Numerical Simulation of Fluid-Structure Interaction and its Application in Impact of Low-Velocity Projectiles with Water Surface

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Abstract: In this article, finite element method and ALE formulation were used to numerically simulate impact of low-velocity specific projectiles with water surface. For the purpose of simulation, Ls-Dyna finite element code was used. Material models which were used to express behavior of air and water included Null material model, where for the projectile, rigid material model was applied. Mie-Gruneisen equation of state was also attributed to air and water. First, the results were validated by analyzing the impact of metallic cylinder with water surface and then impact of a mine as a low-velocity projectile was simulated. Among major outputs were force and pressure applied to the projectile, velocity and acceleration variations upon entering water, stress-strain variations and variations of water surface in various steps of analysis. The results confirmed that the impact of structure with fluid can be modeled using finite element model with high accuracy in terms of quality and quantity.

Keywords: ALE Formulation, Fluid-Structure Interaction, Finite Element Method

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1 INTRODUCTION

Studying hydrodynamic effect of a moving object and free water surface has various applications in fields such as aviation, landing of spacecraft in sea and impact of projectiles like rockets, missiles and mine-laying in sea. Analysis of this phenomenon is always accompanied by empirical experiments and, recently, various numerical simulations such as finite element. In case of using finite element method, these simulations should be conducted by special codes which provide the possibility of fluid and structure coupling with each other and the relevant codes are created based on Euler and Lagrange finite element methods, specifically for fluids. Critical points of this type of modeling include fluid and structure interaction (or coupling) algorithm and structural modeling of fluid. In 1995, Anghileri and Spizzical studied normal impact of a rigid sphere with water surface using finite element method and used certain experiments to gain variations in acceleration of sphere during impact in order to verify the applied numerical method [1]. Their results were in good agreement with the experimental data. In 2000, Korobkin and Ohkusu performed an interesting research on hydro-elastic coupling of finite element model using Wagner's theory for issue of impact with water [2]. The aim of this research was to measure direct coupling possibility of finite element method for structural part with a state of Wagner's theory about hydrodynamic loads during impact of an elastic object with water surface. In this research, an efficient and proper method was presented and verified in two-dimensional state. Application of this method was low for each elastic object with dead angle.

In 2003, Battistin and Iafrati conducted a numerical study on normal entry into water of a two-dimensional symmetrical or asymmetrical object with a desirable form [3]. This study was conducted considering potential flow of a non-compressible fluid by ignoring effects of gravity and adhesion. In this work, simulation was done by boundary element method; and boundary conditions of free surface were fully non-linear. The concentration of this investigation was on evaluating pressure distribution and overall hydrodynamic load applied to the colliding body. They verified the results for cylinder, sphere and cone forms [3].

In 2003, Park et al., [4] presented a numerical method for calculating impact and buckling forces of objects which quickly entered water. By neglecting fluid viscosity, potential flow was assumed to be non-viscose. This assumption greatly reduced computational time while solution accuracy was preserved by considering non-linear free surface conditions. Park et al., [4] solved this issue using source panel method, in which an object is divided to panel or elements and each panel can be fully floating, partially floating or fully out of water. The results were compared with the laboratory data and valuable results were obtained. In 2004, a thesis was performed by Roe at MIT University in which impact with water of a submarine called REMSAUV was numerically and experimentally analyzed [5]. In this project, finite element method was used to create the simplified model of REMUS and source panel method which was proposed by Dr. Kim at the same university was applied to calculate the added mass. Experimental impact tests were conducted with a specially-instrumented test vehicle to verify the initial impact acceleration calculations, and good agreement was observed for the nearly vertical values of pitch at which the experiment and the model accurately represent the same physical processes.

In 2005, a thesis entitled “Numerical study of impact with water loads of marine structures" was conducted by Kleefsman under support of European Union. In this thesis, a computer program called COMFLOW was used, in which Navier–Stokes equations, which describe non-compressible viscous fluid, were solved [6]. One of the most well-known models for free surface simulation is volume of fluid (VoF) method which was used in this thesis. In 2008, Tveitnes and Fairlie-Clarke conducted a research on impact of wedge-shaped parts with water surface at constant velocity [7]. In their study, computational fluid dynamics (CFD) analysis was used to determine momentum of added mass, momentum of flow and gravity effects during entry of wedge-shaped objects at constant velocity and dead angle of 5 to 45 degrees into water. Numerical solution method which was done by Fluent software was a finite volume method, which solved equations of mass conservation and momentum to obtain flow field. Hydrodynamic forces were not significantly changed by the effect of gravity on the flow fields. A high order boundary element method was developed for the complex velocity potential problem by Wu [8]. His method ensures not only the continuity of the potential at the nodes of each element but also the velocity, where it can be applied to a variety of velocity potential problems. His paper, however, focused on its application to the problem of water entry of a wedge with varying speed. The continuity of the velocity achieved herein was particularly important for this kind of nonlinear free surface flow problem, because when the time stepping method is used, the free surface is updated through the velocity obtained at each node and the accuracy of the velocity is therefore crucial. In this paper, using finite element code (Ls-Dyna), impact of low-velocity specific projectiles with water surface has been simulated.

