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Study on JWL equation of state for the numerical simulation of near-field and far-field effects in underwater explosion scenario

Sourabh Koli [a], P. Chellapandi [c], Lokavarapu Bhaskara Rao [a,*], Akshay Sawant [b]

[a] School of Mechanical and Building Sciences, VIT University, Chennai Campus, Vandalur-Kelambakkam Road, Chennai 600127, Tamil Nadu, India
[b] Valeo India Pvt Ltd, Old Mahabalipuram, Navallur, Chennai, Tamil Nadu, India
[c] INAE, Distinguished Professor, Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai-600036, Tamil Nadu, India

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ABSTRACT

Rapid growth in computational capacity facilitates structural mechanics specialist to facilitate numerical simulation of complex explicit dynamics of detonation shock dynamics and explosive analysis. An attempt is made depict shock wave propagation behaviour and variation of its mechanical properties along the radial line of spherical shaped high explosives in the water domain. JWL equation of state for expansion of detonating products after explosion has been studied for several high explosives and simplified approach with PV^{γ} form has been suggested to reduce complexity of calculation and computational time for underwater explosion phenomenon. Near-field effects cause severe effects on the structures leading to the local deformation and hazard to structure while with the spatial distance away from the explosive centre explosion effects reduces due to expansion of detonating products. There is strong need to segregate such effects to find the vulnerability of structures depending upon target structure distance from explosive centre. Typical spherical high explosives have been studied with variation of charge radius employing homogeneous and heterogeneous explosive model to study such behaviour. Successful criteria to distinguish near-field and far-field effect are evolved after parametric study. All the results with consolidated comparison are presented in this paper.

1. Introduction

An explosion is exothermic chemical reaction process which converts explosive material into product gas of high pressure and temperature which leads to generation of shock waves causing rigorous effect on the surrounding medium due to high pressure pulse. An underwater explosion forms series of events with severe fluid structure interaction on target structure, shock wave propagation under water, cavitation with bubble formation, whipping effect followed by bubble collapse leading to water jet impact. After the detonation, shock wave and expanding gas bubble will generate resulting in very high pressure underwater. This process is accomplished by series of sequential physical and chemical reactions with release of large quantities of heat, formation of gas products and energy propagation in the form of pressure waves. Thus underwater explosion pose a significant and devastating effects on the waterborne structures through destructive pressure waves up to denoting long range.

Water is having relatively higher density compared to air which increases inertia of water as well as makes it harder to compress by pressure. These two things makes water good conductor of shock waves for long range in water field in deep underwater explosion. The effects of an underwater explosion are depend upon many parameters such as explosive strength i.e. energy of an explosive, distance of target and depth from water surface to explosion source. Depending upon depth of explosion source underwater explosion is classified as deep and shallow underwater explosion. The criteria for classifying underwater explosion as deep or shallow are given by Le Mehaute, Bernard and Wang Shen [1]. Generally in deep underwater explosion crater formed on the surface is trivial while in case of shallow underwater explosion crater is considerable. This effect is extremely emphasised in case of designing submarines and anti-warships. In an underwater explosion effects can be amplified due to water movement on waterborne structure along with shock wave impact. Same quantity of explosive can cause greater damage in underwater explosion with less attenuation of pressure waves than in air.

Water is incompressible in nature due to this any localized pressure applied to a particular region of water; it will transmit in the form of wave to other parts spatially. This phenomenon

* Corresponding author.
E-mail address: bhaskarbabu_20@yahoo.com (L. Bhaskara Rao).
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generate pressure wave with large velocity and generation of peak pressure involving local motion of water. If this waves are generated from the blast loads due to detonation of explosive in the spherical pattern, the amplitude of pressure wave decreases from source rapidly with radial inline distance from the detonation point in the water domain. This creates pressure difference from spherical deviation which is known as surge phenomenon [2].

A detonation creates a shock wave propagating at supersonic speed due to continuous exothermic chemical reaction taking place just behind detonation front inside high explosive. This shock front is result of expansion of gaseous products transformation upon detonation of solid high explosive. This process occurs instantaneously and resulting shock wave propagates radially outwards in spherical domain. This induced shock waves with speed much more than acoustic velocity comes out of explosive-interface and hit the water domain. This shock wave transforms quickly in seismic p-wave while travelling through the water at specific acoustic velocity. Hempen firstly uses 'pressure waves' as a general term to describe waves propagating through water regardless of distance from the source or velocity of shock wave [3]. Thus inside explosive wave is referred as shock wave travelling at supersonic speed while when it comes to water domain it results in compression p-wave that travels at sonic velocity termed as pressure wave. The arrival of pressure waves can be detected easily by instantaneous rise in pressure to sharp peak value and it is followed by the exponential decay of the corresponding pressure wave spatially in the water domain. This achievement of sharp peak pressure and decaying effect process is of the order of few milliseconds. The peak pressure of pressure waves is assumed to act as a quasi-static load applied normal to the structure inside water, which is important for finding out damage potential of explosion [4].

Pressure wave propagation generated from underwater explosion is the main focus of researchers to study the critical parameters of explosion and blast load effects on underwater structure like ship hulls and submarines for their protection [5]. Development in computational capacity with progression in numerical methods in the recent years leads to accurate numerical simulation of complex underwater explosion scenario. Thus effects of underwater explosion in terms of the detonation of high explosives, propagation of pressure waves, and expansion of detonation products with proper equation of state, study of near-field and far-field effects of underwater explosion are need to be studied.

1.1. Near-field and Far-field effects in underwater explosion studies

On account of underwater explosion, the shock waves began from the detonation of explosive cause critical destruction to the structures lodging the water and in addition inundated in the water. The intensity of the damage relies on the strength of the pressure wave, which thus relies on the characteristic distance of structures from the detonation point; aside from explosives own particular characteristics and mass. In particular, the nature and degree of damage to the structure for near-field effects is very severe and quiet different as it is near to the explosive-water-interface while in case of far-field effects structure is kept at long distance hence effects are moderate in range due to wave attenuation. Depending upon the distance between the target structure and centre of explosion, underwater explosion effects can be classified in two types viz. near-field effects of explosion and far-field effects of explosion. The near-field effect comprises generation of sudden high pressure wave causing severe damages with rupture of structures in the vicinity by local deformation which involves detonation phenomenon and build up pressure inside boundary of explosive up to Chapman-Jouguet (C-J) value of particular explosive. After some point effects on structure placed at increasing radial distance from explosive charge centre starts reducing, at some point it will only elastically deforms the structure without rupturing. Thus beyond this point explosion is known as far-field effect of explosion [6]. Hence target distance from explosive centre is the important parameter in the pressure field of explosion so as to study the structure integrity assessment and make provision of shock absorbing mechanism to survive from the underwater blast loading. Keeping in mind the end goal to evaluate the near-field and far-field effects under a spherical explosion, the pressure wave's effects from source of explosion starting from the explosive-water interface should be exactly evaluated.

Near-field and Far-field effects differs tremendously especially in terms of strength of mechanical effects produced by shock wave, in near field of explosive it is very high and further it immensely decreases due to expansion of gas products after detonation. In case of cylindrical explosive charge, a flat wave is generated at the end of explosive, further with progression of time this wave will curve by influence of lateral expansion of detonation gas products at the charge end into a hemispherical configuration [7].

