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Numerical modeling of river bed evolution in abrupt hydraulic changes

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ABSTRACT: The current research work utilizes the HEC-RAS model solving unsteady one-dimensional water surface profiles incorporating sediment transport and movable bed calculations. The model is applied to predict erosion and deposition in a linearly converging–diverging open channel as well as in a channel with an abrupt change in the longitudinal bottom profile. In the first application the comparisons are made against of a previously validated two-dimensional, explicit, finite-volume numerical model. In the second application, the computed bed profile satisfactory matches available experimental measurements.

1 INTRODUCTION

The movement of sediments by fluids is an important environmental process. Sediment erosion, transportation and deposition magnitudes of solid particles have shaped the present landscape of our world and can cause severe engineering and environmental problems. Reliable, quantitative predictions not only of velocity or water depth distributions but also of sediment transport and bed level variations are very important factors in river control engineering, bridge construction, water management projects or in determining the total discharge and the probable flooding extent.

Aggradations and degradation of river bed was a subject in many studies. Bhallamudi et al. (Bhallamudi, 1991) developed an explicit numerical model to simulate the one-dimensional scour and deposition. Farsirotou et al. (Farsirotou, 2002) developed a fully coupled two-dimensional subcritical and/or supercritical, free-surface flow numerical model to calculate bed variations in alluvial channels. In this paper comparisons are presented for bed level profiles using the one-dimensional model (HEC-RAS) with those of a) previously validated two-dimensional numerical model and b) experimental measurements.

2 RIVER BED EVOLUTION USING ONE DIMENSIONAL SIMULATION MODEL

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) support a one-dimensional, steady and unsteady, flow river hydraulics and sediment transport calculations. The river hydraulic parameters must first be determined in order the HEC-RAS model be able to compute the sediment transport and the bed level variations. The HEC-RAS model uses a hydrodynamic simplification, that of the quasi-unsteady flow assumption and it is based on a continuous hydrograph with a series of discrete steady flow profiles. Each discrete steady flow profile is divided and further subdivided into shorter blocks of time for sediment transport computations. Water surface profiles are computed from one cross section to the next by solving the energy equation to a body of water enclosed by two cross-sections at locations 1 and 2 as:

$$h_2 + z_2 + \frac{a_2 V_2^3}{2g} = h_1 + z_1 + \frac{a_1 V_1^3}{2g} + h_e \qquad (1)$$

V is the average velocity, h is the water depth, z is the bed elevation, a is a velocity weighting coefficient and h_e is the energy head loss. The energy head loss between two cross-sections is comprised of friction losses and contraction and expansion losses as:

$$h_e = LS_f + C\left(\frac{a_2 V_2^2}{2g} - \frac{a_1 V_1^2}{2g}\right) \tag{2}$$

L is the distance between cross-sections 1 and 2 along the direction of the flow, S_f is the friction slope, which is calculated using Manning's equation, and C is expansion or contraction loss coefficient.

The HEC-RAS sediment routing routines solve the sediment continuity equation:

$$(1-p)B\frac{\partial z}{\partial t} = \frac{\partial Q_{sx}}{\partial x} \tag{3}$$

x is the Cartesian coordinate position in the longitudinal direction, t the time, z the bed elevation, p the sediment porosity, B the channel width and Q_{sx} the sediment discharge. This equation states that the change of sediment volume in a control volume, aggradation or degradation, is equal to the difference between inflowing and outflowing loads. The sediment continuity equation is solved by computing a sediment transport capacity through the control volume associated with each cross-section.

3 TWO-DIMENSIONAL COMPUTATIONAL ANALYSIS USING AN EXPLICIT FINITE-VOLUME METHOD

A previously developed and validated two-dimensional, viscous, unsteady, fully coupled, subcritical and/or supercritical, free-surface flow calculation numerical algorithm which simulates flow–field and bed level changes due to aggradation and degradation in rivers is also employed (Farsirotou, 2000, 2002). Vertically averaged free-surface flow equations in conjunction with sediment transport equation are numerically solved using an explicit finite-volume scheme in integral form. Hydrostatic pressure distribution is assumed throughout the flow field.

