest to study the literature on
CHAPTER 4. SCOUR HOLE DEVELOPMENT IN TIME IN THE RHINE-MEUSE DELTA

scour under these specific conditions and possibly combine it with the theory on scour hole development behind bed protections (Breusers, 1965).

3. The $\gamma$ values for 3D-scour proposed by Meulen and Vinjé (1975) were based on one single experiment with a sill having 3D effects on the flow. This did not include the 3D effects that can be caused by the shape of the scour hole. Moreover, the equations for the calculation of the depth development in time contains variables which were not treated in the sensitivity analysis. The calibration coefficient $K$ and exponents 1.7 and 4.3 in equation 4.2 are determined empirically (Hoffmans and Verheij, 1997), for which, among others, Dietz and Wittke (1969) proposed certain values. Since these values are also determined empirically based on a specific type of scour it is difficult to use these for scour hole development in the delta.

4. Most of the scour holes in the Oude Maas show a steeper dominant upstream slope than the downstream slope which agrees to what is expected by Breusers (1965). Although some scour holes show the opposite, the difference between the steepness of these slopes is small. On the contrary, the scour holes in the Dordtsche Kil show a steeper dominant downstream slope in most cases except for one scour hole. Even though the flow velocities of the ebb and flood flow do not differ that much, the upstream and downstream slopes do show large differences in steepness. Since Breusers’ theory does not include a downstream non-erodible layer and especially in the Dordtsche Kil the poorly-erodible layers are very thick, it can be questioned if this theory can be applied on the downstream slope.

The overall steepness of the slopes of all scour holes varies strongly between 1° and 30°, of which most are milder than expected by Breusers (1965). This could be the result of micro and macro instabilities in the slopes which causes the slope to fail and end up in a milder slope (Hoffmans and Verheij, 1997) and even possibly reducing the depth of the scour hole. Milder slopes could also be explained by the tidal influence. When the flow is reversed it could flatten the former upstream slope and steepen the former downstream slope and when the flow reverses again this process is repeated. This way it is possible that a maximum slope is never reached resulting in overall milder slopes. This process of reversing flow is also verified by experiments in a scale model by Zuylen and Sloff (2015). Other scour holes show much steeper slopes than predicted. This could be the result of a thick poorly-erodible layer. That slopes are even steeper than the critical slope and the internal angle of friction could also be because of other soil layers. Although in Chapter 2 it was mentioned that clay has a smaller angle of repose, steeper clay slopes are observed in the field (Huismans et al., 2015). Moreover, the separation of the flow near the edges of the scour holes and the recirculation area that develops consisting of a return flow can possibly sustain steep slopes, see Chapter 2.

Taking all these aspects into account it can be said that it is complex to apply Breusers’ theory on scour holes in the Rhine Meuse delta and it raises questions if the theory can be used at all. The scour hole depths in the field vary strongly, are less deep than expected and the slopes vary with a broad range of steepness. Factors such as the local flow velocity (including turbulence), tide, the heterogeneous subsoil, the choice of local water levels and the value for $\gamma$ are all of influence on determining the scour hole development. To obtain a better understanding on the influence of the heterogeneous subsoil and the 3D effects, experiments in a scale model are performed and presented in Chapter 5.
Chapter 5

Scour hole development in a scale model

Previous chapters showed that scour hole development in the field is a complex process influenced by many factors. Due to varying hydrodynamic and geological conditions and the difficulties that arise when performing measurements in the field, the information required to better understand scour hole growth in the field is not easily obtained. Performing experiments in a physical scale model may give more insight into the development of a scour hole in heterogeneous subsoil as the response to certain aspects can be tested one by one in a controlled way. As mentioned in Chapter 2, Zuylen and Sloff (2015) performed experiments inducing scour hole growth in a sand layer partly covered by a non-erodible top layer. Although these experiments give insight into scour hole development under these specific conditions, it differs from scour hole development in the field in two important ways. Steel plates were used as top layer, leaving a gap in the center in which the scour hole could develop. This gap was evenly distributed over the width creating a quasi-2D situation for scour hole development while scour hole development in the field is considered to be a 3D situation. Moreover, the steel plates did not fail after the undermining started of the downstream edge resulting in non-realistic behaviour of the top layer, since the clay layer in the field is expected to fail.

A pilot study is therefore executed by performing experiments in a scale model to investigate the influence of 3D effects and a poorly erodible layer on scour hole development. To induce 3D effects the shape of the scour hole is adapted which does not spread over the entire width of the flume and an attempt is done to simulate a more realistic top layer which has the ability to fail and therefore shows more similarities with the clay layer in the field. It is expected that the 3D effects would cause the scour hole to grow faster and deeper due to the attraction of flow (Mosselman and Sloff, 2002). It is expected that the top layer slows down the scour hole process but fails after undermining has started.

The methods of Breusers (1965) that were used in the previous section to predict scour hole development were based on scour hole growth behind a non-erodible bed protection of a sill. Although it does show similarities with scour holes in a heterogeneous subsoil, this bed protection is non-erodible and only located upstream. Moreover, the 3D effects induced by the shape of a scour hole are not included in the theory. The experiments will therefore give insight into the applicability of Breusers’ theory on scour hole development in this particular scale model and consequently on scour holes in the delta.

To verify the hypothesis on the influence of 3D effects and the heterogeneous subsoil the following questions are treated.

• How does the shape of a scour hole influence the 3D flow pattern around the hole and with this the development of the scour hole with respect to a 2D shaped scour hole?
• How does a poorly erodible layer influence the scour hole development?
CHAPTER 5. SCOUR HOLE DEVELOPMENT IN A SCALE MODEL

5.1 Experimental methodology

5.1.1 Experimental setup

In the Waterlab of the Delft University of Technology a flume of 12 m length, 0.8 m width, 0.25 m depth is constructed. An illustration of the side and top view of the experimental set up is shown in figure 5.1. The flume is symmetrical and has a horizontal bed to allow flow reversal to simulate the tidal influence in future experiments. The entire bottom consists of an 1 cm thick layer of concrete except for an oval opening in the center of 0.5 m length and 0.3 m width. The cement layer surrounding the oval covers a box of sand. The flume simulates a river with a non-erodible bed and a local discontinuity in the top layer exposing an underlying sand layer. This way a scour hole can develop in the oval opening.

The flume is a closed system where a constant amount of water is circulated by a pump with a constant frequency to reach the required discharge throughout the experiment. Also, after the first few experiments a sediment trap is introduced at the downstream end of the flume in order to achieve scour under clear-water conditions. In order to compare the outcome of these experiments with previous research, the flow conditions are based on the conditions of the experiments performed by Zuylen and Sloff (2015). By scaling the field conditions with the use of scaling rules considering a sufficient turbulent and sub-critical flow (Zuylen and Sloff, 2015) chose a representative water depth and flow velocity of respectively 0.13 m and 0.45 m/s. The sand that is used is fine sand with a $d_{50}$ of 260 µm.