A near-field explosion leads to devastating effects on the structures in the vicinity of explosion causing large fluid-structure interaction on target, subsequently forming cavitation and bubble formation which causes high peak pressure in underwater explosion. A series of experiments are conducted for investigating this phenomenon on waterborne structures by shock wave loading to successfully establish relationship between model target and effects of aluminized and non-aluminized explosives. The experimental results obtained with these experiments are crucial for developing and successful deployment of numerical models for underwater explosion simulation as benchmark for studying near-field effects on the target geometries [8].

The load-structure interaction from explosion induced dynamic loading, on the structures in the vicinity is complicated and varies according to situation. Far-field effects on the structures have been studied intricately with numerical modelling as well as experimental analysis [9–12] while near field effects in case of underwater explosion has been studied by [10,13]. Utilization of underwater shock wave propagation event is now a day's very much emphasized in advanced manufacturing process like metal forming and explosive welding processes. Thus for effective accomplishment of this manufacturing process one must have control on the underwater shock wave propagation phenomenon with idea of near-field and far-field effects.

Generally structure attached in the blast loading for studying far field effect of an explosion scenario is at a distance of one or more order of magnitude of the characteristic radius of explosive itself. Whole structure is impacted by blast loads, hence more sophistically large part of structure interaction problem needed to be modelled. Effects of near-field detonation produced by an underwater explosive device are studied on the inundated concrete wall in close range from explosion source, for a particular explosive device defined by its mass; near-field range has been materialized by a minimum reduced radius under which the adiabatic characteristics are significantly recognized due to high pressure generated subsequent to detonation in near-field. Arbitrary Lagrangian Eulerian (ALE) algorithm is adopted in LS-DYNA to numerically study depth of damage in concrete wall depending upon explosive mass and distance of detonation point and target with experimental validation of results [14]. Understanding the explosive characteristics and its influence on the blast wave propagation has been the study under research and plays an important role for design and safety measures [15–18].

A currently used numerical model for explosives comprises shell finite elements and material behaviour from quasi-static models to inevitably nonlinear. Structure introduced at near-field of explosive upon detonation it will suffer from high stress or high

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strain rates, but due to energy considerations such high intensity impact will last for very short time as well as very short distance [19].

1.2. The importance of such studies

There is strong need to distinguish between far-field and near field effects in underwater explosion. In this study an attempt is made for establishing criteria for distinguishing near-field and far-field effects in underwater explosion. Vulnerability of structure inundated in the water to the blast loads can be predicted depending upon these criteria evolved for far-field and near-field effects. This study also gives more simplified approach for far-field effects using simple model for numerical investigations depending upon the distance for structure and explosive. For designing war-ships, submarines and underwater structure and protect them against blast loads this study is extremely useful. The expansion of detonation products after explosion is compared for commonly used JWL (John-Wilkins-Lee) equation to study their subsequent behaviour for typical high explosives. The simplified approach for the JWL equation of state has been recommended with adiabatic index (γ) for adiabatic expansion ($PV^{\gamma} form$) of detonation products for studying far-field effects with homogeneous explosive model using the strength of various high explosives in terms of their internal energy and adiabatic JWL curves are compared so as to get idea of damage potential of high explosives.

1.3. Necessity of simplified approach for the simulation of explosive characteristics

For numerical simulation of underwater explosion problem, depending upon the parameters of explosion i.e. detonation, expansion of hot gaseous produced after detonation, shock waves propagation, etc. are important parameters along with characteristics of explosive used. Thus mechanical effects produced after explosion which abruptly damage structures are as consequence of these properties of particular explosive. Depending upon the concern of effects i.e. far-field or near-field effects structure is suffering, subsequent damage potential of shock wave varies. Thus quick, easy and efficient numerical model is necessary for studying far-field effects. Hence more simplified approach is needed for looking underwater explosion on the grounds of distance and consequence of parameters of explosive characteristic. The equation of state used for expansion of detonation products plays vital role in generating shock wave velocity and peak pressure inside water domain. This equation of state influence on expansion of product gas after detonation, needed to be evaluated for developing more efficient numerical model.

1.4. Scope of the present paper

Analytical and experimental study of detonation process and shock dynamics for any present explosive model has been difficult task with possibility of experimental and human error apart from risk and environment hazard, in the calculation. Numerical simulation of such multi-dimensional, multi-disciplinary problem is efficient, cost effective and faster way for studying propagation of shock waves in underwater explosion scenario by detonation of high explosives. Underwater explosion of high explosive for studying their mechanical effects and determining damage potential on the waterborne structure with spatial variation around explosive is necessary for evaluating their damage assessment in defence, civil and academic problems. This work aims at (i). To study characteristics of high explosives commonly used with Comparison of JWL curves and relative expansion of detonation products of typical high explosives, (ii). Establishing the criteria for the application of simplified approach with analytical study of JWL equation for near-field and far field effects of underwater explosion, (iii). To determine pressure wave propagation behaviour in underwater explosion phenomenon and associated mechanical effects i.e. spatial and temporal peak pressure variation and velocity distributions in the water field starting from explosive-water interface, (iv). To establish criteria for distinguishing near-field and far-field effects on the basis of mechanical effects.

1.5. Simulation of near-field and far-field effects with JWL equations

To study near-field and far-field intricate effects of explosion in underwater one must have knowledge of the typical explosives in terms of their characteristics and equation of state for propagation of detonation products used. Among most of the explosives used for underwater explosion typical high explosives which are used frequently worldwide are TNT (Trinitrotoluene), PETN (Penta Erythritol Tetra Nitrate), SEP and C4. Hence their parameters are compared for detecting their behaviour after explosion and expansion of product gaseous with the help of JWL equation.

Several equation of state are proposed for describing expansion of gaseous products produced upon detonation of high explosives, but JWL Equation of State (EOS) is used for numerical simulations in many standard codes due to their simplicity in hydrodynamic calculations and mostly aligned results with experimental test. JWL EOS contains parameters describing relationships between volume, energy and pressure of detonation products. These parameters are determined by metal cylinder expansion test of detonation products. The chemical energy released during time interval is stored in the burnt products of the explosive itself. The burnt products are assumed to behave as a homogeneous gas undergoing adiabatic thermodynamic process defined by Jones-Wilkins-Lee (JWL) equation of state. The principal value of the JWL equation of state lies in its capability to give an accurate depiction of' the C-J adiabat [20]. The JWL equation is obtained from the expansion of internal energy E, in the neighbourhood of an isentrope of the detonation products [21].

The JWL EOS is represented as

$$P = A(1 - (\omega/R_1V))e^{-R_1V} + B(1 - (\omega/R_2V))e^{-R_2V} + (\omega E/V) \quad (1)$$

Thus JWL EOS is used for calculating pressure of detonation products with spatial and transient variation. Here, V stands for the relative volume, this expression relates pressure P to the relative specific volume $V = v/v_0$ and energy E. Here, specific volume v_0 is the inverse of the initial density of the explosive, and the specific volume V is the independent variable. The energy term E contains chemical bond energy as well as kinetic energy associated with the momentum aspect of the flow. A and B are the pressure coefficients while R_1 and R_2 are the principal and secondary Eigen values to depict the short range and long range behaviour of the explosive products respectively. The parameter 'ω' is the fractional part of the energy (E) contributing for the pressure. However, substitution of V for V_{SP} (specific volume) * ρ_0(loading density) will convert these expressions to specific volume [16]. A limited number of explosives have been subjected to a rigorous comparison in which coefficients are determined by matching the equation with experimental C-J conditions, calorimetric data, and expansion behaviour by cylinder test data

1.6. Definition of problem

The investigation deals with numerical simulation of deep underwater explosion of a spherical shape charge of high explosives namely PETN, TNT and SEP with varying charge radius from

20 mm to 100 mm together with interval of 10 mm increment of radius.

