Evaluation of the SPH Method in Two Dimensional Open Channel Flow Modeling

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Abstract
This paper presents the application of the smoothed particle hydrodynamics (SPH) method for the modeling of two dimensional open channel flow. In order to produce dependable conclusions the SPH mesh-free approach was compared with another two essentially different modeling methodologies already established in open channel flow computation. The performance of the different approaches was explored using previously verified computer codes. The main difference between the evaluated numerical models is a result of the varying integrated numerical approaches. The first approach was the finite difference method that relies on a structured mesh. The second approach was the finite element method that uses an unstructured mesh. The considered models were employed for the numerical simulation of a steady flow situation using data from a laboratory experiment. The methods were evaluated through the comparison of computed and measured velocity components. The computer code based on the SPH method demonstrated the ability to accurately reproduce measured velocities in certain segments of the modeled domain, it needs additional analysis to evaluate its performance when applied to highly irregular river bed geometry or long term simulations.

Keywords
Smoothed particle hydrodynamics; finite element method; finite difference method; numerical model

INTRODUCTION

The importance of numerical modeling in open channel flow analysis is observable simply by the variety of the existing modeling approaches such as the finite element method (Galland et al., 1991), finite volume method (Erduran, 2013), finite difference method (Cioffi et al., 2003), SPH methods (Vacondio et al., 2012c) and others. The objective of this paper is to conduct a study that investigates the applicability of the smoothed particle hydrodynamics (SPH) method for the modeling of two dimensional open channel flow. The SPH is a mesh free method that is less sensitive to rapidly changing flows than other grid-based methods. Therefore, the SPH method could prove to be a more convenient solution for the future modeling of open channel flows. Whit this in mind, the authors conducted an analysis by comparing the performance of an SPH based numerical model with two other existing models that are based on well established approaches for modeling this type of occurrences. The first is a grid based method (structured grid) that uses the fractional step method is the MoBed2 code (Horvat et al., 2014). The second model was the Telemac-2D (Galland et al., 1991) that relies on the finite element approach (unstructured grid). The SPH models performance was tested by simulating a previously conducted steady state flow measurement descrivbed by Kapor, 1983. and comparing the measured and computed values. The conducted analysis was expanded by including the previously mentioned mathematical models in the simulations. Using the models MoBed2 and Telemac-2D to simulate the same steady state situation, the authors included another approach for the SPH models evaluation, by comparing the calculated values among themselves, and by their comparison with the measured values.

METHODS

The objective of this paper was to assess the performance of the SPH method in modeling two dimensional natural watercourses. Consequently, an existing numerical model based on the SPH method was engaged in modeling a steady flow situation. The model was addiotionaly examined by comparing its results with two other existing models based on different numerical approaches, the finite element method and the finite difference method. Telemac for the finite element technique (Galland et al., 1991), MoBed2 for the finite difference method (Horvat et al., 2014) and SPH for the smoothed particle technique (Vacondio et al., 2012a, Vacondio et al., 2012b, Vacondio et al., 2012c).

The SPH is an interpolation method that allows any function to be expressed in terms of its values at a set of disordered points - the particles. The physical quantities in any particle are determined using the neighboring particles and a weighing function whose value decreases with the increase of distance between neighboring particles. The computational procedures implemented in the SWE-SPHysics computer code along with detailed explanations are given by Vacondio et al., 2012b, Vacondio et al., 2012c. The time integration of the velocities and positions of the particles is done using a leap-frog scheme including an additional term that is based on artificial viscosity in order to conserve the stability of the solution (Vacondio et al., 2012b, Vacondio et al., 2012c). When engaging in dynamic simulations the particles are moving thus producing changes of the particle density through time. In these situations one can obtain the accuracy and computer efficiency by changing the smoothing length.

The issue of setting boundary conditions on the impermeable boundaries using the SWE-SPHysics code was also attended. SWE-SPHysics code allows the definition of a virtual impermeable boundary that can fabricate the needed zero-velocity boundary condition. Nevertheless, in situations of boundaries that are not pre-defined and highly irregular boundaries these adjustments are impossible. By the introduction of small changes in the open-source code the authors enabled the reduction of the velocities on these boundaries until attaining small enough values to neglect.

The MoBed2 computer code incorporates the depth averaged equations in the orthogonal curvilinear coordinate system that are solved using the fractional step and are given in more detail in Horvat et al., 2014.

The Telemac system was constructed of a series of computer programs based on finite element techniques used for simulating different hydraulic situations. This study focused on the the Telemac-2D program that solves the shallow water equations (Hervouet, 2007). Telemac-2D is based on the finite element approach. Aiming to achieve a certain flexibility in the modeled domain's description, Telemac-2D incorporates linear triangles – an unstructured grid. The Telemac-2D offers different approaches for the solution algorithms (the fractional step technique using the characteristics method, several variants of the Streamline Upwind Petrov-Galerkin method (SUPG) and a hybrid scheme that combines the characteristic and SUPG approaches). Since the MoBed2 implements the method of characteristics combined with the split operator approach, the same approach was chosen in the Telemac-2D model as well.