![Figure 5.1: An illustration of the side and top view of the experimental set up.](image)

Measuring equipment

To measure the flow velocity electromagnetic flow meters were installed. However, since the pump caused large disturbances in the measurements it was decided to base the flow velocity on the discharge through the pipe and the water height in the flume. The discharge through the pipe is continuously measured by an ultrasonic flow meter mounted on a straight part of the feeding pipe. The water height is measured with the use of two lasers which were approximately located 2.1 m from the center, one on the upstream side of the oval opening and one on the downstream side. The scour hole depth and subsequently the bed level profile, is also measured by a laser. It is placed in a small boat with a glass bottom connected to a cart above the flume which can change...
position in longitudinal direction by rolling over a track on the side of a flume and by sliding it by hand in transversal direction. Note that the laser can not measure the undermining of the concrete top layer. Throughout the experiments cameras were used to record the development of the scour hole. By adding pink dye to the water, the local water behaviour has been made visible.

Figure 5.2: Top views of the flume without water, showing the oval shape in the concrete bottom where in (a) the sand is still covered with a piece of wood and in (b) a scour hole is formed in the sand.

5.1.2 Experimental program

Before starting with the experiments the set up is tested and the equipment is calibrated. The setup is checked for leaks and whether the flow straightener on the upstream side causes the flow to be sufficient uniform at the upstream edge of the oval opening. The flow is checked with the Reynolds and Froude number in order to achieve a turbulent and sub-critical flow. The Froude number is calculated with equation 5.1 and the Reynolds number is calculated with 5.2.

\[ Fr = \frac{u}{\sqrt{gh}} \]  
\[ Re = \frac{uR}{\nu} \]

\( \nu \) kinematic viscosity (m\(^2\)/s)

The roughness of the bed is calculated by using the relation of Chézy, see equation 5.3, based on the difference in water level along the flume.

\[ C = \frac{u}{\sqrt{Ri}} \]

\( i \) slope in water level \( \frac{dh}{dx} \) (-)

The lasers used for measuring the water depths and the scour depth are calibrated based on measurements with a ruler. Finally, the required pump frequency is determined to achieve a constant discharge providing the required flow velocity and water depth.

In total, four experiments were carried out. The first two experiments were done to investigate the 3D effects induced by the shape of the scour hole. Because the closed system caused a recirculation of a significant amount of sand, it resulted in a live-bed scour situation. Since the experiments by Zuylen and Sloff (2015) were done under clear-water conditions, a sediment trap was installed after the first experiment.
Several attempts were done to simulate the behaviour of the poorly erodible clay layer as observed in the field. Different materials were tested to cover the sand in the oval opening. A smaller circular opening was left untouched that still exposed the sand. This way the scour hole development is more dynamic and free to grow in width and length because the edges are not fixed anymore but have the ability to fail as soon as the edges are undercut. From the tested materials, river clay and fine sand hardened with spray paint seemed to be the most suitable options and were therefore used in the respectively third and fourth experiment. These experiments focused on the behaviour of the top layer and its influence on the scour hole growth. An overview of the experiments is shown in Table 5.1.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type of scour</th>
<th>Fixed/dynamic shape</th>
<th>Material top layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Live-bed</td>
<td>Fixed</td>
<td>Concrete</td>
</tr>
<tr>
<td>2</td>
<td>Clear-water</td>
<td>Fixed</td>
<td>Concrete</td>
</tr>
<tr>
<td>3</td>
<td>Clear-water</td>
<td>Dynamic</td>
<td>River clay</td>
</tr>
<tr>
<td>4</td>
<td>Clear-water</td>
<td>Dynamic</td>
<td>Spray paint</td>
</tr>
</tbody>
</table>

5.2 Method of applying Breusers’ theory on scour hole development in the scale model

For the scour hole in the scale model the development in time and the upstream slope as expected by Breusers (1965) is calculated with equations 2.8 and 2.15. The scour holes did not reach an equilibrium state as the duration of the experiments was not long enough. A comparison based on equilibrium depths is therefore not possible. However, it is interesting to do the calculation to see how deep the scour hole would have grown if not limited in length. For the calculations the following variables are used.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational constant</td>
<td>g</td>
<td>9.81</td>
<td>m/s²</td>
<td>-</td>
</tr>
<tr>
<td>Relative density</td>
<td>Δ</td>
<td>1.65</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Chézy value</td>
<td>C</td>
<td>93</td>
<td>m¹/s²</td>
<td>-</td>
</tr>
<tr>
<td>Median nominal grain diameter</td>
<td>d₅₀</td>
<td>260</td>
<td>µm</td>
<td>Zuylen and Sloff (2015)</td>
</tr>
<tr>
<td>Critical Shields parameter</td>
<td>ψ</td>
<td>0.04</td>
<td>-</td>
<td>Zuylen and Sloff (2015)</td>
</tr>
<tr>
<td>Calibration coefficient</td>
<td>K</td>
<td>330</td>
<td>m²/s³</td>
<td>Graauw and Pilarczyk (1981)</td>
</tr>
<tr>
<td>Exponent</td>
<td>γ</td>
<td>0.4 - 0.8</td>
<td>-</td>
<td>Meulen and Vinjé (1975)</td>
</tr>
</tbody>
</table>

5.3 Experimental results

5.3.1 Calibration and testing

A required pump frequency of 42.4 Hz was determined to achieve a discharge of 46.3 l/s which is needed to get a water depth of approximately 0.13 m. With a flume width of 0.8 m this results in a flow velocity of approximately 0.45 m/s. After doing the calculations for the Froude and Reynolds number it resulted in values of respectively 0.4 and 38225, indicating that the flow is fully turbulent and sub-critical.

Figure 5.3 shows the water depth measured at a distance of 2.1 m upstream and downstream of the center of the flume.
By calculating the average values the difference in water depth is computed. A difference of approximately 0.1 cm is found, which results in a roughness of approximately 93 m$^2$/s which is, as expected, considered as smooth. However, these measurements contain an inaccuracy range as seen in figure 5.3.

5.3.2 Experiment 1 - Live-bed scour and fixed shape

The first experiment ran for six hours. Sand dunes were clearly visible from the start of the experiment which moved downstream until they left the oval shape, see Figure 5.4. The sand dunes starting at the upstream edge of the scour hole followed the round shape of the oval where the sides of the dunes moved faster than in the center. The sand dunes increased in width as the width of the oval widened. Where the oval started to narrow again more downstream, the sand dunes did not follow the shape of the oval but moved outside of the shape keeping a more or less constant width. The deepening of the scour hole was the fastest a few centimeters downstream of the upstream edge. Figure 5.5 shows the depth development over six hours based on longitudinal sections taken over the center of the scour hole.

Considering the depth of the scour hole it shows that during the first two hours the scour hole continuously deepens and reaches a maximum depth of 4.1 cm. However, after 1.5 hours sediment-
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...ation of the scour hole is already visible at the upstream slope due to the inflow of sediment from upstream. It fills the scour hole and reduces the depth significantly. After three hours the scour hole reaches a dynamic equilibrium as the average scour hole stays constant at approximately 2.5 cm except for the moving sand dunes on the bottom. In the first few hours there was some undermining of the downstream edge, but the sand dunes were able to fill the gap. After three hours the sand dunes were not high enough anymore and the undermining really starts. This undermining is not visible in the longitudinal sections but is seen as a vertical slope as the laser can not measure below the concrete top layer. At the end of the experiment the extent of the scour hole under the downstream edge was estimated with the use of a measuring rod. The undermining of the side edges and the downstream edge was respectively in the order of 2 cm and 7 cm. The scour hole did not grow upstream and the upper part of the upstream slope stayed at a constant value of approximately 1:4.3. The lower part of the slope changed when the scour hole started sedimentating.

