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CFD SIMULATION FOR THE OPERATION EFFECT OF GATES OPENINGS OF AL-HAY REGULATOR ON THE LOCAL EROSION

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Abstract

Hydraulic structures such as regulators play an important role to control flow in open channels. The inappropriate operation of the gates of such structures generates unpredictable scour patterns. For the past few years, Al-Hay Regulator has suffered from scouring especially at the upstream of the structure due to improper operation of its openings. Also, the sediment started to collect up in different locations in Al-Gharraf River which diminishes the flow capacity of the river. The present study aims to simulate the sediment transport and the best operation of the gates of Al-Hay Regulator which is constructed on Al-Gharraf River, south of Iraq. Computational Fluid Dynamics (CFD), specifically the SST k-ω turbulent model was applied to investigate the sedimentation problems with different flow conditions and different options for the opening of the five gates that the regulator consists of. Moreover, the effect of symmetry operating of gates on the local scour was studied. The results show that the maximum scour depth and the quantity of soil removed around the regulator is increased directly with the Froude number. Besides that, the number of open gates and the operation sequence of gates have a significant effect on the scour behaviour especially downstream of the regulator.

Keywords: Al-Gharraf river, Open channel flow, Operation of regulators, Scouring simulation.

1. Introduction

Scour is characterized as the ejection of soil particles from the channel banks and bed due to water activity. It happens as a result of a characteristic change of water stream through the channel or due to man activities such as the construction of hydraulic structures. The local scour near hydraulic structures can be considered as the foremost phenomenon which may debilitate the stability of the structures [1]. As the full structure assurance from scouring is highly expensive, the maximum depth of scour as well as the scour depth must be pre-specified to reduce maintenance costs and failure hazard as well [2].

Several existing hydraulic structures in Iraq, such as regulators have suffered from scouring issues downstream and sometimes upstream these structures due to the improper operation of the multi-openings involved in these structures, which leads to unusual scour patterns. The inappropriate operating in such hydraulic structures may be resulted from; a specified and firm routine operation rules followed, and deficient and irregular maintenance for the gates and their mechanical instruments. The sedimentation process such as scouring or accumulation upstream and downstream of Al-Hay regulator, which is located in the middle reach of Al-Gharraf River south of Iraq, got to be one of the imperative issues that concern and worry the Ministry of Water Resources in Iraq due to the noteworthy impacts of sedimentation that threatening the regulator stability. The local scour depth and length upstream and downstream of the regulator may be affected by the variety of specific parameters.

The most important parameters are the sediment size, Froude Number, flow velocity, and the operation regime or the sequence of gate opening that will be considered to study their effects on local scour adjacent to the regulator with different conditions of flow. One of the most recent studies done in this field conducted by El-Gamel et al. [3] who conducted experiments on the practical channel at Mansoura University, the experiment was carried out in two types of sand, having different gate opening, with the Froud Number ranging from 0.26 to 0.45 at a different speed for each operation. Further, by using the theory of dimensions-analysis, the conclusion drawn was that by increasing the Froud number, the depth of the scours increased.

Verma and Goel [4] performed a laboratory investigation to observe the scour caused by a horizontal submerged jet next to a sluice gate flowing over the apron. After conducting graphical relations between the scour depth and Froude number, using the data used in the experiment, the authors found that the scour depth decreases when decreased with the Froude number. Bakhiet et al. [5] noted in their study, that the hydraulic structures consist of numbers of openings and the improper operation of these gates will generate different velocity which leads to the occurrence of many patterns of scouring.

Aamir and Zulfequar [6] performed 18 operations to determine the depth of the scour for the downstream resulting from the jet coming from the gate opening. Each operation uses different values for the parameter that affects the process of scouring, such as sluice open, velocity, tailwater depth, Froude number (Fd), median particle diameter (d50). It was seen that the scour depth increased with increasing velocity and the Froude number. Rustiati et al. [7] stated that the process of movement of the gate up and down will affect the velocity of the water, and this fluctuating rate causes the process of scouring. They also concluded that if the gate was raised, the depth of local scour decreased while the flow increased due to a drop in the velocity upon raising the gate to a large height, which in turn generates a decrease in the depth of local scour. Elsayed et al. [8] conducted laboratory investigations to determine the impact of different gate operations on local scour, below the downstream under free-flow conditions. They revealed that the number of non-closed gates and their arrangement gets affected by the depth of the scour.

