NUMERICAL SIMULATION OF AN UNDERWATER EXPLOSION BY SPH METHOD

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Abstract. This paper presents theoretical and practical fundamentals regarding numerical analysis of an underwater explosion. Its parameters and effects upon submerged structures represent the aim of the numerical analysis by Smoothed Particles Hydrodynamics (SPH). SPH method is a version of a more general numerical method, named free particle method. The fundamentals of explosion theory and of the SPH method are supposed to be known, so this paper intends to present only the particularities of an underwater explosion and how its parameters and effects can be modeled by SPH method. The example finishing the paper represents an available numerical model for such problems.

Key words: SPH, explosion, cavitations, bubble gas, underwater, blast wave.

1. INTRODUCTION

All the aspects regarding explosives, explosions and the effects of these upon structures present a high complexity and many difficulties for any approaching ways (analytical, numerical and experimental). Among all explosion types, those underwater have some particularities which make them a special issue. The scientific literature shows us that the studies of explosives, of explosions and their effects have been increased after Second World War.

Like many other issues, underwater explosions are very closed by the progress made in investigated possibilities (specially numerical and experimental ways). In this context, the present paper comes to us with a new numerical method, very fitted and efficient one in fluid mechanics. It is about the free particles method with its version Smoothed Particle Hydrodynamics (SPH) method.

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Ro. J. Techn. Sci. – Appl. Mechanics, Vol. 61, N° 1, pp. 89–107 , Bucharest, 2016

2. PARTICULARITIES OF UNDER WATER EXPLOSIONS

Chemical transformation of the explosive, from solid state in gas state, in a underwater detonation, makes a gas bubble which remains confined by water on all sides. The high pressure inside the bubble, together the water with its hydrostatic pressure and moving mass make an oscillating system, having the pressure peaks in water and in bubble too.

What happens inside the explosive is the subject of detonation theory. The parameters and detonation phenomena can be modeled and quantified by empirical formulas and by numerical simulation. What happens in the water surrounding the explosive represents the subject of explosion theory or blast wave theory.

The parameters and the effects of an underwater explosion present characteristics quite different from an air explosion or a land surface explosion. Some aspects are similarly; for instance (Fig. 1), the variation of the pressure in time, in a point somewhere in water has an exponential variation [2, 12].

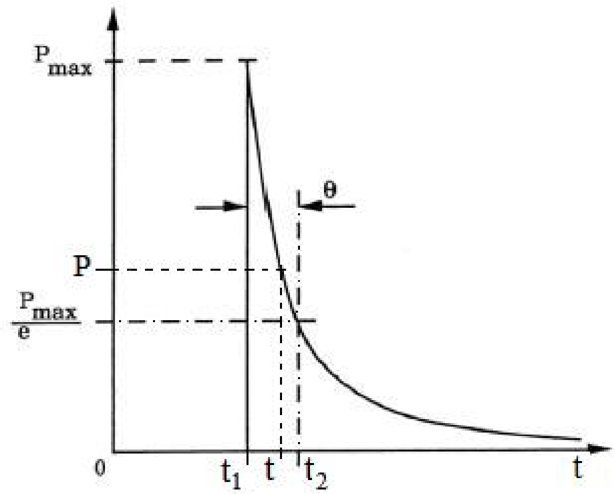


Fig. 1 – Time variation of pressure in an underwater point.

Some parameters, maximum pressure $P_{\max}$ [psi], decay constant θ [msec], time pressure $P(t)$ [psi], the total energy E_T [ft*lbf] at the specified standoff distance R [ft] and others, can be calculated by formulas using empirical parameters. Here are such formulas [1, 12]:

$$P_{\max} = K_1 \left(\frac{W^{\frac{1}{3}}}{R} \right)^{A_1}, \tag{1}$$

$$\theta = K_2 W^{\frac{1}{3}} \left(\frac{W^{\frac{1}{3}}}{R} \right)^{A_2}, \tag{2}$$

$$P(t) = P_{\max} e^{-\frac{t-t_1}{\theta}}, \tag{3}$$

$$E_T = 4\pi K_4 W \left(\frac{W^{\frac{1}{3}}}{R} \right)^{A_4 - 2}. \tag{4}$$

In the relation (1–4), W[lb] is the explosive mass, the constants $K_1 ... K_4$, A_1, A_2 and A_4 have the values depending on explosive type. Passing to metric unit system can be easily made for final result, knowing the relations between those two systems. Each of bubble oscillations transmits a secondary pressure pulse in the surrounding water, but the bubble pulsation generates considerably lower pressure than the first shock. Figure 2 presents gas babble time evolution [1, 12, 14].

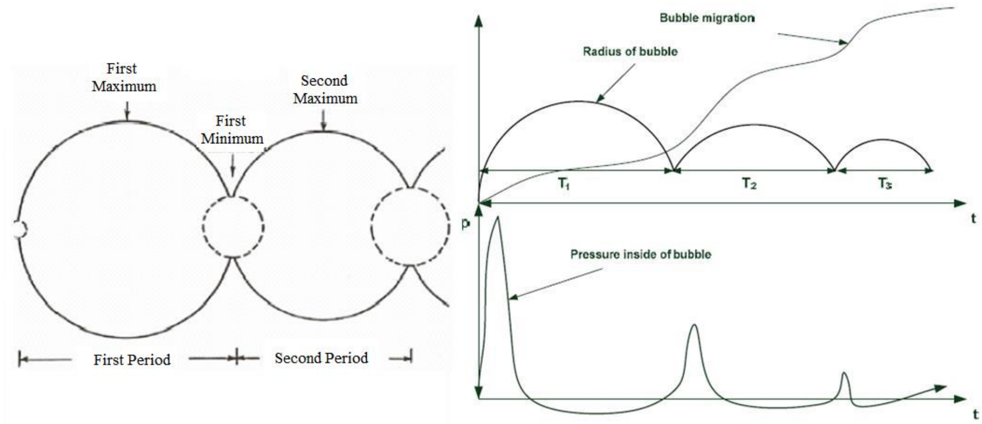


Fig. 2 – Gas bubble oscillations.

The pressure and the positive impulse, generated by bubble oscillations vary in time and they depend on charge weight W, range R and depth D. Most important aspect which has the most important effect upon a submerged structure is first peak pressure.

Also, other conditions like reflection phenomenon generated by the rigid walls (navigation channels), by the free water surface or by the bottom, could significantly influence the peak pressure and finally the explosion effects upon an under water structure.