The axisymmetric benchmark geometry is further extended to incorporate water medium surrounding the explosive charge to investigate the near-field effects close to explosive-water interface and further along notable radial distance to study far-field effects, in terms of mechanical effects variation i.e. peak pressure variation and velocity distribution of shock waves along surrounding boundary of the explosive. The outer boundary radius of water is selected relatively infinite, which ensures the non-reflecting boundary conditions so as captures the essential near-field effects without alteration.

1.7. Typical high explosives and their properties

TNT (trinitrotoluene) is one of the most commonly used high explosives in military weapons and in civilian mining and excavation activities. The yellow-colour solid is frequently used as a main charge in artillery projectiles, mortar rounds, and aerial bombs. TNT is classified as a secondary high explosive because it is less susceptible to ignition and requires a primary explosive to ignite it. It has fairly high explosive power, good chemical and thermal stability, and is compatible with other explosives. TNT is considered the standard measure of strength of explosives. PETN (Penta Erythritol Tetra Nitrate) is one of the strongest known high explosives, i.e., more sensitive to shock and friction than TNT. It is primarily used in booster and bursting charges of small caliber ammunition and in detonators of some land mines as well as shells. PETN does not occur naturally, and the production and use of this kind of compound can lead to contagion of the environment. PETN is white in colour. SEP high explosive is mixture of 65 per cent PETN and 35 per cent Paraffin. C-4 is a common variety of the plastic explosive family known as Composition C. C-4 is composed of explosive, plastic binder, plasticizer to make it malleable, and usually a marker or odorizing tangent chemical. C-4 has a texture analogous to molding clay and can be mold into any preferred shape. C-4 is stable and an explosion can only be initiated by the combination of extreme heat and shock wave from a detonator [26]. The JWL Equation of state properties is taken from [22,23,24].

This property of high explosives has been adopted from [24,25]. These similar properties are used in numerical study in this work. JWL EOS properties for typical explosives are presented in Table 1.

1.8. Homogeneous and heterogeneous numerical model for Explosion:

For numerical simulation of underwater explosion of high explosives two types of explosive models are used here viz. 'homogeneous explosive model' and 'heterogeneous explosive model'. Homogeneous explosive model (Fig. 1(a)) is one in which it contains high pressure burnt product gas of corresponding explosive in gaseous state which releases instantaneously upon ignition in turns creating high pressure suddenly and expansion of this high pressure gaseous products proceeds according to Jones-Wilkins-Lee (JWL) EOS as discussed in above section 2.0, while in heterogeneous model (Fig. 1(b)) solid high explosive is being ignited upon detonation and has ability of building up pressure inside boundary of explosive by Detonation Shock Dynamics (DSD) phenomenon following Chapman-Jouguet (C-J) theory with employment of burn fraction model. Homogeneous model of explosion has an advantage that it can easily numerically simulate without consideration of detonation theory and any burn fraction model.

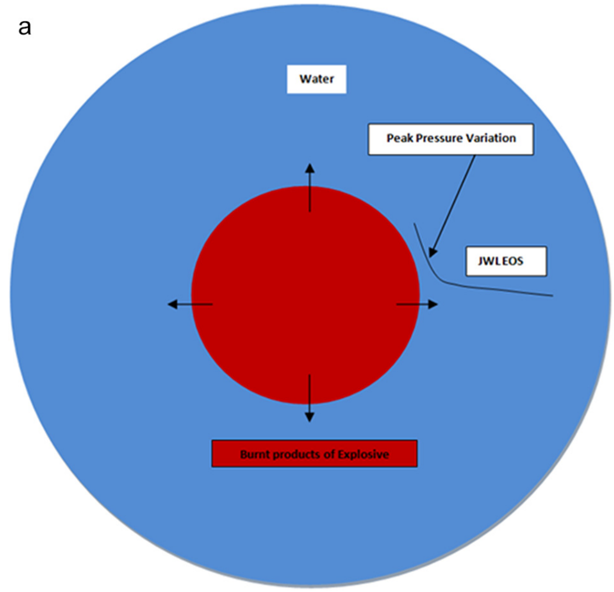

Fig. 1a. Homogeneous Explosive Model.

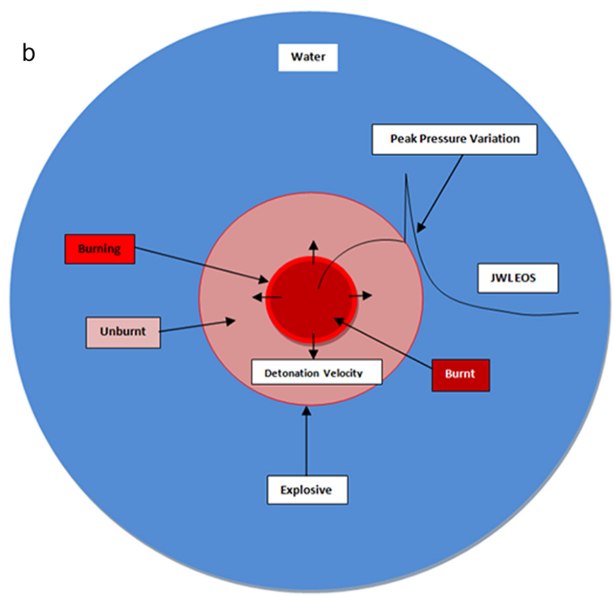

Fig. 1b. Heterogeneous Explosive model.

Table 1
JWL EOS properties for typical explosives.

Explosive	Density(kg/m^3)	A(Mbar)	B(Mbar)	R_1	R_2	W	E(Mbar)
TNT	1610	3.712	0.0323	4.15	0.95	0.30	0.070
PETN	1750	6.170	0.2167	4.40	1.32	0.25	0.0913
C4	1601	5.981	0.137	4.5	1.5	0.32	0.087
SEP	1310	3.640	0.0231	4.3	1	0.28	0.0282

*MAT_HIGH_EXPLOSIVE_BURN model in LS-DYNA software for identifying detonation effects needs explosive parameters in the terms of detonation velocity, density and C-J pressure value of explosive. This is given in Table 2.

Table 2
Explosive properties.

Explosive	Density (kg/m^3)	Detonation Velocity (m/s)	C-J Pressure (Mbar)
PETN	1700	7530	0.2518
TNT	1610	6845	0.21
SEP	1310	6970	0.1591

Fig. 1(a) shows schematic representation of Homogeneous explosive model for numerical simulation of high explosive. In this model it contains detonation products of high explosive in gaseous state. Upon ignition it readily expands in the form of homogeneous gas undergoing adiabatic thermodynamic process following JWL EOS in the spherical domain and consequently generating pressure waves in the water medium.