The present study aims to develop a numerical model to simulate the sediment transport in the reach of Al-Hay regulator using Computational Fluid Dynamic (CFD) software, considering the effect of Froude number, the number of gates opening, and the sequence of gates opening. Moreover, find out the suitable operation of the gate opening to reduce scouring near the regulator structure.

2. Formulation and Theory of CFD Model

The Naiver-Stokes equations have been used in the CFD modelling, which are based on the presumptions of preservation of mass and energy inside a moving fluid. Within the non-appearance of sources of mass and energy, the preservation of mass is depicted by the differential equation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho v) = 0 \tag{1}$$

where the density and the velocity are denoted by ρ and v respectively. The preservation of energy is additionally portrayed by the equation:

$$\frac{\partial}{\partial t}(\rho v) + \nabla \cdot (\rho v v) = -\nabla p + \nabla \cdot \tau \tag{2}$$

where the pressure and the stress tensor are denoted by $\boldsymbol{p}$ and $\boldsymbol{\tau}$ respectively. In arrange to represent the impacts of turbulence on the flow, extra transport equations are illuminated for different turbulence amounts.

3. CFD Model Setup

In this study, the CFD model is considered first to simulate the hydrodynamic model for Al-Hay regulator using the k-ω SST turbulence model to verify the model for further studies by using the combination of the hydrodynamic and Morphological models to investigate the effect of gates operation on the flow properties and scour patterns around the regulator.

3.1. Hydrodynamic model of Al-Hay regulator

The simulations described here are run using FLUENT. For the validation study, The hydrological field measurements of the study were conducted by the Iraqi Ministry of Water Resources (MOWR) [9] at Al-Gharraf River which is considered the biggest tributaries of Tigris River there for it’s the most resource of water for the Iraqi cities which lies in the middle and south of it. The sections were taken near to Al-Hay Regulator were achieved at two sections, the first section at a distance of 200 m upstream of Al-Hay regulator and the second one is located at a distance of 150 m downstream of the regulator and as shown in Fig. 1. The cross-sections of the riverbed as shown in Fig. 2.

Fig. 1. Satellite image of Al-Hay regulator at Al-Gharraf river, Google earth.

Fig. 2. Geometry of Al-Hay regulator and Al-Gharraf bed river.

3.2. Verification of Al-Hay regulator model

To validate the cross-section and flow properties of Al-Hay regulator using CFD model comparison between the manning coefficient which is calculated from the CFD model and the manning coefficient computed from previous researches done by Mohammed et al. [10] and Daham and Abed [11], both of these studies are conducted to calculate the manning coefficient by using the HEC RAS software at the Gharraf River in the unsteady and steady flow conditions for the area between Al-Kut (U/S of the study) and Al-Hay Regulator (D/S of the study), the calibration process was done to the manning coefficient which is ranged from (0.025 to 0.027) for several discharges with the normal operation of Gharraf regulator (gate openings of fully in regulator). In case of lower water levels upstream of Al-Hay regulator down to in normal operation the value of Manning's n may be increased to 0.027 in the reach since higher levels introduce areas of higher resistance Manning's n was affected by a variety of water level and backwater curve of Al-Hay regulator by raising water levels along upstream reach [10, 12]. The manning coefficient calculated using the local method and depends on the flow profile upstream of Al-Hay regulator from the

CFD calculations shown in Table 1 and Fig. 3 is equal to 0.264 with Root Mean square, RMSE value 0.949.

Table 1. Manning coefficient calculation using local method

Q (m^3/s)	*Y* (cm)	*Yo* (cm)	*A* (m^2)	*P* (m)	*R* (m)	$0.128*R^{1/6}$	ln(*Y*/*Yo*)-0.9	*n* (local)
150	947	0.478	1045	151	6.92	0.177	6.7	0.0264