In order to fill up the scour hole for the next experiment approximately 3.85 kg of fine sand was needed. That amount is approximately the net eroded volume of sand from the scour hole. To determine the effect of the inflow of sediment due to the recirculation, the amount of incoming sand was estimated. The bed forms that arose upstream were vacuumed over a section of 0.3 m length and 0.8 m width. The collected wet sand was dried and weighted. The sediment transport rate resulted in approximately \(0.3 \pm 0.1 \times 10^{-3} \text{ kg/(s m)}\). For example, assuming a constant amount of sand that is circulated, this could result in a sediment inflow of 4 kg after four hours. Although not all of the sediment ends up in the scour hole since it does not take up the entire width of the flume and the bed forms are located more at the sides of the flume, it does influence the scour hole development significantly.

5.3.3 Experiment 2 - Clear-water scour and fixed shape

In this experiment the inflow of sediment from upstream was reduced to a negligible amount by installing a sediment trap at the downstream end of the flume. This way a situation with clear-water scour was realized. Figure 5.6 shows the depth development over four hours based on longitudinal sections taken over the center of the scour hole. Note that the positive bed levels at the downstream edge of the scour hole are the result of movement of grains over the concrete bed. Figure 5.7 shows the development of the maximum depth of the scour hole over four hours. After two hours sand dunes start to form, but since the overall shape of the scour hole is followed, these deeper troughs are not taken in to account when determining the maximum depths.

![Figure 5.6: Longitudinal depth profiles taken over the center of the scour hole in experiment 2 after 0.5 - 4 h.](image)

![Figure 5.7: Maximum depths of the scour hole in experiment 2 after 0.5 - 4 h.](image)
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Because there is no inflow of sediment from upstream the scour hole grows faster and deeper than the scour hole in the first experiment. After four hours the maximum depth in the scour holes is 5.2 cm and even 6.4 cm if the troughs of the sand dunes are taken into account. In this experiment the scour hole does not grow upstream, similar to what was observed in experiment 1, and keeps a constant upstream slope of approximately 1:2.4. The downstream slope before the undermining starts is approximately 1:9. With a measuring rod the undermining was measured after four hours. The undermining of the side edges and the downstream edge is respectively in the order of 6 cm and 10 cm. With the use of longitudinal profiles spread over the width over the scour hole, side slopes of approximately 1:2 could be determined. In order to fill up the scour hole for the next experiment approximately 5.42 kg of fine sand was needed. This is approximately 1.5 kg more than what was used for experiment 1 after six hours. This proves the significant difference between live-bed and clear-water scour. A picture of the scour hole after four hours is shown in figure 5.8.

Figure 5.8: Picture of the scour hole in experiment 2 after 4 hours.

Figure 5.9: Picture of the scour hole in experiment 3 after 13 min.

5.3.4 Experiment 3 - Clear-water scour and dynamic shape with a clay top layer

To simulate a poorly erodible layer as seen in the field a 2 mm thick layer of river clay was spread over the oval opening covering the sand. Only a small circular opening with a diameter of 8 cm was left untouched, exposing the sand to the flow. When the experiment was started, sand particles were transported resulting in undermining of the downstream edge, showing similar behaviour to the previous experiment. However, the clay appeared to be too cohesive and strong that no failing of the clay layer occurred. Due to a air accumulation underneath the clay layer, a crack formed after 13 minutes causing an extra hole more downstream see figure 5.9. Due to the cohesion and weight of the thin clay the part that came loose was easily transported by the flow. Since in the field it is expected that the poorly erodible layer falls down on the sand, it was concluded that the clay is not the right material to represent the poorly erodible layer as observed in the field. The experiment was therefore stopped and the clay layer was removed entirely.

5.3.5 Experiment 4 - Clear-water scour and dynamic shape with a spray paint top layer

The same experiment as experiment 3 was performed except now by using spray paint instead of clay. Paint was sprayed on top of the sand, hardening the sand and creating a relatively strong layer of approximately 0.5 mm, see figure 5.10a. Like in the previous experiment a small circular part was left uncovered. During the experiment the hole started to develop and started to undermine the downstream edge. Due to scale effects that occur in this scale model the behaviour of the top layer is not simulated correctly. The weight of the top layer is too light and too cohesive with respect to the forces that act on it resulting in more undermining before the layer fails.
When it eventually fails it is easily transported downstream by the flow. To counteract these effects, undermined parts were pushed down on top of the sand that lies underneath. The scour hole grew further in depth but now also gradually in width and length in downstream direction. After 30 minutes the last part of the downstream top layer let loose entirely. At that moment the undermining of the concrete layer started again. The growth in width of the scour hole resulted in a more or less symmetrical widening under an angle of 1:8, see figure 5.10b.

![Figure 5.10: Picture of the scour hole in experiment 4 after (a) 20 min and (b) 1.5 h.](image)

Figure 5.11 shows the depth development over 1.5 hours based on longitudinal sections taken over the center of the scour hole. Note, the cracking of the top layer caused some disturbances downstream, resulting in positive bed levels in the figure.

![Figure 5.11: Longitudinal depth profiles taken over the center of the scour hole in experiment 4 after 20 min - 1.5 h.](image)

Similar to previous experiments, the scour hole did not grow upstream and the slope kept a constant value of approximately 1:3. In comparison with the scour hole development with fixed edges in experiment 2, the depth development is slightly slower in the first hour (1.8 cm versus 2.9 cm after 0.5 hours). With the use of longitudinal profiles taken on varying locations over the width of the scour hole, side slopes of between 1:1.5 and 1:2 could be determined, steeper than the slopes in longitudinal direction.
5.4 Application of Breusers’ theory on scour hole development in the scale model

For the calculations with Breusers’ theory only experiment 2 and 4 are considered. Experiment 1 is a situation with live-bed conditions while Breusers’ theory are only applicable for scour hole development under clear-water conditions and experiment 3 was stopped before a scour hole could really develop.

The maximum depth development of experiment 2 and 4 are shown in figure 5.12. The same figure indicates the depth development according to Breusers’ theory by using a value of $\gamma = 0.6$.

![Figure 5.12: Depth development in time based on results from experiment 2 and 4 and calculations with Breusers’ theory using a value for $\gamma$ of 0.6.](image)

The figure shows that the calculations with Breusers’ theory underestimate the depth as observed in the flume. The calculation of the equilibrium depth for a situation without a downstream non-erodible layer results in 28 cm and a $t_1$ of 59 hours.

The upstream slope according to Breusers (1965) is the same for both experiments, 18.6° (1V:3.1H), as all the required variables stayed constant in all the experiments. The slope of the scour hole in experiment 2 is slightly steeper than expected, but the slope of the scour hole in experiment 4 agrees with what was expected. In both experiments, before the downstream edge is reached, the upstream slope was steeper than the downstream slope since the downstream slope is in the order of 1V : 9H.

