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A NUMERICAL INVESTIGATION OF FLOW DYNAMICS OVER A TRAPEZOIDAL SMOOTH OPEN CHANNEL

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Abstract. *The paper presents a numerical investigation of the flow dynamics in a laboratory flume. The adopted geometry consists of a U shaped trapezoidal smooth open channel with a fixed slope and unerodible bed. The branches, 3m of length each, are linked with a joint 1m long, realizing two 90 degrees bends. The system is fed upstream with a water discharge under critical conditions while a Cipolletti weir is set downstream to control flow profiles. Steady flow characteristics are deduced by means of three different softwares: a pure Lagrangian developed by the author, based on the Weakly Compressible Smoothed Particle hydrodynamics (WCSPH) technique, Flow3D® and HEC-RAS®. Depending on the specific boundary conditions being given, velocity profiles and water interfaces at certain cross sections are deducted by using the first two codes. Results are discussed then spatially averaged in terms of mean velocities and water depths respectively to make a comparison with the ones obtained with HEC-RAS, showing a satisfactory agreement.*

1 INTRODUCTION

Experimental investigations of free surface flows, either laboratory or full-scale based, are aimed at describing complex fluid dynamics. They represent a viable tool for the design of structures interacting with liquids as well as for the verification under variable operating conditions. Needless to say, the related literature is quite consistent. Just to mention some meaningful examples, related studies concern the analysis of the interaction between fluids and solid [1,2] or porous interfaces [3-5], the assessment of the solid transport, either of bed or suspended or both types [6-8], sea waves [9,10], granular flow movements [11,12],

Although the effectiveness of experimental studies has been demonstrated by several investigations, the search for numerical solutions [13] is considered as a valuable alternative, as well as a supporting option [12], because it is cost-effective, easily adaptable to the variation of operating condition, more and more convenient for the endless increase of computer power. Numerical methods, either Lagrangian [14], Eulerian [15] or mixed [16] have been extensively applied over the last century as practical tools to give response to engineering and scientific problems. Among Lagrangian types, an emerging method, known as Smoothed Particle Hydrodynamics [17, 18], eventually coupled with others to exploit related advantages as in [19,20], has been applied since the last two decades, see for instance [21, 22].

The aim of this paper is to check the feasibility of three numerical models to describe the flow dynamics in a complex laboratory flume. Over the past three decades, two-dimensional and three-dimensional algorithms have been widely used to describe free surface flows, see for instance [23].

A full three-dimensional investigation is carried by mean of a Lagrangian code, based on the Weakly Compressible Smoothed Particle hydrodynamics (WCSPH) technique [24, 25] and the Eulerian-based software Flow3D® [26, 27]. Related results are compared in terms of velocity distribution and water profiles at certain cross sections. Average fields are then compared with the ones obtained using the one-dimensional computer program HEC-RAS [28, 29]. The algorithm based on the WCSPH technique and Flow3D® basics [30,31] are already described in [32], therefore they are not discussed here. Related applications are given in [33-36]. HEC-RAS (River Analysis System) is a freeware software for modeling open channel flows with the presence of bridges, culverts, weirs and other structures. Developed by the Hydrologic Engineering Center (HEC) of the United States, it is commonly used for engineering design, flood hazard mapping and flood insurance studies. Governing equations are one-dimensional, i.e. there is no hydraulic dependence on the cross section shape or channel bends.

2 MATERIALS AND METHODS

The trapezoidal open channel flow shown in the next Fig.1 is adopted in the present investigation. It is actually used for experimental investigations @ the Environmental and Maritime Hydraulics Laboratory (LIDAM) of the University of Salerno. As the flume is made of stainless steel, the roughness is neglected when carrying three dimensional studies. Manning's roughness is set as $n=0.012 s/m^{1/3}$ [37] when using HEC-RAS instead. The branches, 3m of length each, are linked with a joint 1m long and of trapezoidal shape as well, realizing two 90 degrees bends. The slope of each branch is kept fixed at 1%. The system is fed upstream with a water flow rate Q under critical conditions while a Cipolletti weir of height h measured from the bottom is set downstream to control flow profiles. Steady conditions can be reached in the reality thank to the presence of a recirculating system, consisting of a centrifugal pump which connect the outlet and inlet tanks. Here, steady state conditions are reached after a transitory which is of the order of tens of seconds. During such initial phase the inflow volume takes the space behind the weir: the higher is the latter, the longer is the transitory.

