Scour holes in heterogeneous subsoil

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An experimental study to improve knowledge of the development of scour holes in heterogeneous subsoil
Scour holes
in heterogeneous subsoil
by
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It was beautiful to finally enter the fluid mechanics laboratory for a decent purpose after seven years. It is nice that, besides all numerical modeling, that it is still possible to contribute to scientific research with flume experiments. I spent many hours in the laboratory for configuration, waiting and other non-essential issues. Nevertheless, it was all worth it. I admire all the help from the laboratory technicians. From the beginning they supported me with small and large technical adaptations.

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J.G. (Joost) Stenfert
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Summary

In the Rhine-Meuse delta many scour holes have developed. These scour holes pose a potential risk on the stability of nearby bridge piers, levees, dikes, weirs and tunnels. The Rhine-Meuse delta is a densely populated area and failure of important water infrastructures could have considerable consequences. Scour holes can develop through several causes. Commonly, scour holes develop when there is a local change in hydrodynamic conditions or in erosive capacity. Extensive research has been done on scour holes close to hydraulic structures, however, for the scour holes in the Rhine-Meuse delta, the heterogeneity of the subsoil is an important driving factor.

The subsoil in deltas consists of many alternating layers of different types of soil (e.g. peat, clay and sand) with different erosive capacities. To improve knowledge on scour hole formation in heterogeneous subsoil a combination of field data analysis, numerical simulations and scale model experiments is required. In this research, experiments are executed on a scour hole formation with a concrete top layer, mimicking a poorly erodible top layer and an oval shaped hole, exposing the underlying sand to the flow. Water depth, flow velocity and the size of the scour hole are systematically varied to identify dependencies of the development of a scour hole on these parameters. Additionally, general observations are executed on the flow structures and scour development in and around the scour hole.

It is concluded that, in general, a different development pattern is present compared to earlier experiments on scour hole development behind a structure or bed protection. As a result of the non-erodible top layer no equilibrium depth is reached. The maximum depth reached in the experiment depends heavily on the shape and size of the scour hole. This maximum depth is created due to undermining of the downstream edge of the non-erodible top layer. The influence of undermining increases over time and eventually becomes significantly large creating a horizontal recirculation of sediment without transport out of the scour hole.

The experimental data is compared with the existing empirical formulas (Breusers, 1966) for prediction of two-dimensional scour hole development downstream of a hydraulic structure. It is concluded that the presence of a non-erodible top layer creates a different time development compared to the formulas. The non-erodible top layer creates three-dimensional flow patterns in the development stages which can increase the scour hole development. The non-erodible top layer significantly slows down the scour hole development in later stages. Predictions on the equilibrium depth based on an empirical formula showed significant differences with the results. First of all, the different experimental configurations showed significantly smaller variance in equilibrium depth compared to the predictive formula. Secondly, the equilibrium scour depths are significantly lower in the experiments from this research compared to the values obtained by the predictive formula.

Water depth, flow velocity and geometry show influence on scour hole development to a greater or lesser extent. The effect of water depth is small in the development phase and increases over time. During the timespan of the experiments, no significant differences were observed, by fitting the equilibrium depth for different water depths showed small differences. A lower water depth leads to more shallow scour holes. Higher flow velocities lead to deeper scour holes and significantly faster time development. A change in the size of the geometry (equal aspect ratio) showed the most significant changes. A larger size showed significantly deeper scour holes and faster development.

Flow patterns are observed by measuring velocities and using dye visualization. In this experimental setup it was not possible to precisely measure the velocity profiles inside the scour hole. Grains of pigment have been used to visualize flow directions at the bottom of the scour hole. A recirculation zone is observed at the centre line with a reattachment point at 3.75 - 5 times the maximum scour depth, measured from the upstream edge. Additionally, diverging flows are observed at the bottom on both sides of the scour hole which indicate the presence of a horse-shoe vortex in the scour hole.
A constant upstream slope attached to the upstream edge is observed during the experiments. Possibly, this slope remains stable over time as a result of the recirculation pattern in the upstream part of the scour hole. The downstream edge is undermined in later stages during the experiments. It is expected that in reality this amount of undermining is not present, and a poorly erodible top layer will fail earlier which can lead to further development of a scour hole. In tidal circumstances this can create scour development in both the upstream and downstream direction as a result of alternating flow directions.

The non-erodible top layer limits the scour hole development in all experiments. The scour depth \( S \) only changes significantly when the geometry is changed, which leads to a relatively constant value of \( S/L_{geo} \) in which \( L_{geo} \) is a length scale of the geometry. A poorly-erodible top layer seems to create widening of the scour hole at the downstream side as a result of undermining. It is concluded that the effect of the water depth in the experiments of this research is significantly lower compared to the effect according to predictive formulas from Breusers (1966).

A first indication of influential parameters for scour hole development is obtained by this research. Water depth has a small dependency, flow velocity has large influence and the size of the geometry is the most decisive parameter. The set of experiments is not yet sufficient for deriving a generic predictive formula for this type of scour holes. More experiments on the effect of the grain size, bed roughness and the size of the geometry are needed. The upstream part remains attached to the edge and the downstream part is undermined which suggests scour hole development in the direction of the flow. This should be investigated in a flume with use of a poorly erodible top layer which can bend and fail. Additionally, it is expected that the thickness and strength of the poorly erodible top layer is of great importance for scour hole development. Therefore it is important to understand and map the composition of the surrounding subsoil lithology.
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<tr>
<td>$A$</td>
<td>surface</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>$A_c$</td>
<td>conveyance area</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>$b_A$</td>
<td>width of flume section A</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$C$</td>
<td>Chezy value</td>
<td>$[m^{1/2}/s]$</td>
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<tr>
<td>$C_0$</td>
<td>40</td>
<td>$[m^{1/2}/s]$</td>
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<td>$C_{D,F,L}$</td>
<td>coefficient</td>
<td>[-]</td>
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<tr>
<td>$D$</td>
<td>height of sill</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$d$</td>
<td>grain diameter</td>
<td>$[m]$</td>
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<td>$d_{50}$</td>
<td>median grain size</td>
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<tr>
<td>$d_{\text{max}}$</td>
<td>maximum scour depth</td>
<td>$[m]$</td>
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<tr>
<td>$F_L$</td>
<td>force in normal direction</td>
<td>$[N]$</td>
</tr>
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<td>$F_F$</td>
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<td>$F_D$</td>
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<td>$[N]$</td>
</tr>
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<td>$F_L$</td>
<td>lift force</td>
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</tr>
<tr>
<td>$F_S$</td>
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<td>water depth</td>
<td>[-]</td>
</tr>
<tr>
<td>$h_A$</td>
<td>water depth section A</td>
<td>$[m]$</td>
</tr>
<tr>
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<td>water depth in flume</td>
<td>$[m]$</td>
</tr>
<tr>
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<td>$[m]$</td>
</tr>
<tr>
<td>$H$</td>
<td>energy head</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$i_b$</td>
<td>bed slope</td>
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</tr>
<tr>
<td>$k$</td>
<td>turbulent kinetic energy</td>
<td>$[m^2/s^2]$</td>
</tr>
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<td>equivalent roughness of Nikuradse</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$K$</td>
<td>coefficient</td>
<td>$[K = 330 \ m^{2.3}/s^{1.3}]$</td>
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</tr>
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<td>length of bed protection ($L_{\text{bed}} &gt; 6D$)</td>
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</tr>
<tr>
<td>$n_y$</td>
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<tr>
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<td>$[Pa]$</td>
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<td>$P$</td>
<td>perimeter</td>
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</tr>
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<td>discharge upstream per unit width</td>
<td>$[m^2/s]$</td>
</tr>
<tr>
<td>$Q_B$</td>
<td>discharge downstream per unit width</td>
<td>$[m^2/s]$</td>
</tr>
<tr>
<td>$R$</td>
<td>hydraulic radius</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$r_0$</td>
<td>relative turbulence intensity</td>
<td>[-]</td>
</tr>
<tr>
<td>$S_1$</td>
<td>scour first part</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$S_2$</td>
<td>scour second part</td>
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<tr>
<td>$S_{2\text{cours}}$</td>
<td>equilibrium scour depth second part</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$S_{1\text{cours}}$</td>
<td>scour data fitted with experimental data</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
<td>$[s]$</td>
</tr>
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<td>characteristic time at which $y_m = h_0$</td>
<td>$[hrs]$</td>
</tr>
<tr>
<td>$t_s$</td>
<td>moment of switching between equations</td>
<td>$[hrs]$</td>
</tr>
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<td>$T_1$</td>
<td>characteristic timescale first part</td>
<td>$[hrs]$</td>
</tr>
<tr>
<td>$T_2$</td>
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</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
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</tr>
<tr>
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</tr>
<tr>
<td>$u$</td>
<td>flow velocity</td>
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<td>$\bar{u}$</td>
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<td>$[m/s]$</td>
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<td>$u'$</td>
<td>fluctuating part of velocity</td>
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<td>$u_1$</td>
<td>velocity of main flow</td>
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<td>velocity adjacent flow</td>
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<td>$u_g$</td>
<td>local velocity</td>
<td>$[m/s]$</td>
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<td>$u_{c,c}$</td>
<td>critical bed shear-velocity</td>
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<tr>
<td>$u_A$</td>
<td>average velocity section A</td>
<td>$[m/s]$</td>
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<tr>
<td>$\bar{u}_{0,m}$</td>
<td>maximum mean velocity</td>
<td>$[m/s]$</td>
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<tr>
<td>$\bar{u}_0$</td>
<td>mean velocity $(Q/A)$</td>
<td>$[m^2/s]$</td>
</tr>
<tr>
<td>$u_c$</td>
<td>critical mean velocity</td>
<td>$[m^2/s]$</td>
</tr>
<tr>
<td>$u_t$</td>
<td>velocity in scour hole</td>
<td>$[m/s]$</td>
</tr>
<tr>
<td>$U$</td>
<td>depth averaged velocity at end of bed protection</td>
<td>$[m/s]$</td>
</tr>
<tr>
<td>$U_c$</td>
<td>critical velocity</td>
<td>$[m/s]$</td>
</tr>
<tr>
<td>$w$</td>
<td>width of geometry</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$W$</td>
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<tr>
<td>$x$</td>
<td>longitudinal distance</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$y_m$</td>
<td>maximum scour depth at t</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$y_{m,e}$</td>
<td>maximum scour depth in equilibrium phase</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$y_p$</td>
<td>quantity prototype</td>
<td>[-]</td>
</tr>
<tr>
<td>$y_{model}$</td>
<td>quantity model</td>
<td>[-]</td>
</tr>
</tbody>
</table>

$\alpha$ coefficient depending on flow velocity and turbulence intensity [-]
$\alpha_{emp}$ empirical constant [-]
$\alpha_s$ angle of slope [°]
$\beta$ slope angle of upstream slope [°]
$\gamma$ coefficient [-]
$\Delta$ relative density [-]
$\delta$ width of boundary layer [-]
$\theta$ temperature [°C]
$\kappa$ 0.4, constant of Von Kármán [-]
$\mu$ variance [-]
$\nu$ kinematic viscosity $[m^2/s]$ |
$\rho$ fluid density $[kg/m^3]$ |
$\rho_w$ sediment density $[kg/m^3]$ |
$\sigma$ standard deviation [-]
$\Psi_c$ critical mobility parameter [-]
Introduction

1.1. Background information

The Rhine-Meuse Delta is a densely populated area in the Netherlands, which requires solid defenses to prevent this area from flooding. Within the Rhine and Meuse river, many local depressions in the river bed exist. These so called scour holes may pose risk on surrounding hydraulic structures like bridge piers, levees, groynes, weirs and tunnels. Based on measurements from 2012, around 100 scour holes have been identified in the Rhine-Meuse delta (RMD), as indicated in Figure 1.1(a). In general, scour holes nearby structures have clear causes for developing due to changes in flow processes nearby those structures. In the RMD, the composition of the subsoil lithology plays an important role. As a result of a complex composition of the subsoil and the alternating erosive capacity (See Figure 1.1(b)), scour holes can develop at locations not nearby hydraulic structures (Sloff et al., 2013) (Huismans et al., 2016).

![Figure 1.1: Presence of scour holes in the Rhine-Meuse delta (Sloff et al., 2013) (Huismans et al., 2016).](image)

Extensive research has been conducted on scour holes to increase knowledge on the influence of hydraulic structures (e.g. bridge piers, weirs) (Breusers, 1966) (Van der Meulen and Vinje, 1975) (de Graauw and Pilarczyk, 1981) (Jorissen and Vrijling, 1989) based on which several empirical relations have been developed to predict development and scour depth. Most of these analyses focused on two-dimensional cases within homogeneous subsoil. The obtained empirical relations generally relate the scour depth to a characteristic length scale of a hydraulic structure (e.g. bridge piers, weirs).

Van Zuylen (2015) performed experiments on scour hole development in heterogeneous subsoil in a two dimensional situation. A first short investigation on the influence of three-dimensional geometries on the development of scour holes is executed by Koopmans (2017). It shows significant differences between two-
dimensional and three-dimensional cases suggesting the relevance of three-dimensional flow structures. How these three-dimensional flow patterns influence the scour hole growth and depth has not yet been unraveled. Additionally, significant differences are observed as a result of heterogeneous subsoil. For a better understanding and prediction of the scour hole development in heterogeneous subsoil, further research is required.

1.2. Problem description
For estimating potential risks on the stability of dikes and other infrastructure, predictions on the evolution of scour holes in heterogeneous subsoil are desirable. Insight in the flow patterns and erosion patterns inside a scour hole will help to design proper protection measures.

So far, only formulas on scour hole development are available for scour holes nearby structures in alluvial beds and are mostly based on experiments on scour hole formation in a two-dimensional situation (Breusers, 1966) (Dietz, 1969) (Mosonyi and Schoppmann, 1968) (Van der Meulen and Vinje, 1975). To obtain predictive formulas for three-dimensional scour hole development in heterogeneous subsoil, systematic research is needed on how flow conditions and geometric conditions are of influence. With the help of data analyses, numerical models and flume experiments knowledge of development of scour holes in heterogeneous subsoil can be improved. Koopmans (2017) already executed data analyses on scour holes in the RMD and parallel to this study Bom (2017) is investigating scour holes with a numerical model.

1.3. Research objective and questions
The aim of this research is to better understand and predict scour hole development in heterogeneous subsoil. This will be done by carrying out flume experiments with three-dimensional geometries and a simplified heterogeneity of the subsoil lithology. By investigating the influence of the flow characteristics and scour hole geometry on the scour hole growth, existing predictive equations may be adjusted for the specific type of scour hole development studied here. Furthermore, the flow patterns inside the scour hole will be studied, to understand their influence on the erosion process.

Main research question is:

*How do scour holes in heterogeneous subsoil develop and how can they be predicted?*

With four subquestions:

- What is the influence of a poorly erodible top layer on development of the scour hole?
- Is it possible to describe scour holes in heterogeneous subsoil with existing empirical formulas for scour hole development?
- Which parameter, characterizing scour development in a river, is correlating with scour hole development in heterogeneous subsoil?
- How are flow structures inside a scour hole with three-dimensional geometry contributing to scour hole development?

1.4. Methodology
Experiments are used to systematically investigate the influence of the average velocity and water depth on scour hole development. Additionally, the effect of the size of the geometry is investigated.

During the experiments flow processes have been visualized with dye. Additionally, velocity measurements have been executed to establish a view on the most important flow processes inside the scour hole which contribute to the scour hole development.
In the analyses the experimental data is compared with previous research by Koopmans (2017) and Van Zuylen (2015). Additionally, comparisons are made with the existing predictive formulas for scour hole development. Thereby, relations between the systematically varied parameters and scour hole development are obtained to evaluate the dependencies of the scour hole growth on each parameter.

1.5. Outline of the report

Chapter 2 gives an overview of existing relevant knowledge on scour hole development and the related hydrodynamic and sediment transport processes. The experimental set-up is discussed in Chapter 3 and Chapter 4 shows the outcome of the executed experiments. Chapter 5 contains analyses on the experimental data followed by a discussion on the experimental results and the executed analysis in Chapter 6. Conclusions and recommendations for further research are given in Chapter 7.
Background and Theory

Scour emerges due to complex interaction between water flow and sediment. Within this literature study, theoretical knowledge is presented on the formation of scour holes. The first part elaborates on basic flow properties. Additionally, previous research on scour holes and analogous cases are presented. This knowledge is the foundation of hypotheses and experiments discussed in following chapters. In Appendix A more background information is present on for example the possible types of flow, the definition of turbulence and the conditions for sediment transport.

2.1. Characterization of flow

The two most important dimensionless numbers for describing flow are the Froude Number and the Reynolds number. The Froude number presents the ratio between inertia and gravitational forces, as described in Equation 2.1. From the Froude number it can be derived whether a flow is sub- or supercritical. Flow is sub-critical when \( Fr < 1 \) and supercritical when \( Fr > 1 \).

\[
Fr = \frac{u}{\sqrt{gL}} \tag{2.1}
\]

\( u \) = flow velocity \([m/s]\)
\( g \) = gravitational acceleration \([g = 9.81 \ m/s^2]\)
\( L \) = length scale \([m]\)

The Reynolds number describes the ratio between inertia and the viscous forces, as described in Equation 2.2. The Reynolds number gives information on whether the flow is laminar or turbulent and gives an indication of the amount of turbulence. Flow is significantly turbulent when \( Re \gg 1000 \).

\[
Re = \frac{uL}{v} \tag{2.2}
\]

\( v \) = kinematic viscosity \([m^2/s]\)

2.2. Scour hole development

2.2.1. Flow patterns

In Figure 2.1 a two-dimensional flow pattern of sub-critical flow behind a sill is presented. As a result of the rapid change of geometry of the sill, flow will be detached. Detachment of flow creates a recirculation zone and a mixing layer downstream of the sill. The reattachment point is the location where largest impact by the flow is present. At this point a return flow develops opposite to the main flow direction. This creates the recirculation zone where the suspended load close to the bed is significantly less compared to the initial phase.
2. Background and Theory

conditions, mainly due to the lowering of flow velocities close to the bed (Hoffmans, 1993).

Within the mixing layer, transport of mass and momentum is present which leads to a deceleration of the main flow. Additionally due to presence of high shear stresses, high turbulence intensities will be present in the mixing layer (Schiereck, 2012). According to literature the mixing layer grows linearly (Bailly and Comte-Bellot, 2015). Higher velocities lead to larger transfer of momentum between two flows, but this momentum transfer is transported downstream faster as a result of higher advective forces. An empirical relation for the size of the mixing layer is given in Equation 2.3.

\[
\frac{d\delta}{dx} = \alpha_{emp} \cdot \frac{u_2 - u_1}{\frac{1}{2}(u_1 + u_2)}, \quad \alpha_{emp} \approx 0.085
\]  

\(\delta\) = width of boundary layer [m]  
\(u_1\) = velocity of main flow [m/s]  
\(u_2\) = velocity adjacent flow [m/s]  
\(x\) = longitudinal distance [m]  
\(\alpha_{emp}\) = empirical constant [-]

When flow separation occurs, for example at a backward facing step, the created recirculation will have a speed of approximately 30 % of the main stream velocity (Bailly and Comte-Bellot, 2015). Equation 2.3 shows that if the ratio between velocities in the recirculation zone and the main flow is more or less constant at different main flow velocities, the mixing layer will have similar shapes for different upstream flow velocities.

Within the mixing layer and the recirculation zone turbulence intensity is high compared to uniform flow. When flow is influenced by vertically changing geometries, circular flow, which is called a vortex, may occur. When the influence of a vortex street is insignificant, the flow is more or less two-dimensional (Hoffmans and Verheij, 1997). An analogy can be drawn between scour behind a sill and scour as observed in the field in heterogeneous subsoil. A relatively steep upstream slope will lead to similar behaviour in a two-dimensional situation.

![Figure 2.1: Schematization of flow zones behind a sill (Hoffmans and Verheij, 1997).](image)

### 2.2.2. Phases in development

Breusers (1966), Dietz (1969) and Zanke (1978) distinguished four different phases in the evolution of a two-dimensional scour hole behind a protection based on clear-water scour: an initial phase, a development phase, a stabilization phase and an equilibrium phase as can be seen in Figure 2.2.

The initial phase experiences uniform flow. Observations on fine sediments showed that at the start of the development bed material gets into suspension directly downstream of the protected bed (Breusers, 1966). Most suspended particles will remain in suspension as a result of a balance between the upward and downward flux.

In the development phase the ratio between maximum scour depth and distance from the end of the bed protection to the point where the scour hole is at its maximum is more or less constant. The shape of the
scour hole does not change, but the scour depth will increase significantly. Measurements showed that the
top part of the upstream slope is constant over time, where the bottom part will keep developing (Hoffmans,
1990). Velocities near the bed will decrease, so suspended load close to the bed decreases considerably,
despite the increase in turbulence.

During the stabilization phase the rate of development in depth decreases. Erosion in the lowest point of
the scour hole is very small compared to the erosion capacity downstream of the reattachment point. This
means that the scour hole develops more in longitudinal direction than in vertical direction. The longer this
process continues, the more the flow velocities above the bottom part of the upstream slope decrease. The
equilibrium for the upstream scour slope and the maximum scour depth is almost achieved in the stabiliza-
tion phase. The equilibrium situation is defined as the phase without significant changes in dimensions of
the scour hole (Hoffmans and Verheij, 1997).

\[ \frac{y_m}{y_{m,e}} = 1 - e^{\gamma \left(1 - \frac{h_0}{y_{m,e}}\right)} \left(\frac{t}{t_1}\right)^\gamma \]  

\[ \frac{y_m}{h_0} = \left(\frac{t}{t_1}\right)^\gamma \]  

Dietz (1969) did research on two-dimensional scour downstream of horizontal beds and low sills to evaluate
these considerations of Breusers. Dietz found an identical relation but proposed different empirical coeffi-
cients and exponents which showed better fits on the experimental data. Van der Meulen and Vinje (1977)
investigated the three-dimensional scour process downstream of a channel constriction. Their conclusion
was that the shape of the scour hole is independent of bed material and flow velocity and that equation 2.7 is
also of use for three-dimensional flow if the turbulence factor \( a \) is defined correctly (Hoffmans and Verheij, 1997).

Equation 2.4 can only be used when the scour depth is larger than the water depth. However, it is possible that scour holes can reach their equilibrium depth without being deeper than the water depth. Therefore, Equation 2.6 is proposed for calculating the equilibrium scour depth by Van Velzen et al. (2015).

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

**(Power-law \((\gamma)\))**

Several researches did experiments on the development of scour in time to investigate the value of coefficient \( \gamma \). In Table 2.1 an overview is given of obtained values in the 60’s and 70’s.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>( \gamma )</th>
<th>Flow condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Breusers, 1966)</td>
<td>0.38</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>(Mosonyi and Schoppmann, 1968)</td>
<td>0.27 - 0.35</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>(Dietz, 1969)</td>
<td>0.34 - 0.40</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>(Van der Meulen and Vinje, 1975)</td>
<td>0.4 - 0.8</td>
<td>Three-dimensional</td>
</tr>
</tbody>
</table>

Table 2.1: Coefficient \( \gamma \) (Hoffmans and Verheij, 1997).

For two-dimensional cases the considerations of Breusers (1966) were confirmed by later studies. However, in situations where three-dimensionality was induced, deviating values have been found. \( \gamma \) is strongly depending on the degree of turbulence generated by the vortex street (Hoffmans and Verheij, 1997). Three-dimensionality was present as a result of flow constriction. More information on the three-dimensional character of the experiments by Van der Meulen and Vinje (1975) is presented in Appendix A.2.9.

**Characteristic time scale**

The dependence of the characteristic time \( t_1 \) on upstream flow conditions is researched several times. It appears that for steady flow the influence of different parameters on the time scale can be expressed by (Hoffmans and Verheij, 1997):

\[
t_1 = \frac{K h_0^2 \Delta^{1.7}}{(\alpha \bar{u}_0 - \bar{u}_c)^{4.3}} \quad [hrs]
\]

\( K \) = coefficient \([K = 330 \ m^{2.3}/s^{4.3}]\)  
\( h_0 \) = water depth \([-]\)  
\( \Delta \) = relative density \([-]\)  
\( \alpha \) = coefficient depending on flow velocity and turbulence intensity \([-]\)  
\( \bar{u}_0 \) = mean velocity \((Q/A) \ [m^2/s]\)  
\( \bar{u}_c \) = critical mean velocity \([m^2/s]\)

**Turbulence coefficient**

Turbulence in open-channel flow is related to random, three-dimensional fluctuations corresponding to high Reynolds numbers. Each different geometry will generate a certain flow pattern with its associated turbulence properties (Uijtewaal, 2003). According to Section 2.2.1, the recirculation zone and mixing layer behind a sill experience high turbulence intensities, which leads stirring of sediments.