<table>
<thead>
<tr>
<th>Experiment 2</th>
<th>Experiment 4</th>
<th>Breusers (1965)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.4° (1V : 2.4H)</td>
<td>18.9° (1V : 3.1H)</td>
<td>18.6° (1V : 3.1H)</td>
</tr>
</tbody>
</table>

5.5 Discussion on scour hole development in a scale model with a non-erodible bed and 3D effects and the applicability of Breusers’ theory

1. As mentioned in Chapter 2, the flow is expected to separate at the upstream edge of the scour hole. By adding pink dye just upstream of the scour hole to the flow this separation was made visible showing vortexes at the upstream edge of the scour hole. Due to the shape of the scour hole in the scale model these vortexes followed a horse shoe shape. The flow was slightly attracted towards the center of the scour hole due to the larger depth in that
part of the scour hole. The point where the recirculation zone ended the flow seemed to reattach to the bed again. This point was initially located a few cm's downstream of the upstream edge and corresponded to the part of the scour hole which showed the strongest erosion. Here the scour hole growth was the strongest and as the scour hole deepened the reattachment point moved downstream, moving the deepest part of the scour hole in downstream direction, see figures 5.6 and 5.11. Further downstream, the pink dye showed that the vortexes transformed into less structured wakes with slightly increased turbulence levels. This causes the downstream part of the hole and also its sides to erode further. As the streamlines gradually diverge and the turbulence intensity decreases, the scouring process in the downstream part of the hole is slower. As seen in figure 5.10 the gradual widening of the streamlines tends to follow a 1:8 angle. The scour processes as illustrated by Uijttewaal et al. (2016) are shown in figure 5.13.

Figure 5.13: Scour hole processes as observed in the 3D scale model experiments (Uijttewaal et al., 2016).

2. In the experiments the scour hole did not grow in upstream direction and its upstream slope stayed constant. This can be explained by the recirculation area just downstream of the upstream edge of the scour hole as explained in Chapter 2. In this area a balance is achieved between the upstream directed flow and the downstream directed component of the gravitational forces. As mentioned above, this was verified by adding pink dye to the flow just upstream of the scour hole which indeed showed an eddy at the upstream edge, keeping the dye recirculating at the same location for a longer time. As expected, the upstream slopes of the scour holes in the experiments are steeper than the downstream slope before the downstream edge is reached and are in the same order of magnitude as predicted by Breusers (1965) (between 1V:2.4H and 1V:3.1H). The side slopes however, are steeper than the slopes in longitudinal direction in experiment 5 (between 1V:1.5H and 1V:2H).

3. According to Breusers (1965), scour holes do not tend to grow upstream. This was also observed during the experiments in the scale model having an unidirectional flow. However, there are scour holes in the delta that do grow upstream. One example is shown in figure 5.14. Based on longitudinal sections taken over the center of the scour hole it shows the development of the scour in time from 05/2008 to 04/2014. An explanation could be that the scour hole is located at a location where the tidal influence is large, where reversed flow cause upstream erosion. Also, the upstream edge of the scour hole is located near a confluence.

Scour holes in tidal rivers with heterogeneous subsoil under anthropogenic influence
and as mentioned before, this could influence the scour hole development. Depending on the shape of the confluence, the increase in flow velocity could be the largest at the upstream side of the scour hole. Finally, the local thickness of the layer of "Wijchen", that is surrounding the scour hole at a level of approximately -19 m +NAP, could vary between the upstream and downstream side and is of influence on the growth of the scour hole.

Figure 5.14: Longitudinal depth profiles taken over the center of the scour hole (OMS 6) based on bed topography data from 05/2008 - 04/2014.

4. In Chapter 2 the difference was explained between live-bed and clear-water scour and illustrated in figure 2.6. The scour hole development as observed in experiments 1 and 2 show exactly that behaviour. The scour in Experiment 1 first occurred under clear-water conditions since there was no sediment circulating yet through the system. Therefore its initial growth in the first hour agrees with the clear water scour in experiment 2. When the sediment starts coming in from upstream it transforms to live-bed scour. As the scour hole starts to fill up with sediment, the depth decreases and eventually fluctuates around a equilibrium depth due to the passing bed forms. This also verifies the hypothesis in Chapter 4 that scour holes in the delta are possibly less deep due to the live-bed conditions than expected by the theory of Breusers (1965) which is based on clear-water conditions.

Figure 5.15: Longitudinal depth profiles taken over the center of the scour hole in experiment 1 after 1h - 6h, illustrating the transition from clear-water scour to live-bed scour.
5. Both experiments 2 and 4 were performed under clear-water scour conditions. It was expected that scour hole development follows a curve starting with a fast initial growth and later reaching an equilibrium state. As expected, both experiments seem to have a larger growth rate in the beginning. However, in a situation without a non-erodible downstream edge the equilibrium depth would be 28 cm and the $t_1$ of 59 hours, according to Breusers’ theory. The decrease in growth rate in time is therefore not necessarily the result of a decrease in transport capacity of the flow due to a decrease in flow velocity. A more likely cause as explained by Zuylen and Sloff (2015) would be the influence of the non-erodible downstream edge decreasing the bed transport once it is undermined.

6. The first two experiments were done with a fixed non-erodible bed and experiments 3 and 4 were done with a poorly-erodible bed that had the ability to fail. When comparing experiment 2 with experiment 4, it was expected that the spray paint layer, after it was pushed down on the underlying sand, would reduce the scour hole development based on the results of Zuylen and Sloff (2015). Figure 5.12 shows this is indeed the case until the spray paint layer is completely eroded. From that moment the scour development is similar again in the two experiments.

7. When the scour was not limited in width in experiment 5, it showed a gradual and symmetrical widening under a slope of 1:8. Since one of the main risks of scour holes is the growth in width towards the river banks, it is interesting to further study the behaviour of a scour hole in sidewards direction.

8. It was expected that the shape of the scour hole would induce 3D effects which would increase the scour hole growth with respect to scour hole growth in 2D experiments. Figure 5.16 shows the maximum scour depths as observed in the 2D experiments of Zuylen and Sloff (2015) and in experiment 3 and 5 of the 3D experiments. The 2D experiments were performed under similar conditions with a flow velocity of 0.45 m/s, a water depth of 0.13 m and a gap between the steel plates of 0.5 m.

The 3D experiments indeed show deeper scour hole growth. However, there was one more difference between these experiments and the experiments performed by Zuylen and Sloff (2015). The concrete bed was considered smooth having a Chézy value of approximately 93 m$^{1.2}$/s whereas the 2D experiments were performed with a rough bed having a Chézy value of approximately 43 m$^{1.2}$/s. As mentioned in Chapter 2 the roughness of the upstream bed influences the scour hole growth. The maximum load of the flow that exerts on the grains is a combination of the local flow velocity and the local turbulence, both near the bed. A rough surface induces more turbulence which causes a larger force on the sediment grains.
This results in a faster and deeper scour. On the contrary, a rough surface decreases the flow velocity near the bed, now decreasing the force on the grains. This results in a slower and more shallow scour. The exact opposite is expected with a smooth surface. To determine which effect is dominant, turbulence or velocity, a calculation of the maximum flow velocity is done for different roughnesses.