4 APPLICATIONS

4.1 *Bed-level variation in a converging – diverging open channel*

Subcritical flow in a linearly converging-diverging open channel is numerically simulated using the one-dimensional HEC-RAS model and the two-dimensional finite volume numerical technique (Farsirotou 2002). Figure 1 shows the schematic plan view and geometry of the channel. At the inlet flow region the width is equal to 5.0 m and at the axial distance of 5.0 m the geometry converges symmetrically, until the width takes the value of 2.0 m. The throat area extends to a distance of 4.0 m and the width keeps a constant value of 2.0 m. At the axial distance of 12.0 m, away from the inlet, the channel side wall diverges symmetrically. The contraction angle is equal to the expansion angle and both are equal to 26.56°. The channel was carrying an initial uniform flow discharge of 0.1 m^3/sec at a uniform flow depth of 0.1 m. The initial bed slope was equal to 0.0. The bed material consists of sand with a mean diameter of 0.32 mm and the Manning's roughness coefficient is estimated to be 0.022. Figures 2 and 3 shows the comparison of the bed level variation between the two models along the center flow line of the channel, after 1 hour and 2 hours, respectively, using the empirical Engelund and Hansen (1967) sediment transport equation. In the converging part of the channel the flow accelerates and bed degradation occurs. In the diverging region, as flow decelerates, aggradation develops. The regions of expected erosion and deposition are satisfactorily predicted from the one-dimensional sediment transport model. Comparisons between bed level variation computed with the one-dimensional model, using various sediment transport equations: Engelund and Hansen (1967), Ackers-White (1973), Yang (1984) and Toffaleti (1968), are presented in Fig. 4. As it was expected, the results vary depending on the parameters over which the transport function is developing.

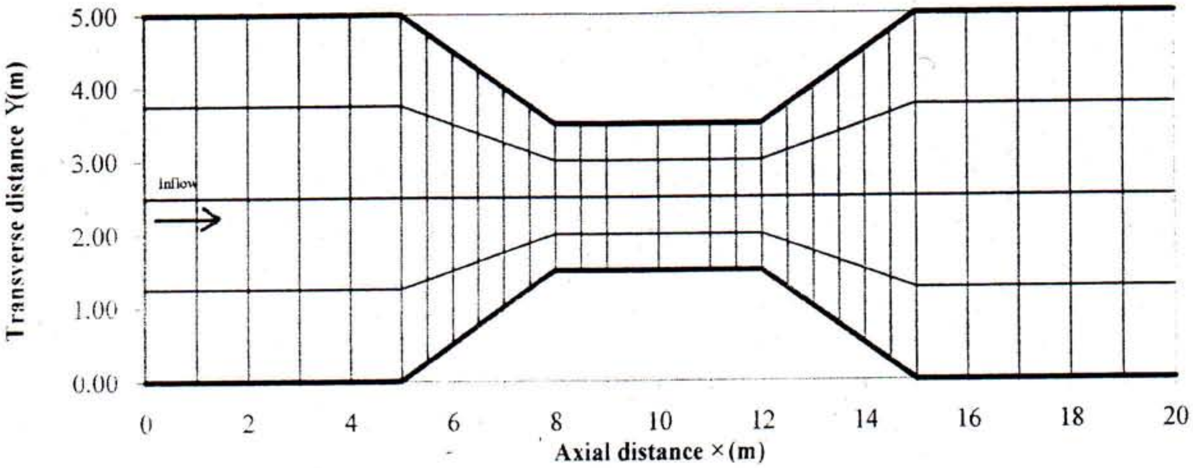

Figure 1. Geometry of the converging-diverging channel.