A relation between the turbulence coefficient and the relative turbulence intensity can be written in a generalized form and can be explained as a measure for the erosion capacity which is depending on the flow velocity and the turbulence intensity:

\[
\alpha = constant + r_0 \cdot constant
\]
2.2. Scour hole development

$r_0 \quad = \quad \text{relative turbulence intensity [–]}$

Jorissen and Vrijling (1989) updated earlier obtained relations between $\alpha$ and $r_0$ for two-dimensional flow to:

\[
\alpha = 1.5 + 5r_0 \tag{2.9}
\]

This equation is based on use of a local depth-averaged velocity $\bar{u}_{0,l}$ in the scour formula (equations 2.5 and 2.7). When a three-dimensional flow is studied and the mean flow-velocity $\bar{u}_0$ is used in the scour formula, $\alpha$ has to be multiplied by $\bar{u}_0, l / \bar{u}_0$ (Hoffmans and Booij, 1993). Additionally, not only the influence of relative turbulence intensity is significant but also the flow-velocity profile near the bed is important for the scour process. The influence of a smooth bed is introduced by $f_C$ in equation (2.10) and verified by experiments (Hoffmans, 1993). Additionally, if a smooth bed is present, $\alpha$ must be increased with a value between 0.3 and 0.5, to account for larger momentum impact close to the bed compared to a rough bed.

\[
\alpha = 1.5 + 4.4r_0 f_C \tag{2.10}
\]

$f_C \quad = \quad \text{roughness function (} f_C = \frac{C}{C_0}, \quad f_c = 1 \text{ when } C \leq 40 \text{ m}^{1/2}/\text{s} \text{)}$ 

$C_0 \quad = \quad \text{Chézy number [40 m}^{1/2}/\text{s} \text{]}$

$r_0 \quad = \quad \text{relative turbulence intensity [–]}$

Relative turbulence intensity

The turbulence coefficient present within the empirical relations is related to the upstream geometry, based on trial and error (Hoffmans and Booij, 1993). Hoffmans and Booij (1993) derived an analytical relation for the depth-averaged turbulence intensity:

\[
r_0 = \sqrt{0.0225 \left(1 - \frac{D}{h_0}\right)^2 \left(L - 6D \left(\frac{6.67h_0}{L} + 1\right)^{1.08} + 1.45 \frac{g}{C^2}\right)} \quad \text{for } L > 6D \tag{2.11}
\]

$C \quad = \quad \text{Chézy number [m}^{1/2}/\text{s} \text{]}$

$D \quad = \quad \text{height of sill [m]}$

$g \quad = \quad \text{gravitational acceleration [} g = 9.81 \text{ m}^2/\text{s}^2 \text{]}$

$L_{\text{bed}} \quad = \quad \text{length of bed protection (} L_{\text{bed}} > 6D \text{) [m]}$

Within the characteristic time for scour hole development (see Equation 2.7), a parameter for the erosion capacity is enclosed which includes the turbulence factor $\alpha$. According to Breusers this turbulence coefficient is related to the relative turbulence intensity ($r_0$) at the transition of the fixed to the erodible bed and not to local turbulence inside the scour hole. Equation 2.11 is only valid downstream of the reattachment point ($L > 6D$).

2.2.4. Semi-empirical formula for the equilibrium depth

According to Schiereck (2012), the equilibrium depth in the case of clear water scour is reached when the velocity in the scour hole multiplied by the turbulence factor is equal to the critical velocity (see Equation 2.12). This might misrepresent the equilibrium depth since the turbulence factor is determined at the upstream edge of the scour hole. Therefore, in practice, the value is reduced with a factor of about 0.5 based on an educated guess (Hoffmans and Verheij, 1997).

\[
\begin{align*}
\frac{u_c}{u_s} & = 0.5 \alpha u_s \\
\frac{h_{se}}{h_0} & = \frac{0.5 \alpha u_s - u_c}{u_c}
\end{align*} \tag{2.12}
\]

$h_{se} \quad = \quad \text{equilibrium scour depth [m]}$

$h_0 \quad = \quad \text{water depth [m]}$

$u_s \quad = \quad \text{velocity at scour hole [m/s]}$

$u_t \quad = \quad \text{velocity in scour hole [m/s]}$

$u_0 \quad = \quad \text{upstream velocity [m/s]}$

$\alpha \quad = \quad \text{coefficient depending on flow velocity and turbulence intensity [–]}$

Dietz (1969) deduced Equation 2.13 for the equilibrium scour depth based on experiments.
y_{m,e} = \frac{\omega u_0 - u_c}{u_c}

\begin{align*}
y_{m,e} &= \text{equilibrium scour depth [m]} \\
h_0 &= \text{water depth [m]} \\
u_0 &= \text{upstream velocity [m/s]} \\
u_c &= \text{critical velocity [m/s]} \\
\omega &= 1 + 3r_0 [-]
\end{align*}

2.2.5. Upstream slope

The stability of sediments on a slope depends on the fluid motion and the material properties. An equilibrium for the upstream scour hole slope of non-cohesive material is reached by equating the instantaneous bed shear-stress sloping downward to the instantaneous bed shear-stress upward.

This leads to a semi-empirical relation for the upstream slope angle of non-cohesive sediment (Equation 2.14) with a shear stress factor and a turbulence factor which expresses skewness of the instantaneous bed shear-stress (Hoffmans, 1993) (Hoffmans and Pilarczyk, 1995). This equation was developed for the upstream slope of a scour holes downstream of a bed protection (Hoffmans and Verheij, 1997).

\[ \beta = \arcsin \left( 2.9 \times 10^{-4} \frac{U^2}{\Delta g d_{50}} + 0.11 + 0.75r_0 f_C \right) \quad \text{with} \quad f_C = \frac{C}{C_0} \]  

\[ \beta = \text{Slope angle of upstream slope [°]} \\
U = \text{Depth averaged velocity at end of bed protection [m/s]} \\
d_{50} = \text{Median grain size [m]} \\
\Delta g = \text{gravitational acceleration [m/s^2]} \\
r_0 = \text{relative turbulence intensity [-]} \\
f_C = \text{roughness function [-]} \\
C = \text{Chézy coefficient related to bed upstream from scour hole [m}^{1/2}/\text{s}] \\
C_0 = 40 \text{ m}^{1/2}/\text{s}, \quad \text{if } C < C_0 \quad \text{then} \quad f_C = 1
\]

Equation 2.14 shows that turbulence has a large influence on the development of the upstream slope. More turbulence upstream leads to steeper slopes. Additionally, bed roughness has impact on the slope. A smooth bed results in steeper upstream scour slopes because velocities close to the bed have greater momentum and cause more rapid expansion of the flow in the scour hole. Within deltaic areas with relatively fine sediments and velocities larger than 1 [m/s], the shear stress factor largely determines the upstream scour slope. Equation 2.14 matches with measured dimensions of a scour hole in a sub-critical flow upstream of the scour hole (Hoffmans and Verheij, 1997). Measurements of Hoffmans (1990) showed that the top part of the upstream scour slope is already in equilibrium in the development phase, while the bottom part is still in motion (Hoffmans, 1993).

This equation is for a uniform directional flow, so tidal influence is not taken into account. Tide changes the configuration of the scour hole when flow reverses. The flatter downstream slope will become the upstream slope and vice versa.

Upstream slope according to Breusers (1966)

According to Breusers the upstream slope has a dynamic equilibrium in which the transport by the recirculation and the rate of suspension are important. In Figure 2.3 the importance of fall velocity on the upstream slope is shown according to Breusers. More turbulence upstream led to steeper slopes within the experiments of Breusers. Additionally, Figure 2.3 shows steeper slopes for larger fall velocities relative to the main flow.

2.2.6. Influence of heterogeneity

Within the Rhine-Meuse Delta, a heterogeneous subsoil is present as a result of the interaction between river and sea. Sea-level rise, variations in river discharge, changing sediment supply in the river and for example storm events all have influence on the development of the subsoil, eventually creating an alternating pattern.
2.2. Scour hole development

Huismans et al. (2016) and Koopmans (2017) showed that most of the scour holes in the Rhine-Meuse delta are created by the influence of structures or local changes in river geometry. Some scour holes are not located close to those local geometry changes or hydraulic structures. In this case, heterogeneous subsoil stratigraphy together with anthropogenic influences shape the creation of the scour holes. Development of scour holes in time depends heavily on the mixed type of soil. A clay layer may slow down the development, but when a clay layer is locally eroded, scour development might accelerate again (Van Velzen et al., 2015). Clay or peat layers may also influence growth in extent in lateral and longitudinal direction. As a consequence of thick edge layers of clay or peat, the slopes of scour holes may increase (Huismans et al., 2016).

2.2.7. Undermining

Undermining can be characterized as the erosion which occurs below a bed protection or a poorly-erodible top layer. In heterogeneous subsoil conditions undermining might occur due to a poorly erodible top layer. Besides gradual undermining due to gradual erosion, abrupt undermining may arise as well, when flow slides occur. This undermining occurs as a result of higher turbulence energy and larger erosion capacity of flow in the recirculation zone (Hoffmans, 1993). Measurements from physical scale experiments with sand as scour material showed that the end of a bed protection is undermined if the dimensionless parameter $a_u$ exceeds $a_{u,c} \approx 1.75$ (Buchko, 1986).

$$a_u = \frac{\alpha \bar{u}_{0,m} - \bar{u}_c}{\bar{u}_0}$$

where:

- $\alpha$ = turbulence coefficient defined in equation (2.10) [-]
- $\bar{u}_{0,m}$ = maximum mean velocity [m/s]
- $\bar{u}_0$ = mean velocity [m/s]
- $\bar{u}_c$ = critical mean velocity [m/s]

For two-dimensional scour, the maximum depth-averaged flow velocity approximately equals the initial depth-averaged velocity. However, for three-dimensional scour $\bar{u}_{0,m}$ depends heavily on the geometry upstream of the scour hole.
2.3. Recent experimental research on local scour holes

Van Zuylen (2015) performed experiments on scour holes in a two-dimensional situation with a simplified heterogeneous subsoil created by two steel plates with a gap in between. Van Zuylen (2015) executed experiments with varying velocity configurations, between 0.40 – 0.65 [m/s]. Additionally Van Zuylen (2015) investigated the influence of the distances between non-erodible plates on two-dimensional scour hole development. The sediment used for the experiments is Silica M32 \( (d_{50} = 260 \text{ [m]}). \) Figure 2.4 presents the two-dimensional experimental setup of Van Zuylen (2015).

The experiments with steel plates showed significant undermining of the downstream plate. After significant undermining the scour hole development was decreased since only suspended load was able to be transported downstream as a result of whirls and other instabilities close to the edge of the downstream plate.

The fixed distance between the steel plates limits the growth of the scour hole. In some experiments, the downstream steel plate was shifted downstream when significant undermining occurred. After shifting, the scour hole increased again until undermining occurred repeatedly. The distance between the plates is determining the maximum scour depth possible. A decrease of the distance between the plates creates a decrease in scour depth as observed in Figure 2.5(a).

![Figure 2.4: Setup of Van Zuylen (2015) for two-dimensional experiments on local scour holes with a non-erodible top layer created with two steel plates (Van Zuylen, 2015).](image)

(a) The scour depth per distance of plates with flow velocity based on information by Zuylen (2015).

The experiments showed deeper scour holes with higher velocities. Additionally, experiments with flow reversal demonstrated that the scour hole is reshaped after flow reversal. The upstream slope tends to become stable, even in conditions with flow reversal if the time between reversals and the sediment supply is sufficient. The data showed an increase in the time factor compared with the equations developed by Breusers (1966) once the downstream plate is undermined.

In the first stages of development it was possible for sediment to be transported as bed-load. During later stages of development the downstream boundary was undermined creating conditions in which only suspended load could be transported downstream. In reality, this downstream plate might behave as a falling
2.4. Scale effects in laboratory experiments

apron which possibly stabilizes the downstream slope. Due to undermining of the downstream boundary, development of the scour hole is delayed. Initially within the downstream part of the scour hole dunes were formed which disappeared slowly, while the deepest point of the scour hole propagated downstream. Added disturbances to the bed where flattened by the flow. Return currents where observed which stabilized the upstream slope. The effect of tide was investigated by reversing the flow direction in the flume. Flow patterns were opposite leading to a new stable upstream slope. The Breusers formula performed an overestimation compared to results from these measurements, as shown in Figure 2.5(b) (Van Zuylen, 2015).

An experimental pilot-study by Koopmans (2017) was a first attempt on mimicking a poorly erodible top layer with a physical scale model (Koopmans, 2017). Additionally, a three-dimensional scouring process was tested from which a conceptual flow pattern is deduced as shown in Figure 2.6(a).

At the upstream edge of the scour hole, water flow detaches. As a result of geometric differences of the scour hole in both lateral and longitudinal direction, a horse shoe vortex is created. During the experiments the angle of downstream widening followed an approximate 1:8 line. Three-dimensional scour holes tend to become deeper, probably due to the convergence of streamlines leading to higher velocities near the bed and as a result of more turbulence development (Uijttewaal et al., 2016).

A first attempt on mimicking a poorly erodible layer in a physical scale model has been done by Koopmans (2017). Spray paint was used to create a poorly erodible top layer which had lower erosive capacity but was also possible to fail. The result is shown in Figure 2.6(b). The scour hole in a heterogeneous subsoil led to a scour hole with increasing downstream width. Further optimization of the top layer might lead to more realistic behaviour (Uijttewaal et al., 2016).

2.4. Scale effects in laboratory experiments

To assure that the experiments behave similar as the prototype situation, concerning flow and morphology, the ratio of forces should be equal between model and prototype. Scale effects occur when this ratio of forces between prototype and model is different (Heller, 2011) (Julien, 2002) (Abderrezzak et al., 2013). In general, the scale of a physical quantity is determined as the value of the prototype divided by the value of the model. For example for a certain quantity \( y \) the scale factor is:

\[
\text{scale} : \quad n_y = \frac{y_p}{y_m}
\] (2.16)
The larger the scale difference, the more diverging the force ratios are compared to the prototype. Due to different importance of phenomenas and parameters the significance of scale effects may differ substantially. Thereby, fluid forces are generally more important within the model than within the prototype. So scale effects usually have a ‘damping’ effect (Heller, 2011). It is possible to reach geometric similitude when the sizes of both the model and prototype have equal scales and kinematic similitude is met when the fluid flow of both the model and prototype have equal flow characteristics.

2.4.1. Water flow

Two important dimensionless numbers describe the flow of water as already discussed in Section 2.1. The Froude number describes the importance of gravitational forces and the Reynolds number shows the importance of viscous forces on the flow pattern. As shown in Equation 2.17 and 2.18, both relations can only be true on full scale.

\[
Fr = \frac{u^2}{gh} \rightarrow \frac{n_u}{\sqrt{n_g n_h}} = 1 \rightarrow \frac{n_u}{n_h^{1/2}} = 1
\]

\[
Re = \frac{uh}{\nu} \rightarrow \frac{n_u n_h}{n_v} = 1
\]

2.4.2. Sediment transport

Within this research sediment transport is important. The possibility to choose sediment types gives an extra degree of freedom within a model. Similitude in sediment transport is established by similarity in Shields number, particle Reynolds number and the relative particle fall velocity. The latter one is commonly not used when only bed load transport is examined (Julien, 2002). All relevant equations on sediment transport are discussed in Appendix A.2.

\[
\Psi_c = \frac{\rho u_{\star c}^2}{(\rho_s - \rho)g d} \rightarrow n_{\Psi_c} = \frac{n_i n_h}{n_\rho \rho \rho d} = 1
\]

\[
Re_{\star} = \frac{u_{\star} d}{\nu} \rightarrow n_{Re_{\star}} = n_u n_d = n_i^{1/2} n_d = n_i^{1/2} n_h^{1/2} n_d = 1
\]

To ensure similarity on sediment mobility, the critical Shields number should be equal in both prototype and model. This can be obtained by maintaining a relatively high particle Reynolds number to remain significantly turbulent (Abderrazak et al., 2013). In models, shear velocity is often relatively low. To obtain an equal Shields number, it is possible to use other particles than sand. Bakelite, Polystyrene or PVC are good alternatives for sediment (Mercer, 2011). However, in this case, the scour hole consists of slopes which might be important for development of these holes. Using different materials than sand would induce an extra complexity since other materials might react differently on a slope.
2.5. Flow processes in a scour hole

This section presents an overview of theory about flow patterns inside the scour hole. First, the two-dimensional situation, considering stages of development and flow processes in the scour hole are presented, followed by concepts for flow in a scour hole with a three-dimensional geometry.

2.5.1. Flow stages

During development of a scour hole with a fixed up- and downstream edge, three stages with corresponding flow patterns can be distinguished. The first stage can be characterized by flow over a flat bed, in which shear is exerted on the grains due to normal river flow, as sketched in Figure 2.7(a). Whether sediment transport exists or not depends on the amount of shear stress on the grains as already discussed in Section A.2.1.

Figure 2.7: Three stages in development of a scour hole. With Figure 2.7(a) as a plane bed without the presence of a scour hole. Figure 2.7(b) shows a small scour hole in which the flow is still attached to the bottom. Figure 2.7(c) represents a fully developed scour hole in which a mixing layer, recirculation zone and a new boundary layer is present.

Figure 2.7(b) shows the second stage in which a relatively small scour hole is developed. The shape of the hole is such that flow remains attached to the bed. There will not be significant energy loss, since the bed geometry is still relatively flat. The scour hole is created at the upstream rigid edge since the highest increase of sediment is present at that location.

The third stage of development is defined by flow processes inside the scour hole due to separation of flow at the upstream edge, as indicated in Figure 2.7(c) and also partially explained in Section 2.2.1 in which the situation of an upstream sill was discussed. Detachment of flow at the upstream boundary of the scour hole leads to strong velocity gradients, creating a mixing layer and a recirculation zone in which transfer of momentum is present. The recirculation zone will have a speed of more or less 0.3 times the main channel speed (Bailly and Comte-Bellot, 2015). Downstream of the reattachment point, where the mixing layer touches the bed, a new boundary layer is developed. Within this entire stage, significant turbulence is existing inside the scour hole maintaining erosion capacity. An overview of flow processes in this third stage of development is given in the next section.

2.5.2. Flow processes inside scour hole

During the third stage of development, three main flow processes occur in a two-dimensional situation. Detachment of flow occurs as a result of an abrupt change of the geometry and leads to the presence of a mixing layer at the upstream edge of the scour hole and to a recirculation zone both illustrated in Figure 2.8. After the reattachment of flow a new boundary layer is formed further downstream.

Two-dimensional mixing layers and recirculation patterns

According to Bernoulli’s law, Section A.1.5, pressure increases with decreasing velocity. It is assumed to have lower velocity in the zone below the mixing layer, which implies higher pressure. Therefore, a pressure gradient is present over the vertical at the upstream boundary of the scour hole creating detachment of flow, as illustrated in Figure 2.9.

The mixing layer will get larger over a longer distance due to turbulent mixing of different flows. Eventually, the lower part of the mixing layer will touch the bed defining a reattachment point. Since, the flow approaches the bed relatively normal, increase in local pressure at the reattachment point is expected creating a pressure
2. Background and Theory

Figure 2.8: Illustration of the presence of a mixing layer and a recirculation zone eventually created by the mixing layer.

gradient to both sides parallel to the bed. Pressure gradients together with shear exerted by the main flow give rise to a recirculating pattern below the mixing layer in a clockwise direction.

Figure 2.9: Illustration of the initiation of recirculation in a scour hole, as a result of different flow velocity magnitudes and a stagnation point both creating pressure differences leading to a recirculating flow.

Three-dimensionality
Mixing is also present in the horizontal plane due to differences in the conveyance area. This deceleration creates changes in velocity over the width creating exchange of momentum and turbulence. Figure 2.10 illustrates this effect of horizontal velocity gradients.

Figure 2.10: Illustration of the effect of a scour hole on the average velocity, which leads to an average deceleration in the scour hole. At height of the bed, the flow velocity increases in the scour as a result of less friction.

Contraction can occur as a result of the effect of potential vorticity conservation, as already discussed in Section 2.2.1. Gradients in flow velocity in lateral direction must be present to activate vorticity. Upstream of the scour hole, the flow is constant without significant changes over the width. However, over the scour hole flow velocity gradients are generated. According to potential vorticity conservation, vorticity scales with depth. When the depth becomes smaller, the width of the vortex will increase, leading to diverging stream-
lines downstream of the scour hole.

Detachment of flow occurs to a greater or lesser extent at each location where the flow is non parallel to the edge of the geometry, indicated with the arrows in Figure 2.11(a). When the bed geometry change is significant and flow is reattached, water is recirculated upwards on both upstream and side slopes of the scour hole. The upstream rigid edge of the scour hole varies in both lateral and longitudinal direction. Therefore, detachment of flow and all associated processes (e.g. recirculation and deceleration of flow) occur at varying locations. This enhances a three-dimensional character of flow downstream of the rigid edge in the scour hole and possibly the horse-shoe vortices as hypothesized in experiments by Koopmans (2017).

As a result of the symmetric geometry, larger impact is present in the centre of the scour hole because flow from both sides is contributing to the down flow present in the symmetry axis, as illustrated in Figure 2.11(b).

Figure 2.11: Presence of recirculation zones over the entire upstream part of the non-erodible edge, with variation in both longitudinal and lateral direction creating three-dimensional flow patterns.

2.6. Discussion on literature review

Most of the earlier investigations by for example Breusers (1966) focused on scour holes close to hydraulic structures. Scour holes are created close to hydraulic structures as a result of changes in flow patterns. Those scour holes increase risk for the stability of the hydraulic structures. These previous experimental investigations mostly focused on two-dimensional situations within homogeneous subsoil.

From measurements in the Rhine-Meuse delta it is known that scour holes are also created without the influence of hydraulic structures. Eventually, those scour holes might decrease for example the stability of adjacent levees. In deltaic areas, the subsoil is often heterogeneous consisting of alternating layers of peat, clay or sand, which might change the evolution of scour holes. Additionally, observed scour holes have a clear three-dimensional character.

Recent research by Van Zuylen (2015) and Koopmans (2017) showed interesting processes with a highly simplified poorly erodible top layer, mimicking heterogeneous subsoil. Additionally those investigations showed significant differences between two-dimensional and three-dimensional scour hole formation. This research can improve empirical knowledge on scour holes with a three-dimensional character together with the influence of alternating heterogeneous subsoil. Experimental investigation is required since the processes causing the scour holes in a three-dimensional situation with a poorly-erodible top layer are not yet well understood.
2. Background and Theory

2.7. Hypotheses

In this section hypotheses are presented for expectations on the experimental results. First of all, general thoughts on the scour hole development are presented, with expectations on undermining and flow patterns in and around the scour hole. Additionally, the hypotheses on the effect of average velocity, water depth and geometry are presented.

2.7.1. General

Undermining

Sediment transport is present in both bed load and suspended load. When undermining develops sediment can leave the scour hole when it is in suspension only. Larger particles moving as bed load remain in the scour hole. This change in sediment transport might lead to slower development of a scour hole after start of undermining in general.

Contraction

It is expected that small effects of contraction at the upstream side of the scour hole are presented. Due to generation of vortices inside the scour, divergence will be expected at the downstream side of the scour hole. The effect of divergence is expected to be larger than the effect of convergence.

Three-dimensionality

It is hypothesized that the symmetrical character of the recirculating flow inside the scour hole enhances the erosion in the symmetry axis. Additionally, coherent three-dimensional flow patterns can attribute to scour hole development. So scour holes with a three-dimensional character will become deeper compared to two-dimensional scour holes.

2.7.2. Effect of velocity

The shear stress on grains and the generation of turbulence depends on the velocity. When a scour hole is created, the average velocity at the height of the scour hole decreases. The scour hole keeps developing until the critical shear stress on the grains is reached and grains cannot be transported anymore. When the upstream velocity is higher, the flow can experience more reduction of the average velocity at height of the scour hole. This implies deeper scour holes with higher upstream velocities. Equation 2.21 presents this influence of the flow velocity on the maximum scour depth in a two-dimensional situation based on mass conservation, where it is hypothesized that the maximum scour depth is reached when the critical velocity is not exceeded anymore. Equation 2.21 shows dependency on upstream water depth and flow velocity. The influence of turbulence is not included, however, very important for the scour process. Additionally the scour hole is not present over the whole depth and Equation 2.21 is based on a two-dimensional case. Nevertheless, this equation gives an indication on relative differences between flow conditions. Figure 2.12 demonstrates the definition of the parameters used in Equation 2.21.

\[
\begin{align*}
Q_A &= u_A h_A \\
Q_B &= u_c (h_A + d_{max}) \\
Q_A &= Q_B 
\Rightarrow d_{max} &= \frac{u_A u_c}{u_A - u_c} = h_A \left( \frac{u_A}{u_c} - 1 \right), \quad u_A > u_c
\end{align*}
\]  

\begin{align*}
Q_A &= \text{discharge upstream per unit width [m}^2/\text{s]} \\
Q_B &= \text{discharge downstream per unit width [m}^2/\text{s]} \\
d_{max} &= \text{maximum scour depth [m]} \\
h_A &= \text{water depth section A [m]} \\
u_A &= \text{average velocity section A [m/s]} \\
u_c &= \text{critical velocity [m/s]}
\end{align*}
Besides the different expected equilibrium depths, it is expected that the development over time is more quickly with higher flow velocities.

### 2.7.3. Effect of water depth

The effect of water depth is expected to be small. The velocity close to the bed in the scour is small and significantly determined by the amount of turbulence. Extra creation of turbulence in the scour hole is important for the scour process, which is created by the local changes in geometry and independent of the water depth. The water depth does influence the amount of mass in the flow and therefore influence the reduction of velocity at the height of the scour hole as observed in equation 2.21. However, since the velocities close to the bed are expected to be very small, changes in the velocity close to the bed as a result of changing water depth are expected to be small as well.

