CFD simulation of local scour in complex piers under tidal flow

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ABSTRACT

We report the qualitative simulations of local scour in complex bridge piers under tidal flow using the commercial Computational Fluid Dynamics (CFD) model Flow-3D. The model was applied to compute the initial stages of scour development in a complex pier made of a large pile cap and 10 cylindrical piles. Flow-3D was able to correctly reproduce the expected interaction between the piles. The CFD model was also applied to simulate scour in a 3-pile group under tidal flow reversal. The results were in qualitative agreement with measurements reported in the literature, demonstrating that Flow-3D has potential as a hydraulic design tool for complex piers under various flow conditions.

INTRODUCTION

Several bridges are currently under construction or in the final design phase in both the Fraser River and the Pitt River, in Vancouver, Canada. These bridges are relatively large, spanning over channel widths between 300 m and 1000 m and supported on several large piers located on the riverbed. In contrast with older bridges which have massive solid piers, sometime founded on piles, that were normally built using caissons or cofferdams, the new bridge piers are usually built by driving cylindrical piles into the ground from a floating barge. A horizontal pile cap on top of the piles is located at the water surface and it is used to transfer forces from the superstructure down to the piling foundation, and also to provide protection against ship collision. The height of the pile cap is design such that its bottom and top elevations cover the lowest and highest water levels, thus remaining visible for all flow conditions. The geometry of the pile cap and the layout of the piles can be rather complex, not necessarily following the classical bridge pier shape assumed in local scour predictors. Figure 1 shows an example of a bridge pier in the Fraser River with a dumbbell-shaped pile cap over two groups of piles arranged in hexagonal patterns;

33rd IAHR Congress: Water Engineering for a Sustainable Environment

ISBN: 978-94-90365-01-1

while Figure 2 shows a bridge pier in the Pitt River made of rectangular pile cap with rounded ends resting over 10 piles made of two different diameters.

Some analytical formulations exist for computing scour in complex piers. For example, HEC-18 manual (Richardson and Davis 2001) computes the total scour depth as the addition of three scour components produced by the pier stem, pile cap and pile group. The pile group is replaced by a solid pile whose widths is equal to the projected widths of the piles in the group, multiplied by correction factors for the effects of pile spacing and number of aligned rows. Ataie-Ashtiani and Beheshti (2006) studied the effects of pile grouping in local scour (without a pile cap). Their experimental results showed that for very closely spaced piles in a side-by-side arrangement, scour depth can increase 50%; while for a tandem arrangement, scour in the front pile increases, while in the rear shielded pile it decreases. In any case, the scour amplification effect tends to disappear when the spacing S between piles is larger than four times the pile diameter D ($S/D > 4$). However, these formulations assume that the piles are evenly spaced in grid-like layouts, which is clearly not the case on the piers shown in Figures 1 and 2. To complicate the problem even further, the Fraser River and especially the Pitt River are subject to flow reversal caused by tides.

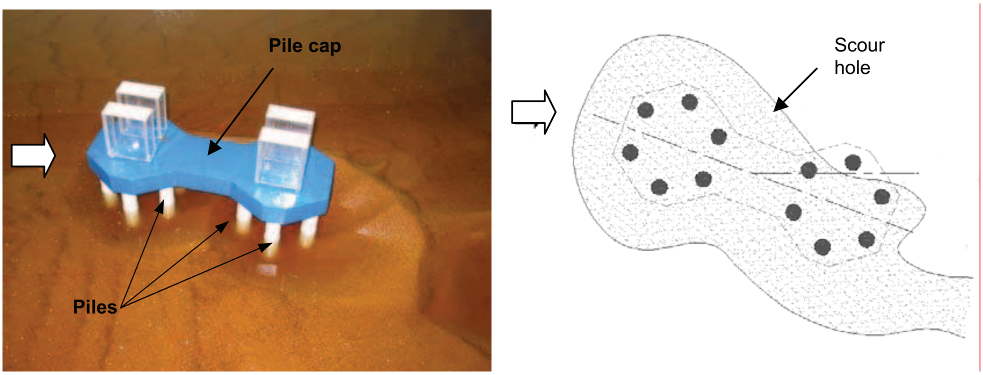

Figure 1. Example of bridge pier with dumbbell-shaped pile cap and hexagonal pile layout, showing also scour hole measured in a physical model.

