THE DESIGN OF GRANULAR SCOUR PROTECTION

TESTING DESIGN FORMULAS FOR GEOMETRICAL OPEN FILTERS.

Auteur: Rinse Joustra and Jord Warmink

Scour represents one of the most critical threats to water infrastructure in rivers, coastal and offshore environments throughout the world. Scour is the removal of underwater material by waves and currents. In the United States alone, 60% of 1000 bridge failures where due to the mechanism of scour (Briaud et al., 1999). Other hydraulic structures subjected to scour are for example: pipelines, abutments (i.e. bridge approach to river embankment), spur dikes, breakwaters, power plants, offshore oil platforms and wind farms. Scour can either be accepted or designed for by constructing a deeper pier foundation or a scour protection measure can be constructed. Granular scour protection using stones or rocks are one of the many possible scour protection measures. In this study we focussed on two design formulas for granular scour protection, which are applied in determining the required minimum layer thickness of the geometrical open filter layer. This MSc graduation study of Rinse Joustra was carried out at the Water Engineering and Management department under supervision of Jord Warmink and Marjolein Dohmen-Janssen in close cooperation with Ben de Sonneville from Deltares and Henk Verheij from Deltares & Delft University of Technology and Kees Dorst from Rijkswaterstaat.

GRANULAR FILTERS

Two subcategories of granular scour protection are the traditional geometrical closed filters and geometrical open filters. Geometrical closed filters (figure 1 Left) require construction of multiple layers of different diameter material (i.e. one armour layer and one, or more filter layers), such that it is impossible for the bed material to be transported, as the pores of the filter are too small. The filter layer prevents transport of the bed material, while the armour layer prevents erosion of filter material. However, this type of scour protection is complex (and time consuming) to construct, because it requires often multiple filter layers and because of the loss of the fine filter layer material due to local flow velocities during construction. In contrast, a geometrical open filter (figure 1 Right) combines the function of the armour layer and filter layer in a single grading. This reduces the number of layers and the application of layers with gradings with finer particles in the granular protection, which reduces the difficulties during construction. A geometrical open filter is, therefore a more cost-effective granular protection against scour.

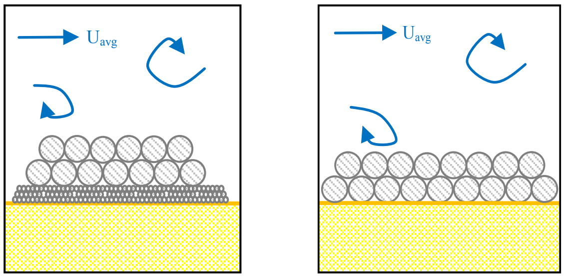


FIG. 1 Left: Geometrical closed filter, with the bed material below (yellow) and on top one filter layer and an armour layer that covers the filter layer.
Right: Geometrical open filter. Single grading system. This figure shows 2 layers of filter stones.

In contrast with the geometrical closed filter, in a geometrical open filter the fine bed material (e.g. sand) can be transported through the pores of the filter if the hydraulic load is higher than the critical load. However, the filter works because loads (e.g. the water flow above the filter) are reduced in the pores, so the bed material will not be transported. The layer should be sufficiently thick to reduce the hydraulic load in the pores and protect the bed material, otherwise the bed material below the filter will be eroded and the protection will fail (figure 2). To determine how thick the geometrical open filter layer should be, we compared two design formulas to see which one is more reliable for different flow conditions.

