ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ – СОФИЯ

Юбилейна приложна научно-техническа конференция
„65 години Хидротехнически факултет и 15 години немскоезиково обучение"

6–7 ноември 2014
6–7 November 2014

International Jubilee Conference
„65th Anniversary Faculty of Hydraulic Engineering and 15th Anniversary Hydraulic Engineering in German"

ANNUAL OF THE UNIVERSITY OF ARCHITECTURE, CIVIL ENGINEERING AND GEODESY – SOFIA

XLVII том vol. 2014 св. fasc. I-A

MODELLING OF THE UNSTEADY FLOW-SEDIMENT INTERACTION-GRAIN SIZE APPROACH

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Keywords: *2-D unsteady flow-sediment interaction, modeling concepts, the Danube River Bezdan-Mohach field data, model's results*

Research area: *hydraulic engineering*

ABSTRACT

This paper presents a two-dimensional mathematical model of the unsteady flow-sediment interaction with sediment mixtures in natural watercourses, based on an enhanced MOBED2 modeling system. The hydrodynamic formulation is based on depth-averaged RANS equations. Bed and near-bed sediment processes are described using the active-layer and active-stratum approach, including bedload transport, bed-elevation changes, and the sediment exchange between the suspended material and the bed and near-bed material. This results in an essentially two-dimensional hydrodynamic formulation in the plane parallel to the bed's surface. Suspended-sediment transport is described by the depth-averaged form of the general three-dimensional advection-diffusion equation. The sediment mixture is represented through a suitable number of sediment size classes, and all sediment equations are re-formulated for sediment mixtures. Besides the modeling concept and associated numerical considerations, this paper presents the model's formulation, calibration and verification, based on two field-data sets collected at the Danube River experimental Bezdan-Mohach reach.

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1. Introduction

In order to establish the set of the 1D, 2D and 3D mathematical models of water flow and sediment transport, during the period of 23 to 27 May 2011, corresponding measurements are carried out on the river Danube as part of an IPA project. For experimental river section, the location between city of Mohacs on the Hungarian side, and the city of Bezdan on the Serbian side, is chosen. The flow measurements included bathymetry, velocity and discharge data, while the suspended sediment and bed material sampling were part of the sediment measurements.

Seven cross sections, distributed nearly evenly along the central part of selected river section (rkm 1438 ÷ rkm 1432), represents the measurements locations respectively. Utilizing the collected flow and sediment data, the 2-D mathematical model of water flow and sediment interaction, based on the depth-averaged equations transformed in to the curvilinear coordinate system using the non-orthogonal transformation, is applied. Numerical results are compared with corresponding field data. Analysis, which include velocity and free surface elevation comparison for the flow, and suspended sediment mixtures for the sediment data, shows very good agreement with the results obtained from the mathematical model.

2. Mathematical formulation

2.1. Flow equation

The basic flow equations are the depth-averaged RANS equations, written herein in tensor notation:

The depth-averaged mass-conservation equation:

$$\frac{\partial h}{\partial t}+\frac{\partial (h\tilde{u}_j)}{\partial x_j}=0\,, \tag{1}$$

The depth-averaged momentum-conservation equations:

$$\begin{aligned}&\frac{\partial \tilde{u}_i}{\partial t}+\tilde{u}_j\frac{\partial \tilde{u}_i}{\partial x_j}=-g\frac{\partial (Z_b+h)}{\partial x_i}+\frac{1}{\rho h}\frac{\partial}{\partial x_j}\left(\tilde{\tau}_{ji}h\right)\\&+\frac{\tau_{si}-\tau_{bi}}{\rho h}-\frac{1}{\rho h}\frac{\partial}{\partial x_j}\int_h \rho\left(u_j-\tilde{u}_j\right)\left(u_i-\tilde{u}_i\right)dz \quad i=1,2\end{aligned}\;, \tag{2}$$