The first period T [s], or the time taken to reach the first bubble-radius minimum and the maximum bubble radius $r_{\max}$ [ft], can be calculated with relations (5) and (6), where D [ft] is the depth of explosion and constants K_5 and K_6 depend on charge type.

$$T = K_5 \frac{W^{\frac{1}{3}}}{(D+33)^{\frac{5}{6}}}, \tag{5}$$

$$r_{\max} = K_6 \frac{W^{\frac{1}{3}}}{(D+33)^{\frac{1}{3}}}. \tag{6}$$

All these relations are true only for distances 10 to 100 times the explosive radii away from the detonation point and also only for a duration of up to one decay constant (θ) after detonation initialization.

A rigid surface reflections generate compression waves and water free surface reflections generate rarefaction waves, which superimpose on the original shock wave. These rarefaction waves represent physical support of the cavitations phenomenon which occurs near the water free surface in some conditions.

The effect of water free surface caused by the reflection phenomenon can be watched in Fig. 3 [12]. This figure presents a geometrical calculus model for cavitation phenomenon, also present in underwater explosions.

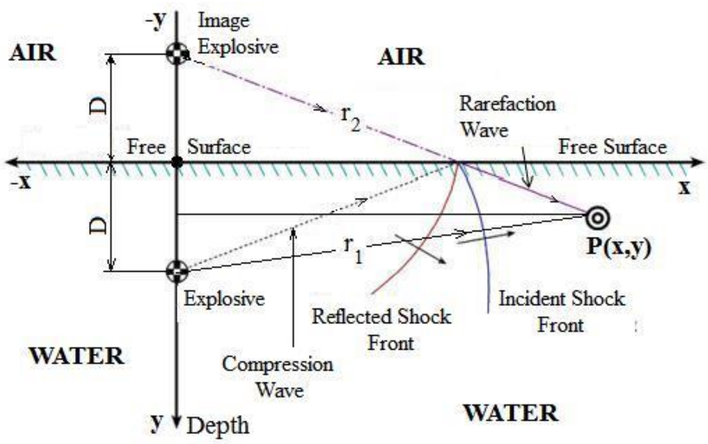


Fig. 3 – Reflection of the blast wave at the water free surface level.

Cavitation phenomenon occurs in a fluid, when a negative pressure exists.

This pressure state can be in a point (local cavitation), or in many other points representing a volume (bulk cavitation). A fluid, like water, is compatible with a compression wave, but it is incompatible with a rarefaction wave, because a negative pressure causes a tensile force.

A fluid cannot sustain such a force, and so cavitation is formed, consisting in appearing of vapor bubble, which will collapse, leading to a water hammer (effect) which sends out a pressure wave (cavitation pulse). If the point of closure of the cavitation region lies close to the hull of a ship, then a reloading may occur.

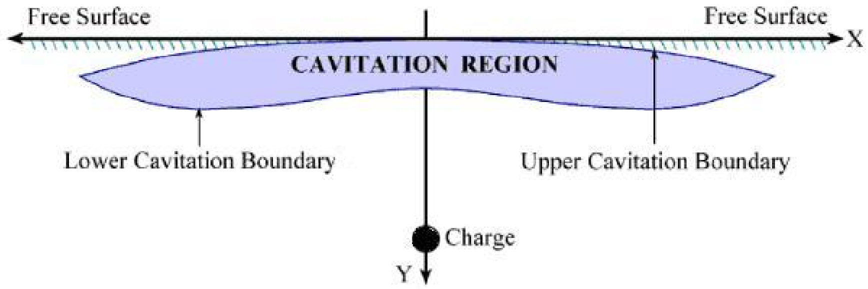


Fig. 4 – A plane general aspect of bulk cavitation.

A shock wave propagates in a spherical enlarging circle from the charge detonation point, so the cavitation region has to be understood as a volume, axis-symmetric towards *Y* axis.

The technical literature regarding underwater explosions gives the relations and methodologies for calculus and graphical representing of the upper and lower boundaries. More about cavitation caused by an underwater explosion are beyond the aim of this paper [12, 14].

3. TYPES OF UNDER WATER EXPLOSIONS

Generally, an under water explosion is an explosion having the detonation point below the surface of the water. By experiment and even by numerical and just analytical studies, explosion developing and specially its effects depend on the water depth at which detonation occurs.

Two main under water explosion types exist (shallow and deep) and these are so classified by empirical relation (Le Méhauté and Wang, 1995); if $d/W^{1/3} < 1$, a shallow explosion occurs and if $d/W^{1/3} > 16$, a deep explosion takes place. In these relations, d is the explosive position (depth) to the free surface (expressed in feet) and W is the mass of the explosive (in pounds), for TNT. For other explosives the equivalence relations have to be used.

For a ***surface explosion***, the gas bubble vents to the atmosphere, so no subsequent bubble oscillations exist. By the first gas bubble, the explosion energy is transmitted to the water and the reflection of the shock wave from the free surface is not a very important one by effects. On the other hand, a substantial attenuation of the pressure and positive impulse occurs.

The most important blast wave front is developed above the free surface, and the effects appear both above and bellow the free surface. A characteristic phenomenon is the crater formed at the water surface, which is large one, comparatively with the depth of the explosion, and a hollow water column.

In the case of a ***deep underwater explosion***, much more explosion energy is delivered to the water, so the heights of the water free surface waves can be significantly by height and volume, being able to damage coastal areas, next to the damages of an underwater structure.

In underwater explosion (especially deep explosion) the gas bubble (sphere of gas with high temperature and pressure) interacts with the surrounding water (fluid) in two different phases.

The first phase is characterized by a transient shock wave, which causes a rapid change of the fluid velocity and a large inertial loading. Also, the peak pressure is very high, but its duration is very short.

The second phase is represented by a radial pulsation of the gas bubble. The oscillations of the gas bubble are repeated for a number of cycles (ten or more).

The period of the bubble pulsations is very long comparatively with the shock wave period and pulsation duration is long enough for the gravity force to become effective. So, such a gas bubble appears to have a great buoyancy and migrates upwards in time. Its buoyancy, its floating up is not compared with a balloon, because the gas bubble goes upward in jumps.