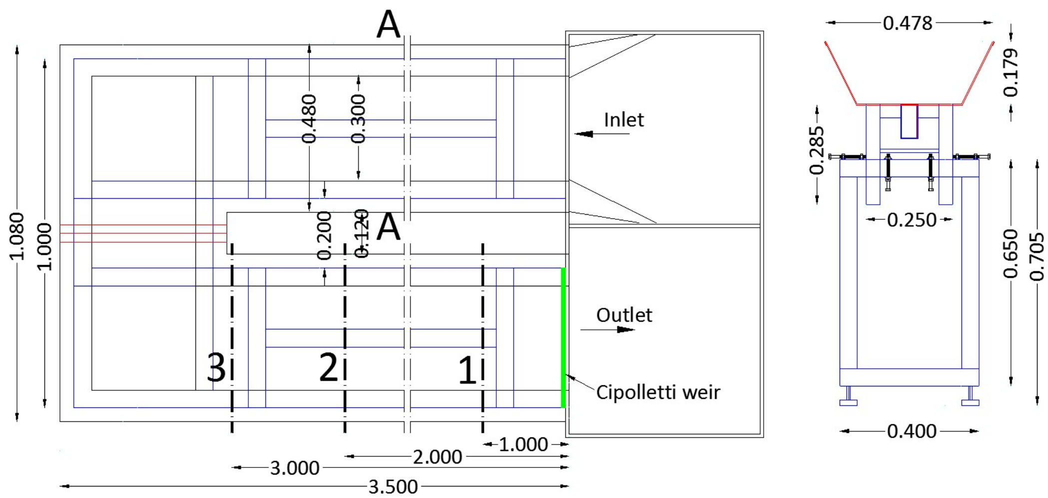


Figure 1: The open channel flow adopted in the present investigation. Left side: top view. Right side: vertical cross section A-A. 3D velocity field is extrapolated from vertical cross sections 1, 2 and 3.

Numerical simulations have been carried out taking the portion of the system between the Inlet and the Outlet zones, i.e. the flume itself. Related geometry was first created in a CAD environment as a collection of three-dimensional solids (Fig. 2, left side), then exported as a STereoLithography (stl) file, a standard compatible with Flow3D®. It basically contains a list of triangular surfaces that approximate the CAD model. The same file was finally converted in a text (xyz) file using TextPad®, obtaining the vertex coordinates of boundary particles (Fig. 2, right side), to be given as input to the WCSPH algorithm. The mesh size of the computing domain was set equal to 0,005m. The same value was adopted as reference for the edges of triangles listed in the stl file.

In the present study we consider the combination of two water discharges (Q_1=0.0085m^3/s, Q_2=0.0170m^3/s) set upstream and four weir's height (d_1=0.025m, d_2=0.05m, d_3=0.070m, d_4=0.010m) for a total of height scenarios. The upstream condition can be straightforwardly fixed in Flow3D® while in WCSPH it is set by fixing the velocity of the inflow particles.

3 RESULTS

This section yields the numerical results obtained with the WCSPH algorithm and the Flow3D® solver. To be concisely, a graphical comparison (Fig. 3) is given only for the simulations with Q_1=0.0085m^3/s and d_3=0.070m, in terms of velocity distribution over the cross sections 1,2 and 3 depicted in Fig. 1, left side. A general view of the dynamics is sketched in Fig. 4.

