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# SPH Simulation of Waves Associated with Underwater Explosion

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## ABSTRACT

The current manuscript presents the validation of Smoothed Particle Hydrodynamics (SPH) techniques for wave generation by underwater explosion, utilizing the so-called DualSPHysics numerical model. This numerical method is used to analyze generated waves which are initiated by man-made or natural explosions below free surface level of sea. In spite of the modeling limitations (e.g. absence of open boundary conditions), reasonable agreement is accomplished with predictions of the existing formula as well as experimental results. This proved that SPH techniques such as incorporated in DualSPHysics are becoming a suitable alternative to existing classical approaches to this particular water waves problem. It is also provided an inherently more accurate computational for the prediction of wave characteristics generated by underwater explosions.

# 1. Introduction

Underwater explosions are known to generate relatively slow, outward-moving surface waves, with certain recognizable characteristics. Such waves, originating in the volume oscillations and upward movement of the explosion-induced gas bubble breaking on the surface, eventually form a train spreading in widening circles of steadily diminishing height around the still water level. Predominantly, the first surface wave near the burst is too steep a waveform to be sustainable; consequently, it breaks into a turbulent kind of motion, dissipating a large part of the initial energy that would otherwise be available to create surface waves. Subsequently, the wave-train usually travels over deep waters almost without further loss of energy.

Past studies on waves generated by underwater explosion lead to valuable results regarding the behavior of waves and developing wave theories. Moreover, given the similarity of these waves to the waves caused by the impact of meteorites in large water bodies, exploding volcanoes and tsunamis caused by underwater landslides, therefore, by virtue of studying waves induced by controlled underwater explosions, the derived results may be similarly applicable to for the simulation of other types. Naturally, the waves produced by a downward surface elevation impulse, or via an underwater explosion, constitute a dispersive system whose properties are not constant as wave characteristics such as representative periods, celerities and wave-lengths often increase over duration of propagation and waveheights decrease with increasing travelled distance. Various theoretical concepts have been established often rooted in analytical derivations in combination with empirical observations to characterize wave properties at a given place and time in order to achieve good conformity with measurements, however, a study of the literature points to the fact that in recent era numerical modeling tools are yet to be widely used in tackling this interesting topic. Therefore, it is strived in this article to address this issue by applying state-of-the-art numerical modeling tools for the sake of better understanding explosion created water waves as well as other waves of similar mode of generation.

A number of previous studies on underwater explosion phenomena have been performed in different related realms, such as, field experiments, laboratory investigations, analytical approaches, and numerical modeling. Generally, water waves due to underwater explosions are originated by a pulsating bubble. As a result, some researchers focused on the ensuing bubble behavior during its movements, while others worked on the stage of the bubble collapse and wave initiation, utilizing similar methodologies and assumptions which present study is more close to the last series of researches.

The first theoretical treatment of wave generated by an initial free surface disturbance of infinitely small radius, but finite energy, is due to Cauchy (1815) and Poisson (1816). An early study of considerable significance in the field of bubble research is investigation by Lord Rayleigh (1917) about collapse of a spherical cavity in an infinite fluid. The generalization of Lamb's method to a case of an initial disturbance of finite extent was developed by Terazawa (1915), for the cases of deep and intermediate water depth. Terazawa also investigated the effect of the depth of burst in the case of an impulsive explosion. Rayleigh's idea was extended in the context of underwater explosion research by Lamb (1923) who assumed that the pressure within the explosion bubble is variable. For motion under the influence of buoyancy alone Herring (1941) first gave the system of equations describing the evolution of the explosion bubble. A numerical investigation of the generation and propagation of an underwater blast wave was undertaken by Penney (1941) and Penney and Dasgupta (1942) in which the equations of compressible flow integrated were along characteristics. Penney and Price (1942) were motivated to consider the stability of an initially spherical bubble rising under the action of buoyancy forces. The significant practical technique employed being high speed photography by Taylor and Davies (1943) and Bryant (1944), which allowed accurate records of the bubble shape as a function of time and the migration of the bubble to be obtained, with data also being recorded during collapse phase of the motion. Charlesworth (1945) performed a series of tests and studied underwater explosion effects on wave generation and propagation. Penney (1945) proposed an analytical relation for dome and crater formation during bubble collapse near free surface of water. Besides he worked on gravity waves in water caused by explosions. Bryant (1945) applied Penney's analytical solution for test results. Herring (1949) presented a discussion of possible loss mechanisms including radiation of acoustic energy, turbulence and heat transfer and concluded that although the principal loss mechanism is via radiation [1].

