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The Scour Bridge Simulation around a Cylindrical Pier Using Flow-3D

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ABSTRACT

Scour simulation is a way to prevent a bridge against the possible major damages. In this study, local scouring around a cylindrical pier in non-cohesive bed sediment was simulated with the aid of Flow-3D model capabilities. A rectangular channel with 0.4 m width and 1.0 m length and a vertical cylindrical pier with diameter of 0.03 m and height of 0.3 m were specified for simulation of scour depth. Simulations were performed at different flow rates of 5, 10, 19 and 30 L/sec., separately and parameters of flow velocity, fluid depth, Froude number, packed sediment height and changes in net sediment motion were investigated. According to the results obtained from the simulations and after 600 sec., maximum scour depths for different inflow rates were equal to 0.0, 1.3, 2.4 and 3.6 cm for 5, 10, 19 and 30 L/sec., respectively. It was also observed that the scour depth was comparatively higher in upstream while it was lower in downstream part of the pier. Comparisons between the simulated and observed scour depths, however, showed underestimates of 30% to 20% for upper and lower parts of the pier, respectively.

1. Introduction

Scour or the removal of material from the bed and banks of streams and near the piers and abutments, always occurs due to flow acceleration, turbulence and erosive action of flowing water (Soltani-Gerdefaramarzi et al., 2013a and 2014). This process is affected by a large number of variables, mainly, the flow, fluid, pier and sediment characteristics. It can be divided into three main forms of general scour, contraction scour and local scour (Soltani-Gerdefaramarzi et al., 2013b). However, general scour (or evolution of the waterway) occurs naturally in river channels by aggradation and degradation of the river bed. A change in the river hydraulic parameters is known as the major cause for this type of scouring. Contraction scour occurs by reduction of channel's cross-sectional area at the location of water structures (like bridge piers and abutments) that increases the flow velocity and bed shear stresses and finally, transport of the bed sediments (Briaud et al., 2012). Local scour is the third type of scouring that occurs in the vicinity of bridge piers or abutments. In such a scouring, downward flow is induced at the upstream end of the pier and leads to a localized erosion around the pier. It depends on the balance between streambed erosion and sediment deposition (Prendergast and Gavin, 2014).

Based on this fact and the mode of sediment transport in the approaching flow, two types of local scour can be distinguished, namely clear water scour and live bed scour. In clear water scour, no sediments are delivered by the river approaching flow, while an interaction exists between sediment transport and the live bed scour process. Local type of scour has long been acknowledged as a major cause of the bridge failures around the world, causing major human and financial losses. For example, Alabi (2006) reported that the average cost for flood damage repair of the United States highways was $50 million per year. Additionally, it was estimated that at least $20 million have been invested on scour research in the United States in the last two decades (Briaud et. al, 2012). Alabi (2006) also cited that the associated repair costs of the bridge collapse in 1993 (due to scour) in the upstream Mississippi and downstream Missouri river basins were more than $8,000,000. Considering more severe and more frequent floods due to climate change, it is gaining an ever-increasing importance to mitigate the risk of bridge failure (Prendergast and Gavin, 2014).

Monitoring of the local scour is a way to avoid major damages that may occur (Elsebaie, 2013) and to ensure the continued safe operation of the structure. But, most traditional monitoring techniques are based on installation of expensive underwater devices that may be damaged during a flooding event, when the highest risk of scouring exists. In such circumstances, computerized simulation of the scour occurrence can be introduced as a low cost/time consuming alternative for the prediction of the probable failures. The application of simulation software is in many ways similar to the set-up of an experiment, in which Computational Fluid Dynamics (CFD) methods are always used for the simulation of flow process by discretization and solving of Navier-Stokes and continuity equations for the

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computational cells. Flow-3D (Flow Science, Inc., 2007) is CFD software that employs numerical techniques to solve the fluid motion equations to obtain transient, three-dimensional solutions to multi-scale, multi-physics flow problems. An array of physical and numerical options allows users to apply Flow-3D to a wide variety of fluid flows and heat transfer phenomena. This software is widely in use for solving different hydraulic problems. For example Jafari et al. (2017) simulated flow pattern around inclined bridge group pier using Flow-3D Software. The results showed that the maximum shear stress occurred when the foundation level was at the bed level and the maximum shear stress exerted on the bed decreased by factors of 17% and 53% in the cases of foundation level to be below and above bed levels, respectively. In addition, the amount of vortex flows increased in upstream piers group and near bed in the case of setting the foundation above the bed. This is because of the fact that the volume of piers group acting as an obstacle against flow was more than other level settings. Ramezani and Babagoli Sefidkoohi (2016) compared experimental results and numerical simulation of bed shear stress around bridge abutment in a compound channel by Flow-3D model.

In this study, scour simulation around a cylindrical pier will be further discussed. The main purpose of this study is to evaluate the model's ability for simulation of scour-hole depth for non-cohesive sediment conditions under various inflow rates. For this purpose, the results of Flow-3D are compared with the experimental data.