Schematic model for Heterogeneous explosive model is shown in Fig. 1(b), where initial spherical explosive is in solid state which ignites on detonation by C-J Theory forming detonation waves inside the explosives and subsequently formation of pressure waves inside in surrounding water. The explosive-water interface is subjected to steep pressure peaks emanate from the explosion due to the mechanical impact effects on the boundary surface of water, which is nearly incompressible. This explosion scenario is complex physical process generating detonation waves. According to C-J theory release of chemical reaction is complete and instantaneous with shock moving through explosive compressing, heating explosive to activate chemical reaction resulting in formation of detonation front to propagate with constant detonation velocity or C-J velocity. Detonation velocity generally lies between 6000 and 8000 m/s based on the explosive characteristics. The best understood detonation initiation process involves an input shock wave through primary explosives or friction i.e. by external initiation which starts the chemical reactions and eventually develops into a steady detonation wave, usually on the microsecond time scale. This is called a shock-to-detonation transition (SDT) and sometimes also referred as Deflagration to Detonation Transition (DDT) so as to reach constant detonation velocity by shock front. Detonation front generated distinguishes burnt and un-burnt zones inside explosives with propagation of burning zone as shown in Fig. 1(b). Typical transmission time inside the explosive would be order of few milliseconds to convert explosive in product gaseous. The detonation wave converts the solid explosive into a very hot, high-pressure gas. Due to Detonation Shock Dynamics (DSD) phenomenon shock waves induces chemical reaction inside reactive medium and this feeds shock wave to propagate detonation front with detonation velocity thus chemical energy drives shock wave and creating higher building up pressure peaks of order of magnitude 10–50 GPa possessing higher damage potential in the vicinity of explosive. Thus understanding difference between DSD phenomenon in the heterogeneous model and propagation of shock wave by high pressure product gas without DSD in case of homogeneous model for high explosives needs to be studied thoroughly to investigate their correlation which will classify near-field and far-field effect on the basis of damage potential. Many literatures evaluated in the context of detonation theory, propagation of detonation products with numerical simulation and experimental validation [27–31] are few to name.

The difference between homogeneous and heterogeneous model while numerically modelling it with LS-DYNA is Heterogeneous model considers detonation phenomenon with build-up pressure formation inside explosive causing pressure spike at the explosive-water interface with burn fraction model. Thus for considering near-field effects heterogeneous model is important. Once solid state high explosive completely detonates it is converted into the gaseous products and thus behaves as homogeneous model.

1.9. Simplified approach for far field study using JWL equation of state (Fig. 2)

Curve index of JWL equation curve for high explosive varies in zones of the adiabatic expansion process are observed in analytical study of JWL EOS via MATLAB code using explosive properties given in Table 3. The JWL adiabatic curves are plotted against pressure verses relative volume of expansion, V_{rel} is the relative volume indicating ratio of current volume of expanded bubble of detonation products to the original volume of explosive charge. The curves are reversible adiabatic i.e. isentropic in nature as this process happens so quickly. This curves shows variation of adiabatic index gamma in zones within the process of expansion. With deployment of curve fitting technique, the variation of curve index can be accurately detected. The following curve index variations with zones obtained are shown in Table 3.

The subsequent index of JWL curves for PETN, TNT, SEP and C4 high explosives are compared in Fig. 2. Logarithmic scale is used for easy interpretation of JWL curves. Comparing JWL curve of all the above explosives it is experiential that curve for SEP is steeper having largest slope following higher gamma value, thus for same pressure variation in expansion process work done will be least because it will expand by the less amount, thus less energy will release. SEP is having lowest peak pressure value while C4 having largest. The JWL curve for C4 has least slope therefore work done under same pressure variation is largest in C4 following highest release of energy. JWL curves for TNT and PETN are moderate in nature as compared to above explosives. This analysis demystifies the behaviour of the high explosives used in the underwater explosion and gives idea of damage potential on the structure placed in the vicinity depending on the strength of explosive used and their spatial variation in the. The curve index of polytropic process is observed to be high at initial zone and with time progression it tends to reduce in further zones with expansion.

Table 3
JWL curve index variation with zone.

Explosive	First zone index	Second zone index	Third zone index
PETN	2.704	1.39	1.28
TNT	3.1759	1.8514	1.2859
SEP	3.98	2.65	1.2803
C4	3.2492	2.23	1.323

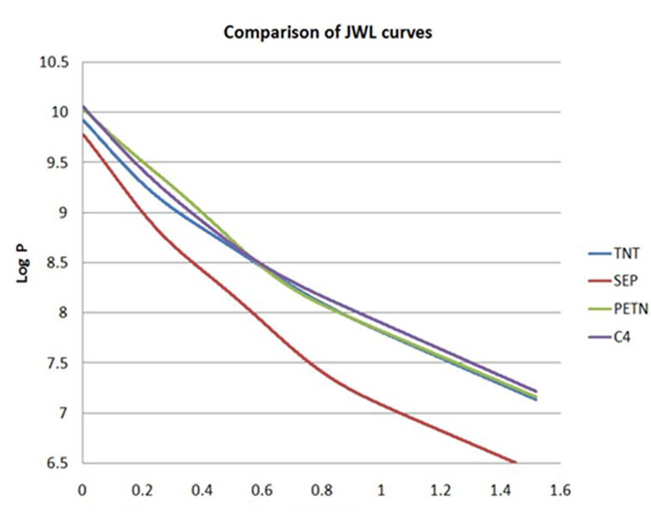

Fig. 2. Comparison of JWL curves for typical high explosives.

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Table 4
Properties of high explosives in PV^{γ} form EOS.

Explosive	Initial Pressure (GPa)	First phase curve index (γ)
PETN	10.905	2.704
TNT	8.383	3.1759
SEP	6.018	3.98
C4	11.361	3.2492

This curve index is dependent on the volumetric expansion of these gaseous products with time. As water is incompressible fluid it does not allow expansion of explosive charge or it is not much significant in practice. The product gas bubble formed after detonation of high explosive in water remains almost of constant volume, due to constrained space for expansion induced from incompressibility and hydrostatic force of water at deep altitude. Thus for underwater explosion JWL curve is restricted for first zone and it not allows expanding in further zones. The peak pressures generated with these explosives in the first zone with subsequent adiabatic index are shown in Table 4.

The JWL equation of state forms analogy with PV^{γ} form of adiabatic expansion of detonation product gaseous. This process is rapid, showing quick reduction of energy with small increase in volume. Thus for modelling high explosive for far-field effects study along with homogeneous explosive model, PV^{γ} form equation of state can be used successfully with using initial pressure generated and curve index obtained in the first zones by analytical study in case underwater explosion. Thus complexity of JWL equation with large parameters is avoided by using only two parameters. The behaviour of adiabatic expansion process is easy to interpreted, as the engineers are familiar with it.

1.10. About computer code LS-DYNA and methodology

LS-DYNA explicit finite element code is used for analysis of underwater explosion phenomenon in deep infinite water boundary medium. LS-DYNA is particularly used code for large deformation dynamic response for structures as well as coupled fluid–structure interaction problems based on explicit time integration occurrence. With facility of spatial discretization using discrete elements, four nod tetrahedron and eight node solid elements, truss elements, eight node solid elements and rigid bodies. Material is modelled using constitutive material models and its behaviour using EOS. LS-DYNA has ability to solve problems using different finite elements methodologies viz. Lagrangian, Eulerian and Arbitrary Lagrangian Eulerian (ALE). In a typical numerical simulation of underwater explosion event large mesh distortion problem will arise due to shock wave and hence trouble explicit calculations. To deal with this problem ALE method is deployed to tackle with this problem. ALE method has capability of rezoning mesh with split operator technique.

Equation of state (EOS) models employed in LS-DYNA to transmit the internal energy, density, pressure and volume of specified materials. EOS is used for initializing internal characteristics of elements in the specified domain. EOS along with material models are used for formative internal force function of elements in specific domain. In this problem water has been modelled with Gruneisen EOS to specify characteristics of water. This EOS has ability to handle shock waves propagation in underwater explosion phenomenon due to ability to handle fluid in tension and compression as well as ability to integrate nonlinear shock velocity-particle velocity relationship.