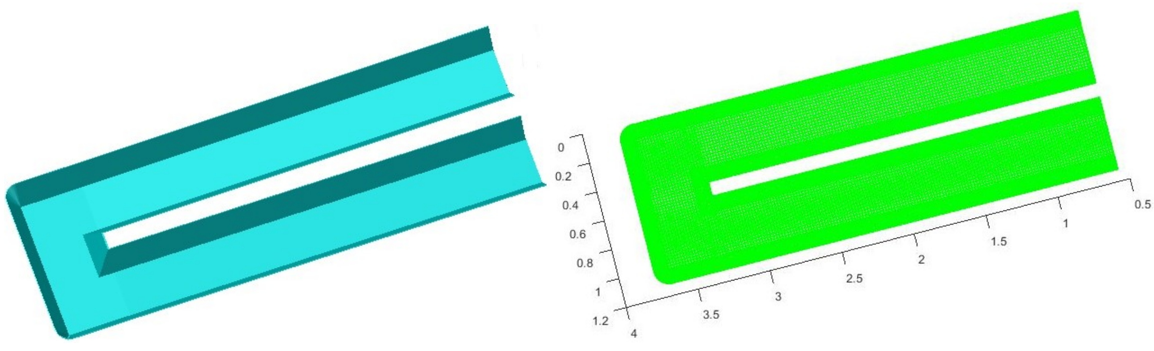
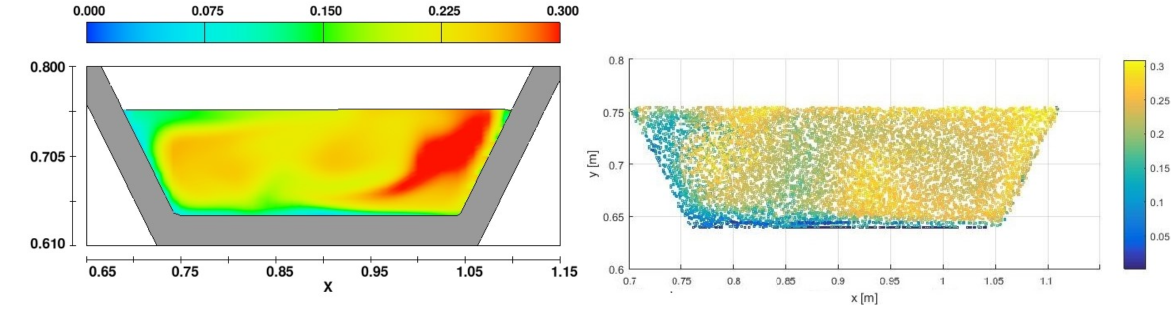
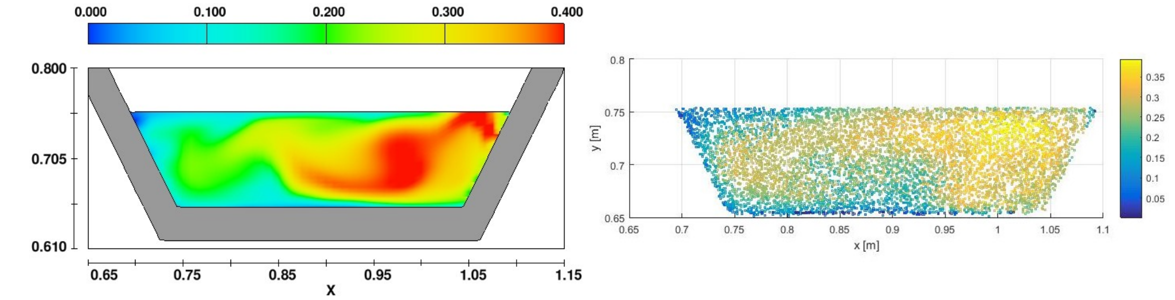


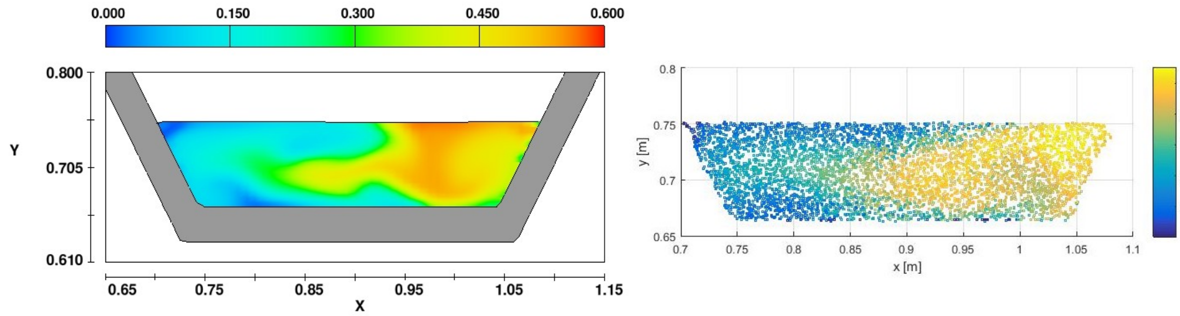
Figure 2: The flume was first created in a CAD environment (left side) then exported as STereoLithography file for Flow3D simulations and finally converted as boundary particles for the WCSPH algorithm.