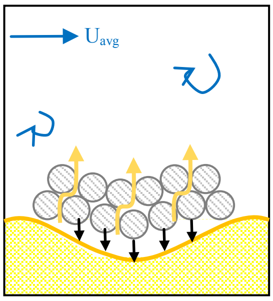


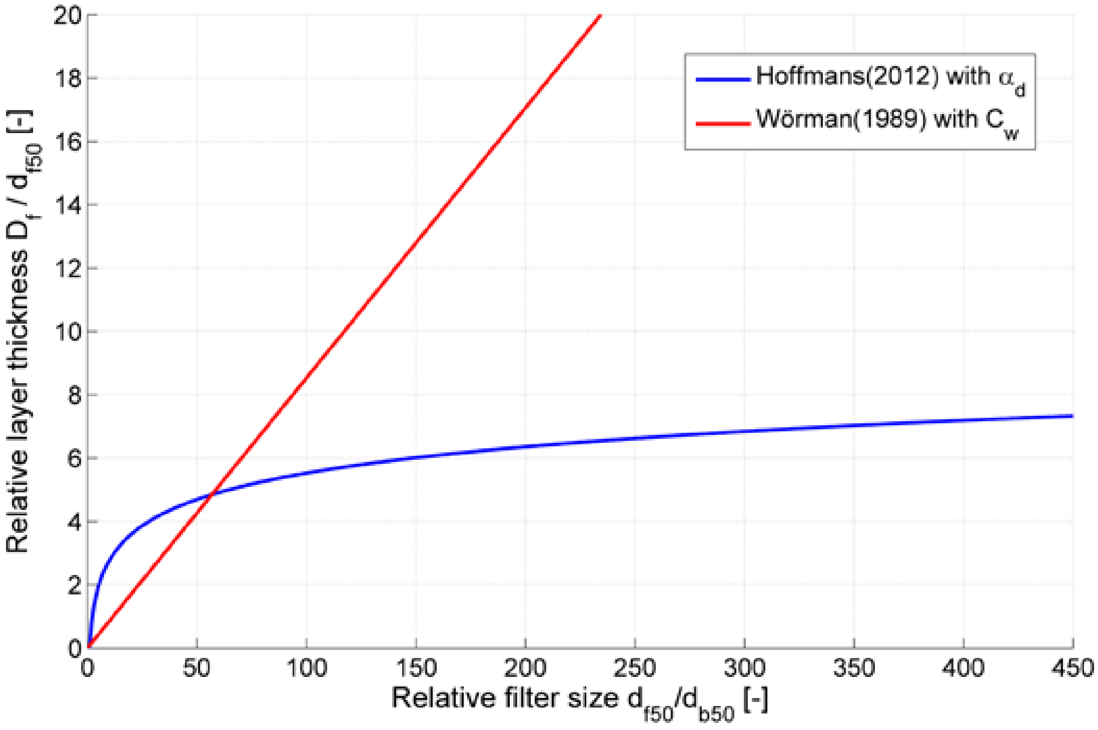
FIG. 2 Failure of the geometrical open filter layer, because the thickness is insufficient to damp the hydraulic load on the bed material. The underlying bed material is transported through the filter layer pores, which causes filter layer settlement.

TWO DESIGN FORMULAS FOR OPEN FILTERS

The optimal design of a granular open filter layer is if both bed and filter material will move simultaneously. If only the filter material will move, the layer is too thick and the filter is over-dimensioned, but the filter material will erode. If the bed material will move, the layer is too thin and fails.

The design formula of Hoffmans (2012) can be applied to calculate the optimum layer thickness to prevent transport of bed material through the pores of the geometrical open filter in uniform flows. The formula should theoretically also be applicable in non-uniform flows, but was only tested with scarce data by Van de Sande (2012) and Van Velzen (2012). The Hoffmans formula is logarithmic and applies the load damping coefficient α_d to describe the slope of the line that indicates simultaneous movement of bed and filter material (figure 3). From an engineering perspective: positions above the line indicate that the thickness is over dimensioned, but sufficient. Positions below the line indicate that the bed material moves first, so the thickness is insufficient. For those positions on top of the line, the filter grain size is and filter layer thickness should theoretically not be over dimensioned.

FIG. 3 Illustration of the Hoffmans and Wörman formulas . Positions above the curves indicate that the filter moves first and the thickness of the filter layer is sufficient. Positions below the curve indicate that bed material moves first or simultaneous erosion of bed and filter, which implies that the layer thickness is insufficient.



Another design formula, the formula of Wörman (1989), was derived based on experiments with a cylindrical pier (i.e. non-uniform flow) and was only tested for thin layer thicknesses (<0.1 m) and low flow velocities (< 0.5 m/s). The Wörman formula is linear and distinguishes between stable or instable bed materials using an empirical coefficient C_w (figure 3).

THE THESIS AIM

The aim of this MSc research was to test the design formula of Hoffmans (2012) for flows with sill-induced additional turbulence (i.e. non-uniform flow), and flows with a cylindrical pier and to test the validity of the design formula of Wörman (1989) for flow velocities over 0.5 m/s and filter layer thicknesses over 0.1 m at flows with cylindrical piers.

