Under Water Explosion Pressure Prediction and Validation Using ANSYS/AUTODYN

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Abstract: ***Behavior of blast wave due to underwater explosion is of interest to ship designers and metal forming community. Underwater explosion is, also a potential hazard to the water intakes or plant spent fuel pool. Therefore in this paper blast wave propagation in underwater explosion is studied using commercial program ANSYS/AUTODYN. One of the most important far field parameter, pressure obtained from analytical method has been compared with simulation result obtained from ANSYS/AUTODYN. The blast pressure is highly dependent of water incompressibility. The incompressibility of water in AUTODYN can be modeled using different "Equation of States". This paper also has the details of different material models available to model water in AUTODYN and its effect on blast pressure. In this paper pressure generated due to under water explosion (explosion of TNT) have been measured at different standoff distances using ANSYS/AUTODYN. Two "Equations of States" #1 shock, #2 polynomial available in AUTODYN are used to model the water and its results are compared with analytical solution. The underwater explosion is modeled using 1D analysis of AUTODYN with Multi-Material solver. TNT and Water materials are taken from AUTODYN material library. A detonator is placed at the center of TNT to start the ignition. Results are highly dependent on mesh size, for most refined mesh (0.5mm) and at the farthest stand off point there is difference of 0.8% with analytical solution using shock Equation of state. However with the same mesh size there is difference of 17% using polynomial Equation of state.***

Keywords: Underwater blast, Pressure, AUTODYN, Equation of state (EOS), shock**.**

1. Introduction

Explosion is a chemical reaction which produces gases of very high temperature and pressure. The explosion process leads to the formation of shock waves in the surrounding water and also generates superheated highly compressed gas bubbles [1].

The study of shock response of underwater explosion is very important for structural designers and metal forming experts to understand the relationship between impulsive forces and the structural deformation and its fracture behavior [3, 4]. Therefore determination of blast parameters is very important for structural designers.

The pressure time history, P(t), at a fixed location starts with an instantaneous pressure increase to a peak pressure P_m, (in less than 10^{-7} sec) followed by a decay which in its initial portion is usually approximated by an exponential function [2]. The pressure profile at a certain distance from the explosion with respect to time is shown in Figure 1.

$$P(t) = P_m e^{-t/\theta} \tag{1}$$

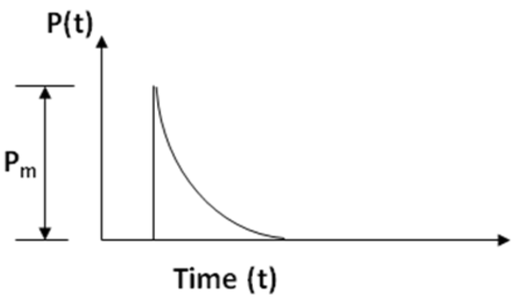


Figure 1: Pressure vs. time graph for under water explosion

The peak pressure and the decay constant depend upon the size of the explosive charge and the standoff distance from this charge at which the pressure is measured. [5]. In 1948 Prof. Cole gave an analytical formula for calculating pressure at any standoff point from the center of explosion [2].

$$P_m = 52.16\left(\frac{W^{1/3}}{R}\right)^{1.13} \tag{2}$$

$$\theta = 96.5(W^{1/3})\left(\frac{W^{1/3}}{R}\right)^{-0.22} \tag{3}$$

Where P_m is in MPa, θ is decay constant in microseconds valid for $0 < t < \theta$. W is expressed in kg of TNT and the standoff, R, is measured in meter.

Cole's formulae applicable for any size of charge, from a small to huge explosions, exploded at any depth except in the immediate vicinity of the explosive charge (10 times the charge radius), where the peak pressure is higher than the formula predicts.

In this paper blast pressures at different standoff distances are calculated using Multi-Material solver of numerical simulation code AUTODYN. The blast pressure also depends upon the incompressibility of water. Therefore two Equations of States (EOS) of water are used in AUTODYN to model the incompressibility of water and their results are compared with Cole's analytical results [2].