2. Methodology

Flow-3D uses the Volume of Fluid (VOF) method to track fluid-fluid or fluid-sediment interfaces for solving the nonlinear Navier-Stokes equations in a three dimensional space. Also, Fractional Area/Volume Obstacle Representation (FAVOR) method is used to illustrate the complex boundaries of the solution domain. Flow-3D also allows for several turbulence closure schemes to be incorporated and tested. These closure schemes include simple eddy viscosity, one-dimensional Prandtl mixing length, two-equation k-e, large-eddy, and four-equation Re-Normalized Group (RNG) models. The 3D-CFD model implemented in Flow-3D represents a conventional river channel with 0.4 m-wide rectangular inlet with the length of 1.0 m. A vertical cylindrical pier with the diameter of 0.03 m and height of 0.3 m was inserted in the center of the channel as a solid standard component. A packed sediment type component was used for the channel bottom with dimensions of 1.0, 0.4 and 0.12 m for length, width and height, respectively. Particle size diameter was 0.72 mm with a density of 2650 kg/m^3 with critical shields number of 0.031 and drag coefficient of 0.5. A mesh block of 20000 cells was fitted to the model geometry. To increase the model accuracy around the pier, two mesh planes with finer resolutions were defined for both sides of the pier in *x* and *y* directions, separately. Also, two solid components were settled at the outer sides of the geometry (both for beginning and end parts of the channel) to prepare an inflow bottom at the top edge of the sediment (elevation of 0.12 m) in order to prevent against upward movement of sediments in the beginning of simulations. Boundary conditions were volume flow rate at the inlet, outflow at the outlet, wall on the bottom, right and left sides, and symmetry on the top of the block. Figure 1 and Table 1 show the model geometry and meshing structure, defined in model setup tab of Flow-3D software.

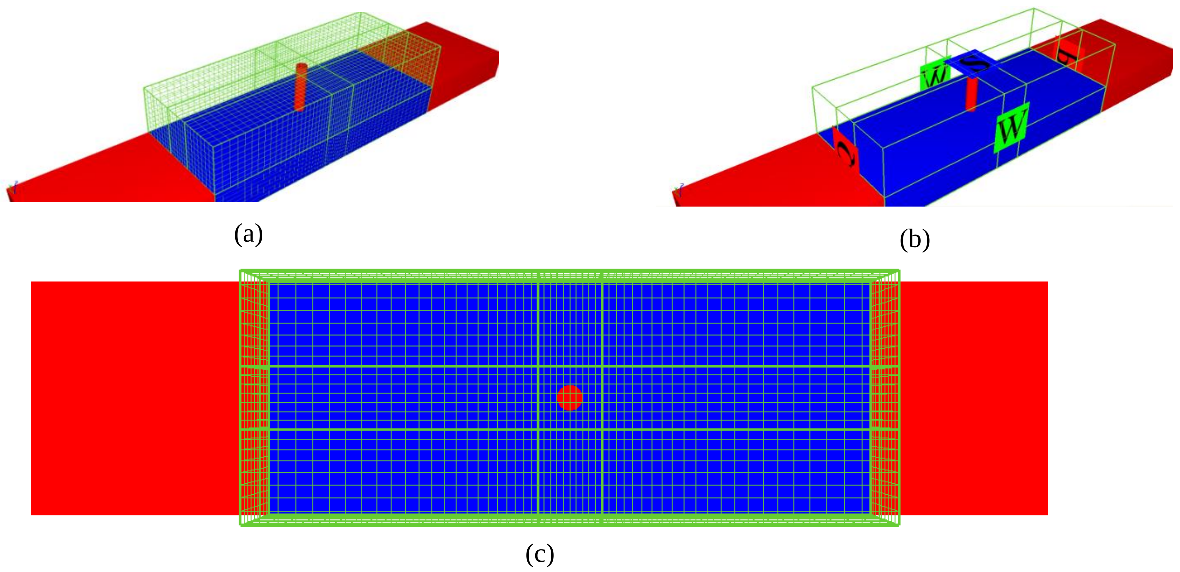


Figure 1. Geometry and meshing structure of the model for simulation of scour around a cylindrical pier

Table 1. Meshing and geometry of the model

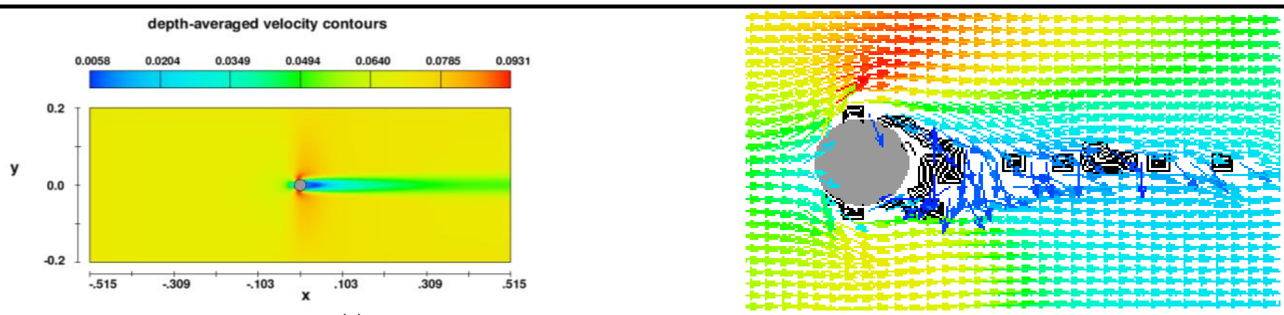
Mesh cell number	Sediment size (mm)	Density of sediment (kg/m^3)	Pier diameter (mm)	Channel width (m)	Turbulent model
20000	0.72	2650	30	0.4	Re-Normalized Group (RNG)

