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A PRACTICAL METHOD FOR STUDING HYDRAULICS OF COMPOUND RIVER CHANNELS WITH HIGH EROSION AND SEDIMENTATION PROCESSES

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Several 1D or 2D models have recently been developed by various researchers for the study of flow hydraulics in compound channels, both in laboratory flumes and natural rivers. In all of these methods, only one fixed typical geometry of channel under consideration must be assumed. This assumption is valid as long as the total changes in cross section over the time period of considration could be ignored. However, in some natural rivers, this is not so and high erosion and sedimentation may be occurred in the main channel due to flash floods. In this case, to evaluate the hydraulic behavior of the channel, it is no logical to consider only one fixed geometry. To overcome this problem in general, a new method called the Envelope Sections Method (ESM) has been developed and is described in this paper. Using this method with a depth-averaged 2D analytical model (Shiono and Knight 1988), the hydraulics of Minab River has been simulated for both inbank and overbank flow conditions. Comparisons of these results with observed data have showed good applicability of this method for rivers with high erosion and sedimentation processes such as Minab River in Iran.

1 Introduction

There are many studies regarding to the flow hydraulics in compound open channels. In recent years, compound channels have achieved many interests by the researchers. This is mostly due to their importance in river engineering projects such as flood alleviation schemes and sediment management. Previous studies, especially the research carried out in a large flood channel facility at Wallingford, have shown that the traditional approach for analyzing the flow hydraulics in compound channels is misleading. Many mathematical models have been developed to modify the traditional approach by taking into account the significant lateral momentum transfer across the interface between main channel and flood plains (Knight et al 1990; Shiono and Knight 1988, 1990; Wormleaton and Merrett 1990; Wark et al 1990; Ackers 1992, 1993; Lambert and Sellin 1996; Knight 1996; Lambert and Myers 1998; Bousmar and Zech 1999; Ervine et al 2002; Haidera and valentine 2002). For all of these modified approaches, a specified cross section must be defined and computations are done for this cross section. Hence, Most of these methods have been utilized in compound laboratory flumes with rigid boundaries and few of them in regular and stable natural rivers. However, many natural alluvial rivers are very irregular and have high variable cross sectional geometries. Hence, in this case, defining a typical or specified cross section is difficult.

In this paper, to cope with this difficulty, a new approach named Envelope Sections Method (ESM) is presented. This new method combined with a two dimensional mathematical model (Shiono and Knight 1988) has been utilized for analyzing the flow hydraulics of Minab river in Iran. In the next section, a brief description of theoretical basis of two-dimensional analytical model (Shiono and Knight 1988) has summarized. Also, the application procedures of the new method (ESM) for evaluation of flow and sediment rating curves of Minab river have been presented by details.

2 Two Dimensional Analytical Model of Shiono & Knight

Shiono and Knight, on the basis of Navier-Stokes equation, have developed a two dimensional analytical model for solving the transverse variation of depth-averaged velocity and boundary shear stress in a prismatic compound channel under steady uniform flow and neglecting the secondary flow effects;

$$\rho g H S_0 - \rho \frac{f}{8} u_d^{\,2} \sqrt{1+\frac{1}{s^2}} + \frac{\partial}{\partial y}\left\{ \rho \lambda H^2 \left(\frac{f}{8}\right)^{1/2} u_d \frac{\partial u_d}{\partial y} \right\} = 0 \tag{1}$$

Where ρ = fluid density; *g* = acceleration of gravity; *H* = local water depth; S_0= channel streamwise slope; *f* = Darcy-Weisbach friction factor; u_d = depth-averaged velocity; *s* = channel side slope of the banks (1:*s*; vertical:horizental); λ = dimensionless eddy viscosity; and *y* = lateral direction.

The Secondary flow effects are significant in some cases that must be considered (Shiono and Knight 1991; Ervine et al 2002; Knight and Abril 1996). An example of these cases are narrow and meandering compound channels. In these certain cases, the right hand side of Eq. (1) is not zero.