Axi-symmetric solutions for explosion generated water waves was given by Kranzer and Keller (1959) in which the influence of water depth was taken into account [2]. The characteristics of explosion cavities at reduced pressure have been modeled in detail on a small scale by Kaplan and Goodale (1962). A generalization of the Cauchy-Poisson Theory to a finite disturbance of arbitrary form was developed by Le Mehaute (1963). By approximating the dispersion relationship to include only the long wave portion of the spectrum and limiting the source disturbance to a long narrow strip, Kajiura (1963) arrived at results same as Eckart's works (1948). Applications of Kranzer and Keller analytical approach were presented by VanDorn (1964), Whalin (1965), Hwang and Divoky (1967). Theory was developed to predict the wave properties at a given travel time and distance for given source energy, displacement and travel path depth profile by Jordaan (1965). In their landmark paper Benjamin and Ellis (1966) introduce the concept of the Kelvin impulse to the study of bubble dynamics. Some researches were performed about propagation of water waves due to explosions and a sort of concepts were raised, such as VanDorn et. al (1968). They also found the behavior of explosion generated water waves on the continental shelf and its effect on costal area. Chapman (1971) employed a marker in cell technique and computed the collapse of an initially spherical vapor cavity adjacent to a rigid boundary. A theoretical mathematical model for the simulation of the hydrodynamics related to underwater explosion and subsequent bubble dynamics and free surface effects was formulated by Amsden (1973); Hirt and Rivard (1983); Fogel, et al. (1983) and Mader (1988) [1].

Bottin and outlaw (1987) prepared a class of field investigations about explosion generated waves in shallow water [3]. The vulnerability of coastal facilities and vessels to explosion generated water waves was studied experimentally by Bottin and outlaw (1988) in US army engineer waterways experiment station [4]. Wilkerson (1988) studied theoretical cavity shapes and potential flow by numerical methods. For a given experimental wave record at a defined distance from zero surface, the initial conditions are determined numerically by reverse transforms by Le Mehaute, et al. (1989), Wang, et al. (1989) and Khangaonkar and Le Mehaute (1991). Le Mehaute and Khangaonkar (1991) proposed a simple relationship for horizontal radius of the cavity when it is developed in depth of water. Wang (1992) worked on simulation of crater formation and surface movement [5].

The effects of an underwater explosion depend on several parameters, including distance from the explosion source, energy of the explosion, the depth of the explosion, and the water depth. Underwater explosions generate relatively slow, outward-moving surface waves, which have certain recognizable characteristics. These waves, originating in the oscillations of the gas bubble as it breaks the surface, eventually form a train spreading in widening circles of steadily diminishing intensity around the surface zero. Generally, the first surface wave near the burst is too steep to be sustained; consequently, it breaks into a turbulent kind of motion, consuming a large part of the initial energy that would otherwise have been available to create surface waves. Subsequently, the wave train travels over deep water often almost with no further loss of energy. Certain characteristics of surface waves become more pronounced when the detonation occurs in shallow water rather than in deep water. Field test observations showed that the first wave behaved differently from the succeeding ones; it was apparently a long, solitary wave, generated directly by the explosion, receiving its initial energy from were probably formed by the venting of the gas bubble and refilling of the cavity in the high-velocity outward motion of the water accompanying the expansion of the gas bubble. Some other tests indicated that the initial, solitary wave is characteristic of explosions in shallow water. Detonations in deep water generate a train of waves in which the number of crests and troughs increases as the train propagates outward from the center of the explosion. The properties of dispersive wave motion in the spacetime field were derived for general conditions and certain practical applications. Maximum wave heights, periods, lengths, velocities, travel times, envelopes, group velocities, and the modification by a shoaling bottom can be uniquely expressed in terms of the initiating disturbance and stated by VanDorn (1964), LeMehaute (1964), Whalin (1965) and Jordaan (1964) [6].