4. DAMAGE MECHANISMS BY UNDERWATER EXPLOSION

An underwater explosion may cause serious damages upon nearby immersed structures. The water, being much less compressible than air, the same amount of explosive can produce greater damages. There are three damage mechanisms of an immersed structure.

The first damaging mechanism is based on high pressure. Just after the detonation, a shock wave appears together with the high pressure gas bubble which is expanding. The shock wave moves at very high speed, generating very high pressure. When this shock wave will hit the structure, the first damaging mechanism begins. This mechanism is the main one.

The second damaging mechanism is known as whipping effect. This is a result of the gas bubble oscillations, when large water accounts are moving, all these meaning pressure variations applied to a structure. If the frequency of the bubble oscillation matches the eigen-frequency of the structure a so-called "whipping" effect occur, which represents the second damaging mechanism.

The third damaging mechanism or "jet impact" occur in the collapse phase of an immersed structure. As the gas bubble goes to a structure and this is touched, a high speed water jet traverses the bubble and impact the structure. Such a phenomenon is known as third damaging mechanism or jet impact mechanism, which can develop or amplify the damages.

5. PROBLEM FORMULATION

The main aspects, regarding an underwater explosion, solved by SPH method, will be presented for a problem consisting in an underwater pipe (it could be: empty, oil pipeline, or gas conduit) with a diameter of 1 m, which pass through a channel (with rigid walls) full of water. The influence of the atmosphere is neglected and the pipe is empty. The problem sketch is presented in Fig. 5.

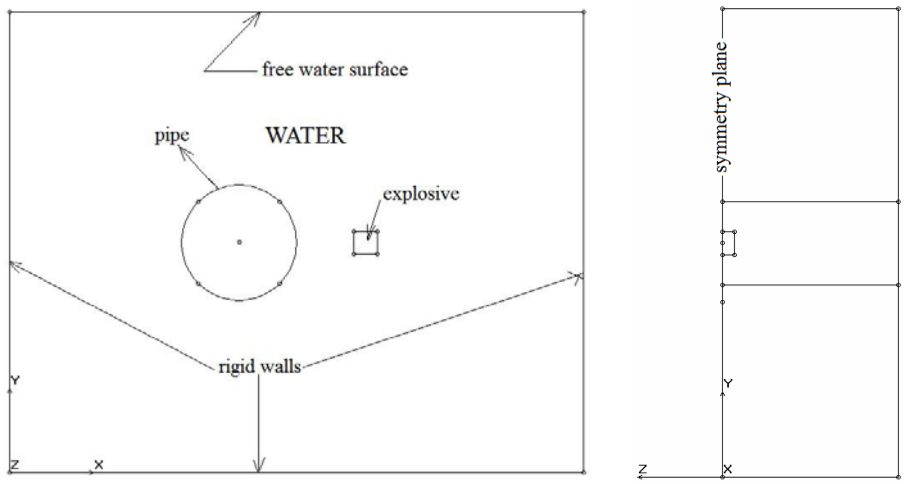


Fig. 5 – The problem sketch.

The channel has the dimensions 4 × 5 × 3 m; the pipe has the wall thickness of 0.01 m and its center placed at 2 m from bottom and from a rigid wall. At this level a charge of TNT with dimensions 0.2 × 0.2 × 0.2 m (cubic shape, 13.04 kg) at a 0.50 m distance towards the pipe exist.

There is a symmetry plan, so the problem dimension becomes 4×5×1.5 m, as we can see in the above figure and the TNT mass is only 6.52 kg. The constraints applied to all nodes belonging to this plane consist in requirement that all these nodes to remain in the symmetry plan (UZ = 0).

The main aim of the numerical analysis consist in evaluation of the explosion effects upon the pipe; next to it, the numerical analysis has to make a quantitative evaluation of some explosion parameters, including some aspects regarding cavitation phenomena.

6. THE NUMERICAL MODEL OF THIS PROBLEM

The numerical model uses shell finite elements for modeling of the pipe and free particles for explosive and water modeling. So, the numerical solving of the problem uses in the same time those two methods: FEM and SPH.

The adopted numerical model of the problem is presented in Fig. 6.

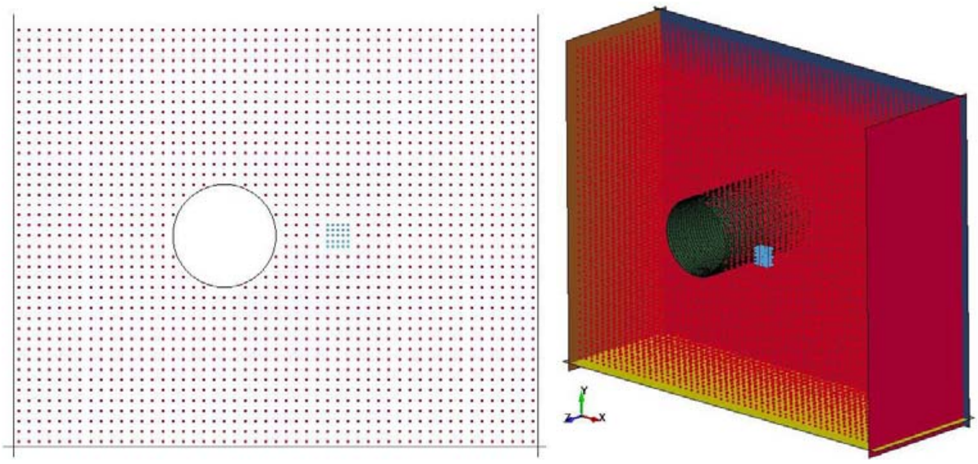


Fig. 6 – The numerical analysis model.

The model version presented above, consist in 32 014 particles of water, 75 particles of explosive and 3 600 shell elements with 3 720 nodes for pipe. In this version of the mesh, the distance between nodes was 0.10 m and the shell side length was 0.05 m.

According with the main aim, watched in this study, the computing time was established from condition that wave front does not touch the channel walls (for avoiding the effects of reflected waves).

For watching of the gas bubble evolution or of the water state, an analysis time much larger one would have been adopted.

As the material model is concerned, for water, MAT_NULL material model with a LINEAR_POLYNOMIAL equation of state (EOS) was used; for explosive, HIGH_EXPLOSIVE_BURN material model was used with Jones-Wilkens-Lee-Baker (JWLB) equation of state; for pipe, PLASTIC_KINEMATIC material model was used. All these material models are those implemented in Ls-Dyna material library. The ignition point was the middle of the explosive.