For simulation, turbulent model of Re-Normalized Group (RNG) was specified (Ramezani and Babagoli Sefidkoohi, (2016) indicated that the RNG model had a better agreement with experimental observations), surface tension and wall friction were neglected, and the simulations were performed at different flow rates of 5, 10, 19 and 30 L/sec. separately. Simulations were performed with Flow-3D solver version 10.0.1.3 with four processors of a 64-bit laptop operating system. Additionally, existing laboratory measurements (Heidarpour et al., 2010) were incorporated to compare the results of Flow-3D with the experimental data. The channel and pier dimensions for this study were specified as same as the above mentioned dimensions. In their investigation, only the results of one inflow rate (19 L/sec.) were accessible in which maximum scour depths for upstream and downstream points (before and after the cylindrical pier, respectively) at times of 50 minutes and 52 hours were measured as well (Heidarpour et al., 2010). In their study, it was investigated that 19 L/sec. can be regarded as a threshold inflow for scour occurrence in the specified channel dimension. In this study, the Flow-3D simulations were performed during a 10-minute running time for four inflow rates of 5, 10, 19 and 30 L/sec. separately, and then were extended to 50 minutes for the inflow rate of 19 L/sec to compare these results with experimental data.

3. Results and Discussion

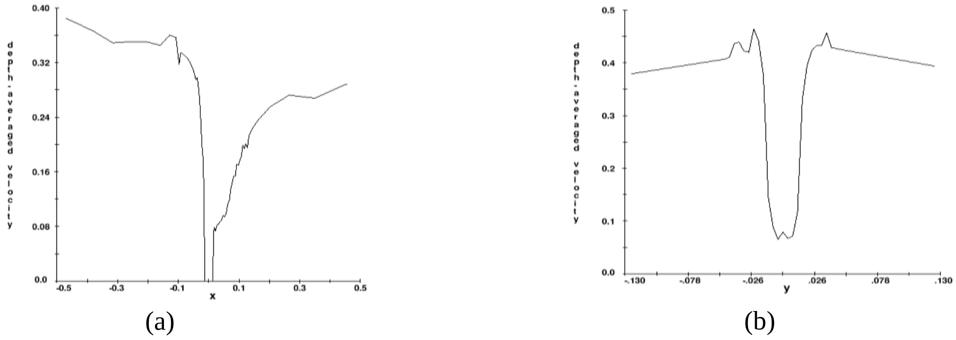
Figure 2 shows the general pattern of depth averaged velocity contours around the cylindrical pier as an obstacle. As shown, higher velocities can be observed in both sides of the pier, while the lower values exist in front side of the pier and more extensively, in the downstream parts. Downward flow at the upstream side, horseshoe vortex, and vertical wake vortices would be the results of these considerable velocity and pressure gradients. Similar observations were reported by Soltani-Gerdefaramarzi et al. (2013b). They reported that at downstream of pier and near and rear of the cylinder, the longitudinal velocity is small and negative showing flow reversal towards the water surface. Moving from water surface, streamwise component velocity becomes positive and increases but decreases within the scour hole.

To see the magnitude of velocity gradient, depth averaged velocity profiles for longitudinal and transverse channel directions were plotted (Figure 3) for an inflow rate of 30 L/sec. as an example. Considering the pier orientation (x=0), higher and lower velocity values can be observed and compared together spatially. The velocity profile shapes would be the same for other inflow rates, but would vary in their values. As shown (Fig. 3b), maximum velocity values can be seen across the channel and besides of the pier, where two red hot spots can be distinguished in Figure 2a. Soltani-Gerdefaramarzi et al. (2013b) showed that the longitudinal velocity (u-component) decreases away from the water surface, and becomes negative in the scour hole (z < 0), notably close to the bed layer where these results agree with their results. As shown, when there is an obstacle and the inflow rate is increasing, the flow depth fluctuation increases, especially near the pier.



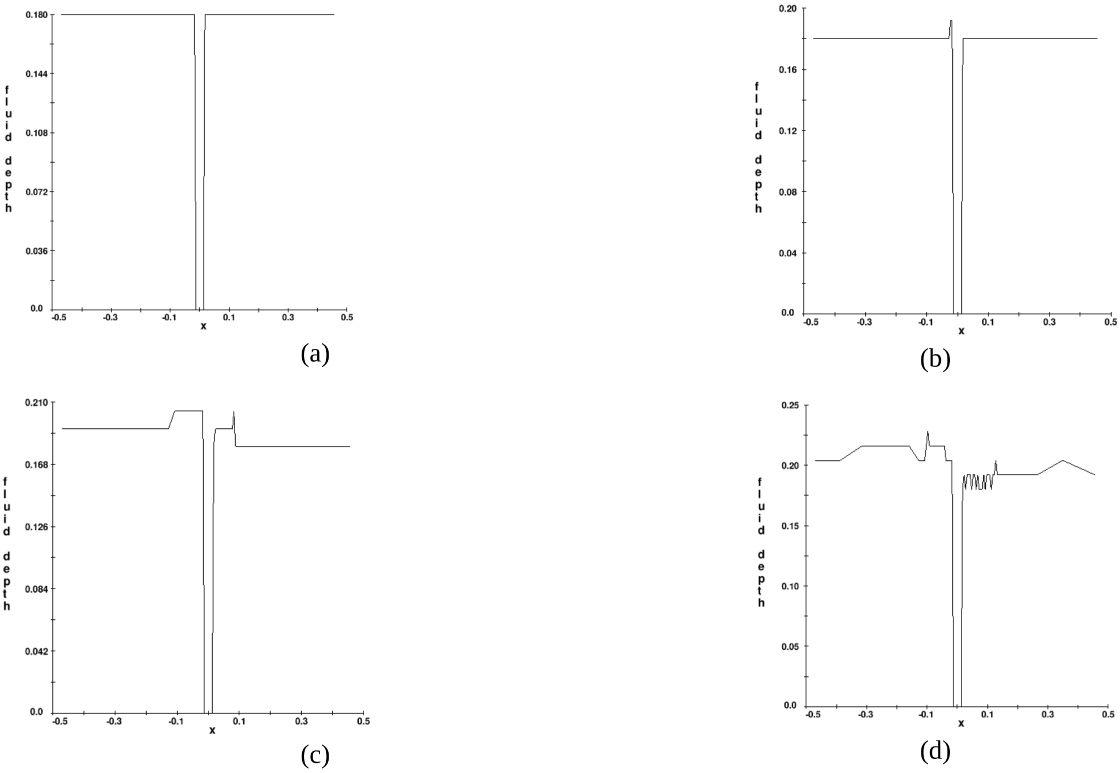
(a) (b)