where: t = time; x_i = i – coordinate direction; $\tilde{u}_i$ = i – direction component of the depth-averaged flow velocity; h is the flow depth; Z_b = the bed-surface elevation; ρ = the density of the water and suspended-sediment mixture; $\tilde{\tau}_{ji}$ = i – direction component of the depth-averaged turbulent diffusion stress, and τ_{si},τ_{bi} = i – direction components of the free-surface and the bed shear stress, respectively. The depth-averaged turbulent diffusion stress $\tilde{\tau}_{ji}$ and the dispersion term τ_{ji}^{disp} are further expressed as $\tilde{\tau}_{ji}+\tau_{ji}^{disp}=\left(\nu_t+\nu^{disp}\right)\left(\partial\tilde{u}_i/\partial x_j+\partial\tilde{u}_j/\partial x_i\right)$, where $\tilde{\nu}_t$ represents the Boussinesq eddyviscosity coefficient (evaluated by using an appropriate turbulence model), and ν^{disp} represents the dispersion coefficient (evaluated by using the dispersion theory). The wind-shear stress at the water surface was neglected, since it has far less influence over the sediment processes than the bed shear stress. The bed-shear stress was expressed in the traditional manner: $\tau_{bi} = C_f \rho \tilde{u}_i \sqrt{\tilde{u}_1^2 + \tilde{u}_2^2}$, where C_f is the friction coefficient. More details can be found in Spasojevic and Holly (1990a, 1990b, 2007).

2.2. Sediment equation

As shown in Figure 1, the otherwise single and continuous domain of sediment-processes is divided herein into three subdomains: the suspended-sediment subdomain, the active-layer sediment subdomain, and the subsurface sediment subdomain (divided into so-called active stratum and other strata below). Governing sediment equations are then defined for each subdomain, including sediment exchange mechanisms between them. The sediment mixture is represented though a suitable number of sediment size classes k_s=1,....KS, where KS represents the total number of size classes, allowing for the definition of, wherever appropriate, the governing-equations' terms as size-class specific.

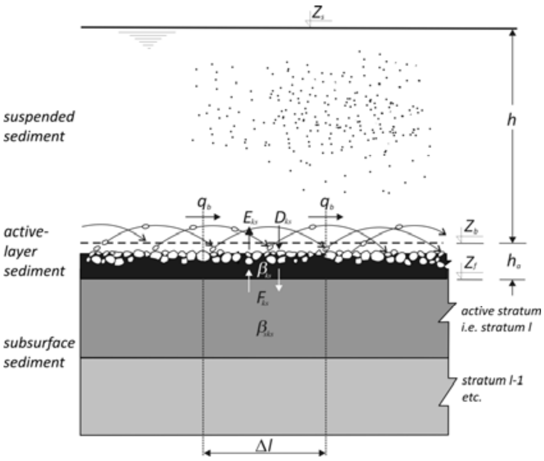

Figure 1. The Definition Sketch for Sediment Subdomains

2.3. Suspended solids

The governing equation for suspended sediment processes is obtained by depth-averaging the three-dimensional mass-conservation equation, written for size class k_s of sediment particles. Then, the depth-averaged suspended-sediment mass-conservation equation, written for sediment size class k_s, reads:

$$\begin{aligned} &\frac{\partial \tilde{c}_{ks}}{\partial t} + \tilde{u}_j \frac{\partial \tilde{c}_{ks}}{\partial x_j} = -\frac{1}{h}\frac{\partial}{\partial x_j}\left(\tilde{q}_{s\,ks\,j} h\right) \\ &-\frac{1}{h}\frac{\partial}{\partial x_j}\int_h \left(c_{ks} - \tilde{c}_{ks}\right)\left(u_j - \tilde{u}_j\right) dz + \frac{E_{ks} - D_{ks}}{h}, \end{aligned} \tag{3}$$