7. RESULTS

A first investigated aspect was referring to the bulk cavitation, for to know if the structure is found or not in that area. Using the relations and procedure, presented in technical literature [8], and by an original computing way, the result is that presented in Fig. 7, which shows that the pipe is outside of the bulk cavitation.

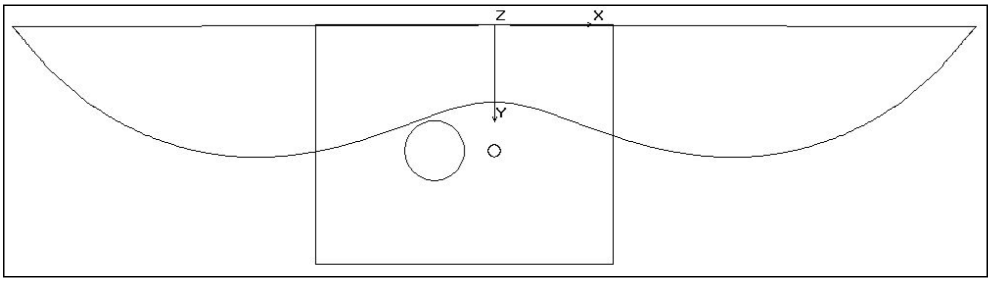


Fig. 7 – The structure position towards the bulk cavitation area.

The dimensions of the bulk cavitation area, in the case of given problem, can be seen in Fig. 8. The grid dimension is 0.10 m and the points 83 (x = 8.08 m, y = 0.025 m) and 26 (x = 3.962 m, y = 2.21 m), by their coordinates, show the overall dimensions.

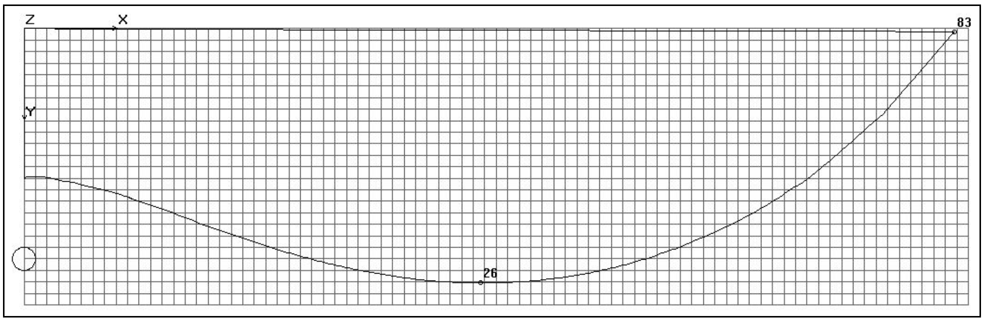
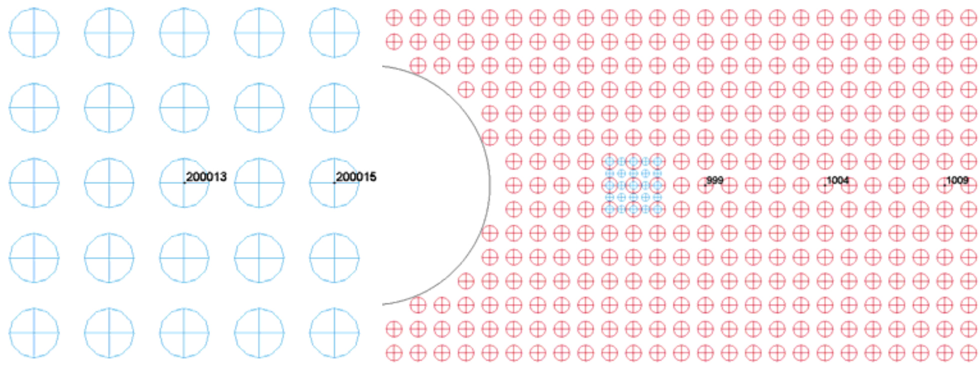


Fig. 8 – The dimensions of the bulk cavitation area.

The evolution of the gas bubble, during computing time ($4\cdot10^{-3}$ s), is presented in the Figs. 11–13.

So, Fig. 9 shows the particles taken into account for numerical analysis of the pressure, in TNT (Fig. 9a), respectively in water (Fig. 9b).

In Fig. 10, the variation in time of the pressure, inside the explosive (detonation pressure), is presented. Those two particles are placed in the middle of explosive (Particle No. 200 013) and at the explosive boundary (Particle No. 200 015), at the contact with the water. If the maximum pressure is approximately the same, in time, the pressure inside the gas bubble is different from a point to other point, but without important time variation. The pressure in gas bubble is greater at its boundary. The values, obtained by numerical analysis, are comparable to those in the technical literature.



a) *b)*

Fig. 9 – The particles taken into account for analysis of some parameters (symmetry plane).

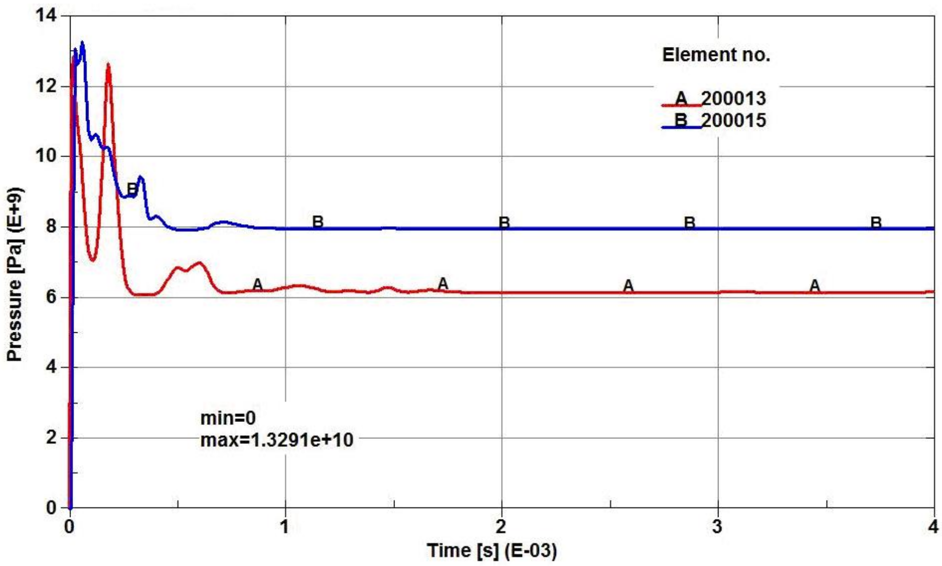


Fig. 10 – Pressure time variation for two TNT particles.

