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A NUMERICAL INVESTIGATION OF LIQUID IMPACT ON PLANAR SURFACES

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Abstract. *The impact of a free surface liquid flow on planar surfaces is a common occurrence and a challenging issue in many research fields. There are many situations in science and technology where this field of study finds related applications: the falling objects on a liquid surface, sloshing dynamics, flow run-up and overtopping, the action of train waves on maritime structures. Under certain circumstances, the impact process may result into high, spatially localized pressure peaks, thus inducing dangerous solicitations. The present work focuses on some relevant computational aspects of the fluid impact on inclined planar surfaces, making use of the Weakly Compressible Smoothed Particle Hydrodynamics (WCSPH) Lagrangian technique. With reference to the early stages of the impact process, pressure distribution is described as function of the incident wave's features and the angle of incidence of the solid surface assumed. Results are then discussed and compared with the corresponding ones obtained via Eulerian software.*

1 INTRODUCTION

Assessing the interaction of fluids and structures (FSI) is a topic of great interest in nature and science. The literature is huge, therefore no attempt is made here to review it. Some general, yet worth examples are reported in [1-4]. Among so many applications, the propagation and impact of steep sea waves on coastal structures [5-7] or the run-up and overtopping on defense structures [8, 9] have probably been studied in more detail starting from the pioneering work of by Kirkgöz [6], therefore they can provide some deeper insight.

Over the last few decades the prediction of impact pressures have been made by some developed theories. Peregrine and co-workers [10] proposed the "Pressure-impulse" approximation where the pressure is considered within a significant time window. The impulsive pressure field is therefore used for the derivation of the velocity field as the impact takes place. Korobkin proposed the "acoustic approximation" in [11], where the pressure distribution is evaluated analytically for a cylindrical jet impacting on a rigid plane and the "Asymptotic" assumption in [12] where the liquid-wall interaction is analyzed with the method of matched asymptotic expansions, through which properties such as compressibility are taken into account. Recently a semi-analytical model based on the Wagner theory has recently proposed in [13].

Current literature provides many contributions about full scale, laboratory or empirical investigations as well. More than a century went by since the publication of the original work of Stevenson [14] in which conditions which affect the force of impacting waves are discussed. In [15], an extensive campaign of pressure measurements on a vertical wall were performed at the Deltares laboratory of Delft (Holland) under wave impact. In [16] a large number of field measurements were carried with the aim of detecting most violent wave impacts on the Admiralty breakwater, Alderney (United Kingdom). Bullock and co-workers [17] measured a large number of impacts, showing that in some – rare – circumstances, local pressures are comparable with corresponding ones obtained from the water hammer model [18,19]. Blackmore and Hewson [20] recorded measurements of full-scale wave impact pressures on seawalls over a period of about four years. They derived an empirical expression for wave impact pressure that takes into account the concentration of entrapped air.

Lagrangian [21], Eulerian [22] or mixed [23] numerical methods have been extensively developed and applied as well. In [24] the impact process resulting from the interaction of breaking waves with a vertical wall was numerically solved by means of a Finite Difference (FD) scheme, based on the Volume of Fluid (VOF) method [25]. Among Lagrangian types, an emerging method, known as Smoothed Particle Hydrodynamics [26], has been applied in the recent past, see for instance [27, 28].

The aim of this paper is the study of the interaction between an approaching steep wave and a planar surface by means of two numerical approaches: a Lagrangian one, based on Weakly Compressible Smoothed Particle Hydrodynamics (WCSPH) technique and an Eulerian one, making use of the Flow3D ® commercial package.

2 THE WCSPH MODEL

The Weakly Compressible Smoothed Particle Hydrodynamics technique (WCSPH) is based on integral interpolants using kernels that approximate the delta function. See [21, 26, 29, 30] for up-to-date reviews and related applications. SPH is a mesh-free Lagrangian method based on computing particles discretizing the evolving domain. Hydrodynamic properties on a location, either fixed or moving with a particle, depend on the local particle neighbourhood where the kernel W is defined (Fig.1).