Figure 2. (a) Longitudinal depth averaged velocity contours and **(b)** velocity vectors' alignment around the cylindrical pier after 600 sec. of simulation with Flow-3D software



(a) (b)

Figure 3. Depth averaged velocity profiles for longitudinal **(a)** and transverse **(b)** channel directions for an inflow rate of 30 L/sec.



(a) (b) (c) (d)

Figure 4. Longitudinal changes of fluid depth at time of 600 sec. for different inflow rates: **(a)** 5 L/sec., **(b)** 10 L/sec., **(c)** 19 L/sec. and **(d)** 30 L/sec.

Longitudinal changes in flow depth for various inflow rates of 5, 10, 19 and 30 L/sec. can be observed in Figure 4. As is evident, the flow rate of 30 L/s had the highest flow depth and the flow depth reached 20 cm approximately.

Considering the flow velocity and depth, Froude number (F_r) was be formulated and simulated around the mentioned cylindrical pier. Figure 5 shows longitudinal changes of Froude number for various inflow rates, after elapse of 10 minutes from the simulation starting time. Vertical axis values show that the inflow rates are subjected to demonstrate a laminar flow condition for both upstream and downstream parts of the channel (F_r<1). Generally, lower F_r values occurs at downstream part, just behind the pier (x<0.1) and the absolute F_r value depends on the flow velocity and depth at that time and section. These changes can alter the sediment height, especially around the pier, as illustrated in Figure 6. In this figure, velocity magnitude can be found as colored arrows, in which red, green and blue ones show the high, medium and low velocity values, respectively.

Considering 2D illustration of sediment condition at different inflow rates (at time of 600 sec.), it is obvious that sediment transportation and movement can be observed for higher inflow rates (e.g. 30 L/sec.) as compared to lower values at the mentioned time. Additionally, initial point of scouring can be specified in upstream part of the pier (-0.1<x<0). It is also considerable that the scour depth is comparatively higher in upstream, while it is lower in downstream part of the pier. Reasons of such occurrence can be ascribed to downward flow at the upstream side of the pier, horseshoe vortex and vertical wake vortices that lead to velocity and pressure gradients and therefore, sediment movement in the channel. As Soltani-Gerdefaramarzi et al. (2013b) showed, vertical velocity (w-component) is always positive in the downstream of the pier and that it starts to diminish and get reversed as it approaches the water surface. Accordingly, the formation of positive wake vortices at the rear of cylinder causes the bed material remove from the bed, deepening scour hole.

According to the results obtained from the simulations and 600 sec. after the beginning of the simulations, maximum scouring depths were equal to 0.0, 1.3, 2.4 and 3.6 cm for 5, 10, 19 and 30 L/sec. inflow rates, respectively. These results show the formation of a deeper scour hole associated with tests conducted with a higher flow rates. This is consistent with the results found in literature, e.g., Soltani-Gerdefaramarzi et al. (2013a). As stated before, the Flow-3D simulations were extended to 50 minutes for the inflow rate of 19 L/sec. Figure 7 demonstrates progressive sediment condition at different time intervals from the beginning (0 sec.) to the end (3000 sec.) of simulation process, respectively. Location of sediment scouring can be distinguished in the Flow-3D simulation results. As shown, scour of sediments starts from upper side of the pier (-0.1<x<0) and then develops to the whole upstream channel and finally advances to the channel full length. Quantitatively, Figure 8 illustrates temporal changes of packed sediment height as well.