where: $\tilde{c}_{ks}$ = depth-averaged volumetric concentration of the size class ks particles; $\tilde{q}_{s\,ks\,j}$ – the depth-averaged suspended-sediment turbulent mass diffusion flux of the size class ks particles. The depth-averaged turbulent mass diffusion flux $\tilde{q}_{s\,ks\,j}$ and the mass-dispersion term $q_{s\,ks\,j}^{disp}$ are expressed as $\tilde{q}_{s\,ks\,j} + q_{s\,ks\,j}^{disp} = \left(\varepsilon_s + \varepsilon^{disp}\right) \partial \tilde{c}_{ks} / \partial x_j$, where ε_s represents sediment mass-diffusivity coefficient and ε^{disp} represents the sediment mass dispersion coefficient.

2.4. Active layer sediment and subsurface sediment

Governing equations for bed and near-bed processes are based on the active-layer and active-stratum approach, used in conjunction with a modeling concept designed for the treatment of sediment mixtures, as introduced by Spasojevic and Holly (1990a, 1990b). Additional details can be found in Spasojevic and Holly (2007). The active layer (Figure 1) is assumed to comprise sediment moving as a bedload, as well as bed-surface and immediate subsurface sediment already agitated and ready to be set into motion.

The mass-conservation equation for size class ks of sediment in the active-layer control volume ΔV is written as follows:

$$\rho_s \left(1 - p_b\right) \frac{\partial \left(\beta_{ks} h_a\right)}{\partial t} + \frac{\partial q_{bks\,j}}{\partial x_j} + E_{ks} - D_{ks} - F_{ks} = 0\,, \quad (4)$$

where: β_{ks} = active-layer fraction of the size class ks, defined as a ratio of the mass of particles of the size class ks inside the active-layer control volume ΔV to the mass of all sediment particles contained in ΔV; and $q_{bks\,j}$ = the bedload flux component for the size class ks. As Figure 1 indicates, the only bedload particles changing the mass balance inside the active-layer control volume are the ones entering and leaving the volume. Other bedload particles start and end their trajectories inside the same active-layer control volume, remaining within the volume and not changing the mass balance within it. In order to enable use of a conventional bed-material porosity p_b, the active-layer thickness h_a in Eq. (4) is defined assuming that such bedload particles are positioned at the bed surface. Terms E_{ks} and D_{ks} represent an upward sediment entrainment flux and a downward sediment deposition flux, both for the size class ks, respectively, and correspond to the same terms in Eq. (3), but with the opposite signs. The entrainment and deposition fluxes are evaluated at some distance above the bed surface, and that location is considered to be the bed or near-bed boundary of the suspended sediment subdomain. The term F_{ks}, called herein the active-layer floor source and again specific to the size class ks, represents the exchange of sediment particles between the active-layer and the active-stratum control volumes due to active-layer floor movement. The active-layer floor, which is at the same time an active-stratum ceiling, descends or rises whenever the bed elevation changes due to deposition or erosion occurring in the active-layer control volume.

The mass of a particular size class in the active-stratum control volume may change only due to active-layer floor movement, i.e. due to exchange of material between the active layer and active stratum, while the active-stratum floor elevation remains unchanged. This is expressed by a mass-conservation equation written for the size class ks in the active-stratum control volume:

$$\rho_s \left(1-p_b\right)\frac{\partial}{\partial t}\left[\beta_{sks}\left(Z_b-h_a\right)\right]+F_{ks}=0\ , \tag{5}$$

where: β_{sks} = active-stratum fraction of the size class ks; and $\left(Z_b-h_a\right)$ = active-layer floor elevation, i.e. active-stratum ceiling.

