A numerical study of liquid impact on inclined surfaces.

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Abstract: - Liquid impact on planar surfaces is a challenging issue in many research fields. Under certain circumstances, these phenomena may occasionally produce high, spatially localized pressure peaks, thus inducing dangerous solicitations. The present work focuses on some relevant computational aspects of the fluid impact onto inclined planar surface, 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.

Key-Words: - SPH, WCSPH, FSI, Slamming loads, Numerical methods in fluids

1 Introduction

Fluid impact on solid surfaces has been studied intensively in the past, owing the great interest that related events have in the practice. Starting from the pioneering work by Belytschko [1], different approaches to predict impact pressures have been followed in recent years. It is worth mentioning available developed theories: the "Pressure-impulse approximation [2] of Peregrine and co-workers, the “acoustic approximation” [3] and the “Asymptotic” assumption [4] of Korobkin, in which liquid compressibility effects are accounted. In [2] the velocity field during liquid-liquid/solid impact is modelled by means of an impulsive pressure field. In [3], the pressure distribution is evaluated analytically for a cylindrical jet impacting on a rigid plane while in [4] the liquid-wall interaction is analyzed with the method of matched asymptotic expansions, through which properties such as compressibility are taken into account. In [5] a semi-analytical model based on the Wagner theory was recently proposed. Accurate results can be obtained by solving the problem within the framework of the weighted residuals approach. Care must be taken in choosing the basic profiles and the weighting functions such as to recover the known behaviour of the asymptotic solutions and to limit the number of differential equations retaining special physical features inherent to the problem [6].

Various examples of laboratory and full scale studies of wave impact are available in literature, starting from the original work of Stevenson [7]. In [8] pressure measurements on a vertical wall were performed at the Deltares laboratory of Delft (Holland) under wave impact. In [9] a large number of test measurements were carried with the aim of detecting most violent wave impacts on the Admiralty breakwater, Alderney (United Kingdom). Bullock and co-workers [10] measured a large number of impacts under the BWIMCOST (Breaking Wave IMpacts on COastal STructures) project, showing that in some – rare – circumstances, local pressure values are comparable with corresponding ones obtained from the water hammer model [11]. Such evidences have been further confirmed in [12] for more generalized circumstances. Blackmore and Hewson [13] 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 percentage of air entrapped in the incident wave.

Numerical approaches, Lagrangian [14], Eulerian [15] or mixed based [16] have been developed and applied as well. In [17] the impact process resulting from the interaction of breaking waves with a vertical wall was numerically solved by means of Finite Difference (FDM) scheme, based on the Volume of Fluid (VOF) method [18]. VOF methods have been extensively adopted for the purpose as in [19] for a wide range of engineering problems. Among Lagrangian types, an emerging, yet not full mature method, known as Smoothed Particle Hydrodynamics [20] has been applied in the recent past, see for instance [21].

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2 Materials and methods

2.1 The WCSPH model

A Lagrangian code developed by the authors, based on the well known Weakly Compressible Smoothed Particle Hydrodynamics (WCSPH) technique [14], [20], [22-24], has been employed for the purpose. SPH is a mesh-free Lagrangian method in which particles elements, discretizing the computing domain, move with the flow of the fluid. Properties on a moving or fixed point, where mass is thought to be concentrated, depend on its neighbouring particles inside the domain of influence, usually of spherical shape for 3D problems.

Recently, SPH has been considered as a valuable method for solving problems in maritime engineering [25-27]. 3D dam break propagation and impact of liquids have been investigated in [28] by means of a parallel SPH algorithm. In [29] a full SPH-based framework for solving problems involving large fluid motion and large structural deformations and failure is proposed.

