Physical modeling of fluvial obstacle marks at a sediment layer of limited thickness

A. Oliver Schloemer *Department of Geography, University of Bonn, Germany – oschloem@uni-bonn.de*
B. Juergen Herget *Department of Geography, University of Bonn, Germany – herget@giub.uni-bonn.de*

ABSTRACT: A series of 36 clear-water flume experiments were conducted to investigate the influence of a limited layer of uniform medium sand on the morphometry of obstacle marks at a cylindrical pile. The focus was particularly on the scour hole morphometry. Regarding systematical analyzation constant flow conditions and two diameters of cylindrical piles (0.01 m and 0.02 m) were chosen. The thickness of the sedimentary layer ranged from 0.08 m to 0.005 m and was continuously reduced. Results showed that scour hole morphometry differed at a limited sediment layer. While scour depth was greatly reduced, other characteristic parameters (e.g. scour width, scour length) still achieved large parts of their steady state dimensions due to sediment transport induced by the hydraulic processes around the piles.

1. INTRODUCTION

Obstacle marks are sedimentary bedforms induced by an obstacle exposed to a current. As consequence of the variety of potential obstacles in nature like blocks, boulders and woody riparian plants, they are integral components of the fluvial and marine systems (e.g. Breusers & Raudkivi, 1991; Melville & Coleman, 2000). Such obstacles cause the flow to separate, resulting in a complex and high turbulent vortex system around the obstacle, denoted as “horseshoe vortex” (e.g. Muzzammil & Gangadhariah, 2003; Dey & Raikar, 2007). The approaching flow is pushed downwards in front and gets accelerated at the lateral parts of the obstacle resulting in rotating vortex system, which increases bed shear stress and induce sediment mobilization in front and around the obstacle. The legs of the vortex system are stretching around the obstacle base in a horseshoe-like pattern and transport eroded sediment out of the scour hole into the wake. In addition to that, detached shear layers interact with these extended legs causing the formation of trailing vortices, which have the potential to generate sediment accumulations with lengths up to several tenths of the obstacle diameter (Herget et al., 2013). These sediment accumulations are termed as “sediment ridge” (Euler & Herget, 2011, 2012). The sediment ridge and the adjacent frontal, crescent-shaped scour hole are forming a typical obstacle mark (c.f. Fig.1), (e.g. Allen, 1982). A dynamic interaction between hydraulic and sedimentary processes causes a non-linear development towards a steady state (e.g. Melville & Coleman, 2000). Actually this interaction is characterized by positive feedback mechanisms between scour hole incision and horseshoe vortex action, where sliding due to gravity and the angle of repose related to grain size of the sediments are the main processes for scour hole enlargement (Euler & Herget, 2011, 2012). Obstacle mark dimensions are variable and depend on flow, obstacle and sediment characteristics as well as on temporal dynamic (e.g. Breusers & Raudkivi, 1991; Melville & Coleman, 2000). A unique aspect of obstacle marks is their development even when the mean flow velocity is well below the critical threshold for general particle movement (Euler & Herget, 2012).

1.1. Outline for the present research

The formation of obstacle marks is controlled by a variety of independent variables. Many of these variables have been investigated systematically (e.g. Breusers & Raudkivi, 1991; Melville & Coleman, 2000; Arneson et al., 2012). According to recent investigations by flume experiments several morphometric variables could be determined as order parameters of the obstacle mark topography at steady state conditions. These include maximum scour depth, width of the frontal scour hole, length of the frontal scour hole and width of the sediment ridge, (c.f. Fig. 2), (Euler & Herget, 2011, 2012).

