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Evaluating a Numerical Model to Simulate the Variation of River Bed Due to a Mining Pit Based on Experimental Data

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ABSTRACT

One of the major problems in river engineering is the erosion of the bed river due to improper removal of sand and gravel from the river bed. Therefore, investigating the hydraulic condition of the river is necessary in order to prevent the bed erosion of the rivers. Nowadays, With respect to the limitations of laboratory models and economical problems, usage of numerical models in hydraulic engineering problems is growing. All numerical models make some form of approximations to solve the basic principles of conservation of mass, energy and momentum, which form the basis of fluid mechanics. In this paper, after explaining the destructive effects of mining an inappropriate pit in the bed river and giving a brief introduction about the physical model which is made for investigating the variation of bed profile due to a mining pit, the capability of a leading one-dimensional hydraulic engineering software (HEC-RAS) in modeling the bed variation of the experimental model is investigated. The simulation results were also compared to experimental data and the comparison showed a good agreement between simulated and experimental data. Therefore, this numerical model can be so useful to help solving the mining problem which will occur due to improper removal of sand and gravel from river's bed.

Key words: Bed erosion, numerical modeling, sediment transport, sand and gravel removal

INTRODUCTION

Sand and gravel are particularly desirable sources of aggregate because weak materials are eliminated by abrasion and attrition, leaving durable, rounded, well-sorted gravels (Barksdale, 1991). Inappropriate removal of sand and gravel from river bed may result in scouring and deposition, which will cause migration of the mining pit and changing the river morphology. This phenomenon may put in damage the stability of adjacent structures seriously. Unfortunately, there are many reports of ruining structures in many rivers of Iran such as Balarud bridge, historic bridge Papilla, Kahank bridge in Khuzestan province, Talaar and Alavi kola bridges in Mazandaran province and Dinevar river in Kermanshah province. Since similar problems are observed in Karaj, Minab, Tajan, Zanjan-rud and Nazlochaei rivers, investigation of this problem will be very important and useful. Figure 1 shows severe scour around the Kahank bridge piers in Khuzestan province and Fig. 2 shows dropdown in the Talaar bed river in Mazandaran province.

Fig. 1: Severe scour around the Kahank bridge piers in Khuzestan province

Fig. 2: Dropdown in the Talaar bed river in Mazandaran province

As Fig. 1 and 2 show, the effect of improper removal of sand and gravel from river bed will be so destructive. Therefore, for investigating this problem, in this study a physical model is introduced which is made at the laboratory of Soil Conservation and Watershed Management Research Institute (SCWMRI) institute, Tehran, Iran.

MATERIALS AND METHODS

Experimental setup: The experiments were carried out in a rectangular flume and consisted of 12 m long, 0.6 wide and 0.8 m in depth. A sill with height of 27 cm was built for preventing sediment movement. The flow was uniform and a triangular sharp edge weir was installed at the end of the channel which was used to measure discharge. Average particle size (d_{50}) and σg of the experimental materials are 0.9 mm and 1.4, respectively. Experiments have been done for 4 different of pit dimensions and 2 different hydraulic conditions (Table 1). The longitudinal slope of the sediment was set to 0.001. A rectangular control gate was used to adjust flow depth at the downstream of the flume. For creating the pit, a cubic metal mold with desired dimensions was used and was put into the desired location and the materials in it were removed. For prevention of moving bed materials, Water with low depth went through the flume. Afterwards, the level of the flow would be increased little by little. When water level was increased enough, the metal mould would be removed. Since the materials did not have any adhesion together, the corners of the materials fell and rectangular pit turned into trapezoidal pit. By using the control gate, the desired water level was adjusted and from this time onwards, the experiment would start. To determine the water surface profile and topography of the bed, a Profile Indicator PV-09 (Delft Hydraulics) which has primarily been developed to monitor bed levels in hydraulic scale models is used. Figure 3 shows the experimental setup and Fig. 4 shows the variation of bed due to migration of the trapezoidal pit. Figure 5 shows the Soil gradation curve of bed sediment.