2 FINITE ELEMENT METHODS

In analyses of structure impact with water surface, various methods such as Lagrange, Euler or arbitrary Lagrangian Eulerian (ALE) were used. In finite element analysis, movement of all particles of an object from their initial situations to final configuration is considered using Lagrangian formulation. Lagrangian formulation for movement of a body in a fixed Cartesian coordinate system is based on the assumption that an object can have large displacements, large strains and a non-linear adaptive response. While analyzing object impact with water, the colliding object and water can be modeled using Lagrangian method. In case of water modeling using Lagrangian method, when material mass is stored in a defined element in Lagrangian formulation, water mesh is affected by upper deformation during impact due to penetration of the colliding object where results in remarkable increase in time step [9], [10].

In Eulerian formulation, concentration is on a constant control volume which is used to measure equilibrium and mass continuity of fluid particles. In Eulerian formulation, an independent equation is used to state volume conservation. Moreover, inertial forces consist of convective terms, which lead to a matrix with asymmetrical coefficients in numerical solution and depend on the calculated velocities. Eulerian formulation provides the possibility of using simple stress and strain sizes; so, instead of displacement values (in extremely small displacement analysis), it is required to calculate velocities.

In arbitrary Lagrangian Eulerian method (ALE), since a matter flows through a mesh which is completely fixed in space, there is the possibility for each element to be a combination of various materials. In this method, element deformation is fully prevented and Eulerian-Lagrangian coupling algorithm can be used to define movement of some parts of Lagrangian formulation model. By transferring, rotating and deforming multi-material mesh using a controllable method, mass flux of elements can be minimized and mesh size can be kept smaller than Eulerian model (as shown in Fig. 1). ALE mesh is compatible with situation and form of the colliding object during its deformation.

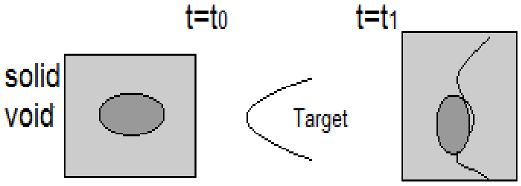


Fig. 1 Motion of AlE mesh in impact simulation [10]

An ALE formulation consists of a Lagrangian time step which is followed by an advection step. This time step performs incremental rezone which refers to the fact that position of the nodes is only displaced as much as a small fraction of characteristic lengths of the adjacent elements. In contrast to manual rezone, topology of the studied mesh in an ALE formulation is constant. An ALE calculation can be implemented in case a completely new mesh is needed for continuing the calculation. Cost of implementing advection step in element is usually much more than the cost of the Lagrangian step.

A major part of implementing advection step is spent on calculating transferred materials among adjacent elements and only a small part of it is spent on calculating manner and location of mesh adjustment. Uniform advection algorithms with second-order accuracy, in spite of their high costs in elements, are generally used in software. Therefore, possibility of precise calculation in coarser meshes and consequently possibility of calculating by much farther elements are provided in comparison with the algorithm with first-order accuracy. The simplest strategy for minimizing computational cost of ALE is through their implementation only in very small time steps [11].

3 SIMULATING IMPACT OF METAL CYLINDER ON WATER SURFACE AND VALIDATING THE RESULTS

3-1- Finite Element Modeling

Finite element simulation was done in three general stages using main components of LS-DYNA code. The first stage of model construction was done using internal pre-processor of FEMB (finite element modeling builder) or another modeling builder such as hypermesh. The second stage was non-linear dynamic analysis and the final one was post-processing the analysis results using Post-GL processor, code LS-DYNA, for interpreting the calculated data. Details related to specific techniques of modeling required for presenting an efficient finite element model on parameters are: 1) presenting finite element model, types and properties of elements for various model parts, 2) making and allocating material properties, 3) defining equations of state, 4) defining boundary and initial conditions, 5) defining type and contact interfaces and 6) defining control parameters.

3.2. Describing Geometry and Finite Element Model

In simulating impact of cylinder with water, a cylinder with diameter of 5.5 meter and length of 2 meter impacted on water from distance of 15 cm. Geometry of water and air was as follows: water had length of

275 meter, width of 110 meter and height of 2 meter. Air had length of 110 meter, width of 110 meter and height of 2 meter. In modeling impact of structure with water surface, dimensions of finite element model of water and air in terms of width and length should be at least 8 times greater than those of the colliding object. Finite element modeling in this issue was conducted three-dimensionally using 8-node solid elements. Total number of the elements used in finite element model was 119550 and the number of nodes was equal to 134233. In this simulation, element classification of metal cylinder was done using three-dimensional solid elements with ELFORM 0. Water and air were also modeled using ALE (solid ALE) solid elements with ELFORM 12 (point integration with single material and void), where Fig. 2 shows finite element model related to cylinder, air and water.