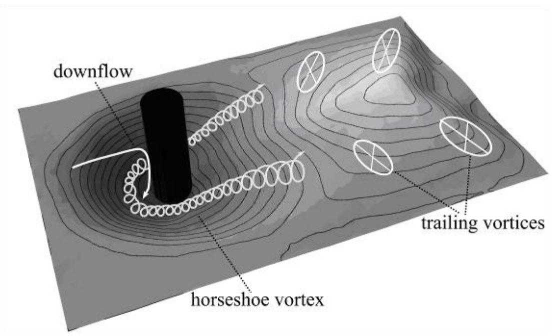

Figure 1. Simplified flow field around an emergent cylinder with frontal scour hole and sediment ridge in the wake. Direction of flow is from left to right (modified from Herget et al., 2013: 304).

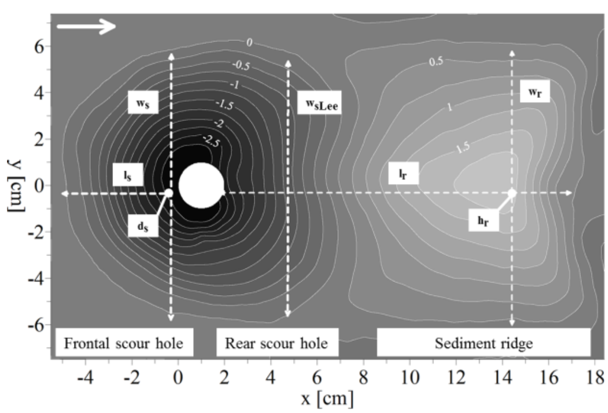

Figure 2. Contour plot of an obstacle mark at a cylindrical pile. Dashed lines indicate locations of morphometric order parameters and topographical profiles (d_s – frontal scour depth; l_s – frontal scour length; w_s – frontal scour width; w_{sLee} – rear scour width; w_r – ridge width; h_r – ridge height; l_r – ridge length. Arrow indicates direction of flow (modified after Euler & Herget, 2012: 40).

The unique characteristic of these variables is their interdependent relationship to each other (Herget et al., 2013). The parameters sediment ridge width and length are not suited for correlation, as they strongly vary with time (Euler & Herget, 2012).

In contradiction to these idealized morphological patterns, obstacle marks in the field are often not fully developed or preserved. This is especially valid for giant obstacle marks generated by Pleistocene megafloods (e.g. Herget 2005). Especially the scour holes are often very wide, but not very deep (e.g. Herget et al., 2013).

The formation of clear and fully developed structures and forms might be inhibited by numerous factors. One of those is a depth-limited cover of erodible sediments in front of an obstacle.

2. METHODOLOGY

To systematically investigate the influence of a limited sediment layer on the morphology of obstacle marks, 18 flume experiments under constant boundary conditions in regard to flow, obstacle and sediment characteristics were carried out. Each run was repeated to avoid coincidences, leading to a total number of 36 experimental runs. To predict the potential maximum scour depths under given boundary conditions the HEC-18 pier scour equation was used (cf. Arneson et al., 2012). Limited sediment thickness was in this context defined as condition, in which the depth of the sediment layer was less than the potential maximum scour depth. Starting with a sufficient depth of sediment in front of the obstacle, the sediment thickness was continuous reduced after each run. The experiments were not prototype-based and no similarity criterions were applied.

2.1 Experimental setup

The physical modelling experiments were conducted at rectangular flume of 5 m length, 0.32 m width and 0.27 m high working section. The slope was fixed at 0.003 m/m. Cylindrical piles of diameters 0.01 m and 0.02 m and heights of 0.18 m served as obstacles and were mounted in the middle of the working section at the plane of symmetry. Water depth (0.08 m) and mean flow velocity (0.24 m/s) were kept constant during the experiments leading to a stationary discharge (0.00614 m^3/s). The obstacles were emergent (water depth < obstacle height). Froude and Reynolds numbers were 0.27 and ~ 12,000 respectively. The experiments were conducted over 24 hours to reach steady state conditions of the morphometric order parameters (e.g. Melville & Chiew, 1999). Uniform sand with median grain size 0.055 mm was used in the experiments. The natural angle of repose of the particles is 30°. Bed shear stress was equal to 57 % of the critical bed shear stress so that clear-water conditions prevailed and no general particle movement occurred.