2. Numerical Simulation

10 KG of TNT is exploded in water and pressure is being measured at standoff distances 1.2, 2.0, 3.0, 4.0 and 5.0m from the centre of explosion using numerical code AUTODYN.

Blast in water is one dimensional in nature. One-dimensional simulation in AUTODYN can be modelled using 2D-axisymmetric solver and with the shape of a wedge. The angle of the wedge is defined by AUTODYN. Only wedge inner radius and outer radius needs to be defined. A schematic diagram of the wedge is shown in Figure 2.

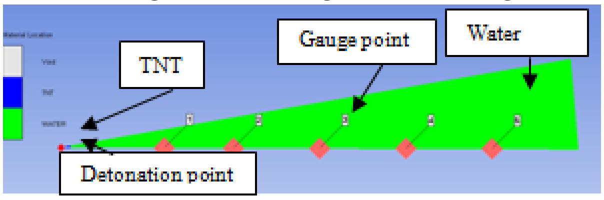


Figure 2: One dimensional wedge model in AUTODYN

The dimension of the wedge depends upon charge weight and location of pressure measurement. However radius of the charge can be defined based on below formula.
Volume of TNT= mass of TNT/density of TNT
Density of TNT = 1.63 gm /cm3
Volume of TNT = 4/3 * π *(R3- r3)
Here, r = 10.0 mm (minimum wedge radius)

The size of wedge is 6000mm and the radius of charge to model 10kg of TNT is 113mm.

The blast pressure is highly dependent of water incompressibility. The incompressibility can be modelled using two EOS (shock and polynomial) present in AUTODYN. Therefore following two cases have been solved in AUTODYN for blast pressure validation.

Case-1: Pressure validation of 10 kg of TNT blast in water at 1.2, 2.0, 3.0, 4.0 and 5.0m distance from the centre of explosion using Shock EOS of Water.

Case-2: Pressure validation of 10 kg of TNT blast in water at 1.2, 2.0, 3.0, 4.0 and 5.0m distance from the centre of explosion using Polynomial EOS of Water.

2.1 Material Properties

All materials are selected from AUTODYN material library.
TNT has JWL EOS. The JWL equation of state is the most appropriate equation used for modelling explosives. In addition, it can be applied to calculate the pressure reduction of up to 1 Kbar. The JWL equation of state is as follows [6]. See Eq.4. Table-1 shows the parameters values used by AUTODYN to model the TNT.

$$P = A\left(1-\frac{w}{R_1V}\right)e^{-R_1V} + B\left(1-\frac{w}{R_2V}\right)e^{-R_2V} + \frac{wE}{V} \tag{4}$$

Table 1: Material Properties of TNT

Variable	*Value*
Reference Density (kg/m3)	1630
A	3.73e+08
B	3.74e+06
R1	4.15
R2	0.09
w	0.35
C-J Detonation Velocity (m/ms)	6.93e+03
C-J Energy/unit volume (MJ/m3)	6.00e+06
C-J Pressure (MPa)	2.10e+07

The incompressibility of water in AUTODYN has been modelled using Shock and Polynomial Equation of State. Table-2 and Table-3 respectively shows the parameters values used by AUTODYN to model the water with shock and polynomial EOS.