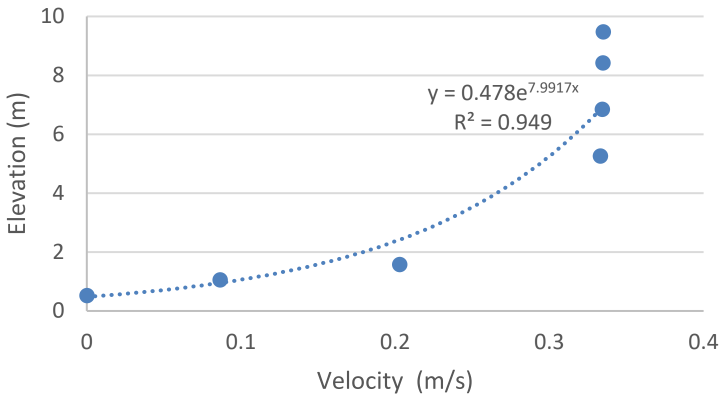

Fig. 3. Velocity profile upstream of Al-Hay regulator.

Figure 4 shows the velocity streamlines upstream and downstream al-Hay Regulator with all gates was opened. It can be noticed that due to the unsymmetrical operation of the regulator gates, which occurred with time by many gates got out of order and therefore, the sediment accumulated around the stopped gates and causes unsymmetrical flow and vortices downstream of the regulator as shown in Fig. 4. The Calibration of the sediment model may be a noteworthy handle to examine the model approval to simulate the real situation of Al-Gharraf River and illuminate the sedimentation issue. In this study, the model was calibrated utilizing perception estimations of the cross-section conducted by the Iraqi Ministry of Water Resources (MOWR) [9] will be displayed for the four years periods expanded from 2012 to 2016 and the measurements conducted by Mohammed et al. [10].

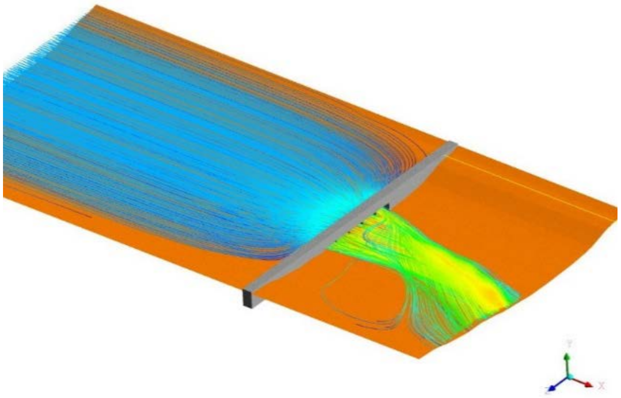

Fig. 4. Velocity streamlines upstream and downstream of Al-Hay regulator.

This study aims to develop a numerical model to simulate the sediment transport upstream and downstream of Al-Hay regulator and discover the reasonable treatment for sedimentation issues in that reach.

4. Morphological Model

Besides the hydrodynamic flow characteristics, the sediment movement is taking into account an important parameter that should be accurately modelled in a scour simulation. The sediment transport is considered to happen directly when the bed shear stress, exceeds the critical shear stress of the sediment particle [13]. After the particle start motion, the sediment transport rate becomes another parameter to describe the sour development with time. The most commonly used equation to predict the sediment movement is based on the excess critical shear stress [14]. The critical shear stress of sediment is defined by:

$$\tau_{b.cr} = \rho g(s-1)d_{50}\theta_{cr} \tag{3}$$

$\tau_{b.cr}$ = critical shear stress of sediment; s is referred to the sediment particle relative density; where the diameter of sediment particle is denoted by d_{50} ; and the critical Shields number $=\theta_{cr}$, which is shown below:

$$\theta_{cr} = \begin{cases} 0.24D_*^{-1} & , D_* \le 4 \\ 0.14D_*^{-0.64} & , 4 < D_* \le 10 \\ 0.24D_*^{-0.10} & , 10 < D_* \le 20 \\ 0.013D_*^{0.29} & , 20 < D_* \le 150 \\ 0.055 & , 150 < D_* \end{cases} \tag{4}$$

where $D_* = d_{50}[(s-1)g/\vartheta^2]^{1/3}$; and ϑ is the coefficient of kinematic viscosity; The formula of dimensionless critical shear stress, as presented in Equation 5