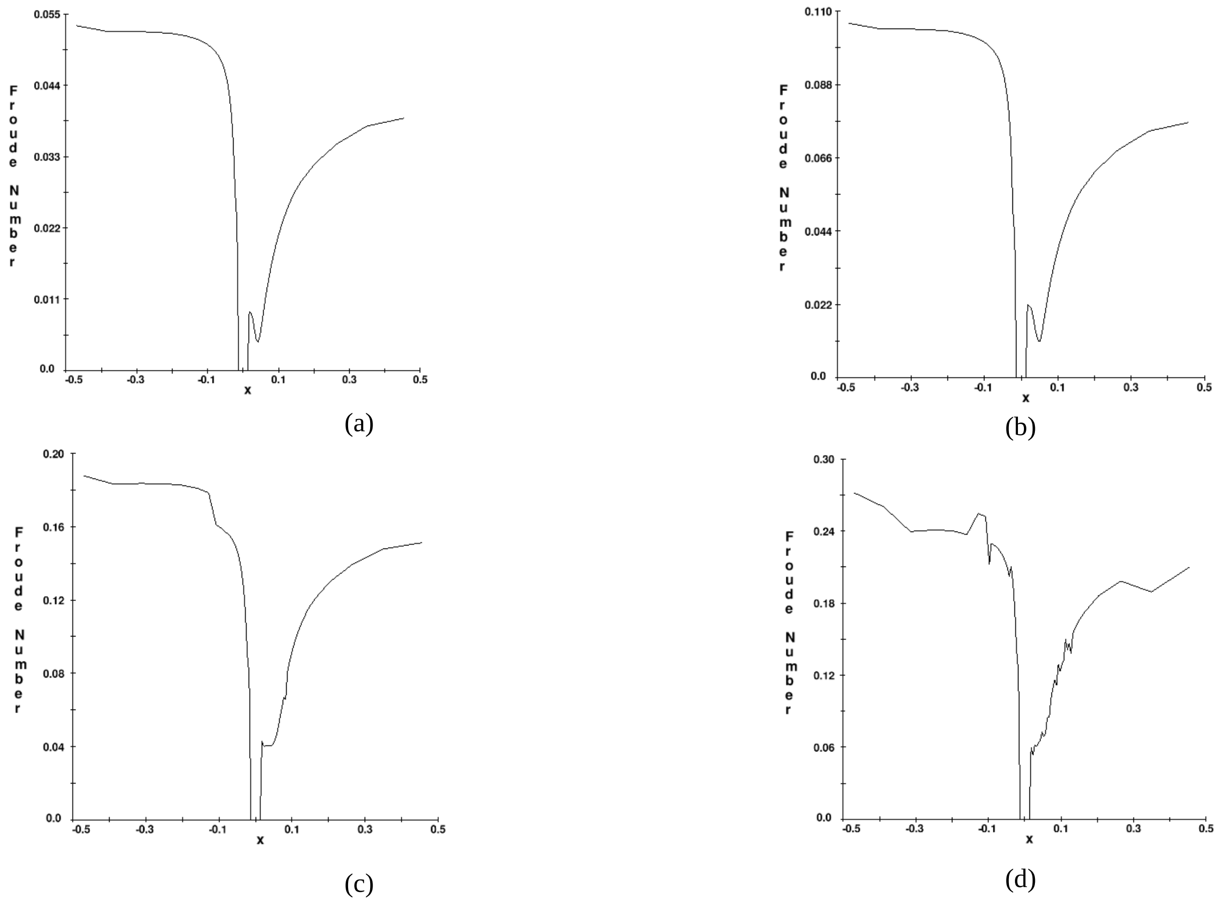
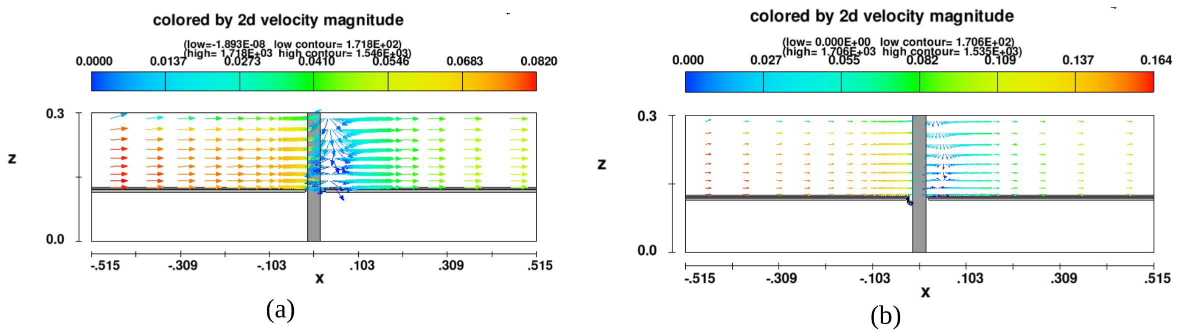
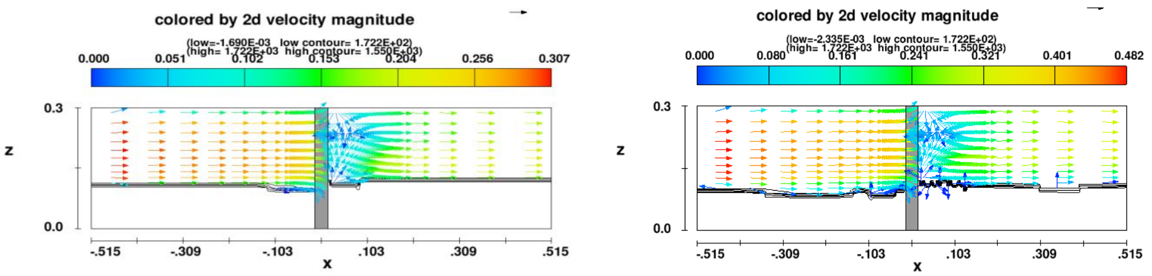


Figure 5. Longitudinal changes in Froude number for different inflow rates: **(a)** 5 L/sec., **(b)** 10 L/sec., **(c)** 19 L/sec. and **(d)** 30 L/sec.





