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THREE DIMENSIONAL NUMERICAL MODELING OF PIER SCOUR

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A three-dimensional computational fluid dynamics model is applied to predict local scour around a circular pier in a rectangular laboratory flume. When modeling local scour, steep bed slopes up to the angle of repose occur. In order to be able to predict the depth and the shape of the local scour correctly, the reduction of the critical shear stress due to the sloping bed has to be taken into account. The focus of the present study is to investigate an approach for the threshold of non-cohesive sediment motion on sloping beds. The transversal angle (perpendicular to the flow direction) as well as the longitudinal angle (stream wise direction) of the bed are taken into account.

The numerical model solves the unsteady Reynolds-averaged-Navier-Stokes equations in all three dimensions to compute the water flow. The turbulence is computed with the k-ε model. The convection-diffusion equation is solved to calculate the suspended sediment concentration. Sediment continuity in combination with an empirical formula is used to capture the bed load transport and the resulting bed changes. When the sloping bed exceeds the angle of repose, the bed slope is corrected with a sand slide algorithm. The results from the numerical simulations are compared with data from physical experiments. The reduction of the bed shear stress on the sloping bed improved the results of the numerical simulation significantly.

Key Words : *pier, numerical modeling, incipient motion, sandslide*

1. INTRODUCTION

When it comes to flood damage, local sour is the prime cause for failure of infrastructure in and around rivers, removing foundations of bridges, roads, houses etc. Therefore the prediction of local scour has always been of great interest for hydraulic engineers. Constructions in contact with rivers create an obstruction for the water flow. This leads to locally increased turbulence and bed shear stress, which initiate local scouring. In a scour hole the bed slope may become very large. Due to gravity and tractive forces, the high bed slopes cause a reduction of the critical shear stress of the bed particles, which accelerates the erosion process. For non-cohesive sediments, the bed slope becomes as steep as the angle-of-repose. When this threshold is reached, slope failure in the form of a sandslide occurs. In order to be capable of predicting the correct depth, size and shape of a local scour, the combined mechanism of critical shear stress reduction and sandslide has to be considered.

In this paper a fully three-dimensional computational fluid dynamics model with an integrated bed change module is used to predict local scour. This approach promises to be the most general one, since even complex flow situations can be allowed for. The goal of the present paper is to test an approach for bed shear stress reduction on a sloping bed in combination with a sandslide algorithm. The algorithm is tested against pier scour measurements from the laboratory.

Previous work on numerical modeling of pier scour can be found in Olsen and Kjellesvig (1998) and Roulund et al. (2005). Olsen and Kjellsvig were the first to use a three dimensional numerical model to calculate a complete pier scour. They compared the modeled scour results with empirical formulas, which showed good agreement. Roulund et al. performed an extensive experimental campaign and offer a detailed description of the pier scour mechanisms. They also used a three dimensional numerical model to calculate the pier scour, but the results are presented rather qualitatively and contour plots of the pier scour geometry are not included.

2. EXPERIMENTAL DATA

The pier scour experiments were conducted in the hydraulic laboratory of the Technical University Darmstadt by Link (2006). The flume was 37 m long, 2 m wide and 1 m deep. The sides were confined by plexiglass walls. The pier, made of plexiglass as well, has a diameter of 0.2 m. It was placed in the flume center. The bed material consists of natural sand (diameter: 0 – 2 mm) from the river Rhine with a d_{50} of 0.97 mm, a uniformity coefficient of 1.47, density of 2.65 t/m^3 and an angle-of-repose of 29° in air.

The pier scour geometry was measured with a laser distance sensor, which was placed inside the pier. That way the scour hole could be surveyed continuously during the experiment without having to stop the water flow.

From a total of eleven runs, the one with a discharge of 0.18 m^3/s and a water level of 0.3 m was chosen for the comparison in the present study. For this run clear-water scour conditions were present. The duration of the run was 21 h, or 75.600 sec respectively.

3. NUMERICAL MODEL

For the investigations in this paper a numerical model is used (Olsen, 2007). The Reynolds-Averaged Navier-Stokes (RANS) equations are solved in all three dimensions, making it fully three-dimensional. The standard k-ε model (Rodi, 1980) was used to compute turbulence. Using the finite-volume approach on a structured non-staggered grid, the RANS-equations and the equations of the turbulence model are numerically discretized with the first order upwind differencing scheme and the second order upwind differencing scheme. The non-hydrostatic pressure is computed with the SIMPLE method (Patankar, Spalding, 1972). The free surface elevation is determined with the help of the pressure field, using the Bernoulli equation.

Van Rijn's sediment transport formula (1984a) is used to calculate the bed load. The convection-diffusion equation describing the suspended sediment concentration is solved by the means of the finite-volume method. Van Rijn's (1984b) formula for the suspended load capacity serves as boundary condition. The critical bed shear stress is calculated from the Shields graph (Shields, 1936). The bed changes for both erosion and deposition are calculated from sediment continuity in the bed cells. The difference between inflow and outflow of sediment concentration is converted into a volume by taking the submerged density into account.

