Development of scour in non-cohesive sediments under a poorly erodible top layer

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1. Introduction

This study deals with the development of deep scour holes in the river bed of the Dutch Rhine delta in the Netherlands. Assessment of multi-beam surveys, laboratory-flume experiments, and 3D numerical modelling, shows how fast this type of scour holes grows in depth and width. These typical scour holes are found in the tidal deltaic rivers that experience a general incision. This erosion decreases the thickness of the erosion resistant clay/peat layer that is covering and protecting the underlying Holocene and Pleistocene sand (Sloff et al, 2012). Consequently, when this layer breaks, deep scour holes are formed where easily erodible sand is exposed. These scour holes pose risks to the stability of nearby embankments and structures.

Laboratory experiments were designed on basis of the field observations, showing rapid deepening, and only slow growth in horizontal dimension. Subsequently, the findings of the flume experiments were used to study and understand the flow in the scour holes in more detail, using a numerical model, and introducing different flow conditions and calculating the shear stresses.

2. Field observations

Relatively new scour holes have been selected from series of annual multi-beam measurements in the Rhine-Meuse delta in the period 2005-2014. Several of these scour holes have reached depths of about 20 m relative to the original bed, and at some locations where these holes are located in the vicinity of river banks, expensive reinforcements have been implemented to prevent failure of embankments (most critical mechanism for failure is flow slides). The areas protected by these embankments are heavily populated and occupied, and have a very high protection level (up to 1:10,000-year).

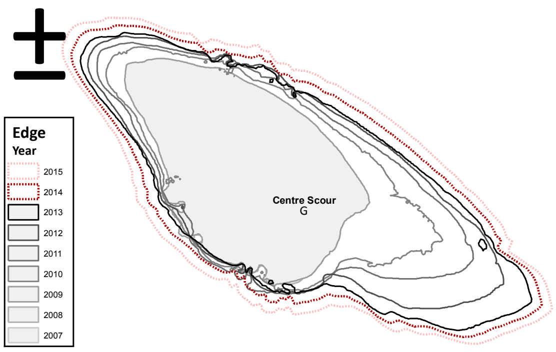

Figure 1: Contours in subsequent years for scour hole in Oude Maas, flow is from bottom right to top left.

Figure 1 shows the contours of a scour hole in the Oude Maas River, based on subsequent annual surveys. The length of the hole is about 200 m, and its depth about 28 m-MSL. The figure shows that the hole is growing 'rapidly' in longitudinal direction (10 to 60 m per year) by crumbling of the clay layer on top, but only slowly in transverse direction. The maximum depth remains more or less constant. Generally these scour holes initially show a rapid deepening, followed by a slow gradual growing in longitudinal and transverse direction with more or less stable depth. The shape of the scour-hole contour is variable, and determined by the strength and thickness of the remaining clay layer around the hole, and by the hydraulic conditions.

3. Laboratory experiments

2DV mobile bed experiments were carried out at the laboratory of Fluid Mechanics of Delft University of Technology to study this scour process. Steel plates with an added roughness were placed on top of a sand bed. The flume width is 0.4 m. A local opening between the steel plates, with varying lengths of 0.1, 0.2, 0.5 and 1.0 m, represented the broken resistant top layer. See Figure 2.

Figure 2: Flume experiment with scour hole. Flow is from right to left

The scour hole initially developed in correspondence with the known theories for scour behind a structure or revetment. However, once the scour hole extended to the edge of the downstream top layer, this layer was undermined. As a result, the sediment was only able to leave the scour hole by transport in suspension. And, although the turbulence within the scour hole was increasing, the rate of scour decreased. With the steel plates remaining at a fixed location, the scour hole approached an equilibrium depth. However, in the field observations, undermining of the top layer has not been observed. The erosion of the sediment below the resistant clay layer would lead to failure and crumbling of this layer: block-failure at the edges occurs (blocks of clay can be seen in the multi-beam soundings of these holes). Deformation of the erosion resistant layer may even stabilize the slopes like a falling apron.

Note that due to the 2DV character of the flume experiment, the influence of the shape of the scour hole (planview) could not be investigated. The ellipsoidal shape of the scour hole may lead to attraction of flow from its neighbourhood, and lead to converging flow lines within the hole causing the hole to remain deep.

