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Investigation of Live-Bed Scour Around Circular Bridge Piers Under Flood Waves by Using Flow-3D

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Abstract

In this study, an experiment concerning live-bed scour around circular bridge pier under unsteady flow conditions and its simulation performed by using the software FLOW3D are presented. Different turbulence models such as LES, RNG and two equations $k-\epsilon$ were tested separately and their effects on scour process were compared to each other, together with experimental findings. It was revealed that the LES turbulence model simulated better the scour around the pier while the RNG turbulence model simulated better both the scour in the wake region and the sediment transport. All these three turbulence models underestimated the scour depths compared to the experimental ones.

Key words

Live-bed Scour, Bridge Pier, Flood Waves, Flow-3D

1. INTRODUCTION

Local scour around bridge piers was registered as the most important reason for the bridge failures [1]. The mechanism of the local scour plays an important role in the design of the bridge foundations and the determination of the protection measures. There are many theoretical and experimental studies performed to enlighten the mechanism of the local scour, to predict the geometry of the scour hole and to evaluate the safety precautions ([2], [3], [4], [5], [6], [7] etc). Channel bottom slope, grain diameter, grain uniformity, flow characteristics, type and shape of the foundation etc. and the relationships between these parameters can differ significantly and result in numerous combinations. It would be extremely inconvenient to study all these combinations experimentally, and the financial burden would be very heavy. Therefore, it is more convenient to perform 3D numerical analyses with different combinations, as performed by various researchers in recent years.

Local scour is investigated under two headings; clear water scour, without sediment motion in the channel and live-bed scour at which sediment moves in the channel and feeds the scour hole during the scour process. Live-bed scour studies are quite rare compared to those performed in clear water conditions and there are very few live-bed scour investigations performed under unsteady flow conditions.

In this study, an experiment concerning live-bed scour around circular bridge pier under unsteady flow conditions and its simulation performed by using the software FLOW3D are presented. Different turbulence models such as LES, RNG and two equations $k-\epsilon$ were tested separately and their effects on scour process were compared to each other, together with experimental findings.

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2. EXPERIMENTAL SET-UP

Experiments were carried out in a tilting flume 18.6 m long, 0.8 m wide and 0.75 m deep constructed in the Hydraulic Laboratory of Dokuz Eylul University Civil Engineering Department, within the scope of the project TÜBİTAK 106M274. The channel bottom slope was equal to 0.006. A schematic view of the flume is given in Figure 1 (a).

The circular pier of diameter 4 cm was placed at the 12th meter of the flume. The first 8 m and the last 5 m of the flume were filled with 20 cm thick gas concrete blocks. After the 3rd meter of the flume, the flume was covered with non-rippling sediment having 1.63 mm median diameter (d_{50}) and 1.303 geometric standard deviation (σ_g) to form a bed 25 cm thick.

Scour depth around the bridge pier was measured by Ultrasonic Velocity Profiler (UVP). Three transducers were located as follows: one at the upstream of the pier (T2) and two at the flanks of the pier (T1 and T3), as shown in Figure 1 (b).