3.3. Constitutive Equations of Material (Material models)

The constitutive equations are used to explain the behavior of the materials under environmental variations. In this article, rigid, null and plastic-kinematic material models have been employed for the metal cylinder, the air and water and the projectile respectively.

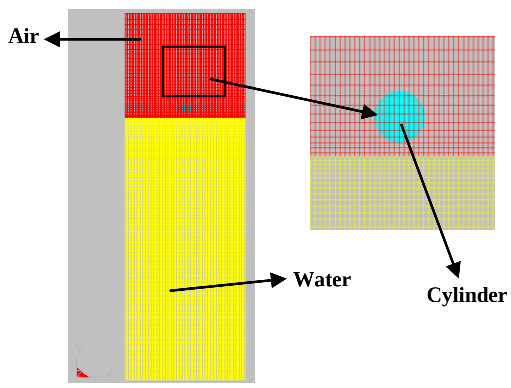


Fig. 2 Finite element model

3.3.1. Rigid Material Model

Rigid material model presents a simple method for combining one or more parts including beams, shells or solid elements in a rigid body. Two parts of unique rigid materials do not have common nodes unless they are merged using integration of rigid body. A rigid body can be made of discontinuous finite element meshes. If the rigid object is used in defining contact interface, in this case, Young's modulus, E, and Poisson's coefficient, υ are used to determine parameters of sliding interface. In this analysis, a metal cylinder was modeled using material model no. 20, where the properties used in this material model are demonstrated in Table 1.

Table 1 Material properties for metal cylinder [9]

Prop	ρ (Kg/m^3)	E (GPa)	υ	N	COUPLE	M
Value	7830	200	0.3	0.0	0.0	0

3.3.2. Null Material Model

In analyzing impact of metal cylinder with water surface, the surrounding air and water are modeled using Null material model. In modeling behavior of fluid against the solid body, it should be noted that deformation of the solid object is done based on gradient of displacement or strain; but, fluid deformation is conducted based on velocity gradient or strain rate. In other words, displacements are dependent variables in solid mechanics; but, in fluid mechanics, velocities are dependent variables. Null material model is used to state behavior of materials by semi-fluid deformations (air, water, etc.). This material model presents viscous stress in the material (viscous stress has the same characteristics as deviatoric stresses) [9].

$$\sigma_{ij}^{v} = \sigma'_{ij} = \mu \, \varepsilon'_{ij} \tag{1}$$

in which σ'_{ij} is deviatoric stresses, μ is fluid viscosity coefficient and ε'_{ij} is the rate of deviatoric strain. Deviatoric stresses can be calculated using the aforesaid equation. This material model requires an equation of state for determining pressure. By combining characteristic and equations of state, total tensions are estimated [9].

$$\sigma_{ij} = \sigma'_{ij} + \frac{1}{3}\sigma_{kk}\,\delta_{ij} = \mu\,\varepsilon'_{ij} + P\,\delta_{ij} \tag{2}$$

Where δ_{ij} is kronecker delta and P is hydrostatic pressure. The input requirements for this characteristic equation in stating behavior of fluid include coefficient of fluid viscosity, pressure cutoff and dependent volume (V/V_0) which is greater than unit for erosion in tension. Dependent volume (V/V_0) for erosion in pressure is smaller than unit by nature. In fact, behavior of the fluid can be approximately modeled using elastic equations and applying conditions and specific and suitable input coefficients. In Table 2, characteristics and constants of Null material model for water with which the metal cylinder impacts and in which it is sunk are mentioned.

Table 2 Null material properties for water [10]

Property	$\rho(Kg/m^3)$	P_c (MPa)	Mu (MPa.S)
Value	982.5	-10e10	0.858e-9

As shown in Fig. 2, air has surrounded metal cylinder and upper part of the water. Numerical simulation of air was also conducted using Null material model. Properties of the material model used in numerical simulation for air are given in Table 3.

Table 3 Null material properties for air [10]

Property	$\rho(Kg/m^3)$	Pc (Mpa)	Mu (MPa.S)
Value	1.2	-10e10	0.0

3.4. Equations of State

3.4.1. Mie-Gruneisen Equation of State

Mie-Gruneisen equation of state is one of the most important equations of state which is appropriate for liquid and solid materials. Similar to other equations of state, this equation of state expresses the relationship between pressure, density and energy. Equation of state for $\bar{\mu}>0$ means that the material is as follows while being compressed [9]:

$$P=\frac{\rho_0 C^2\bar{\mu}\left\{1+\left[1-(\gamma_0/2)\right]\bar{\mu}-(a/2)\,\bar{\mu}^2\right\}}{\left[1-(S_1-1)\,\bar{\mu}-S_2\dfrac{\bar{\mu}^2}{\bar{\mu}+1}-S_3\dfrac{\bar{\mu}^3}{(\bar{\mu}+1)^2}\right]}+(\gamma_0+a\,\bar{\mu})\,E \tag{3}$$