LABORATORY EXPERIMENTS

In the summer of 2012 physical model tests were carried out at the Atlantic basin research facility of Deltares in Delft (figure 4). The test program was commissioned by Rijkswaterstaat, with the aim to populate a database for research into the relation

FIG. 4 Illustration of the experimental facility at Deltares. Flow is from bottom to top. The measurements were carried out at the end of the concrete channel.

between transport of bed material through the filter and the filter and bed characteristics for different flow conditions: these conditions being (1) uniform flow, (2) flow with sill-induced additional turbulence and (3) conditions with a cylindrical pier. An additional aim was to populate the database with measurements of pressure signals and signal fluctuations within the filter, which was applied in another study by Deltares. The full dataset comprised bathymetry measurements, pressure measurements inside the filter at several depths and flow velocity measurements above the filter layer. Figure 5 shows the experimental set-up with the two test sections. Section 1 consisted of a filter without pier; section two contains the filter around the pier. 11 tests were carried with uniform flow, 6 tests were carried out with additional turbulence, by putting a wooden beam in front of the test section and 16 tests were carried out for the pier. The filter grain sizes, filter layer thickness and flow velocity were systematically changed within the test program.

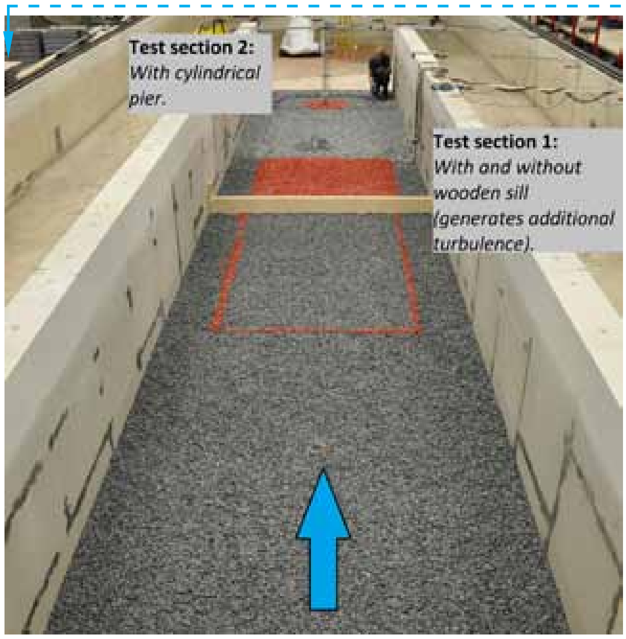


FIG. 5 Set-up of laboratory experiments. The blue arrow marks the flow direction. The red filter stones indicate both test section. The wooden beam was used to induce additional turbulence in test section 1.

METHOD

Filter and bed stability were determined visually for each test from observation using underwater camera images and processed videos (figure 6 & 7). In addition, the bed material instability classification is verified with 3D Stereo photography images for conditions (1) and (2). The tests were classified by the instability of filter and/or bed (figure 8). The formula of Hoffmans (2012) was compared with the classification for respectively flow condition (1), (2) and (3). The formula of Wörman (1989) was compared with the classification for tests with condition (3). Finally, results based on data of the experiments are combined with previous validation results based on data of Van de Sande (2012) and data of Van Velzen (2012).

RESULTS & CONCLUSION

For the uniform flows 8 of the 11 tests showed that both filter and bed were stable, while 3 tests showed instable bed material. For the additional turbulence, 3 tests showed that both filter and bed were stable, one test showed instable bed material and for 2 tests no observations were possible, due to the low visibility of filter and bed material in the flow. For the pier, 4 tests showed that both bed and filter were stable, 12 tests showed that bed material was instable and 1 test showed that only filter material was instable. These results suggest that for equal flow velocity and water level, the filter failed more often if additional turbulence or a pier was present.

The coefficient α_d as defined by Van de Sande (2012) is 0.82. Comparison with the Hoffmans (2012) formula showed that the tests with uniform flow are in agreement. The tests with flows with sill-induced additional turbulence and flows with a cylindrical pier suggest that an increasing of the coefficient α_d is required. A rough estimate for additional turbulence is probably within the range $1.2 < \alpha_d < 2.5$, but further research is highly recommended due to the uncertainty in results and the low number of tests. This implies that for future construction of granular open filters, the layer thickness should be roughly 1.5 to 3 times larger. A new estimate of α_d for cylindrical piers is probably within the range $2.4 < \alpha_d < 3.7$, which implies that layers around cylindrical piers, such as near bridges, require roughly a 3 to 4.5 times larger layer thickness. Furthermore, the results showed that in the design of a scour protection it is important to assess if there is additional turbulence involved to determine the thickness of the granular scour protection.