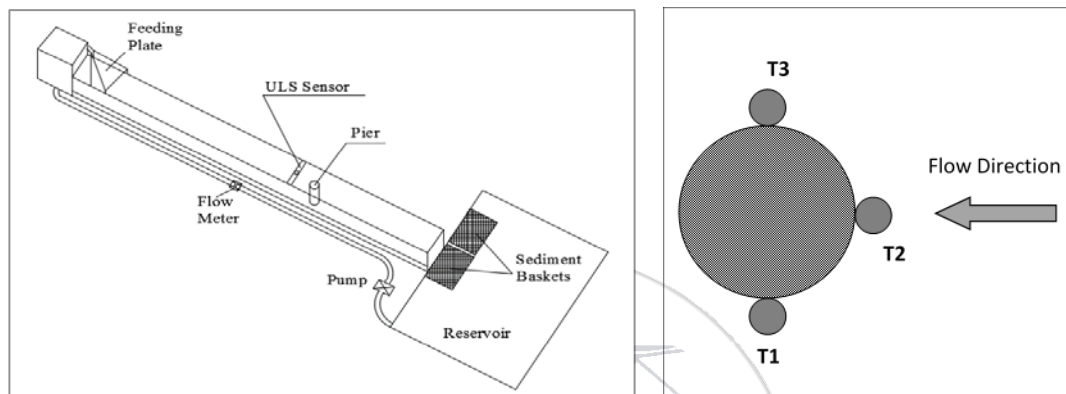


Figure 1. (a) Schematic view of the flume

(b) Location of the UVP transducers

Flow depths were measured by UltraLab ULS (Ultrasonic Level Sensor) manufactured by General Acoustics. Sediment was fed into the flume manually by means of the sediment feeding plate designed to provide uniform feeding, and collected by means of the baskets located at the end of the flume. Initially, a base flow of 1.5 L/s was conveyed to the flume for 10 minutes to provide a steady state. No scour was observed during this stage, as intended. Then, the triangular hydrograph with peak discharge of 20 L/s was generated. The durations of rising and falling limbs were equal to 3 minutes. The evolution of the scour was recorded by means of a high precision camera. Experiments were repeated to ensure the accuracy of experimental findings.

3. NUMERICAL STUDY

In the numerical model, the last 5.6 meters of the flume was disregarded in order to reduce the number of the mesh cells, hence saving the simulation time. Mesh cell side was taken as 1 cm along the flow and lateral directions and 0.5 cm in the vertical direction. General overview of the flume model is given in Figure 2. Red zones indicate the concrete blocks, blue zone indicates the packed sediment and cyan layer corresponds to the initial water surface.

Initial conditions (flow depth, velocity etc.) were defined as the initial steady state of the experiment. Simulation was realized by the isosceles triangle shaped hydrograph. LES, RNG and two equations $k-\epsilon$ turbulence models were used during the simulations. Maximum turbulent mixing length was chosen as “dynamically computed” because of time-varied flow depths. Critical Shields parameter was calculated from Shields diagram as 0.038. The frequently used Meyer-Peter & Müller equation was chosen to predict the bed load transport. As suggested in Flow-3D manual, the bed load and entrainment coefficients were taken as 8 and 0.018 respectively [8].

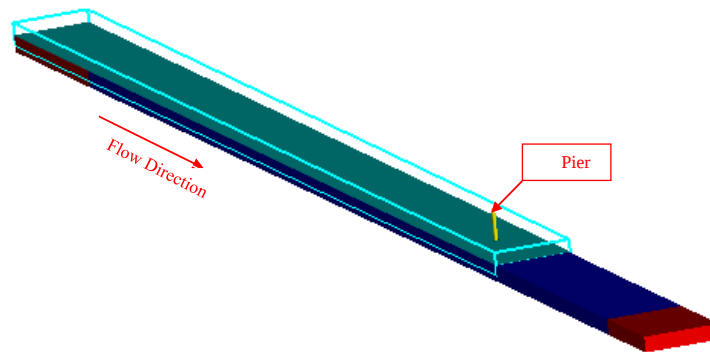


Figure 2. General overview of the flume model

4. RESULTS AND DISCUSSION

During the experiment, water level in the flume began to rise after the base flow of ten minutes. Flow filaments were evidently separated into two directions at the flanks of the pier and wake region began to develop. Two separate scour holes began to form at the flanks of the pier and met in front on the pier a few seconds later. With the increasing discharge, the development of horseshoe vortices enhanced the size of the scour hole rapidly and the scour hole took the shape of a frustum. After the flow velocity reached its critical value, sediment began to move and supply to the scour hole, causing fluctuations in scour depth and scour depth began to decrease during the falling limb. The bed material removed from the scour hole, and was drifted to downstream, 3-4 pier diameters away from pier, by wake vortices.

Similar process was obtained from the simulations. Figures 3 (a) and (b) represent the velocity fields in the wake region and at surrounding of the pier at peak time, respectively. In Figure 3 a, the wake region with the separation of the flow due to the pier existence can be distinguished. Its boundaries can be seen between the yellow and orange velocity fields. According to the velocity fields in Figure 3 b, downflow and horseshoe vortices seem not to be fully reflected.