In case of deep water or near surface explosions with low quantity of yield, after reaching bubble to the free surface region of water, sea surface started to deform into a dome shape body (see Figure 1). During this process water layer which is located on top of water become thinner and unstable until its strength be broken, so confined gas and vapor inside the bubble will be released outward. Finally the fragmented bubble will be reshaped into a crater which is surrounded by lip shape all around it (see Figure 2) [7, 8, 9, 10].



Figure 1. Rising dome due to expansion and upward migration of bubble



Figure 2. Generating crater and lips after bubble collapse

#### 2. SPH numerical model

SPH is a Lagrangian method in which the continuous medium can be discretized into a set of disordered points [11]. SPH allows any function to be expressed in terms of its values at a set of the particles by interpolation without using grid to calculate spatial derivatives. In this way physical properties of each particle, such as: acceleration, density and etc. are quantified as an interpolation of the same values in neighbor nodes. The main feature of the SPH technique is to approximate a scalar function  $A(\mathbf{r})$  at any point with r vector of position, as follows [12, 13, 14]:

$$A(\mathbf{r}) \cong \int A(\mathbf{r}') \cdot W(\mathbf{r} - \mathbf{r}', h) d\mathbf{r}'$$
(1)

where in Eq.(1) h is called smoothing length to represent the influence of the nearest particles in a neighboring domain, so it is weighted in accordance with distance between particles. Kernel function  $W(\mathbf{r} - \mathbf{r}', h)$  is used to estimate the amount of participation by means of smoothing length parameter. In discrete form Eq.(1) becomes [12, 14]:

$$\langle A(\boldsymbol{r}_a) \rangle \approx \sum_b \left(\frac{m_b}{\rho_b}\right) \cdot A(\boldsymbol{r}_b) \cdot W(\boldsymbol{r}_a - \boldsymbol{r}_b, h)$$
 (2)

where in Eq.(2) the summation is extended to all the particles within the neighboring distance of particle "a", and the volume associated with the particle "b" is  $\frac{m_b}{\rho_b}$ , so  $m_b$  and  $\rho_b$  are respectively the mass and the density of this neighbor particle. The kernel functions shall have several properties [12, 13], including: positivity inside the area of interaction, compact support, normalization, and monotonic decrease with distance. One kernel option is the quintic kernel described by Wendland (1995), for which the weighting function vanishes for inter-particle distances greater than 2h. It is defined as (Altomare et. al., 2014, 2015):

$$W(q) = \alpha_D \left( 1 - \frac{q}{2} \right)^4 (2q+1) \ ; \ 0 \le q \le 2 \tag{3}$$

Where in Eq.(3),  $q = \frac{|r|}{h}$  is defined as ratio of particle distance to smoothing length and  $\alpha_{\rm D}$  is a

normalization constant, which is equal to  $\frac{7}{14\pi h^2}$  in two dimensions and  $\frac{21}{16\pi h^3}$  in three dimensions.

The conservation laws of continuum fluid dynamics, in the form of differential equations, are transformed into their particle forms by the use of the kernel functions. The momentum equation proposed by Monaghan (1992) has been used to determine the acceleration of a particle "a" as the result of the particle interaction with its neighbors, such as particle "b" [12, 13]:

$$\frac{d\boldsymbol{v}_a}{dt} = -\sum_b m_b \left(\frac{P_b}{\rho_b^2} + \frac{P_a}{\rho_a^2} + \Pi_{ab}\right) \boldsymbol{\nabla}_a W_{ab} + \boldsymbol{g}$$
(4)

where  $\boldsymbol{v}$  is particle velocity, *P* is particle pressure,  $\boldsymbol{g}$  is gravitational acceleration vector equal to (0,0, -9.81), and  $W_{ab}$  is the kernel function that depends on the distance between particles "a" and "b".  $\Pi_{ab}$  is the viscous term according to the artificial viscosity proposed by Monaghan (1992) [12, 13]:

$$\Pi_{ab} = \begin{cases} -\frac{\alpha_{v} \cdot \bar{c}_{ab} \cdot \mu_{ab}}{\bar{\rho}_{ab}} & ; \quad \boldsymbol{v}_{ab} \cdot \boldsymbol{r}_{ab} < 0\\ 0 & ; \quad \boldsymbol{v}_{ab} \cdot \boldsymbol{r}_{ab} \ge 0 \end{cases}$$
(5)