5. $$T = (\tau_b - \tau_{b.cr})/\tau_{b.cr} \tag{5}$$

where the dimensionless critical shear stress and the sediment shear stress are denoted by T; and τ_b. Once τ_b becomes greater than $\tau_{b.cr}$ the sediment particles start to move immediately. After the sediment movement begins, the sediment transport rate becomes another key parameter that describes the scour process. The rate of sediment transport is characterized as the movement of solid particles, both particulate and dissolved, that goes over a given stream transverse cross-section of a given flow in a unit time, and its calculation can be given by van Rijn [15]:

$$\frac{dh}{dt} = 0.00033\,\rho_s(\Delta g d_{50})^{0.5}\,\frac{D_*^{0.3}}{n}\,T^{1.5} \tag{6}$$

In which h = riverbed height; t = time; n is the sediment void ratio (which is set as 0.4 [16, 17]); ρ_s = sediment material density; $\Delta = (\rho_s - \rho)/\rho$ = relative density; ρ = fluid density; g = acceleration due to gravity; and T should be calculated using Equation 5. By programming Equation 6 using User Defined Function (UDF) code, the bed of the river can be changed regarding the computed shear based on the riverbed elevation (h) at each time step of the flow simulation. This way the transient variations of the riverbed elevation can be technically accounted for in real-time using the CFD simulation.

Scour applications of flow over a multi-gate regulator in rectangular open channel

In this section a regulator with five gates located at a rectangular channel with a flat and movable bed has been investigated using CFD simulation as shown in Fig. 5 the gates have been numbered from G1 to G5 to study the effect of gates opening on the scour depth. In this study, the investigation has been divided into six cases depending on the opened gates number and pattern. The discharge is ranged from 100-350 m^3/s. For all cases of the gate opening, a constant grain size of the sand bed was used the geometry of the regulator and the number of gates and dimension is similar to Al-Hay regulator and the channel properties such as the flow discharge and the particle size of the bed have been taken similar to Al-Gharraf river reach to the regulator in Al-Hay city and as shown in Fig. 5. The open channel length is 350 m with 150 m upstream of the regulator channel width and height are equal to 48 m and 8 m, respectively.

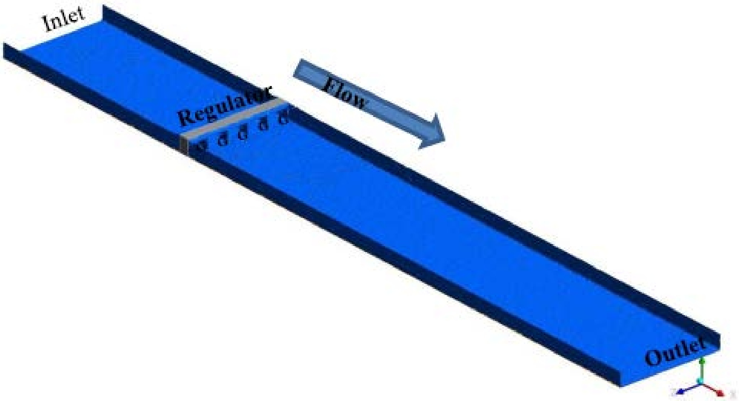

Fig. 5. The channel and regulator geometry.

In this section, results set using CFD were presented. This section focuses on the effects of Froude number on the relative of scour depth and discusses the effects of relative gates opening on the relative of scour depth.

The cases were studied in this paper have been depending on the number of gates opened and the pattern of opening. i.e., case 1 is referred to all gates opened, for the case of all gates opening except gate 3 is showed in case 2, case 3 is designed for three opening gates (gate 1, 3, and 5), case 4 indicated for just gates 2 and 4 have been opened. All these cases are designed to study the effect of the symmetrical operation of the regulator. There are two more cases presented in this study to show the effect of the unsymmetrical operation of gates on the scours around the regulator. Case 5 is indicated for the case when gate 1, 2 and 3 have been opened, whereas Case 6 is referred to the case when just gate 1 and 2 have been opened. The relation between relative scour depth and the Froude number represents the relation between the inertia force of the flow and gravitational force.

In this work the Froude number is ranged from 0.02 to 0.058, Fig. 6 presents the relation between the scour relative depth and the Froude number under symmetrical and unsymmetrical operations of the regulator gates. As shown in Fig. 6, it can be seen that the relative depth of the scouring for case 6 for D50 of 0.2 mm have least value of 0.15 for Fr = 0.058 which can be considered as the worst operating case, because of the opening of two gates in an unsymmetrical way leads to increase velocity flow, this is a major reason for the increase in the depth of the scour.