Eq. (1) has been solved analytically to give lateral distribution of depth-averaged velocity (Shiono and Knight 1988; Knight et al 1989; Jacobs 1990):

I. For a constant depth domain (subsection 2, 4 and 6 in Fig. 1)

$$u_d = \left[A_1 e^{\gamma y} + A_2 e^{-\gamma y} + \frac{8 g S_0 H}{f} \right]^{1/2} \tag{2}$$

II. For a linear side slope domain (subsection 1, 3, 5 and 7 in Fig. 1)

$$u_d = \left[A_3 Y^{\alpha} + A_4 Y^{-\alpha-1} + \omega Y \right]^{1/2} \tag{3}$$

In which *A* values are unknown constants which must be obtained from boundary conditions. In two above equations we have:

$$\gamma = \left(\frac{2}{\lambda}\right)^{1/2} \left(\frac{f}{8}\right)^{1/4} \frac{1}{H} \tag{4}$$

$$\alpha = -\frac{1}{2} + \frac{1}{2}\left\{1 + \frac{s\sqrt{1+s^2}}{\lambda}\sqrt{8f}\right\}^{1/2} \tag{5}$$

$$\omega = \frac{gS_0}{\frac{\sqrt{1+s^2}}{s}\frac{f}{8} - \frac{\lambda}{s^2}\sqrt{\frac{f}{8}}} \tag{6}$$

and *Y*=depth function on the side slope domains.

For a typical compound cross section shown in Fig. 1, there are seven distinct subsections and therefore seven equations in form of (2) and (3) are. In this case, there are 14 unknown *A* constants (A_1... A_{14}) that can be obtained with help of 14 boundary conditions. These boundary conditions are continuity of depth-averaged velocity and its transverse gradient across joints of domains, together with no slip condition at the edge of floodplain side slopes.

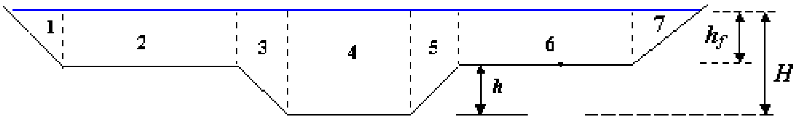

FIG. 1. Typical Compound Cross Section Geometry

3 Minab River at Berentine Hydrometric Station

The Minab River, Berentine station, has located in southern region of Iran in Hormozegan province. Fig 2 shows the site location. The bed slope of this river is nearly 0.002. Cross sections of Minab River at Berentin station have a high variation in shape due to occurring of floods. The variation of these cross sections in only three-years period (1995-1997) is shown in Fig. 3. During this time period, the flow depth and top width of the river have varied between 0.4-4.4 m and 45-170 m respectively. Therefore, it is very difficult to define a typical cross section geometry for analyzing the flow and sediment hydraulic behaviors of the river.