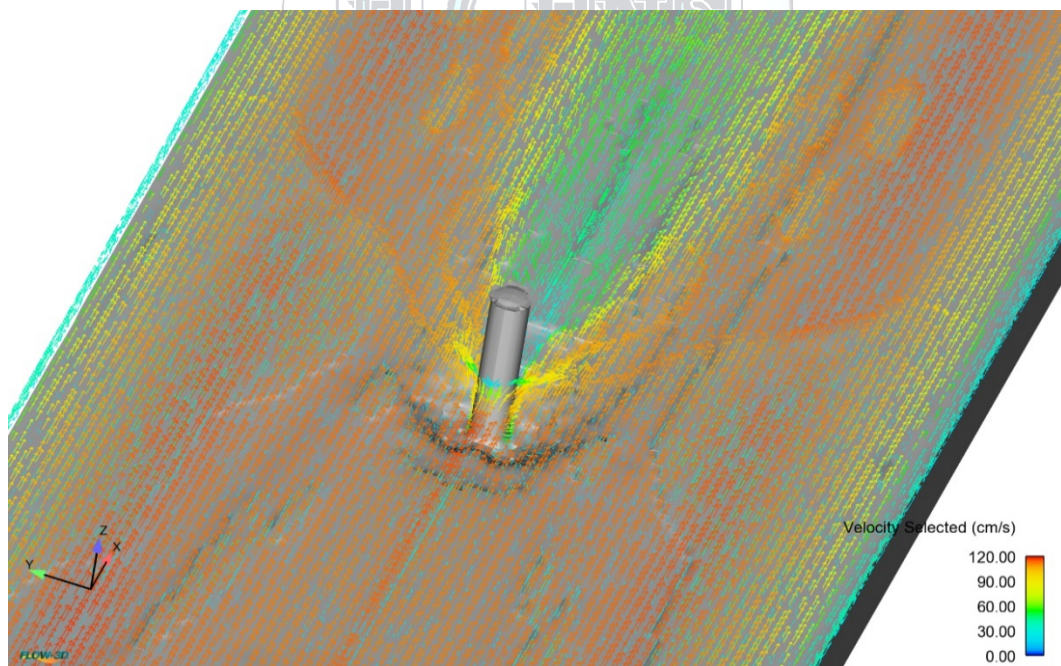


Figure 3. (a) The velocity field at the peak time in the wake region

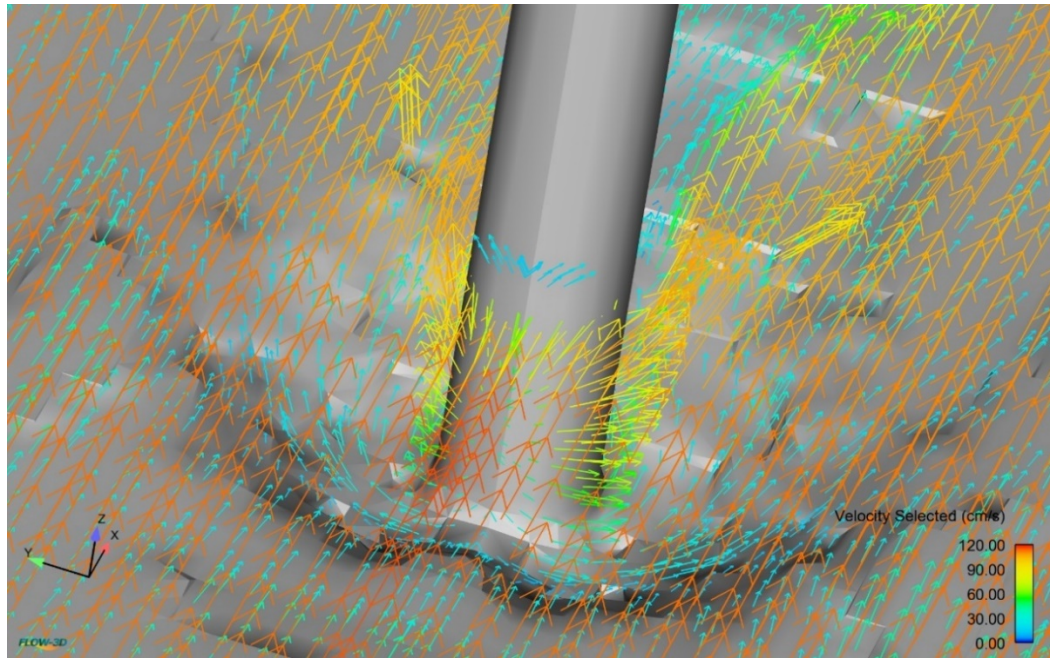


Figure 3. (b) The velocity field at the peak time in the surrounding of the pier

3D pictures of the scour hole were taken for each turbulence model at every 60 seconds. They are given in Figures 4, 5 and 6. for LES, RNG and two equation k- ϵ turbulence models, respectively.