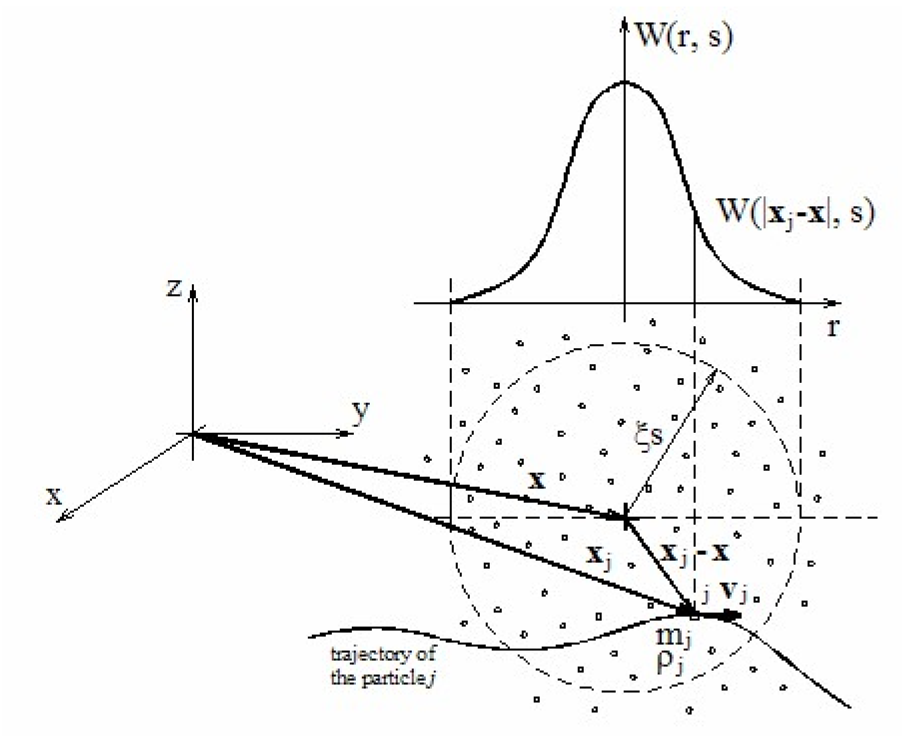


Figure 1: Hydrodynamic computation at the location **x** on the basis of neighbouring particles within a circular (2D) or spherical (3D) compact support where the interpolating kernel is defined. A neighbouring particle j, with mass m_j, density ρ_j and velocity $\mathbf{v}_j$ is sketched along with its trajectory.

Despite its inception in 1977 [31,32], we found hydrodynamic applications of SPH only since mid-1990s [33] and specific investigations of FSI since 2000s [34,35]. Recently, SPH has been considered as a valuable method for solving real-life problems in coastal engineering as in [36] due its intrinsic capability to deal with large deformation and complex geometries. Altomare et al., [37] carried advanced investigations of wave interaction with armour block sea breakwater.

In this work, mass and momentum equations

$$-\frac{1}{\rho}\frac{\mathrm{D}\rho}{\mathrm{D}t} = \nabla \cdot \underline{v} \tag{1}$$

$$\rho\frac{D\underline{v}}{\mathrm{D}t} = -\nabla p + \mu\nabla^2 \underline{v} + \underline{f} \tag{2}$$

are discretized as in [18] yielding the numerical scheme

$$\begin{aligned} \frac{\mathrm{D}\log(v_\mathrm{i})}{\mathrm{D}t} &= \sum_{\mathrm{j=1}}^{\mathrm{N_i}}\left(\underline{v}_\mathrm{i} - \underline{v}_\mathrm{j}\right)\cdot\nabla_\mathrm{i}W_\mathrm{ij}\cdot\mathrm{d}\Omega_\mathrm{j} + \\ &+ \xi\, h\, c_0 \sum_{\mathrm{j=1}}^{\mathrm{N_i}}\psi_\mathrm{ij}\cdot\nabla_\mathrm{i}W_\mathrm{ij}\cdot\mathrm{d}\Omega_\mathrm{j} \end{aligned} \tag{3}$$