Shock EOS has Rankine-Hugoniot equations for the shock jump condition can be regarded as defining a relation between any pair of the variables [6].

$$U = C_0 + su_p \tag{5}$$

Mie-Gruneisen form of EOS based on the shock Hugoiot is used

$$P = P_H + \Gamma\rho(e - e_H) \tag{6}$$

$$P_H = \frac{\rho_0 c_0^2 \mu(1+\mu)}{[1-(s-1)\mu]^2}$$

$$e_H = \frac{1}{2}\frac{p_H}{\rho_0}\left(\frac{\mu}{1+\mu}\right)$$

Polynomial Equation of State is general form of the Mie-Grueisen form of equation of state and it has different forms for states of compression and tension [6].
For compression ($\mu > 0$)

$$p = A_1\mu + A_2\mu^2 + A_3\mu^3 + (B_0 + B_1\mu)\rho_0 e \tag{7}$$

For Tension $(\mu < 0)$

$$p = T_1\mu + T_2\mu^2 + B_0\rho_0 e \tag{8}$$

Table 2: Material Properties of Water with Shock EOS

Variable	*Value*
Reference Density (kg/m3)	9980
Gruneisen Coefficient	0.0
C1	1.64e3
S1	1.921
S2	0.0
VE/V0	0.0
VB/V0	0.0
C2	0.0
S2	0.0
Reference Temperature (K)	0.0
Specific Heat (J/kgK)	0.0
Thermal Conductivity (J/mKs)	0.0

Table 3: Material Properties of Water with Polynomial EOS

Variable	*Value*
Reference Density (kg/m3)	1000
A1	2.2e6
A2	9.54e6
A3	1.45e+07
B0	0.28
B1	0.28
T1	2.20e+06
T2	0.00
Reference Temperature	0.00
Specific Heat	0.00
Thermal Conductivity	0.00

2.2 Gauge Points

Gauge points are located at 1.2, 2.0, 3.0, 4.0 and 5.0m from the centre of blast in case-1 and case-2 respectively to measure the pressure at these points.

2.3 Detonation

A detonation point is located at the canter of explosive (0, 0, 0) to start the explosion at time zero.

2.4 Mesh

One degree quadrilateral element has been used to model the wedge. Since accuracy of the results is highly dependent on mesh therefore mesh sizes 0.5, 1.0, 2.0, 4.0 and 8.0 of meshes have been used in case-1 and case-2.

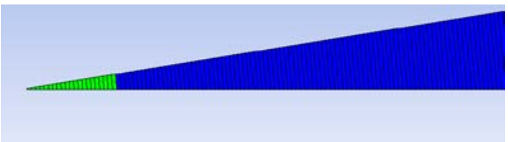


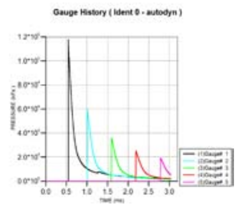
Figure 2: Mesh Model

3. Result and Discussion

Case-1**:** Table -4, shows the blast pressure, due to blast of 10kg of TNT in water. AUTODYN spherical symmetric analysis with shock EOS of water results are compared with analytical equation given by Cole. Different element sizes are used in AUTODYN model to study the mesh convergence.

Table 4: Overpressure in AUTODYN with Shock EOS and Cole

Maximum Pressure (MPa) at different Standoffs (mm)					
Mesh sizes in millimeter	1.2	2.0	3.0	4.0	5.0
0.5mm	117.5	59.75	35.88	25.12	19.18
1.0mm	116.75	59.2	35.34	24.83	18.80
2.0mm	115.71	58.23	34.56	24.07	18.24
4.0mm	113.53	56.46	33.24	22.95	17.30
8.0mm	110.31	53.76	31.21	21.38	15.99
Analytical solution	100.17	56.24	35.57	27.87	19.97



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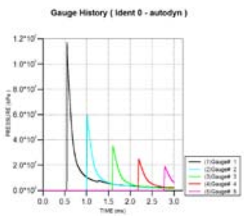

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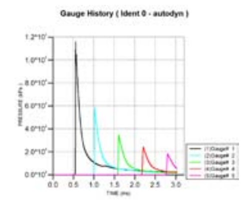

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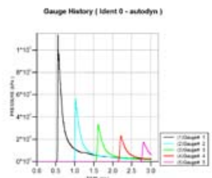