The picture of scour hole corresponding to the end of the experiment is given in Figure 7.

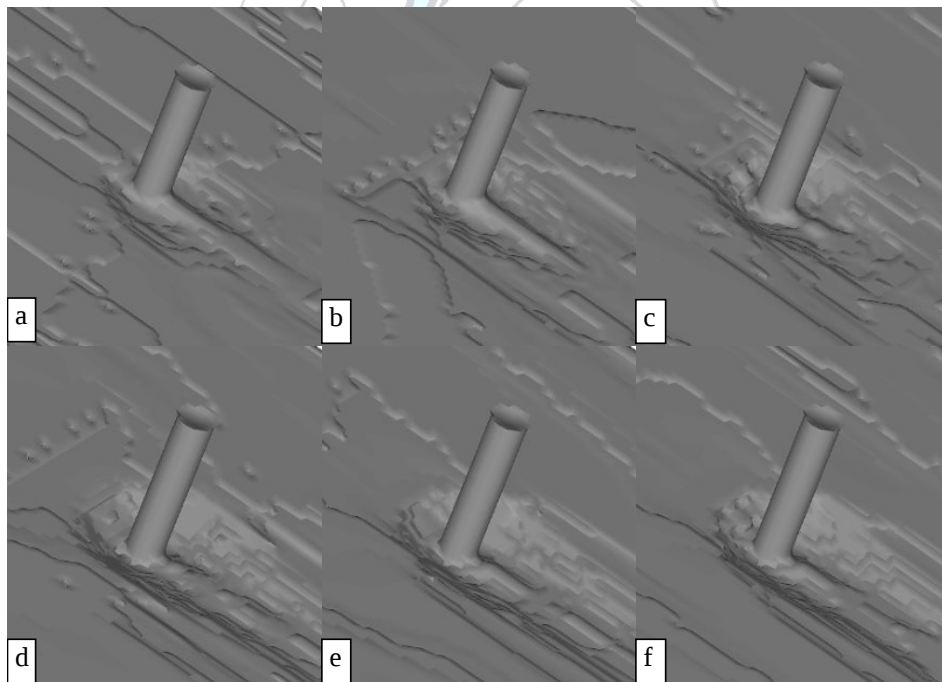


Figure 4. Pictures of the scour hole for LES turbulence model at a) 60 s. b) 120 s. c) 180 s. d) 240 s. e) 300 s. f) 360 s.

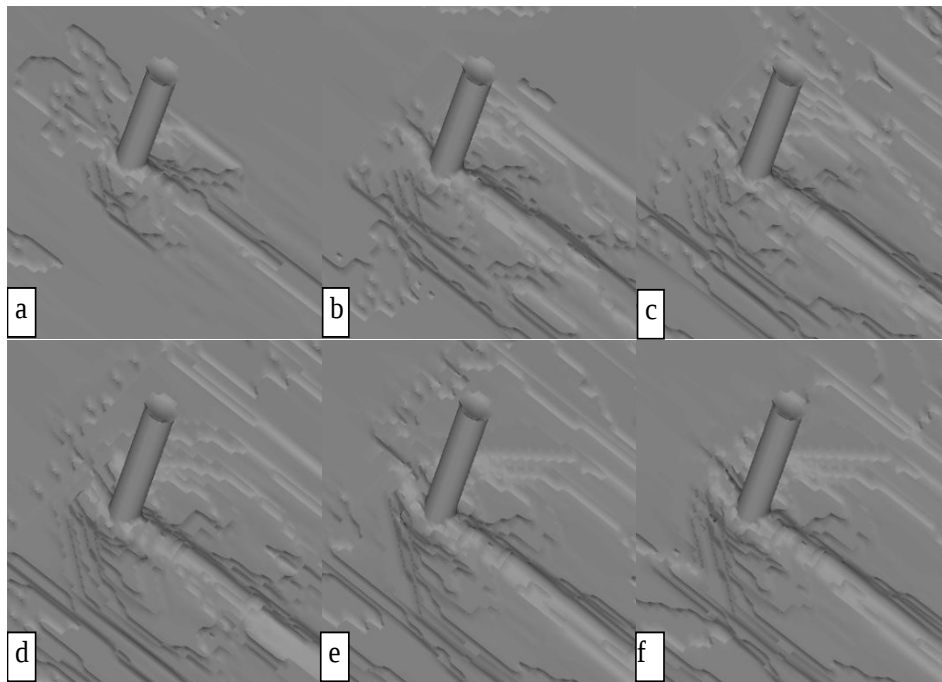


Figure 5. Pictures of the scour hole for RNG turbulence model at a) 60 s. b) 120 s. c) 180 s. d) 240 s. e) 300 s. f) 360 s.