The formula of Wörman (1989) estimated the minimum required

FIG. 6 Single images (also see FIG. 7) of cameras that were used to determine bed and filter movement during the test. Camera on test section 1 without pier

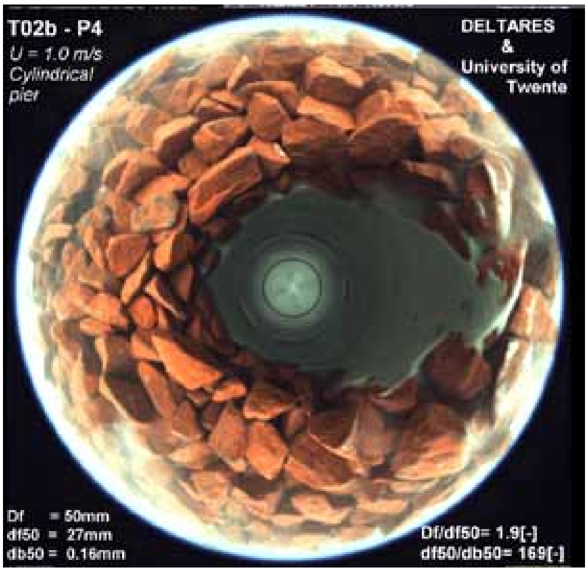


FIG. 7 360 degree camera inside the pier. Flow velocity from left to right.

layer thickness reasonably well for average flow velocities over 0.5 m/s and layer thicknesses over 0.1 m. However, the results indicate that increasing the C_W coefficient from 0.16 to between 0.22 and 0.33 results in better agreement with the new test data. This implies that the layer thickness increases roughly with a factor1.4 to 2 for the Wörman (1989) equation. Comparison between the derivations of both formulas for flows with a cylindrical pier provides most confidence in layer thickness calculated with the formula of Wörman. Finally, in the near future the results will be implemented in an update of a guideline for granular filters.

AFTER GRADUATION

For those students that wonder what to do after your graduation, I started a few weeks after my graduation as a junior consultant at the consultancy Infram. At Infram I worked on a pilot study for the fresh water supply of the Eemshaven, commissioned by the province of Groningen. A project which is quite similar to the project based courses in the bachelor and master curriculum of Civil Engineering at the University of Twente. At the moment, I develop a reference database for the Dutch flood safety program 2.0 (Hoogwaterbeschermingsprogramma 2.0) and also work for a program Professionalizing inspection of Dutch flood defence systems (PIW 2.0) at the STOWA. ■

REFERENCES:

Briaud, J. L., Ting, F. C. K., Chen, H. C., Gudavalli, R., Perugu, S., & Wei, G. S. (1999). SRICOS: Prediction of scour rate in cohesive soils at bridge piers. Journal of Geotechnical and Geoenvironmental Engineering, 125(4), 237-246

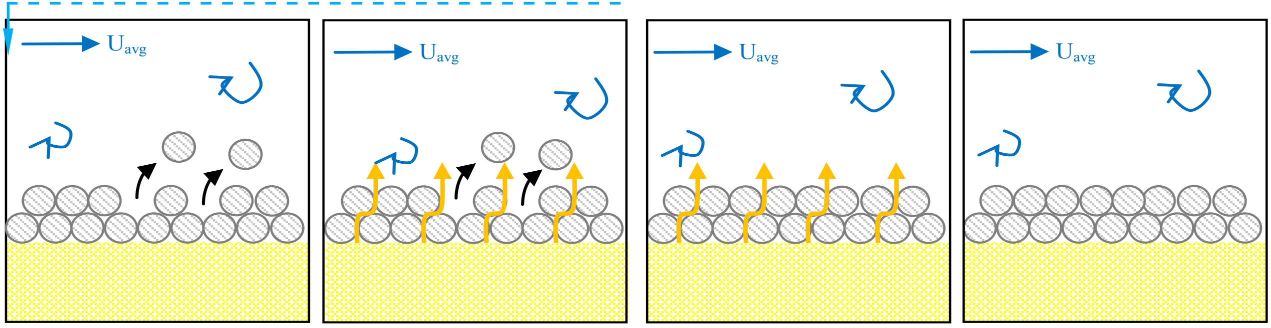
Hoffmans, G .J.C.M. (2012). The Influence of Turbulence on Soil Erosion. Delft: Eburon Acadamic publishers.

Van de Sande, S. A. H. (2012). Stability of open filter structures. MSc thesis. Delft: Delft University of Technology.

Van Velzen, G. (2012). Flexible scour protection around cylindrical piers. MSc thesis. Delft: Delft University of Technology.

Wörman, A. (1989). Riprap protection without filter layers. Journal of Hydraulic Engineering, vol. 115 (12).

FIG. 8 Classification of filter and bed stability.



I) Filter is *instable, bed is stable*.

II) Both filter and bed are *instable*.

IIII) Filter is stable, bed is *instable*.

IV) Both filter and bed are *stable*.