The maximum flow velocity consists of a velocity and a turbulence part according to relation 5.4. This is also seen in equation 2.9, which was used as a multiplication factor for the average flow velocity.

\( u_{max} = (1.5 + 5r)u_0 \)  
\( u_{max} \) maximum flow velocity \( (m/s) \)

According to Nezu (1977) the relation for local turbulence is related to the roughness of the upstream bed.

\( r = \frac{\sqrt{k}}{u} \) where \( k(z) = 3.3u_0^2 e^{xp(-\frac{2z}{h_0})} \)  
\( r \) turbulence energy \( (m^2/s^2) \)
\( z \) height in the water column with respect to the bed level(m)

The turbulence energy is the resultant of flow velocity fluctuations in longitudinal, transverse and vertical direction. The local flow velocity at a certain height in the water column with respect to the river bed is calculated with the following equation (Schierack, 2012).

\( u(z) = \frac{u_0}{\kappa} \ln \left( \frac{z}{z_0} \right) \) with \( u_0 = \sqrt{\frac{\tau}{\rho}} = \sqrt{\frac{g}{Ri}} = \frac{\bar{u} \sqrt{g}}{C} \)  
\( u_0 \) local flow velocity \( (m/s) \)
\( \kappa \) constant of Karman \( \kappa = 0.4 \) (-) \( z_0 \) roughness height \( (m) \)

To show the influence of the bed roughness on the maximum flow velocities near the bed in the case of the physical model, the flow characteristics of the experiments are used for the calculation of the maximum flow velocities. The roughness height, \( z_0 \), is related to the average height of the surface irregularities. The value for \( z_0 \) is determined by iteration until a depth averaged flow velocity of 0.45 m/s is reached. To determine the average flow velocity, the local flow velocity is integrated and divided by the water depth, see Equation 5.7.

\( \bar{u} = \frac{\int_{1}^{h} \frac{u_0}{\kappa} \ln \left( \frac{z}{z_0} \right)}{h} \approx \frac{u_0}{\kappa} \ln \left( e^{-1} \frac{h}{z_0} \right) \)  
\( \bar{u} \) average flow velocity \( (m/s) \)

Since the processes near the bed are of importance, this analysis focuses on the area between the bed and 0.25 times the water depth \((z/h_0 = 0 - 0.25)\).

The figures 5.17a - 5.17c show the profiles for the flow velocity, relative turbulence and the corresponding maximum flow velocity near the bed for a varying bed roughnesses (Chézy = 45 - 90 m^{1/2}/s ). A Chézy value of 45 m^{1/2}/s is considered as rough and a Chézy value of 90 m^{1/2}/s is considered smooth. The figures show that, as expected, a rough bed (a low Chézy-value) causes a decrease in flow velocity near the bed, see figure 5.17a and an increase in turbulence near the bed, see figure 5.17b. The combination of the turbulence and the flow velocity according to equation 5.4 results in the maximum flow velocity, see figure 5.17c. It
shows that near the bed the flow velocity is more dominant for determining the maximum velocity than the turbulence. A rough bed results in lower maximum flow velocities near the bed. Moving upwards from the bed, the flow velocity becomes less and less dominant until the turbulence becomes more dominant. The point where this happens is at the intersection of the lines which is, in this example, approximately at 0.045 times the water depth, see figure 5.18. With a water depth of 0.13 m this corresponds to a height of 5.8 mm.

Figure 5.17: Profiles of the local (a) velocity, (b) turbulence and (c) maximum velocity for different roughnesses.

Figure 5.19 shows, as a comparison, the ratio between the maximum flow velocity with a rough \( (C = 45 \frac{1}{2}/s) \) and a smooth bed \( (C = 45 - 90 \text{ m}^2/s) \). Below the intersection point at a height of 5.8 mm, the peak flow velocity is higher for a smooth bed. Since the sand that is used in the experiments has a grain diameter of 200 \( \mu \text{m} \) which is much smaller than 5.8 mm, it is possible that the smooth upstream bed induced higher near bed flow velocities and thereby increasing the scour hole growth. However, it all depends on the choice of the near bed area.

Figure 5.18: Maximum flow velocity profile for different roughnesses.

Figure 5.19: The ratio of the maximum flow velocity in the case of a smooth bed over the case of a rough bed.

9. The depth development according to Breusers’ theory underestimates the scour hole depth, see figure 5.12. It was expected that Breusers’ theory would overestimate the scour depth based on results of Zuylen and Sloff (2015). Since the smooth bed in the 3D experiments could increase scour, the influence of the roughness is also studied in the equations of Breusers (1965).

As mentioned in Chapter 2, according to equation 5.8, a rough upstream surface would induce more turbulence compared to a smoother surface, which results in a higher value for...
\( \alpha \). A higher value for \( \alpha \) causes a faster scour hole growth in depth and a larger equilibrium depth. However, in this equation the influence of the local flow velocity induced by the roughness of the bed surface, is included by the factor \( f_c \).

\[
\alpha = 1.5 + 4.4 r_0 f_c \quad \text{with} \quad f_c = \frac{C}{40} \quad (f_c = 1 \text{ for } C \leq 40 \sqrt{\text{m/s}})
\]  

(5.8)

This equation is however only applicable when equation 5.9 is not reduced to 5.10, as done by Zuylen and Sloff (2015), assuming a negligible sill height, \( D \), and a very long bed protection, \( L \). In that case the roughness gets canceled out of the equation, having no influence on the scour hole development.

\[
r_0 = \sqrt{0.0224 \left( \frac{1 - \frac{D}{h_0}}{0.67} \right)^2 \left( \frac{L - 6D}{6.67h_0} + 1 \right)^{-1.08} + 1.45 \frac{g}{C^2}} \quad \text{for } L > 6D
\]

(5.9)

\[
r_0 = 1.21 \sqrt{\frac{g}{C}}
\]

(5.10)

In the case of the 2D experiments of Zuylen and Sloff (2015) this did not cause problems, since a rough bed was used in the 2D experiments. When using Breusers’ theory in the case of the 3D experiments having a smooth bed this could underestimate the scour hole depth. This is also the case for the upstream slope, \( \beta \), however in equation 2.15 the roughness does not get canceled out of the equation which results in a smaller variance.

To study the significance of the differences between the two equations, the influence of the roughness of the bed on the scour hole development is studied for both equations. For equation 5.9 a certain sill height, \( D \) was assumed and a bed protection length, \( L \). The results for \( \alpha \) and the upstream slope, \( \beta \) can be seen in figures 5.20a and b. Of course, the values for \( \alpha \) and \( \beta \) depend on the choice of the sill height and the length of the bed protection. These are therefore chosen in a way that for \( C < 40 \text{ m}^1/\text{s} \) the difference between the two equations is negligible. For \( \alpha \) this resulted in a sill height and bed protection length of respectively 2m and 15m and for the calculation of \( \beta \), 2 m and 60 m.