The variation of the pressure in the center of gas bubble (curve B in Fig. 10) can be explained by many reasons, but the main cause is the appearing of that oscillating system (gas bubble and water).

Figure 11 presents comparatively, the initial dimensions of the charge (Fig. 11-a) and the dimensions of the gas bubble after 0.004 seconds (Fig. 11b).

The variation in time of the distances, presented in Fig. 11b, put in evidence variation in time of the gas bubble dimensions, or in other words, the existing of that oscillating system with two components: gas bubble and water.

In Figs. 12 and 13, the variations in time. of the distance betweeen particles 200 011 and 200 015, along *x*-axis, respectively *y*-axis, are presented.

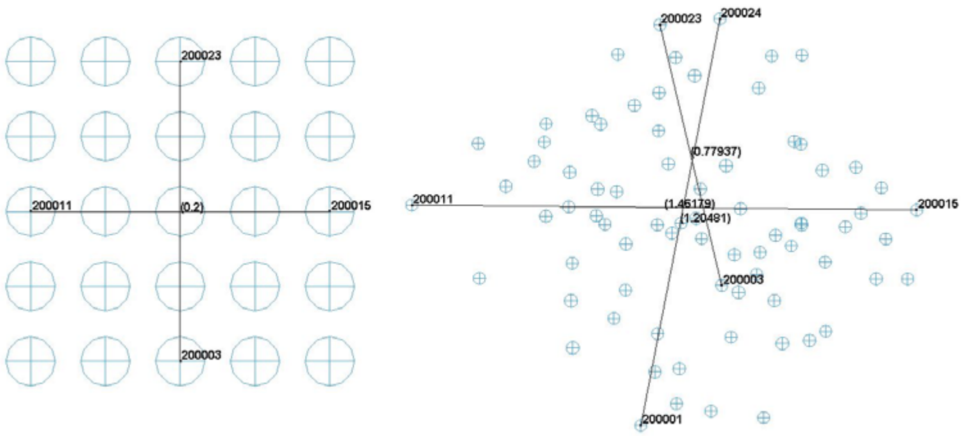


Fig. 11 – Developing of the gas bubble after 4 milliseconds.

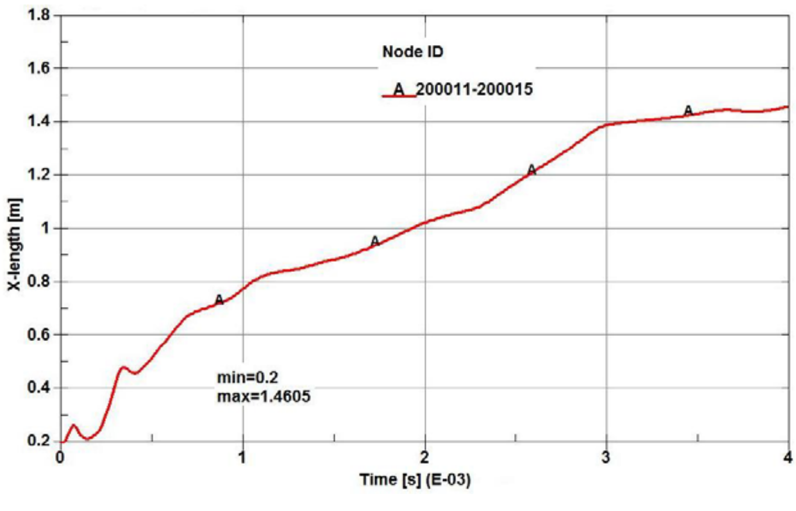


Fig. 12 – Time variation of the *X*-distance between those two particles.

The distance evolution between particles, presented in Figs. 12 and 13 shows us the phenomenon of dimension variation of the gas bubble, as a result of oscillating system working.

The pressure evolution in water (particles 999, 1004 and 1009, Fig. 9b) is presented in Fig. 14.

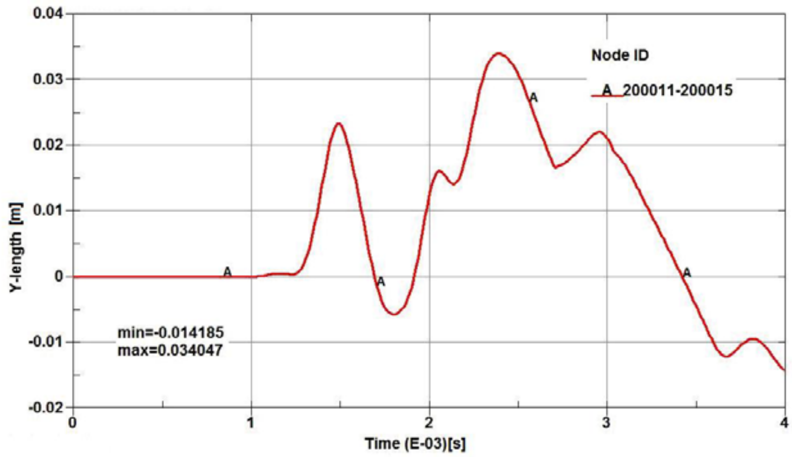


Fig. 13 – Time variation of the particle distance along *y*-axis (vertical direction).

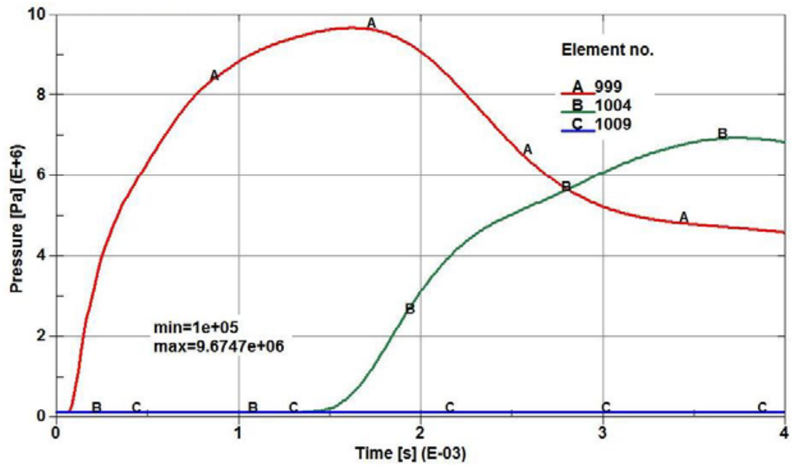


Fig. 14 – Time evolution of pressure for three water particles.