In case the material is expanded, then $\bar{\mu}<0$ and equation of state will be as shown below: [9]

$$P=\rho C^2\,\bar{\mu}+(\gamma_0+a\bar{\mu})E \tag{4}$$

In the aforesaid equations, S_1, S_2 and S_3 are the first, second and third coefficients of slope curve, U_S-U_P (U_S is velocity of shock wave and U_P is velocity of the particle, respectively). E is initial internal energy, V is dependent volume, a is volumetric correction coefficient, γ_0 is Gruneisen coefficient and C volumetric sound velocity or the amount of intercept of the curve U_S-U_P. $\bar{\mu}$ is stated as follows: [9]

$$\bar{\mu}=\left(\rho/\rho_0\right)-1 \tag{5}$$

Where ρ is current density and ρ_0 is initial density.

Table 4 Constants of Mie-Gruneisen equation of state for water and air [10]

	C(m/s)	S1	S2	S3	GAMA	A	E0
Water	164.7	1.921	-0.096	0	0.350	0	0.0
Air	343.7	0.0	0.0	0	1.40	0	0.0

3.5. Solution Method

In the analysis of cylinder impact with water surface, ALE solution method was considered. This method can be stated in two stages as follows: first, material in Lagrangian stage was deformed exactly like Lagrangian method. Then, Lagrangian elements were re-transferred or distributed inside the meshing network.

3.6. Constraints, Boundary and Initial Conditions

The initial condition governing this issue was that the initial velocity was 10 m/s, applied to all nodes of metal cylinder in the form of relevant PART. In this analysis, the relationship between air and water was confined by metal cylinder using CONSTRAINED_LAGRANGE_IN_SOLID constraint. Also, the metal cylinder, air and water in one part set were selected as SLAVE and MASTER, respectively. The selected coupling was of PENALTY COUPLING type and coupling direction was NORMAL DIRECTION, COMRESSION ONLY. Another selected initial condition in this simulation was selecting VOID initial condition for air.

3.7. Control Parameters

In issues such as impact and penetration of projectile or explosive loading on structures in which large deformations occur, value of time step Δt changes during simulation. Δt is defined as $\Delta t=\alpha\frac{l}{\upsilon}$ in which α is the scaling coefficient of time step that is usually assumed as a figure less than 0.9. In numerical analysis of cylinder impact with water surface, α was equal to 0.01. Total time interval was also 1200 ms and time step for designing graphic files was assumed 20 ms. Hourglass control parameter was also selected in all the analysis in order to prevent deformation modes of zero energy. Therefore, hourglass viscosity coefficient was equal to 0.1 and type of bulk viscosity was considered 1. Another important control parameter for this analysis was FSI control parameter, in which the value of OUTPUT INTERVAL was

5.0e-5. Other control parameters such as energy control and ALE can be selected as were presumed.

3.8. Results and Validation

In this section, outputs are first presented based on the simulation results and then they are validated.

3.8.1. Variations of Force versus Time and Validating the Results

In Fig. 3, force changes made by impact of cylinder with water surface are shown. As shown, upon the cylinder's impact with the expected water surface, its applied force suddenly increased and reached to about 8412 kN. Then, by sinking to water, the amount of force was reduced to 1000 kN and became almost constant. One of the fundamental parameters which can be considered in issues of structure to water impact as a criterion for evaluating results and quantitatively comparisons is the dimensionless parameter of slamming coefficient, C_S, defined as follows [12]:

$$C_s = \frac{F_s}{\rho R V^2} \tag{6}$$

in which F_S is slamming power, ρ is density of impact medium (water), R is radius of rigid cylinder and V is falling velocity (impact velocity) of the impacting cylinder.

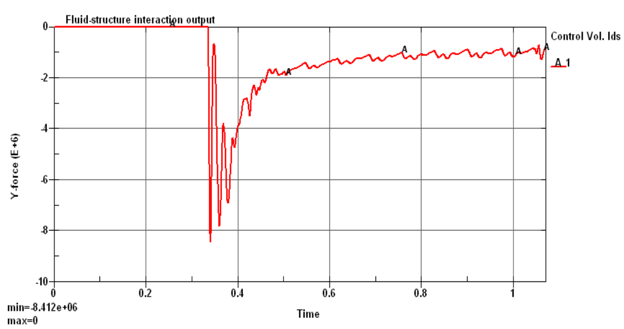


Fig. 3 Variations of force on cylinder in water entry

In Fig. 4, variations of slamming coefficient relative to parameter h/R (h has been shown in Fig. 5) are presented in four different diagrams in terms of numerical simulation using finite element method. Each of the drawn diagrams in Fig. 4 partly shows the variations of slamming coefficient relative to (h/R) variations. Curve A demonstrates variations of slamming coefficient relative to (h/R) in real situation. In curves B and C, maximum and minimum values of curve A are given next to the main curve. However, curve D which has interpolated a suitable curve for the variations using Harris model interpolation has values between maximum and minimum values. This diagram is the basis of quantitative comparisons in this section.