The bar chart in Fig. 7 shows the quantity of removed sediment close to the regulator for different cases of gates operation for a constant discharge (200 m^3/s). It can be clearly seen that the volume of sediment was removed in case 6 (1406 m^3) is about four times the quantities of sediment were removed in case 5 (347 m^3) for Fr =0.058. it is clear that from Figs. 6 and 7 that the scour depth and the quantity of removed sediment depend on the number of gates openings and the operation pattern of these gates and the effect of unsymmetrical operation has a significant influence on the scour depth when the number of gates opening is less than half of the total number of gates and this is clear for case 5 and 3, both cases have three opening gates but the difference with the operation system, it can be noticed that there are no noteworthy alter in the maximum scour depth and also with the volume of sediment removed around the regulator. However, in the case of just two gates opened out of five as shown in Figs. 6 and 7 for cases 4 and 6 respectively, it can be seen that the percentage of increase in maximum scour depth and the quantity of sediment removed in case of unsymmetrical operation of gates (case 6) greater than compared with the case with the symmetrical operation of gates (case 4).

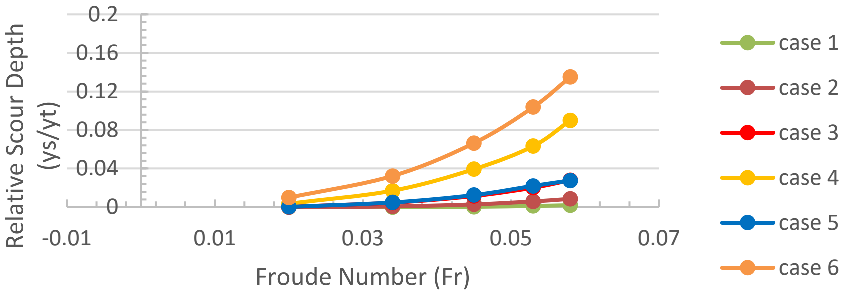

Fig. 6. The relation between the Froude number and the relative scour depth for different cases of gates operations.

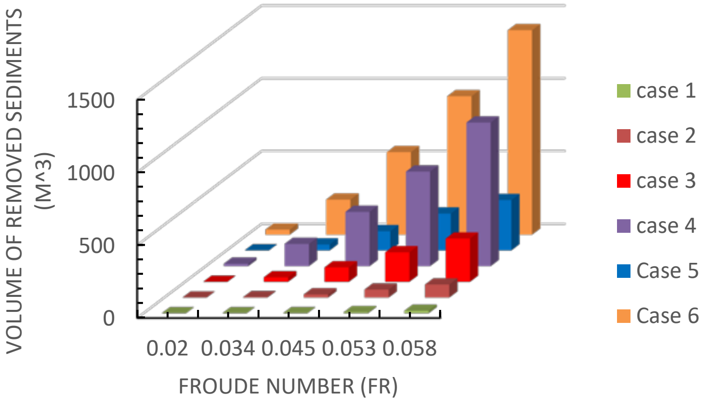

Fig. 7. The relation between the volume of removed sediment and Froude number for different cases of gates operations.

The pie chart in Fig. 8 shows the percentage of removed sediment for all cases of opening gates with a constant discharge (200 m^3/s). It can be noticed that the percentage of sediment removed increases with a decrease in the number of gates opened and with the system of operation of gates opened as asymmetrical on an unsymmetrical operation.

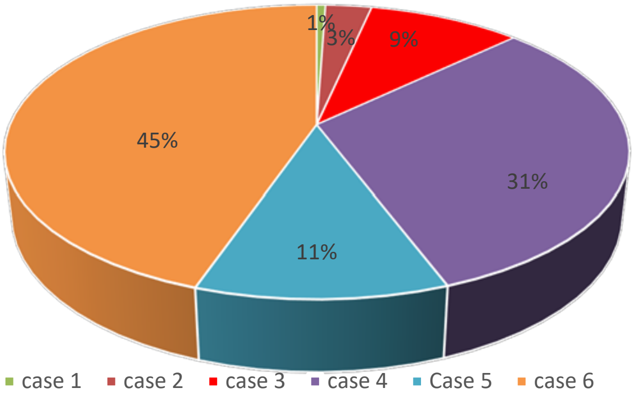

Fig. 8. The percentage of the volume of removed sediment with respect to different cases of gates operations.