In Table 1, Q is the inflow discharge, Y is the depth of the flow in the flume, H_{pit} is the height of the pit, L_{pit} is the length of the pit, B_{pit} is the width of the pit and Fr is the Froude number. The experimental results showed that variation of bed profile due to deformation and migration of mining pit can be categorized in two periods. The first period will start from the beginning of the experiments till the upstream boundary of mining pit moves to the original downstream end of the

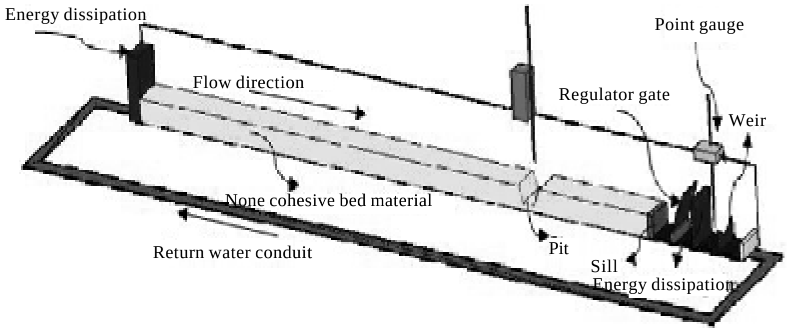


Fig. 3: Experimental setup

Fig. 4: The variation of bed due to migration of the trapezoidal pit

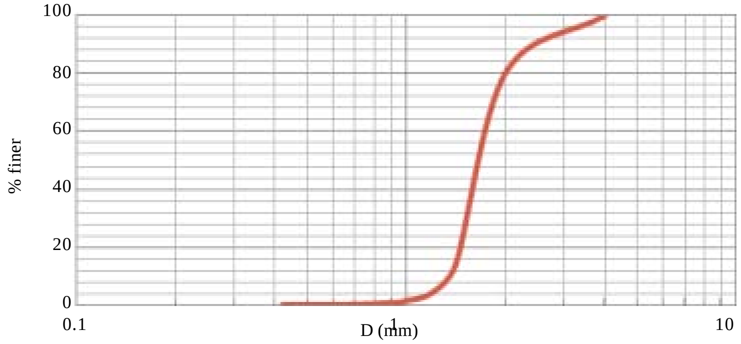


Fig. 5: Soil gradation curve of sediment

Table 1: Experimental characteristics

Q (Lit sec^{-1})	Y (cm)	Fr -	H_{pit} (cm)	L_{pit} (cm)	B_{pit} (cm)	Location of the pit from upstream of the flume
20	8.7	0.415	10	60	60	3.6
20	8.7	0.415	10	30	60	3.6
20	8.7	0.415	20	30	60	3.6
20	8.7	0.415	20	30	60	3.6
20	8.7	0.415	20	60	60	3.6
20	8.7	0.540	20	60	60	3.6
20	7.3	0.540	10	60	60	3.6
20	7.3	0.540	20	30	60	3.6
20	7.3	0.540	10	30	60	3.6

pit. The second period starts from that moment onward. The first period is named "convection period", during which the maximum scour depth remains more or less constant, spatially and temporally. The second period is referred to as "diffusion period", in which maximum scouring depth decreases with time. Based on the dimensionless analysis and studies of Lee *et al*. (1993), the variation of bed profile due to deformation and migration of mining pit, is a function of H (original mining pit depth), L (original mining pit length), y (upstream flow depth), u*(upstream shear velocity), g (gravitational acceleration), ρ and V (density and kinematic viscosity of water), ρ_s and d_m (density and mean particle size of sediment), t (time), T_f (time of end of convection period). Therefore, the variation of bed profile due to deformation and migration of mining pit, against the bed elevation would be gained experimentally and can be compared with numerical data.