As distinguished from the previously mentioned parameters the depth of the sedimentary layer was not constant and ranged from 0.005 m up to 0.08 m. For bathymetric surveys along topographical profiles during and at the end of the runs, an ultrasonic punctual distance meter (UltraLab UWS, General Acoustics) was used. Additionally an Acoustic-Doppler Velocimeter (ADV) (Vectrino, Nortek) was used for analysing the flow field around the obstacles, applying the turbulent kinetic energy approach (e.g. Stapelton & Huntley, 1995). Further details on the measurement techniques are given in Euler & Herget (2011, 2012)

3. EXPERIMENTAL RESULTS

3.1 General obstacle mark evolution

Despite the variable sediment layer thickness, obstacle marks developed during each experimental run. The erosion of the scour hole started immediately while reaching the desired flow conditions at the frontal face of the cylindrical pile. The particle-transport out of the developing scour hole into the wake region was driven by the processes of saltation and sliding. At the end of the experimental runs the scour holes completely surrounded the cylinder, while the sediment ridges consisted of a central crest and two lateral flanks with a slight depression in the lee.

3.2 Morphometry

Figure 3 shows the normalized dimensions of the scour hole parameters in relation to normalized sediment thickness. At sufficient sediment thickness the order parameters reached a constant steady state and were general larger at larger obstacle diameter. The observed maximum scour depths corresponded well to predicted values at both obstacle diameters and served as "critical depth" in regard to the thickness of the sedimentary layer.

Below this critical depth the obstacle mark dimensions gradually decreased and did not reach their steady state dimensions under given boundary conditions. While not surprising that the scour depth was reduced significant, the other order parameters still reached a large part of their potential steady state dimensions.

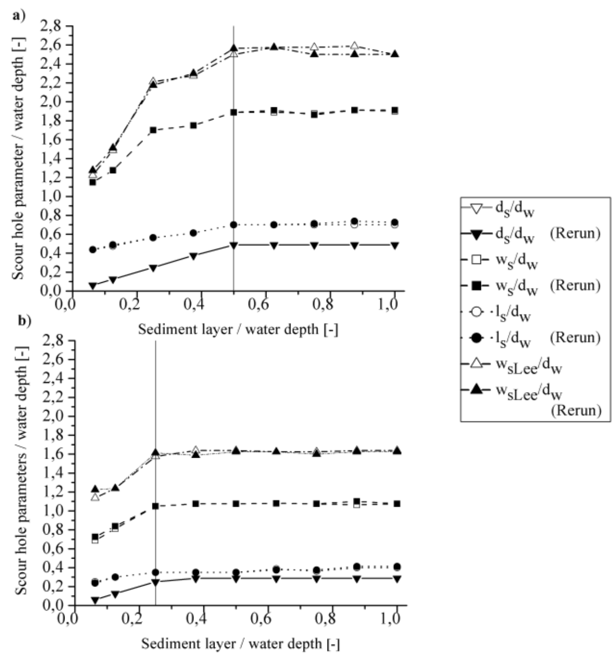

Figure 3. Normalized scour hole parameters in relation to normalized sediment layer thickness (all runs considered). Vertical lines represent maximum scour depths under given boundary conditions. a) obstacle diameter 0.02 m. b) obstacle diameter 0.01 m. d_w denotes water depth (= 0.08 m). Other abbreviations: see Figure 2.

These development resulting in unproportional morphometry of obstacle marks at limited sediment layer (cf. Table 1). This finding was supported by bathymetric surveys during the runs showing that maximum scour depth was already reached in the initial phase of obstacle mark development (< 2 min), whereas slight enlargement of the frontal scour width (w_s) and rear scour width (w_{sLee}) could be observed at subsequent measurements.

Table 1. Obstacle mark parameters at limited sediment thickness in relation to steady state dimensions at obstacle diameter 0.02 m. Sediment layer thickness is in m.