In the simulation conducted in this research, as demonstrated by the results of Fig. 4, the maximum and minimum values of slamming coefficient were about 6 and equal to 3.2 at the beginning of impact, respectively. Based on the curve fitted using Harris model, the maximum value was equal to 5. In Fig. 5, variations of slamming coefficient are shown using five different methods. Von Karman's theory estimates $C_S = \pi$ in the first contact whereas this value is $C_S = 2\pi$ for Wagner's theory. In the empirical data, slamming coefficient varied from $C_S = 5.5$ to $C_S = 6.5$ [12].

In Table 5, maximum and minimum values of six methods are compared with each other. In this table, the last row is related to finite element method and simulation was done using LS-DYNA software. As represented by the results in Table 5, there was good agreement between FEM method conducted in this research and other methods.

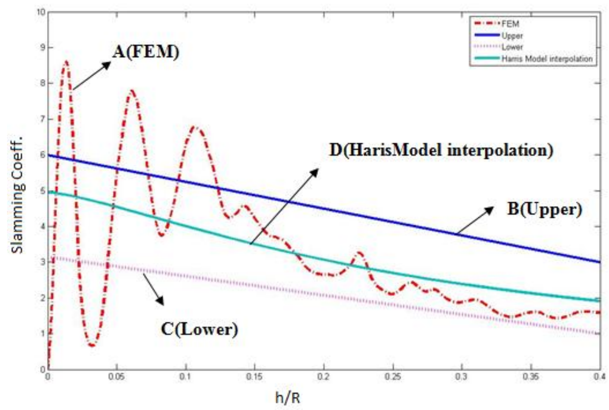


Fig. 4 Variation of slamming coefficient to (h/R)

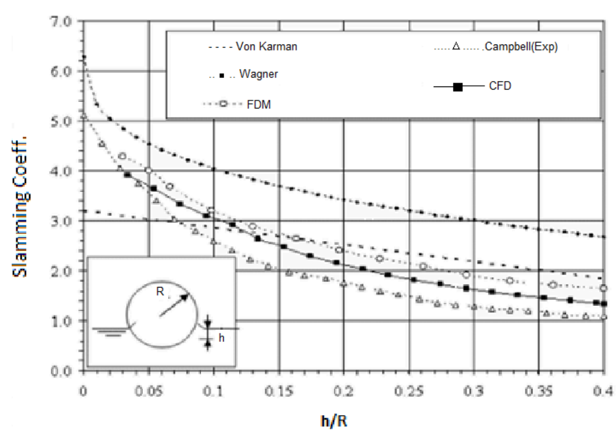
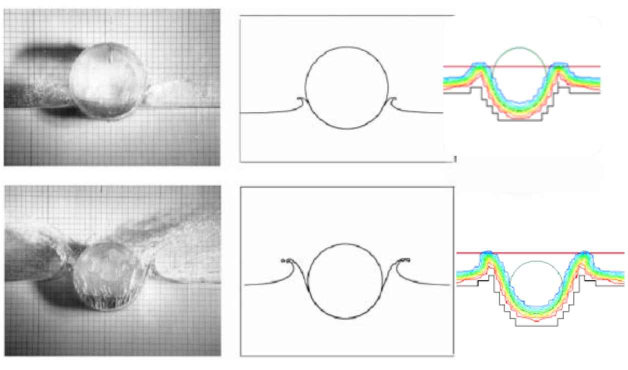


Fig. 5 Variation of slamming coefficient to (h/R) [13]

Table 5 Comparison of results between different methods in impact of cylinder with water surface

Method	Min C_S	Min (h/R)	Max C_S	Max (h/R)
Von Karman	1.9	0.4	3.2	0
Wagner	2.8	0.4	6.3	0
Aria(FDM)	1.7	0.4	4.3	0.03
Compbell (Exp)	1.1	0.4	5.1	0
CFD	1.4	0.4	3.9	0.035
PeresentCalc (FEM)	1.8	0.4	5	0



(a) (b) (c)

Fig. 6 Images of cylinder impact with water surface at two different times, a) COMFLOW results b) Greenhow & Lin [14] c) FEM results

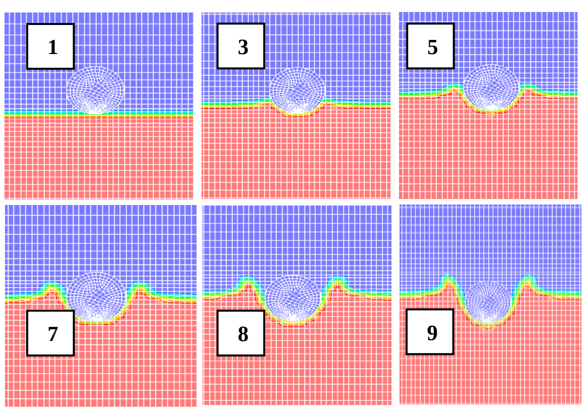


Fig. 7 Variations of water surface in cylinder impact at six different times (simulation by Ls-Dyna)

3.8.2. Changes of Water Level over Time

In this section, entry of circular cylinder into water and changes during its impact with water surface are studied. Image of cylinder impact with water surface at two different times using results of experiments by Lin and Greenhow, COMFLOW software and FEM analyses are compared in Fig. 6 [14]. In Fig. 6, the results of numerical simulation using FEM results are presented. As demonstrated, the free surface image which was created in the experiment was well modeled by FEM method. All the details of spraying water drops did not exist in the simulation; but, the jet which was made around the cylinder was fully estimated. By comparing the results presented in Figs 6 and 7, it can be concluded that numerical modeling of issues of structure impact with water surface using finite element method had proper accuracy in terms of quality.