The Gruneisen EOS with cubic shock velocity-particle velocity defines pressure for compressed material as

$$P = \rho_0 C^2 \mu [1 + (1 - \gamma_0/2)\mu - a/2\mu^2]/[1 - (S_1 - 1)\mu] + (\gamma_0 + a\mu)E \quad (2)$$

wherere $= (1 - V)/V$, ρ_0 = 1000 kg/m^3, C = Sonic velocity = 1484 m/s, γ_0 = 0.11, S_1 = 1.979, a = 3 and E = 0 for water.

Similarly different explosives in the problem have been modelled with JWL EOS. *MAT_NULL material model is used for modelling fluids, it has ability to define dynamic viscosity with inclusion of strain rate and capability to calculate stresses in fluid. *MAT_NULL material model is used for modelling water and explosive only in case of homogeneous explosive model used in this case as it contains products of high explosive in gaseous (fluid) state along with using their respective density with *INITIAL_VOLUME_FRACTION_GEOMETRY card as this treats material represented by boundary of geometry same as it is modelled with mesh.

For modelling high explosives in case of heterogeneous model as defined earlier * MAT_HIGH_EXPLOSIVE_BURN material card in LS-DYNA is used for modelling high explosives with JWL EOS for calculating pressure. This material model is incorporated with burn fraction algorithm and pressure inside explosive upon detonation is calculated by controlling release of chemical energy.

$$P = F.P_{JWL} \quad (3)$$

where, F is burn fraction. This burn fraction (F) is calculated with two means; with one is beta burn option, Beta = 1 which is used to calculate burn fraction (F_1) of high explosives by volumetric compression. Another option is calculating burn fraction by beta programmed burn option. Beta = 2, programmed burn algorithm for calculating burn fraction (F_2), works on the principle of lighting time t_1 calculated for each element by dividing the distance from the detonation point to the centre of an element by detonation velocity (D) for any particular time t, as detonation front swipes each element to calculate F_1 where material behaves as elastic-plastic material and allows compression without detonation.

$$F_1 = 2(t - t_1)DA_{emax}/3v_e, when t > t_1; F_1 = 0, when t \le t_1 \quad (4)$$

$$F_1 = 1 - V/1 - V_{CJ} \quad (5)$$

where, F exceeds 1, it is reset to 1 by default, t is the current time, V is the current volume, V_{CJ} is the C-J pressure of the explosive and A_{emax} is the maximum projected area of an element. Finally maximum burn fraction between F_1 and F_2 is taken for use in equation which will be used in equation (5)

$$F = max(F_1 or F_2) \quad (6)$$

Thus detonation will initiate by detonation front propagation or volumetric compression whichever is earliest in the sense. This burn fraction plays crucial role in the propagation of detonation wave inside the explosive which is deployed in heterogeneous model by controlling release of chemical energy and separating burnt and un-burnt zones with control on propagation of detonation front.

In * MAT_HIGH_EXPLOSIVE_BURN model needs to provide corresponding density, detonation velocity, C-J Pressure of high explosive. The detailed information about LS-DYNA code with material cards and EOS has been adopted from [32].

1.11. Parameters studied and important results (Figs. 3–20)

This study emphasis on the prediction of characteristics of pressure wave and its mechanical effects i.e. pressure and velocity variation along the travel starting from explosive-water interface so as to find the damage potential of explosive on the waterborne structures through numerical modelling of underwater explosion in LS-DYNA software code with typical spherical high explosives along with variation of charge weight ranging from 40 g to 7 kg which is achieved by varying radius of charge from 20 mm to 100 mm for PETN, SEP and TNT each with increment of 10 mm interval.

The spatial pressure and velocity variation along spherical radial line of detonation/explosion centre in the water medium are presented in the graphical format starting from explosive-water interface, comparing for a particular explosive with same parameters, at same distance for both homogeneous and heterogeneous explosive model. Similar methodology has been adopted for analysis of all explosives. The meshing of spherical explosive has been done by deployment of quadrilateral-shell ALE elements. The analysis has been carried out for different cases in the range of 250 μs to 500 μs termination time depending upon explosive type and range in water field to be considered. The LS-DYNA has provision of automatically selecting the time step control of simulation; here it is in the range of 1e-7 to 3e-7 depending upon the explosive radius and type for analysis.

Actual curves are shown for peak pressure Variation of shock wave with distance while for velocity distribution variation trend line is preferred. Velocity distributions of pressure waves are calculated depending upon time taken between two consecutive peak pressures with respect to distance of propagation.

While evaluating this results, a point in water domains comes after which the mechanical effects shows similar trend of variation comparing homogeneous and heterogeneous explosive model for same charge radius and same explosive type. The distance from explosive centre to this transition point is called transition radius (R). Here maximum 10 percentage tolerance is allowed for selecting the transition radius. Due to space limitation results for 20 mm, 50 mm and 100 mm charge radius for each type of explosives are shown in Figs. 3–20.

Upon minute study of the behaviour of pressure wave propagation and its mechanical effects, both the explosive model found that beyond certain distance (transition Radius), propagation of pressure wave is merely same in both the models irrespective of the explosive type, thus having same damage potential considering peak pressure and velocity of shock wave. Beyond transition radius there exists only far-field effects.

1.12. Synthesis of result (Figs. 21 and 22)

All the consolidated results are assembled to form successful relation establishment of spatial variation of pressure as well as for velocity of shock wave among homogeneous and heterogeneous explosive model in underwater explosion. The variation of transition radius with respect to the charge radius for all explosives is shown in Fig. 21. Thus beyond transition radius both models tend to have same variation of peak pressure. The relation obtained between the variation of transition radius for high explosives with

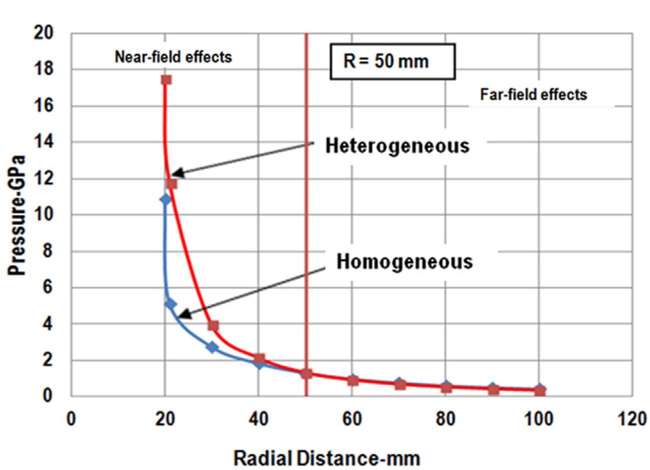

Fig. 3. Spatial variation of pressure for 20 mm charge radius of PETN.

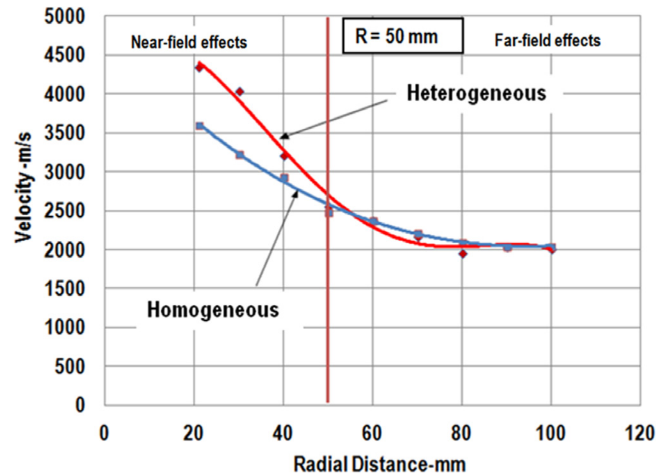

Fig. 4. Spatial velocity distributions for 20 mm charge radius of PETN.