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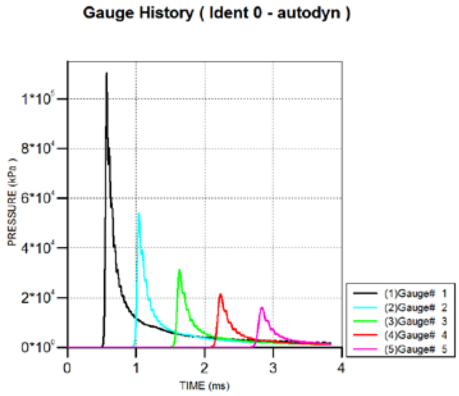


Element size=8.0mm

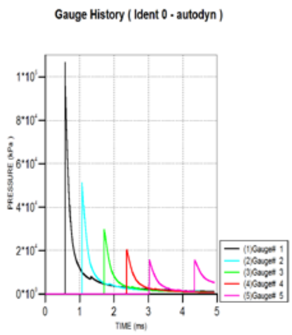
Figure 4: Overpressure vs. time graph for different element sizes at different standoffs in AUTODYN using Shock EOS

Figure 4 shows the overpressure-time histories for different element sizes used in AUTODYN model. The AUTODYN pressure profile at a particular standoff is exactly matching with theoretical graph given by Cole in Figure 1. This result shows that as mesh is refined, overpressure value come closure to analytical equation result. With most refined mesh i.e. element size 0.5mm at the farthest point (5.0mm), difference in AUTODYN result and analytical result is 0.8%. Case-2: The same analysis is repeated for Polynomial EOS of water and its results are compared with Cole's analytical formula results. Table 4 summaries the result for same.

Table 5: Overpressure in AUTODYN with polynomial EOS and Cole

Maximum Pressure (MPa) at different Standoffs (mm)					
Mesh sizes in millimetre	1.2	2.0	3.0	4.0	5.0
0.5mm	106.6	51.0	29.62	20.52	15.68
1.0mm	106.27	50.66	29.31	20.23	15.28
2.0mm	105.07	50.03	28.77	19.76	14.86
4.0mm	103.0	48.85	27.91	19.03	14.24
8.0mm	100.0	46.84	26.50	17.96	13.36
Analytical solution	100.18	56.24	35.577	27.87	19.97

The simulation result depends on mesh size. With most refined mesh the pressure value at the farthest point vary 17% with analytical value. Figure 5 shows the overpressure-time histories for different mesh sizes of AUTODYN model. The simulation result depends on mesh size. With most refined mesh the pressure value at the farthest point vary 17% with analytical value. Figure 5 shows the overpressure-time histories for different mesh sizes of AUTODYN model.



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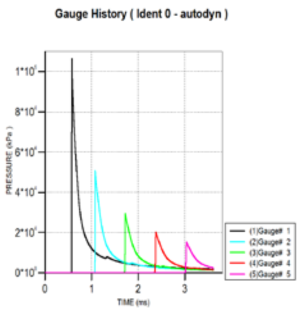

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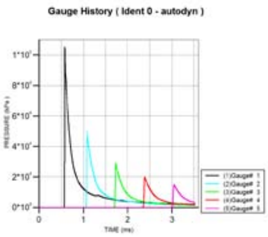

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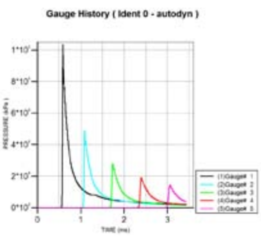

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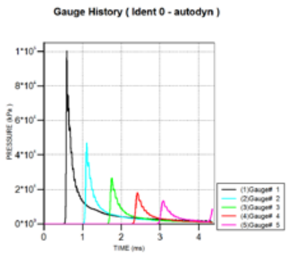
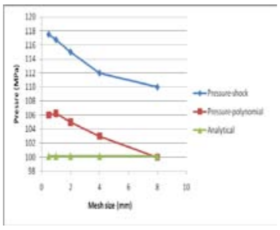
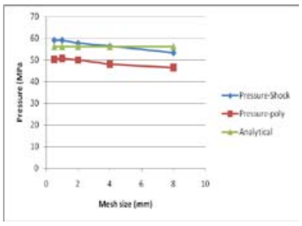