where  $\mathbf{r}_{ab} = \mathbf{r}_a - \mathbf{r}_b$ ,  $\mathbf{v}_{ab} = \mathbf{v}_a - \mathbf{v}_b$ ; which are the particle position and velocity, respectively.  $\alpha_v$  is a coefficient that needs to be tuned in order to introduce the proper dissipation. The value  $\alpha_v = 0.01$  was used in this work because it is the minimum value that prevents instability and spurious oscillations in the numerical scheme.  $\bar{c}_{ab} = \frac{c_a + c_b}{2}$  is the mean speed of sound of particles,  $\bar{\rho}_{ab} = \frac{\rho_a + \rho_b}{2}$  is the mean density of particles and  $\mu_{ab} = \frac{h \cdot v_{ab} \cdot r_{ab}}{r_{ab} \cdot r_{ab} + \eta^2}$  with  $\eta^2 = 0.01 \times h^2$ .

Equation of states for ideal gases is as follow [12, 13, 14]:

$$P = B\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] \tag{6}$$

$$B = \frac{c_0 \cdot p_0}{\gamma} \tag{7}$$

$$c_0 = c(\rho_0) = \sqrt{\frac{\partial P}{\partial \rho}}\Big|_{\rho_0} \tag{8}$$

the parameter *B* is a constant related to the fluid compressibility modulus,  $\rho_0 = 1000 \text{ kg/m}^3$  is the reference density, chosen as the density at the free surface,  $\gamma$  is a constant, normally between 1 and 7, and  $c_0$  is the speed of sound at the reference density [14].

#### **3. Present Approach**

In this study, it is aimed to simulate the initiation and primary wave propagation via underwater explosion phenomena partaking of the SPH method. Results of the adopted SPH model were compared with some of well-known experimental, analytical and numerical studies, focusing on the primary wave formation after cavity collapse and wave propagation aspects.

It is intended to investigate of the flow after the cavity in the free surface reaches its maximum dimensions, assuming that the flow is single phase type, neglecting any two-phase flow effects, as well as that the surrounding fluid is deemed approximately at rest at the time of reaching the maximum bubble radius [15]. As stated in user manual of the DualSPHysics code [16], it has been developed starting from the SPH formulation implemented in SPHysics [17]. This FORTRAN code is robust and reliable but is not properly optimized for huge simulations [18, 19]. DualSPHysics is implemented in C++ and CUDA language to carry out simulations on the CPU and GPU respectively Furthermore, [20]. better approaches are implemented, for example particles are reordered to give faster access to memory, symmetry is considered in the force computation to reduce the number of particle interactions and the best approach to create the neighbor list is implemented [21]. The CUDA language manages the parallel execution of threads on the GPUs. The best approaches were considered to be implemented as an extension of the C++ code, so the most appropriate optimizations to parallelize particle interaction on GPU were implemented [22]. The DualSPHysics code has been developed to simulate real-life engineering problems using SPH models such as the computation of forces exerted by large waves on the urban furniture of a realistic promenade [14] or the study of the run-up in an existing armour block sea breakwater and wave forces on coastal structures [12, 13].

The main purpose of the present study is to investigate the precision of SPH-type methods for computing water waves generated by underwater explosion occurrences. Hence, some new modeling test cases were compared with analytical-rooted solutions proposed in the literature, and with experimental data as well as traditional numerical modeling results.

DualSPHysics version 3.1 (2013) is used in the current study, requiring hardware with run of a Central Processing Unit (CPU) or a Graphical Processing Unit (GPU) in addition. The computational efficiency offered by the GPU has made high performance computing more readily available for computational fluid dynamics applications, especially in the case of very large modeling domains.

Two types of GPU cards on different machines were used in current study. Applied machines and processors are as following: (1) GeForce GTX 680 with 1536 CUDA cores on a personal computer with a CPU type of AMD A8-3870 APU, (2) GeForce GTX 780M with 1536 CUDA cores on a MSI laptop which has CPU type of Intel® Core<sup>™</sup> i7-4700MQ.