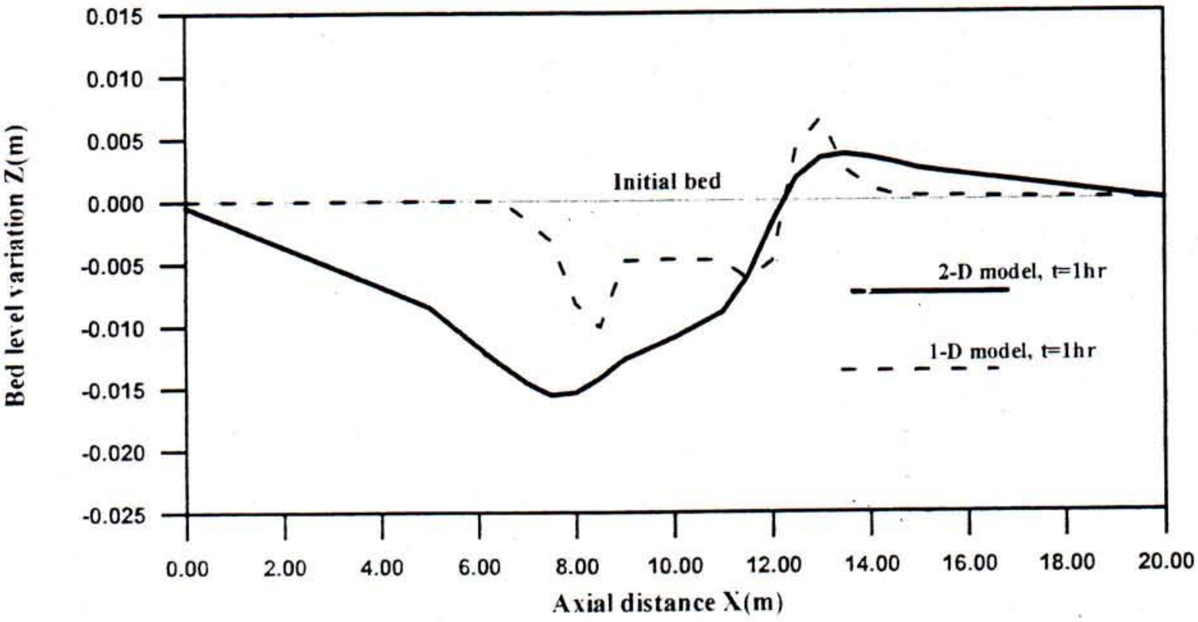

Figure 2. Computed bed level variation using the one-dimensional Engelund and Hansen sediment transport equation and the two-dimensional finite-volume sediment transport numerical models after 1.0 hour.