During first stages of development, the scour depth will be mainly determined by the generation of turbulence, created by changes in geometry. Within this stage, no differences in scour hole development over time are expected considering different water depths. When reduction of the mean velocity becomes significant, variations might appear, which eventually can create larger scour holes with a larger upstream water depth based on conservation of mass or momentum.

### 2.7.4. Effect of geometry

It is assumed that the scour hole at its deepest part has an ellipsoidal shape over the cross section. Figure 2.13 shows a sketch of two scour holes with different widths. If it is assumed that mass conservation applies between upstream of the scour hole and the deepest part of the scour hole, Equation 2.22 can be deduced. This equation calculates the maximum scour depth possible based on mass conservation between point A upstream and the deepest part of the scour hole. The maximum depth is reached when the critical velocity is reached. A larger width of the scour hole leads to more shallow scour holes, as can be observed in Equation 2.22.

\[
\begin{align*}
Q_A &= u_A b_A h_A \\
Q_B &= u_c (h_A b_A + \frac{1}{2} \pi \frac{1}{2} w d_{max})
\end{align*}
\]

\[Q_A = Q_B \quad \rightarrow \quad d_{max} = \frac{b_A h_A (u_A - u_c)}{\frac{1}{2} \pi w} \quad \frac{u_c}{u_c} \quad (2.22)\]

\[b_A = \text{width of flume section A [m]} \]
\[w = \text{width of geometry [m]} \]

During first stages of development, the scour depth will be mainly determined by the generation of turbulence, created by changes in geometry. Within this stage, no differences in scour hole development over time are expected considering different water depths. When reduction of the mean velocity becomes significant, variations might appear, which eventually can create larger scour holes with a larger upstream water depth based on conservation of mass or momentum.
Experimental setup

From Chapter 2 it is obtained that experimental research can improve knowledge on the dominant processes for scour hole formation in heterogeneous subsoil without the influence of hydraulic structures.

The goal for these experiments is to find correlations between characteristic river parameters and development of scour holes and to observe different development patterns for this type of scour. Hypotheses on flow patterns inside a scour hole and the evolution of the scour hole were verified by executing these experiments. In this chapter information on the experimental setup and the execution is given, calibration and verification of measuring equipment is explained, procedures during the experiments are elaborated on and lastly, a description of the executed experiments is given. The experiments are conducted at the Fluid Mechanics Laboratory at Delft University of Technology.

3.1. Overview of setup
3.1.1. Flume characteristics

Figure 3.1 shows a sketch of the experimental setup. The flume at the Water Lab of Delft university of Technology is 12 metre long, 0.8 metre wide, rectangular and has a maximum possible water depth of 0.18 metre. Figure 3.2 shows pictures of the key parts of the experimental setup. In this flume it was possible to systematically vary parameters while keeping other parameters relatively constant.
Water flows in through a pipe connected with a large storage basin in the laboratory. At the upstream side, water is calmed and smoothened with several measures as presented in Figure 3.2(a). A foam board is used on top of the water to reduce water surface irregularities and small pipes (diameter of 0.02 $[m]$) were used to straighten the flow. The bottom is horizontal over the entire flume to enable equal flow from both directions (i.e. tide). This results in small deviations from uniform flow within the flume. Figure 3.2(b) shows the laser boat, in the left down corner, used for bed measurements and the velocity measuring device at the right part of the figure. A trigger wheel is installed to start the measurements and to determine the position of the laser boat in longitudinal direction. The length of the flume from inflow point to scour hole is 6 $[m]$, such that full developed flow is reached, which means that the boundary layer is present over the entire water column, as calculated with Equation 3.1 for a representative case. A sharp crested weir, which can be changed by different sizes, is installed downstream to regulate water depth in the flume, as shown in Figure 3.2(c). The fixed bed consists of a thin concrete layer. In the centre of the flume an oval shaped hole is present where sand may erode. At this location a box full of sand is present underneath the bottom, as presented in Figure 3.1. This set-up is a simplified case of a scour hole in heterogeneous subsoil. Both bed and velocity measurements were used to retrieve data on the scour hole development.

\[ \delta > h_{flume} \rightarrow x > 45R \quad x > 45 \frac{A}{P} \approx 4.95 \quad [m] \]  

(3.1)

**Sand**

The use of sediment in scale models is complex, since it is difficult to scale sediment in accordance with other existing scaled forces. Silica M32 is used by Koopmans (2017) and Van Zuylen (2015) to investigate scour hole development. This quartz sediment type has a $d_{50}$ of 260 [$\mu m$] and a density of 2650 [$kg/m^3$]. Silica M32 is used for the experiments, based on both practical and theoretical reasons. With Silica M32, comparison of the experiments with Koopmans (2017) and Van Zuylen (2015) is more evident, since scale effects of sediment were similar at those experiments. Additionally, the possibility to filter sediment out of the flume at the down-stream end should be present. The larger the sediment, the easier the filtering process. Table 3.1 shows the most important characteristics and calculated parameters of this sediment type. Appendix B.1 shows more information on the choice of sand.

<table>
<thead>
<tr>
<th>Type of sand</th>
<th>$d_{50}$[$\mu m$]</th>
<th>$D^*$[–]</th>
<th>$\Psi_c$[–]</th>
<th>$u_c$[m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica M32</td>
<td>260</td>
<td>6.58</td>
<td>0.015-0.04</td>
<td>0.16-0.25</td>
</tr>
</tbody>
</table>
3.1. Overview of setup

Bed roughness
Due to presence of small acceleration in downstream direction in the flume it is not possible to calculate the bed roughness of the flume with Chezy-law, see Appendix A.1.4. Therefore, the concrete bed is measured with a laser and the standard deviation of the bed height is used to define an equivalent bed roughness for the concrete bed (Figure 3.3). Based on investigations by Chirol et al. (2015) and Smart et al. (2004) the standard deviation of the bed height is used to calculate the equivalent bed roughness. Based on both investigations, the standard deviation times 1.5 is used for the equivalent bed roughness.

\[ k_s = \frac{(1 \cdot \sigma + 2 \cdot \sigma)}{2} = 0.0006 \ [m] \]

(3.2)

Based on the roughness calculated with Equation 3.2 it is determined that the bottom is intermediate rough close to smooth conditions. The Chezy number for an average situation in the flume is calculated in Equation 3.3. The equation officially applies to rough beds but the resulting value looks satisfying.

\[ C = \frac{\sqrt{K}}{\kappa} \ln \left( \frac{12R}{k_s} \right) \approx 70 \ [m^{1/2}/s] \]

(3.3)

\[ \kappa = 0.4, \text{ constant of Von Kármán [–]} \]

\[ k_s = \text{equivalent roughness of Nikuradse [m]} \]

Figure 3.3: Measured bed height.

3.1.2. Measuring equipment

Velocity measurements
The Vectrino Profiler designed by Nortek is used for velocity measurements. This product uses Acoustic Doppler Velocimetry to determine velocities in three directions. It has a sampling profile up to 30 mm between 45 and 75 mm distance from the probe as indicated in Figure 3.4(a). The smallest resolution possible is 1 mm and the sampling frequency can be up to 100 Hz. In addition it can measure distance to bottom and the temperature. The instrument is mounted on a cart which can ride in longitudinal direction above the water, additionally it is possible to shift location in transverse direction (Nortek, 2011) (Craig and Loadman, 2011). Height can be changed accurately by using a pulley device. When measuring velocities, the cart is stabilized in longitudinal direction to avoid deviations by movement of the cart. Correlations above 80 to 90 % between the velocity measurements are required for good results. Sontek recommends a correlation higher than 70% to ensure quality of the velocity measurements. When the supplied water is clean, it should be seeded to create enough objects for the sound of the Vectrino Profiler to reflect on. The Signal-to-Noise Ratio (SNR) indicates whether the flow is well seeded. The minimal SNR should be 15, though, the higher the better. During the experiments oxygen bubbles have been generated, with the use of electrolysis, to seed the flow right upstream of the measuring location. Figure 3.4(b) shows the stick and the wire mesh which have been used to create the oxygen bubbles of about 0.1 [mm]. The SNR with seeding of oxygen bubbles was on average between 30 and 50 [–].
3. Experimental setup

**Bed and water depth measurements**
Lasers were used to measure bottom profiles and slopes of the water surface. For determination of bed profiles a laser is installed in a boat with a perspex bottom, as shown in Figure 3.2(b). During measurements, the boat is partly immersed to avoid refraction errors. The cart on which the boat is mounted always starts at the same point and subsequently is pushed manually downstream over the area of interest. The trigger wheel monitors the traveled longitudinal distance. Lasers for water depth measurements were installed approximately 2.20 [m] upstream and downstream of the centre of the scour hole. The combination of both laser measurements determines the water depth at the scour hole assuming a linearly changing water level over the flume. All lasers have a measuring range from 6 to 26 cm, corresponding with 2 to 10 Volts. The lasers have an accuracy of ± 0.001 Volt which corresponds with an accuracy of 0.04 [mm]. With the laser boat it is possible to change location of the laser in transverse direction by sliding the mount over the cart, to measure other longitudinal cross sections than the symmetry axis, as showed in Figure 3.5(a). Reflection of the laser signal at the water surface is needed to achieve results for the water depth measurements. Figure 3.5(c) shows the use of paper to achieve reflection at the water surface for the measurements of water depth.

**Discharge measurements**
To calibrate the discharge through the inlet, and thereby the average velocity in the flume, the Proline Prosonic Flow 91W Ultrasonic flowmeter is mounted on a pipe connected to the inlet. Data from this device is compared with the velocity profiles measured by the Vectrino Profile. The data from the discharge meter is processed in MATLAB, whereby 2 V corresponds with 0 $dm^3/s$ and 10 V with 55 $dm^3/s$. Figure 3.5(b) shows the discharge meter.
3.2. Description of experiments

Before creating the correct settings for the experiments, the flume is cleaned. When there is no flow, very fine particles can settle and the bed can get dirty. Subsequently, the hole in the centre of the flume is filled with Silica M32 and loaded so sand particles can consolidate and air is between the sand particles over the hole box of sand. After sufficient consolidation, the surface of the hole is smoothened with a plate of timber and excessive grains are removed from the flume. With use of a laser measurement it is verified whether the surface is smoothed properly. If so, the experiment starts by slowly opening the upstream valve. Especially during the start of an experiment slow increase in discharge is required to prevent occurrence of shock waves, created by the combination of the downstream weir and an abrupt increase of discharge. When overflow at the weir starts, the upstream valve is opened more quickly to reduce time latency in measurements. The exact combination of discharge, checked before the start of the experiment, is reached in an iterative way at the start of the experiments. When an experiment is paused to be continued next day, the upstream valve is closed. The sand bed of the scour hole remains submerged during this pause.

3.2.1. Experimental configurations

To evaluate the effect of the upstream water depth, velocity and the size of a scour hole, several experimental configurations were used. Two unique geometries were used to investigate the effect of the size of scour holes on the development of scour holes. Table 3.2 shows all executed experiments. As shown, for the variation in water depth, the average velocity at each experiment on water depth is not equal. For experiments on the effect of water depth, equal shear velocity is required to exclude effects of different velocity profiles. To obtain equal shear velocity for different water depths, different average velocities need to be used, see Equation 3.4, in which water depth is present in the denominator. The configurations have been chosen as wide as possible considering the boundaries of the flume. Figure 3.7 presents the boundaries of the experiments based on limits of the flume and limits on the type of flow in the flume. The height of the flume creates a boundary both in maximal discharge and maximum water depth. Experiments 1, 2, 3, 7 and 8 are on the effect of upstream velocity and experiments 2, 5, 6, 7 and 9 are experiments on the effect of water depth, as shown in Table 3.2. The effect of water depth and upstream velocity on scour hole development are investigated for two geometries, from now on called Geometry 1 and Geometry 2. Figure 3.6 presents both geometry configurations used during the experiments.

![Figure 3.6: Geometry sizes used for the experimental configurations with on the left side Geometry 1 and Geometry 2 on the right](image)

\[ u_\ast = \frac{u_0 \sqrt{g}}{C} \]  

\[ u_\ast = \text{shear velocity [m/s]} \]
\[ u_0 = \text{average velocity [m/s]} \]
\[ g = \text{gravitational acceleration [m/s}^2] \]
\[ C = \text{Chezy value [m}^{1/2}/\text{s}] \]
### 3. Experimental setup

**Range of experimental configurations**

![Graph showing range of experimental conditions]

The geometry has been systematically changed to a larger hole with equal aspect ratio compared to the smaller hole, mimicking a further developed scour hole in a next time step, assuming growth in length and width. Table 3.3 shows the dimensions of both created holes.

#### Table 3.2: Experiments on velocity and water depth.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>discharge [l/s]</th>
<th>Fr [-]</th>
<th>Re [-]</th>
<th>Weir height [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geometry 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1: ( h = 0.143 ) m, ( u_{avg} = 0.290 ) m/s</td>
<td>36.4</td>
<td>0.24</td>
<td>( 4.1 \times 10^4 )</td>
<td>0.073</td>
</tr>
<tr>
<td>2: ( h = 0.141 ) m, ( u_{avg} = 0.344 ) m/s</td>
<td>39.5</td>
<td>0.34</td>
<td>( 4.9 \times 10^4 )</td>
<td>0.059</td>
</tr>
<tr>
<td>3: ( h = 0.140 ) m, ( u_{avg} = 0.400 ) m/s</td>
<td>45.6</td>
<td>0.39</td>
<td>( 5.6 \times 10^4 )</td>
<td>0.053</td>
</tr>
<tr>
<td>4: ( h = 0.141 ) m, ( u_{avg} = 0.459 ) m/s</td>
<td>52.6</td>
<td>0.45</td>
<td>( 6.5 \times 10^4 )</td>
<td>0.047</td>
</tr>
<tr>
<td>5: ( h = 0.175 ) m, ( u_{avg} = 0.351 ) m/s</td>
<td>50.1</td>
<td>0.27</td>
<td>( 6.2 \times 10^4 )</td>
<td>0.073</td>
</tr>
<tr>
<td>6: ( h = 0.111 ) m, ( u_{avg} = 0.331 ) m/s</td>
<td>30.4</td>
<td>0.32</td>
<td>( 3.7 \times 10^4 )</td>
<td>0.047</td>
</tr>
<tr>
<td><strong>Geometry 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7: ( h = 0.141 ) m, ( u_{avg} = 0.346 ) m/s</td>
<td>39.5</td>
<td>0.34</td>
<td>( 4.9 \times 10^4 )</td>
<td>0.049</td>
</tr>
<tr>
<td>8: ( h = 0.141 ) m, ( u_{avg} = 0.459 ) m/s</td>
<td>52.6</td>
<td>0.45</td>
<td>( 6.5 \times 10^4 )</td>
<td>0.047</td>
</tr>
<tr>
<td>9: ( h = 0.115 ) m, ( u_{avg} = 0.332 ) m/s</td>
<td>30.4</td>
<td>0.32</td>
<td>( 3.7 \times 10^4 )</td>
<td>0.073</td>
</tr>
</tbody>
</table>

#### Table 3.3: Aspect ratio created scour holes.

<table>
<thead>
<tr>
<th></th>
<th>width [cm]</th>
<th>length [cm]</th>
<th>ratio [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>First hole</td>
<td>22.4</td>
<td>50.4</td>
<td>2.27</td>
</tr>
<tr>
<td>Second hole</td>
<td>33.6</td>
<td>75.6</td>
<td>2.27</td>
</tr>
<tr>
<td>Ratio [-]</td>
<td>1.5</td>
<td>1.5</td>
<td>1</td>
</tr>
</tbody>
</table>

### 3.2.2. Calibration and verification

Before the actual experiments, calibration experiments were used to verify reproducibility of the experiments. Results showed constant outcomes for equal experimental configurations with stable conditions considering discharge and water depth. The validation of experimental configurations is presented in Appendix C.1.

#### Velocity profile

The velocity measurements obtained with the Vectrino Profiler show fluctuations and therefore require averaging. During a calibration experiment the required measuring time was determined by plotting the average velocity signal with a changing averaging time. Figure 3.8(a) shows relatively small changes in the average...
value after an averaging time of 1.5 minutes. For future velocity measurements a measurement time of two minutes is chosen.

Due to non-uniformity of flow, velocity changes over the flume. Figure 3.8(b) shows the outcome of velocity measurements 1.5 metre upstream and downstream of the center of the scour hole with a discharge of 44 l/s and a water depth of 10 cm without the presence of a significant scour hole. The measured velocity profile suggests the existence of a small acceleration. In general velocity measurements show satisfying results, also for other configurations (i.e. other discharge and water depth). The theoretical velocity profile, plotted as well in Figure 3.8(b), is based on the discharge measured in the inlet and the water depth measured by the lasers to verify the velocity measurements.

During each measurement, the Vectrino Profiler evaluates 30 cells over the vertical. However, the outer cells showed significant deviations so it was decided to not use the outer 5 cells at both sides to ensure reliability. Additionally, a relatively small correction is applied on the depth measurements from the Vectrino Profiler, since the bottom measurements showed a small deviation. The correction value is based on depth similarity between the laser measurements and the depth measurements by the Vectrino Profiler.

Laser calibration
The laser's output is a certain voltage between 2 and 10 Volt, corresponding with respectively 6 and 26 cm (in air) with a linear change in between. Water depth is the calculated difference between the situation with and without water, in other words, the difference between the reflection at the bottom and at the water surface. Floating paper is used to ensure a reliable reflection from the water surface. The submerged boat used for the bed profile measurements is calibrated with the use of a block with known size of 5 centimetre on a flat bottom. Figure 3.9 shows these measurements from which a factor of 1.305 has been determined for compensating the different refraction index for the laser in water compared to air.
3.2.3. Data smoothening
The 'RLOWESS' method is applied for smoothening the laser data, which is a robust version of the general 'LOWESS' method. The robust procedure is used to remove outliers from the data, due to laser scatter. Each value is based on the surrounding data represented within a certain span. The method is based on a locally weighted linear regression, which gives more weight to data points closer to the considered data point. The span is determined based on visual observations and is 40 data points, which corresponds with 4 millimeters.

Before processing the data of velocity measurements, a de-spiking method is used to remove outliers from the velocity data. The de-spiking method uses a phase-space method developed by Goring and Nikora (2016). These outliers can among other reasons occur when oxygen bubbles become to large.

3.2.4. Execution
Experiments were executed without intermittent stops, since experience with intermittent stops of the flow showed instabilities at the slopes within the scour hole when refilling the flume for the restart of the experiment. Experiments were completed when undermining of the rigid edges was disturbing the scour hole formation by feeding the deepest parts of the scour hole.

As the initial development is fastest, the longitudinal section of the bed profile is measured each 15 minutes during the first hour, every 30 minutes between the first and fifth hour, followed by hourly measurements. At several fixed time steps, the complete scour hole is measured as well. After more or less 10 to 15 hours the measurements were taken at practical time steps if hourly measurements were not possible anymore. During the experiments, the scour hole formation is observed closely with the aid of recorded movies. Measurements were processed immediately after completion to check whether retakes of measurements were needed.

After the experiments on scour hole development, the scour hole geometry is fixed and velocity measurements were executed to evaluate hypotheses on the shape and intensities of flow processes inside the scour hole (e.g. mixing layer, recirculation zone). After development of a scour hole the flume is dried and water is removed from the sand bed by a valve at the bottom of the bed. When the sand is sufficiently dried, the scour hole is fixed with the help of sprayed car lacquer and hair coat. Experience showed sufficient strength during velocity measurements. Figure 3.8(a) shows that the measuring time span is about two minutes to obtain accurate results on velocity measurements. Experience showed the need for longer time spans close to the reattachment point in the scour hole, since changing flow patterns (coherent flow and more chaotic flow) were present over longer time scales.
In this chapter, the results of the executed experiments are presented. Section 4.1 elaborates on the general results observed in every experiment. Section 4.2 presents the results of the influence of depth, velocity and scour hole size on the scour hole development.

### 4.1. General results of development

#### 4.1.1. Three stages of development

Figure D.16 shows the general evolution of the scour hole as observed in all conducted experiments, three phases can be distinguished. During the first phase, dunes form inside the scour hole and propagate in downstream direction. When the scour hole is developed sufficiently, these dunes vanish and a next stage starts in which the maximum depth of the scour hole increases and the deepest point propagates downstream. Undermining starts to develop when the deepest point is too close to the downstream edge. During this third stage, the downstream slope becomes unstable and sand is removed from the area below the concrete layer, which can be observed in Figure D.16 in which the downstream slope is undermined suddenly. The amount of undermining cannot be observed with laser measurements, since the bed is mapped from above.

![Experiment 3: h = 0.140 [m], u = 0.400 [m/s]](image)

Figure 4.1: Results of experiment 3, as example for the general scour hole development.

The undermining processes observed during the three development stages are sketched in Figure 4.2. During the stage in which dunes were present, the downstream boundary is alternately filled and undermined. This ends when the deepest point of the scour hole reaches a depth of -3 to -3.5 centimetres for geometry 1 and -4 to -4.5 centimetres for geometry 2. Within the following stage a smooth and relatively steep slope is present at the downstream end. When the downstream slope gets to steep, undermining of the concrete plate starts to develop again.
When the undermining is significant a secondary process is initiated inside the scour hole. The undermining starts at the downstream edge and develops in upstream direction along the sides, as illustrated in Figure 4.3. This development to the side and in upstream direction, is created as a result of horizontal recirculation as indicated in the last stage of Figure 4.3. There is a critical point where a large horizontal recirculation pattern is generated which feeds the lower parts of the upstream slope and the deepest parts of the scour hole with sediment originating from the undermined parts. From this point onwards, the scour hole does not increase in depth anymore and side parts are undermined severely, so scour does develop in width and length underneath the concrete layer. At this point, undermining creates a relatively large step height at the downstream edge of the scour hole, making it more difficult for sediment to be transported out of the scour hole.

The measured length of undermining, as in Figure 4.4(a), was 7.5 [cm] and the width was 4.5 [cm], as in Figure 4.4(b), measured at the end of Experiment 5.

The three stages of development, as observed with laser measurements, were also noticeable downstream of the scour hole. Sand paths were created downstream of the scour hole indicating specific locations for sediment transport out of the scour hole. Figure 4.5 shows three different patterns of sediment downstream of the scour hole. Figure 4.5(a) presents sand paths at both sides of the scour hole during the end of the first stage with dunes. During the second stage, sediment is transported out of the scour hole in three paths, as observed in Figure 4.5(b). During the third stage sediment only exits the scour hole at the symmetry axis of the scour hole, as can be seen in Figure 4.5(c).
4.1.2. Development of slopes
In Figure D.16, it is observed that the upstream slope remains attached to the upstream edge over the entire experiment. For both geometries, the slope is measured by taking values from the laser measurements at equal ratio from the upstream edge, which is illustrated in Figure 4.6(a). The upstream slope remains equal over time, which is observed in both Figure D.16 and Figure 4.6(b). Additionally, the slope remains equal between different experimental configurations, and between the two different geometries. Some experiments show reduction of the upstream slope due to feeding of sediment from the downstream undermined parts.

4.1.3. Flow velocity patterns
Velocity measurements are conducted inside the scour hole at both Geometry 1 and 2. Figure 4.7 shows the average velocity of each measurement in longitudinal direction for Geometry 1. The water depth was 0.141 $[\text{m}]$ and the average upstream velocity was 0.39 $[\text{m/s}]$ during the measurements. The average velocity profiles show that in the upstream part of the scour hole large gradients are present over the vertical axis, which indicates generation of extra turbulence. Additionally, it is visible that the velocity profile flattens over the vertical axis in downstream direction. Downstream of the scour hole a new boundary layer develops.
Figure 4.7: Velocity measurements of Geometry 1.

Figure 4.8: Turbulence intensities Geometry 1.
Figure 4.9 presents the turbulent kinetic energy in all directions at the symmetry axis of the scour hole for geometry 1. Large turbulent kinetic energy values correspond with large velocity gradients over the vertical axis in Figure 4.7.

Figure 4.9 shows velocity measurements of Geometry 2. Velocity and water depth were equal to the experiments in which measurements for Geometry 1 were performed. This scour hole is significantly larger and deeper compared to Geometry 1. Figure 4.10 shows a close up of the upstream side of the scour hole, where recirculation occurs. Near the bed, negative velocities are observed with maximum values around 1.2 [cm/s]. This recirculation zone is probably also present in Geometry 1, but it was not possible to measure, because seeding of the flow was difficult for Geometry 1. Figure 4.11 shows the measured turbulent kinetic energy at Geometry 2 in the longitudinal symmetry axis.

Figure 4.10: Close up of the upstream side of the scour hole.

Figure 4.11: Measured turbulent kinetic energy at Geometry 2.
With the Vectrino Profiler it was not possible to measure the flow velocity and flow direction very close to the bottom. Additionally, the lateral components of the flow in the scour hole are significantly smaller than the flow magnitude in longitudinal direction, which made it impossible to obtain clear average flow patterns over a cross-section. With use of dye, the complex flow patterns could be visualized in the scour hole. Grains of solvable pigments were placed on the bed and used to display flow directions close to the bed. Additionally, a bottle filled with dye was used to visualize the flow higher in the water column. Equal experimental configurations were used as with the Vectrino Profiler velocity measurements.