After detonation occurring, the positions of the particles begin to change. The curves A, B and C begin the evolution at different time, function of the distance towards the charge. The nearest one (particle A) has the maximum pressure value. The farthest particle (1 009), during analysis time (4 ms), is loaded only by the hydrostatic pressure (10^5 Pa).

In Fig. 15, the resultant (total) displacements in time, of those three particles, are presented. Figure 16 shows the particle velocities along *x*-axis. Analyzing these two figures, we can see that the particles have significant movements and they have significant velocities.

As particle 1009 is concerned, this begin its displacement much later (after 3 ms). All these observations, which are not completely, highlight the water movement as a result of the blast wave.

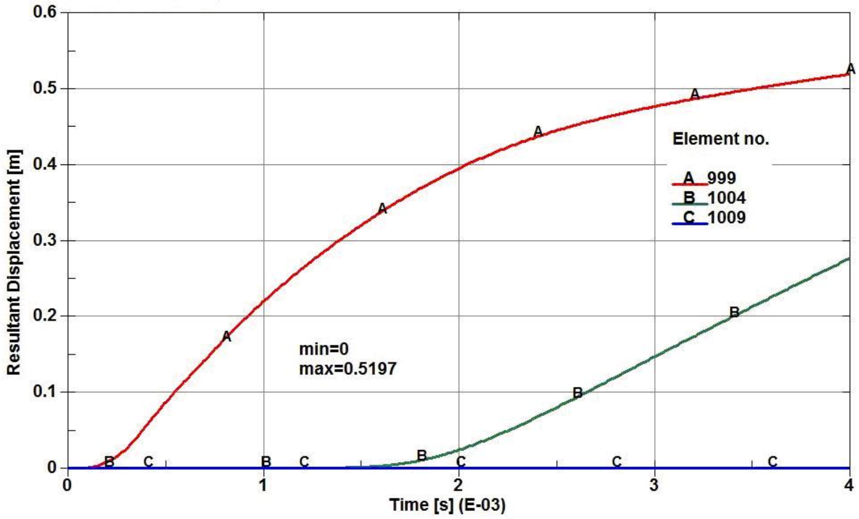


Fig. 15 – Resultant displacements of those three particles, in time.

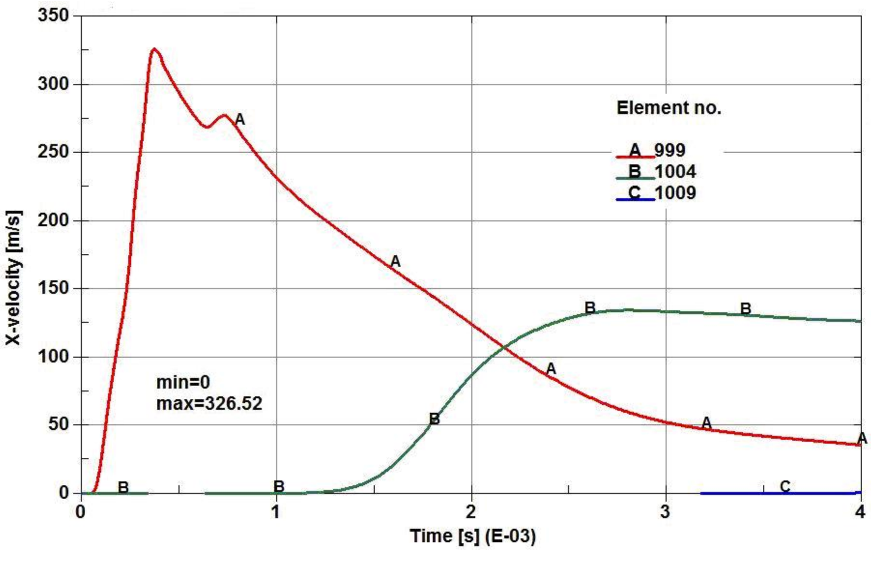


Fig. 16 – The particle *X*-velocities during analysis time.

The dynamic state of water, after explosion, can be evaluated by velocity field representation (Fig. 17). For this short analysis time, the water state has a strong local perturbation.

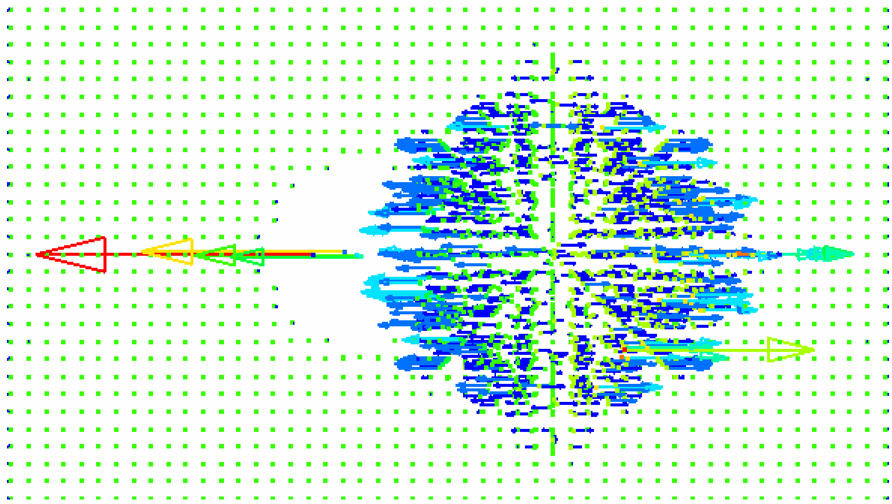
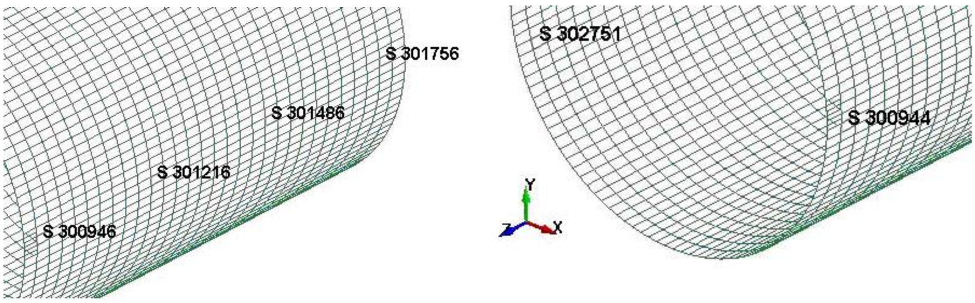


Fig. 17 – Velocity vector field along *X*-axis at 0.004 se (very different speeds in both directions; some particles have already penetrated into the pipeline because this was fractured – Fig. 23).