# 4. Comparison of simulation results with existing analytical and empirical solutions

Before application of the code for field tests, appropriate justification of the DualSPHysics was required to clarify that the numerical model could reliably simulate free surface shock propagation phenomena due to predefined initial condition [23]. Thus, several recognized analytical solved problems were simulated, so the generated wave shapes and behavior of propagated waves due to initial crater of underwater explosion were monitored. Finally the results were compared with those are described in reference works and literature. There are too many theories and formulae about underwater explosion waves, so in this study the Penney's (19450 theoretical relations [24], Charlesworth (1945) experimental results [25] and Mader (1976) numerical experiences [26], were considered as case studies.

#### 4.1. Charlesworth's experimental setup

One of the experiences in a field-laboratory environment was performed by Charlesworth (1945) at the Road Research Laboratory, London [25]. A complete description of the experimental definition and set of outputs were provided by him. This field test was an underwater explosion experiment within a semi rectangular bay, which was limited by banks in west and south directions respectively 55 ft (16.76 meter) and 70 ft (21.34 meter) from surface zero. Water depth was approximately uniform, from 15 to 18 ft (4.57 to 5.49 meter), all around the charge location (see Figure 3). Charge depth locations and weights were considered variable. Wave amplitudes in specified locations were captured by a camera on south bank.



Figure 3. Site plan of underwater explosion tests (Charlesworth, 1945)

In this study, the recorded amplitudes of surface waves produced by a 32 lb (14.5 kg) charge detonated in water at a depth of 8 ft (2.44 meter) which was recorded for point at 56.5 ft (17.22 meter) from the charge, were considered for evaluation of SPH modeling.

#### 4.2. Penney's analytical solution

Analytical solution proposed by Penney (1945) for initial condition of cavity formation due to underwater explosion [24], especially in deep water, was examined by Bryant (1945) for last mentioned experiment by Charlesworth (1945) [25]. The same three dimensional SPH model was applied for comparison of results (see Table1). In this case both initial conditions, Penney's theory and modified Penney's curve as described by Bryant (1945), were tested in simulations.

Table 1. SPH-3D model parameters of the simulation of Charlesworth's experiment and Penney's analytical solution by bryant

Characteristic	Value
Particle size	0.2 ~ 0.5 [ <i>m</i> ]
Smoothing length	0.015 [ <i>m</i> ]
Number of particles	1,000,000 ~ 3,700,000 [-]
Artificial viscosity	0.01~0.5 [-]
Speed of sound coefficient	10 ~ 20 [-]
CFL number	0.2 [-]
Kernel function type	Wendland [-]

#### 4.3. Mader's numerical experiences

As mentioned before, some researchers tried to model underwater explosion and its effects such as surface water waves. One of this kind of researches, is numerical simulations of waves generated from surface cavities by Mader (1976) [26]. Mader applied two reference numerical model, SWAN and ZUNI, for simulation purposes in his works [26]. Here the results of Mader were used for re-assessing the primary wave generation from cavity formation of underwater explosion phenomenon. Mader studied the wave motion resulting from cavities in the ocean surface, using both the long wave, shallow water model and the incompressible Navier-Stokes equations. He found that the fluid flow resulting from the calculated collapse of the cavities is significantly different for the two models. Also he supposed that the experimentally observed flow resulting from explosively formed cavities is in better agreement with the flow calculated using the incompressible Navier-Stokes model.

#### 4.4. Prins' experimental setup

In this section SPH modeling results are also compared with the experimental data provided by J.E. Prins (1956) at Wave Research Laboratory of the Institute of Engineering Research, University of California, Berkeley [27, 28]. The model investigations were carried out in a flume one foot wide by sixty foot long. In this experimental research water depression was created by an air-tight box of Plexiglas with a sliding front wall in which the water level could be elevated or depressed by means of a decreased/increased pressure in the air compartment. By pulling the slide upward in the shortest possible time it was possible to develop a free elevated or depressed area of uniform height with all the water particles effectively at rest. The back wall of the box was considered to cause a total reflection and hence is the axis of symmetry of the system. At the opposite end of the channel a wave absorber was installed. The vertical movement of the water surface,  $\eta$ , was recorded as a function of time simultaneously at five places along the channel with a six-channel recorder by using parallel wire resistance wave gages [27, 28]. The test results with water depth d=2.3 ft (0.7 meter), upward initial bore Q=0.4 ft (0.12 meter) by a length of L=2 ft (0.61 meter) were considered for modeling purposes. Recorded wave profile at X=15 ft (4.57 meter).