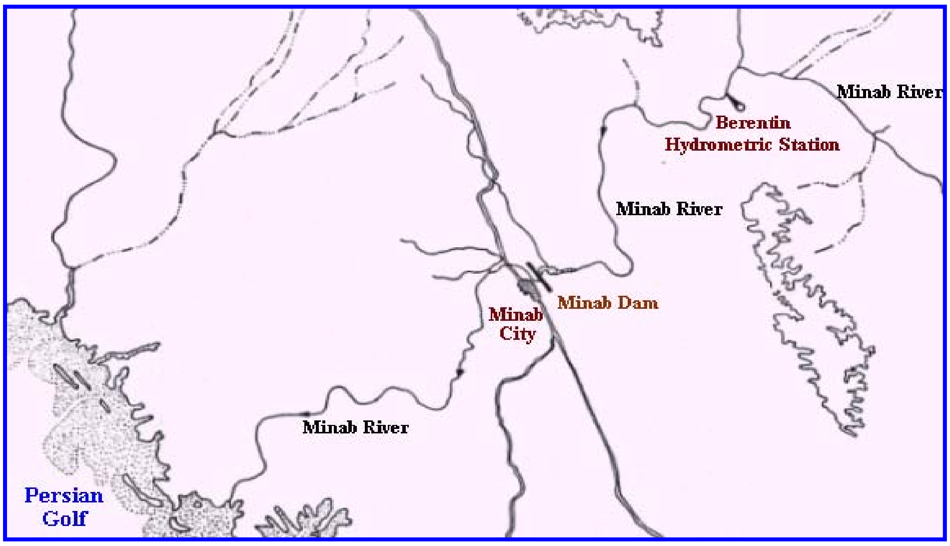

FIG. 2. Site Map of Minab River

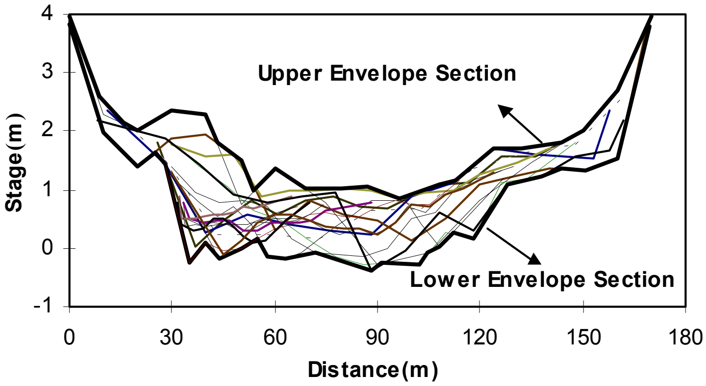

FIG. 3. Variations of Cross Section Geometry of Minab River, Berentine Station

4 Envelope Sections Method (ESM)

The Envelope Sections Method (ESM) has been presented in this paper for alluvial river compound channels which have a high variation in cross sectional geometry. As explained in previous sections, Minab river has this specific condition. So, for analysis of this river, the new method of ESM has utilized. The application procedures of this method are as follows:

4.1. *Defining of the Upper and Lower Envelope Sections*

All surveyed cross sections should be plotted in a chart altogether, regardless time of surveying. Then the upper and lower envelope cross sections may be defined by connecting the highest and lowest point elevations, respectively. These two envelope sections are shown in Fig. 3.

4.2. *Calibration of Darcy- Weisbach Friction Factors*

For applying the two dimensional Shiono and Knight model to natural rivers, this model must be calibrated. This is done using the lateral depth-averaged velocity distribution measured during the flood, the known cross section geometry and bed slope of the river. At first, for any observed flood flow condition, the compound river channel is divided to some distinct sub-areas with constant or linear variable flow depth. In natural alluvial river channels there is very few constant flow depth domains and most of them are variable flow depth domains. The numbers of created sub-areas depend to the shape complexity of the river in the main channel and floodplain. In Minab river, there are 10 sub-areas in the flood stage of 2.6 m (Q=397 m^3/s) and 20 sub-areas for the flood stage of 3.97 m (Q=1254 m^3/s). After defining the sub-areas, the lateral distribution of depth-averaged velocity can be solved across the full section by using the explained boundary conditions. For doing this, the Manning's roughness coefficients of each sub-area must be estimated. In this paper, it is assumed that Manning's roughness coefficients are independent of flow depth and depend only to the physics of boundaries. These Manning's coefficients of each sub-area are determined by solving the 2D model and using the observed lateral distribution of velocity for each flood stage by iteration. This is led to estimation of calibrated Manning's coefficients and hence Darcy-Weisbach friction factors. Therefore, the lateral distribution of calibrated friction factors for each observed flood stage can be determined.

4.3. *Determination of Friction Factors for Envelope Sections*

Knowing the lateral distribution of friction factors for each observed flood stage, the lateral distribution of friction factors for upper and lower envelope sections can be calculated. These are attained by assumption of a constant lateral distribution of friction factors across wetted perimeter of both calibrated and envelope sections.

4.4. *Application of 2D Mathematical Model to the Envelope Sections*

Using the hydraulic and geometric characteristics of upper and lower envelope sections determined in the 4.1., the lateral distribution of depth-averaged velocity of these envelope sections are calculated for each arbitrary flow stage using the 2D Shiono and Knight model and the manner explained in the above steps. By lateral integration of depth-averaged velocities, the flow discharge can be obtained for each flow stage so, the flow rating curves for upper and lower envelope sections can be calculated.

4.5. *Evaluation of Flow Rating Curves of Envelope Sections*

From all flow rating curves of envelope sections in observed flood stages (calibrated cases), the most appropriate condition must be chosen. Firstly, all flow rating curves are drawn together. Then the case which its flow rating curves have the least area between them, is selected as the best condition for analysis of hydraulic behavior of the river under consideration. Hereafter, only this flow condition is used for next computations.

In addition to friction factors, for using the 2D Shiono-Knight model, the dimensionless turbulent eddy viscosity coefficients (λ) must be estimated for the each sub-area. The estimation procedure of these coefficients is presented by Ayyoubzadeh (1997) in details. However, default overall values of these coefficients are in the range of 0.07-0.5 and the standard value of 0.067 is determined by the theory of boundary sub layer. For open channels and trapezoid canals the values of 0.13 and 0.16 are recommended. Based on measured data in a large flume with compound cross section, these coefficients are determined 0.27 and 0.22 for smooth and rough floodplains respectively (Shiono and Knight 1990). The study of Knight and Abril (1996) showed that the 2D Shiono-Knight model has low sensitivity to this parameter and yields reasonable results for velocity lateral distribution even using a constant value of this parameter across the section. Calibration of 2D model in the River Severn at Montford Bridge by Knight et al (1989) has led to estimation of dimensionless eddy viscosity in the range of 0.07-3. They have also reported very low sensitivity of 2D model to this parameter in Severn River. According to these recommendations and especially the recommend of Shiono, developer of the 2D model, the constant value of 0.15 is used across the section of Minab river in this paper (1999, Personal communication).