Velocity field shows the dynamics of water particles at each moment. At the time 0.004 s, a strong water perturbation occurred, which loaded the pipe.

The numerical model, based on SPH method, allow the evaluation of the explosive effects upon the pipe too.



a) *b)*

Fig. 18 – The analyzed shell finite elements of pipe.

In Fig. 19, the time evolution of the pressure, applied to the finite element selected in Fig. 18a, is presented. The nearest finite elements are most loaded, but for all of them the pressure has oscillations with changing the sign. Beyond the dynamic aspect, the curves indicate the possibility of local cavitation appearing.

Similar observations can be made, comparatively, for two finite elements (Fig. 20), like those selected in Fig. 18b. As expected the pipeline side from explosive is much more loaded.

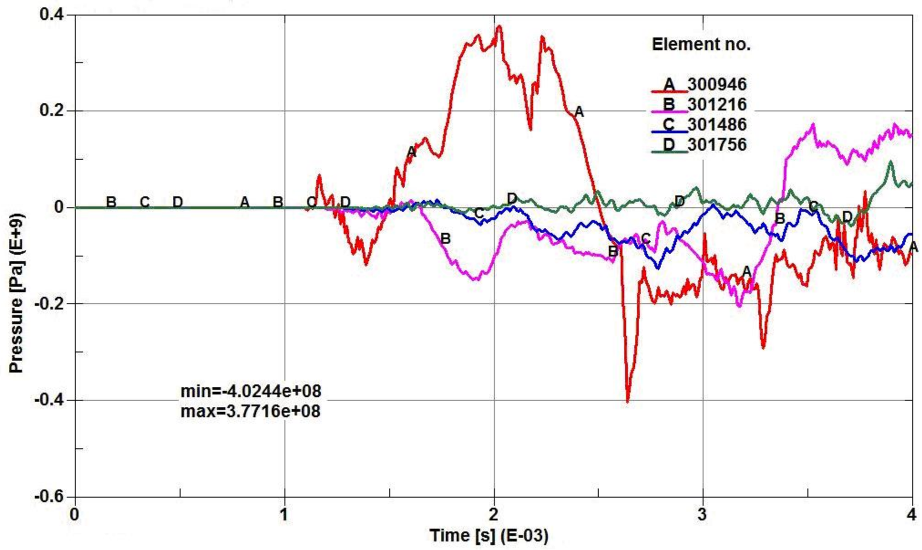


Fig. 19 – Dynamic pressure applied to finite elements (Fig. 17a).

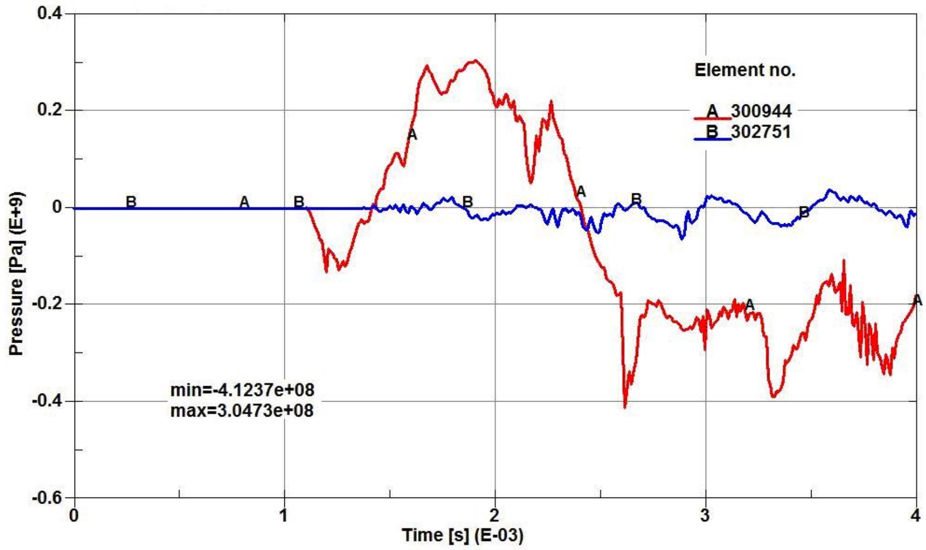


Fig. 20 – Dynamic pressure applied to those two finite elements (Fig. 18b).

The *x*-displacements, for those elements 300 944 and 302 751, are quite and significantly different. The *x*-displacement of the element 300 944 (Fig. 21) is a large and about linearity one.

The *x*-displacement of the element 302 751 (Fig. 22) is much smaller and strong oscillatory. Also, it is seen, both as pressure and *x*-displacement, for finite analyzed elements, that the starting time of evolution curves is different.

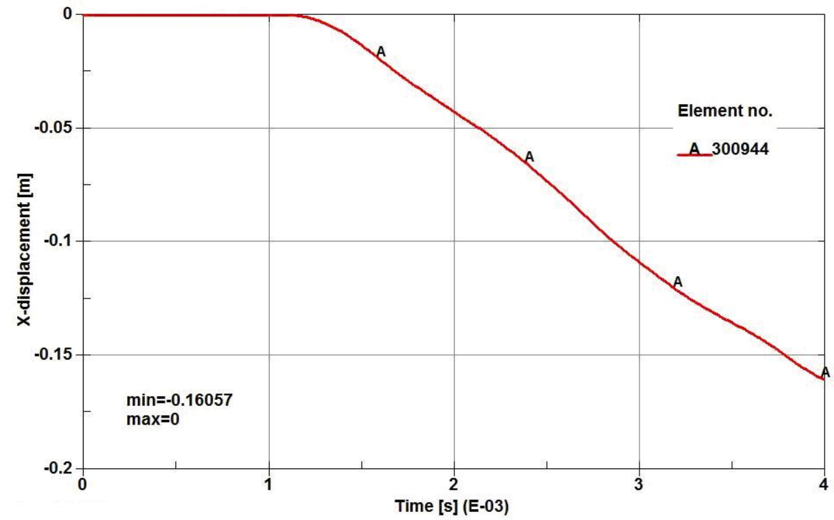


Fig. 21 – The *x*-displacement of the finite element 300 944.