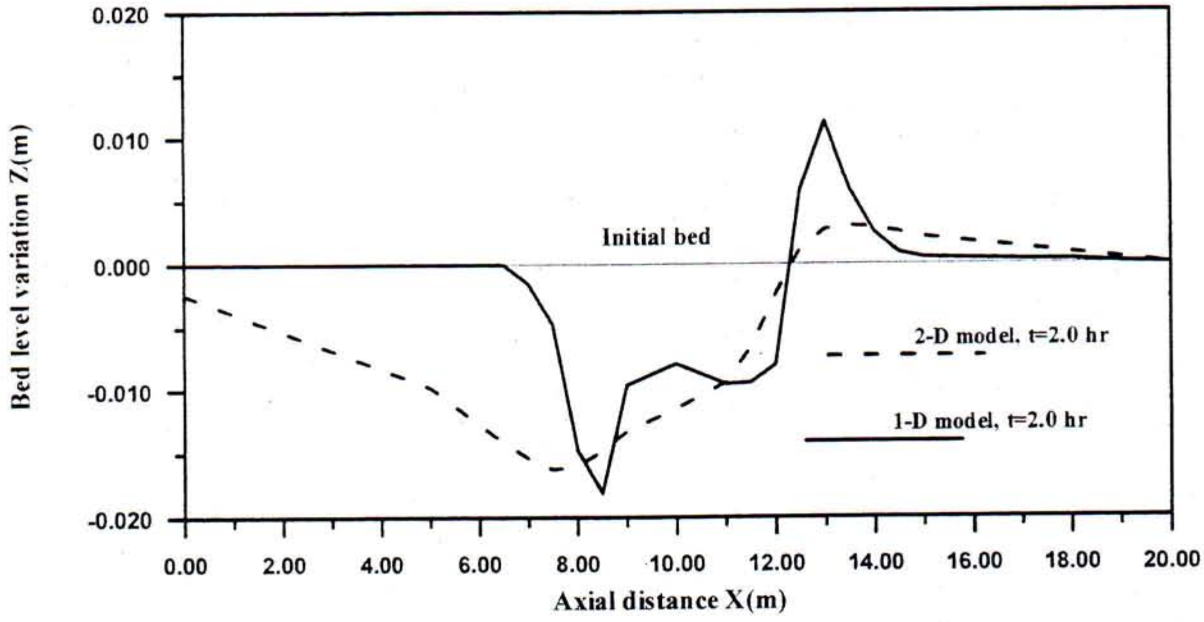

Figure 3. Computed bed level variation using the one-dimensional Engelund and Hansen sediment transport equation and the two-dimensional finite-volume sediment transport numerical models after 2.0 hours.

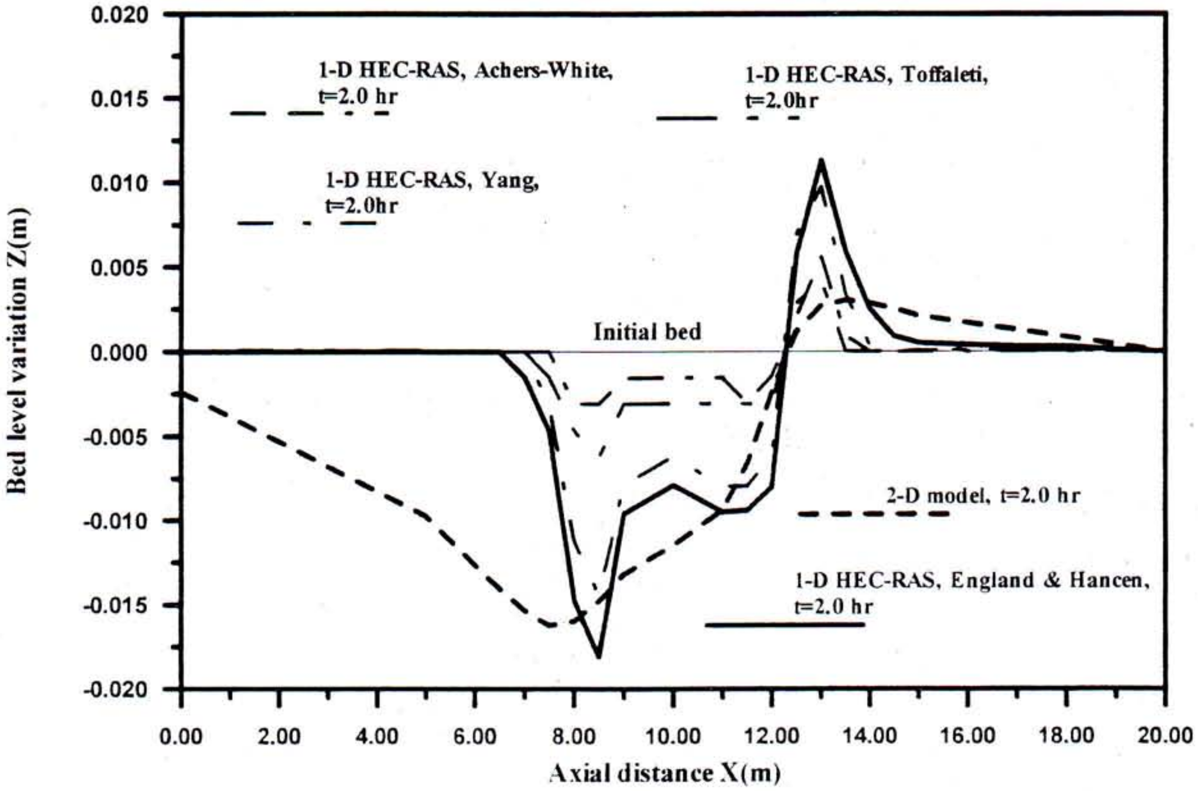

Figure 4. Comparison between computed bed profile using various bed-load formulae after 2.0 hours.