NUMERICAL MODELING

Introduction and development of numerical models: Usage of numerical models in hydraulic engineering due to simplicity and savings in time and money has come in a wide range of shapes (one, two or three dimensions, steady or unsteady flow conditions etc). All are based on derivations of the basic principles of fluid mechanics and make some numerical approximations to solve these principles.

Fluid motion is controlled by three basic principles that are, conservation of mass, energy and momentum. Derivatives of these principles are commonly known as the continuity, energy and momentum equations. However, as situations become increasingly complex, the track of these essential principles is lost. Basic equations are replaced by empirical approximations and mathematical calculations with numerical models. Numerical are based on derivations of the basic principles and all are required to make some form of numerical approximation to solve these principles which will cause some limitation in usage of them in some complex problems. Therefore, the ability of numerical softwares to simulate different hydraulic problems under different situations should be checked and the validity of the simulation results must be investigated. As it mentioned above, one of the complex problems in hydraulic engineering is improper mining of sand and gravel from bed rivers. In this research, a leading software in hydraulic engineering (HEC-RAS v 4.1) is briefly introduced and its capability in modeling the variation of the bed due to a mining pit is investigated.

Introduction of HEC-RAS: HEC is an abbreviation for Hydrologic Engineering Center. It is a part of US Army Corps of Engineers. HEC-RAS is a one-dimensional hydraulic model designed to aid hydraulic engineers in channel flow analysis and floodplain determination. The results of the model can be applied in floodplain management and flood insurance studies. In one dimensional models, Flow properties must be calculated based on characteristic properties of the cross-section (e.g., hydraulic diameter, average velocity). Therefore one dimensional model is only appropriate for modeling well-defined and constant flow paths. One-dimensional hydraulic models may be categorized as steady or unsteady. Steady flow describes conditions in which depth and velocity at a given channel location do not change with time. Gradually varied flow is characterized by minor changes in water depth and velocity from cross-section to cross-section. The primary procedure used by HEC-RAS to compute water surface profiles assumes a steady, gradually varied flow scenario and is called the direct step method. The basic computational procedure is based on an iterative solution of the energy equation:

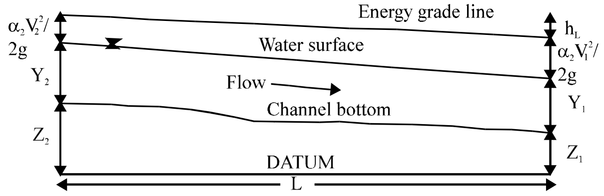


Fig. 6: Representation of terms in energy Eq. (1)

$$H=Z+Y+\frac{\alpha V^2}{2_g}$$

which states that the total energy (H) at any given location along the stream is the sum of potential energy (Z+Y) and kinetic energy ($\alpha V^2/2g$). The change in energy between two cross-sections is called head loss (h_L). The energy equation parameters are illustrated in Fig. 6:

$$\left(g+z_0+\frac{\alpha V^2}{2_g}\right)_2-\left(d+Z_0+\frac{\alpha V^2}{2_g}\right)_1=LS_f+C\left[\frac{\alpha V_2^2}{2_g}-\frac{\alpha V_1^2}{2_g}\right] \tag{1}$$