The procedure here adopted has been widely applied and validated in a number of situations as in [30-32]. Navier – Stokes equations

$$-\frac{1}{\rho}\frac{D\rho}{Dt} = \nabla \cdot \underline{v} \qquad (1.a)$$

$$\rho\frac{D\underline{v}}{Dt} = -\nabla p + \mu \nabla^2 \underline{v} + \underline{f} \qquad (1.b)$$

are discretized as in [11], yielding

$$\frac{D\log(\nu_i)}{Dt} = \sum_{j=1}^{N_i} \left(\underline{v}_i - \underline{v}_j\right) \cdot \nabla_i W_{ij} \cdot d\Omega_j + \xi\, h\, c0 \sum_{j=1}^{N_i} \psi_{ij} \cdot \nabla_i W_{ij} \cdot d\Omega_j \qquad (2.a)$$

$$\frac{D\underline{v}_i}{Dt} = -\sum_{j=1}^{N_i}\left(\frac{p_i}{\rho_i} + \frac{p_j}{\rho_j} + 19.2\nu\left(\frac{\underline{v}_{ij} \cdot \underline{r}_{ij}}{r_{ab}^{2} + \varepsilon \bar{h}_{ij}^{2}}\right)\right)\nabla_i W_{ij} d\Omega_j + \underline{f}_i \qquad (2.b)$$

where i denotes the pointed moving particle, j refers to one of its N_i neighbours, ν_i is the specific volume, that is $1/\rho_i$, being ρ_i the i-th particle density, p is the pressure, $\underline{v}$ is the velocity vector, $\underline{f}$ is the external force, W is the so called kernel or weighting function defined onto a compact support, $\nu = 10^{-6}$ m^2/s is the kinematic viscosity. The additional terms ξ and ψ_{ij}, appearing inside the diffusion term, are implemented as suggested in [33].

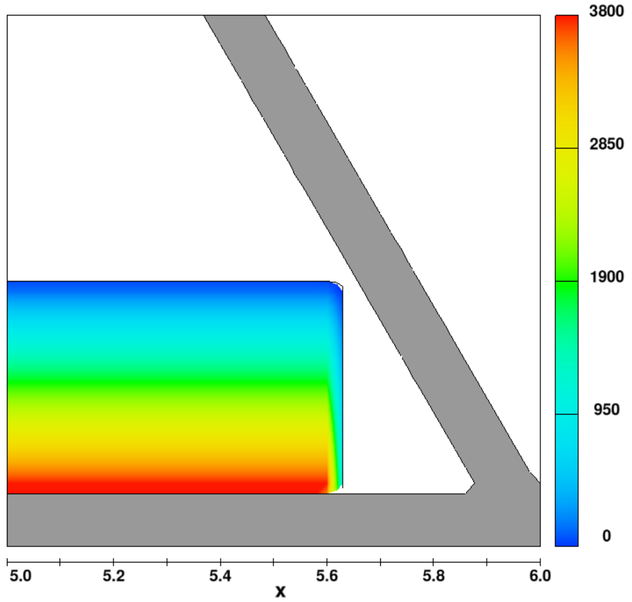


Fig. 1. Initial conditions set in WCSPH and Flow3D. Colour bar refers to pressure contour. Hydrostatic distribution of pressure was assumed.

The corrective terms in the continuity equation, are meant to filter out pressure oscillations, a peculiarity of standard WCSPH schemes.

2.2 The Flow3D model

Flow-3D solver [34] is a CFD software system originally developed at Los Alamos Laboratory. It is based on Finite Volume formulation of the Navier Stokes equations in a Eulerian framework. Free surfaces and interfaces are solved with the volume of fraction (VOF) method [35] and the Fractional Area/Volume Obstacle Representation. 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 [36-37].