Summation of Eqs. (4) for all size classes in the active-layer control volume and use of the basic constraint:

$$\sum_{ks=1}^{KS}\beta_{ks}=1\ , \tag{6}$$

leads to the global mass-conservation equation for the active-layer control volume. A similar global mass-conservation equation (again invoking Eq. (6)) can be obtained for the active-stratum control volume. Summation of global mass-conservation equations for active-layer control volume and for active-stratum control volume gives the global mass-conservation equation for bed sediment:

$$\rho_s \left(1-p_b\right)\frac{\partial Z_b}{\partial t}+\sum_{ks=1}^{KS}\left(\frac{\partial q_{bks\,j}}{\partial x_j}+E_{ks}-D_{ks}\right)=0\ . \tag{7}$$

All active-layer sediment and subsurface sediment equations are essentially two-dimensional in the plane parallel to the bed surface.

2.5. Sediment exchange mechanisms

Sediment exchange between suspended sediment and active-layer sediment is defined by sediment entrainment E_{ks} and deposition D_{ks} terms in Eqs. (3), (4), and (7). Sediment exchange between active-layer and subsurface (active stratum) sediment is defined by the active-layer source term F_{ks} in Eq. (4).

Based on Eq. (3), the upward active-layer sediment entrainment (resuspension) flux E_{ks} and the downward suspended sediment deposition flux D_{ks} are modeled herein as a near-bed upward turbulent mass-diffusion flux, and a near-bed downward fall-velocity flux (Spasojevic and Holly, 1993):

$$E_{ks}=-\beta_{ks}\varepsilon_s\frac{\left(c_{ks}\right)_{a+\Delta a}-\left(c_{ks}\right)_a}{\Delta a}\ ,(8)$$

and

$$D_{ks}=w_{fks}\left(c_{ks}\right)_{a+\Delta a}\ , \tag{9}$$

where $\left[\left(c_{ks}\right)_{a+\Delta a}-\left(c_{ks}\right)_a\right]/\Delta a$ represents the near-bed non-equilibrium concentration gradient, subscript 'a' denotes that the mass-diffusion flux (i.e. the near-bed concentration gradient) is evaluated at a near-bed point some distance a above the bed, β_{ks} reflects the availability of the size class ks in the active-layer control volume, $\left(c_{ks}\right)_a$ is a near-bed active-layer sediment concentration, while $\left(c_{ks}\right)_{a+\Delta a}$ represents a near-bed non-equilibrium concentration at distance $a+\Delta a$ above the bed surface, extrapolated from the suspended-sediment computations, and w_{fks} represents the particle fall velocity for the specific size class.

Following Spasojevic and Holly (1990a, 1990b), the active-layer source term F_{ks} is expressed by using Eq. (5). When the active-layer floor (active-stratum ceiling) descends, then:

$$F_{ks} = -\rho_s\left(1-p_b\right)\frac{\partial}{\partial t}\left[\beta_{sks}\left(Z_b-h_a\right)\right], \tag{10}$$

gives the mass of the size class ks, formerly comprising size fraction β_{sks} of the active-stratum control volume, which becomes part of the active-layer elemental volume. When the active-layer floor (active-stratum ceiling) rises, then:

$$F_{ks} = -\rho_s\left(1-p_b\right)\frac{\partial}{\partial t}\left[\beta_{ks}\left(Z_b-h_a\right)\right]. \tag{11}$$

gives the mass of the particular size class, formerly comprising size fraction β_{ks} of the active-layer elemental volume, which becomes part of the active stratum control volume.

3. Numerical solution

The governing flow equations, i.e. Eqs. (1) and (2), as well as the governing sediment equations, i.e. Eqs. (3), (4), and (7), are transformed from Cartesian into general non-orthogonal curvilinear coordinates, following the rules of complete coordinate transformations.

3.1. Numerical solution approach

The flow equations, i.e. the continuity equation and two momentum-conservation equations, are solved in three consecutive steps (performed during each computational time step): advection, diffusion, and propagation. The hyperbolic-type flow advection-step equations describe the change of local acceleration components due to the sole action of advection terms in momentum-conservation equations. The elliptic-type flow diffusion-step equations describe the change of local acceleration components due to the action of diffusion terms in momentum-conservation equations, added to the action of advection terms. The flow propagation step combines the continuity equation and the propagation parts of momentum-conservation equations. The propagation parts of the momentum-conservation equations describe the change of local acceleration components due to the action of propagation terms (gravity and pressure) and the bed-shear stress term, added to the action of advection and diffusion terms. Once the depth is computed, propagation parts of the momentum equations yield the final local „advection-diffusion-propagation“ acceleration.