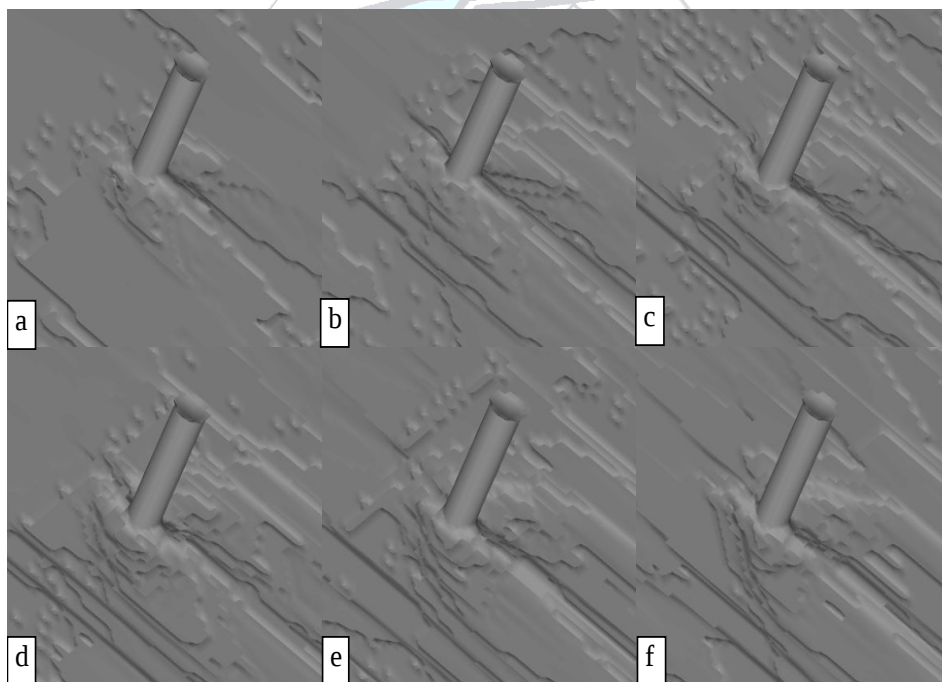


Figure 6. Pictures of the scour hole for $k-\epsilon$ turbulence model at a) 60 s. b) 120 s. c) 180 s. d) 240 s. e) 300 s. f) 360 s.

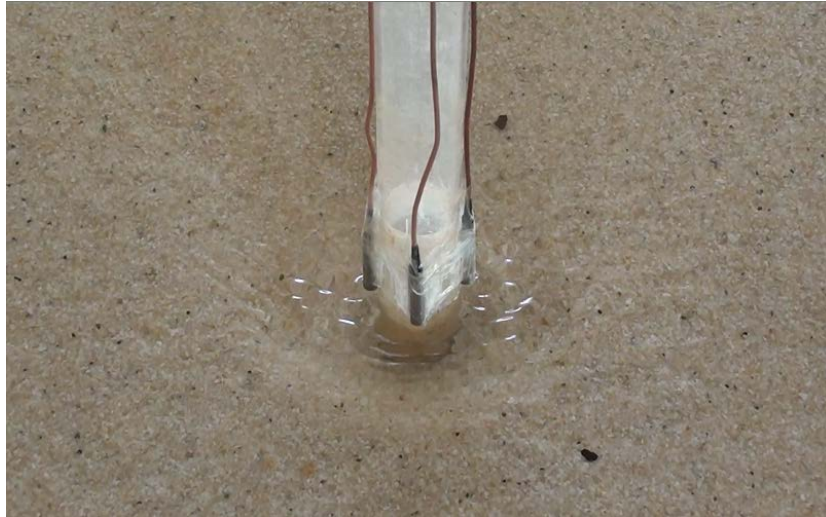


Figure 7. Picture of the scour hole at the end of the experiment ($t=360$ s)

It was found that the scour hole obtained by using the LES turbulence model was more similar to that obtained from the experiment. A “linear bump” occurred in front of the pier in all turbulence models but, this fact was not observed during the experiments. The frustum shaped of the scour hole seen in Fig. 7 was not obtained in the used turbulence models, except LES turbulence model at which this configuration appeared between 180 and 240 seconds. This situation caused lower scour depths in front of the pier compared to those at flanks, this fact being contradictory to the experimental results.