$$\frac{D\underline{v}_i}{Dt} = -\sum_{j=1}^{N_i}\left(\frac{p_i}{\rho_i} + \frac{p_j}{\rho_j} + 19.6\nu\left(\frac{\underline{v}_{ij}\cdot\underline{r}_{ij}}{r_{ab}^{\;2} + \varepsilon\overline{h}_{ij}^{2}}\right)\right)\nabla_i W_{ij}\,d\Omega_j + \underline{f}_i \tag{4}$$

where i denotes the generic moving particle, j refers to one of its N_i neighbours (see Fig. 1), ν_i is the specific volume $1/\rho_i$, defined as

$$\frac{D\log(\nu_i)}{Dt} = -\frac{1}{\rho_i}\frac{D\rho_i}{Dt} = \nabla\cdot\underline{v}_i \tag{5}$$

ρ is the density, p is the pressure, $\underline{v}$ is the velocity vector, f is the external force, W is the above mentioned kernel or weighting function, defined over a compact support of radius r=2h, being $h=1.3d_0$ the smoothing length proportional to the initial interparticle distance d_0 = 0.005m, $\nu = 10^{-6}$ m^2/s is the kinematic viscosity of water at 20°C, c_0 is the speed of sound in the case of no compression.

Ruling equations (3,4), constrained with (5) and coupled with the Tait equation of state

$$p_i = \frac{c_0^2\rho_0}{\gamma}\left[\left(\frac{\rho_i}{\rho_0}\right)^{\gamma} - 1\right] \tag{6}$$

being $\gamma = 7$, are then solved in time with a second order predictor – corrector step scheme, already tested in a variety of situations, see for instance [38,39]

3 THE FLOW3D SOLVER

Flow3D® solver [40] is a CFD commercial software based onto a Finite Volume formulation of the Navier Stokes equations (eqs. 1-2) in a Eulerian framework. Free surfaces and interfaces are solved with the volume of fraction (VOF) method and the Fractional Area/Volume Obstacle Representation (FAVOR). Velocity and pressure fields are coupled by using the time-advanced velocities in the continuity equations and time-advanced pressures in the momentum equations. The model has been widely validated over the years particularly in connection with wave impact, see for instance [41, 42].

Water compressibility is treated by the acoustic approximation, which links the density variation to the pressure increase by the following $c^2 = \partial p/\partial\rho$. All the tests shown in the following have been carried out by assuming a fluid with a reference density ρ_0 = 1000 kg/m^3 and a reference sound speed c_0 = 1400m/s, as in the SPH model. The chosen values, representing realistic liquids, satisfy the acoustic condition $|\delta\rho/\rho| < 0.1$ which stands for low Mach numbers as it is of order 10^{-2} or less.

4 THE NUMERICAL SET-UP

An open channel water flow with an initial velocity v_0 and liquid height h_0 = 0.50m is assumed to suddenly impact against a planar surface (Fig. 2). The angle of the impacting surface, measured counterclockwise with respect to the vertical direction, ranges between -45° and +45° (Fig. 3), for a total of 19 geometry configurations. Therefore, the incremental angle between two consecutive configurations is equal to 5°. For computational purposes, a 4.00m long volume of fluid was assumed to be close to the solid interface.