Figure 9 presents the longitudinal profile of the maximum scour depth location for each case of the gate opening. It can be seen that case 6 with two opened gates in unsymmetrical operation had the maximum scour depth compared with other cases followed by case 4 which has the same numbers of open gates as case 6 but with the symmetrical operation.

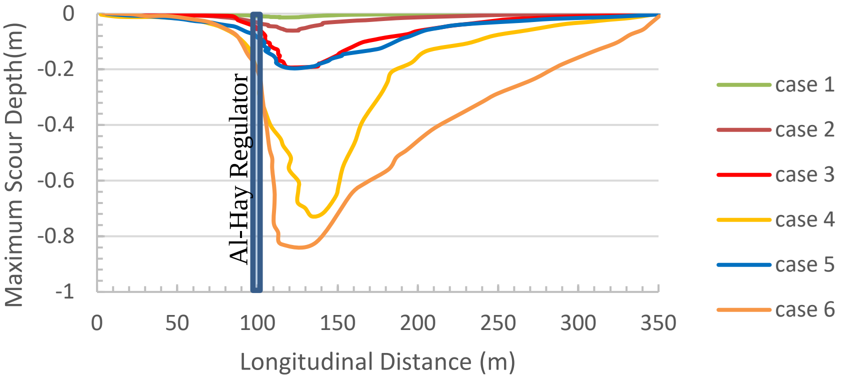

Fig. 9. The profile of the maximum scour depth location for each case of the gates opening.

Figure 10 shows the relative maximum scour depth during the time of flow for all cases of opening gates. The simulation of scouring for all cases has been investigated for the first two hours of the flow in the open channel. The behaviour of relative scour with time for case 6 is the largest compared with other cases followed by case 4. Case 3 and case 5 have the same behaviour of scour depth with time. Case 1 which has five gates opened has the minimum relative scour depth compared with other cases.

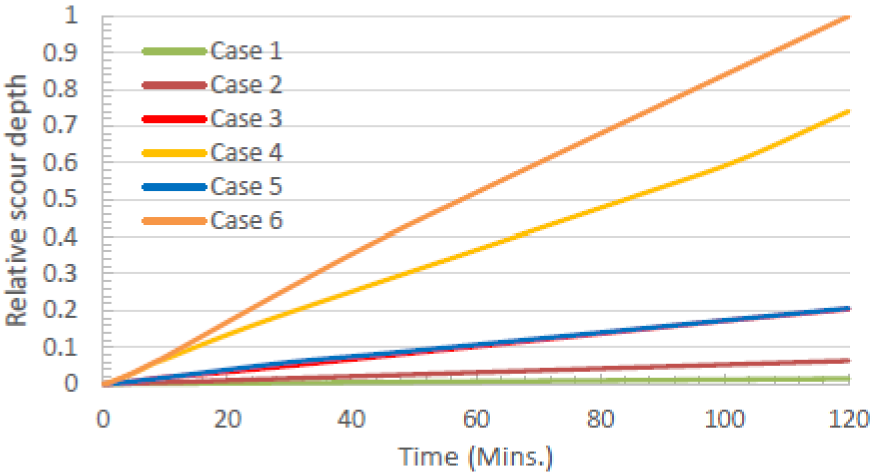

Fig. 10. The relative maximum scours depth with respect to flow. duration.

For more details about the quantity of sediment removed Figs. 11 and 12 show the channel bed and scour depth contours for unsymmetrical (case 5 and case 6) and symmetrical (case 3 and case 4) operation for regulator gates.