(c) (d)

Figure 6. 2D demonstration of packed bed sediments across the channel length at time of 600 sec. for different inflow rates: **(a)** 5 L/sec., **(b)** 10 L/sec., **(c)** 19 L/sec. and **(d)** 30 L/sec. (colored arrows show the velocity magnitude)

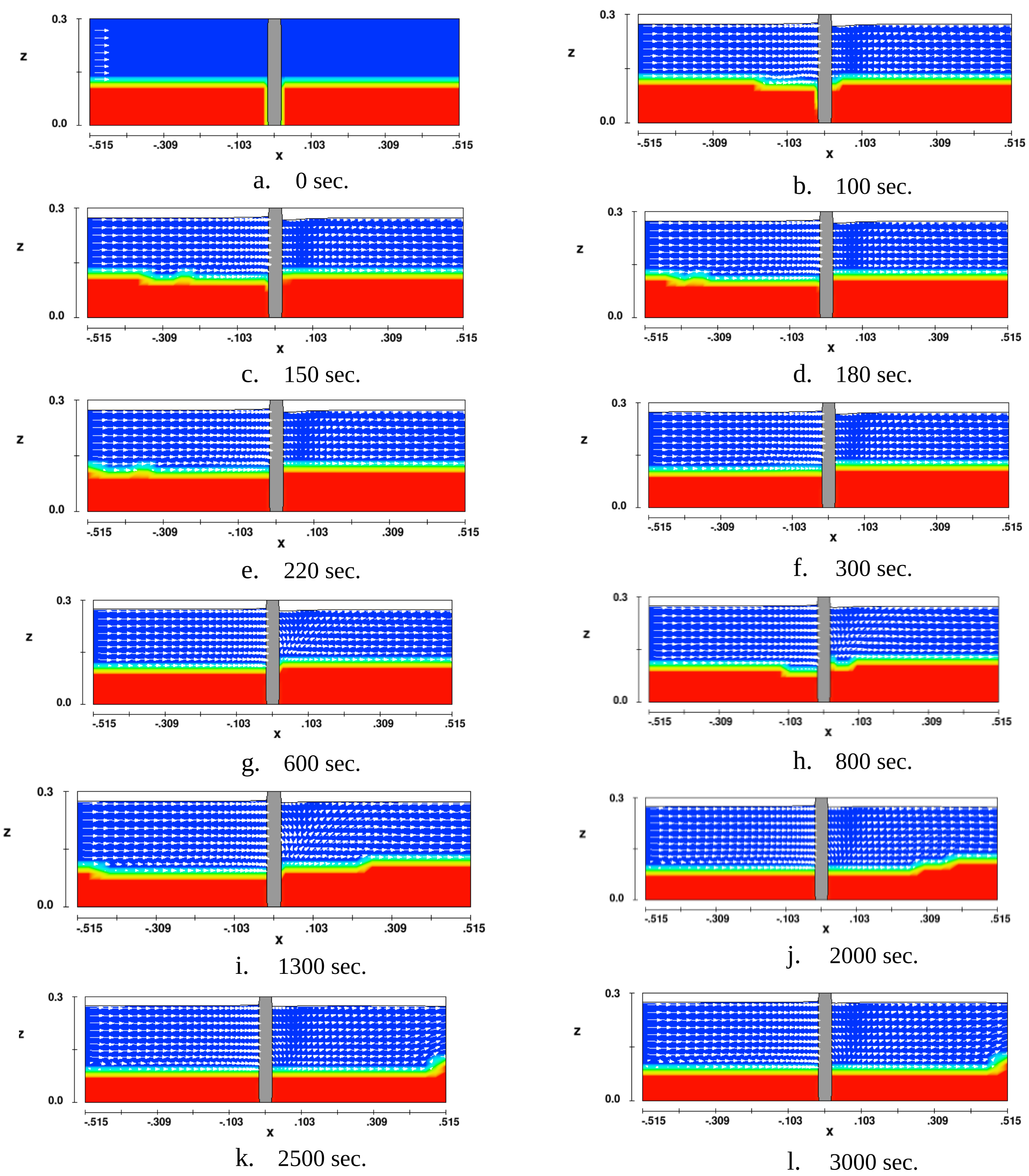


Figure 7. 2D demonstration of progressive packed bed sediments for inflow rate of 19 L/sec

Based on these figures, longitudinal changes of sediment height can be compared with initial value of 12 cm (Figure 8a), at different time intervals. Also, scour depth and location can be distinguished. Some constraints, however, exist in the comparisons due to automatic changes of scale and value in the vertical axis. But it would be obvious that scouring process starts from upper side of the pier (Figure 8b) and then develops to the whole upstream channel (Figure 8c) and finally to the channel full length (Figure 8h). Results also indicated that sedimentation and scouring progresses turn into stable condition after elapse of a short time (about 25 minutes). This short converging time can be considered a challenge of Flow-3D model for scour simulation. In such a condition, laboratory measurements have reported a time of 50 minutes for completion and stability of these processes.