Figure 4.12 shows the existence of a recirculation zone at the upstream side in the scour hole. In Figure 4.12(a), dye visualizes flow in the upstream direction in the recirculation zone. Figure 4.12(b) visualizes the flow direction of a different time step at the same location as in Figure 4.12(a). At this time step, the flow is scattered in several directions. In general, these observations showed that coherent structures inside the scour hole were fluctuating over time. The location of a reattachment point is varying in both lateral and longitudinal direction. Nevertheless, a clear recirculation pattern is observed at the upstream slope of the scour hole, with a reattachment point between 0.21 to 0.28 [m] from the upstream edge for Geometry 2. This corresponds with respectively 3.75 - 5 times the maximum scour depth.
4. Results

Figure 4.12: Recirculation at the bed level in Geometry 2 visualized with dye, with changing flow patterns over time observed in both figures.

Figure 4.13 shows the flow direction close the bed at the sides of the scour hole. Figure 4.13(a) visualizes the flow at the left side of the scour hole and shows a diverging flow in downstream direction. Higher in the water column, dye is transported to the centre of the scour hole, indicating a horse-shoe vortex. Figure 4.13(b) shows the flow direction at the right part of the scour hole. It also visualizes a diverging flow in downstream direction. Both figures show the general flow direction. Over time the flow directions were fluctuating significantly.

Figure 4.13: Flow at the bed in Geometry 2 visualized with dye in which a diverging flow is present in downstream direction and a converging flow higher in the water column.

Figure 4.14 displays four moments after the addition of pigment dye upstream of the scour hole. Figure 4.14(a) shows the entrance of dye in the scour hole, where down flow of dye is present. In Figure 4.14(b), dye is transported more downstream inside the scour hole. A recirculation pattern is observed and dye is spread in lateral direction over the bed. Figure 4.14(c) and 4.14(d) show that dye is still present at the entrance of the scour hole due to recirculating flow at the upstream slope. Additionally, more spreading of dye at the bed is present. Most of the dye exits the scour hole at two paths indicated by the arrows in Figure 4.14(d).
4.2. Variation of parameters

In this section the results of each varied parameter is given. Each experiment is corresponding with a unique colour.

4.2.1. Effect of geometry

Figure 4.15 shows the maximum measured depths from experiments 2, 4, 7 and 8. Equal velocity and water depth conditions were used at both geometries to investigate the influence of change of geometry only. Scour development in Geometry 2 occurs faster compared to Geometry 1.
4.2.2. Effect of average velocity

Figure 4.16 presents the all deepest points of the scour hole in the symmetry axis from experiment 1, 2, 3 and 4. Figure 4.16 shows the same results on a semi-log scale, which reveals parallel development on a log-scale of the deepest point of the scour hole for different velocity configurations. In the experiments, a maximum depth is reached as a result of the process of undermining which leads to re-feeding of the deepest part of the scour hole. All experiments have a maximum depth, as partly observed in Figure 4.16.

![Maximum measured scour depth of experiments with different velocities](image)

Figure 4.16: Measured depths of experiments 1, 2, 3 and 4 to demonstrate the effect of velocity on scour hole development.

4.2.3. Effect of water depth

Figure 4.17 shows maximum depths measured at the experiments with different upstream water depth conditions. It is clearly observed that different water depths do not create significant differences in scour hole depth during this part of the development stage.
Figure 4.17: Measured scour depths for experiments 2, 5 and 6 on normal and log scale to demonstrate the effect of configured water depth on scour hole development.

The experiments on water depth have also been executed with Geometry 2, where larger scour depths were possible. Figure 4.18 shows results from those experiments. Small differences arise over time, which might indicate a small influence of water depth. However, small deviations in shear velocity between both experiments can already nullify the observed differences in scour depth.
4.3. Poorly erodible top layer

Koopmans (2017) performed experiments with a poorly erodible top layer, which showed interesting behaviour. For this thesis the choice was made to do research on characteristic river parameters, to systematically investigate the influence of those parameters on the development of scour holes in a simplified heterogeneous subsoil. Parallel to the experimental program, several attempts were done to create an improved poorly erodible top layer compared to Koopmans (2017), which has the flexibility to bend, is brittle enough to fail and is not too stiff for the small scale experiments. Different compositions of sodium silicate (known as waterglass), sodium aluminate, sand and water were tried. However, none of the compositions showed good results according to the preferred characteristics. Nevertheless, it is likely that a composition of these substances can be found which creates a proper poorly erodible top layer. The most promising composition consisted out of 18% sodium silicate, 2% sodium aluminate and 80% water.
In this chapter the analyses of the experimental results are presented. In Section 5.1 general observations for each experiment are analyzed. Section 5.2 demonstrates the application of Breusers formulas on the experimental data. Based on the experimental results a new formula is derived for predicting the time development of scour holes in Section 5.3. Section 5.4 presents the comparison of the executed experiments with Van Zuyl (2015), Koopmans (2017) and field data.

5.1. General observations

5.1.1. Stages of development

During the experiments, three stages are observed, illustrated in Figure 5.1(a). Before starting an experiment, the sediment bed is flat. After initiation of the experiment, dunes start to develop. As a result of the presence of dunes, high turbulence intensities are present, creating favorable conditions for sediment to be transported downstream. In general during the initial stage, the downstream rigid edge is undermined temporarily due to the high turbulent activity and dune development. The scour hole is formed just downstream the concrete layer, since there is no supply of sediment from upstream. The large transport of sediment is also visible downstream of the scour hole, where sediment is visibly transported over the concrete layer in downstream direction.

In the next stage, a scour hole is present without the existence of dunes and undermining of the rigid edges. In this stage a typical shape of the scour is present with the deepest part more upstream from the centre of the scour hole, a constant upstream slope and an increasing slope over time at the downstream end. Over time, the scour hole gets deeper and the deepest part moves further downstream, which can be related to the increased step height, which causes the reattachment point to be located further downstream. As a result of a deeper scour hole and the change of the location of the deepest point, the downstream slope gets steeper.

The deeper the scour holes, the less turbulent activity and the lower flow velocities close to the bed, making it more difficult for sediment to be stirred and transported. Additionally, a steeper downstream slope makes it more difficult for sediment to be transported downstream over the slope. These effects together cause a decrease of development of the scour hole in general.

When the downstream slope is too steep, undermining starts to develop at the downstream edge. When undermining increases, sediment transport decreases significantly and sediment is only transported out of the scour hole occasionally by whirls at the downstream edge. At a certain amount of undermining, transport of sediment is no longer possible. Redistribution of sediment takes place inside the scour hole, resulting in a decrease in scour hole depth. When redistribution is present, the experiment is stopped and considered finished. In most experiments a maximum depth was present as a result of this process of undermining and an equilibrium depth based on conservation of mass or momentum was never reached as expected and discussed in Section 2.7.
The three stages of scour hole development are presented in Figure 5.1. Figure 5.1(b) shows the deepest points over time of experiment 3 together with the observed differences in stages. Simplified illustrations of each stage are given in Figure 5.1(a). Re-feeding in stage 3 leads to decreasing development of the scour hole and eventually to more shallow scour depths. Therefore, stage 3 is not included in the following analyses.

Figure 5.1: Three stages in scour hole development. The initial stage is defined by the presence of dunes. The second stage experiences development of the scour hole in depth and the third stage is defined by significant undermining and eventually redistribution of sediment to the deepest parts of the scour hole.

5.1.2. Maximum scour depth

Comparison with theoretical depth

In this section the observed maximum depth is compared with the calculated critical depths based on mass conservation. The calculated depths are based on Equation 2.21 used for $d_{\text{max,1D}}$ and Equation 2.22 used for $d_{\text{max,2DH}}$ and $d_{\text{max,3D}}$. Table 5.1 presents the calculated critical depths. Based on mass conservation over the complete width, the scour holes become unrealistically deep ($d_{\text{max,3D}}$). On the other hand, calculating the equilibrium depth based on the symmetry axis is not convenient as well, since results show that the width of the scour hole is of importance and flow is not uniform in lateral direction. However, the calculations give an indication of the expected scour depths.

The calculated values are based on free movement of grains above the critical velocity. Blockage by a rigid edge influences the free movement of those grains by creating a slope at the downstream ridge and eventually the occurrence of undermining also creates blockage of sediment transport, which are both not included in the calculated depths.
Table 5.1: Calculated numbers of critical depth based on 1D, 2DV and 3D flow compared with the observed maximum depth.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$S_{\text{observed}}[m]$</th>
<th>$d_{\text{max,1D}}[m]$</th>
<th>$d_{\text{max,2DV}}[m]$</th>
<th>$d_{\text{max,3D}}[m]$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geometry 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 1: $h = 0.143[m]$, $u_{\text{avg}} = 0.290[m/s]$</td>
<td>0.050</td>
<td>0.08</td>
<td>0.10</td>
<td>0.36</td>
</tr>
<tr>
<td>Experiment 2: $h = 0.141[m]$, $u_{\text{avg}} = 0.344[m/s]$</td>
<td>0.063</td>
<td>0.10</td>
<td>0.13</td>
<td>0.47</td>
</tr>
<tr>
<td>Experiment 3: $h = 0.140[m]$, $u_{\text{avg}} = 0.400[m/s]$</td>
<td>0.063</td>
<td>0.14</td>
<td>0.18</td>
<td>0.65</td>
</tr>
<tr>
<td>Experiment 4: $h = 0.141[m]$, $u_{\text{avg}} = 0.459[m/s]$</td>
<td>0.067</td>
<td>0.18</td>
<td>0.22</td>
<td>0.81</td>
</tr>
<tr>
<td>Experiment 5: $h = 0.175[m]$, $u_{\text{avg}} = 0.351[m/s]$</td>
<td>0.066</td>
<td>0.13</td>
<td>0.17</td>
<td>0.62</td>
</tr>
<tr>
<td>Experiment 6: $h = 0.111[m]$, $u_{\text{avg}} = 0.331[m/s]$</td>
<td>0.060</td>
<td>0.08</td>
<td>0.10</td>
<td>0.35</td>
</tr>
<tr>
<td><strong>Geometry 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 7: $h = 0.141[m]$, $u_{\text{avg}} = 0.346[m/s]$</td>
<td>0.081</td>
<td>0.11</td>
<td>0.13</td>
<td>0.32</td>
</tr>
<tr>
<td>Experiment 8: $h = 0.141[m]$, $u_{\text{avg}} = 0.459[m/s]$</td>
<td>0.085</td>
<td>0.18</td>
<td>0.22</td>
<td>0.54</td>
</tr>
<tr>
<td>Experiment 9: $h = 0.115[m]$, $u_{\text{avg}} = 0.332[m/s]$</td>
<td>0.076</td>
<td>0.07</td>
<td>0.09</td>
<td>0.23</td>
</tr>
</tbody>
</table>

The calculated values in Table 5.1 are based on mass conservation, without the influence of turbulence. If turbulence is included, the calculated critical depth should increase as a result of the surplus of force on the grains. Figure 5.2 shows data of Experiment 2 together with the velocity relative to the critical velocity and gives a perception of the height of the velocity in the scour hole. Appendix D.4 shows this type of graph for each experiment.

![Experimental data compared with the critical velocity](image)

Figure 5.2: Experimental data with the ratio of the average velocity in the scour hole with the critical velocity ($u_c = 0.20[m/s]$) for sediment transport. The maximum scour depth is reached before the critical velocity in the scour is reached.

**Maximum depth**

Results and observations during the experiments showed that the process of undermining leads to a maximum depth as a result of re-feeding of the deepest parts of the scour hole by sediment from the undermined parts. This process occurred per geometry at about equal maximum depth, despite different experimental configurations. Figure 5.3 shows the experiments in which re-feeding was observed visually for both Geometry 1 and 2. When feeding of the deepest parts occurs, the scour hole could still grow in depth when the output of sediment was still larger than the feeding source, which occurred during the experiments with relatively higher velocities.
5. Analysis

Figure 5.3: Critical depth as a result of the process of undermining. Figure 5.3(a) shows the observed moment of re-feeding for geometry 1 and Figure 5.3(b) shows the observed moment of re-feeding for geometry 2.

Figure 5.4 presents the data of Experiment 4 together with the ratio of the calculated velocity in the scour hole to the critical velocity. It is shown that a maximum depth is already reached before the critical velocity is reached, so the size of the scour hole in combination with the undermining process creates a maximum depth.

Figure 5.4: Data of experiment 4 with the ratio of the average velocity in the scour hole with the critical velocity \( \left( \frac{u_{scour}}{u_c} \right) \) for sediment transport. The maximum scour depth is reached before the critical velocity in the scour is reached.

5.1.3. Effect of rigid edges

The experiments showed influence on the development of the scour hole of the fixed downstream edge and the side edges. A steep downstream slope is created by the downstream edge which blocks bed load transport to a great extent. Additionally, as a result of the fixed edge, undermining occurs, creating a large step height which leads to blocking of the bed load sediment transport. A larger distance between the fixed edges creates a deeper scour hole as also observed by Van Zuylen (2015). Figure 5.5 presents measurements from both geometry 1 and 2 at \( t = 16.8 \) [hr s], which shows a deeper scour hole for a larger distance between the edges. Additionally, it is observed that in both geometries the shape of the scour hole is relatively similar.
Van Zuylen (2015) investigated the influence of the distance between non-erodible plates on the depth of the scour hole for equivalent conditions as used in experiment 4 and 8 \( (u_{\text{Zuylen}} = 0.45\,[m/s] \) and \( h_{\text{Zuylen}} = 0.13\,[m] \). Figure 5.6(a) shows the influence of different plate distances in the experiments by Van Zuylen (2015). The increase of scour depth as a result of the increase of plate distance from 0.5\,[m] to 1.0\,[m] is between 5\%–10\%. A similar analyses is executed to compare the scour depths between Geometry 1 and 2. Figure 5.6(b) presents the results which show an increase of scour depth with 12\%–20\% as a result of the increase in length from 0.5\,[m] to 0.75\,[m]. Note that the increase in plate distance by Van Zuylen (2015) is larger compared to the increase in length between Geometry 1 and 2.

The results of Van Zuylen (2015) show a significantly smaller effect of the distance between the downstream and upstream edge compared to the performed experiments in this research. This result can be explained by taking a look at the width of the scour hole. The rigid side edges block the development of the scour hole in lateral direction. Additionally, there is a maximum for the angle of the side slope, since the sediment at the side edges is protected by the upstream edges. If it is assumed that a scour hole has a certain constant angle, scour holes can get deeper when the width is larger and the maximum depth based on conservation of mass or momentum is not yet reached, which is illustrated highly simplified in Figure 5.7.
Figure 5.7: Effect of a larger width on the deepest part of the scour hole.

Figure 5.8(a) shows the location of the deepest point over time for all experiments. The used location is illustrated in Figure 5.8(b). It is observed that relative to the length of the scour hole and the equilibrium depth, the evolution of the deepest point is similar in all experiments. The equilibrium depth is based on the fitted equilibrium depths obtained further on, in Section 5.3.

Figure 5.8: Measured location of deepest part in the scour hole relative to the scour hole length and the equilibrium depth.

5.1.4. Flow patterns

Figure 5.9 shows the flow directions in the longitudinal direction of the scour hole with $u_{avg} = 0.39\,[m/s]$ and $h = 0.141\,[m]$. The velocity in $z$ direction is multiplied with a factor 3 to make the changes in flow direction more visible. It is observed that downflow is present above and in the scour hole.

Figure 5.9: Vector plot of velocity measurements with multiplied vertical velocity component to visualize the down flow. $L_{hole}$ is defined as the length of the scour hole and $S_0$ as the fitted equilibrium depth.
Based on velocity measurements and dye visualization (Figure 5.10(a) and 5.10(b)) it is concluded that a recirculation zone is present within the scour hole. The reattachment point is present between 0.21 to 0.28 [m] for Geometry 2 downstream from the upstream edge, with $u_{avg} = 0.39[\text{m/s}]$ and $h = 0.141[\text{m}]$. Measurements on the horse-shoe vortex were extremely difficult on this spatial scale, so grains with pigment were used to visualize flow direction close to the bed in the zone where the horse-shoe vortex should be present, as presented in Figure 5.10(c) and 5.10(d). The flow was highly alternating, however, on average a flow direction with an angle to the sides was found. Flow directed to the sides of the scour hole got influenced by the main flow higher in the water column, creating a recirculating pattern propagating in downstream direction.

Figure 5.10: Recirculation at bed visualized with dye.

Figure 5.11 presents the measured velocities in longitudinal direction compared with the model simulations by Bom (2017) of an equal shaped scour hole with the same flow conditions. The velocity measurements show a small recirculating flow, however, the recirculation is significantly underestimated compared to the simulations by Bom (2017). The difference in results might be addressed to the lack of oxygen bubbles. Within the recirculation zone velocities are relatively small and some parts have a directional component in downstream direction. The oxygen bubbles might not follow this downflow inside the recirculation zone.
Comparison of measurements with modelled velocities by Bom (2017)

Figure 5.11: Comparison of velocity measurements in the longitudinal symmetry axis with the results from model simulations by Bom (2017).

Figure 5.12 presents the measured turbulent kinetic energy together with the turbulent kinetic energy deduced from the model simulation of Bom (2017). The measurements show significantly higher energy levels in the recirculation zone and on the surface between the mixing layer and the recirculation zone, nevertheless, the overall pattern shows similarity between model and experiments.

Comparison of measured TKE with model simulations of Bom (2017)

Figure 5.12: Comparison of measured turbulent kinetic energy with model simulation of Bom (2017).

5.2. Application of Breusers formulas

The Breusers formulas, discussed in Section 2.2.3, are the most commonly used equations for prediction of scour hole development and scour depth. Breusers empirically determined an equation for scour development over time in the development phase (for \( t < t_1 \)). Additionally Breusers determined a formula for scour development including the equilibrium depth (for every \( t \)) and an equation for the equilibrium depth (for \( t \to \infty \)) is often used to determine the expected maximum depth. This section demonstrates the applicability of all these formulas on scour hole formation in heterogeneous subsoil as executed in the experiments.

5.2.1. Formula for scour development in development phase

According to Breusers (1966), the formula for scour development in the development phase is used when \( t < t_1 \). \( t_1 \) is the calculated characteristic time scale for scour hole development described in Equation 5.1. Breusers (1966) defined the characteristic timescale as the moment when the depth of the scour hole is equal to the water depth \( (y_m = h_0) \).
\[ t_1 = \frac{K h_0^2 \Delta^{1.7}}{(\alpha \bar{u}_0 - \bar{u}_c)^{4.3}} \quad [hrs] \]  

Equation 5.2 presents the Breusers formula for the development phase.

\[ \frac{y_m}{h_0} = \left( \frac{I}{t_1} \right)^\gamma \]

Figure 5.13 shows the experimental data of Experiment 2 and 8 together with the calculated and fitted scour depth development according to Equation 5.2 derived by Breusers. Two fits of Equation 5.2 are included in each figure. The first one uses \( \gamma \) as single fitting constant and uses the calculated characteristic time. The second one uses both \( \gamma \) and \( t_1 \) as fitting constants. The best fit is based on the smallest root mean square error (RMSE) between the fit and the experimental data. It was found that using both the characteristic time \( t_1 \) and the power \( (\gamma) \) as fitting constants showed a lower RMSE. The calculated characteristic time scale should apply in every situation, however, Table 5.2 demonstrates significantly lower values for the fitted characteristic timescale.

As discussed in Section 2.2.3, three-dimensional flow should have a value of \( \gamma \) between 0.4 and 0.8. Table 5.2 presents the fitting constants for all carried out experiments in which \( \gamma_1 \) represents the fit with one fitting constant \( \gamma \) and \( \gamma_2 \) and \( t_1 \) represent the fit with two fitting constants. The values show that \( \gamma \) is in general lower than the expected value between 0.4 and 0.8. Note that the three-dimensional flow in previous research was induced by a flow constriction upstream of the area of interest, which is significantly different compared to the three-dimensional situation in the research, where the erodible area is three-dimensional as well. Appendix D.1 shows the outcome of the Breusers prediction with \( \gamma = 0.4 \).

Figure 5.13: Fit of Breusers formula for development on experimental data with both one and two fitting constants.
5. Analysis

Table 5.2: Fitted power and characteristic timescale for fits with one and two fitting constants compared with the calculated characteristic time.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>fit γ₁ [-]</th>
<th>fit γ₂ [-]</th>
<th>fit t₁ [hr s]</th>
<th>Calculated t₁ [hr s]</th>
<th>t₁/t₁,calc [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1: h = 0.143[m], u_avg = 0.290[m/s]</td>
<td>0.57</td>
<td>0.42</td>
<td>1190.0</td>
<td>527.3</td>
<td>2.26</td>
</tr>
<tr>
<td>2: h = 0.141[m], u_avg = 0.344[m/s]</td>
<td>0.44</td>
<td>0.40</td>
<td>241.3</td>
<td>176.9</td>
<td>1.36</td>
</tr>
<tr>
<td>3: h = 0.140[m], u_avg = 0.400[m/s]</td>
<td>0.39</td>
<td>0.37</td>
<td>86.6</td>
<td>76.5</td>
<td>1.13</td>
</tr>
<tr>
<td>4: h = 0.141[m], u_avg = 0.459[m/s]</td>
<td>0.35</td>
<td>0.35</td>
<td>35.4</td>
<td>36.7</td>
<td>0.97</td>
</tr>
<tr>
<td>5: h = 0.175[m], u_avg = 0.351[m/s]</td>
<td>0.48</td>
<td>0.43</td>
<td>355.5</td>
<td>254.9</td>
<td>1.39</td>
</tr>
<tr>
<td>6: h = 0.111[m], u_avg = 0.331[m/s]</td>
<td>0.41</td>
<td>0.42</td>
<td>125.9</td>
<td>139.3</td>
<td>0.90</td>
</tr>
<tr>
<td>Geometry 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7: h = 0.141[m], u_avg = 0.346[m/s]</td>
<td>0.46</td>
<td>0.37</td>
<td>178.4</td>
<td>176.9</td>
<td>1.01</td>
</tr>
<tr>
<td>8: h = 0.141[m], u_avg = 0.459[m/s]</td>
<td>0.29</td>
<td>0.33</td>
<td>25.0</td>
<td>36.7</td>
<td>0.68</td>
</tr>
<tr>
<td>9: h = 0.115[m], u_avg = 0.332[m/s]</td>
<td>0.33</td>
<td>0.36</td>
<td>124.4</td>
<td>147.3</td>
<td>0.84</td>
</tr>
</tbody>
</table>

5.2.2. Formula for time development with equilibrium depth

As already discussed in Section 2.2.3, the equation for the time development and equilibrium depth derived by Breusers does not apply in the experimental situation, since the condition that the scour depth is larger than the water depth does not hold.

Van Velzen et al. (2015) adapted the equation so it is applicable for every $t$ without any depth restriction. Equation 5.3 is used for prediction of scour hole depth as a function of time including the equilibrium depth. The characteristic time $t₁$ is calculated with Equation 5.1.

$$\frac{y_m}{y_{me}} = 1 - e^{-\left(\frac{t}{t_1}\right)^\gamma} \quad (5.3)$$

$y_m =$ scour depth [m]

$y_{me} =$ equilibrium scour depth [m]

$t =$ time [hrs]

$t₁ =$ characteristic timescale [hrs]

Figure 5.14 shows the fit for Equation 5.3 with the smallest RMS error possible. The data in stage 3 (re-feeding stage) is not included in the fitting procedure, since this stage introduces a completely new process in the scour development which probably not occurs in the field. Used fitting constants are, the equilibrium depth $(y_{me})$ and the power $(\gamma)$. It is observed that the equilibrium depth is underestimated. In the first hours, the fit underestimates the data and over time the experimental data is overestimated and underestimated again.

![Figure 5.14: Best fit based on Equation 5.3 with overshoot and undershoot of the experimental data.](image)
The inaccuracies in the fit from Figure 5.14 suggest that a different relation would be more appropriate for fitting these results. Equation 5.3 uses one equilibrium depth and one characteristic time scale. It is expected that different development stages have different dominant hydrodynamic processes and subsequently sediment transport and thus different characteristic timescales.

### 5.2.3. Formula for equilibrium depth

In Section 2.2.4, two formulas are given for the equilibrium depth. Equation 5.4 is used to predict and compare the equilibrium depth with the observed depth.

\[
\frac{y_{m,e}}{h_0} = \frac{\omega u_0 - u_c}{u_c}
\]  

\(y_{m,e}\) = equilibrium scour depth [m]  
\(h_0\) = water depth [m]  
\(u_0\) = upstream velocity [m/s]  
\(u_c\) = critical velocity [m/s]  
\(\omega = 1 + 3r_0\) [-]

Table 5.3 presents the calculated equilibrium depth for each experiment based on Equation 5.4, together with the observed maximum depth in each experiment. Figure 5.15 presents both the calculated and the observed scour depths from Table 5.3. It is observed that the calculated equilibrium depth shows a significantly wider range of scour depths, compared to the observed scour depths. Apparently, the scour hole with rigid edges leads to damping of the scour depth concerning different water depth and velocity configurations.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(h_{s,e}[m])</th>
<th>(S_{observed})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geometry 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 1</td>
<td>0.121</td>
<td>0.050</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.149</td>
<td>0.063</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>0.194</td>
<td>0.064</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>0.236</td>
<td>0.067</td>
</tr>
<tr>
<td>Experiment 5</td>
<td>0.191</td>
<td>0.066</td>
</tr>
<tr>
<td>Experiment 6</td>
<td>0.112</td>
<td>0.060</td>
</tr>
<tr>
<td><strong>Geometry 2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 7</td>
<td>0.152</td>
<td>0.081</td>
</tr>
<tr>
<td>Experiment 8</td>
<td>0.236</td>
<td>0.085</td>
</tr>
<tr>
<td>Experiment 9</td>
<td>0.110</td>
<td>0.076</td>
</tr>
</tbody>
</table>
5.3. Prediction of scour hole development

5.3.1. Finding the characteristic time scale and equilibrium depth

The previous section showed that no proper equilibrium depth and representative characteristic time scale for the experimental data could be found by using the empirical relations of Breusers. Based on this, it may be concluded that the Breusers formulas are not applicable for development of scour holes with a non-erodible top layer. To find the proportionality between the varied parameters and the scour hole development, an equilibrium depth ($S_0$) and characteristic timescale ($T_{char}$) must be determined. Ideally, the equilibrium depth is found from the experiments, which subsequently can lead to the characteristic time scale. However, as a result of horizontal re-feeding, which is an artifact of the experimental setup, the equilibrium depth is never reached. Therefore, a fitting procedure is needed to find the equilibrium depth and the following characteristic time.