5 Application of ESM for Analysis of Flow Hydraulics in Minab River

In this section, application of 2D Shiono and Knight model using the ESM procedure outlined above, in Minab river at Berentin station for an observed overbank flow with flow stage of 2.6 m and flow discharge of 397 m^3/s occurring in 12/12/1995 has described for example. Firstly, the known surveyed geometry of cross section after the flood, is divided to distinct sub-areas with constant or linear variable flow depth. For this cross section, the numbers of resulting sub-areas are 10. Then, using the 2D model and the observed lateral distribution of depth-averaged velocity measured by propeller during this flood. Then Manning's roughness coefficients and following them, the friction factors for every 10 sub-areas are determined by model calibration. Using the lateral distribution of local friction factors and the assumption made in 4.4. from application procedure of ESM, the lateral distribution of friction factors in the upper and lower envelope cross sections is calculated. Therefore, the flow rating curves of these two envelope sections can be determined. This is repeated for each observed overbank flow selected for calibration of 2D model in Minab river. The results of the lateral distribution of depth-averaged velocity for two observed overbank flows are shown in Fig. 6. The field measurements of the lateral distribution of velocity in this river are presented too.

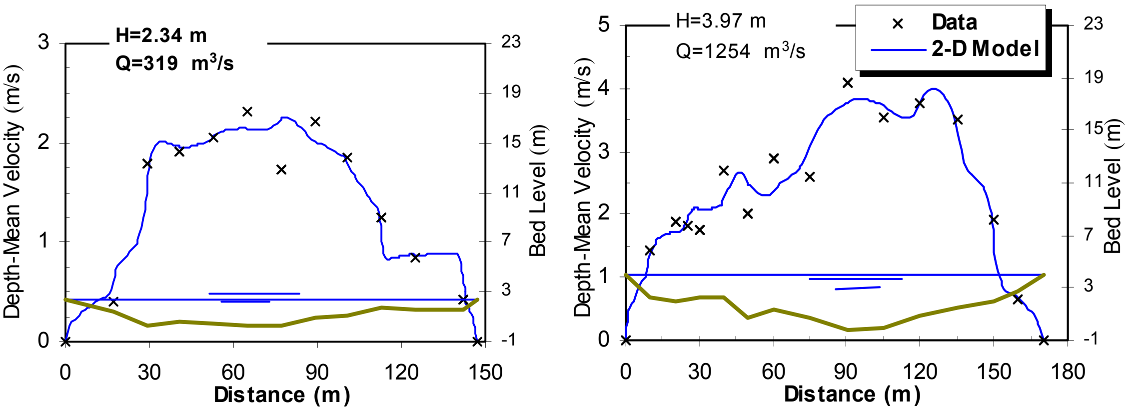

FIG. 6. Lateral Distribution of Calculated and Measured Velocities in Minab River at Berentine Station for Overbank Flows

Flow rating curves of two envelope sections for all observed overbank flows are then computed. Almost, the area enclosed between two envelope sections in all of these flow rating curves is the same. However, the flood stage of 2.6 m (discharge of 397 m^3/s) is slightly better than the others. This rating curve is shown in Fig. 7. Hereafter, only the calibrated friction factors for this overbank flow are used for analysis the flow hydraulics of Minab river. As shown in Fig. 7, the low or inbank discharges of the Minab river coincide very well with the upper envelope section's flow rating curve, however, the high or overbank discharges agree with the lower flow rating curve. For practical use of ESM, it is better to define a unique flow rating curve for both inbank and overbank flow conditions. This equation may be has the following form;

$$Q = \alpha\, Q_L + (1-\alpha) Q_U \tag{7}$$

Where α is the weighting coefficient of flow discharge $(0 \leq \alpha \geq 1)$, Q_L and Q_U are the calculated flow discharges for lower and upper envelope sections, respectively. The weighting factor (α) provides a transition between the flow discharges given by the upper and lower envelope cross sections. Variation of α with the flow stage of Minab river at Berentine station is shown in Fig. 8. This curve is obtained from observed depths and discharges data and calculated flow discharges of the upper and lower envelope rating curves. This curve is represented very well by an equation with exponential form:

$$\alpha = 0.0713\, e^{0.703H} \tag{8}$$

Where H is the flow stage. Therefore, in order to calculate both inbank and overbank flow discharges of Minab river, it needs only the Eqs. (7) and (8). Using these two equations, the flow rating curve of the river is obtained and shown in Fig. 9. It can be seen that the calculated curve is agree very well with the measured one.