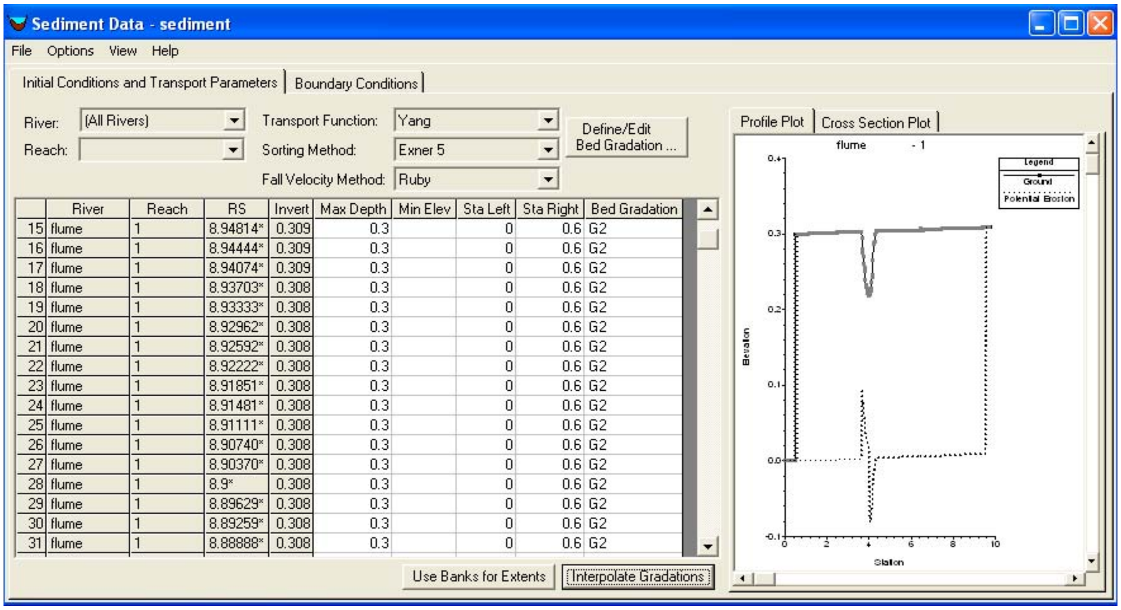
By given the flow and water surface elevation at one cross-section, the goal of the direct step method is to compute the water surface elevation at the adjacent cross-section. Whether the computations proceed from upstream to downstream or vice versa, depend on the flow regime. The dimensionless Fr is used to characterize flow regime, where:

- $Fr<1$ denotes subcritical flow
- $Fr>1$ denotes supercritical flow
- $Fr = 1$ denotes critical flow

For a subcritical flow scenario, which is very common in natural and man-made channels, direct step computations would begin at the downstream end of the reach and progress upstream between adjacent cross-sections. For supercritical flow, the computations would begin at the upstream end of the reach and proceed downstream. Unlike steady-state modeling, which uses a solution of the continuity and energy equations, unsteady modeling is based on a solution of the continuity and momentum equations. The derivation of these equations into a format suitable for one-dimensional modeling is complex but quite well introduced by Henderson (1966) and reference manuals of HEC-RAS.

Simulation process with HEC-RAS: In order to examine sediment properties by HEC-RAD, 3 series of general information including geometric data, Sedimentary materials and information about upstream and downstream boundary conditions is needed which will be briefly introduced below.

Geometric data: Cross sections of river, length of the interval between cross sections of river and manning roughness coefficients should be introduced to the model. Also the depth of bottom sediments of the river is an important factor and the model recognizes it as a thick layer of river bottom that has the potential to be eroded.



River: (All Rivers)
Reach:
Transport Function: Yang
Sorting Method: Exner 5
Fall Velocity Method: Ruby

	River	Reach	RS	Invert	Max Depth	Min Elev	Sta Left	Sta Right	Bed Gradation
15	flume	1	8.94814*	0.309	0.3		0	0.6	G2
16	flume	1	8.94444*	0.309	0.3		0	0.6	G2
17	flume	1	8.94074*	0.309	0.3		0	0.6	G2
18	flume	1	8.93703*	0.308	0.3		0	0.6	G2
19	flume	1	8.93333*	0.308	0.3		0	0.6	G2
20	flume	1	8.92962*	0.308	0.3		0	0.6	G2
21	flume	1	8.92592*	0.308	0.3		0	0.6	G2
22	flume	1	8.92222*	0.308	0.3		0	0.6	G2
23	flume	1	8.91851*	0.308	0.3		0	0.6	G2
24	flume	1	8.91481*	0.308	0.3		0	0.6	G2
25	flume	1	8.91111*	0.308	0.3		0	0.6	G2
26	flume	1	8.90740*	0.308	0.3		0	0.6	G2
27	flume	1	8.90370*	0.308	0.3		0	0.6	G2
28	flume	1	8.9*	0.308	0.3		0	0.6	G2
29	flume	1	8.89629*	0.308	0.3		0	0.6	G2
30	flume	1	8.89259*	0.308	0.3		0	0.6	G2
31	flume	1	8.88888*	0.308	0.3		0	0.6	G2