The previous section showed that one timescale is not sufficient for finding these two parameters. During the experiments, three stages of development were observed (stages of dunes, stage until undermining and a stage until re-feeding). Re-feeding led to a decrease of development and even a decrease of the scour scour depth sometimes. Therefore, the last stage of undermining is not used for fitting and two time scales (and two equations) are introduced for the prediction of $S_0$ and $T_{char}$.

Equations 5.5 and 5.6 were used to fit the experimental data, using two timescales. Five unknown parameters have been fitted with the smallest RMSE possible. Two examples are given in Figure 5.16 showing improved fits compared to fitting with one timescale. The switching point is defined as the moment in time when the fit changes from the equation for $S_1$ to the equation for $S_2$. Using two timescales for fitting can be interpreted as if more dominating processes are present during the development of a scour hole with fixed edges. For example when the scour hole is developed sufficiently, the rigid edges can introduce larger resistance for sediment to be transported out of the scour hole. Extra information on how the best fit is found on the experimental data, is presented in Appendix D.2.

\[
S_1 = \tilde{S}_1 \cdot \left( 1 - e^{-\frac{t}{T_1}} \right) \tag{5.5}
\]
\[
S_2 = \tilde{S}_2 \cdot \left( 1 - e^{-\frac{t-t_s}{T_2}} \right) + \tilde{S}_1 \cdot \left( 1 - e^{-\frac{t}{T_1}} \right) \tag{5.6}
\]
\[
S(t) = \begin{cases} 
S_1 & \text{if } t < t_s \\
S_2 & \text{if } t > t_s 
\end{cases}
\]
When a fit makes extrapolation possible, an estimation can be made of the possible equilibrium scour depth of the deepest point in the scour hole, based on the experimental data. Appendix D.5 shows all fitted functions for all executed experiments. Table 5.4 gives all parameters used for the fits with the smallest RMSE possible. The equilibrium depth is defined as the depth when the fitted formula has a gradient smaller than 0.00001\([\text{m}]\).

Table 5.4: The extrapolated equilibrium depth with the fitting constants derived from the fitting procedure with \(S_0 = \) determined equilibrium depth and the fitting constants according to Equations 5.5 and 5.6.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(S_0) [m]</th>
<th>(S_1) [m]</th>
<th>(S_2) [m]</th>
<th>(T_1) [hr]</th>
<th>(T_2) [hr]</th>
<th>(t_s) [hr]</th>
<th>RMSE [(\text{m}^4)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1: (h = 0.143) [m], (u_{avg} = 0.290) [m/s]</td>
<td>0.0595</td>
<td>0.0317</td>
<td>0.0313</td>
<td>10.55</td>
<td>65.72</td>
<td>23.5</td>
<td>4.436 (\cdot) 10(^{-5})</td>
</tr>
<tr>
<td>2: (h = 0.141) [m], (u_{avg} = 0.344) [m/s]</td>
<td>0.0632</td>
<td>0.0450</td>
<td>0.0237</td>
<td>3.92</td>
<td>13.33</td>
<td>9.38</td>
<td>5.402 (\cdot) 10(^{-4})</td>
</tr>
<tr>
<td>3: (h = 0.140) [m], (u_{avg} = 0.400) [m/s]</td>
<td>0.0670</td>
<td>0.0422</td>
<td>0.0315</td>
<td>1.04</td>
<td>4.85</td>
<td>1.91</td>
<td>1.772 (\cdot) 10(^{-4})</td>
</tr>
<tr>
<td>4: (h = 0.141) [m], (u_{avg} = 0.459) [m/s]</td>
<td>0.0755</td>
<td>0.043</td>
<td>0.0314</td>
<td>0.36</td>
<td>1.77</td>
<td>0.75</td>
<td>1.290 (\cdot) 10(^{-5})</td>
</tr>
<tr>
<td>5: (h = 0.175) [m], (u_{avg} = 0.351) [m/s]</td>
<td>0.0642</td>
<td>0.0522</td>
<td>0.0364</td>
<td>5.07</td>
<td>14.42</td>
<td>3.96</td>
<td>2.510 (\cdot) 10(^{-4})</td>
</tr>
<tr>
<td>6: (h = 0.111) [m], (u_{avg} = 0.331) [m/s]</td>
<td>0.0605</td>
<td>0.0498</td>
<td>0.0302</td>
<td>4.40</td>
<td>13.25</td>
<td>4.13</td>
<td>2.467 (\cdot) 10(^{-4})</td>
</tr>
<tr>
<td>Geometry 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7: (h = 0.141) [m], (u_{avg} = 0.346) [m/s]</td>
<td>0.0861</td>
<td>0.0425</td>
<td>0.0479</td>
<td>1.76</td>
<td>19.39</td>
<td>3.96</td>
<td>4.431 (\cdot) 10(^{-4})</td>
</tr>
<tr>
<td>8: (h = 0.141) [m], (u_{avg} = 0.459) [m/s]</td>
<td>0.0902</td>
<td>0.0509</td>
<td>0.0455</td>
<td>0.36</td>
<td>2.51</td>
<td>0.74</td>
<td>1.010 (\cdot) 10(^{-4})</td>
</tr>
<tr>
<td>9: (h = 0.115) [m], (u_{avg} = 0.332) [m/s]</td>
<td>0.0804</td>
<td>0.0477</td>
<td>0.0379</td>
<td>2.66</td>
<td>19.39</td>
<td>5.90</td>
<td>1.261 (\cdot) 10(^{-4})</td>
</tr>
</tbody>
</table>

To verify whether the two timescales relate to different development stages, the moment of the switching point is plotted against the moment when the last dune resolves from the scour hole in Figure 5.17(a). The determination of the moment when the last dune resolves is based on analyzing Figures C.1 to D.1 at each time step. Both timescales show good accordance with each other. The switching point at this point can be explained in two ways. First, dunes create higher turbulence intensities locally, therefore, the scour hole development can be more quick when dunes are present. Secondly, Figure 5.17(b) shows the relation between the switching point and the scour depth. After dunes resolve from the scour hole a significant hole is devel-
oped. This can create significant three-dimensional flow patterns (e.g. horse-shoe vortices and contraction) which will influence scour hole development.

Using the information presented in Table 5.4, an estimation of the equilibrium scour depth is made, which makes it possible to display the experimental scour depth data on a dimensionless scale and to analyze the representative timescales per experiment. Figure 5.18 shows the experiments with the y-axis normalized with the fitted equilibrium depth. It is observed that the larger the average velocity the faster the scour hole reaches the fitted equilibrium depth. Additionally it is found that with Geometry 1 (the smaller geometry) the equilibrium depth is reached more rapidly.

Based on Figure 5.18 an estimation of the total characteristic timescale is made. The area between the scour development and the maximum scour depth gives a timescale which can be used as a timescale which qualitatively represents the scour hole development. Equation 5.7 shows the definition of the characteristic time scale and Figure 5.19 shows an example of the area used for the calculation of the characteristic timescale for each experiment.

$$T_{char} = \int_0^T \frac{S_0 - S_{scour}}{S_0} \, dt$$  \hspace{1cm} (5.7)
5.3. Prediction of scour hole development

\[ S_{scour} = \text{scour data fitted with experimental data} \ [m] \]
\[ S_0 = \text{equilibrium scour depth} \ [m] \]

As explained in Section 5.2, two timescales are used to extrapolate the experimental results. However, one timescale to represent the executed experiments would be more useful for finding a proportionality between the varied parameters and the scour hole development. The first period does not show clear corresponding results between different experiments which suggests that dunes create different erosion capacities, as a result of a local enhancement of turbulence intensities. After vanishing of the dunes more stable and consequent development of the scour hole is observed. This second stage in each experiment gives better results to work with, however, the first part of scour hole development should be included in the characteristic timescale as well. Therefore one characteristic timescale is chosen, based on equation 5.7, to represent the scour development. Figures 5.20(a) and 5.20(b) present the relation between the two fitted timescales \( T_1 \) and \( T_2 \) and the \( T_{\text{char}} \). A linear relation is observed between \( T_2 \) and \( T_{\text{char}} \). Figure 5.20(a) shows less consistency especially for experiment 7 and 9.

The calculated characteristic timescale of each experiment is used to obtain relations between scour hole development and the varied parameters. The results of the obtained characteristic timescales are presented in Figure 5.21. It is concluded that the calculated characteristic time scale is a proper qualitatively representation for each experiment.
5. Analysis

5.3.2. Effect of upstream average velocity

In this section, the dependency of the upstream average velocity on the development in time of the scour hole is analyzed. Table 5.5 shows the characteristic values for the experiments on the effect of velocity.

Table 5.5: Characteristic numbers of the experiments on velocity, with the equilibrium depth $S_0$ and the characteristic timescale $T_{char}$ derived using the fitting procedure.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$h$ [m]</th>
<th>$u$ [m/s]</th>
<th>$S_0$ [m]</th>
<th>$T_{char}$ [hr]</th>
<th>$u_{avg}/u_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 1</td>
<td>0.143</td>
<td>0.290</td>
<td>0.0595</td>
<td>50.17</td>
<td>1.45</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.141</td>
<td>0.346</td>
<td>0.0632</td>
<td>9.79</td>
<td>1.73</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>0.140</td>
<td>0.400</td>
<td>0.0670</td>
<td>3.55</td>
<td>2.00</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>0.141</td>
<td>0.459</td>
<td>0.0710</td>
<td>1.77</td>
<td>2.30</td>
</tr>
</tbody>
</table>

From the determined characteristic timescales, relations between scour hole development and the systematically varied parameters can be found. Figure 5.22(a) shows a plot with the different velocity configurations from each experiment with the corresponding characteristic timescales. A fit is made on the data points based on the smallest RMSE within the plot to express the relation between the upstream average velocity and the characteristic timescale.

![Figure 5.22(a)](image)

Relation $T_{char}$ and $u_{avg}/u_c$ 
Fit $(3.47 \times (u_{avg}/u_c)/u_c)^{-3.35}$

![Figure 5.22(b)](image)

Relation $S_0$ and $u_{avg}/u_c$

Figure 5.22: Proportionality between the configured velocity and the characteristic timescale and the proportionality between the fitted equilibrium depth and the configured velocities.
The relation for the effect of velocity on the characteristic timescale is presented in Equation 5.8. Figure 5.23 shows the results of the dependency of the upstream velocity processed in the time at the x-axis.

\[ T_{char} \propto \left( \frac{u_{avg} - u_c}{u_c} \right)^{-3.35} \text{ for } u_{avg} > u_c \]  

\[ u_{avg} = \text{average velocity [m/s]} \]
\[ u_c = \text{critical velocity [m/s]} \]

Figure 5.23: Effect of the configured velocity on scour hole development.

### 5.3.3. Effect of water depth

It is evident that there is an effect of the water depth on the scour hole development, because a very low water depth would definitely change the scour hole development compared to the used water depths during the experiments for example, since significant reduction in flow velocity will determine the maximum scour depth. Water depth is changed systematically to see what the influence is on the development of scour holes. During the timespan of the performed experiments, no significant change was observed between the experiments. By fitting the data, as shown in Section 5.2, extrapolation of the measured data was possible. Using this extrapolation, varying characteristic timescales and varying equilibrium depths were found for different water depth configurations. Table 5.6 presents the relevant data for finding the proportionality of water depth to the time development of the scour hole.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( h [m] )</th>
<th>( u [m/s] )</th>
<th>( S_0 [m] )</th>
<th>( T_{char} [hrs] )</th>
<th>( u_* [m/s] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.141</td>
<td>0.346</td>
<td>0.0632</td>
<td>9.79</td>
<td>0.0181</td>
</tr>
<tr>
<td>Experiment 5</td>
<td>0.175</td>
<td>0.351</td>
<td>0.0642</td>
<td>10.71</td>
<td>0.0180</td>
</tr>
<tr>
<td>Experiment 6</td>
<td>0.111</td>
<td>0.331</td>
<td>0.0605</td>
<td>9.47</td>
<td>0.0178</td>
</tr>
<tr>
<td>Geometry 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 7</td>
<td>0.141</td>
<td>0.346</td>
<td>0.0861</td>
<td>13.54</td>
<td>0.0181</td>
</tr>
<tr>
<td>Experiment 9</td>
<td>0.115</td>
<td>0.332</td>
<td>0.0804</td>
<td>12.94</td>
<td>0.0178</td>
</tr>
</tbody>
</table>

Figure 5.24(a) shows the relation between the characteristic timescale of scour development and the configured water depth in the flume. Larger water depth leads to larger timescales. Note the relatively small differences between different timescales. Additionally, Figure 5.24(b) shows the relation between the configured water depth and the equilibrium depth from fitting. Within the experimented range, the characteristic timescale shows a slight dependency on water depth as presented in Equation 5.9.
Figure 5.24: Proportionality between the calculated characteristic timescale and both the configured water depth and the fitted equilibrium depth.

\[ T_{\text{char}} \propto \left( \frac{h}{L} \right)^{0.25} \]  
\[ h = \text{water depth [m]} \]
\[ L = \text{length scale [m]} \]

Figure 5.24(b) shows an increase in equilibrium scour depth with a larger water depth. However, for water depths larger than 0.14[m], a significantly smaller increase in scour depth is observed. The found proportionality for water depth is evaluated in Figure 5.25(b).

Figures 5.26(a), 5.26(b) and 5.26(c) show the scour depths for different water depth configurations in the development phase. It is observed that differences are present in the very beginning of development, as a result of different dune development. After the stage with dunes, scour depths are equal for different water depths, as a result of relatively equal shear velocity configurations between the experiments. Over time the development of the scour holes start to differentiate for different water depths.
5.3. Prediction of scour hole development

5.3.4. Effect of geometry

In this section, the effect of the geometry is analyzed. Table 5.7 presents the information to find the proportionality between the geometry and the scour depth.

Table 5.7: Characteristic numbers of experiments on the effect of the geometry with the fitted equilibrium depth and characteristic timescale

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$h [m]$</th>
<th>$u [m/s]$</th>
<th>$S_0 [m]$</th>
<th>$T_{char} [hr]$</th>
<th>$w_{geometry} [m]$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geometry 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.141</td>
<td>0.346</td>
<td>0.0632</td>
<td>9.79</td>
<td>0.224</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>0.141</td>
<td>0.459</td>
<td>0.0710</td>
<td>1.77</td>
<td>0.224</td>
</tr>
<tr>
<td><strong>Geometry 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 7</td>
<td>0.141</td>
<td>0.346</td>
<td>0.0861</td>
<td>13.54</td>
<td>0.336</td>
</tr>
<tr>
<td>Experiment 8</td>
<td>0.141</td>
<td>0.459</td>
<td>0.0902</td>
<td>1.78</td>
<td>0.336</td>
</tr>
</tbody>
</table>

The geometry is changed during the experiments, as already discussed in Section 3.2.1. The aspect ratios were not changed creating equal ratios for length and width between both geometries. Undermining disturbs the results at the downstream edge of the scour hole. From Section 5.1.3 it is known that both the length and width of the scour hole influence the scour depth. However, the exact amount of influence of the length on the scour hole development is not known. Therefore, the width of the scour hole was used to analyze the effect of a larger scour hole. Figure 5.27(a) shows the relation between the characteristic time of the scour hole development and the constructed width of the scour hole. A larger width leads to a longer characteristic time. It is also visible that, in absolute sense, a larger timescale create larger differences. Figure 5.27(b) shows the relation between the constructed width and the equilibrium depth. A clear difference is present between the tested geometries. A larger width creates deeper scour holes. This is expressed relative to the total width of the flume in Equation 5.10.
5. Analysis

Figure 5.27: Proportionality between the calculated characteristic timescale and the effect of the width of the scour hole.

\[ T_{\text{char}} \propto \left( \frac{w}{B} \right)^{0.75} \quad \text{for} \quad w \leq B \quad (5.10) \]

\( w = \) width of geometry [m]
\( B = \) width of flume [m]

Figure 5.28 shows the experiments on the effect of the geometry with and without effect of Equation 5.10.

From previous research by Zuylen (2015) it is known that scour over the full width leads to more shallow scour holes compared to 3D experiments from this research. This seems contradictory since a scour width over the full length (2D) should lead to deeper scour holes, according to extrapolation of the experiments. This suggests the importance of for example three-dimensional flow for scour hole development.

5.3.5. Overview of dependency on time development and equilibrium depth

Time development

In the experiments, the influence of three important river parameters on scour hole development were investigated. All parameters show effects on scour hole development to a greater or lesser extent. Within this section, all three parameters were handled collectively to create a master curve for the executed experiments. Figure 5.29 presents the result of the investigated parameters.
The effect on the time development of scour holes is determined as:

\[
I = t_{\text{exp}} \left( \frac{u_{\text{avg}} - u_c}{u_c} \right)^{3.35} \left( \frac{h}{L} \right)^{-0.25} \left( \frac{W_{\text{geometry}}}{B} \right)^{-0.75} \quad [T]
\]  

(5.11)

Equilibrium depth

Figure 5.30 presents the overview of the fitted equilibrium depths for each experiment. Figure 5.30(a) shows that the differences between experiments are relatively small, except for the experiments with a different geometry. Figure 5.30(b) presents the equilibrium depths normalized with a characteristic length scale of the scour hole, in this case the width. It is observed that the fitted equilibrium depths for each experiment show relatively small variations. According to the Breusers formula for equilibrium depth, variations should be significantly larger.

\[
\beta = \arcsin \left( 2.9 \times 10^{-4} \frac{U^2}{\Delta g d_{50}} + 0.11 + 0.75 r_0 f_c \right) \quad \text{with} \quad f_c = \frac{C}{C_0}
\]  

(5.12)

5.4. Comparison with other experiments and field data

5.4.1. Slopes

In Figure 5.31, the angles of the upstream slopes are compared with experiments of Koopmans (2017), Van Zuylen (2015) and the theoretical value based on Equation 5.12, which is already discussed in Section 2.2.5.
First of all it is observed in Figure 5.31 that the several different configurations of the experiments from this research do not lead to significant changes of the measurements of the upstream slope. This also holds for the calculated theoretical value which remains more or less equal over all experiments, as a result of relatively small changes in conditions considering the upstream slope. This is a result of the relatively small empirically found influence of velocity compared to turbulence and especially bed roughness as observed in Equation 5.12. Nevertheless, in all experiments from this research, the calculated value underestimates the measured angle. This difference between measured and calculated values is much larger compared to the experiments executed by Koopmans (2017). Koopmans (2017) used a different Chezy value, based on uniform flow, which resulted in higher theoretical values.

Van Zuylen (2015) showed significantly lower upstream angles compared to the performed experiments. Van Zuylen (2015) performed two-dimensional experiments with a larger bed roughness ($C = 43 (m^{1/2}/s)$). A larger bed roughness (lower Chezy number) leads to lower angles of the upstream slope, as observed in Equation 5.12. This difference can be an explanation for the observed differences, however, the difference in experimental settings is large, concerning two- and three-dimensional flow.

Koopmans (2017) used equal experimental conditions and configurations leading to more or less equal angles of the upstream slope, however, the experiments showed more fluctuating upstream slopes. Contrary to the experiments from this research, Koopmans (2017) used recirculating flow in the flume. As a result of recirculation, not only water recirculated and the experiments were not carried out for complete clear water conditions leading to more fluctuating results, hence, a wider range of upstream slopes. It is concluded that it is important to define a correct bed roughness, to predict the upstream slopes with the empirical formula. Koopmans (2017) defined the Chezy value according the Chezy formula, which assumes uniform flow. The bed roughness for the experiments of this research was defined by measurements of the bed profile. The actual Chezy-value should be somewhere in between. Therefore, 5.31 shows a bandwidth of the calculated slope for the 3D experiments. Besides the ambiguity in the calculation of the upstream slope concerning the definition of the bed roughness, it is observed that the experiments executed by Van Zuylen (2015) showed significantly lower upstream slopes.

![Figure 5.31: Comparison of the averaged angle of the upstream slope for different experiments. Experiments by Van Zuylen (2015) demonstrate significant lower slope angles, however, more or less accordance with the predictive formula for the upstream slope. The theoretical values are given as one value for all experiments for proper visibility. It also nicely shows that the variance between experimental conditions were relatively small (11.8 – 12.8°).](image)

**5.4.2. Development in time**

In this section, the development over time in the performed experiments are compared visually to the experiments performed by Van Zuylen (2015) and Koopmans (2017). With equal velocities it is observed that scour holes with a three-dimensional character develop faster and become deeper compared to two-dimensional scour holes. Additionally, the experiments of Koopmans (2017) showed less deep scour holes. Koopmans used the same flume, Geometry 1 and the same grain size, however, during Koopmans’ experiments water was recirculating in the flume. This led to recirculation of suspended load and eventually bed load was also recirculated, as already discussed in the previous section.
5.4. Comparison with other experiments and field data

Comparison with experiments by Van Zuylen (2015)

Figure 5.33 presents the experiments on velocity and experiments by Van Zuylen (2015) with a plate distance of 0.5 [m] and different velocities. This plate distance shows best comparison with the performed experiments, in which the length of the scour hole was 0.5 [m]. In both experimental programs can be observed that in general, a higher flow velocity creates deeper scour holes.

It is verified whether the derived proportionality on velocity can also be used for the experiments of Van Zuylen (2015). The equilibrium scour depth should be known to investigate the proportionality between velocity and scour depth in the experiments by Van Zuylen (2015). The equilibrium depth for Experiment 9 and 20 from Van Zuylen (2015) are calculated using the same method used for the equilibrium depth of the experiments. The equilibrium depth of Experiment 9 and 20 are respectively $S_0 = 0.0546$ [m] and $S_0 = 0.0651$ [m]. Applying the determined proportionality of velocity on scour hole development leads to Figure 5.34.
Figure 5.34: Comparing experimental data from this research and experiments by Zuylen (2015) with the proportionality obtained by the analyses on the experiments from this research.

Figure 5.34 shows that the proportionality used for the performed experiments are not in accordance with the experimental results of Van Zuylen (2015). The dependency on flow velocity in the experiments by Van Zuylen (2015) is presented in figure 5.35. The two-dimensional experiments show a lower proportionality with velocity, which suggests other dominating processes compared to the experiments from this research.

Figure 5.35: Comparing experimental data and experiments by Zuylen (2015) with a proportionality between scour hole development and the velocity which fits the experimental data of Van Zuylen (2015).

**Comparison with field data**

In this section, the experiments on small scale are compared with field data, processed by Koopmans (2017). It is possible to compare field data with the performed experiments when there is data present of scour holes which are developed recently, so the starting point of the scour development is known. Additionally it is preferable to only evaluate scour holes which incised a clay layer with a large sand layer below the poorly erodible clay layer. Koopmans (2017) investigated several scour holes in the Rhine-Meuse delta and observed two recently developed scour holes, named OMS6a and OMS4a.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$u_{avg}$ [m/s]</th>
<th>$h$ [m]</th>
<th>$d_{n,50}$ [$\mu$m]</th>
<th>$C$ [$m^{1/2}$/s]</th>
<th>$\Psi_c$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMS4a</td>
<td>0.95</td>
<td>16</td>
<td>350</td>
<td>43</td>
<td>0.54</td>
</tr>
<tr>
<td>OMS6a</td>
<td>1.23</td>
<td>16</td>
<td>350</td>
<td>43</td>
<td>0.54</td>
</tr>
<tr>
<td>Experiments</td>
<td>0.29 - 0.46</td>
<td>0.11-0.175</td>
<td>260</td>
<td>70</td>
<td>0.015-0.04</td>
</tr>
</tbody>
</table>

Figure 5.36 shows the field data and data of several experiments. The equilibrium depths for the field data are estimated to be $S_0 = 5$[m] for OMS4a and $S_0 = 15$[m] for OMS6a. It is observed that the timescale of development of the field data is significantly larger compared to the timescales in the laboratory.
5.4. Comparison with other experiments and field data

Figure 5.36: Comparing experimental data and field data with estimated equilibrium depths.

Figure 5.37 shows the results after processing of the derived proportionality for each varied parameter. Again, the timescale for the field data is significantly larger compared to the timescales from the experiments. This suggests that one or more characteristic parameters are missing for the calculation of a proper scaled time scale.

Figure 5.37: Comparing experimental data and field data with the found proportionality of velocity.
Discussion

This chapter discusses the results from the laboratory experiments with respect to the research questions and considers the use of this research for follow up investigations and application to field cases. This chapter is divided in the interpretation of the experimental results, the implications and use of the results on prototype scale and the discussion of the research questions.