4 SIMULATING IMPACT OF LOW VELOCITY PROJECTILE WITH WATER SURFACE

Below, impact of a mine with water surface with the geometry shown in Fig 8 and velocity of 10 m/s with different angles of 45, 60 and 90 degrees during mining is simulated. Finite element model of this simulation is shown in Fig 9. In simulating mine impact with water surface (as presented in the previous sections), air and water behaviors were stated using Null material model and that if mine was given using plastic-kinematics material model. ALE was the solution method and Mie-Gruneisen equation of state with the properties given in Table 4 was attributed to air and water.

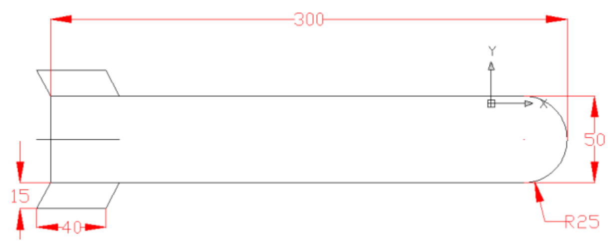
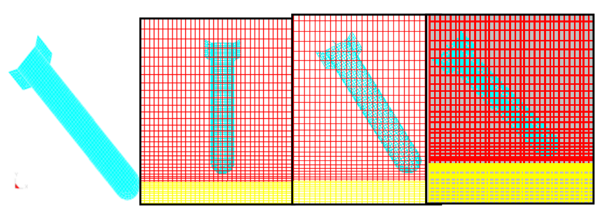


Fig. 8 Mine Geometry (Dimensions in millimeters)



(a) (b) (c) (d)

Fig. 9 Finite element model, a) Mine elements, b) Water and air elements with 90^0 mine impact angle, c) 60^0 mine impact angle, d) 45^0 mine impact angle

4.1. Variations of Displacement over Time

In Fig 10, variations of mine displacement over time are indicated. As shown, curve slope was sharp at the beginning of impact and corresponded with each other for various impact angles; however, over time and with mine entry into a denser area, as was expected, curve slope also decreased. The results showed that, the greater the impact angle with the water surface, the more the displacement would be over time with more limited difference. Displacement difference was limited considering low-velocity impact.

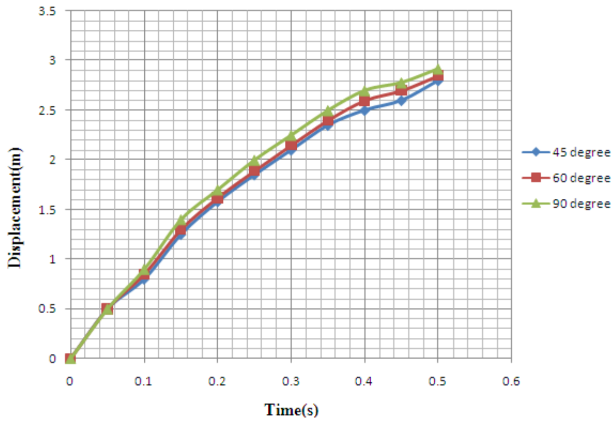


Fig. 10 Variations of mine displacement over time

4.2. Velocity Variations over Time

In Fig. 11, variations of mine velocity are shown over time. As demonstrated in the figure, at the beginning and during a limited time when the mine was travelling inside air, velocity was constant and equal to initial velocity of 100 m/s; but, over time, after impact and mine entry into denser environment of water, velocity exponentially decreased. The results showed that changing impact angle did not have a great effect on velocity difference at specific times.

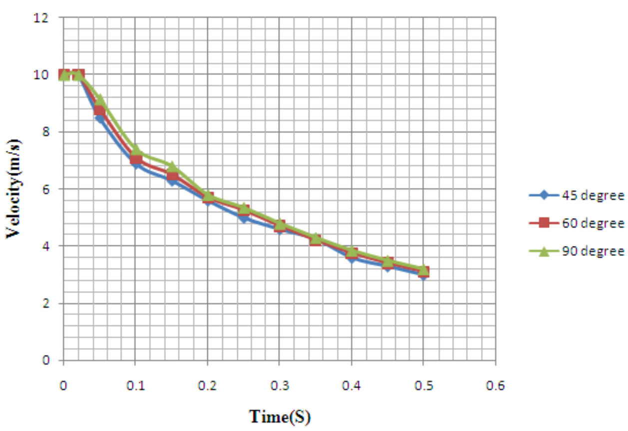


Fig. 11 Variations of mine velocity versus time

4.3. Variations of Pressure over Time

In Table 6, maximum pressure to mine is summarized at different angles. As can be observed, pressure variations depended on impact angle. The more the impact angle relative to the horizon, the more the pressure applied to the mine.