Element size=8.0mm

Figure 5: Overpressure vs. time graph for different element sizes at different standoffs in AUTODYN using Polynomial EOS

Figure 6 shows the comparision of pressure with Shock and Polynomial EOS and Cole's aalytical results for each element size at diferent stand off points. There is 7% of overprediction in simulation result at the neareast stanoff distance


Stand off=1.2mm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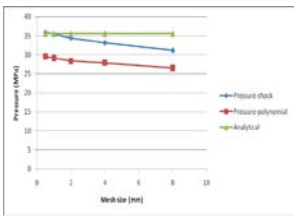
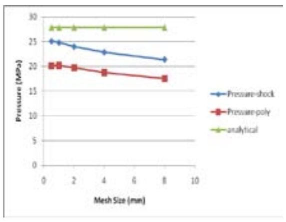
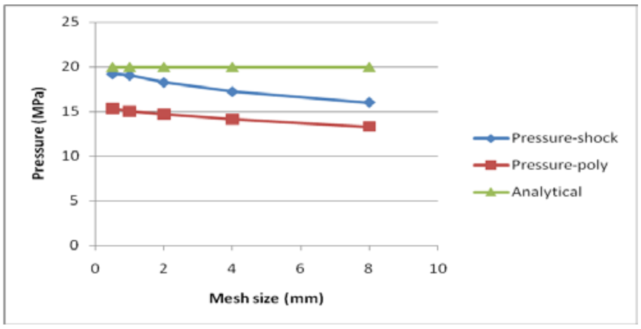

Stand off=3.0mm


Stand off=4.0mm



Stand off=5.0mm

Figure 6: Overpressure vs. element size graph for different Stand offs

Figure 7 shows the pressure vs. stand-off graph for most refined mesh (0.5mm). The Analytical result is compared with AUTODYN results. There is 7% of over prediction of pressure for most refined mesh when pressure is measured near to blast (1.2m)

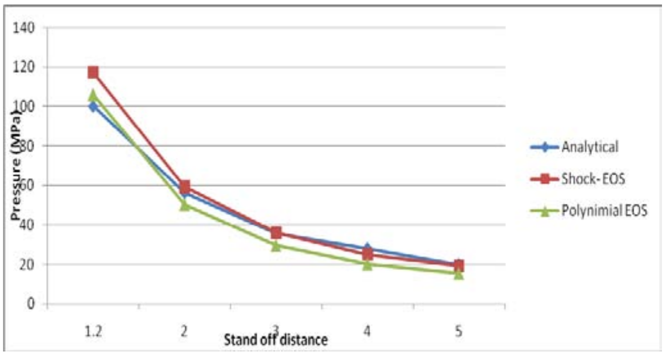


Figure 7: Overpressure vs. stand offs graph for a particular element size

4. Conclusion

In this paper, the explosion phenomenon and blast wave propagation in water are successfully simulated and the blast wave parameter (over pressure) is calculated using ANSYS/AUTODYN program. The two Equation of state of water is used for results comparison & validation point of view. Maximum overpressure which is calculated in ANSYS/AUTODYN is compared with the analytical equation presented by Cole. Simulation studies show that AUTODYN results match very well with analytical equation.

However, the accuracy of simulation is dependent on mesh size; with refined mesh over pressure results obtained is closure to reference results Equation of State of water also influences the maximum values. The values derived with shock EOS agree better to Cole's equation than these derived with polynomial EOS. The general recommendation is to use impulse (integral of pressure over time) for postprocessing instead of pressure values

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