6.1. Interpretation of results

6.1.1. General

This research focused on investigating scour hole development in heterogeneous subsoil. The effect of the upstream velocity and the water depth on this type of scour holes was researched. Additionally the effect of the geometry of the scour hole on its growth was investigated. The investigation of scour hole development in heterogeneous subsoil is complex. The influence of a poorly erodible top layer on the development of a scour hole is large and it is very hard to scale down this layer. In this research, a non-erodible concrete top layer was chosen on top of a sand layer, which was partially exposed to the water flow.

Breusers (1966) derived empirical relations for the prediction of two-dimensional scour hole development in homogeneous subsoil behind a bed protection. The investigated scour holes in this thesis are different compared to the investigated scour holes by Breusers (1966), since a non-erodible top layer was used with a three-dimensional geometrical character.

6.1.2. Comparison with Breusers’ formula and observations

Breusers (1966) defined four stages in scour hole development: initiation, development, stabilization and the equilibrium phase. Within this research three stages were observed. The first two stages are comparable with the first two stages found by Breusers (1966). The non-erodible top layer eventually leads to a different development pattern, since the equilibrium phase observed by Breusers (1966), was never reached.

The experimental data from this research was compared with three different formulas for the prediction of scour hole development. The two used formulas for time development showed different patterns compared to the measured flume data, which can be addressed to the effect of the non-erodible top layer. The formula for the prediction of the equilibrium depth showed significantly larger variations between the experimental configurations than observed. Additionally, the executed experiments demonstrate lower scour depths than calculated with the Breusers formula. Both observed effects can be linked to the effect of the rigid boundaries of the scour hole. Apparently, the rigid edge created a limiting effect on the scour depths for different experimental configurations. Section 6.1.10 further discusses the effect of the non-erodible top layer on scour hole development.
As a result of the choice of Silica M32 \((d_{50}=260\mu m)\), the Rouse number was very low. A low Rouse number suggests little presence of suspended load, therefore, the sediment transport was mainly by bed load transport. If the sediment particles would have been smaller, it might have led to deeper scour holes compared to current results.

### 6.1.3. Fitting

The fitting procedure with the Breusers formulas for time development did not show satisfactory results for finding the equilibrium depth. The analyses showed that two sequentially used equations showed largely improved fits. The transition point coincides with the moment when the last dunes were resolved from the scour hole. It can be argued which physical process is creating this transition point. The stage with dunes shows relatively large erosion which is created by local turbulence generation as a result of rapid changing bed levels. When the dunes are resolved this extra generation of local turbulence is also resolved, which can lead to a different type of development. Secondly, after the dunes are resolved, a proper scour hole is formed. From the velocity measurements and dye visualization it is observed that from this point, three-dimensional flow patterns exist in the scour hole. Those flow patterns may lead to different scour development.

For further analyses on the effect of the varied parameters, one timescale was used as discussed in Section 5.3. The use of one timescale simplified the analysis on the effect of the varied parameters. The first timescale \(T_1\) showed less consistency as a result of the presence of dunes, but the second timescale \(T_2\) is in good accordance with the calculated characteristic timescale \(T_{char}\). It can be argued if the move from two timescales to one scale is valid, since at least two physical processes do play a role apparently. However, with the relatively small amount of data and the relatively large differences in the stage with dunes, it was problematic to analyze the characteristic timescales separately.

Breusers (1966) also uses two equations for the prediction of scour hole development. The transition point used in this research is defined by a physical change in scour hole development. Breusers (1966) used a transition point without connection with a physical change in scour hole development.

### 6.1.4. Effect of velocity

Higher flow velocities led to faster scour hole development. Additionally, higher velocities showed deeper scour holes, however, without large differences. This is in accordance with the expectations based on hypotheses. However, both the predictive formulas and the hypotheses expected significant deeper scour holes than observed during the experiments. This suggests that the rigid edges of the scour hole influence the scour depth significantly.

According to van Rijn (1984) sand transport is strongly related to the depth-averaged velocity to the power 3 to 4. This experiments show this proportionality with the timescale of the scour development. If the power of the velocity is \(u^3\), it is assumed that the sediment is as water, which suggests the importance of turbulence in this erosion process.

### 6.1.5. Effect of water depth

During the experiments no significant difference was observed between the experiments with different water depths. At the experiments on the effect of water depth, the shear velocity was configured equal at each experimental setting, therefore, the velocity profile upstream of the scour hole remained relatively similar for each experiment. As a result of equal shear velocity, the difference between experiments was hardly observed in the development stage, since the shear velocity determines the shear stresses and the related sediment transport. Further in time, the scour hole became increasingly important considering the conveyance area. When the surplus of conveyance area and subsequently the reduction of flow velocity became significant, the influence of different water depths became visible. A small effect of the water depth was found after establishing the equilibrium depth by fitting. A larger water depth led to a deeper scour hole. It is questionable whether the found relation on the effect of water depth is valid, since it was only found by fitting. Nevertheless, the relation found with the use of the fitted equilibrium depth gives an indication on the amount of influence of water depth in these experiments, which appears to be much lower compared to the influence
of water depth on scour holes development deduced by Breusers (1966), which can again be addressed to the effect of the non-erodible top layer. Without a rigid edge at the downstream side of the scour hole it is expected that the differences in scour depth in response to the larger water depth, are observed more clearly.

### 6.1.6. Effect of geometry

In the field, scour hole development can be restricted by the presence of a poorly-erodible layer. Therefore the effect of a limited width and length on the scour hole development was investigated. Van Zuylen (2015) showed that a limitation in length leads to a decrease in scour development. In this research it was observed that the effect of the length and width restriction was larger compared to the results by Van Zuylen (2015).

Van Zuylen (2015) showed similar stages of development in the experiments, but the scour depths were significantly shallower. Differences in results can be explained by looking at the effect of two- and three-dimensional flow, in which a wider scour hole creates more reduction of velocity relative to the depth. Additionally, Van Zuylen (2015) used a higher bed roughness, which might create different scour hole development.

The experiments showed, that a larger width of the scour hole relative to the width of the flume leads to significantly deeper scour holes. Based on the hypothesis, this was not expected. A larger width would result in more reduction of flow velocity and therefore more shallow scour holes based on mass conservation. The observation of a larger depth with a larger width does not correspond with the results of Van Zuylen (2015), where the width is as large as possible. There are two hypotheses developed for this result.

First, it can be hypothesized that larger scour holes induce larger three-dimensional horse-shoe vortices which can create more turbulence and higher velocity and subsequently more scour hole development. When the initial width is equal to the width of the flume so the flow (and the scour hole) becomes two-dimensional, the horse-shoe vortices are not present anymore. When this occurs, the scour depth can decrease significantly, as a result of the two-dimensional flow.

Secondly, during the experiments it was observed that from the rigid edges a slope is created. It is hypothesized that the scour depth is bounded by the effect of these side slopes. This is illustrated in Figure 6.1 and Figure 6.2, in which the scour depth becomes deeper with a larger width of the geometry ($d_2 > d_1$ when $w_2 > w_1$). However, based on mass conservation, the scour hole should become more shallow at a larger width ($d_4 < d_3$ when $w_4 > w_3$). In other words, the possibility of sediment transport out of the scour hole is bounded by the rigid edges of the scour hole.

![Figure 6.1](image1.png)

**Figure 6.1:** Effect of side slopes suppressing the availability of sediment to be transported out of the scour hole.

When the actual slope would be less steep than the critical value for the side slope, the scour depth would decrease with a larger width, since the mass conservation principle is no longer overruled by the effect of the rigid edges. Figure 6.2 shows an illustration of this effect when the critical side slope is no longer contributing to the development of the scour hole.
The importance of processes considering the width is illustrated in Figure 6.3 where importance of both processes is plotted against the width of the geometry. Additionally, a sketch of the effect of the width of the geometry on the scour depth is presented.

Figure 6.3: Theoretical view on the importance of the effect of conservation of mass or momentum and the effect of the side slopes. The scour depth increases with an increasing width when the effect of side slopes is dominant and the width decreases with an increasing width when the effect of conservation of mass or momentum is dominant.

### 6.1.7. Velocity measurements and flow patterns

In Section 5.1.4 the measured velocities are presented. The measured velocities are significantly different close to the bed compared to the model results from Bom (2017). While Bom (2017) showed a clear recirculating flow close to the bed, this was not observed in the flow velocity measurements. The difference may be explained by the use of oxygen bubbles to seed the flow upstream. ADV measurements need material to reflect on. But as it was hard for the oxygen bubbles to reach the lowest part of the scour hole, measurements close to the bed were less accurate. However, with releasing dye in the scour hole, it was visualized that a recirculating flow was present.

Convergence of flow in front of the scour hole is not observed clearly. Whereas, divergence at the downstream end of the scour hole is observed by dye visualization. This can be explained with help of potential vorticity conservation. Horizontal gradients in flow velocity must be present to create vortices in general. Upstream of the scour hole no lateral gradients are present, so upstream of the scour hole there are no vortices present. The scour hole itself creates lateral gradients, which creates vortices and therefore divergence in the downstream direction. Bom (2017) found subtle effects of contraction, with the largest effects lower in the water column.


Koopmans (2017) executed experiments with the same conditions in the same flume. Nevertheless, results from Koopmans (2017) showed more fluctuations in development. Koopmans (2017) used an experimental setup with a pump to discharge the water at the downstream end back to the inlet of the flume. This led...
to recirculation of water and apparently also to recirculation of sediment despite a bypass used to entrap the sediment, creating partial live bed conditions.

Van Zuylen (2015) performed two-dimensional experiments. The results of Van Zuylen (2015) show similar development stages over time. Though, the scour holes of Van Zuylen (2015) are significantly shallower compared to the results from this research. It is suggested that the effect of three-dimensional flow can contribute to further development of a scour hole.

The measured upstream angles show little variation (between 20.3 and 21.8°) despite the significant variation in experimental configurations. This is because the empirical formula especially shows a dependency on bed roughness and small dependency on flow velocity. The bed roughness is not varied in this research. Koopmans (2017) used equal configurations and experienced a larger variation of upstream angles in different experiments. This is possible because Koopmans (2017) encountered partial live bed conditions. Van Zuylen (2015) measured lower angles compared to this research. Van Zuylen (2015) used a larger bed roughness which leads to lower upstream angles according to the empirical formula. The observed difference can be explained by the different bed roughness, therefore, it cannot be concluded or excluded that the difference between two- and three-dimensional flow has influence.

Section 5.4.2 showed a different proportionality between the velocity and the time development for the experiment executed by Van Zuylen (2015). This suggests that the geometry not only affects the equilibrium depth but also affects the time development of the scour hole, by creating different flow patterns (e.g. contraction and horse-shoe vortices) compared to two-dimensional scour holes.

6.1.9. Comparison with numerical simulations by Bom (2017)

Based on the geometry and conditions in the experiments, Bom (2017) executed numerical investigations on the flow patterns in and around the scour hole. The model results show clear three-dimensional flow patterns including a horse-shoe vortex in the scour hole. According to the simulations does contraction of flow occur, though, the transverse component of the velocities remain small. The magnitude of contraction increases when the scour depth increases as expected, however, with a maximum. Bom (2017) relates this maximum to the increasing area of recirculation in larger scour holes which leads to a smaller conveyance area in the scour hole. With a smaller surplus of conveyance area the effect of contraction becomes less. Bom (2017) concludes that a changing water depth does not lead to significant changes in the recirculation pattern, which supports the conclusion of this research that in the development phase no significant differences are observed as a result of different water depths.

Bom (2017) also investigated the shear stresses in the scour hole. With the use of the Meyer-Peter Muller formula the sediment transport capacity for bed load transport is calculated. Figure 6.4 shows a typical outcome of the calculation of the shear stress and the corresponding sediment transport. It is observed that the upstream part (upstream of the reattachment point) of the scour hole does not show any sediment transport capacity, which is in correspondence with the experiments, in which it is observed that the upstream side of the scour hole remains stable. Additionally it is observed that large transport capacity is present at the downstream part of the scour hole (downstream of the reattachment point). In the experiments the largest changes are observed in this area. Bom (2017) also concludes that the presence of large fluctuations around the reattachment point also leads to a large erosion capacity.
6.1.10. Effect of a non-erodible top layer

Koopmans (2017) executed experiments with a poorly erodible top layer which was able to bend and fail. Although the poorly erodible top layer needed some human assistance to fail, a scour pattern was found as presented in Figure 6.5(a). The scour hole developed in downstream direction and widened as it developed. This leads to two new hypotheses, as a result of the undermining process, as discussed in Section 4.1 or as a result of horse-shoe vortices in the scour hole.

Figure 6.5(b) shows the last stage in this undermining process as observed in the experiment with a non-erodible top layer. The water flows under the rigid edge and has impact on the sand but also deflects towards both sides underneath the non-erodible top layer. The deflection of flow can create wider scour holes. The
rigid edge might fail in downstream direction over a larger width than the width of the scour hole, creating a scour hole with a larger width in downstream direction. After failing, a new quasi-stationary situation is generated in which the same undermining pattern can be expected. Figure 6.6 shows a sketch of the proposed theory on scour hole development in downstream direction at two quasi-stationary points in time.

Figure 6.6: Sketch of process of undermining with poorly erodible top layer leading to an increased width in downstream direction.

The second hypothesis is that the widening in downstream direction can also be addressed to the effect of the shape of the scour hole. Bom (2017) did research on the shear stress in a scour hole as a result of three-dimensional flow patterns. Figure 6.7 presents the results of the amount of shear stress in the scour hole with Geometry 1. It is observed that the largest shear stress gradients follow a 1:8 line in downstream direction which corresponds with the widening in the experiment by Koopmans (2017). Besides the suggested theory on widening in downstream direction as a result of undermining, this effect of the shear stress might contribute to the widening in downstream direction.

Figure 6.7: Results of investigation of shear stress in a scour hole. Bom (2017) mimicked geometry 1 with equal conditions as used in the experiments. The largest shear stress gradient followed a line with a 1:8 angle indicated by the yellow circles.

6.2. Model versus prototype

6.2.1. Scale

The experiments are executed at a small scale compared to the prototype situation, which leads to scale effects in the experimental results. Ideally, the Froude number should be scaled properly. On such small scale, however, the flow velocity must be increased to keep the mobility parameter correct. As a result of a correct mobility parameter, the flow velocity is too high for Froude similarity. Therefore, the timescale for scour development at model scale is too small, compared to the prototype scale. The derived proportionality applied on a prototype situation leads to significant underestimation of the timescale of development. Breusers (1966) used an empirical constant to overcome this difference between the timescale from the model scale and the prototype timescale. The relevance of the scale effect can only be derived when all parameters of influence are investigated, since for example the bed roughness and particle size are of importance for scour hole development and therefore influence the time scale.

In each experiment, dunes developed in the initial stage of the scour hole. These dunes are large compared to the size of the scour hole. In the prototype situation, dunes develop as well, but are smaller relative to the size of the scour holes. This could imply that the initial stage in the experiment shows a different development
6. Discussion

compared to the prototype.

6.2.2. Tide
Most scour holes in the Rhine-Meuse delta are affected by tide. Contrary to the experimental conditions, this leads to varying flow directions over time. In the experiments a stable upstream slope and undermining of the downstream edge were observed. Suggesting that extension of the scour hole is most likely to happen in downstream direction. With alternating flow directions, the slopes will experience alternating forces and will try to stabilize and undermine each tidal cycle.

Van Zuylen (2015) performed simplified experiments on the effect of tide, in which it was concluded that the scour hole characteristics change direction. The downstream slope becomes the upstream slope and tends to become stable. And the new downstream slope becomes unstable.

6.2.3. Heterogeneous subsoil
In a prototype situation the top layer can fail, so the undermining as observed in the experiments will not appear. In reality, a top layer will fail at already small undermining. Additionally, very large angles are not observed in bed measurements, which would be expected when undermining is present. At the prototype situation the layer thickness may vary significantly over space, which can create different undermining patterns and therefore different scour hole evolution patterns. A thick poorly erodible top layer will probably not lead significant undermining. These large variance in heterogeneous subsoil may lead to several different types of scour hole development.

The composition of the subsoil is in the prototype situation not as simple as used in the experiments. However, in this way, it was possible to systematically investigate the influence of such a top layer. In the field, there is large variance between each scour hole, creating large differences in scour hole development. As a result of different compositions in the field, the evolution pattern of the scour hole in the field can be significantly different compared to the logarithmic profile found in the experiments.

6.2.4. Applicability in the field
The scour depth is normalized with the fitted equilibrium scour depth for each experiment. In this manner, it was possible to find a proper relation between each varied parameter and the time development. Eventually, the aim is to find a predictive formula for scour development in heterogeneous subsoil. Therefore, it is not useful that the equilibrium depth is needed for the comparison of scour hole development, since this value is hard to obtain when the scour hole is still developing. It is even one of the most important things in scour hole development to predict. A normalization of scour depth with the water depth or the width of the geometry would make it easier to predict scour hole development. It is suggested that a predictive formula based on the geometry (shape and size of scour hole) might be successful, since the geometry shows very large influence on the scour depth development.

Investigation of the effect of the bed roughness, grain size and geometry size on scour hole development will give a complete view of all important dependencies. When all influential parameters are known, a predictive formula for time development can be obtained. Additionally, if the effect of bed roughness is known an exact comparison with experiments by Van Zuylen (2015) can be obtained.

The amount of poorly erodible layers present in the subsoil determines the scour hole development. If thick layers of for example clay are present at the up- and downstream side of a scour hole, the scour hole might be limited in growth as a result of these thick layers. Knowledge of these soil layers is a prerequisite for the prediction of scour hole development in reality. Additionally it is important to have information on the timescale of undermining and subsequently the time scale of failing of the top layer.
6.3. Research questions

The research objective was to obtain knowledge on scour hole development in heterogeneous subsoil with a three-dimensional character. In general, differences between scour hole development in heterogeneous subsoil and previous experiment close to hydraulic structures are observed. The size of the scour hole is of great importance for the development of the scour hole and undermining can be a significant factor for creating a different type of scour hole development. The maximum scour hole depth might eventually only depend on the restricted size of a scour hole. Significant differences are observed between two-dimensional and three-dimensional experiments concerning the time development, the equilibrium depth and flow patterns. The three-dimensional scour holes in this research had larger scour depths, faster time development and three-dimensional flow structures who can possibly explain the difference in scour hole development.

It seems that the geometry of the possible scour hole is important for the growth of the scour hole. Therefore, it is important to know more about the subsoil around a scour hole. Below, each research question is elaborated on separately.

Research question 1: What is the influence of a poorly erodible top layer on development of the scour hole?

The mimicked poorly erodible top layer created significant differences compared to previous experiments. Breusers (1966) observed scour holes going to an equilibrium. This equilibrium depth were reached since the shear stress decreased to such a degree that no sediment transport took place anymore. As a result of the non-erodible top layer this type of equilibrium is not reached in this research.

Nevertheless, each experiment has a maximum depth. This maximum depth is not based on the critical velocity, determined by the minimum shear stress needed to transport grains. As a result of the fixed edges of the scour hole, undermining occurs and eventually creates a situation in which it is impossible for sediment to exit the scour hole. From that point on, only redistribution of sediment in the scour hole has influence on the maximum depth. This critical depth depends heavily on the geometry.

Undermining occurred at each experiment below the downstream rigid edges of the scour hole. When undermining occurred, a circulating flow pattern was present in the horizontal plane. Flow deflects at the undermined parts to both lateral directions. As a result of this deflection of flow the downstream undermined parts become wider than the width of the scour hole. In reality, the downstream edge would have the possibility to fail. As a result of undermining the edge would fail and the scour hole would expand. However, the thickness of the poorly-erodible layer is determining the expansion.

The upstream slope remained constant over time in each experiment. Between experiments, insignificant differences between the angle of the slopes were present. The upstream slope was significantly higher compared to two-dimensional experiments conducted by Van Zuylen (2015), which used a larger bed roughness for the experiments. The upstream slopes were in both experimental campaigns in accordance with the existing empirical formula for the upstream slope. In a case with unidirectional flow a scour hole can develop in downstream direction and will remain stable in upstream direction. In tidal areas, the flow direction reverses which will change this development.

Research question 2: Is it possible to describe this scour holes with existing empirical formulas for scour hole development?

With the Breusers formula for development it was possible to approach the experimental data for a first estimation with the use of fitting with the power ($\gamma$) in the equation. It is observed that the value varies significantly for different experiments. Using both the power $\gamma$ and the characteristic time scale $t_1$ as fitting constants showed improved results. However, good approximations on the development in later stage are lacking. Based on the hypothesis that the dominant processes causing erosion may change in time a new fit was carried out, which was based on two exponential functions. The transition point, turned out to correspond with the moment when dunes disappear from the scour holes, suggesting that during the dune stage
the erosion process is different than during the following stage. As a result of the fixed geometry it is not possible to use one formula for the prediction of the scour hole development.

\[
S_1 = \tilde{S}_1 \cdot \left(1 - e^{-\frac{t}{T_1}}\right)
\]

\[
S_2 = \tilde{S}_2 \cdot \left(1 - e^{-\frac{t-t_s}{T_2}}\right) + \tilde{S}_1 \cdot \left(1 - e^{-\frac{t-t_s}{T_1}}\right)
\]

\[
S(t) = \begin{cases} 
S_1 & \text{if } t < t_s \\
S_2 & \text{if } t > t_s 
\end{cases}
\]

\(S_1 = \) scour first part \([m]\)  
\(S_2 = \) scour second part \([m]\)  
\(\tilde{S}_1 = \) intermediate equilibrium scour depth \([m]\)  
\(\tilde{S}_2 = \) equilibrium scour depth second part \([m]\)  
\(t_s = \) moment of switching between equations \([hrs]\)  
\(T_1 = \) characteristic time scale first part \([hrs]\)  
\(T_2 = \) characteristic time scale first part \([hrs]\)

**Research question 3:** Which length scale, characterizing a river, is correlating with scour hole development?

The effect of the average velocity, water depth and geometry size is investigated. All parameters show effect on the scour hole development. The average velocity has large influence on the time scale of scour development. The timescale for the development of the scour hole is proportional to:

\[
T_{\text{char}} \propto \left(\frac{u_{\text{avg}} - u_c}{u_c}\right)^{-3.35} \quad \text{for } u_{\text{avg}} > u_c
\]

The effect of water depth is in the first part of the development phase not observed, as expected since the flow velocity close to the bed was equal in the experiments on water depth. During later stages differences can occur, however, these are hardly observed. By fitting, a small dependence of water depth on scour hole development is found. This dependency of the water depth on the timescale is:

\[
T_{\text{char}} \propto \left(\frac{h}{L}\right)^{0.25}
\]

It is investigated what the effect is of the size of the geometry. It is observed that a larger scour hole (with equal aspect ratio) leads to faster development and a deeper scour hole. Van Zuylen (2015) already concluded that a larger distance between the down- and upstream leads to deeper scour holes. In this research the effect seems even stronger, which suggests that besides the length, the width is also of importance. A larger scour hole with a larger geometry size is explained by the existence of rigid edges which restrict scour development at a certain depth. If this was not the case, it is expected that a wider scour hole leads to shallower scour holes as a result of less transport capacity (a larger conveyance area leads to more reduction of flow velocity). This is not observed, because the edges are limiting scour hole development. The proportionality between the width (as an equivalent for the geometry size) and the timescale is:

\[
T_{\text{char}} \propto \left(\frac{w}{B}\right)^{0.75} \quad \text{for } w \leq B
\]

This fit is not possible to use for extrapolation, because it is deduced from only two geometries. By varying length and width independently this fit can be improved.
Research question 4: How are flow structures inside a scour hole with three-dimensional geometry contributing to the development of scour hole?

Bom (2017) numerically investigated a scour hole with equal size and conditions as in this research. It was observed in the flume that the reattachment point is present at 3.75 to 5 times the maximum scour depth from the upstream edge. According to the numerical calculations this recirculation is not large enough to create shear stresses which are sufficiently high for sediment transport. It is likely that this is the reason for a stable upstream slope.

It was expected that contraction was present as a result of the three-dimensional geometry of the scour hole. Although numerical calculations show contraction, is this not observed in the scale experiments. Divergence of flow is observed at the downstream end of the scour hole. Additionally there is an indication for the presence of a horse-shoe vortex. How this vortex contributes to the development of the scour hole is not yet known. Nevertheless, it is observed that three-dimensional scour holes develop more quickly than two-dimensional scour holes, which suggests that contraction or the three-dimensional flow have a reinforcing effect on scour hole development. As a result of undermining, bed load transport is not possible. Nevertheless, sediment was transported out of the scour hole as a result of whirls.
Conclusions and Recommendations

In this thesis, the development of scour holes in heterogeneous subsoil is investigated. The research focused on the following research question:

*How do scour holes in heterogeneous subsoil develop and how can they be predicted?*

With four subquestions:

1. What is the influence of a poorly erodible top layer on development of the scour hole?
2. Is it possible to describe scour holes in heterogeneous subsoil with existing empirical formulas for scour hole development?
3. Which parameter, characterizing scour development in a river, is correlating with scour hole development in heterogeneous subsoil?
4. How are flow structures inside a scour hole with three-dimensional geometry contributing to the scour hole development?

Section 7.1 focusses on answering these questions based on the results and findings of this research. Section 7.2 presents recommendations for the practical application and for further research.