Maximum scour depths were observed approximately at the 240th second of the simulations. Figure 8, 9 and 10 show plan views of the scour hole at 240th s of the simulation for LES, RNG and two equations $k-\varepsilon$ turbulence models, respectively (units are in centimeters). The LES turbulence model simulated scouring in front of the pier much better than the other turbulence models even if it gave lower scour depths compared to those at flanks. The RNG turbulence model simulated scouring in wake region better than the LES model.

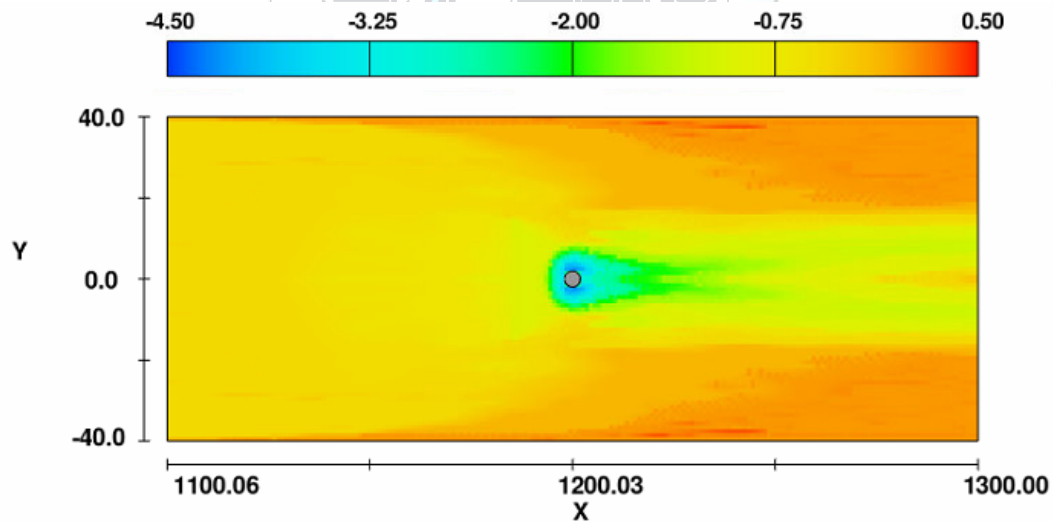


Figure 8. Plan view of scour holes in the case of the turbulence model LES

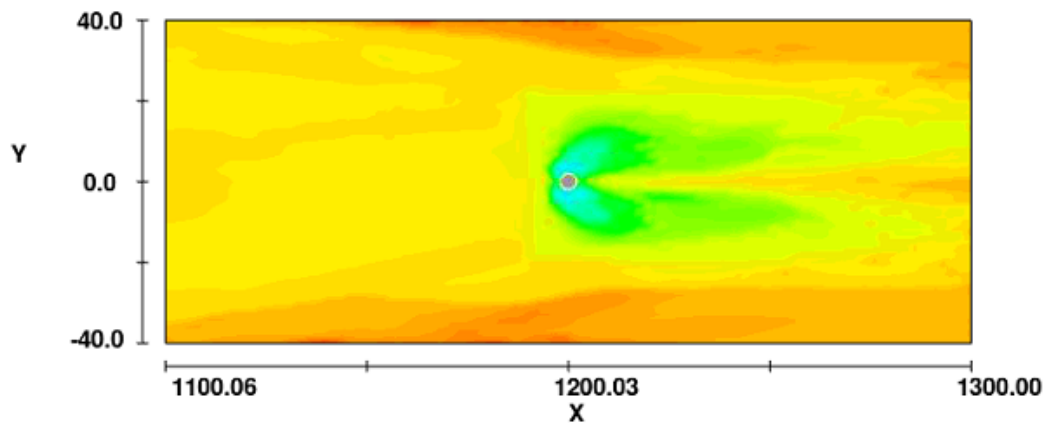


Figure 9. Plan view of scour holes in the case of the turbulence model RNG

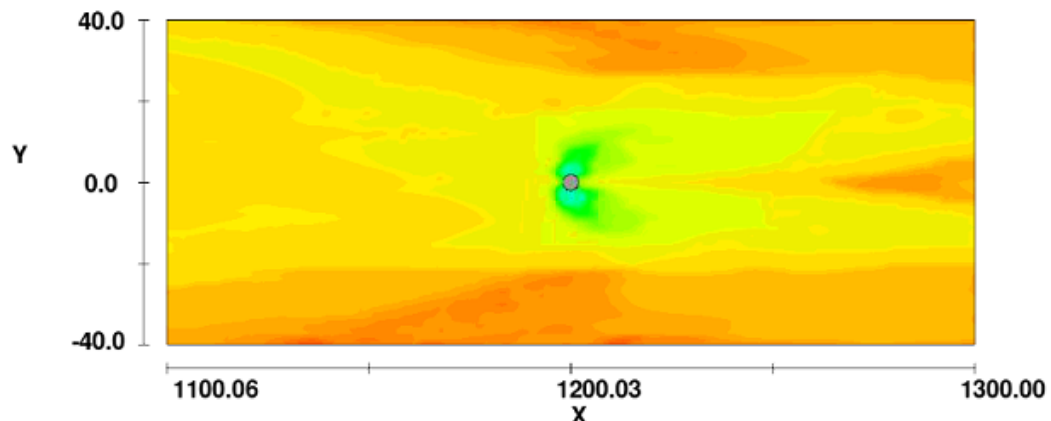


Figure 10. Plan view of scour holes in the case of the turbulence model two equations $k-\epsilon$

The numerical and experimental time dependent scour depths at flank (T1) and front (T2) are given in Figure 11.

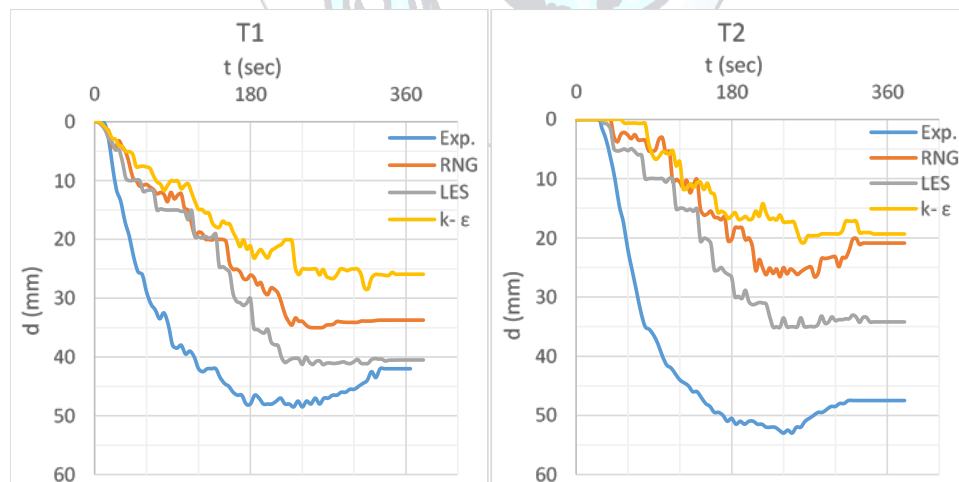


Figure 11. Time-varied numerical scour depths and experimental ones

The time-varied scour depths obtained from the simulations were found to be smaller than the experimental ones.

Scouring was found to be more rapid during the experiments. For example, at flank T1, during the experiments the scour depth of 20 mm was reached approximately at the 40th second, while this value was 115 s, 130 s, and 165 s in the case of the turbulence models LES, RNG and two equations $k-\epsilon$, respectively.

By contrast with experimental findings, the scour depths at front were found smaller compared to those calculated at flanks.

5. CONCLUSIONS

The turbulence model RNG seems to reflect better the sediment transport, since the final scour depth was found to be smaller than the maximum scour depth. On the other hand, the scour depths calculated by using turbulence model LES are relatively much closer to those obtained from the experiments.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

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