#### 5. Results and discussions

This section shows the capability of the SPH method, the DualSPHysics code in particular, to simulate collapse of initial cavity and primary wave domain due to underwater explosion.

The process of numerical simulation of fluid particles, during initiation of primary wave shapes and their radial propagation from surface zero towards all directions, is related on the physical properties at each SPH particle and its interaction with other ones. The wave shapes can be numerically measured by wave gauges in specified locations or by free surface waterline calculations. These techniques were applied in following simulation test cases to assess the results with experimental, analytical or numerical experiences by others.

Prior to applying DualSphyics to model experimental and numerical cases, a simple wave propagation due to free water surface initial condition deformation was tested and wave shapes were monitored qualitatively. In this numerical test, wave forms were originated and propagated very smooth. The effects of variation of different parameters were checked and found that the most critical parameter in this type of hydrodynamic problem is particle sizes. For very large or very small sizes of particles, the waves were dissipated or damped very quickly due to low accuracy in very large sizes and numerical viscosity effects in very small sizes. Finally it has been proven that for a good behavior of numerical model, it is better that the optimum size of particles to be considered in the range of 1/10 to 1/1000 of largest dimension in 3D simulations and 1/1000 to 1/100000 of largest dimension in 2D models. Also it is found that in vertical direction at least 5 to 10 particle is required. The primary wave formation and propagation is shown in Figure 4.



Figure 4. Primary wave generation and propagation due to underwater explosion (times in seconds, distances in meters)

3D presentation of dome evolution in time and primary wave propagation mechanism in Figure 5a, also velocity components in X, Y and Z directions are quoted respectively in Figures 5b to 5d. Two instant of the SPH simulation using DualSPHysics is depicted in Figure 6. Different numerical parameters related to the number of particles and 3D-SPH simulations are summarized in Table 1. A good agreement between experimental and SPH results are presented in Figure 6. Both trends are definitely compatible and besides three peaks are approximately simulated with a shift in time of occurrence which become greater from first crest in curve to the third one (see Figure 6).

Experimental measurements included the time series of the wave amplitudes. These experimental data were also used by Bryant (1945) to validate the Penney's theoretical formula for initiation of water waves and cavity formation. The initial surface condition was considered to be parabolic with the characteristics that are specified in Bryant's work (1945) for both SPH models of Charleston and Penney [28].

Various types of two dimensional SPH models were prepared for these samples, so their simulation parameters are similar to last SPH modeling case that is presented in Table 1.



Figure 5a. Time evolution of dome shape and primary wave propagation with vertical velocity contours







Figure 5c. Time evolution of velocity Y-component contours



Figure 5d. Time evolution of velocity Z-component contours

Such as last numerical experience in present work, there is reasonable agreement between the two curves (see Figure 7).Results of SPH are shown in Figure 8 for SWAN modeling and also Figure 9 for simulations by ZUNI respectively. SPH model properties of these series are quoted in Table 2.



Figure 6. Comparison of Charlesworth's experimental data with SPH results



Figure 7. Comparison of Penney's analytical solution with SPH results



Figure 8. Comparison of SWAN modeling wave generation and propagation due to initial crater (Mader, 1976) with SPH results (Current study) in different time steps



Figure 9. Comparison of ZUNI modeling wave generation and propagation due to initial crater (Mader, 1976) with SPH results (Current study) in different time steps

 
 Table 2. SPH-2D model parameters of the simulation of Mader's numerical experiment

Characteristic	Value
Particle size	$0.01 \sim 0.05 \ [m]$
Smoothing length	0.015 [ <i>m</i> ]
Number of particles	20,000 ~ 100,000 [-]
Artificial viscosity	0.01~0.5 [-]
Speed of sound coefficient	10 ~ 20 [-]
CFL number	0.2 [-]
Kernel function type	Wendland [-]

It is important to note that wave shapes are very similar but a slight time shift in wave propagation is visible. Water levels and especially geometry of primary wave are approximately simulated by SPH technique. A series of two dimensional SPH models of Prins's tests were built, which their simulation properties are presented in Table 3.