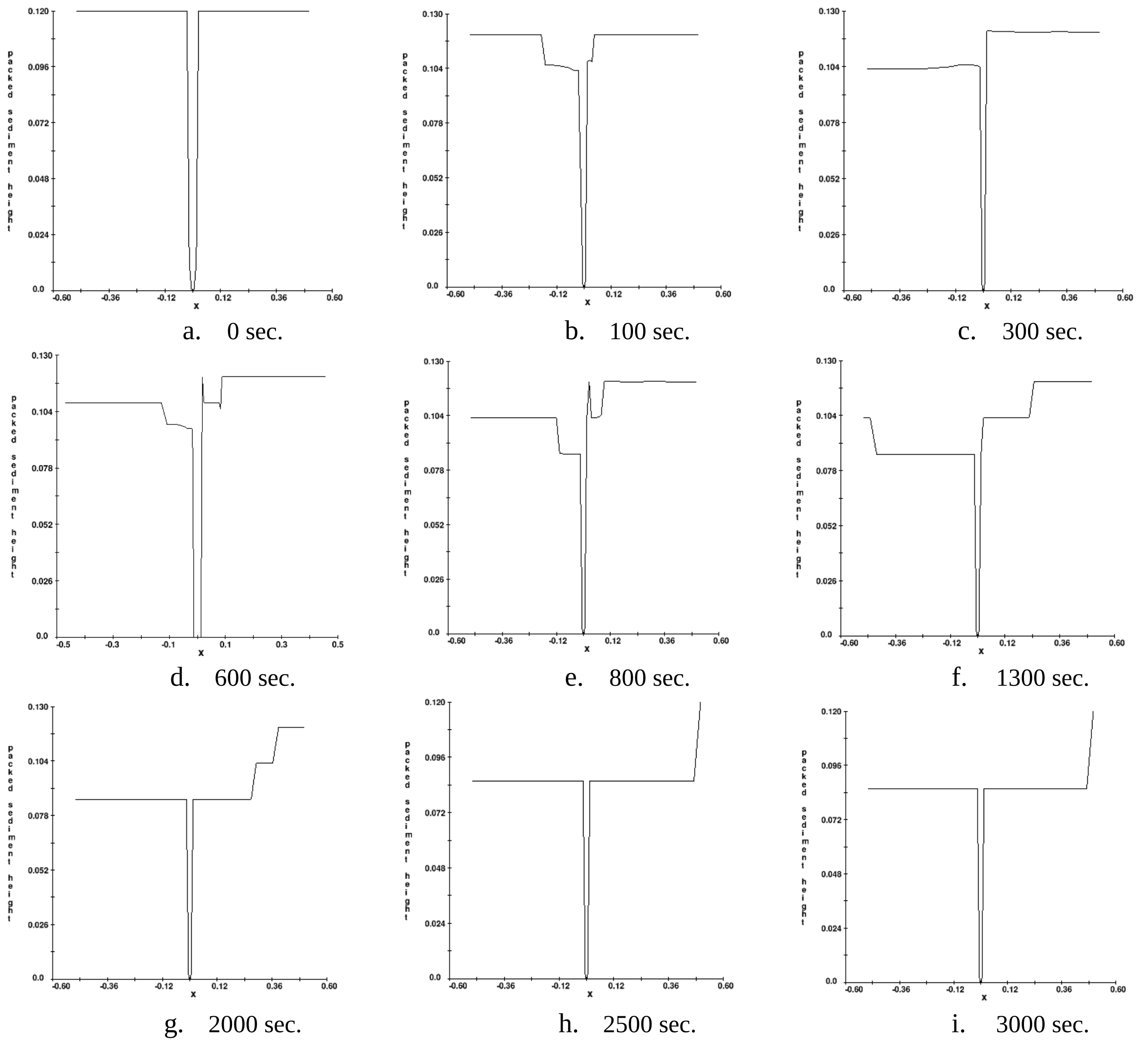
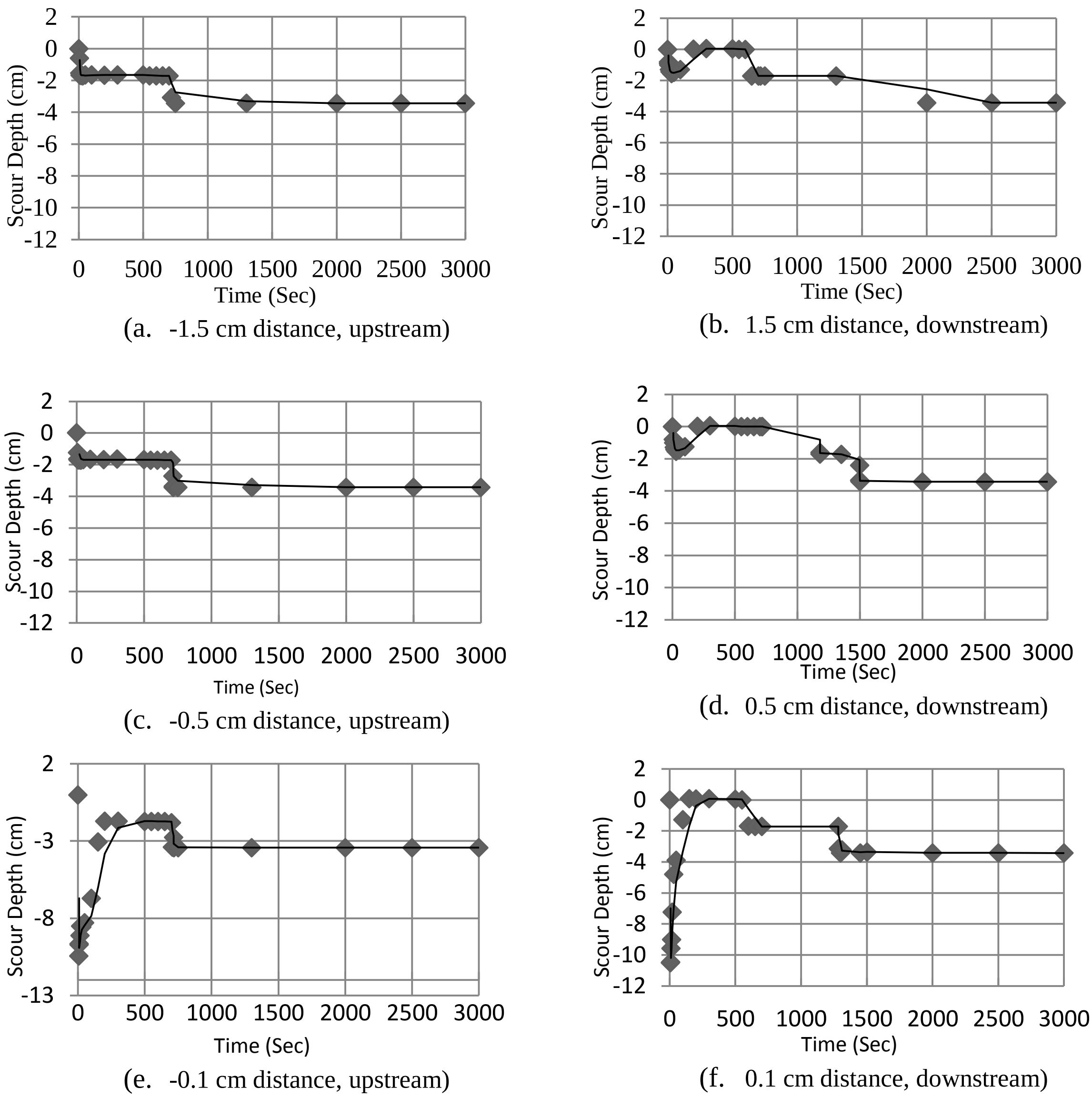