Tidal scour in bridge piers has not been studied in the same detail as unidirectional scour, although some notable studies on the topic indeed exist. Escarameia (1998) carried out experimental investigation of local scour under tidal flow conditions, assessing the influence of reversal on flow direction, tidal cycle duration, water depth, pier shape, and sediment size on local scour of single circular and rectangular piers. As expected, sediment size had no effect on local scour depth. The maximum scour depth in tidal conditions remained always below the equilibrium scour depth for unidirectional flow if no bedforms were present (clear-water scour). Scour depths for rectangular piers were found to be 10 to 14% smaller than square piers. In square piers the scour holes created upstream and downstream of the pier during the tidal cycle merge, which does not happen if the pier is rectangular. May and Escarameia (2002) studied the temporal evolution of local scour under tidal conditions, using square and sinusoidal tides. They concluded that in clear-water scour the equilibrium scour at hydraulic structures in tidal flows can be significantly less than scour with unidirectional flow. However, in live-bed scour, the equilibrium depths are likely to be close to the unidirectional flow value due to the faster development of scour holes in each tidal cycle and due to the formation of dunes around the structure. Margheritini et al. (2006) conducted experiments of local scour around large diameter piles in unidirectional and tidal flows with sediment movement (live-bed conditions). The final equilibrium scour for both cases was similar. The scour hole in tidal flow was symmetrical, with a circular shape and a volume larger than the unidirectional scour hole.

At present, physical modeling seems as the only practical engineering tool for assessing local scour in piers with complex shapes that do not conform to the assumptions of available scour equations. Three-dimensional (3D) numerical modeling has been applied successfully to reproduce local scour in a single cylindrical pile, but it has not been applied to model scour in complex piers or in pile groups under tidal flow reversal. The objective of this paper is to present preliminary qualitative results of local scour in a real complex pier and in an idealized 3-pile group under tidal flow reversal using a commercially available 3D Computational Fluid Dynamics (CFD) model.

NUMERICAL MODELING OF PIER SCOUR

Since the early work of Olsen and Melaan (1993), several 3D numerical models have been successfully applied to model local scour in a single cylindrical pier (see review by Roulund et al. 2005). However, 3D scour simulations in complex bridge piers have rarely been attempted. There are two probable reasons for that. Most models are based on structured curvilinear boundary-fitted grids that have difficulties to accommodate to the geometry of complex piers. Another important limitation is computational time, which is still today significantly larger than the time required to perform a local scour test in a physical model. Nevertheless, numerical models can provide valuable information and have great potential for the future when computer speed is expected to increase even more. The CFD model used here was Flow-3D, developed by Flow Science in Santa Fe, New Mexico.

Flow-3D is a commercial CFD package with special modules intended for hydraulic engineering applications. Despite using a structured orthogonal grid, it can model complex geometries by the application of the fractional area/volume method (FAVOR), which allows a rectangular computational cell to be partially blocked by an obstacle. Sharp free surface (e.g. hydraulic jumps, free jets in air) are modeled by the Volume-of-Fluid (VOF) method. Flow-3D has also unique capabilities to model local scour, as detailed by Brethour (2001). These capabilities are illustrated in Figure 2, which shows how the model can reproduce the geometry of a complex pier and the initial stages of scour development under clear-water conditions.

The complex pier shown in Figure 2 encompasses a pile cap 51.5 m long, 12.5 m wide and 6.7 m thick with rounded ends. Three distinct pile groups are located below the pile cap. Two groups (U & D) of three 2.4 m diameter piles are located at both upstream and downstream ends of the pile cap, while four smaller 1.8 m piles (C) are located around the center. The bottom of the pile cap is about 13 m above the bed. The numerical mesh was 115 m long, 50 m wide and 22 m high with a uniform cell size of 0.5 m (46,176 cells). The simulations were made for a water depth of 15.8 m, a constant flow velocity of 1.5 m/s and a sediment size of 0.35 mm. Flow-3D was used to assess the influence of pile interference on local scour. Since it was not feasible to perform a long-term simulation because of the excessive computational time required, only the initiation of scour during the first hour was simulated.

When the relative spacing S/D between the piles is taken into account, Flow-3D results shown in Figure 2 are in very good agreement with experimental observations regarding the interaction between piles reported by Ataie-Ashtiani and Beheshti (2006). The results suggest that the C piles around the center of the pier behave more like 2 pairs in tandem. It appears to be no interference between the 2 pairs of piles at the left and right sides (C1-C2 and C3-C4, $S/D = 4$); while pile C1 (C2) appears to shield pile C3 (C4) from scour ($S/D = 2.3$). Figure 2 also shows that the scour holes of the 3-pile groups U and D at both ends of the pile cap have already merged, suggesting a strong interaction between the 3 piles ($S/D = 0.9$). Also, the 3-pile group U does not seem to shield the smaller piles C ($S/D > 5$).