### 7.1. Conclusions

**Research question 1**: *What is the influence of a poorly erodible top layer on development of the scour hole?*

- Three stages of development are observed: initiation, development and undermining. While at scour holes behind a hydraulic structure (Breusers, 1966) four stages are observed: initiation, development, stabilization, equilibrium.
- Due to presence of a non-erodible top layer, undermining occurs instead of stabilization and reaching the equilibrium. After substantial undermining, deflection of flow under the non-erodible top layer occurs, leading to horizontal flow patterns creating re-feeding of the deepest parts of the scour hole.
- A maximum depth is reached as result of the fixed geometry of the scour hole.
- The upstream slope remained relatively constant over time and over different experiments.
- In a prototype situation, a poorly-erodible layer will probably fail and a scour will subsequently growth depending on the thickness of this layer.
Research question 2: Is it possible to describe scour holes in heterogeneous subsoil with existing empirical formulas for scour hole development?

- The formula for time development and equilibrium depth derived by Breusers (1966) shows differences in time development and underestimates the equilibrium depth.
- The variance between different experimental configurations is significantly smaller than expected with the predictive formula for equilibrium depth.
- As a result of different dominant processes driving the erosion, two exponential fits had to be used to obtain a proper fit.
- The resulting transition point in time corresponds to the disappearance of dunes from the scour hole.

Research question 3: Which parameter, characterizing scour development in a river, is correlating with scour hole development?

- The velocity has large influence on the time scale of scour hole development. The equilibrium depth shows relatively small dependence.

\[ T_{\text{char}} \propto \left( \frac{u_{\text{avg}} - u_c}{u_c} \right)^{-3.35} \text{ for } u_{\text{avg}} > u_c \]  \hspace{1cm} (7.1)

- The effect of water depth is not observed in first parts of the development phase.
- In later stages of the experiments, differences occur and with the use of fitting a small dependency of water depth on the time development is found.

\[ T_{\text{char}} \propto \left( \frac{h}{L} \right)^{0.25} \]  \hspace{1cm} (7.2)

- The found proportionality with the timescale of development is significantly smaller compared with the proportionality found by Breusers (1966).
- A larger geometry leads to deeper scour holes and faster development in absolute sense.

\[ T_{\text{char}} \propto \left( \frac{w}{B} \right)^{0.75} \]  \hspace{1cm} (7.3)

- The equilibrium depth relative to the size of the geometry is approximately constant.

Research question 4: How are flow structures inside a scour hole with three-dimensional geometry contributing to the scour hole development?

An overview of typical flow patterns in the scour hole during the experiments is presented in Figure 7.1 created during the experiments.
Below, the observed flow patterns in and around the scour hole are discussed. All coherent flow structures are based on average flow measurements and dye visualizations. In the scour hole, flow was alternating constantly:

- Contraction of flow in the scour holes is expected. With use of dye, flow around the scour hole is visualized. Convergent flow is practically not observed, however, divergence at the downstream side of the scour hole is observed. According to numerical simulations of the same scour hole (Bom, 2017), both contraction and divergence happen, though subtle.

- With use of flow visualization and velocity measurements the recirculation is displayed. It was observed that the reattachment point is present at 3.75 to 5 times of the maximum scour depth.

- As a result of the three-dimensional character of the scour hole, a horse-shoe vortex develops, indicated by flow visualization.

- When undermining occurred, whirls close to the edge were present which created the possibility for sediment to exit the scour hole.

- In a prototype situation the general flow pattern can be equal, nevertheless, changes in geometry can lead to extra three-dimensional flow patterns.
7.2. Recommendations

- Results show that the scour hole growth and depth are reduced by the scour hole size. Early intervention in order to keep the scour hole as small as possible is therefore recommended.

- The effect of the geometry on scour hole development needs further research. The width and length should be varied independently to obtain information for a predictive formula based on the geometry.

- To predict scour hole development in the field, flume experiments are required to investigate the influence of bed roughness and the grain size on scour hole development.

- The influence of the width of the scour hole needs more research. In this experiment a relation was found with use of two different widths. A larger variety of scour hole widths should give better information for predicting the influence of the width.

- Scale experiments are recommended with a poorly erodible top layer which can bend and fail to improve knowledge of the influence of this layer.

- The effect of tide is not investigated in this research, however, very important for a prototype situation. Therefore, experiments on the effect of tide are recommended.

- As the subsoil will largely determine the growth of the scour hole, it is recommended to carry out detailed mapping of the surrounding subsoil lithology.

- Flow patterns in a scour hole give insight about the locations of largest forces. Therefore, detailed information about flow patterns in scour holes in the field are recommended.

- Experiments on the effect of the shape of the upstream rigid edge are recommended. The upstream edge is important for the creation of three-dimensional flow. In this research the upstream edge had an equal shape with different geometries.
Bibliography


A

Literature

This Appendix presents information of flow processes in a river. The influence of accelerating and decelerating flow on the generation of turbulence is discussed. Additionally, the effect of roughness on the velocity profile and the friction is discussed. Appendix A.2 elaborates on sediment transport. Information is given about types of sediment transport and the conditions for sediment transport for both cohesive and non-cohesive sediment types. Furthermore, the effect of slopes on stability of soil is discussed, followed by information on three-dimensional scour and experiments on scour holes. Finally, information is presented on scour holes in tidal conditions and the effect of tide on scour hole development.

A.1. Flow properties

A.1.1. Type of flow

Uniform flow

A situation with constant speed and no changes in depth is called uniform flow. This implies a balance between the shear stresses acting on the flow and the pressure component of the flow. Figure A.1 shows the forces in uniform flow together with the fluctuations in the flow and the amount of turbulence.

Normally, river flow is fully developed which indicates that the boundary layer has grown over the entire water depth, resulting in a logarithmic velocity profile, which is elaborated on in Section A.1.3. A boundary layer is the part of a water column which is influenced by viscous shear stress created by the bed. In Figure A.2 an example is given on growth of a boundary layer as a result of the presence of a plate. Growth is present due to exchange of momentum. Which is caused by shear stress along the plate which decelerating the local flow (Schiereck, 2012).

![Uniform flow](image)

The change in boundary layer height can be described by (Schiereck, 2012):

\[
\frac{d\delta}{dx} = -\frac{(4 \text{ to } 5)\delta u_0}{u_0} \frac{du_0}{dx} \tag{A.1}
\]
\( \delta = \) width of mixing layer \([-]\)  
\( u_0 = \) velocity of main flow \([m/s]\)  
\( x = \) length of mixing layer \([m]\)

This equation demonstrates that within uniform flow, the boundary layer remains constant.

**Figure A.2:** Growth of boundary layer as a result of the presence of a plate (Schiereck, 2012).

**Nonuniform flow**

In reality, flow is rarely uniform as a result of bed geometry changes and width constrictions. As described above, the boundary layer is present over the entire water column in stationary, uniform flow. Nonuniform flow indicates acceleration and deceleration in flow. These changes in velocity lead to alterations in boundary layer development. Deceleration leads to an increase of the boundary layer and acceleration dampens the boundary layer. Figure A.3 shows the change in velocity profiles due to deceleration and acceleration leading to changes in the amount of shear stress. Additionally, decelerating flow creates more turbulence, where accelerating flow suppresses turbulence (Schiereck, 2012).

**Figure A.3:** Influence of velocity gradient in longitudinal direction on velocity profile in which acceleration leads to suppression of turbulence and deceleration creates a surplus of turbulence (Schiereck, 2012).

**A.1.2. Turbulence**

Turbulence is described by random patterns and unpredictable motion on various time and spatial scales. Turbulence is created when kinetic energy, driving the motion of the fluid, is high and capable to overpower viscous forces which decelerate fluid (Bailly and Comte-Bellot, 2015) (Uijttewaal, 2003). Turbulence exists as a result of velocity gradients, which produce circumstances for transfer of energy. Two types of turbulence can be distinguished depending on the origin of a velocity gradient. Close to the wall a no-slip condition produces a large velocity gradient, which leads to wall turbulence. Free turbulence exists where adjoining flows have different velocities, creating a gradient on the interface between both flows. Mass and momentum transfer occurs in these, so called, mixing layers (Uijttewaal, 2003).

The existence of turbulence leads to energy loss. Energy is shifted from mean motion to smaller turbulent motion. From the really small scales, at the so-called Kolmorogov length scales, turbulent energy is dissipated and converted into heat.

**Description of turbulence**

Due to the irregular character of turbulent motion, it is essential to use statistical quantities to describe turbulence. A velocity signal is generally decomposed into a mean velocity \( \langle u \rangle \) and a fluctuating part \( u' \). The fluctuating part is represented by the variance which is a measure of kinetic energy (Uijttewaal, 2003):

\[
\sigma^2 = \mu = (u' - \langle u \rangle)^2
\]
A.1. Flow properties

\[ \sigma = \text{standard deviation} \]
\[ \mu = \text{variance} \]
\[ u' = \text{fluctuating part of velocity [m/s]} \]
\[ \bar{u} = \text{mean velocity [m/s]} \]

Together, the fluctuations in all directions represent the total turbulent kinetic energy per unit mass. This is described by Equation A.3:

\[ k = \frac{1}{2} (u_{1}'^2 + u_{2}'^2 + u_{3}'^2) \]  
\[(A.3)\]

\[ k = \text{turbulent kinetic energy [m}^2/\text{s}^2]\]

A.1.3. Velocity profile

Assuming stationary flow, the mean vertical velocity and the gradient of the longitudinal velocity are zero, so a constant shear stress is acting on the flow. A shear stress can be described as a shear velocity \( u_\ast \). With the help of this shear velocity a logarithmic velocity profile can be achieved. At the bottom the velocity is zero, so a constant \( y_0 \) is needed to achieve realistic results at the bottom. This value depends on roughness of the bed, where differences are present between smooth and rough beds.

\[ \frac{u(z)}{u_\ast} = \frac{1}{k} \ln \left( \frac{z}{y_0} \right) \]  
\[(A.4)\]

\[ k_j^+ = k_s \frac{|u_\ast|}{v} < 5 \rightarrow y_0 = 0.11 \frac{v}{|u_\ast|} \text{ smooth} \]
\[ 5 < k_j^+ < 70 \rightarrow y_0 = 0.11 \frac{v}{|u_\ast|} + \frac{k_s}{30} \text{ intermediate} \]
\[ k_j^+ > 70 \rightarrow y_0 = \frac{k_s}{30} \text{ rough} \]  
\[(A.5)\]

From this equations it is observed that equal average velocity and different water depths lead to contrasting velocity profiles.

\[ u = C \sqrt{R_i b} \]  
\[(A.6)\]

\[ u = \text{mean velocity [m/s]} \]
\[ C = \text{Chezy roughness [m/s}^{1/2}\text{]} \]
\[ R = \text{hydraulic radius (R = A/P) [m]} \]
\[ i_b = \text{bed slope [-]} \]
A.1.5. Relation between pressure and velocity

Bernoulli’s theorem describes the interchange between kinetic and potential energy. Equation A.7 shows that without loss and addition of energy the kinetic energy, potential energy and the gravitational potential gravity together correspond with the total energy. In Figure A.5 a constriction is present in which velocity increase, so kinetic energy increases which must come from static energy since the total energy remains equal [50].

\[ H = z + \frac{p}{\rho g} + \frac{u^2}{2g} = h + \frac{u'^2}{2g} = \text{constant along a streamline} \]  

(A.7)

\( H \) = energy head [m]

\( p \) = pressure [Pa]

![Figure A.5: Flow in pipe demonstrating Bernoulli's theorem][50]

A.1.6. Description of turbulence

Covariance, which is the mean product of two fluctuating velocity components, equals momentum transport, and could be interpreted as the turbulent shear stress [51]. Turbulence often consists of moderate structured motions leading to a significant covariance. When both fluctuating components are completely random, the covariance will be zero.

\[ \overline{v'_1 v'_2} = \lim_{N \to \infty} \frac{1}{N} \sum_{n=1}^{N} v'^{(n)}_1 v'^{(n)}_2 \]  

(A.8)

Autocorrelation is a specific case where a certain signal is compared with itself. The autocorrelation function shows how a time series correlates with itself when moved over a certain time interval.

A.1.7. Potential vorticity conservation

As a result of the presence of the scour hole, flow might be attracted to the scour hole which leads to contraction of flow and divergence at the downstream side of a scour hole. Convergence and divergence of streamlines can be explained by the principle of potential vorticity conservation. Figure A.6 illustrates the effect of potential vorticity conservation. In short, when depth increases the amount of vorticity remains equal which leads to reduction of the diameter of the vortex leading to convergence. The opposite occurs when depth decreases again. This only applies when there are gradients in the flow velocity in both the lateral and longitudinal direction (Pietrzak, 2016).
A.2. Sediment transport

A.2.1. Shields

Sediment transport is present as a result of interaction between water and sediment. Sediments can be categorized in cohesive (e.g. clay) and non-cohesive sediments (e.g. sand). Shields (1936) described the initial bed grain instability for non-cohesive sediments using the following parameters: fluid density, sediment density, kinematic viscosity, grain size and bed shear-stress. Movement of sediment depends on the ratio between force on grains and resistance of the grains. Instability, followed by movement of grains, occurs when the bed shear-stress is larger than the instantaneous critical shear-stress. Because of the nonuniform distribution of grains, a broad range was drawn for the initiation of motion, as can be seen in Figure A.7 (Schiereck, 2012) (Shields, 1936).

Transport of sediment can be divided in bed load transport and suspended load transport. Bed load is usually defined as the sliding and rolling of particles close to the bed. When particles are transported higher in the water column, it is called suspended load. A particle might come into suspension when the upward turbulent forces are equal or higher than the submerged particle weight. In reality it is hard to differentiate between both categories. Additionally, a portion of suspended load can be wash load, which remains higher in the water column. The volume of wash load depends on the supply from upstream and is rarely found on the bed.

The force on grains is determined by fluid properties and flow characteristics and the resistance is created by sediment properties. In Figure A.9 quasi-steady forces are presented which act on a single grain. Active forces
on the grain are lift and drag. Passive forces acting against the lift and drag are gravitational forces and forces due to the surrounding grains.

Figure A.9: Forces acting on grain in flow (Schiereck, 2012).

\[
\begin{align*}
\text{Drag force: } F_D &= C_D \rho_w u_g^2 A_D \\
\text{Shear force: } F_S &= C_F \rho_w u_g^2 A_S \\
\text{Lift force: } F_L &= C_L \rho_w u_g^2 A_L
\end{align*}
\] (A.9)

\[
F \propto \rho_w u_g^2 d^2
\] (A.9)

\[
C_{D,F,L} = \text{coefficient [-]}
\]
\[
\rho_s = \text{density of water [kg/m}^3]\]
\[
u_g = \text{local velocity [m/s]}
\]
\[
A_{D,S,L} = \text{surface [m}^2]\]
\[
d = \text{particle diameter [m]}
\]

Although, for small grains often shear stress (Shields) is used to determine sediment transport, Figure A.9 gives insight into the important parameters for transport of sediment. Equation A.9 shows proportionality to the square of velocity for each force and proportionality to the square of the size of a grain. One proportionality remains when an equilibrium is found (Schiereck, 2012):

\[
\rho_w u_g^2 d^2 \propto (\rho_s - \rho_w) g d^3
\] (A.10)

The critical bed shear-stress is defined as:

\[
\tau_c = \rho u^2_{*,c}
\] (A.11)

The critical mobility parameter, defined as the maximum force for which grains still move, is (Shields, 1936):

\[
\Psi_c = \frac{u^2_{*,c}}{\Delta g d}
\] (A.12)

\[
d = \text{particle diameter (d = d}_{50} \text{ is median grain size) [m]}
\]
\[
g = \text{gravitational acceleration [g = 9.81 m/s}^2]\]
\[
u_{*,c} = \text{critical bed shear-velocity [m/s]}
\]
\[
\Delta = \text{relative density [-]}
\]
\[
\rho = \text{fluid density [kg/m}^3]\]
\[
\Psi_c = \text{critical mobility parameter [-]}
\]

For uniform flow the critical mean velocity is:

\[
U_c = \frac{u^2_{*,c} C}{\sqrt{g}} \text{ with } C = \frac{\sqrt{g}}{\kappa} \ln\left(\frac{12R}{k_s}\right)
\] (A.13)
A.2. Sediment transport

\( U_c \) = critical velocity \([m/s]\)
\( C \) = Chezy value \([m^{1/2}/s]\)
\( k_s \) = equivalent roughness of Nikuradse \([m]\)
\( R \) = hydraulic radius \([m]\)
\( \kappa = 0.4 \), constant of Von Kármán

van Rijn (1984) presented empirical relations for \( \Psi_c \). The critical Shields parameter is related to the sedimentological diameter \( D^*_s \), as presented below:

\[ D^*_s = d \left( \frac{\Delta g}{\nu^2} \right)^{1/3} \quad \text{with} \quad \nu = \frac{40 \times 10^{-6}}{20 + \theta} \] (A.14)

\( \nu \) = kinematic viscosity \([m^2/s]\)
\( \theta \) = temperature \(^{\circ}\)C

In Table A.1 the empirical relations for the Shields parameters according to van Rijn (1984) are given. By using Equations A.12 and A.14, the mobility parameter can be determined in Figure A.7.

<table>
<thead>
<tr>
<th>( \Psi_c ) as function of ( D^*_s )</th>
<th>( \Psi_c )</th>
<th>for</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0.24 D^*_s^{-1} )</td>
<td>( \leq 4 )</td>
<td></td>
</tr>
<tr>
<td>( 0.14 D^*_s^{-0.64} )</td>
<td>( 4 &lt; D^*_s \leq 10 )</td>
<td></td>
</tr>
<tr>
<td>( 0.04 D^*_s^{-0.10} )</td>
<td>( 10 &lt; D^*_s \leq 20 )</td>
<td></td>
</tr>
<tr>
<td>( 0.013 D^*_s^{0.29} )</td>
<td>( 20 &lt; D^*_s \leq 1150 )</td>
<td></td>
</tr>
<tr>
<td>( 0.055 )</td>
<td>( D^*_s &gt; 150 )</td>
<td></td>
</tr>
</tbody>
</table>

Compared to non-cohesive sediments, cohesive sediments need larger forces to be transported. More information on the transport of cohesive sediments is presented in Appendix A.2.6.

A.2.2. Transport formulas

Meyer-Peter Muller derived a formula for the calculation of bed load transport on a flat bed. The formula is presented in Equation A.15.

\[ \Phi = 8 (\Psi - \Psi_c)^{3/2} \] (A.15)

The Engelund-Hansen formula for the total sediment transport is given in Equation A.16.

\[ \Phi = \frac{0.05 c_f}{\mu^{5/2}} \quad \text{with} \quad s = m u^n = \frac{k}{D_{50}} u^n \quad \text{with} \quad k = \frac{0.05 c_f^{3/2}}{(\Delta g)^{1/2}} \quad \text{and} \quad n = 5 \] (A.16)

A.2.3. Angle of repose

The angle of repose is the largest angle possible for a granular material to be stacked up before it fails through avalanching. The angle of rest is characterized by the angle of a slope after avalanching has occurred and is smaller than the angle of repose (Carrigy, 1970). Different angles of repose are present in dry, wet or submerged conditions. For sand, the angle of rest is equal in both submerged and emerged conditions and the angle of repose is smaller in submerged conditions (Carrigy, 1970). When sand is wet but not submerged, cohesive forces increase and the angle of repose can increase. Several experiments on the angle of repose of sand are conducted in both wet and submerged conditions, however, outcomes vary significantly. Figure A.10 shows results of experiments on the angle of repose with different ratios of wetness in sand with a diameter around \( d_{50} = 140 \) [\( \mu m \)]. Increasing wetness creates lower angles of repose.

In submerged conditions grains interact with a thin water layer in between. Therefore, the inter-grain friction will be lower in water compared to air. Hydrodynamic lubrication could become relevant, creating a decrease
A. Literature

Figure A.10: Angle of repose in different sand wetness ratios (Webster, 1919).

in angle of repose.

A.2.4. Soil failure
In the Rhine-Meuse delta two main factors for shear failure and flow slides are present. If sand is loosely packed (porosity larger than 40 %), small changes in the composition are able to trigger large flow slides. If loosely packed sand is forced by shear, particles tend towards a denser packing. Since pores are filled with water, overpressure within the pores might occur (see Figure A.11), which leads to less effective shear stress and thereby diminishes the frictional resistance. If the overpressure becomes too high, contact between particles is lost and frictional resistance becomes null. If this occurs close to steep slopes, sand flows away and higher parts of the slope lose support (Hoffmans and Pilarczyk, 1995). If failure occurs in a heterogeneous subsoil with a poorly erodible top layer, undermining might occur due to sliding of sand packages below followed by failure of the top layer.

Figure A.11: Effect of shear on loose and dense sand (Hoffmans and Verheij, 1997).

A.2.5. Scour
Scour is a special case of sediment transport in which local erosion is larger than supply from upstream. It occurs when the local transport of sediment is larger than the amount of sediment which is transported from upstream. This variation can be caused by differences in velocity and/or turbulence and differences in sediment availability. The Exner principle, as shown in Equation A.17, is the general expression for bed changes and is based on conservation of sediment mass. Scour can occur at for example a constriction of flow where differences in velocity magnitudes and flow patterns can lead to scour holes. Scour holes can also be created when the availability of sediment is varying over the location. If a non-erodible layer is alternated with an erodible layer of sand erosion is present without supply from upstream, creating a scour hole.

<table>
<thead>
<tr>
<th>SAND</th>
<th>WATER</th>
<th>ANGLE OF REPOSE</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>pounds</td>
<td>pounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>33°</td>
<td>Dry</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>65°</td>
<td>Not hard</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>120°</td>
<td>Not accurate, but large obtuse angle, hard</td>
</tr>
<tr>
<td>10</td>
<td>1.5</td>
<td>120°–140°</td>
<td>Not accurate, but large obtuse angle, hard</td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
<td>120°–140°</td>
<td>Not accurate, but large obtuse angle, hard</td>
</tr>
<tr>
<td>10</td>
<td>2.5</td>
<td>120°</td>
<td>Not accurate, but large obtuse angle, hard</td>
</tr>
<tr>
<td>10</td>
<td>3.0</td>
<td>48°</td>
<td>Fairly hard</td>
</tr>
<tr>
<td>10</td>
<td>3.5</td>
<td>19°</td>
<td>All mixes</td>
</tr>
<tr>
<td>10</td>
<td>3.75</td>
<td>14.5°</td>
<td>Very slight excess of water</td>
</tr>
<tr>
<td>10</td>
<td>4.0</td>
<td>13°</td>
<td>Water not all absorbed</td>
</tr>
<tr>
<td>10</td>
<td>5.0</td>
<td>12°</td>
<td>Excess of water</td>
</tr>
</tbody>
</table>
A.2. Sediment transport

\[ \frac{\delta z_b}{\delta t} + \frac{\delta S}{\delta x} = 0 \]  

(A.17)

\[
\begin{align*}
  z_b &= \text{position of the bed [m]} \\
  S &= \text{total sediment transport per unit width [m}^2/\text{s}] 
\end{align*}
\]

Figure A.12: General picture of local erosion in which (a) does not lead to scour since the supply from upstream is equal to the amount which is eroded. Part (c) shows a local scour hole in which the erosion capacity is larger than the supply of sediment form upstream (Hoffmans and Verheij, 1997).

Two types of scour are described by Hoffmans and Verheij (1997). Figure A.12 shows the creation of a local scour hole. Clear-water scour exists when no sediment is present upstream \((S_2 > S_1 = 0)\), for example when there is lack of upstream sediment transport or when the upstream bed is rigid. When clear-water scour is present the depth of scour approaches a limit asymptotically. Live-bed scour will be present when sediment is transported over the upstream bed \((S_2 > S_1 > 0)\). In these conditions, the equilibrium scour depth is more shallow than in clear-water scour conditions. As presented in Figure A.13, live-bed scour generally increases fast and fluctuates around a mean value, depending on the bed features (Hoffmans and Verheij, 1997) (Schiereck, 2012).

Figure A.13: Scour depth as function of time (Hoffmans and Verheij, 1997).

A.2.6. Transport of cohesive sediments

Physio-chemical properties of cohesive sediments are important for the resistance of cohesive sediments against flow. Properties depend heavily on granulometric, mineralogical and chemical characteristics of the cohesive soil. Direct relations between physio-chemical properties and erosion of cohesive sediments have not been established yet [27].

Large forces are needed to break cohesive bodies and small forces are needed to transport the sediment. Experiments by Mirtskhoulava (1988, 1991) showed that clay scour in water occurs in different stages. Within the initial stage parts with weak bonds are washed away and parts are detached. Hereby a more rough bed is developed. Larger forces on the surface lead to vibrations and dynamic action. In the end, bonds are destroyed and instantaneously ripped from the bottom and washed away. Based on the experiments an expression for the critical depth-averaged velocity for cohesive sediments has been derived [36]:

\[
U_c = \log\left(\frac{0.8h}{d_a}\right) \sqrt{\frac{0.4}{\rho} \left(\rho_s - \rho\right) g d_a + 0.6C_f} 
\]

(A.18)
\[ U_c = \text{critical mean velocity for cohesive sediments} \ [m/s] \]
\[ d_a = \text{size of detaching aggregates} \ [d_a = 0.004 \ m] \]
\[ h = \text{flow depth} \ [m] \]
\[ \rho = \text{fluid density} \ [kg/m}^3] \]
\[ \rho_s = \text{material density} \ [kg/m}^3] \]

**A.2.7. Bedforms**

As observed in some experiments of Koopmans (2017), bedforms are generated at some stages within the experiment. Those forms induce additional drag on the flow [57]. When shear stress on a flow is excessive, grains will start to move. The bed will evolve into diverse forms. The most relevant forms are ripples, dunes and antidunes. Ripples are sand bodies organized perpendicular to flow with a milder upstream slope than the downstream slope. Dunes are similar, but much steeper on the downstream side compared to the upstream side. Antidunes are more symmetrical and lower and effect the water surface severely [2].