Cross Section 1



Cross Section 2



Cross Section 3

Figure 3: The velocity distribution obtained with Flow3D® (left side) and WCSPH (right side) at vertical cross section 1, 2 and 3.

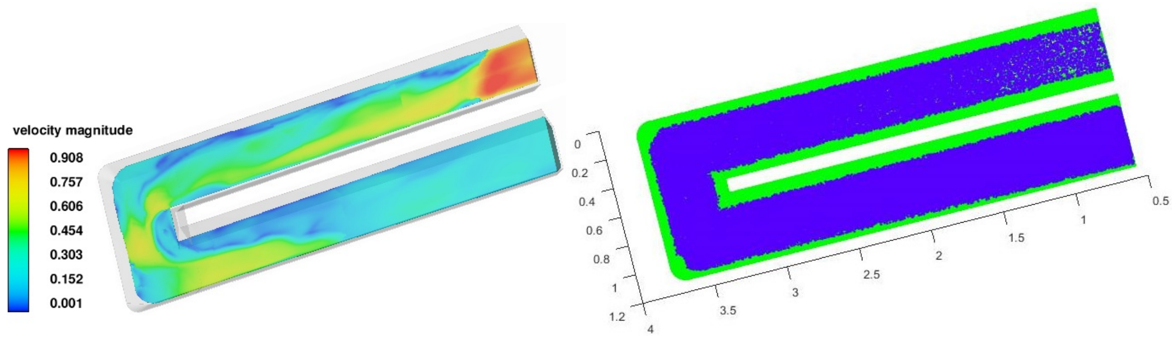


Figure 4: The flow dynamics for Q_1=0,0085m^3/s and h_3=0,070m. It is shown on the left side the velocity distribution obtained with Flow3D® while on the right side the particle disposition obtained with WCSPH.

From Fig. 3 and Fig. 4, left side, it can be observed that the trapezoidal joint influences the flow dynamics.

In particular, the velocity distribution at vertical cross sections is not symmetric respect to the vertical midplane of the branches. Higher velocity values are located on the right hand side of cross sections 1, 2 and 3 because the flow is constrained by the presence of the joint's corners. The phenomenon could be qualitatively compared to some extend to the liquid discharge issuing from a sharp orifice. Symmetry is partially recovered at Section 1 (i.e. the closest one to the weir) as it is the farthest section from what it can be thought as a disturbing region. The comparison of the velocity distribution and water table (the local free surface flow location) is satisfying. Both the numerical approaches basically reproduce the same flow dynamics.

As for the remaining simulations, the next summary Table 1, yield the velocities V_i and water surface elevations h_i, i=1,2,3 at cross sections (CS) 1,2 and 3, obtained by extracting the corresponding output values from HEC-RAS and by spatially averaging the local velocity distribution and the local free surface flow with reference to Flow3D and WCSPH simulations. Comparison among results is satisfying. It can be noted that the weir's height d_j, j=,1,2,3,4 effectively controls water profiles. Anyway, there is not a linear dependence of V_i and WS_i with d_j. This is basically due to the trapezoidal shape of the flume.