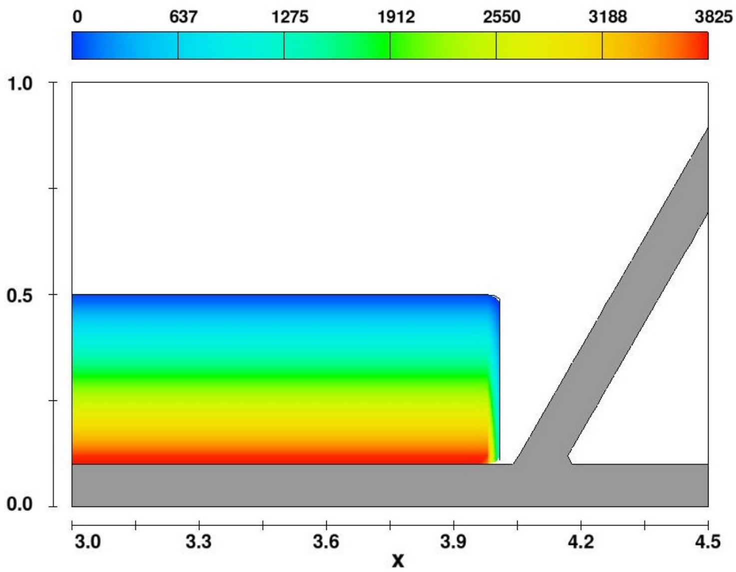


Figure 2: Initial conditions set in WCSPH and Flow3D (picture taken from Flow3D).
Colour bar refers to the pressure field which distribution is assumed to be initially hydrostatic.

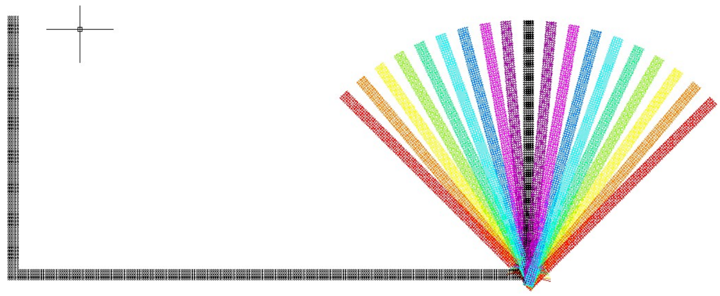


Figure 3: The inclined surface, the wave is impacting with, has an angle with respect the vertical direction ranging between -45° and +45°. Nineteen configurations are therefore assumed in the present work (picture represents solid boundaries given in WCSPH)

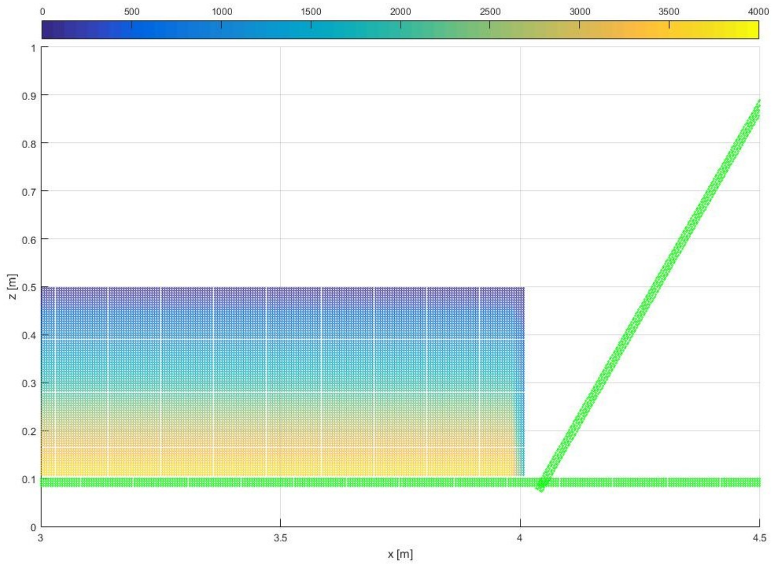
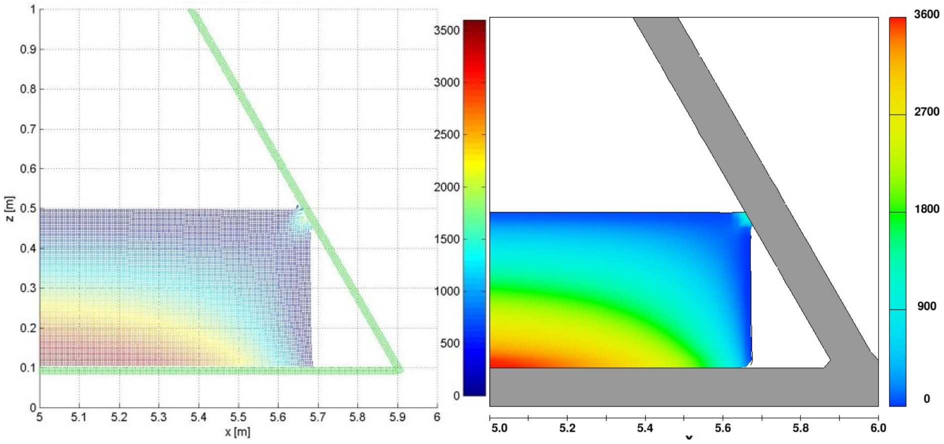