Figure 8. Longitudinal changes of packed sediment height at different time intervals for inflow rate of 19 L/sec.

Figure 9 shows temporal changes of sedimentation /scouring depth at six cross-sectional points, depending on upstream/downstream flows and distance from the pier. In upstream channel (Figures 9a and 9.c), abrupt scour was observed in the beginning of the simulation; with a depth of 1.5 cm. Sediment height was relatively constant in 12.5 minutes. Afterwards, second and final abrupt scour occurred with a depth of 1.9 cm to reach out the sediment scour height to 3.4 cm. Similar events were observed for downstream channel (Figures 9b and 9d), but with a short lag time. Furthermore, sedimentation was observed at time of 100 seconds and behind the pier. Sedimentation depth was about 1.5 cm and lasted to time of 10 minutes. Afterwards, scouring with 1.7 cm depth was observed and lasted to time of 22 minutes. Sediment scour height, then, extended to 3.4 cm and followed a constant value to the end of simulation period. Based on the laboratory measurements, scour depth in upper and lower parts of the pier were 4.8 and 4.3 cm, respectively. Comparisons between simulated and observed scour depths, however, showed underestimates of 30% to 20% for upper and lower parts of the pier, respectively.



(a. -1.5 cm distance, upstream)
(b. 1.5 cm distance, downstream)
(c. -0.5 cm distance, upstream)
(d. 0.5 cm distance, downstream)
(e. -0.1 cm distance, upstream)
(f. 0.1 cm distance, downstream)

Figure 9. Temporal changes of sedimentation/scouring depth for upstream and downstream flows at different distances from the pier

4. Conclusion

According to the results obtained in this study, it was concluded that Flow-3D is a capable model for simulation of different flow attributes (velocity, Froude number and depth) with/without the presence of an obstacle (like bridge pier) at different dimensions of 1D, 2D and 3D as well. But it has some constraints for simulation of sedimentation/scouring processes. In this study, underestimates of 20-30% were observed for simulation of scour depth around a cylindrical bridge pier. Some existing literatures expressed such similar underestimates (Abdelaziz et al., 2010; Smith, 2007; Yildiz et. al., 2013).

Flow-3D employs nonlinear Navier-Stokes equations, while specific equations exist in this field (Melville and Sutherland, 1988) that can be used for better simulation of scour process. Moreover, it seems that the involvement of a threshold value for sedimentation of suspended particles (like gravity or density of particles) can cover some constraints of these equations for the simulation of sedimentation and scouring processes. Moreover, some of the constraints refer to Flow-3D operating time for running a simulation process. It sometimes exceeds 278 hours for an 8-hour scour simulation project (Yildiz et al., 2013). Number and size of mesh and geometry can, however, alter the time of operation, but these parameters should be adjusted at least to appropriate values to obtain acceptable results. Other simulation models (SSIIM by Olsen, 2007) can be recommended as alternatives to such similar studies.

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