The considered numerical models were applied for the simulation of a steady flow situation in a curved channel.

RESULTS & DISCUSSION

The models were assessed through the comparison of the measured and computed velocity components.

The studied domain was described employing a computational grid that coincides with the measurement points, Fig. 1. Two of the investigated models, MoBed2 and Telemac-2D, adopt the displayed mesh, where in case of the MoBed2 the presented points form a mesh that consists of rectangles, while in the case of Telemac-2D the same points design a mash made up of triangles. Since the SWE-SPHysics code is a mesh-free model herein a number of 9000 particles was assigned.

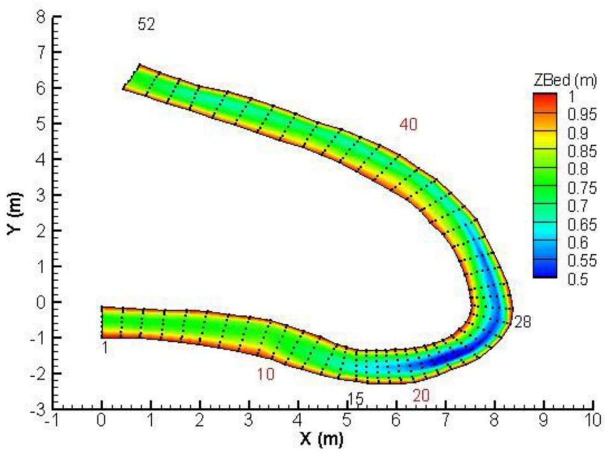

Figure 1. Distribution of the computational points

The upstream boundary condition was set as constant discharge, while preserving a steady water level elevation as the downstream boundary condition. The calibration of the researched models was accomplished through the variation of the Manning's roughness coefficient until managing pleasing correspondence among measured and computed free-surface elevations. Additional evaluation of the results was done subsequently by comparing the computed, u(v)-Telemac2D, u(v)-MoBed2 and u(v)-SWE-SPHysics for the results attained using the MoBed2, Telemac-2D and SWE-SPHysics models sequentially, and measured velocity components, u(v)-meas, Figs. 2-4.

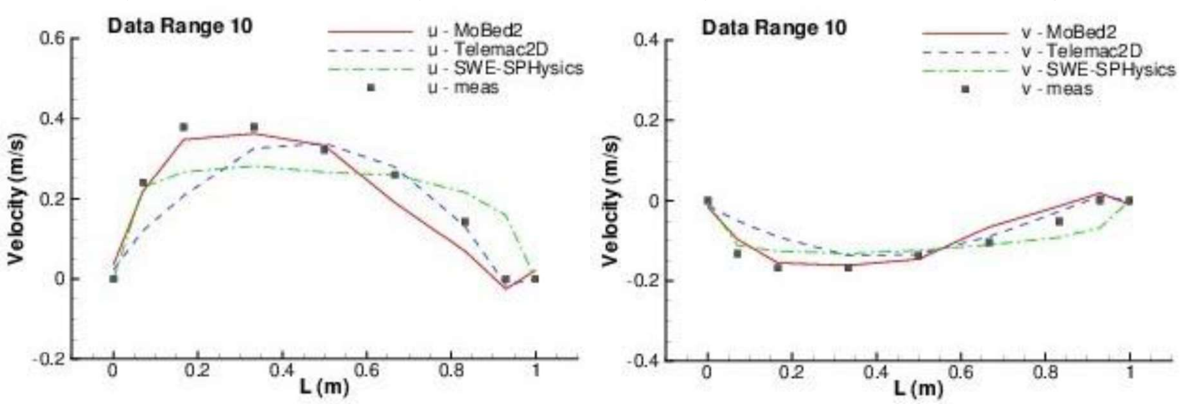

Figure 2. Comparison of measured and computed u and v velocity components at data range 10

By visual evaluation of the results, Figs. 2-4., it can be concluded that the divergence among measured and computed values varies depending on the considered data range and velocity component. One can identify three segments that display essentially different propensities, the first segment on the upstream end - data ranges 1 to 15, the second embracing data ranges 16 to 28 and the third segment on the downstream of the river bend that includes data ranges 29 to 52. Since it would be unreasonable to provide a graphical representation of the results in every data range, three characteristic data ranges were selected, data ranges 10, 20 and 40, for the further investigation.