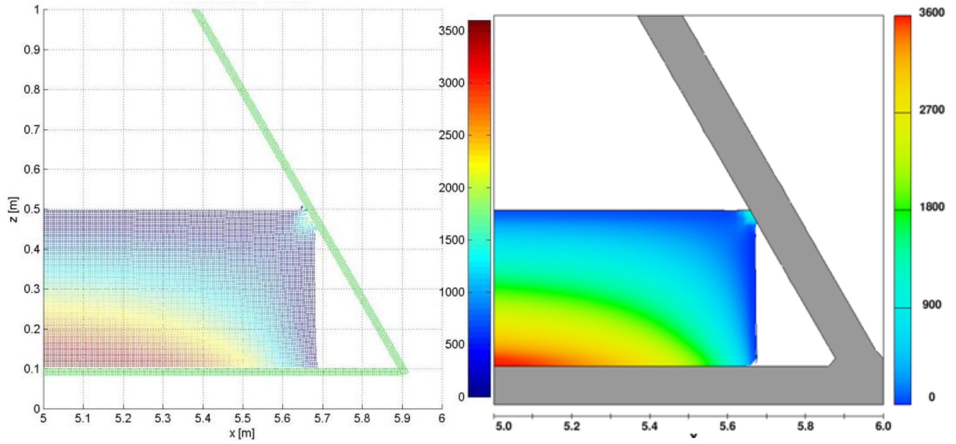
The integration is performed in time with a two step momentum predictor - continuity corrector procedure. The corrector step makes use of a weakly compressible approach, whereby in the continuity equation a variable density mass flow is considered and the compressibility is simulated through a linear law which links the density variation to the pressure increase $c^2 = \partial p / \partial \rho$. No additional dissipation term is included in the momentum equation, so this approach is valid for low Mach numbers and is consistent with the acoustical approximation reported in much of the current literature.

2.3 Numerical set-up

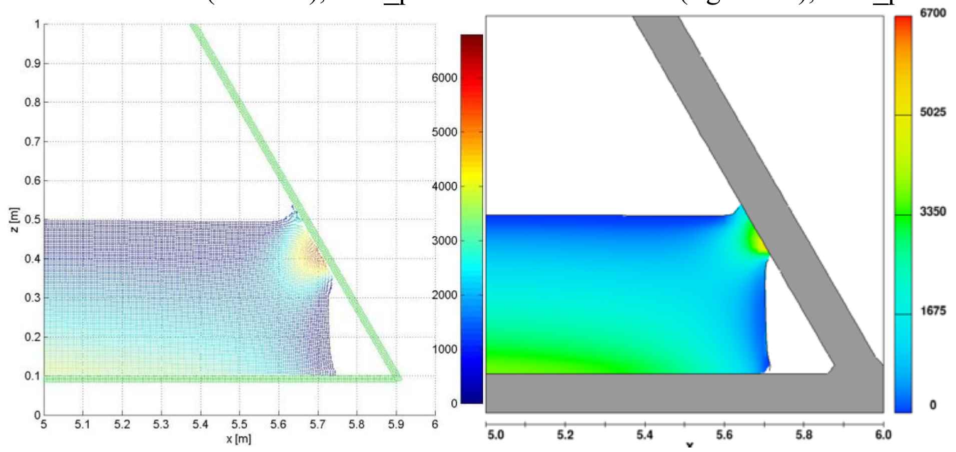
A 2D open channel flow with initial velocity v_0 ranging from 2m/s to 6m/s and water height h_0 = 0.50m is assumed to impact suddenly against a planar wall, inclined of 30° against the approaching mass (Fig. 1). For computational purposes, a 4.00m long volume of fluid was assumed. The nearest point of the liquid mass is close to the wall of 0.05m to let the impact after few timesteps.

3. Results

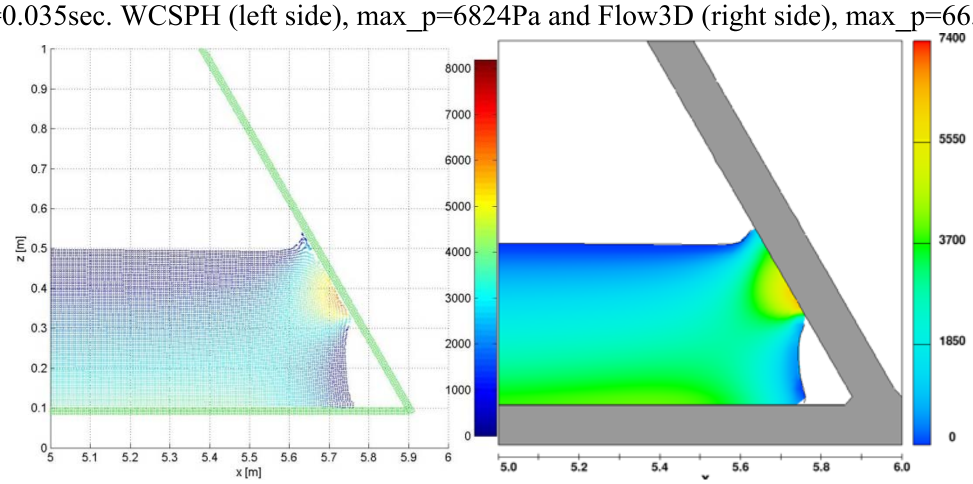
The following figures show results in terms of pressure contour, employing WCSPH (left side) and Flow3D (right side), at various instants in time. Time was measured from the impact instant. A global colour bar scale for pressure was here assumed, in order to make the comparison easy.