Table 6 Pressure variations in different impact angles

Impact Angle (degree)	Minimum Pressure (Pa)	Maximum Pressure (Pa)	Time (s)
45	0	8.023e5	0.517
60	0	4.085E5	0.206
90	0	24870	0.624

4.4. Variations of Force over Time

Force variations in various directions are shown in Table 7 over time for three impact modes. Force variations also greatly depended on impact angle. The more the impact relative to the horizon, the more the force applied to the mine.

Table 7 Force variations in various directions and impact angles

Impact Angle (degree)	**Maximum Force (N)**	**Force Direction**	**Time (s)**
90	5974	X	0.625
90	59920	Y	0.625
90	23150	Z	0.235
60	1.756e6	X	0.207
60	9.72e5	Y	0.207
60	8053	Z	0.207
45	1.439e6	X	0.5166
45	1.099e6	Y	0.5166
45	7.167e5	Z	0.5166

4.5. Stress-strain Variations

In Fig. 12, contour of Von Mises stress variation for the mine colliding with water is indicated in several time steps. As is shown, early in the impact, mine tip had maximum stress; but, then, middle part of the mine had maximum stress, as expected. Possibility of buckling and failure was also expected to occur in this area. In Figs. 13 and 14, variations of shear stress over time for the mine tip at the moment of mine impact with water surface and variations of shear stress over time for middle of the mine mean are illustrated, respectively. As demonstrated in the figure, maximum stress occurred as soon as the mine impacted with water surface and, over time and sinking of the mine to water, shear stress applied to the mine extremely decreased although the mine was still under pressure load. This situation indicated that, in impact analysis, specific attention should be paid to impact loads.

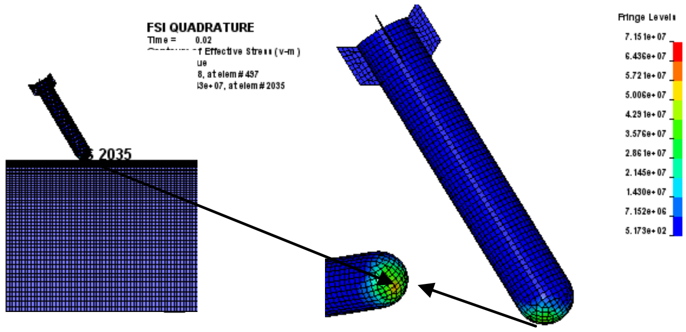


Fig. 12a Contour of Von Mises stress variation for the mine colliding with water (the maximum stress is 71 MPa at the moment of impact).

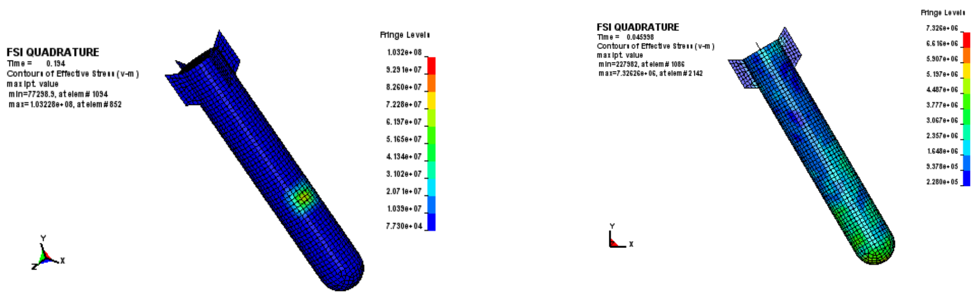


Fig. 12b Contour of Von Mises stress variation for the mine colliding with water at two different times

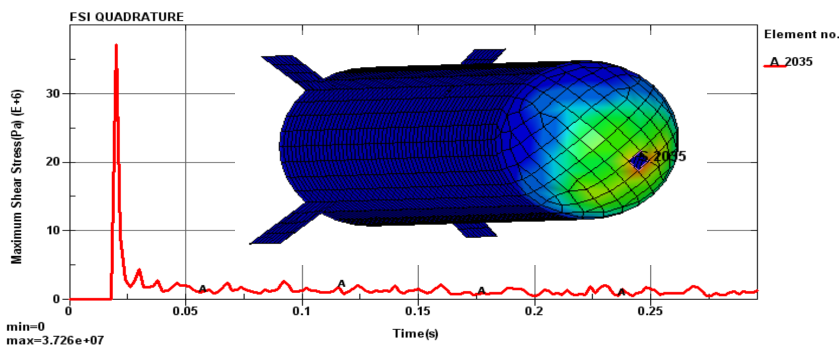


Fig. 13 Variations of shear stress versus time for an element in the tip of the mine at the moment of impact