![Figure 5.20: \( \alpha \) and upstream slope, \( \beta \), where equation 5.9 is indicated in blue and equation 5.10 is indicated in red.](image)
The difference between the two equations results in a difference in $\alpha$ of approximately 0.14 which consequently results in the depth development shown in figure 5.21. This can result in a maximum difference of 0.5 cm in scour hole depth after 4 hours.

Figure 5.21: Depth development in time based on results from the 3D experiments 2 and 4 and calculations with Breusers’ theory using a value for $\alpha$ of 2.06 and 1.92.

This only solves a small part of the underestimation by Breusers’ theory for the scour hole depth. More importantly, this also suggests that the roughness was not the only factor causing the 3D scour hole to be deeper than the 2D scour hole. It is therefore expected that 3D effects enhance scour hole growth. The possible difference in the upstream slope is approximately $2^\circ$, which is practically negligible.

10. As mentioned in Section 4.4 the values for the coefficients and exponents in Breusers’ equations are determined empirically for scour behind a bed protection of a sill. Moreover, the 3D value for $\gamma$ was determined in a case were the sill induced 3D effects in the flow instead of, in this case, 3D effects due to the shape of the scour hole. The values for these coefficients and exponents are therefore possibly different for the 3D scour situation in this scale model. However, as a first step to adapt Breusers’ theory to 3D scour it could be interesting to study the influence of variation in the values for $\gamma$ and $K$.

According to Hoffmans and Verheij (1997) the value for $\gamma$ for 2D conditions values varies between 0.27 and 0.4 (Breusers, 1965; Dietz and Wittke, 1969; Mosonyi, 1968) and for 3D conditions between 0.4 - 0.8 (Meulen and Vinjé, 1975), see Chapter 2. The value for $K$ in 2D scour with rough bed conditions is $330 \text{ m}^{2.3}/\text{s}^{3.3}$ (Graauw and Pilarczyk, 1981). Figures 5.22 and 5.23 show the influence of varying these values on the calculated scour hole development by varying $\gamma$ between 0.4 and 0.8 and $K$ between 100 and 500 $\text{m}^{2.3}/\text{s}^{3.3}$.

Figure 5.22: Depth development in time based results from experiments 2 and 4 and calculations with Breusers’ theory using a value for $\gamma$ of 0.4 - 0.8 and $K = 330 \text{ m}^{2.3}/\text{s}^{3.3}$.
CHAPTER 5. SCOUR HOLE DEVELOPMENT IN A SCALE MODEL

Figure 5.23: Depth development in time based results from experiments 2 and 4 and calculations with Breusers’ theory using a value for $\gamma$ of 0.6 and $K = 100 - 500$ m$^{2.3}$/s$^{1.3}$.

As can be seen from the figures a lower value for $\gamma$ increases the calculated scour hole depth and reduces the underestimation by following Breusers’ theory. However, from studying the literature it was expected that a 3D effects correspond to a higher value for $\gamma$ (Hoffmans and Verheij, 1997). This can be explained that for $t < t_1$ a lower value for $\gamma$ will result in a larger scour hole depth. For $t > t_1$ the opposite occurs. Since in this case only the start of the scour hole is studied, a lower $\gamma$ would be more suitable. Since this does not correspond to what was said in previous studies, more experiments can be performed to verify this and to find a correct value for $\gamma$.

A lower value for $K$ results in a larger calculated scour hole depth. In combination with the change in $\gamma$ this could reduce the underestimation by Breusers’ theory significantly. However, the range of $K$ is only chosen to see the effect of a change in value and is therefore possibly not realistic. Concluding, to adapt Breusers theory to 3D scour hole development, suitable values for $\gamma$, $K$ and the exponents can be found by performing a larger set of experiments.
Chapter 6

Conclusions and recommendations

6.1 Conclusions

Based on the research questions mentioned in Chapter 1 the following conclusions and recommendations are made.

1. Is it possible to make use of a generic method to identify scour holes?
   The development of a generic method to detect and identify scour holes is complex. By basing a representative bed level on the mean minus one standard deviation per kilometer length and comparing this with the maximum depth of the bed level, many scour zones are defined, see Section 3.2. It includes the scour holes identified by Huismans et al. (2015), but also indicates other locations where possible scour holes could be located. This method therefore will suffice as a first approximation. However, as discussed in Section 3.4, when determining a representative bed level based on statistical characteristics of the river depth per interval of a certain length, the dimensions of the scour hole are of large influence. A mode value could be of more use by determining a representative bed level since it is less influenced by the presence of the scour hole. However, these values seem to lie relatively high and are indicating the largest part of the river as a scour zone. By determining this value on smaller intervals per kilometer and subtracting a representative bed variance this could be improved. To identify a scour hole more precisely, significant large slopes could indicate the edges of a scour hole. Applying this method to scour holes in de Oude Maas and the Dordtsche Kil in Section 4.1 however showed that very mild downstream slopes may complicate determining the edge. In addition smaller scour holes may grow inside larger ones, making it hard to define which steep slope to take. Defining scour holes therefore stays a complex and partially subjective process. Although these methods can be used as a first identification method of scour zones, the significance of the risk of the scour holes can only be determined when scour holes are studied in more detail individually.

2. What is the influence of the Haringvliet closure on scour hole development?
   The river bed is currently degrading in the center part of the delta and sedimentating in the northern and southern part. This is likely to have been caused by the Haringvliet closure since this enhanced flow velocities in the central rivers that connect the northern and southern rivers (Sloff et al., 2013). It was expected that due to the degrading trends in the connecting branches the scour hole growth in those branches would also be the largest. However, the largest percentage of scour holes that show growth between 2009 and 2014 is found in the northern branches of the delta, see Section 3.3. What causes this growth remains unclear, especially since the overall bed level is subjected to sedimentation. When focusing on the magnitude of the growth, the scour holes in the north show the largest extent of growth in surface area and the scour holes in the center show the largest extent of growth in depth. However, the differences are small. The bed degradation in the central part of
the delta therefore does not necessarily cause a larger growth of the scour holes in that area with respect to the other rivers. Studying the long term evolution of scour holes in the Oude Maas and the Dordtsche Kil in Section 4.2 learned that most scour holes have already existed for decades and reached a stable state.

In Section 4.2 it was seen that most of the scour holes in the Oude Maas already existed before 1970 but do show a large growth since 1976. This large growth may be related to the closure of the Haringvliet. However, since no data is available on the growth rates before 1970, it could not be verified whether the Haringvliet closure caused a break in the trend. Also since no new scour holes developed in the Oude Maas shortly after 1970, the enhancement of scour hole development in the Oude Maas by the Haringvliet closure is not certain. The scour holes in the Dordtsche Kil originated in a short period after 1970. It is possible that the Haringvliet closure enhanced the scour hole growth. However, as discussed in Section 4.4, since no new scour holes developed in the Oude Maas just after 1970 and the scour holes in the Dordtsche Kil developed within such a short period, it is more likely that the deepening of the river bed in the period 1970 - 1985 by dredging caused a removal of the protecting clay layers exposing the sandy channel belts to the flow (Huismans et al., 2016).