Q_1=8.5l/s	CS 1		CS 2		CS 3	
d_1=2.5cm	V_1	h_1	V_2	h_2	V_3	h_3
SPH	**0.43**	**0.72**	**0.75**	**0.71**	**0.75**	**0.70**
Flow3D	**0.42**	**0.72**	**0.74**	**0.71**	**0.74**	**0.71**
HEC-RAS	***0.44***	***0.71***	***0.75***	***0.70***	***0.75***	***0.71***

Q_2=17.0l/s	CS 1		CS 2		CS 3	
d_1=2.5cm	V_1	h_1	V_2	h_2	V_3	h_3
SPH	**0.56**	**0.74**	**0.67**	**0.76**	**0.62**	**0.75**
Flow3D	**0.57**	**0.74**	**0.68**	**0.76**	**0.61**	**0.76**
HEC-RAS	***0.58***	***0.73***	***0.70***	***0.74***	***0.63***	***0.75***

Q_1=8.5l/s	CS 1		CS 2		CS 3	
d_2=5.0cm	V_1	h_1	V_2	h_2	V_3	h_3
SPH	**0.29**	**0.74**	**0.36**	**0.74**	**0.43**	**0.74**
Flow3D	**0.28**	**0.74**	**0.37**	**0.74**	**0.43**	**0.74**
HEC-RAS	***0.29***	***0.73***	***0.37***	***0.73***	***0.44***	***0.73***

Q_2=17.0l/s	CS 1		CS 2		CS 3	
d_2=5.0cm	V_1	h_1	V_2	h_2	V_3	h_3
SPH	**0.40**	**0.76**	**0.46**	**0.76**	**0.54**	**0.76**
Flow3D	**0.40**	**0.76**	**0.48**	**0.77**	**0.54**	**0.77**
HEC-RAS	***0.41***	***0.76***	***0.48***	***0.76***	***0.55***	***0.76***

Q_1=8.5l/s	CS 1		CS 2		CS 3	
d_3=7.0cm	V_1	h_1	V_2	h_2	V_3	h_3
SPH	**0.22**	**0.76**	**0.27**	**0.76**	**0.31**	**0.75**
Flow3D	**0.23**	**0.76**	**0.28**	**0.76**	**0.33**	**0.75**
HEC-RAS	***0.23***	***0.75***	***0.28***	***0.75***	***0.32***	***0.75***

Q_2=17.0l/s	CS 1		CS 2		CS 3	
d_3=7.0cm	V_1	h_1	V_2	h_2	V_3	h_3
SPH	**0.34**	**0.78**	**0.39**	**0.79**	**0.44**	**0.78**
Flow3D	**0.34**	**0.79**	**0.39**	**0.78**	**0.45**	**0.79**
HEC-RAS	***0.35***	***0.78***	***0.40***	***0.78***	***0.45***	***0.78***

Q_1=8.5l/s	CS 1		CS 2		CS 3	
d_4=10.0cm	V_1	h_1	V_2	h_2	V_3	h_3
SPH	**0.17**	**0.79**	**0.19**	**0.77**	**0.22**	**0.79**
Flow3D	**0.16**	**0.79**	**0.19**	**0.77**	**0.21**	**0.79**
HEC-RAS	***0.17***	***0.78***	***0.20***	***0.78***	***0.22***	***0.78***

Q_2=17.0l/s	CS 1		CS 2		CS 3	
d_4=10.0cm	V_1	h_1	V_2	h_2	V_3	h_3
SPH	**0.27**	**0.82**	**0.30**	**0.82**	**0.33**	**0.81**
Flow3D	**0.28**	**0.82**	**0.30**	**0.81**	**0.33**	**0.82**
HEC-RAS	***0.28***	***0.81***	***0.31***	***0.81***	***0.34***	***0.81***

Table 1: Mean velocities [m/s] and water surface elevations [m] obtained from Flow3D and WCSPH results. A comparison is made with corresponding values (in italic) obtained with HEC-RAS, showing a satisfactory agreement.

4 CONCLUSIONS

The capability of three numerical approaches to reproduce the flow dynamics over a U shaped trapezoidal smooth open channel with a fixed slope and unerodible bed is here discussed. Three-dimensional results obtained by running Flow3D and WCSPH revealed that the velocity distribution at vertical cross sections is not symmetric respect to the vertical mid-plane of channel branches because it is influenced by the presence of the channel joint. Mean velocities and water levels at three cross sections were compared with corresponding values obtained with HEC-RAS, showing a satisfactory agreement.

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