Figure 4: The fluid domain represented by particles in WCSPH. Solid walls are depicted by green particles. Colour bar refers to the pressure field which distribution is assumed to be initially hydrostatic. Conditions are equivalent as those sketched in Figure 2.

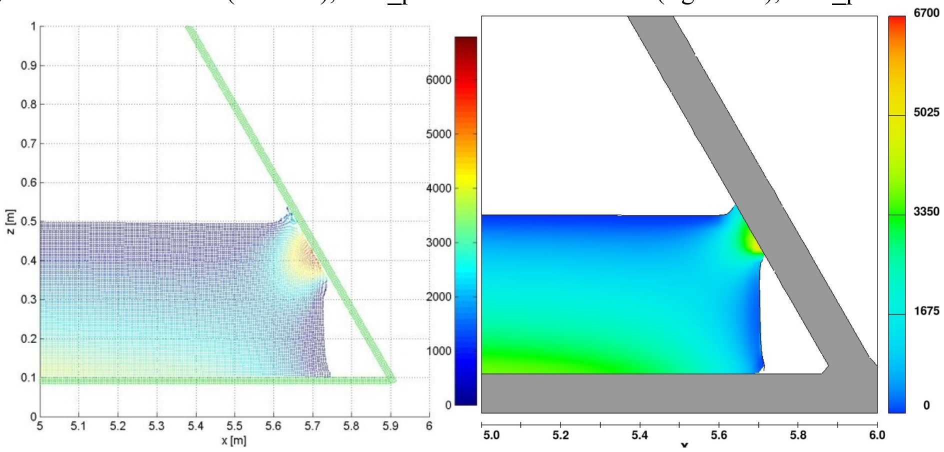
The computation domain is split into square 0.01m wide grid elements in Flow3D environment. Total number of cells is of order of 10^4, depending on how large is the simulating space between left and right walls (see Fig. 3). The fluid domain is discretized into $8 \cdot 10^4$ particles, with an initial interparticle distance d_0 = 0.005m (see Fig. 4, previous page).

5 RESULTS

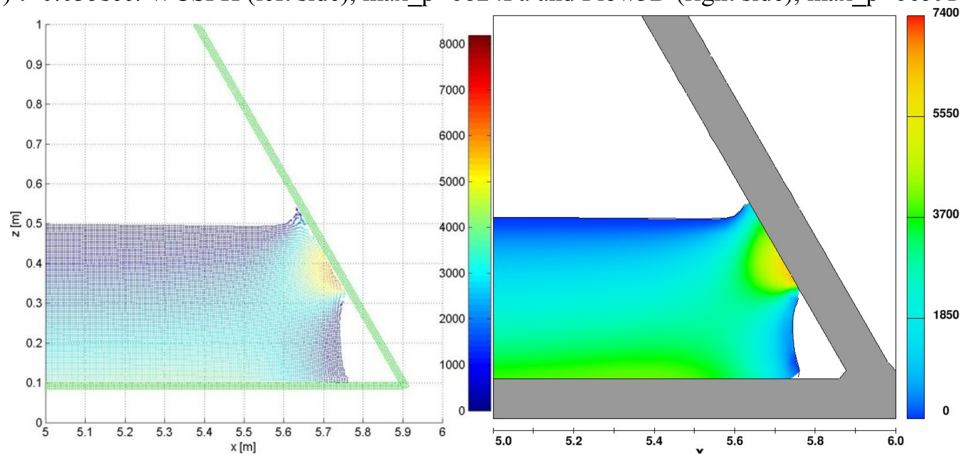
The impact process is here analyzed for the nineteen configurations above introduced (Fig. 2).



a) t=0.02sec. WCSPH (left side), max_p=3524Pa and Flow3D (right side), max_p=3578Pa.