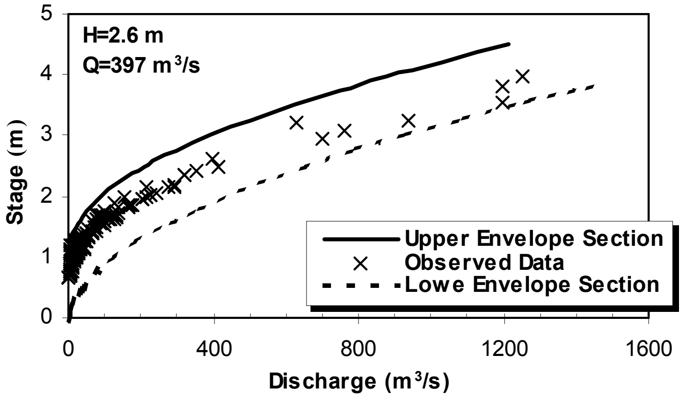

FIG. 7. Flow Rating Curve of Minab River at Berentine Station for Overbank Flows

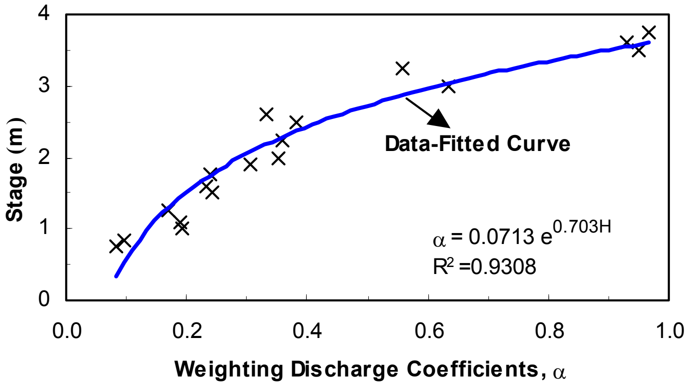

FIG. 8. Data-Fitted Curve of Weighting Discharge Coefficients

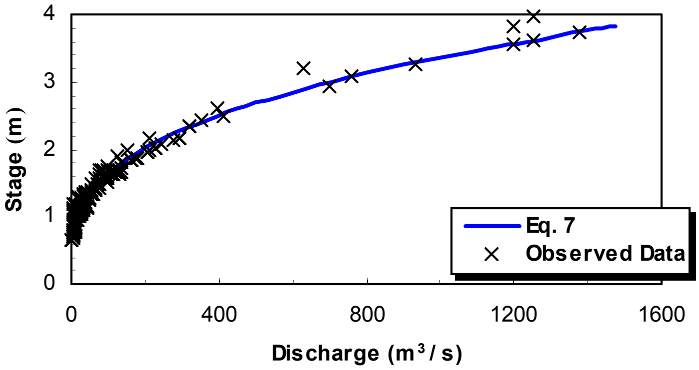

FIG. 9. Flow Rating Curve of Minab River Using the Weighting Discharge Coefficients

6 Evaluation of Flow Rating Curves

As explained in the previous sections, the flow discharges of Minab river in both inbank and overbank flow conditions can be obtained accurately from Eqs. (7) and (8). Eq. (8) is an exponential form depends only to flow stage here in this study for simplicity. However, maybe this isn't the general form for all natural rivers. This equation yields accurate values of weighting coefficients of flow discharges in Minab river which then can be used to calculate the required river flow discharges by Eq. (7). The obtained flow rating curve, has good agreement to measured data with R^2=0.93.

7 Conclusion and Recommendations

For evaluation of two dimensional mathematical model (Shiono and Knight 1988) in Minab river with a high variation of cross sectional geometries mostly due the floods, a new method called Envelope Sections Method (ESM) has presented. Using the 2D mathematical model and the ESM, the flow hydraulic behaviors have obtained for Minab river. Comparison of these results with observed data showed good performance of this method. The simulated flow rating curve of this river has a determination coefficient equal to 0.93.

In this study, an equation with exponential form is used to estimate the weighting coefficients of flow discharges which depends only to the flow stage. Although, this equation has good applicability in Minab river, but it is better to investigate these coefficients more accurately in other compound river channels.

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