Fig. 7: Sedimentary material information window

Sedimentary materials: Information about the sedimentary material in the HEC-RAS model is introduced by soil gradation curve of sediment into the model. There are 6 sediment transport equations in HEC-RAS including Ackers-White, Engelund-Hansen, Laursen, Meyer-Peter-Muller, Toffaleti and Yang sediment transport equations. These functions were selected base on their validity and collective range of applicability. Assumptions applied in the sediment transport functions, Sediment size and Range of hydraulic conditions will cause significant differences in the results obtained from different sediment transport functions. United States Army Corps of Engineers has checked to compare sediment transport functions based on compliance with the results of field and laboratory measurements. As the result, the Yang sediment transport equation has shown the best match with the actual amount of sediment rather than the other sediment transport equations. Besides, application of the Yang sediment transport equation is for gravel and sand beds. Hence, the Yang's sediment transport equation was chosen as the best for modeling. The suspension of a sediment particle is initiated once the bed level shear velocity approaches the same magnitude as the fall velocity of that particle. The particle will remain in suspension as long as the vertical components of the bed level turbulence exceed that of the fall velocity. Therefore, the determination of suspended transport relies heavily on the particle fall velocity. There are three main methods available in HEC-RAS including Toffaleti (1968), Van Rijn (1993) and Rubey (1933). Rubey (1993) method was used to calculate the fall velocity of the particles in this model. Figure 7 shows the sedimentary material information window.

Introduction of boundary conditions: After the river cross sections, initial conditions and sediment transport functions were introduced, the boundary condition for the model would be introduced. The flow series upstream boundary condition was chosen for this case. In order to use the flow series upstream boundary condition, the upper range of cross-sectional studies, however, must first be introduced to the model. Discharge was constant at different times and was equal to