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

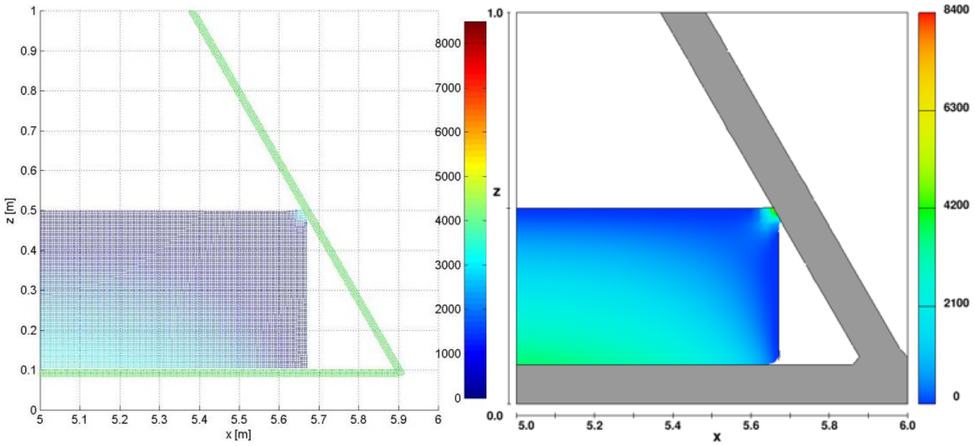


b) t=0.035sec. WCSPH (left side), max_p=6824Pa and Flow3D (right side), max_p=6659Pa.

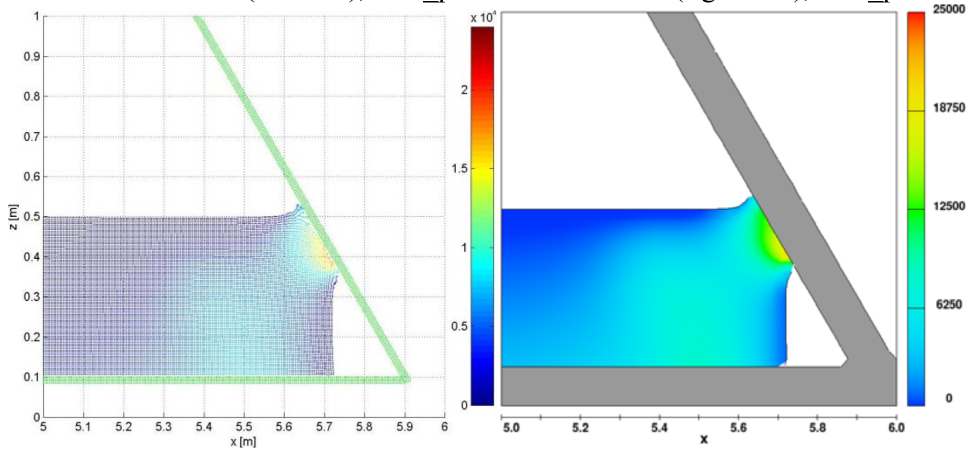


c) t=0.050sec. WCSPH (left side), max_p=8145Pa and F3D (right side), max_p=7482Pa.