The size-class specific mass-conservation equation for suspended sediment is solved in two consecutive steps (again, performed during each computational time step): advection-source step and diffusion step. The hyperbolic-type, suspended-sediment, advection-source step equation describes the local change of the suspended-sediment concentration due to the action of advection terms and the entrainment-deposition terms. The elliptic-type suspended-sediment diffusion step equation describes the local change of suspended-sediment concentration due to the action of diffusion, added to the action of advection-source terms.

The numerical solution of hyperbolic-type equations is prone to numerical problems, such as numerical diffusion, oscillations or instability. To avoid (or minimize) these problems, the flow advection-step equations and the suspended-sediment advection-source step equation are solved by using a characteristics (trajectory) method with higher-order spatial interpolations (Hermite bicubic interpolation (Holly and Preissmann, 1977) for the sediment computations, and quadratic upstream interpolation (Leonard 1979, as described by Ferziger and Peric 2002) for the flow computations. The elliptic-type, flow, diffusion-step equations, the depth (or depth-increment) equation, and the suspended-sediment, diffusion-step equations are solved by using the implicit finite-difference scheme and ADI solution procedure, yielding a satisfactory and unconditionally stable numerical solution.

Due to the slow nature of the bedload movement, mass-conservation equations for the active-layer sediment (i.e. Eqs. (4)), and the global mass-conservation equation for the bed sediment (i.e. Eq. (7)), are discretized by integrating them over the time step and control volume, i.e. using an upwind-like scheme for bedload flux derivatives.

3.2. Numerical coupling considerations

To satisfy the basic constraint (Eq. 6), all bed and near-bed sediment equations (i.e. Eqs. (4) and (7)), containing KS unknown active-layer size fractions β_{ks} and one unknown bed-surface level Z_b, are, for the same control volume, solved simultaneously by using the Newton-Raphson iterative procedure. More details can be found in Spasojevic and Holly (1990a, 1990b).

The bed and near-bed processes and suspended-sediment processes are strongly coupled through the sediment-exchange terms. Thus, numerical coupling for sediment computations is achieved through an iterative solution algorithm, with several iterations within each time step.

The sediment-processes feedback to the flow is modeled herein through changes in: bed elevations, the flow and the suspended-sediment mixture density (due to changes in suspended-sediment concentrations), and the bed friction coefficient (due to changes in bed surface size-fraction distribution). Since the sediment feedback has relatively minor effects during a single computational time step, the iterative coupling between the flow and sediment processes is typically restricted to a single iteration.

4. ADCP, sediment and bathymetry data processing to fit models needs

In order to incorporate field measurements into to the mathematical model in sense of calibration and verification, collected raw data are therefore processed and used in adequate form. Bathymetry measurements, which are taken along the experimental river section on cross sections that are about 100.0 m apart, are handled using the GIS software. Seven ranges are placed approximately at the distance of 950.0 m from each other, containing the seven measuring verticals, nearly evenly distributed along the cross section.

4.1. Flow measurements

As was indicated before, flow measurements included velocity components and flow discharge. For this part of measurements, the standard Acoustic Doppler Current Profiler (ADCP) is used. Having in mind that during the measuring period a possible flow variation may occur, the discharge is therefore measured in every range. Using the four time passing technique, which actually means that in order to achieve better assessment of the volumetric flow rate, minimum 4 vessel passing is required, the discharge data are collected and then averaged applying the arithmetic mean. Enforcing the same criteria regarding the accuracy of measuring methods, for velocity sampling the different approach is adopted. In order to eliminate all the negative influences during the acquiring period, like small and large scale turbulence, the stationary vessel with the minimum 10.0 min of sampling in every vertical is used. Applying the post-processing approach, for which the adequate ADCP software is used, acquired velocity data are then averaged along the each of the measuring verticals. As a result the time averaged velocity components, which include three Cartesian velocity components u (U_{east}), v (U_{north}) and w (U_{vert}), are obtained.