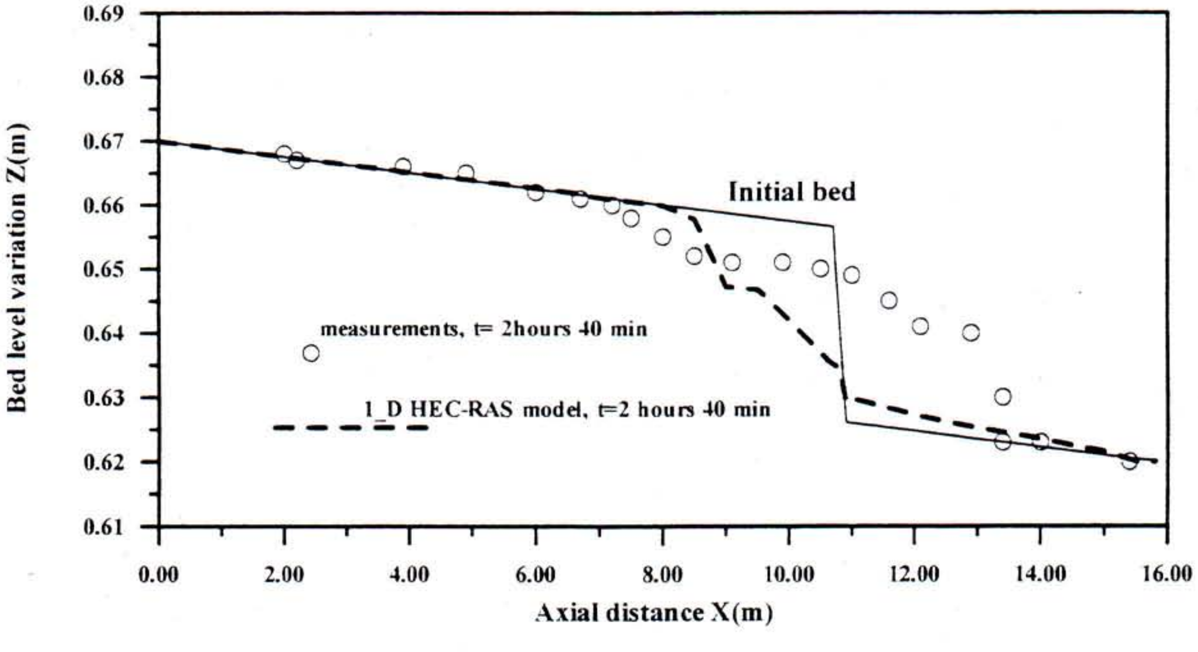

Figure 5. Comparison between measured and computed (HEC-RAS) using Engelund and Hansen sediment transport equation bed level variation after 2 hours 40 min.

4.2 *Bed level variation in an open channel with an abrupt bottom change*

Comparisons between numerical results of bed level changes with experimental measurements (Bhallamudi 1991) in an open channel with an abrupt change in the longitudinal bottom profile, are also provided. The experiment is conducted in a channel with 15.8 m long and 1.2 m wide. A fall of 0.0305 m is provided at 10.8 m from the upstream end to simulate the steepened reach. The channel was carrying an initial unit uniform flow discharge 0.0028 m^2/sec at a uniform flow depth of 0.0305 m. The initial bed slope above and below the point of abrupt change was equal to 0.00125.The bed material consisted of sand which had a mean diameter of 0.67 mm. Figure 5 shows the comparison between measured and computed values of bed level changes after 2 hours and 40 min using the Engelund and Hansen (1967) sediment transport equation. Various empirical sediment transport equations were also investigated (not shown). The Engelund-Hansen (1967) model satisfactorily simulates the experimental measurements.

5 CONCLUSIONS

The current research work utilizes the HEC-RAS model solving unsteady one-dimensional water surface profiles incorporating sediment transport and movable bed calculations. The model is applied to predict erosion and deposition in a linearly converging–diverging open channel as well as in a channel with an abrupt change in the longitudinal bottom profile. Comparison of bed level profiles with those of a previously validated two-dimensional model as well as with experimental measurements led to a useful package with improved and reliable methodology for solving the aforementioned sediment transport problems at various channel geometries.

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