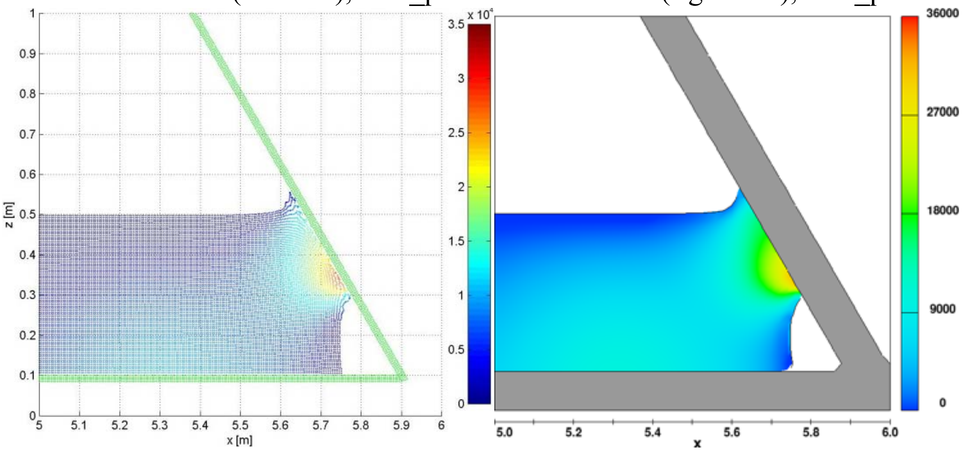
Fig. 2. Comparison of pressure fields for the initial velocity v_0 = 2m/s



a) t=0.010sec. WCSPH (left side), max_p=8478Pa and F3D (right side), max_p=8333Pa.



b) t=0.022sec. WCSPH (left side), max_p=6824Pa and F3D (right side), max_p=6659Pa.



c) t=0.028sec. WCSPH (left side), max_p=34127Pa and F3D (right side), max_p=35092Pa.

Fig. 3. Comparison of pressure fields for the initial velocity v_0 = 4m/s

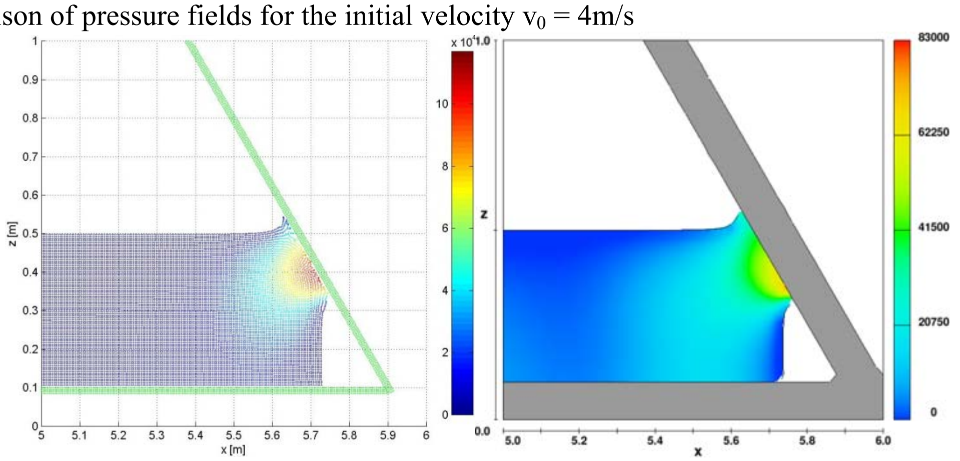


Fig. 4. Comparison of pressure fields for the initial velocity v_0 = 6m/s. t=0.016sec. WCSPH (left side), max_p=116461Pa and F3D (right side), max_p=82098Pa.

Both methods, WCSPH and Eulerian, reproduce a similar build up and evolution of pressure fields. The order of magnitude of maximum pressure as the impact takes place depend on the approaching velocity, as it would be expected according to the Jokowski formula $\Delta p = \rho_0 C_0 \Delta v$, with $\Delta v = v_0$ for symplicity. The pressure front travels backwards, while the inverted reflection from the upper free surface pushes it downwards, justifying the peculiar pressure wave shape.

4 Conclusions

The numerical experiments carried out on the sudden fluid impact of an open surface fluid flow onto an inclined wall have highlighted an elastic Jokowskj kind of pressure wave, modified and attenuated by the presence of the free surface

Comparison of pressure contours is always satisfying, proving that employed methods are both reliable.

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