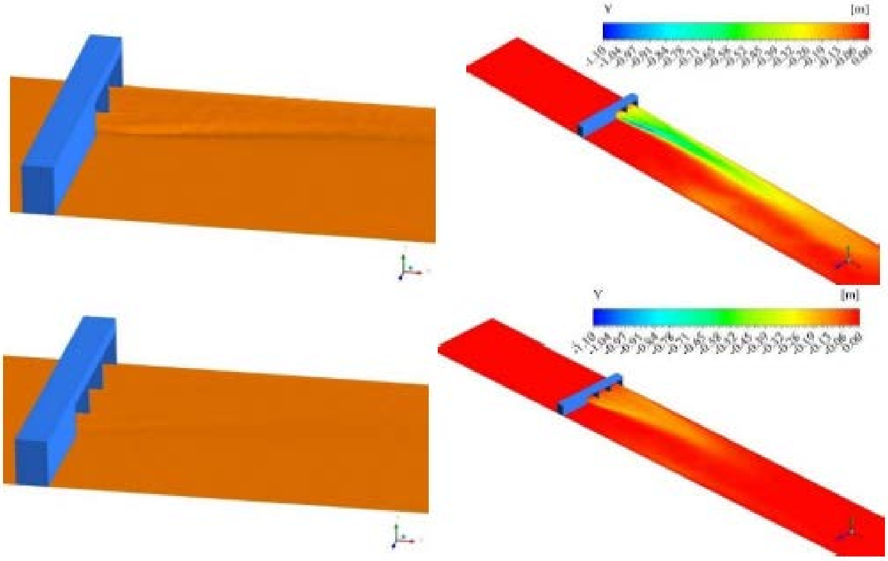

Fig. 11. 3D topography for the riverbed and Contour lines for case 5 and case 6, respectively.

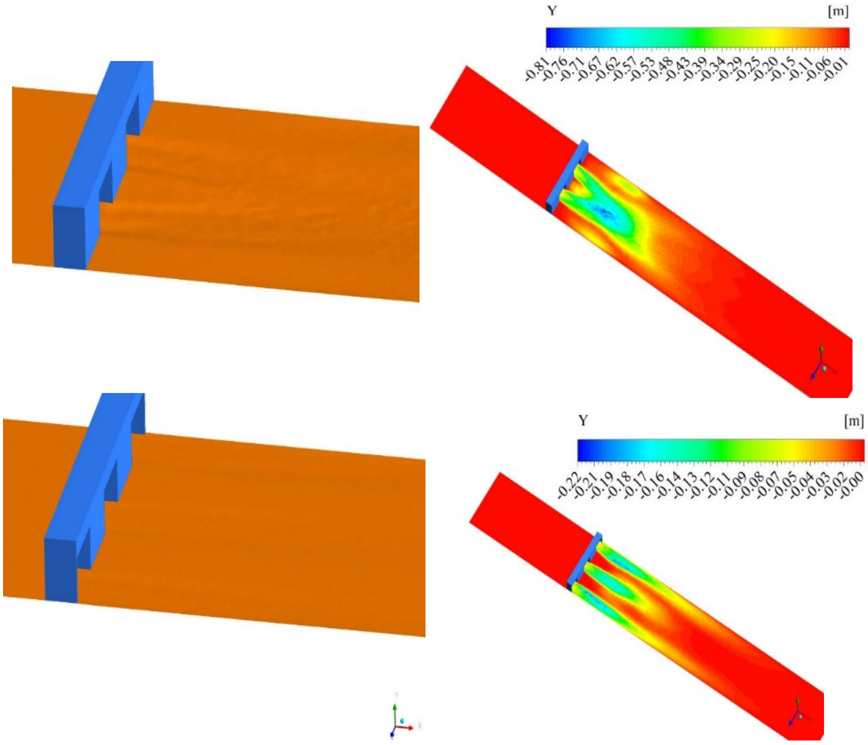

Fig. 12. 3D topography for the riverbed and Contour lines for Case 3 and Case 4, respectively.

6. Conclusions

This study deals with the simulation of sediment transport near Al-Hay Regulator. Extensive runs for CFD software FLUENT model were performed to examine the impacts of Froude number with different flow conditions, as well as investigate the effect of the number and the sequence of gates operation on the scour depth upstream and downstream of the structure.

The results obtained from the sedimentation simulation model extracted the following conclusions: the flow simulation and riverbed movement were well simulated using the developed CFD model compared with field measurements. The length and depth of the local scour are strongly influenced by Froude number.

The maximum scour depth and the quantity of soil removed around the regulator are increased directly with the increase of Froude Number. The number and the sequence of gates opening and the system of operation of gates have a significant effect on the depth of the scour near the regulator.

The depth of the scour hole downstream the regulator is increased as the number of the opened gates reduced. At the upstream and downstream sides, the scouring depth will be greater when irregular (neither symmetric nor regular distributed) gates were opened, as well as when only the gates on one of the regulator sides were opened.

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