4. INCIPIENT MOTION ON SLOPING BEDS

On a sloping bed, the incipient motion of sediment particles is not only a function of hydrodynamic forces. Additional gravity and tractive components have to be taken into account, in order to correct the critical shear stress obtained from the Shields graph. The critical shear stress τ_0 is calculated for a flat bed. Than a reduction factor r is calculated which takes the slope of the bed into account. The reduction factor r is multiplied with τ_0 to give the final critical shear stress τ_c (1).

$$\tau_c = r \cdot \tau_0 \tag{1}$$

Lane's work (1955) marked the beginning of research on sloping beds and their impact on the incipient motion on sediment particles. He focused exclusively on side slopes. This means only the angle perpendicular to the flow direction, the transversal angle α is taken into account. The angle in flow direction, the longitudinal angle θ, was assumed to be close to zero. While Lane's analytical approach only considers the drag force, Ikeda (1982) extended it by including the lift force. Kovacs and Parker (1994) developed a vectorial equation for the threshold for a combined transversal and longitudinal sloping bed. That means also θ was included in the critical bed shear stress reduction The equation was analytically solved by Seminara et al. (2003) as a quadratic equation. Dey (2001) found an empirical expression. It included both the transverse angle α and the longitudinal angle θ. As a result of further research Dey (2003) came up with an analytical form of the formula. Besides α and θ, the lift/drag force ration η was also included in this formula. In order to achieve a proper implementation of the formulas mentioned above into the numerical model, the transverse and longitudinal angle of every bed cell is calculated in a global coordinate system. In a second step, the flow direction in each bed cell is determined for the global coordinate system. According to the flow direction, the global angles α and θ are transferred into a local coordinate system in a way, that θ aligns with the flow direction while α is perpendicular to the flow. That way, r can be evaluated for each bed cell separately.

The five different formulas for the reduction of the critical bed shear stress on sloping beds were tested with the numerical model in a previous study for abutment scour (Bihs and Olsen, 2007). It was shown that the consideration of both the transversal angle α and longitudinal angle θ are important for the bed shear stress reduction and that Kovacs and Parker's formula was most suitable for predicting the abutment scour. Thus the latter formula was used in the present study exclusively to predict the pier scour.

In a real world situation, the banks of a local scour hole will collapse at a an angle around the angle-of-repose. This observation lead to the implementation of a sandslide algorithm. When the slope of a bed cell becomes larger than the angle-of-repose φ, it is corrected. The new angle is then φ-2°. The value 2° was used by Roulund (2005), and parameter testing proved it to be reasonable for the present calculations as well.

For the abutment scour, the use of a constant φ was not very successful. In this case the sandslide algorithm gave all bed cells the same slope, namely φ-2°, giving the scour hole a very uniform look. As a remedy, findings made by Lysne (1969) were implemented into the sandslide algorithm. He observed that slope failure for sand occurred at different angles depending on the direction of the water flow. In the current paper, for downhill flow the angle-of repose is chosen to be 35°, for uphill flow the angle is then 25°.

5. NUMERICAL RESULTS

The numerical simulations were conducted on a grid of 160 cells in x-, 70 cells in y-and 15 cells in z-direction (see Figure 1). The modeled flume stretch is 5 m long. The grid generation is based on an algorithm by Amsden and Hirt (1973). The cells inside the pier are blocked out. For the transient sediment calculations a time step of Δt = 5.0 sec was used.

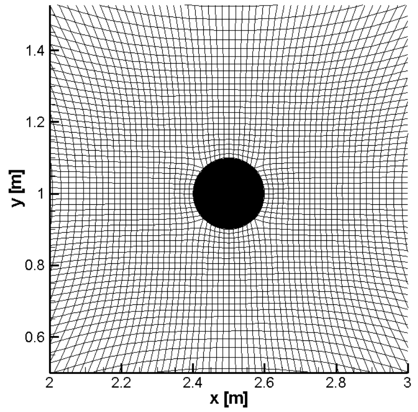

Fig.1 Grid around the pier

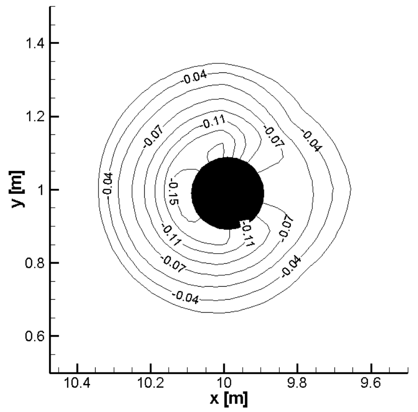

Fig.2 Measured scour at the end of the experiment, values in [m], flow from left to right