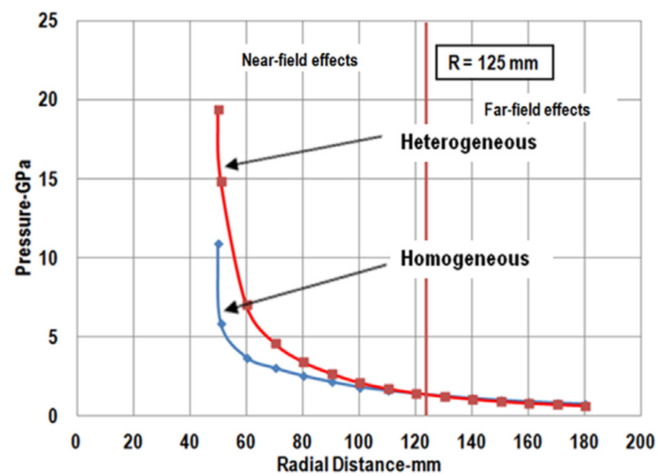

Fig. 5. Spatial variation of pressure for 50 mm charge radius of PETN.

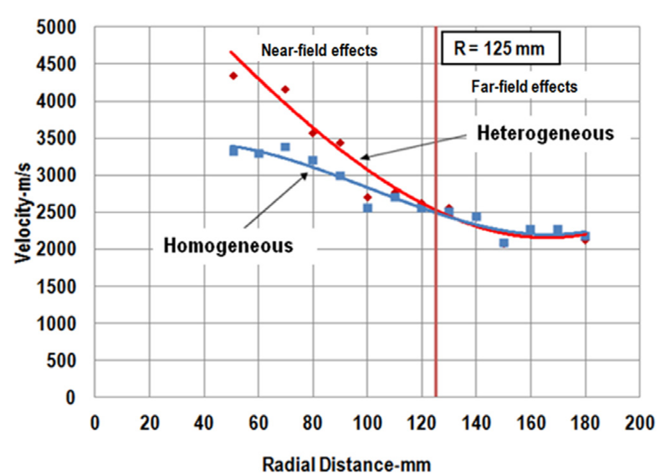

Fig. 6. Spatial velocity distributions for 50 mm charge radius of PETN.

respect to charge radius is following R = 2.490 r. Thus transition radius is 2.490 times that of charge radius irrespective of the explosive used.

Similarly, the velocity distribution results for all the explosives with varying charge radius are compiled together to form

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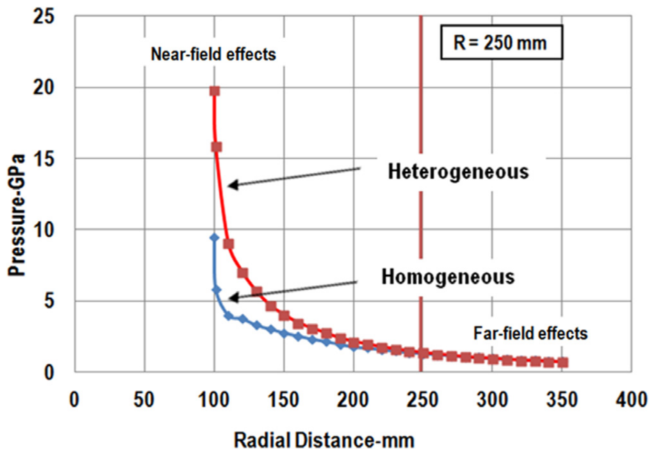

Fig. 7. Spatial variation of pressure for 100 mm charge radius of PETN.

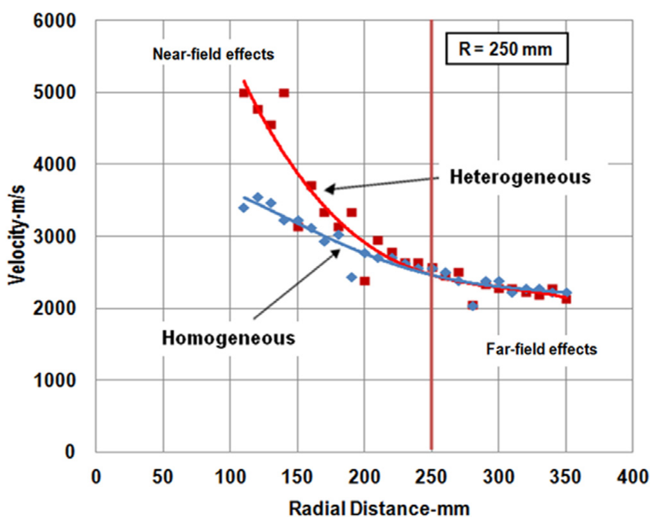

Fig. 8. Spatial velocity distributions for 100 mm charge radius of PETN.

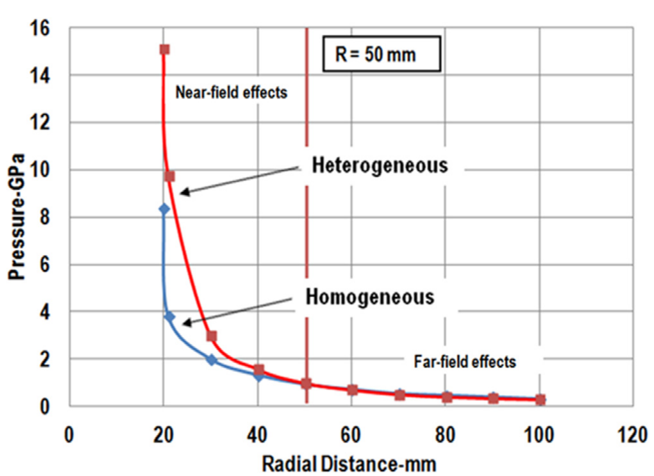

Fig. 9. Spatial variation of pressure for 20 mm charge radius of TNT.

successful relationship between transition radius variation with respect to charge radius shown in Fig. 22. It is observed to be R = 2.437 r. Thus in case of velocity distributions transition radius distinguishing near-field and far-field effects is obtained at distance of 2.437 times that of charge radius. R value for regression in Fig. 21 and Fig. 22 is presented in Table 5 and Table 6. Also,

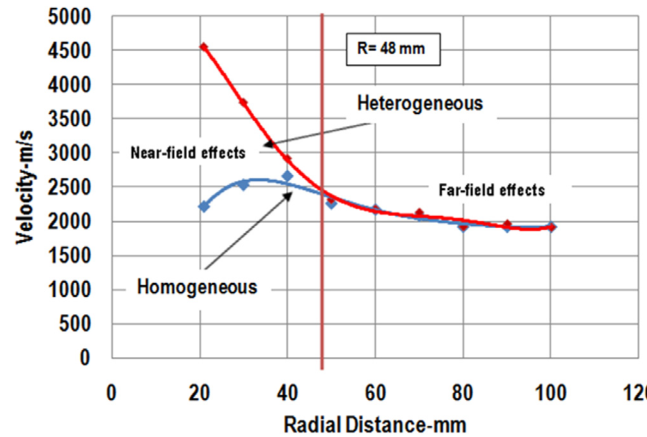

Fig. 10. Spatial velocity distributions for 20 mm charge radius of TNT.