The appearance, shape and size of a bedform depends on depth, velocity intensity and properties of sediment [31]. This influence is reciprocal, since bed forms might affect the flow characteristics [45]. Due to unavoidable irregularities on the bed, small disturbances in velocities are present, which leads to a sequence of scour and deposition. In the longitudinal trajectory, forms are triangular with a steep slope on the downward side and a more gentle slope on the upstream of the bedform. The propagation downstream of those dunes or ripples is much slower compared to flow velocity [44].

Raudviki 1997 concludes that ripples exists due to turbulence bursts on a flat bed forming two-dimensional bed forms expanding over time. Subsequently, those ripples become more waving and will experience more three-dimensionality. Where ripples have no interaction with the water surface, dunes do influence the water surface. Eventually, ripples and dunes lead to more bed roughness [57]. From Figure A.14 it is concluded that ripples are present within the experiments.

![Figure A.14: Stages of bed forms according to several researchers [32]](image)

Ettema [17] shows differences between scour depth development with and without ripples, where ripple forms lead to reduced scour depths compared to non rippled cases. For ripple forms it is not possible to maintain clear-water conditions, creating little sediment transport, eventually leading to reduced equilibrium scour depths [17].

**A.2.8. Stability on slopes**

A sloping bed will decrease or increase the strength depending on the direction of flow. When the slope angle is equal to the angle of repose of the soil, particles are already on the threshold of motion without any induced load. A very small load from the flow in downward direction will already induce motion of particles. On the opposite side, flow might stabilize particles since flow exerts forces opposite to the direction of possible motion [46].

For a side slope, same procedure can be followed. A slope in the flow direction is less favorable than a side
slope, as can be seen at the right in Figure A.15, where both reduction factors are presented. The reduction factor for strength on a slope is (case b):

\[ K(\alpha//) = \frac{F(\alpha//)}{F(0)} = \frac{W \cos \alpha \tan \phi - W \sin \alpha}{W \tan \phi} = \frac{\sin \phi \cos \alpha - \cos \phi \sin \alpha}{\sin \phi} = \frac{\sin (\phi - \alpha)}{\sin \phi} \] (A.19)

\[ K(\alpha//) \quad \text{reduction factor for slope in flow direction} \quad [-]\]
\[ \alpha// \quad \text{slope angle} \quad [\degree]\]
\[ \alpha \quad \text{angle of side slope} \quad [\degree]\]
\[ \phi \quad \text{for non-cohesive material} \quad [\degree]\]
\[ F(\alpha//) \quad \text{Strength on sloped bed}\]
\[ F(0) \quad \text{Strength on horizontal bed}\]

Where for a side slope with angle \( \alpha \), the reduction factor becomes (case c):

\[ K(\alpha) = \frac{F(\alpha)}{F(0)} = \sqrt{\frac{\cos^2 \alpha \tan^2 \phi - \sin^2 \alpha}{\tan^2 \phi}} = \cos \alpha \sqrt{1 - \frac{\tan^2 \alpha}{\tan^2 \phi}} = \sqrt{1 - \frac{\sin^2 \alpha}{\sin^2 \phi}} \] (A.20)

The upstream slope is an interesting part of the scour hole. Previous researches show similarity in the upstream slope during the entire development of the scour hole (Breusers, 1966) (Koopmans, 2017) (Van Zuylen, 2015). This suggests a certain balance of forces on the slope which remains equal over development.

The balance between forces on grains on a slope is based on the acting forces on the grains according to Section A.2. As Section A.2 states, are drag, lift and shear forcing correlation with the velocity and grain diameter in uniform flow. In a recirculation zone in a scour hole, average velocities are low and turbulence intensities are relatively high compared to normal flow. Turbulence attributes to the lift force on a grain. The friction force depends on the angle of repose and the normal force on the slope. By deriving the balance between the forces normal and parallel to the slope a proportionality is found between grain diameter, the amount of turbulence and velocity, with the angle of slope in parallel direction as showed in Equation A.21.

\[ \Sigma F_\perp = 0 \rightarrow F_S + F_D = F_F + W \sin \alpha \]
\[ \Sigma F_\parallel = 0 \rightarrow F_L = W \cos \alpha \]

\[ \alpha \propto f(d, u', u) \] (A.21)

\[ F_\perp \quad \text{force in normal direction} \quad [N]\]
\[ F_\parallel \quad \text{force in parallel direction} \quad [N]\]
\[ F_S \quad \text{shear force} \quad [N]\]
\[ F_D \quad \text{drag force} \quad [N]\]
\[ F_F \quad \text{friction force} \quad [N]\]
\[ F_L \quad \text{lift force} \quad [N]\]
\[ W \quad \text{weight of particle} \quad [N]\]
\[ \alpha_s \quad \text{angle of slope} \quad [\degree]\]
A.2.9. Three-dimensional cases

Van [53] performed a systematic investigation on three-dimensional local scour. Within flumes with different geometries, local scour due to constructions of dams was investigated. Three-dimensionality of flow was induced by a small flow constriction as can be seen in Figure A.17.

Due to the influence of vortices, the deepest point within the scour hole shifts both in lateral and longitudinal direction. The power-law ($\gamma$) is depending on the geometry. Additionally, the influence of different characteristics scales was researched. Results show that the influence of velocity scale, length scale, material scale and geometric situation can be described with the same relationships both for two- and three-dimensional scour holes.

It must be noted that in this case vortices are created by geometry upstream of the researched scour hole leading to three-dimensional flow patterns. Within this experiment there are no three-dimensional geometrical boundaries on the scour hole. The presence of these boundaries might show different scour development.

A.2.10. Coherent structures

Relevance of turbulence on erosion is researched several times. In most of the earlier studies on the entrainment threshold of sediment, the flow velocity and the induced bed shear-stress were described by time-averaged values. In this way, the development of an entrainment threshold criterion based on parameters which are easy to obtain is simpler. Investigations on the influence of turbulence on grains showed that sediment motion associated with near-bed turbulence fields produce a fluctuating character of hydrodynamic forces on sediment particles [14], which shows already relevance of turbulence in scour processes.

A.2.11. Flow processes in scour hole

Downflow

It is possible to have a smooth slope so flow can remain attached. The Coanda effect is described as the tendency of a fluid to stick to a surface. A vortex or eddy must exist to have the effect, since it will create low pressure which causes a stream to bend and follow certain contours (see Figure A.18). Whether this phenomenon occurs or not depends on many factors. However, it depends principally on the balance between
centrifugal force and the suction force due to low pressure fields. Question is in what way this effect is present or measurable in a scour hole (in heterogeneous subsoil) where conditions are far from perfect for the creation of the Coanda effect.

Figure A.18: Sketch of Coanda effect

A.3. Tidal influence

Within tidal flow, velocities change rapidly and regularly compared to unidirectional flow conditions in river flows. Thereby, flow changes direction within a tidal area. Both phenomena lead to more complex hydrodynamics and morphodynamics compared to unidirectional river flow. Studies on the genesis and development of scour holes in tidal environments without direct causes are rarely found [18]. However, several investigations are found on the influence of tide on scour around structures (e.g. piles, bridge piers). These studies show that there are many uncertainties regarding scour in tidal flows. They even have produced conflicting results as to whether tidal scour holes are deeper or shallower than in unidirectional flow [43].

Mcgovern (2014) mainly concluded that changing flow direction and intensity will affect the final scour hole depth and its time development. Thereby the reversed flow causes the scour hole to be more symmetric, which remained permanent throughout the test. The equilibrium scour depth found in the experiment with reversing current conditions was lower than predicted by existing equations, derived from unidirectional current measurements [34].

Porter and Simons (2014) did a flume investigation on scour through a spring-neap tidal cycle around a monopile foundation. Three types of tests were executed with different flow conditions: unidirectional flow with constant depth-averaged velocity, the same depth-averaged velocity with reversed direction every half cycle and a test with varying flow velocity over a tidal cycle with the RMS equal to the velocity in the first two tests. Experiments were conducted in clear water conditions since bed ripple would cause scaling problems. Results show that the scour depth development and time scale of scour are significantly different in the spring-neap cycle compared to scour in reversing or unidirectional flow where the depth-averaged velocity is kept constant. Additionally, tidal asymmetry has strong impact on scour depth development [43].

Escarameia and May (1999) did a laboratory study on obstructions within a flow influenced by reversal of flow, tidal cycle duration, water depth, shape of structure and sediment size. Observations showed that in tidal tests the equilibrium scour depths are somewhat greater than scour depths occurring with unidirectional flow after one half tidal cycle. After several cycles more, the equilibrium depth was significantly less than the equilibrium depth produced by an equivalent unidirectional flow. Besides, when the tidal cycle was increased in duration, the equilibrium scour depth increased as well. Contrary to what has been observed in unidirectional flows, this experiments gave indications that increasing the flow velocity above the critical value causes the equilibrium scour depth to continue to increase. A plausible explanation might be that alternation of flow and thereby generation of bed forms at both sides of the scour hole create significantly different conditions compared to unidirectional flows, where upstream bed forms are usually not present. The study also demonstrated that the flow depth has a noticeable effect on both the equilibrium and maximum scour depths in tidal conditions [16].
A.4. Characteristic time scale at tidal conditions

A scour hole will develop under non-steady flow conditions and therefore the equation for steady flow are extended to unsteady flow conditions. Equation (2.7) uses uniform flow velocities and can be adapted for unsteady flow by taking into account a succession of infinite short-lasting steady situations. The characteristic time scale for cyclic flow can be represented by [27]:

\[
t_{1,u} = \frac{K h_0(0) \Delta^{1.7}}{\int_{t_1}^{t_2} \frac{\alpha u_0(t) - u_c}{h_0(t)} \, dt}
\]  

(A.22)

- \( t_{1,u} \) = Characteristic time in tidal flow \([s]\)
- \( T \) = \( t_2 - t_1 \), half tidal period where \( \alpha u_0 > U_c \) \([s]\)
- \( t_1 \) = time at which \( \alpha u_0 \) first exceeds \( u_c \) during flood tide \([s]\)
- \( t_2 \) = time at which \( \alpha u_0 \) drops below \( u_c \) during ebb tide \([s]\)

In equation (A.22) only the mean velocity and the flow depth are depending on time. If both are given as function of time, \( t_{1,u} \) can be calculated by numerical integration. This equation is derived at a research on the Brouwers dam sluice. Flood flow was dominating in this situation. Besides, the investigated scour hole was situated land inward, so most turbulence was created during flood. Therefore ebb flow was left outside the equation.

The maximum scour depth can be described as:

\[
y_m(t) = \left( \frac{T}{t_{1,u}} \right)^\gamma
\]

(A.23)

\( h_0(0) \) = tide-averaged flow depth \([m]\)

A.5. Experiments on flow in a scour hole

Guan et al. (2014) performed experiments to obtain information on flow patterns, boundary shear stresses, turbulence intensities and Reynolds shear stresses in the scour zone downstream of a submerged weir. They concluded that the presence of a weir significantly changed flow structures. Downstream of the weir, a large recirculation zone developed. Immediately downstream of the weir, vortices were observed, indicated by a recirculation pattern of sediment close to the weir. At the reattachment region, velocities were small and flow was highly turbulent. The maximum scour depth was observed close to this region. Peak turbulence intensities were found at the upstream end of the recirculation zone. From calculations of Reynolds shear stresses and the turbulence kinetic energy it was possible to derive that the large magnitude of turbulence structures on the upstream slope of scour hole governs the scour hole size (Maximum depth and length). In this two-dimensional case strongly paired cellular secondary flows were observed in the scour hole. These secondary flows have significant influence on the development of the scour hole and the final geometry [20].

Bhuiyan et al. (2007) conducted laboratory investigations to determine how a W-weir can affect channel morphology and flow processes. Most earlier researched situations had a rectangular sharp crested weir or a weir with downstream bed protection. Due to the shape of a W-weir, flow patterns are more complex since the dominant flow is three-dimensional. An analogy can be drawn with scour holes in heterogeneous subsoil since the hypothetical three-dimensional flow character is also present and the W-shape shows more geometrical similarity compared to rectangular shaped weirs (Figure A.19). Thereby, the weir was different in height (Figure A.20) and floodplains were present.

Observations showed that vortices generated by the flow were very intense and had a high erosive capacity. The flow over the weir was directed towards mid channel at an angle to the main flow direction. The redirected flow over each section of the crest generated an asymmetric three-dimensional flow pattern and initiated several vortices with vertical axes of rotation. At lowest points of the crest, flow acted like a jet [4]. The W-weir significantly changed turbulence intensities downstream, usually associated with flow shear layers and separation. High turbulence intensities were measured at the reattachment zone. Near the structures and in the scour holes, sediment moved as bed and suspended load [4].
Chiew and Melville (1987) investigated the influence of flow velocity on scour hole formation nearby a pile. Results show a reduction in scour depth for velocities just above the critical velocity and a minimum scour depth is reached at $U_0/U_{0c} \approx 2$. Due to ripples or dunes, vortices and down flow have limited time to remove sediments from the scour hole. Figure A.22 shows separate lines for ripple and non-ripple situations. Both lines join at higher velocities since bed forms are transformed to flat bed conditions.

The recirculation zone due to an abrupt change in bed geometry is suggested to be an important mechanism for stability of slopes in a scour hole. Nakagawa and Nezu (1987) performed an experimental study on turbulence at a backward-facing step. Results show smaller reattachment lengths with higher Reynolds numbers. Figure A.23 shows results from several studies and suggests a constant reattachment length with higher Reynolds numbers and a rapid increase of length with lower Reynolds numbers. Additionally, the reattachment length tends to increase with higher Froude numbers (Nakagawa and Nezu, 1987).

Paarlberg et al. (2007) investigated flow separation and the shape of the recirculation zone. They concluded that the length of the separation area, and thus the recirculation zone is mostly independent of flow conditions and the shape can be approached by a function related to the distance from the separation point (Paarlberg et al., 2007).
Figure A.23: Influence of Reynolds number on the reattachment length. (Nakagawa and Nezu, 1987).
This appendix gives more information on the choice of the sediment in the experiments. Furthermore information is given on the sieve curve and calibration measurements on uniform flow in the flume.

### B.1. Choice of sand

The use of sediment in scale models is rather peculiar, since it is often difficult to scale sediment in accordance with other existing scaled forces. In Table B.1 two types of sand are presented. Silica M32 is used by Koopmans (2017) and Zuylen (2015) to investigate scour evolution. AF100 sand is the sand product with smallest grain size at the preferred supplier. The table shows that the critical velocity of both types of sediment are more or less equal.

<table>
<thead>
<tr>
<th>Type of sand</th>
<th>$d_{50} [\mu m]$</th>
<th>$D^* [-]$</th>
<th>$\Psi_c [-]$</th>
<th>$u_c [m/s]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica M32</td>
<td>260</td>
<td>6.58</td>
<td>0.015-0.04</td>
<td>0.16-0.25</td>
</tr>
<tr>
<td>AF100</td>
<td>130</td>
<td>3.29</td>
<td>0.023-0.06</td>
<td>0.15-0.24</td>
</tr>
<tr>
<td>Field</td>
<td>350</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

As discussed in Section ??, different types of sediment transport exist. Zuylen (2015) [59] showed the importance of both bed load and suspended load. In contrast to the small influence of different grain sizes on critical velocity, significant differences in types of transport are present with different grain sizes. The suspension number ($Z$) expresses the importance of suspended load transport. It is a ratio between the turbulent fluid forces and gravitational forces [56].

$$Z = \frac{w_s}{\kappa u_s} [-]$$  \hspace{1cm} (B.1)

With the fall velocity and the shear velocity:

$$w_s = \frac{10\nu}{D} \left( \sqrt{1 + \frac{0.01 \Delta g D^3}{\nu^2} - 1} \right) [m/s] \hspace{1cm} if \hspace{0.5cm} 100 < D \leq 1000 \mu m$$  \hspace{1cm} (B.2)

$$\tau_b = \rho g h i = \rho c_f u^2 = \rho u_s^2 \rightarrow u_s = \frac{u \sqrt{g}}{C} [m/s]$$  \hspace{1cm} (B.3)

Table B.2 shows estimated values for the suspension number ($Z$), in which standard flume settings ($u = 35 \ [cm/s]$) are compared with the prototype situation. Due to small velocities and water depth within the model, a relatively small part of the sediment gets into suspension. The smaller the grain size, the more the suspension number resembles the suspension number in the field. During experiments with higher velocities, the suspension number is lower. Additionally, a more rough bed might lead to a more realistic Rouse
number.

The interpretation of \( Z \) according to van Rijn is:

<table>
<thead>
<tr>
<th>( Z )</th>
<th>amount of suspension</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>suspended sediment in near-bed layer ( (z &lt; 0.1h) )</td>
</tr>
<tr>
<td>2</td>
<td>suspended sediment up to mid of water depth ( (z &lt; 0.5h) )</td>
</tr>
<tr>
<td>1</td>
<td>suspended sediment up to water surface ( (z &lt; h) )</td>
</tr>
<tr>
<td>0.1</td>
<td>suspended sediment almost uniformly distributed over water depth</td>
</tr>
</tbody>
</table>

### B.1.1. Scaling of model-prototype

Table B.4 shows large scaling factors between model and prototype. Due to practical arguments on filtering and comparison of results with other laboratory investigations on this topic by Koopmans (2017) and Zuylen (2015), a sediment size is selected which generate larger scale effects compared to the ideal sediment size, compared to prototype situation. Additionally, scale effects on geometry are unavoidable since the laboratory flume is fixed concerning slope width and height.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>field</th>
<th>model</th>
<th>scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth</td>
<td>( h )</td>
<td>[m]</td>
<td>15</td>
<td>0.15</td>
</tr>
<tr>
<td>Characteristic length</td>
<td>( L )</td>
<td>[m]</td>
<td>300</td>
<td>0.5</td>
</tr>
<tr>
<td>Slope</td>
<td>( i )</td>
<td>[-]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Flow velocity</td>
<td>( u )</td>
<td>[m/s]</td>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td>Density difference</td>
<td>( \rho_s - \rho )</td>
<td>[kg/m(^3)]</td>
<td>1650</td>
<td>1650</td>
</tr>
<tr>
<td>Grain size</td>
<td>( D_{50} )</td>
<td>[( \mu m )]</td>
<td>350</td>
<td>260</td>
</tr>
<tr>
<td>Bed roughness</td>
<td>( k_s )</td>
<td>[m]</td>
<td>0.825</td>
<td>0.003</td>
</tr>
<tr>
<td>Shear velocity</td>
<td>( u_* )</td>
<td>[m/s]</td>
<td>0.070</td>
<td>0.013</td>
</tr>
<tr>
<td>( h/k_s )</td>
<td>-</td>
<td>[-]</td>
<td>18.2</td>
<td>50</td>
</tr>
<tr>
<td>Froude number</td>
<td>( Fr )</td>
<td>[-]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reynolds number</td>
<td>( Re )</td>
<td>[-]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Particle Reynolds number</td>
<td>( Re_* )</td>
<td>[-]</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
B.2. Sieve curve

![Sieve curve](image)

Figure B.1: Sieve curve.

B.3. Non-uniform flow

The bed of the flume is constructed horizontal without the possibility of tilting, as regularly possible at more sophisticated flumes. This generates nonuniform flow within the flumes, possibly leading to velocity changes in longitudinal direction. This is also observed during experiments. Figure B.2 shows results of measurements with the Vectrino Profiler during different experiments. These observations show larger variations in velocity with higher velocities. Larger Reynolds numbers indicate more turbulence, so scale effects will be reduced at higher velocities.

![Differences in velocity downstream and upstream of scour hole.](image)

Figure B.2: Differences in velocity downstream and upstream of scour hole.

When small water depths are combined with relatively high velocities (e.g. large water level gradient), the downstream end of the flume acts as a weir with overflow. This might create backwater effects within the flume causing nonlinear changes in water depth and velocity as shown in Figure B.3.
Observations show small surface waves, due to irregularities of the side walls and vibrations from the pump. It is not possible to eliminate those fluctuations within the flume since the pump is located and mounted inside the flume system. Thereby, it is concluded that the influence of those surface irregularities are negligible. Tests with a dye showed no significant change in flow patterns in the water column.
In this section all longitudinal measurements of each experiments are presented. These graphs were used to determine the moment of undermining and to observe differences between experiments. Additionally these graphs were used to examine whether the deepest point determination is not disturbed by the effect of dunes.

Figure C.1: Longitudinal measurements experiment 1.

Figure C.2: Longitudinal measurements experiment 2.
Scour development Experiment 3: $h = 0.140$ [m], $u_{avg} = 0.400$ [m/s]

Figure C.3: Longitudinal measurements experiment 3.

Scour development Experiment 4: $h = 0.141$ [m], $u_{avg} = 0.459$ [m/s]

Figure C.4: Longitudinal measurements experiment 4.

Scour development Experiment 5: $h = 0.175$ [m], $u_{avg} = 0.351$ [m/s]

Figure C.5: Longitudinal measurements experiment 5.
Figure C.6: Longitudinal measurements experiment 6.

Figure C.7: Longitudinal measurements experiment 7.

Figure C.8: Longitudinal measurements experiment 8.
C.1. Validation experiments

The experimental configurations were calibrated before execution of the experiments. The measured velocity profiles of Experiment 2 and 5 are presented in Figure C.10(b) to give an example of the experiments on the effect of water depth, in which the shear velocity remains constant over the experiments. Figure C.10(a) shows the variation over time of the configured water depth of those experiments.

For experiments on change of velocity, water depth remained constant to exclude potential effects of water depth. The measured velocity profiles and measured water depths of experiments on the effect of velocity are presented in Figure C.11. The inflow of discharge was constant creating stable conditions during the full length of the experiment.
Figure C.11: Measured water depth and velocities of experiments 1, 2, 3 and 4.
This section presents extra information on Chapter 5. The application of the breusers formula for development is used followed by all fitted experiments. Additionally, the comparison of the scour depth with the critical velocity is given and the three stages of development are illustrated.

### D.1. Breusers formula fit

This section presents the experimental data together with the calculation of the breusers formula for development with $\gamma = 0.4$ as proposed according to literature. It is shown that this value of $\gamma$ leads to severe underestimation of the scour hole development.

![Figure D.1: Breusers formula versus experimental data with $\gamma = 0.4$.](image-url)
D. Analysis

D.2. Fitting of experimental data

Figure D.2: Fit of experimental data of experiment 1, 2 and 3 with two time scales.

Figure D.3: Fit of experimental data of experiment 4, 5 and 6 with two time scales.

Figure D.4: Fit of experimental data of experiment 7, 8 and 9 with two time scales.
D.3. Effect on equilibrium scour depth

S₀ for each experiment

Relation S₀/Wgeo

(a) Measuring area

(b) Equipment for creating air

Figure D.5: Equilibrium scour depth of all experiments.

D.4. Comparison of scour depth and critical velocity

Experimental data compared with the critical velocity

Figure D.6: Experiment 2

Experimental data compared with the critical velocity

Figure D.7: Experiment 3
Experimental data compared with the critical velocity

Figure D.8: Experiment 4

Figure D.9: Experiment 5

Figure D.10: Experiment 6
D.5. More time scales

Several stages of development are observed visually over time. Section 4.1 elaborates on the different stages. Additionally, from Section 5.2 it is concluded that one time scale is not sufficient to get good fits with the experimental data. Fitting with two timescales shows more convenient results. In Table D.1 the moment of
switching between the two different time scales is present. These moments are compared with the figures in Appendix C.

### Table D.1: Two time scales

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$t_s$ [hrs]</th>
<th>$S$ [m]</th>
<th>no dunes $[hrs]$</th>
<th>ratio $t_s$ and no dunes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geometry 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 1</td>
<td>23.5</td>
<td>0.026</td>
<td>23.5</td>
<td>1</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>9.4</td>
<td>0.04</td>
<td>7</td>
<td>0.75</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>1.8</td>
<td>0.037</td>
<td>2</td>
<td>1.08</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>0.75</td>
<td>0.038</td>
<td>0.8</td>
<td>1.07</td>
</tr>
<tr>
<td>Experiment 5</td>
<td>7.3</td>
<td>0.037</td>
<td>4</td>
<td>0.55</td>
</tr>
<tr>
<td>Experiment 6</td>
<td>4.1</td>
<td>0.029</td>
<td>4</td>
<td>0.97</td>
</tr>
<tr>
<td><strong>Geometry 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 7</td>
<td>4.0</td>
<td>0.0425</td>
<td>4.5</td>
<td>1</td>
</tr>
<tr>
<td>Experiment 8</td>
<td>0.7</td>
<td>0.0511</td>
<td>1</td>
<td>1.35</td>
</tr>
<tr>
<td>Experiment 9</td>
<td>5.9</td>
<td>0.0477</td>
<td>5</td>
<td>0.85</td>
</tr>
</tbody>
</table>

### D.6. Three stages of development

![Figure D.14: Results of experiment 3, stage 1.](image1)

![Figure D.15: Results of experiment 3, stage 2.](image2)
Figure D.16: Results of experiment 3, stage 3.