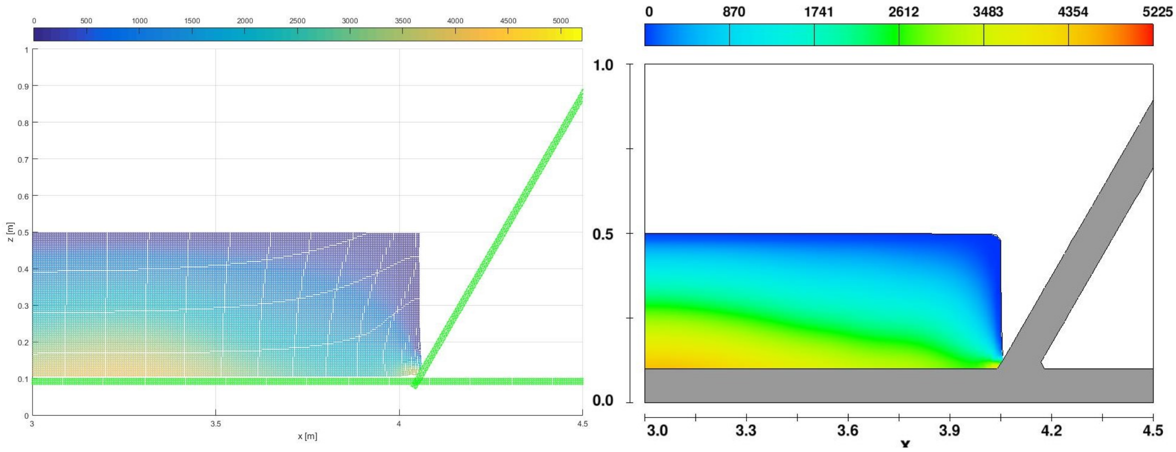
b) t=0.035sec. WCSPH (left side), max_p=6824Pa and Flow3D (right side), max_p=6659Pa.



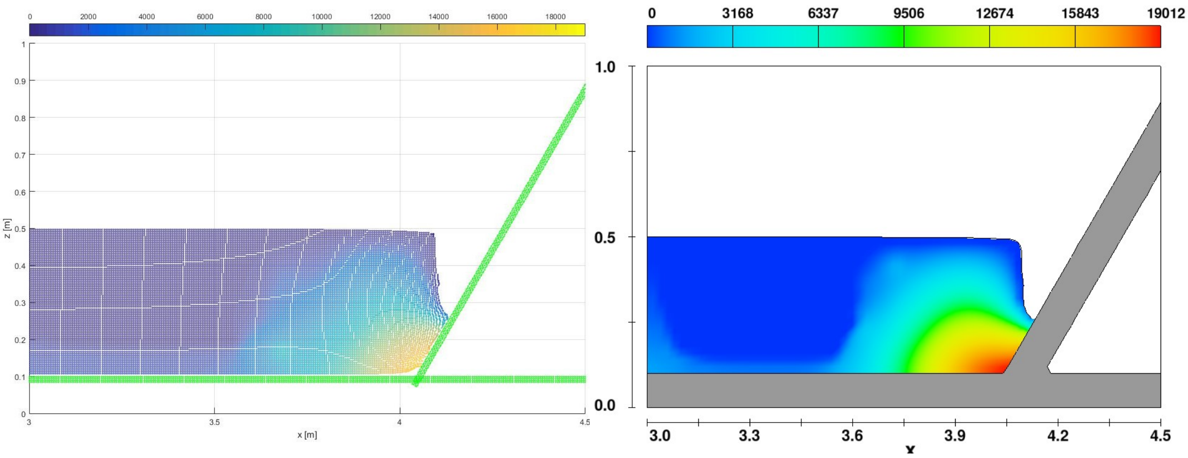
c) t=0.050sec. WCSPH (left side), max_p=8145Pa and F3D (right side), max_p=7482Pa.