Table 3. S	PH-2D mode	el parameters	of the si	mulation of
	Prins's la	boratory expe	eriment	

Characteristic	Value
Particle size	0.0006096 ~ 0.01016 [ <i>m</i> ]
Smoothing length	0.0015 [ <i>m</i> ]
Number of particles	130,000 ~ 365,000 [-]
Artificial viscosity	0.01~0.5 [-]
Speed of sound coefficient	10 ~ 20 [-]
CFL number	0.2 [-]
Kernel function type	Wendland [-]

Results of 2D-SPH modeling are shown in Figure 10 for these experiments. Obviously the location and peak values of wave time histories in SPH models are very close to experimental results.



Figure 10. Comparison of SPH results with Prins' experimental record (1956) at X=15 ft

#### 6. Conclusions

Generation of first leading wave of a cavity type initial condition on free surface of sea water line, is a typical shock wave that is very high and unstable due to its extra ordinary steepness. Most of the time this primary wave is the largest and strongest wave among other wave in a trail of underwater explosion surface waves. Prediction leading wave and calculation of its properties, is important for design of coastal and marine structures that are located in the effective domain of leading wave. Smoothed Particle Hydrodynamics, is a proper numerical method for prediction of turbulent and harsh condition of surface water waves. In this research it is found that:

SPH model can predict first two or three leading waves. It is seen than SPH model prediction has good agreement with experimental or field records (see Figures 6 & 10).

SPH results are more compatible with Eulerian models which are constructed on the basis of Navier-Stocks equations such as ZUNI model (see Figure 9). Obviously shallow water models such as SWAN has not capability of underwater explosion wave generation by free surface initial conditions and results are not compatible. Even in this case the general trend of wave initiation and propagation are the same but they are not match from scale and shape point of view (see Figure 8).

SPH model results has shorter wave crest prediction vs. analytical and other numerical models. This difference is raised from discrete nature of SPH and splash of particles especially in contact moments when some parts of fluid particles coincide with other particles or rigid walls. In these cases, some parts of fluids are separated from the whole body and will drop again in another place with impact. This may cause some extra wave generation or damping of main wave bodies, so the results shows shorter wave heights than other techniques.

The main difference between analytical and traditional numerical models with SPH models is discrete behavior of the last one. This property make it more suitable for modeling of shock phenomena. For instance when initial cavity form of water surface started to collapse, it is very hard for traditional models that simulate mixing multiple layers of fluids, but it is simulate inherently by SPH method.

The major weak point of SPH is its lower accuracy vs. traditional CFD tools, then it may enforce user to create a fine size of particle and cause to larger computational times. On the other hand, by use of coarse size of particles, it is possible to find the main trend of surface waves of underwater explosion phenomenon.

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#### 8. References

1- www.DTIC.mil, Official site of Defense Technical Information Center.

2- Kranzer, H.C. and Keller, J.B., (1959), *Water Waves Produced by Explosions*, AIP Publishing, Journal of Applied Physics, Vol.(3), p. 398.

3- Falade, A. and Holt, M., (1978), *Surface waves generated by shallow underwater explosions*, AIP Publishing, Physics of Fluids, Vol. 21(10), p. 1709.

4- Bottin, R.R., (1990), *Impulsive waves generated by falling weights in shallow water*, Final Technical Report CERC-90-9, Coastal Engineering Research Center, DEPARTMENT OF THE ARMY, Waterways Experiment Station, Corps of Engineers, 3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199.

5- LeMehaute, B. and Wang, S., (1996), *Water waves* generated by underwater explosion, World Scientific, River Edge.

6- Whalin, R.W., (1965), *Water waves produced by underwater explosions: propagation theory for regions near the explosion*, Journal of Geophysical Research, Vol.70(22), p. 5541-5549. 7- Kolsky, H., Lewis, J.P., Sampson, M.T., Shearman, A.C. and Snow, C.I., (1949), *Splashes from Underwater Explosions*, Proceeding of Royal Society of London, Vol. 196, p. 379-402.

8- Kirkwood, J.G. and Seeger, R.J., (1950), *Surface waves from an underwater explosion*, Underwater Explosion Research, Vol. II, ONR, Dept. of Navy, p. 707-760.

9- Fuchs, R.A., (1952), *Theory of surface waves produced by underwater explosions*, Technical Report Series No. 3, Issue No. 335, University of California, Institute of Engineering Research, Berkeley, California.