Sediment layer	Scour depth	Scour length	Scour width	Ridge height	Ridge width	Ridge length
0.03	0.77	0.86	0.92	1.00	0.98	0.95
0.02	0.51	0.79	0.89	1.00	0.98	0.93
0.01	0.26	0.67	0.67	0.75	0.66	0.76
0.005	0.13	0.61	0.61	0.38	0.50	0.66

Furthermore, slope calculations from topographical profiles show that sliding was not a major process in scour hole enlargement at limited sediment thickness, because slopes were mostly below the angle of repose. However, ADV measurements revealed that the flow field around the obstacle was characterized by high values of turbulent kinetic energy, indicating the action of the horseshoe vortex system even for a thin sedimentary layer (< 0.001 m). Therefore the horseshoe vortex system has to be considered as partial driving force in scour hole enlargement (especially scour width) through sediment erosion.

4. CONCLUSION

The results show that limited sediment thickness is a critical boundary condition in the evolution of fluvial obstacle marks. At a first view this is not really a surprising result, but it becomes evident that scour hole parameters (depth, width, length) are not decreasing proportional. As a consequence the significance of linear relationship in comparison to steady state dimensions weakens. From this perspective additional experiments are necessary to identify potential regularities as well as to up-scale these regularities to field boundary conditions (e.g. giant obstacle marks formed by Pleistocene megafloods).

Furthermore, new insights in process dynamics and sediment transport processes of fluvial obstacle marks could be obtained. However, the results of the present study are limited to steady flow, clear-water conditions, sub-critical flow conditions and non-cohesive sediments.

5. ACKNOWLEDGEMENTS

The experiments and results were part of the Master thesis of Oliver Schloemer.

6. REFERECES

Allen, J.R.L. 1982. Sedimentary structures. Their character and physical basis. Volume 2. Developments in Sedimentology 30B. Amsterdam: Elsevier.

Arneson, L.A., Zevenbergen, L.W., Lagasse, P.F. & Clopper, P.E. 2012. Evaluating scour at bridges. Hydraulic Engineering Circular No. 18. Virginia: U.S. Department of Transportation.

Breusers, H.N.C. & Raudkivi, A.J. 1991. Scouring. Hydraulic Structures Design. Manual Series Vol. 2. Rotterdam: CRC Press.

Dey, S & Raikar, R.V. 2007. Characteristics of horseshoe vortex in developing scour holes at piers. Journal of Hydraulic Engineering 133(4): 399-413.

Euler, T. & Herget, J. 2011. Obstacle-Reynolds-number based analysis of local scour at submerged cylinders. Journal of Hydraulic Research 49(2): 267-271.

Euler, T. & Herget, J. 2012. Controls on local scour and deposition induced by obstacles in fluvial enviroments. Catena 91: 35-46.

Herget, J. 2005. Reconstruction of Pleistocene ice-dammed lake outburst floods in the Altai Mountains, Siberia. Geological Society of America Special Publication 386. Boulder: Geological Society of America.

Herget, J., Euler, T., Roggenkamp, T. & Zemke, J. 2013. Obstacle marks as palaeohydraulic indicators of Pleistocene megafloods. Hydrology Research 44(2): 300-317.

Melville, B. & Chiew, Y.M. 1999. Time scale for local scour at bridge piers. Journal of Hydraulic Engineering 125(1): 59-65.

Melville, B. & Coleman, S.E. 2000. Bridge scour. Highlands Ranch: Water Resources Publication

Muzzammil, M. & Gangadhariah, T. 2003. The mean characteristics of horseshoe vortex at cylindrical pier. Journal of Hydraulic Research 41(3): 285-297.

Stapelton, K.R. & Huntley, D.A. 1995. Seabed stress distribution using the interial dissipation method and the turbulent kinetic energy method. Earth Surface Processes and Landforms 20(9): 807-815.