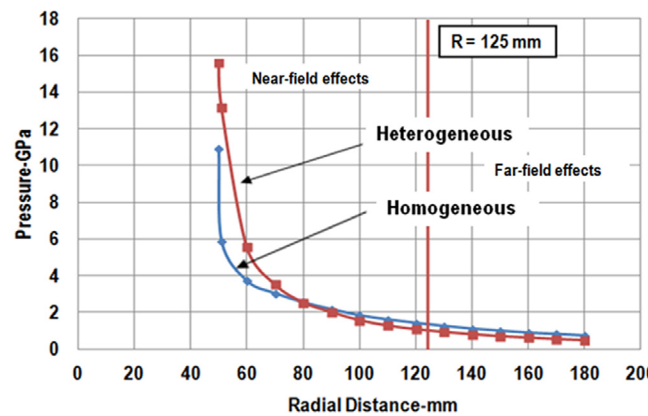

Fig. 11. Spatial variation of pressure for 50 mm charge radius of TNT.

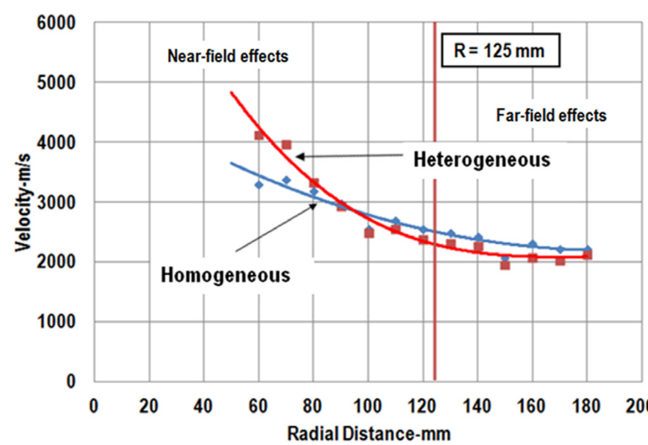

Fig. 12. Spatial velocity distributions for 50 mm charge radius of TNT.

Fig. 23 represents the R value for regression in Fig. 21 (pressure with variation of charge radius) and Fig. 24 represents the R value for regression in Fig. 22 (velocity distributions with respect to charge radius).

1.13. Conclusion

This study makes clear transition between near-field and far-field effects of underwater explosion. Depending upon the charge

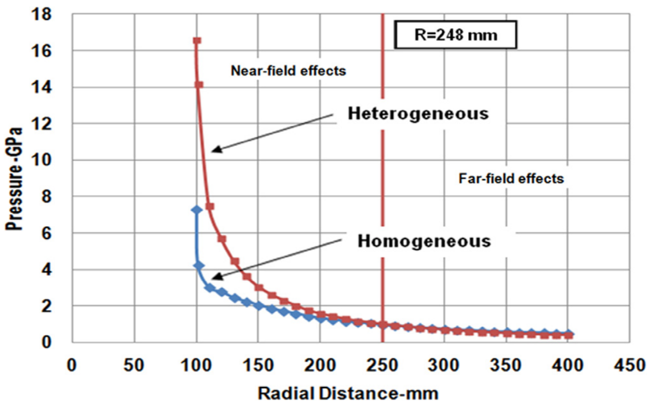

Fig. 13. Spatial variation of pressure for 100 mm charge radius of TNT.

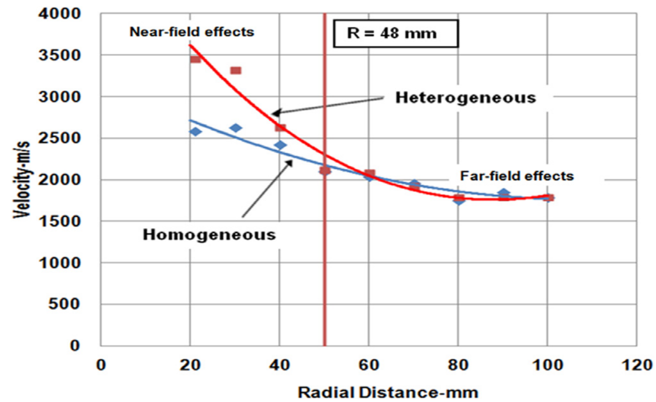

Fig. 16. Spatial velocity distributions for 20 mm charge radius of SEP.

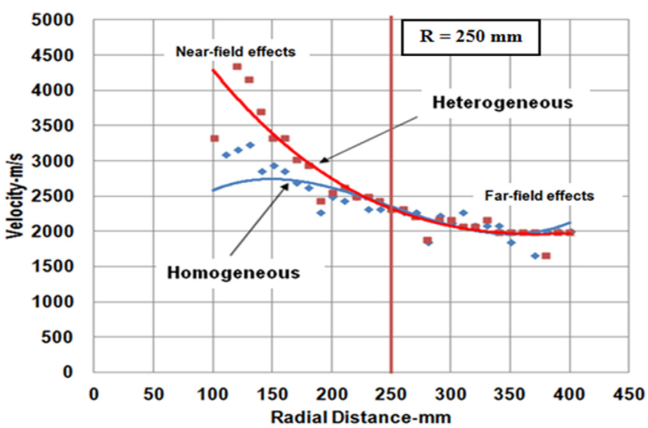

Fig. 14. Spatial velocity distributions for 100 mm charge radius of TNT.

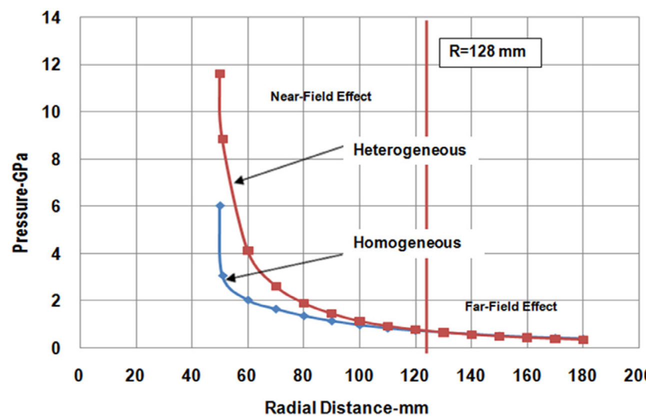

Fig. 17. Spatial variation of pressure for 50 mm charge radius of SEP.

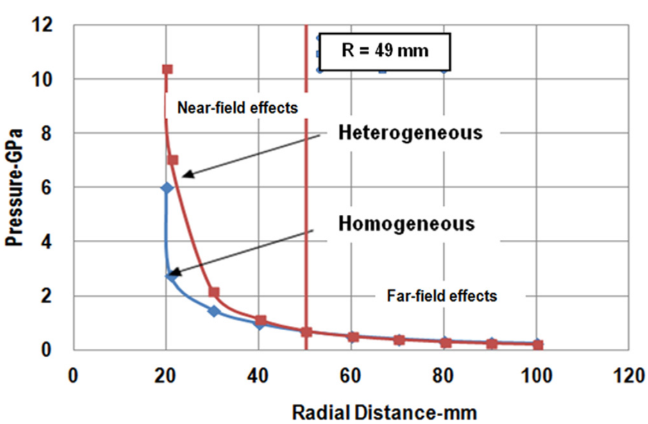

Fig. 15. Spatial variation of pressure for 20 mm charge radius of SEP.