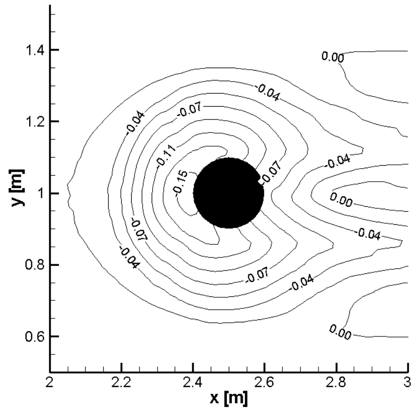

Fig.3 Modeled scour, flow from left to right

Figure 3 shows the modeled scour geometry after 75.600 sec. The maximum scour depth is -15.3 cm and is located on the upstream side of the pier. This corresponds well with the experimental results (Figure 2), here the maximum depth is also -15.3 cm. As a major difference between the two Figures, the bed elevation on the downstream side of the pier can be noted. The numerical results show an arrow shaped scour hole on the downstream side. The measured scour hole is very even shaped and forms a full circle. This can be explained with the

measurement procedure, which was mentioned above. The constraint of this method is, that the bed topography outside the actual scour hole is not considered. The development of the maximum scour depth is shown in Figure 4. The overall tendency is strong erosion in the beginning and less in the end. In the first 5700 seconds the erosion is slightly more intense in the experiment than predicted by the numerical model. After that the situation turns around, the simulated scour depth grows more rapidly until both lines meet up at the end of the run. The shape of both curves indicates, that the equilibrium scour depth has not yet been reached.
In order to clarify the evolution of the scour geometry, Figure 5 shows the simulated scour hole after the first two time steps. The erosion process begins in the form of two separate scour holes on each side of the pier. Gradually they work their way to the upstream side of the pier, where they unite and form a single scour maximum. This agrees with the pier scour development as it has been described in literature (e.g. Roulund, 2005 or Link, 2006).
The free water surface calculation (Figure 6) was included in the numerical simulations, in order to minimize modeling simplifications. The water level increases to 0.31 m on the upstream side of the pier and decreases on the sides of the pier to 0.29 m. This results in a Δh = 2 cm.

6. CONCLUSIONS

A three dimensional numerical model was successfully used to predict pier scour in a rectangular flume. The numerical results agree in magnitude and shape with the measurements. Also the time evolution of the scour maximum is predicted accordingly to the experiments. The numerical model included the effects of incipient sediment motion on sloping beds and sand slides. The general applicability of these algorithms in the context of pier scour has to proven by further testing.

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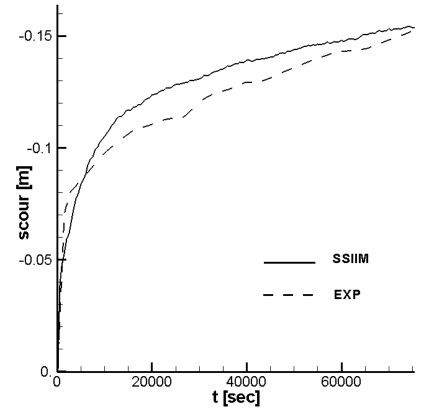

Fig.4 Maximum scour depth over time

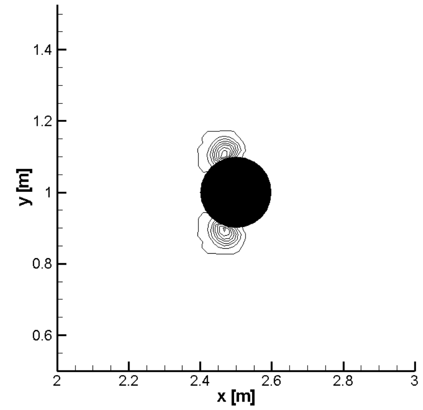

Fig.5 Qualitative modeled scour after two time steps (10 sec.)

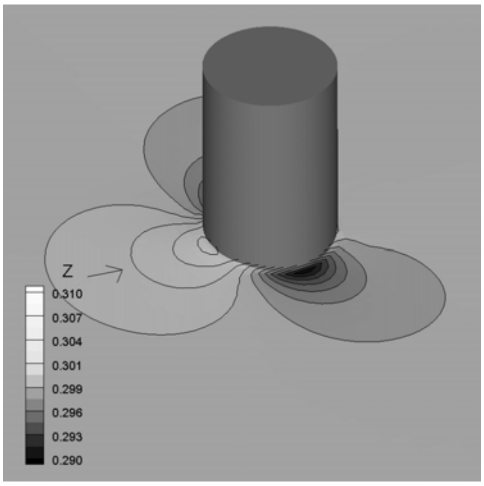

Fig.6 Modeled free water surface around the pier, elevation in [m]

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