4.2. Sediment measurements

In contrast to the flow, sediment measurements are conducted only in 5 medium verticals along each range. The suspended sediment is collected in 5 levels, uniformly spaced across the depth, while the bed material is sampled only at the bottom of measuring verticals. For both sediments the adequate sampler is used. To incorporate sediment data in previously described mathematical model, which is based on the sediment mixtures and interaction between water, suspend sediment and bed material, the acquired material is analyzed using the grain size approach.

5. Calibration and validation of the model

Since the 2-D mathematical model of unsteady flow-sediment interaction with sediment mixtures was applied to the selected domain between the first and the seventh range (Figure 2b), as a first step numerical (computational) mesh is created. For this purpose three possible configurations of the computational mesh have been done, with cell dimension of 10x10 m, 10x20 m and 20x20 m in x and y direction, respectively. As a final configuration, the grid with cell dimension of 20x20 m has been chosen. The hydrograph has been applied as an upstream boundary condition (Figure 6) and a water level graph as a downstream boundary condition (Figure 7b). For the flow simulation the following parameters are set: $\Delta t = 50\ s, \tilde{\nu}_t = 0.00015\ m^2 s^{-1}$, $n = 0.019\ m^{-1/3} s$. As initial conditions, horizontal free surface level and zero velocity components are adopted. In the same manner, the sediment part of the model also requires definition of boundary and initial conditions. Specifying the upstream boundary condition in form of a depth averaged concentration for each size class of the suspended sediment is required, while the initial condition for both sediments (suspended sediment and bed material) includes averaged concentration/fraction of the size class k_s for each size class along the entire section. The simulation period of 5 days is adopted. Comparison of numerical results with the corresponding field data regarding the velocity computation, suspended sediment concentration and fraction of the size class k_s, which have been processed to fit the 2-D model (depth averaged), are presented in Figures 2, 3 and 4.