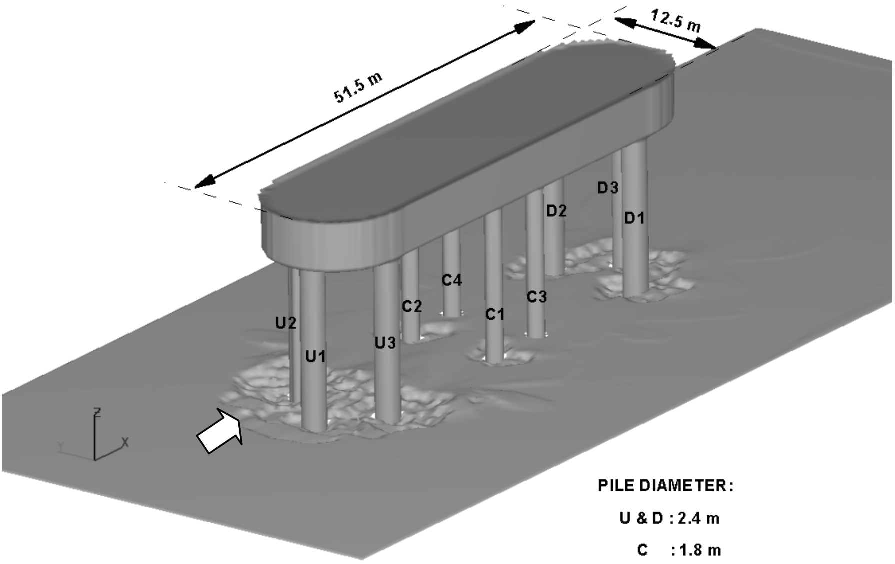

Figure 2. Initial scour development computed by Flow-3D in complex pier.

Although the maximum equilibrium scour depth could not be computed, the insight gained on the interaction between the piles and the pile cap in such a complex pier is still valuable for the understanding of the scour process and the potential design of scour countermeasures.

MODELING TIDAL SCOUR OF PILE GROUP

In order to assess the potential effects of unsteady tidal flows, qualitative simulations using Flow-3D were carried out. Since it was not feasible to simulate an entire pier, an idealized 3-pile group (without a pile cap) was reproduced using a coarse mesh. The diameter of the cylindrical piles was 2 m, arranged in a triangular pattern with a minimum spacing S/D = 0.95. The mesh cell size was 0.5 m. Such a mesh size does not provide enough resolution to solve all the 3D details of the flow around the piles, but was deemed necessary to keep computational time at manageable levels. Therefore, these preliminary simulations are qualitative and have an exploratory nature meant to roughly assess the capabilities of Flow-3D.

The channel was 40 m long, 16 m wide and 6.5 m high. The first and last 10 m at the inlet/outlet were made of a solid rough bed to allow the full development of turbulent flow. The central part of the channel, where the 3 piles were located, was made of 0.75 mm sand. The water depth was 2.5 m. The tidal reversal in flow velocity was simulated using square and sinusoidal tides (Figure 3); the square tide has been used in experiments by Escarameia (1998) and Margheritini et al. (2006). For the unidirectional flow, the peak of the tide (2 m/s) was used.

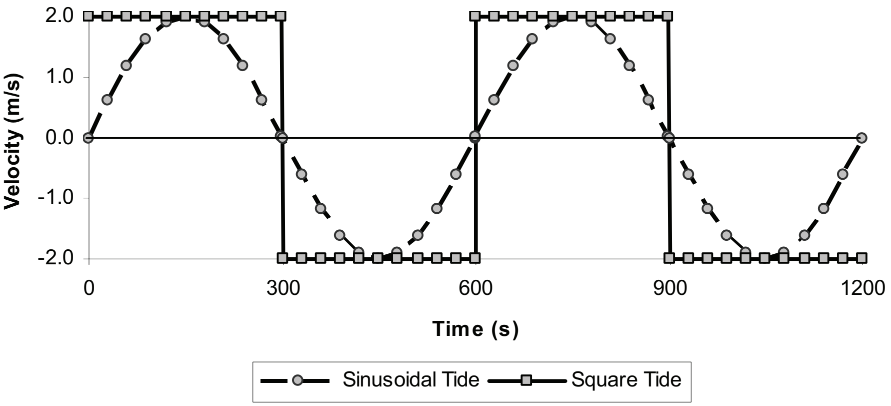

Figure 3. idealized tidal velocity used for numerical simulations.

Longitudinal bed profiles along the channel centerline at 900 s are shown for unidirectional flow and sinusoidal tide in Figure 4; while Figure 5 shows a sequence of 3D images every 300 s for the square tide scenario, the arrow signals the flow direction. Finally, the temporal evolution of scour for the three flow scenarios is shown in Figure 6.

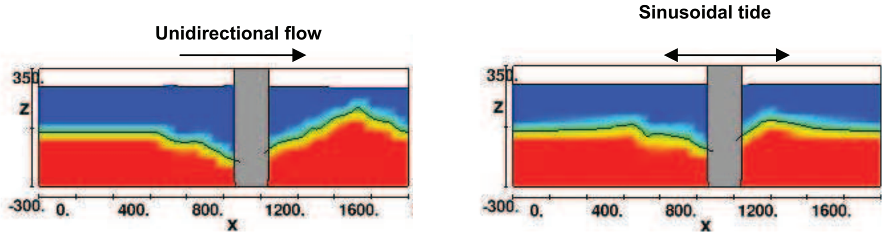

Figure 4. Computed centerline bed profiles after 900 s for unidirectional flow (left) and sinusoidal tide (right).