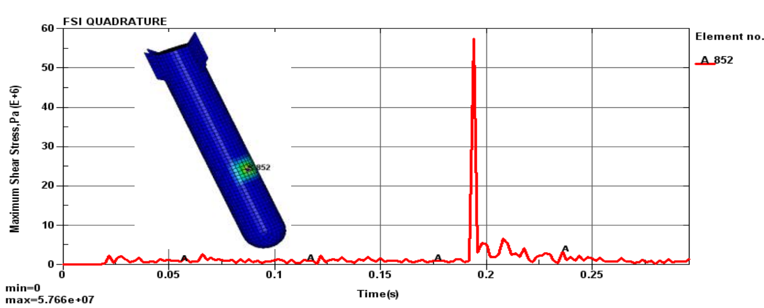


Fig. 14 Variations of shear stress versus time for an element in the middle of the mine

5 CONCLUSION

In this study, Ls-Dyna, an explicit finite element code, with ALE formulation were used to numerically simulate impact of low-velocity projectiles with water surface. The following results have been concluded from this simulation:

- Using FEM method, issues of structure impact with water surface can be simulated and analyzed at better accuracy than theoretical and analytical methods.
- Using Null material modeling water and air in issues of structure impact with water surface provides proper responses.
- Considering numerous deformations in issues of structure impact with water surface, using ALE solution method with appropriate coupling selection had reliable responses.
- Upon impact of the structure with water surface, the force applied to the structure increased in a short period of time and then this force stayed almost constant until complete sinking to water in spite of finite fluctuations.
- In simulating structure impact with water surface, all details of spraying water droplets did not exist; but, the jet created around the colliding object was properly estimated.
- With impact of the object with water surface, in short period of time, the object's acceleration might increase or decrease considering mass, velocity and geometry of the colliding object. However, after the object's sinking to water, acceleration of the colliding object could become closer to gravity acceleration and this process may continue until the colliding object reaches bottom.
- With deformation and velocity change of impact, all parameters of force, pressure, velocity, displacement, acceleration and so on were affected. If velocity of the projectile was slow, impact angle would not have any remarkable effect on the amount of force, velocity, displacement and acceleration.

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REFERENCES

[1] Anghileri, M., Spizzica, A., "Experimental validation of finite element models for water impacts", Proceedings of the second international crash users seminar, Cranfield, UK, June. 1995.

[2] Korobkin, A. A., Ohkusu, M., "Impact of two circular plates one of which is floating on a thin layer of liquid", Journal of Engineering Mathematics, Vol. 50, 2004, pp. 343–358.

[3] Battistin, D., Iafrati, A., "Hydrodynamic loads during water entry of two-dimensional and axisymmetric bodies", Journal of Fluids and Structures, Vol. 17, 2003, pp. 643–664.

[4] Park, M., Jung, Y., Park, W., "Numerical study of the impact force and ricochet behaviour of high speed water entry bodies", Comput Fluids, Vol. 51, 2003, pp. 932-939.

[5] Roe, S. M., "Numerical and experimental analysis of initial water impact of an air dropped REMUS AUV", A thesis submitted for the degree of Master of Science, MIT, 2005.

[6] Kleefsman, T., "Water Impact Loading on Offshore Structures", A Numerical Study, EU Project No.: GRD1-2000-25656, 2005.

[7] Fairlie-Clarke, A. C., Tveitnes, T., "Momentum and gravity effects during the constant velocity water entry of wedge-shaped sections", Ocean Engineering, Vol. 37, No. 5, 2008, pp. 706-716.

[8] Wu, G., "Numerical simulation for water entry of a wedge at varying speed by a high order boundary element method", Journal of Marine Science and Application, Vol. 11, 2012, pp. 143-149.

[9] LS-DYNA Theory Manual, Ver 7, Livermore Software Thechnology Corp, 2007.

[10] Olovsson, L., Souli, M., and Ian, D., "Fluid-Structure Interaction Modeling," Livermore Software Technology Corporation. January 07, 2003.

[11] Halliquist, J. O., "Simplified Arbitrary Lagrangian-Eulerian", LS-DYNA Theoretical Manual, May 1998.

[12] Seif, M., Mousaviraad, S., and Saddathosseini, S., "Numerical Modeling of 2-d Water Impact in One Degree of Freedom", Sintesis Tecnologica, Vol. 2, 2005, pp. 79-83.

[13] Campbell, I. M., Weynberg, P. A., "Measurement of parameters affecting slamming", Report No 440, Wolfson Unit of Marine Technology, Tech. Rep. Centre No. OT-R-8042, Southampton, UK, 1980.

[14] Greenhow, M., Lin, W, M., "Non linear free surface effects: experiments and theory", Report No. 83-19, Department of Ocean Engineering, MIT, Cambridge, MA, 1983.