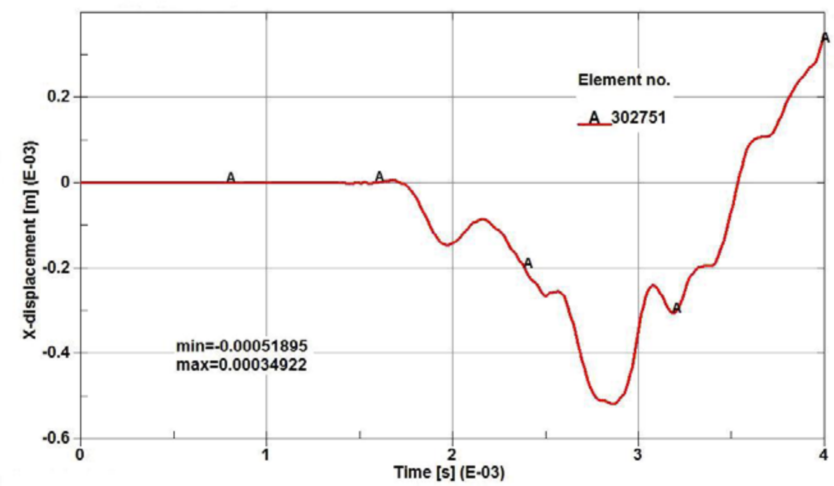


Fig. 22 – The *x*-displacement of the finite element 302 751.

As Fig. 23 shows, the pipeline damages are very important, the pipeline being, after explosion, unusable.

The most important damages occurred in the symmetry plan of the model, just *vis-à-vis* by explosive. The damages decrease along the pipeline, because the distance from explosive becomes longer. The pipeline was strongly deformed and it was perforated. Surely, after a longer analysis time, the damages could have been more, but not as significant.

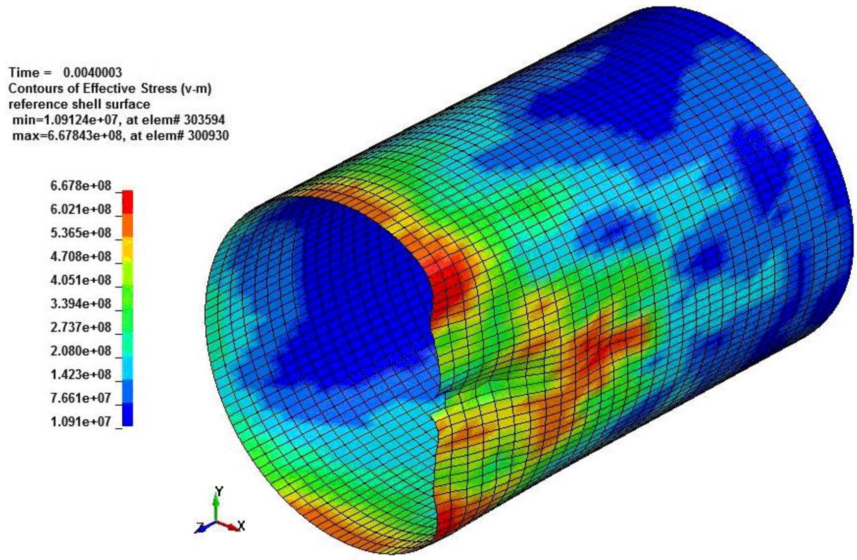


Fig. 23 – Von Mises stress field on deformed shape of pipe at 4 ms after explosion initiation.

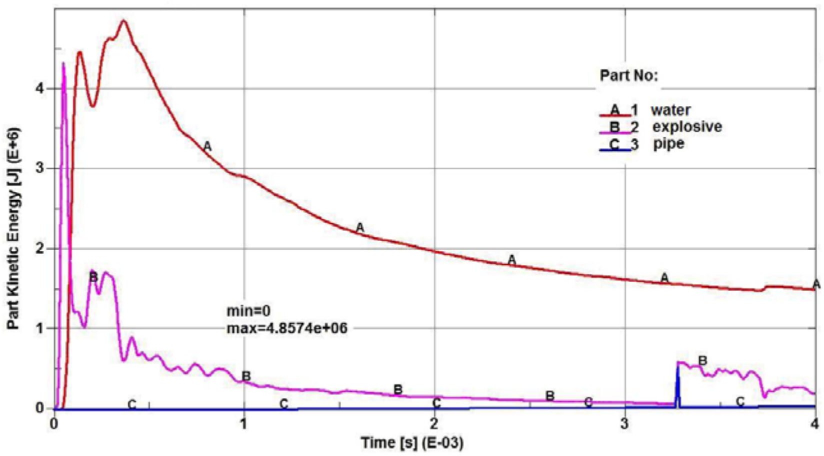


Fig. 24 – Kinetic energy absorbed by those three components.

The aspects presented in this paper and surely not all, produced by an underwater explosion, has one energetic source: the explosive by its detonation.

By this reason could be interesting an energetic balance. How the energy was absorbed by those three components (water, explosive, structure) can be watched in Fig. 24, referring to the kinetic energy. This is important in connection with dynamic phenomena. The largest amount of energy is absorbed by water, then by explosive and the smallest amount of energy is absorbed by the pipeline.

The moment of pipeline perforation with its consequences is reflected in Fig. 24 by allure of curve C.

8. CONCLUSIONS

Using of the SPH method, beyond the fact that it is theoretically and practically validated for fluid mechanics, brings to its users a great advantage: automatically solving of the fluid-structure interaction. Only with one running, we can know a lot about all those three model parts (water, explosive, structure).

Analysis time can be calibrated as function of what is interesting for user. Surely, SPH method will be required more and more in applied mechanics, in solving of most complicated systems.

The reader will find out many conclusions, depending on its proper aims. Our paper is an urge to use the SPH method, especially for Romanian researchers, offering an available numerical model, an approaching way of such a subject and some interpretations of the results.

Received on March 17, 2016

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