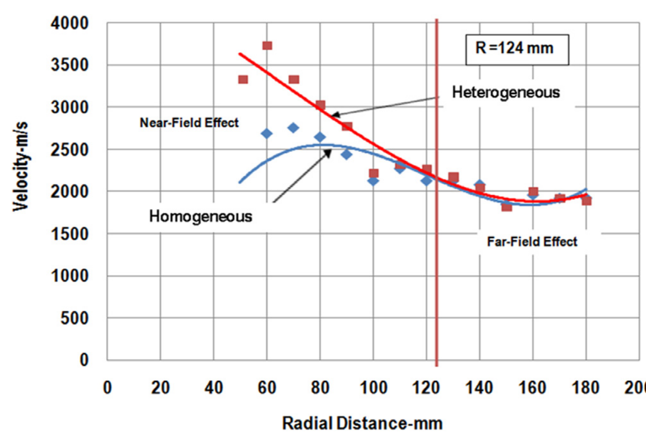

Fig. 18. Spatial velocity distributions for 50 mm charge radius of SEP.

radius of spherical explosive and irrespective of the explosive type near-field effects exists up to distance of 2.5 times that of charge radius in water field i.e. transition radius (R) of explosive, beyond which near-field effects vanishes and only far-field effects remains. This helps for designing and predicting performance of underwater structures depending upon distance from explosion point. Consequently more simplified constitutive model for explosive can be used on these criteria.

Homogeneous explosive model can be used contentedly for studying far-field effects on the structures without using heterogeneous explosive model along with C-J theory and burn fraction model. Moreover depending upon target structure distance if structure is placed beyond 2.5 times radius of spherical explosive instead of JWL equation of state to reduce complexity of calculation and computational time.

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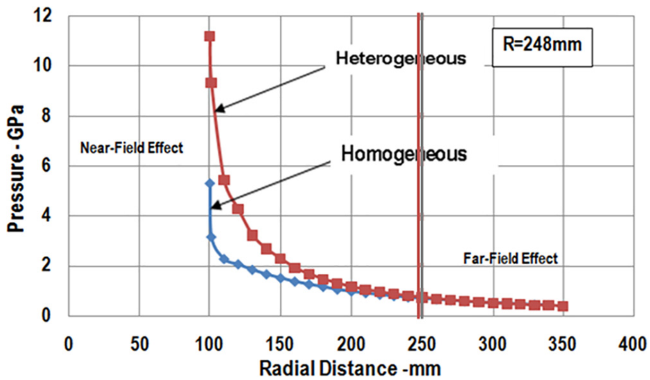

Fig. 19. Spatial variation of pressure for 100 mm charge radius of SEP.

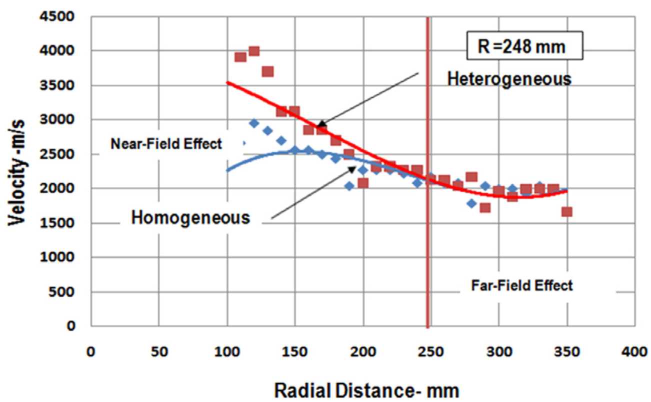

Fig. 20. Spatial velocity distributions for 100 mm charge radius of SEP.

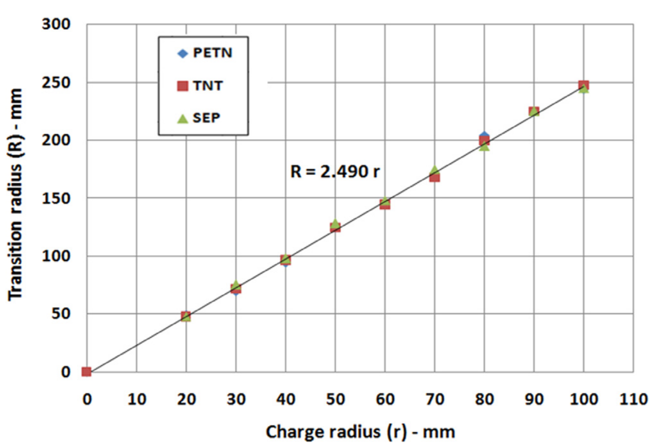

Fig. 21. Variation of transition radius for pressure with variation of charge radius.

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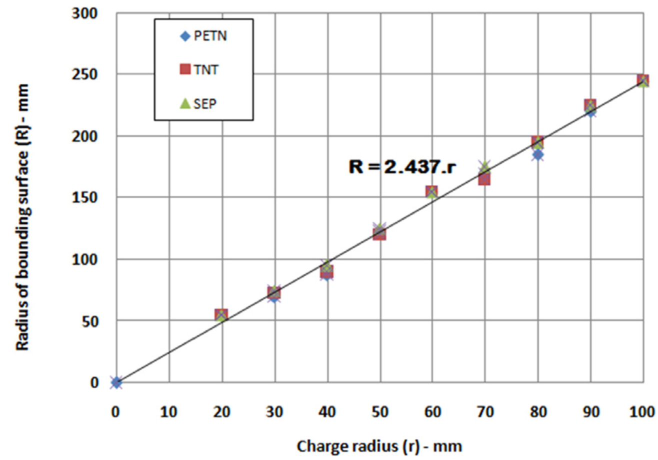

Fig. 22. Transition radiuses for velocity distributions with respect to charge radius.

Table 5
Transition radius variation w.r.t to charge radius for pressure.

R (mm)	r (mm)
0	0
20	48
30	75
40	98
50	128
60	148
70	175
80	195
90	225
100	245

Table 6
Transition radius variation w.r.t to charge radius for velocity.

R (mm)	r (mm)
0	0
20	60
30	80
40	100
50	130
60	160
70	180
80	200
90	230
100	250

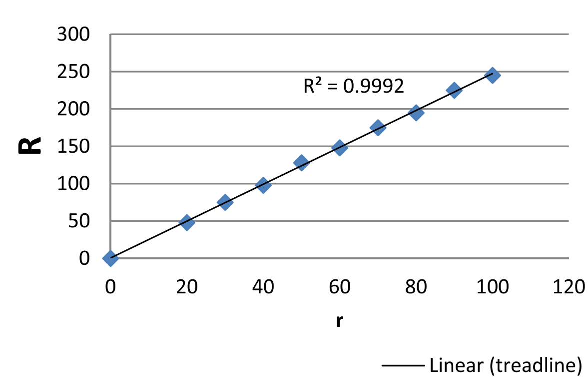

Fig. 23. R value for regression in Fig. 21 (pressure with variation of charge radius).

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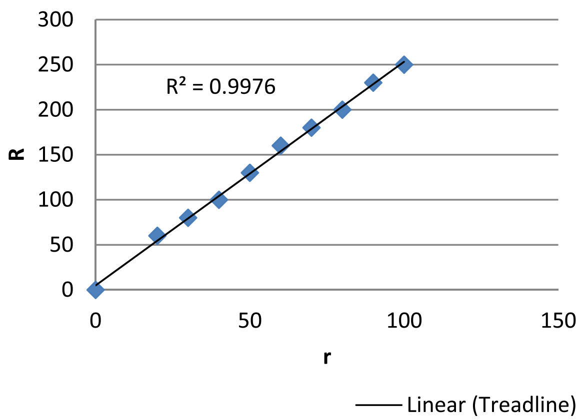

Fig. 24. R value for regression in Fig. 22 (velocity distributions with respect to charge radius).

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