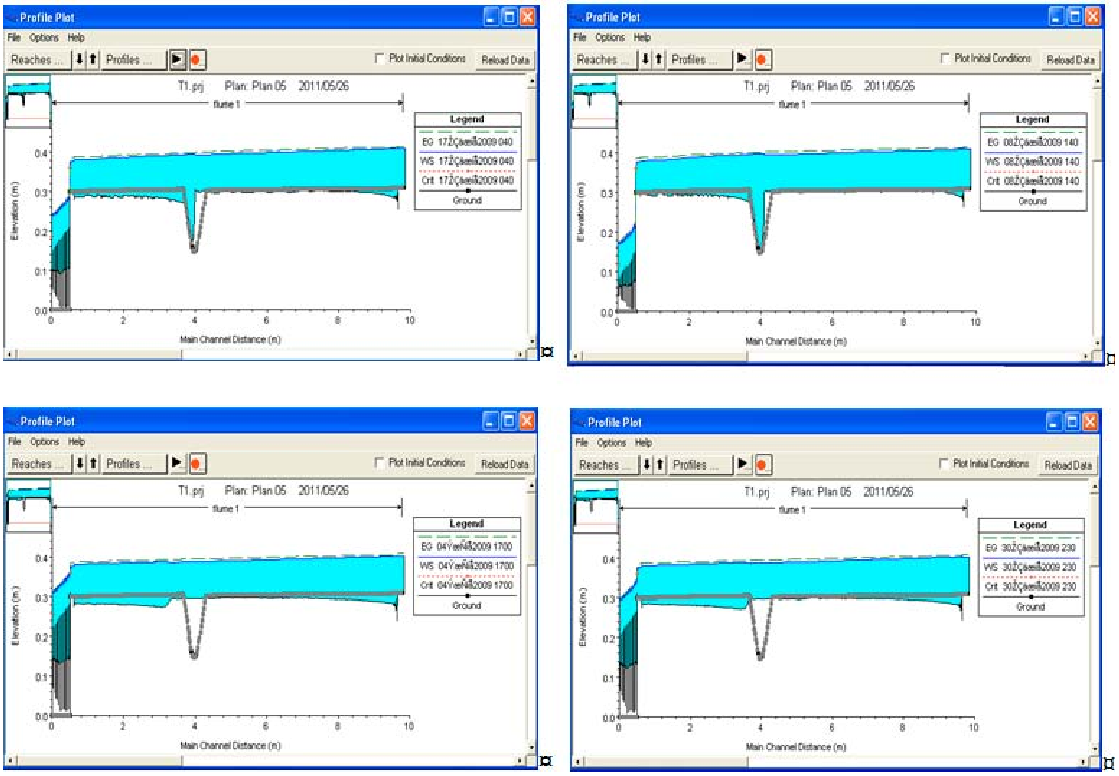


Fig. 8: Simulation results of bed profiles using HEC-RAS at different times

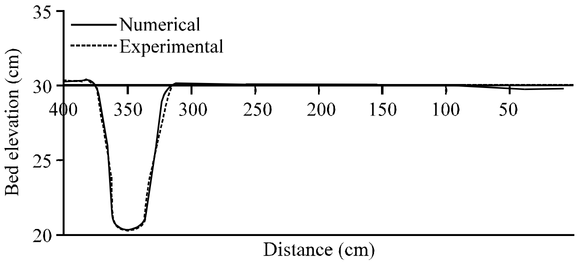


Fig. 9: Comparison between the simulation results of bed profile using HEC-RAS with the measured data at the beginning of the experiment for the pit with the depth of 15 cm and the length of 30 cm and the width of 60 cm

0.02 cubic meters per. the energy line slope which was equal to 0.001 was selected as the bottom boundary condition. The simulation results by HEC-RAS are show in Fig. 8.

The comparison between the simulation and experimental results at different time from beginning of experiments for the pit with the depth of 15 cm and the length of 30 cm and the width of 60 cm are shown in Fig. 9-14. As Fig. 9-14 show, there is a good agreement between the simulation and experimental data.

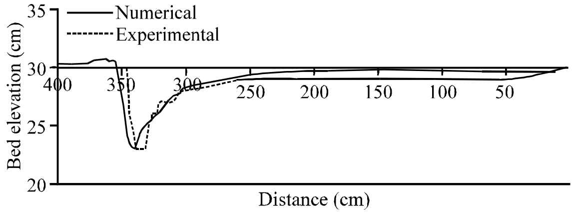


Fig. 10: Comparison between the simulation results of bed profile using HEC-RAS with the measured data after 10 min from the beginning of experiments for the pit with the depth of 15 cm and the length of 30 cm and the width of 60 cm

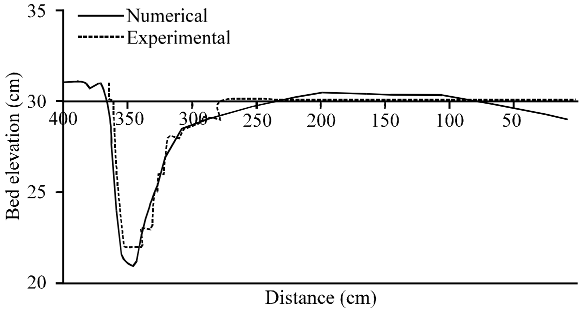


Fig. 11: Comparison between the simulation results of bed profile using HEC-RAS with the measured data after 30 min from the beginning of experiments for the pit with the depth of 15 cm and the length of 30 cm and the width of 60 cm