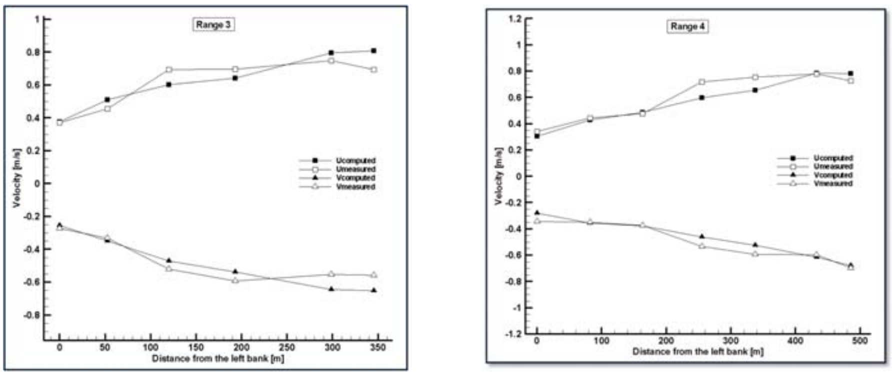

Figure 2. Measured and computed depth-averaged velocity

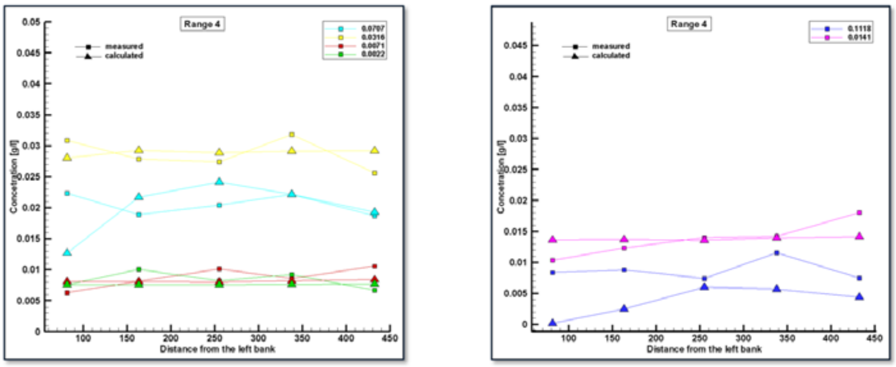

Figure 3. Measured and computed concentration – Range 4

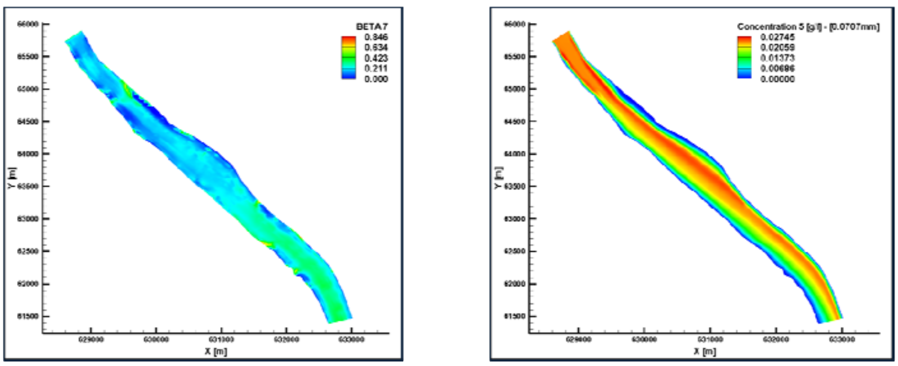

Figure 4. Computed concentration and fraction of the size class 5 and 7, respectively – plane view

6. Conclusion

The presented paper addresses the calibration of 2-D mathematical model of unsteady flow-sediment interaction with sediment mixtures. For this purpose adequate field measurements of flow, suspended sediment and bed material on the river Danube have been used. Obtained filed data are processed to fit models needs.

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МОДЕЛИРАНЕ НА НЕСТАЦИОНАРНИ ПРОЦЕСИ НА ВЗАИМОДЕЙСТВИЕ ТЕЧЕНИЕ–СЕДИМЕНТ

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***Ключови думи**: 2-D нестационарно взаимодействие течение–седимент, моделна концепция, данни от натурни измервания в р. Дунав в участък Бездан–Мохач, моделни резултати*

***Научна област**: хидротехническо строителство*

РЕЗЮМЕ

Настоящата статия представя двудимесионален числен модел на нестационарните процеси на взаимодействие течение–седимент при двуфазни течения в естествени легла, основан на подобрен модел система MOBED2. Моделирането на хидродинамичните процеси се базира на усреднените по време RANS-уравнения (уравнения на Рейнолдс). Процесите в непосредствена близост до и в самата контактна зона течение-седимент са описани чрез прилагане на метода на активния слой и активната среда, включващи транспорта на влачени наноси, промяната на нивото на дъното и обмена на седименти между плаващите наноси, влачените наноси и дъното. В резултат е постигнат един двудимесионален хидродинамичен модел в паралелната на дъното равнина. Транспортът на плаващите в суспендирано състояние наноси е описан посредством класическите тридимесионални уравнения за адвекция и дисперсия, трансформирани за усреднената дълбочина. Седиментният материал е представен чрез подходящ брой зърнометрични класове, като всички уравнения са преработени за работа със седиментните смеси. Освен основите на числения модел, настоящата статия представя още калибрирането и проверката на модела въз основа на натурни данни от две изследвания в участъка от река Дунав Бездан–Мохач.

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