Figure 5: Comparison of pressure fields for the initial velocity v0 = 2m/s. inclined wall angles α=+45°

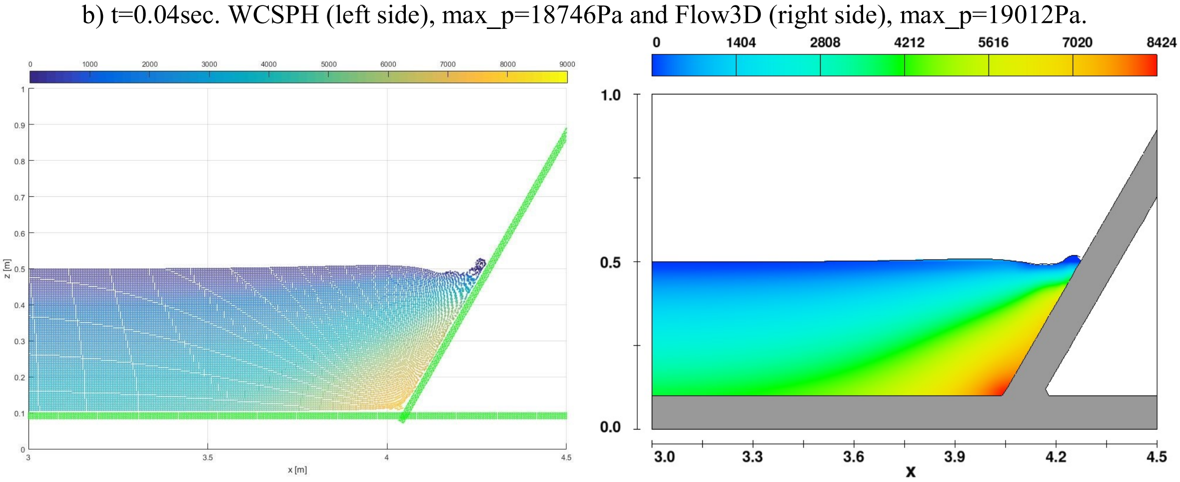
For each configuration, we consider an initial fluid mass advancing at velocities v_0=2m/s, 4m/s or 6m/s. For the sake of clarity and to be concisely, only results with v_0=2m/s and inclined wall angles α=+45° (Fig. 5) and -45° (Fig. 6) are sketched for some significant time instants. The summary Table 1 yields maximum pressures attained at the wall for each simulation being carried out with Flow3D and WCSPH.



a) t=0.02sec. WCSPH (left side), max_p=5158Pa and Flow3D (right side), max_p=5225Pa.



b) t=0.04sec. WCSPH (left side), max_p=18746Pa and Flow3D (right side), max_p=19012Pa.



c) t=0.080sec. WCSPH (left side), max_p=8924Pa and F3D (right side), max_p=8424Pa.

Figure 6: Comparison of pressure fields for the initial velocity v_0 = 2m/s. inclined wall angles α=-45°.