3. How does a heterogeneous subsoil influence scour hole growth in depth and extent?

In Section 3.3 it is shown that in the Rhine-Meuse delta most scour holes are related to the presence of a structure or a local change in geometry. Data analysis shows that in the case these scour holes are also expected to have reached below the layer of "Wijchen" or when they are growing in channel belts, their current scour hole growth is on average higher. A possible explanation is that the heterogeneity of the subsoil becomes influential deeper in the subsoil, enhancing the growth of a scour hole as it deepens.

It was expected that scour growth is enhanced when it reaches the Pleistocene sand below the layer of "Wijchen". To verify this only a few scour holes are available that reached through the layer of Wijchen after 1976 to study in more detail, see Section 4.2. As expected, the growth rate of these scour holes increases after reaching below the base of the layer of Wijchen, incising the Pleistocene sand.

According to Huismans et al. (2016) it is expected that scour holes that are suspected to grow in sandy channel belts are more limited in growth in area and depth than scour holes that reached the Pleistocene sand below the layer of "Wijchen". This is due to the size of the channel belt and the thickness of the layer of Wijchen at the edges of the scour holes. The analysis of the growth of all scour holes in the delta in Section 3.3 seems to verify this hypothesis. However, uncertainties in the analysis arise as the exact location and size of the channel belts is unknown and the age of the scour holes is not taken into account, see Section 3.4.

The scale experiments in Chapter 5 show that, similar to what was found by Zuylen and Sloff (2015), a poorly-erodible downstream layer slows down the scour hole growth. Moreover, when the scour hole growth is not limited in sidewards direction the gradual widening of the scour hole in downstream direction follows a 1:8 line. Finally, the experiments with a poorly-erodible upstream edge show that the scour hole does not grow upstream when subjected to unidirectional flow conditions. However, in the field it was found that some scour holes tend to grow upstream. This could be related to the local thickness of the clay layer surrounding the scour hole but also to the reversal of the flow due to the tide.

4. Do scour holes show similar behaviour when located in the same river reach?

As shown by the data analysis in Section 4.2, the scour hole development varies strongly per hole and does not necessarily show similarities when scour holes are located in the same river reach, even though they are subjected to similar hydrodynamic conditions. Most scour holes already exist for a long time and are currently stable, while others developed more recently. The growth rates of both older and younger scour holes in the period 1976 - 2015 are not always similar and some of their current trends vary by showing either eroding,
sedimentating or stable behaviour. As discussed in Section 4.4, an explanation for this strong variance between scour hole behaviour could be the presence of structures, changes in geometry and the varying composition of the soil. It is therefore important to keep studying scour holes and their environment individually.

5. Is Breusers’ theory applicable to scour holes in a heterogeneous subsoil under influence of tidal flow?

Based on realistic flow patterns a reduction factor of 0.73 has been derived to correct the maximum local flow velocity for tidal influences. This is higher than the factor based on idealized tidal flow characteristics (Zuylen and Sloff, 2015). Even after taking this factor into account, scour holes in the field show smaller depths than expected by using the theory of Breusers (1965) and the slopes as observed in the field do not seem to show any relation to the Breusers’ theory, see Section 4.3. Many explanations were given in Sections 4.4 and 5.5 comparing the scour conditions where Breusers’ equations are based on, to the conditions in the field. The main influences on the deviations between the field and predictions by using Breusers’ theory are likely to be related to the surrounding soil conditions which could influence the steepness of the slopes and limit the scour hole growth. The latter was verified by Zuylen and Sloff (2015) and in the scale experiments in Chapter 5. Moreover, scour holes in the field are expected to develop under live-bed conditions which causes scour holes to reach smaller depths. Since these aspects influence the scour hole growth strongly, scour hole development in heterogeneous subsoil in a tidal area under anthropogenic influences is very complex. The application of Breusers’ theory therefore comes with many uncertainties and it shows that the theory in this form is not applicable to scour holes in the Rhine-Meuse delta.

6. How does the shape of a scour hole influence the 3D flow pattern around the hole and with this the development of the scour hole with respect to a 2D shaped scour hole?

The scour hole development in the 3D experiments showed faster and deeper scour growth with respect to the scour hole development in 2D experiments of Zuylen and Sloff (2015), see Section 5.5. Although the 3D experiments were performed with a smooth bed with respect to a rough bed in the 2D experiments which could increase the scour hole growth, it was discussed in Section 5.5 that this difference is relatively small. Therefore, the larger scour hole depth could be caused by the 3D effects induced by the shape of the scour hole enhancing the scour hole growth.

6.2 Recommendations

- To improve the identification method for scour holes in a river branch an attempt can be done by basing the representative river bed on the mode minus a representative bed level variance. The mode is less sensitive for the presence of scour holes than the mean value, however, a representative bed level variance varies per river reach which makes it more complex make this a generic method which can be applied to any river branch.

- The start of the development of scour holes is in most cases induced around hydraulic structures or at locations where the geometry of the river locally changes. Once these scour holes develop and deepen, poorly erodible layers can decrease their growth, but when a scour hole breaks through a poorly-erodible layer their growth is enhanced. It is therefore important to take the composition of the subsoil into account when constructing new structures or changing the geometry. Moreover, when deepening the rivers, dredging has to be done with care, considering the removal of valuable protective clay layers.

- To get more insight into the influence of the Haringvliet closure on scour hole development in the delta, it is suggested to determine the year of origin of the scour holes in the southern and northern branches and study their depth development just after 1976. If these rivers also show new scour hole development after 1970 or if existing scour holes also show large
growth after 1976, there could be another explanation for scour hole development besides the Haringvliet closure. Since scour holes in the northern part of the delta are growing the most despite the sedimentating trend of the bed level, it could be interesting to investigate possible causes for this growth.

- There are only a few scour holes of which the behaviour around the layer of "Wijchen" can be studied. Their growth rate seemed to increase when they reached the layer of "Wijchen". This could be verified by studying more scour holes that reached below the layer of "Wijchen" in the period after 1976.

- There is much uncertainty on the difference between the influence of the layer of "Wijchen" and channel belts on scour hole development. To verify if scour holes are growing faster when they reached below the layer of "Wijchen" with respect to when they are located in a channel belt, more information is needed on the exact location and characteristics of the channel belt and its surrounding soil layers. Also the development of scour holes in area with respect to the dimensions of the channel belts could give useful information.

- Since the geological conditions are of large influence on scour hole growth more geological research could be done on the heterogeneous subsoil of the Rhine-Meuse delta. A better understanding should be obtained on the behaviour of scour holes in varying soil layers and the failure mechanism of the poorly erodible layers near the edges of a scour hole. It should therefore also give more insight into the overall stability of the slopes of the scour holes.

- In order to obtain a better understanding of 3D scour in heterogeneous subsoil it is recommended to perform more experiments with for example varying scour hole shapes and materials for the poorly-erodible top layer. By measuring the velocity in and around the scour hole a better understanding can be obtained of the 3D effects on the local flow velocity and turbulence intensity which influence the scour hole growth. This way an attempt can be made to adapt Breuser’s theory to 3D-scour and more suitable values for the $\gamma$ values, the calibration coefficient, $K$, and the exponents in Breuser’s equations can be determined.