10- Kozachenko, L.S. and Khristoforov, B.D., (1972), *Surface events during underwater explosions*, Translated from Fizika Goreniya i Vzryva, Vol. 8(3), p. 433-438.

11- Crespo, A.J.C., Altomare, C., Dominguez, J.M., Suzuki, T., Verwaest, T. and Gomez-Gesteira, M., (2015), *SPH modeling in coastal engineering*, Eproceedings of the 36th IAHR World Congress, Hague, The Netherlands.

12- Altomare, C., Crespo, A.J.C., Rogers, B.D., Dominguez, J.M., Gironella, X. and Gomez-Gesteira, M., (2014), *Numerical modelling of armour block sea breakwater with smoothed particle hydrodynamics*, Computers & Structures, Vol. 130, p. 34-45.

13- Altomare, C., Crespo, A.J.C., Dominguez, J.M., Gomez-Gesteira, M., Suzuki, T. and Verwaest, T., (2015), *Applicability of Smoothed Particle Hydrodynamics for estimation of sea wave impact on coastal structures*, Coastal Engineering Journal, Vol. 96, p. 1-12.

14- Barreiro, A., Crespo, A.J.C., Domínguez, J.M. and Gómez-Gesteira, M., (2013), *Smoothed Particle Hydrodynamics for coastal engineering problems*, Computers & Structures Vol. 120, p. 96-106.

15- Swegle, J.W. and Attaway, S.W., (1995), On the feasibility of using smoothed particle hydrodynamics for underwater explosion calculations, Comp. Mech. Vol. 17, p. 151-168.

16- Crespo, A.J.C., Domínguez, J.M., Gómez-Gesteira, M., Barreiro, A., Rogers, B.D., Longshaw, S., Canelas, R. and Vacondio, R., (2013), *User Guide for DualSPHysics v3.0.* 

17- www.SPHysics.org, Official site of SPHysics software.

18- Gomez-Gesteira, M., Rogers, B.D., Crespo, A.J.C., Dalrymple, R.A., Narayanaswamy, M. and Dominguez, J.M., (2012), *SPHysics - development of a free-surface fluid solver – Part 1: Theory and formulations*, Computers & Geosciences Vol. 48, p. 289-299.

19- Gomez-Gesteira, M., Rogers, B.D., Crespo, A.J.C., Dalrymple, R.A., Narayanaswamy, M. and Dominguez, J.M., (2012), *SPHysics - development of a free-surface fluid solver – Part 2: Efficiency and test cases*, Computers & Geosciences Vol. 48, p. 300-307. 20- www.dual.SPHysics.org, Official site of DualSPHysics software.

21- Domínguez, J.M., Crespo, A.J.C., Gómez-Gesteira, M. and Marongiu, J.C., (2011), *Neighbour lists in Smoothed Particle Hydrodynamics*, International Journal for Numerical Methods in Fluids, Vol. 67(12), p. 2026-2042.

22- Domínguez, J.M., Crespo, A.J.C. and Gómez-Gesteira, M., (2013), *Optimization strategies for CPU and GPU implementations of a smoothed particle hydrodynamics method*, Computer Physics Communications, Vol. 184(3), p. 617-627.

23- Monaghan, J.J. and Gingold, R.A., (1983), *Shock simulation by the particle method SPH*, Journal of computational Physics, Vol. 52, p. 374-389.

24- Penney, W.G., (1950), *Gravity waves produced by surface and underwater explosions*, Underwater Explosion Research, Vol. II-The gas globe, Office of Naval Research, Department of the Navy, p. 679-700.

25- Bryant, A.R., (1950), Surface waves produced by underwater explosions Comparison of the theory of W.G. Penney with experimental results for a 32-lb. charge, Underwater Explosion Research, Vol. II, ONR, Dept. of Navy, p. 701-706.

26- Mader, C.L., (1976), *Calculations of waves formed from surface cavities*, Proc. of 15th Conf. on Coastal Engineering, Vol. 15, p. 1079-1092.

27- Prins, J.E., (1957), *Water waves due to a local disturbance*, Proc. of 6th Conf. on Coastal Engineering, Vol. 6, p. 147-162.

28- Noda, E.K., (1971), *Water waves generated by a local surface disturbance*, Journal of Geophysical Research Vol. 76, p. 7389-7400.