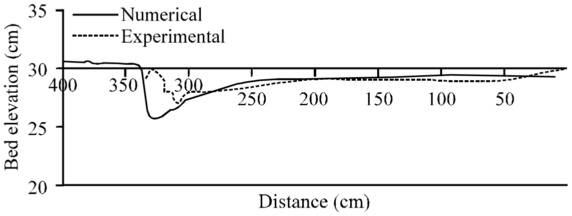


Fig. 12: Comparison between the simulation results of bed profile using HEC-RAS with the measured data after 60 min from the beginning of experiments for the pit with the depth of 15 cm and the length of 30 cm and the width of 60 cm

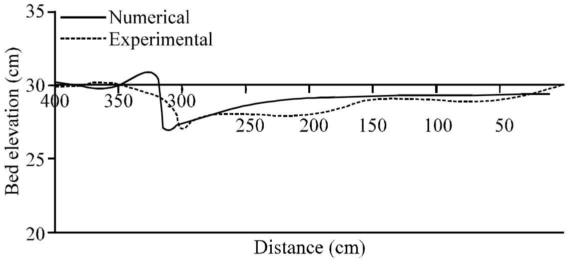


Fig. 13: Comparison between the simulation results of bed profile using HEC-RAS with the measured data after 75 min. from the beginning of experiments for the pit with the depth of 15 cm and the length of 30 cm and the width of 60 cm

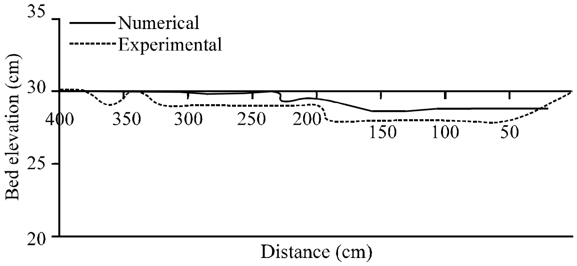


Fig. 14: Comparison between the simulation results of bed profile using HEC-RAS with the measured data after 150 min from the beginning of experiments for the pit with the depth of 15 cm and the length of 30 cm and the width of 60 cm

RESULTS AND DISCUSSION

Sand and gravel are particularly desirable sources of aggregate because weak materials are eliminated by abrasion and attrition, leaving durable, rounded, well-sorted gravels (Barksdale, 1991). They are the main source of construction of dams, buildings and many other structures. Unfortunately inappropriate removal of sand and gravel from river bed may results in scouring and deposition, which will cause migration of the mining pit and changing the river morphology. In this paper, after explaining the destructive effects of mining an inappropriate pit in the bed river, a brief introduction about the physical model which is made for investigating the variation of bed profile due to a mining pit is given. Based on experiential data, the capability of leading one-dimensional hydraulic engineering software (HEC-RAS) in modeling the bed variation of the experimental model is checked. The simulation results were compared to experimental data and the comparison showed a good agreement between simulated and experimental data. Therefore, the usage of HEC-RAS in modeling the mining problem which will occur due to improper removal of sand and gravel from river's bed is so useful.

HEC-RAS is a one-dimensional software which assumes that the flow is in one direction only and there is no direct modeling of changes in flow distribution, cross-section shape, flow direction, or other two and three-dimensional properties of the flow. So flow properties must be calculated based on characteristic properties of the cross-section (e.g., hydraulic diameter, average velocity). Therefore the ability of one-dimensional modeling is only appropriate for modeling well-defined and constant flow paths. Usage of other software with capability of modeling sediment transport like MIKE 11, MIKE 21 and FLOW-3D V9.4 should be checked and their limitation in modeling the variation of the bed due to migration of the pit should be shown. For example the Meyer, Peter and Muller bed-load transport function has been added to FLOW-3D V9.4 which is a three-dimensional numerical model. So it is probably suitable for this kind of hydraulic problem in more complex situations.

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