Since most scour holes are located near structures and changes in geometry, other relations to determine the scour hole development in for example, bends and confluences or around bridge piers, can be applied to the scour hole development in the delta and perhaps combined with the relations for scour hole development downstream of bed protections (Hoffmans and Verheij, 1997).

There are several other theories on scour hole development behind bed protections than the one that is. A suggestion would be to study the difference in the methods by using for example the theory developed by Hoffmans (2012).

More accurate flow velocities as input for Breuser’s equations can be obtained by generating the output of the SOBEK calculations at the locations of the scour holes. It would be even more useful to measure the flow velocities in the field upstream, downstream and in the scour holes. Also, since the tide causes a large variance in the velocity in both directions it would be interesting to follow the scour hole development in a non tidal river to see if the predictions by using Breuser’s theory agree more with the scour hole depth and slopes in these rivers.

- Scour hole development in sideward direction is interesting for the stability of river banks. It is therefore recommended to study the growth in width of scour holes in the field and the steepness and stability of the slopes. Moreover, scale model experiments focusing on the sideward growth of a scour hole could be performed.

- Many aspects influence scour hole growth in the delta and were not all taken into the scale model experiment since it only focused on the shape of the scour hole and the poorly erodible layer. Future experiments could focus on other aspects as for example the effect of the local water depth, varying and reversing flow velocities due to the tide, other types of river bed
material with corresponding roughnesses and perhaps measures that can prevent or reduce scour hole development.
References


Breusers, H. N. C. (1965). Conformity and time scale in two-dimensional local scour. Delft Hydraulics Laboratory Delft, the Netherlands. v, vi, 2, 3, 9, 10, 12, 13, 16, 17, 31, 33, 37, 39, 43, 48, 50, 51, 52, 53, 54, 55, 58, 63, 64, 65, 68, 70, 75


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Appendix A

Year average bed level change in 2000 - 2012

Table A.1: Year average bed level change in 2000 - 2012 (Becker, 2015)

<table>
<thead>
<tr>
<th>River branch</th>
<th>Part</th>
<th>Average river bed change [cm/y]</th>
<th>Average dredging [cm/y]</th>
<th>Nett [cm/y]</th>
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</thead>
<tbody>
<tr>
<td>Oude Maas</td>
<td>East</td>
<td>0.5</td>
<td>-0.3</td>
<td>0.8</td>
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<tr>
<td>Oude Maas</td>
<td>Centre</td>
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<td>-0.3</td>
<td>-2.4</td>
</tr>
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<td>-5.8</td>
</tr>
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<td>Oude Maas</td>
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<td>-0.3</td>
<td>-0.1</td>
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<tr>
<td>Spui</td>
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</tr>
<tr>
<td>Dordtsche Kil</td>
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</tr>
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<td>Haring Vliet</td>
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Appendix B

The location of the scour holes in the Oude Maas and Dordtsche Kil

Figure B.1: QGIS image of the Oude Maas and the Dordtsche Kil colored dark blue
APPENDIX B. THE LOCATION OF THE SCOUR HOLES IN THE OUE MAAS AND DORDTSCHE KIL

Figure B.2: QGIS image of the Oude Maas (darkblue) and the scour holes (red dots) identified by Huismans et al. (2015)

Figure B.3: QGIS image of the Dordtsche Kil (darkblue) and the scour holes (red dots) identified by Huismans et al. (2015)
Appendix C

Longitudinal profiles of the scour holes in the Oude Maas and Dordtsche Kil in 2009 and 2014
APPENDIX C. LONGITUDINAL PROFILES OF THE SCOUR HOLES IN THE OUDE MAAS AND DORDTSCHE KIL IN 2009 AND 2014

Figure C.1: Longitudinal sections of the scour holes of the Oude Maas 1-9

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APPENDIX C. LONGITUDINAL PROFILES OF THE SCOUR HOLES IN THE OUDE
MAAS AND DORDTSCHE KIL IN 2009 AND 2014

Figure C.2: Longitudinal sections of the scour holes of the Dordtsche Kil 1-4
Appendix D

The maximum depth of the Oude Maas and Dordtsche Kil in the period 1976 - 2015

Figure D.1: Oude Maas: Maximum depth per km in the period 1976 -2015

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Figure D.2: Dordtsche Kil: Maximum depth per kmr in the period 1976 -2015
Appendix E

Bed topography images and the development in time per scour hole
APPENDIX E. BED TOPOGRAPHY IMAGES AND THE DEVELOPMENT IN TIME PER SCOUR HOLE

Figure E.1: Left: QGIS image based on bed topography data from the scour hole in 2014; center: Deepest point per cross-section at the location of the scour hole in 1976 - 2015; right: Deepest point per scour hole in the period 1976 - 2015
Figure E.2: Left: QGIS image based on bed topography data from the scour hole in 2014; center: Deepest point per cross-section at the location of the scour hole in 1976 - 2015; right: Deepest point per scour hole in the period 1976 - 2015
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APPENDIX E. BED TOPOGRAPHY IMAGES AND THE DEVELOPMENT IN TIME PER SCOUR HOLE

Figure E.4: Left: QGIS image based on bed topography data from the scour hole in 2014; center: Deepest point per cross-section at the location of the scour hole in 1976 - 2015; right: Deepest point per scour hole in the period 1976 - 2015
Figure E.5: Left: QGIS image based on bed topography data from the scour hole in 2014; center: Deepest point per cross-section at the location of the scour hole in 1976 - 2014; right: Deepest point per scour hole in the period 1976 - 2014.
Figure E.6: Legend of figure E.5
Appendix F

Growth in depth of the scour hole ”OMS 4”

Table F.1: Development of the maximum depth of OMS 4, 2008 - 2014

<table>
<thead>
<tr>
<th>Date</th>
<th>Difference [months]</th>
<th>Maximum depth [m]</th>
<th>growth [cm/month]</th>
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Appendix G

Slopes of the scour holes in the Oude Maas and Dordtsche Kil in 2014

Table G.1: Slopes per scour hole based on bathymetric data of 2014 where $\beta_1$ stands for the dominant upstream slope, $\beta_2$ the dominant downstream slope and $\beta_{\text{max}}$ the maximum slope in either of the slopes. The steepest slope per scour hole is indicated in bold

<table>
<thead>
<tr>
<th>Scour hole</th>
<th>$\beta_1$</th>
<th>$\beta_2$</th>
<th>$\beta_{\text{max}}$</th>
</tr>
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<tbody>
<tr>
<td>OMS1</td>
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<td>11.0</td>
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<td>OMS2</td>
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<tr>
<td>OMS3a</td>
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</tbody>
</table>

Scour holes in tidal rivers with heterogeneous subsoil under anthropogenic influence
Scour holes in tidal rivers with heterogeneous subsoil under anthropogenic influence
Appendix H

Subsoil composition of the Oude Maas

Figure H.1: Subsoil composition at the location of the Oude Maas (Stouthamer and De Haas, 2011) and the locations of the scour holes as identified by Huismans et al. (2015) indicated with red dots.

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