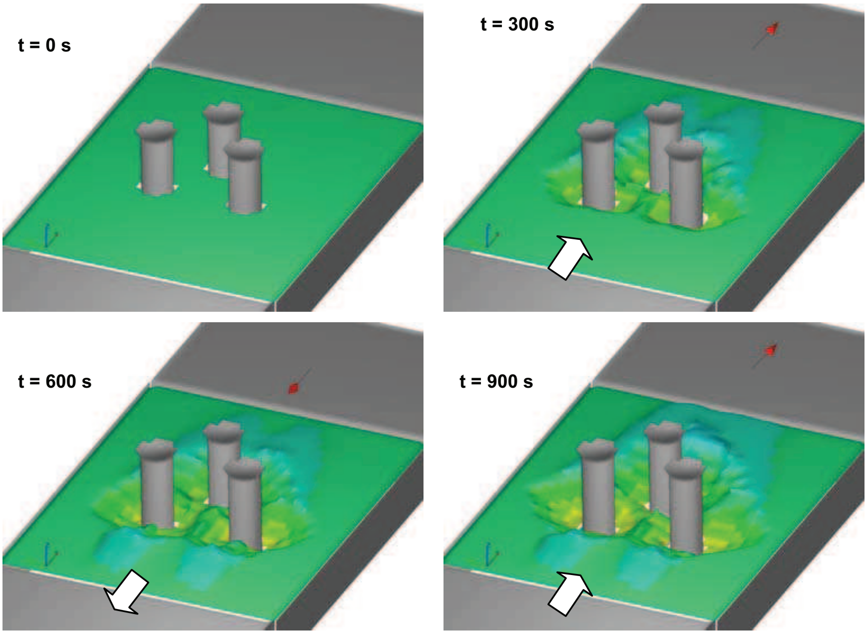

Figure 5. 3D view of scour under square tide conditions (every 300 s).

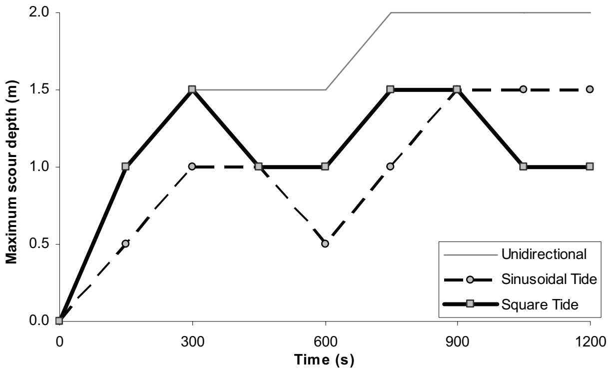

Figure 6. Temporal evolution of maximum scour depth under steady and tidal flow conditions (grid resolution is 0.5 m)

Qualitatively, the model correctly reproduces the expected scour behavior. In unidirectional flow, scour develops upstream, while sediment accumulates behind the piles (Figure 4). In tidal conditions, flow reversal temporarily fills the scour holes developed in the previous tidal cycle. The computed temporal evolution of scour (Figure 6) resembles that of experiments by Margheritini et al. 2006. Tidal scour initially increases, but as the flow reverses it slightly decreases to grow up again in the next cycle. Flow-3D predicted that for the clear-water conditions of the simulation, tidal scour is slightly lower than unidirectional scour, in agreement with Escarameia (1998). However, the exact magnitude of scour reduction can not be precisely resolved because of the coarse 0.5 m mesh resolution employed. Also, the model was not run long enough to achieve an equilibrium scour depth.

CONCLUSION

Flow-3D is probably the first CFD commercial model with capabilities for modeling local scour in complex structures, without the usual limitations of structured boundary-fitted grids. When applied to a complex pier made of a large pile cap and several piles, Flow-3D was able to correctly predict the interaction between the piles, demonstrating its potential as a design tool for real engineering applications.

Qualitative simulations of an idealized 3-pile group under clear-water tidal flow using Flow-3D showed that the scour depth decreases under tidal conditions with flow reversal, compared to that of unidirectional flow with the same peak velocity. Those numerical results agree with experimental data. However, additional research using finer grids is needed to quantitatively verify the model.

At present, the main practical limitation of Flow-3D, and CFD models in general, is computational time. If a very large grid is needed for modeling the structure, computing long-term equilibrium scour may require an exorbitant amount of computational time, much larger than that required for running a physical model.

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