v_0=2m/s	+45°	+40°	+35°	+30°	+25°	+20°	+15°	+10°	+5°	0°
SPH	**8145**	**9057**	**9528**	**10279**	**10175**	**10879**	**12076**	**13249**	**11905**	**14212**
Flow3D	**7482**	**7635**	**8386**	**9714**	**10988**	**10460**	**11303**	**13007**	**13628**	**12200**
v_0=2m/s	-5°	-10°	-15°	-20°	-25°	-30°	-35°	-40°	-45°	
SPH	**14020**	**13527**	**15167**	**14506**	**15177**	**16419**	**16813**	**17812**	**18746**	
Flow3D	**14304**	**14223**	**16504**	**15446**	**18062**	**15860**	**17802**	**19455**	**19012**	
v_0=4m/s	+45°	+40°	+35°	+30°	+25°	+20°	+15°	+10°	+5°	0°
SPH	**34127**	**36623**	**36874**	**37934**	**41188**	**44703**	**42685**	**47103**	**51634**	**57794**
Flow3D	**35092**	**38570**	**43283**	**40688**	**42289**	**45736**	**52629**	**58442**	**63862**	**63974**
v_0=4m/s	-5°	-10°	-15°	-20°	-25°	-30°	-35°	-40°	-45°	
SPH	**49490**	**61920**	**57162**	**60870**	**60410**	**63688**	**67250**	**72083**	**71240**	
Flow3D	**59970**	**68335**	**71138**	**74727**	**73549**	**72211**	**88151**	**81375**	**86762**	
v_0=6m/s	+45°	+40°	+35°	+30°	+25°	+20°	+15°	+10°	+5°	0°
SPH	**116461**	**135041**	**129161**	**135434**	**152353**	**159675**	**151696**	**159429**	**170968**	**191092**
Flow3D	**82098**	**92074**	**101800**	**97465**	**114190**	**111149**	**121455**	**145804**	**149615**	**156696**
v_0=6m/s	-5°	-10°	-15°	-20°	-25°	-30°	-35°	-40°	-45°	
SPH	**165619**	**177112**	**200596**	**182267**	**204412**	**216512**	**222823**	**242878**	**231928**	
Flow3D	**158871**	**177986**	**171353**	**186598**	**191367**	**209781**	**199594**	**227296**	**214957**	

Table 1: Detected maximum pressure values as function of the impacting velocity v_0 and surface's inclination α.

As can be seen from the above Table 1, the Eulerian and the Lagrangian approaches yield maximum pressure values in a good agreement. In addition, from the following Fig. 7 it is possible to derive that, under the operating limits of the present investigation, the maximum pressure is almost linear with the surface's angle, keeping fixed the impacting velocity v_0. This is mainly due to the characteristics of the impacting area: for positive surface's angles the contact region is located in the upper part of the liquid domain. As a consequence the liquid, once in contact with the solid surface, is free to spread both sides along it. In contrast, for negative surface's angles the contact region is located in the lower part of the liquid domain. In this case the interacting liquid is constrained to move only ahead along the inclined surface as it opposes to the remaining approaching mass.

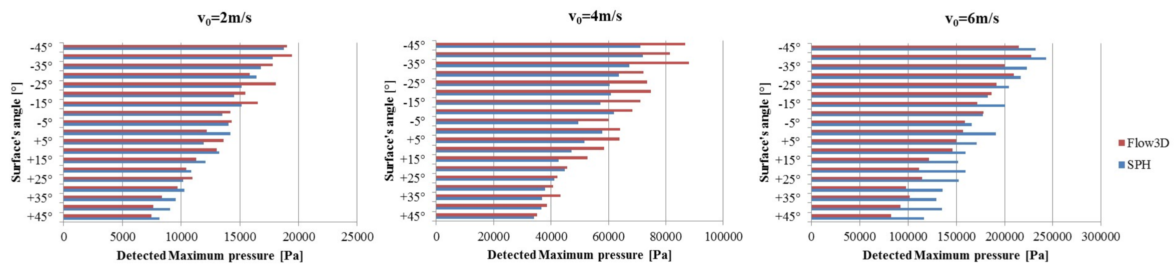


Figure 7: The Maximum detected pressures.

6 CONCLUSIONS

The interaction between an approaching liquid mass and an inclined surface was investigated by means of a Lagrangian and an Eulerian numerical approach. The obtained reflected waves and maximum pressure are in good agreement. A linear dependency of the maximum pressure from the surface's angle was deduced. Therefore, the lower is the surface's angle the worse are normal solicitations at the contacting area as the impact takes place.

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