4. Computational model experiments

It is difficult to identify all relevant phenomena from the small-scale flume experiments. Adaptations of the laboratory experiments to investigate different parameters, geometry,etc. are time consuming and result in high costs. Therefore a 2DV and 3D computational modelling study was made, to see whether the relevant features can be simulated with 3D computational models, and subsequently whether they can be scaled up to prototype conditions. The finite-element solver FINEL3D (Svašek Hydraulics) has been used for these simulations. The results were compared with the experiments.

4.1 2DV model

The results of the laboratory experiments were tested for different turbulence models:

- Constant eddy viscosity
- Bakhmetev mixing length
- k-L model
- k-epsilon model

The simulations have shown large differences in flow velocities along the longitudinal profile. The results of the Bakhmetev and k-L model gave a good indication of the flow velocities. However, the ‘simple’ constant eddy viscosity model appeared to be more accurate. Furthermore, the k-epsilon model, which is often applied for large river models, was very diffusive and too much dependend on the grid definition. An example of the flow velocity in the scour hole is shown in Figure 3.

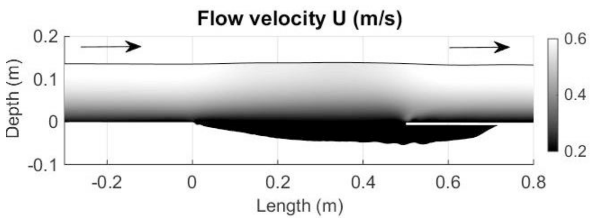

Figure 3: The flow velocity along the longitudinal profile, calculated with a constant eddy viscosity.

One of the problems with verifying these 2DV models was the three-dimensional motion of the flow in the experiments, specifically at the lower edge of the scour hole in the flume (vortex development during undercutting).

4.2 3D model

A next step was made by implementing the obtained results into a 3D model of the Rhine delta branches (prototype scale with realistically shaped scour holes). The model shows a similar distribution of flow velocities at the scour holes as the 2DV flume model. Furthermore, it shows the highest bed shear stresses at the sides of the scour hole, see Figure 4. The scour hole is shown by a lighter ellipse in the centre of the figure. The straight lighter lines were formed by a decrease of cells over the depth, which raised the velocity in the cells.

The high shear stresses at the slopes of the scour hole support the assumption that by deformation of the erosion resistant layer (after undercutting). The shear stresses are higher than the critical shear stress of the sand layer (τ_c 0.30 N/m^2), indicating that the slopes of the scour hole are covered and stabilised by this erosion resistant material.

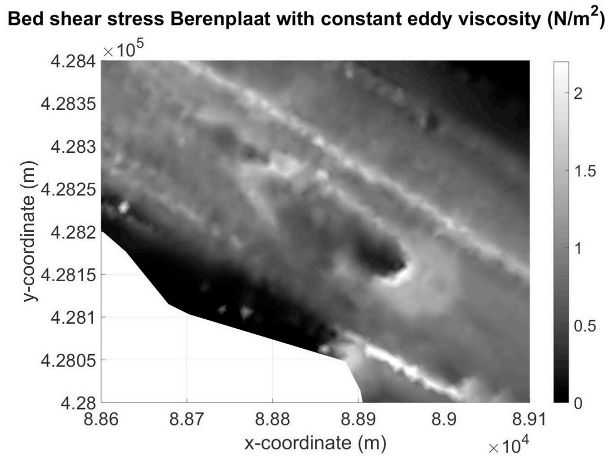

Figure 4: The Shear stresses at the scour hole, the flow is from bottom right to top left.

5. Conclusions

Subsequent surveys in the Dutch Rhine delta show that deep scour holes occur when a clay/peat layer breaks, and underlying sand is exposed. Initially they show rapid deepening (more than 20 m), followed by a slow growth in plan form without further deepening.

In flume experiments the erosion resistant layer was represented by a steel plate, which was apparently too stiff to represent reality. The observed undermining at the downstream edge of the scour hole will not occur in the prototype. Undermining apparently causes the erosion resistant layer to deform and function as a falling apron. Furthermore, the failure of the poorly erodible layer by breaking of blocks of clay lead to subsequent growth of the scour hole.

Computations with several turbulence models showed high shear stresses at the edges of the scour hole. This supports the proposition that the material from the crumbling edges is protecting the slopes. Further research to the behaviour of this erosion resistant layer should be carried out to validate the assumed process. Furthermore, the models show that the complex 2DV and even 3D flow patterns in the scour hole cannot be reproduced easily with classical turbulence models. It is necessary to make more detailed field measurements of flow fields and sediment transport in prototype conditions. Note that the actual conditions in the Rhine-Meuse delta are even more complicated, because of flow reversal due to tidal flows.

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