In the first segment of the modeled domain MoBed2 proved to have a slight advantage over the other two models. Regarding the first segment, both MoBed2 and Telemac-2D reproduced the tendencies observed in the laboratory experiment, denoting greater velocities on the left bank as presented on Fig. 2. Nevertheless, MoBed2 appears to provide a slightly better replica of the measured values. Results acquired by SWE-SPHysics seem to lag behind the two previous models.

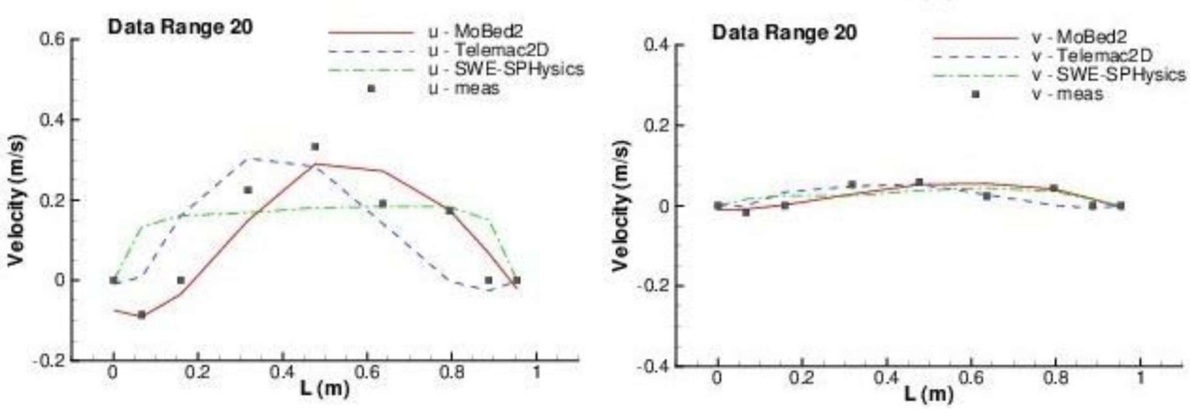

Figure 3. Comparison of measured and computed u and v velocity components at data range 20

Results attained in data range 20 proved to be the most inconsistent among the three considered data ranges. Although MoBed2 was capable of reproducing the negative u velocity components on the left bank, Fig. 3., Telemac-2D showed only a decrease of these velocities, even though reflecting the emerged trend. Lastly, SWE-SPHysics could not reproduce the previously illustrated tendency so effectively.

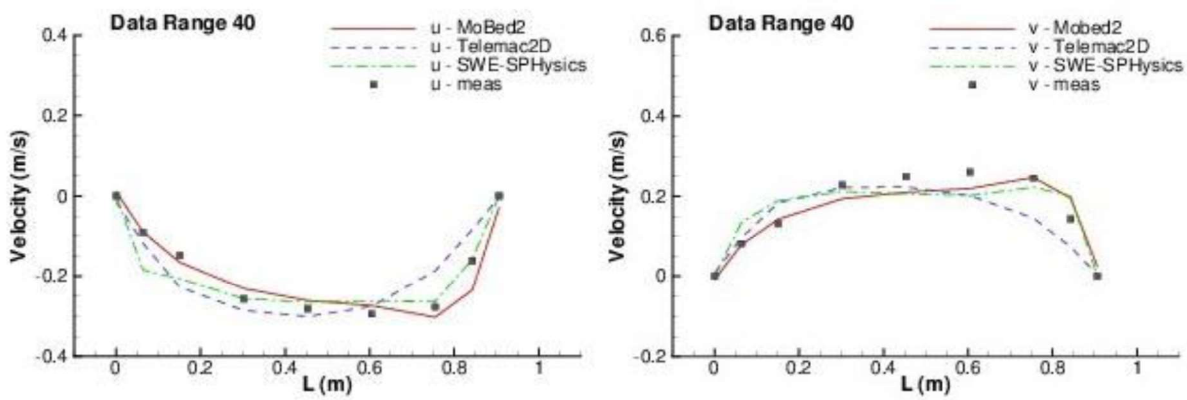

Figure 4. Comparison of measured and computed u and v velocity components at data range 20

Figure 4. presents the velocity components in the third section at data range 40. By analyzing the results it is self evident that SWE-SPhysics produced the finest results. This indicates certain inconsistency regarding the evaluated models since in the first two sections SWE-SPhysics displayed inferior performance, on the other hand, in the last section it provided the best quality results.

CONCLUSION

The main goal of the presented study was to evaluate the performance of the SPH method in two dimensional open channel flow. As a representative of the SPH method the SWE-SPHysics computer code was selected. In order to attain a more comprehensive study, the selected model's performance was compared to two other well established models. The models were applied for a steady flow simulation and examined using laboratory measurements. Although the SWE-SPHysics model performed inferior in comparison to the other considered models, it produced the finest results downstream of the curve thus indicating that its further improvement may possibly result in satisfying simulation results for steady flow analysis in natural watercourses.

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