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Impact Dynamics and Interaction of Naval Structures with Waves and Sea Bottom

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Award #: N00014-10-1-0230

LONG-TERM GOALS

The long term goal of this research is twofold: (1) develop advanced multi-physics, multi-scale models to predict nonlinear dynamic behavior of water free-surface and sea-bottom impact, and subsequent burial and flow-induced motion of flexible structures and surrounding sediments in the marine environment; and (2) calibrate resulting models with experimental and field measurements. The predictive capabilities developed in this research will be integrated into an overarching computational framework for the analysis and simulation of the dynamic behavior of naval systems in the marine environment of arbitrary water depth.

OBJECTIVES

The deployment of mines via airdrop and subsequent sea free-surface impact, sinkage, sea-bottom impact, burial and scour around sediments is of vital interest to the Navy. Until recently, no numerical codes that can accurately model and simulate this sequence of dynamic motions and their effects on the overall burial behavior at the sea bottom are available. The major objectives of this research include assessment of the state-of-the-art analytical and numerical modeling capabilities, evaluation of the predictive capabilities of the numerical codes for coupled dynamic motions of submerged mines on a seabed in the marine environment, and further improvement of these analytical models and numerical codes to suit naval analysis, design and operational needs. The analytical and numerical predictive capability of these models will be calibrated against experimental results.

APPROACH

The dynamic behavior of sea-surface impact and submergence of air-dropped mines and their subsequent interaction with surrounding sediments has been of interest to the Navy in recent years. During 1960s-1980s, U.S. Naval scientists developed a few burial prediction models that can be used for mine countermeasure tactical planning and for development of environmental support: sea-surface impact, sea-bottom impact burial, sand ridge migration, and wave-induced scour. Capabilities for accurate modeling and prediction of motions of mines impact at the water free surface and sea bottom, and their effects on the subsequent burial behavior considering the detailed physics of the entire coupled mine-fluid-sediment-seabed "system" are needed. In this phase of the project, we focus our research efforts on the development of a 3-dimensional (3-D) multi-physics numerical codes and semi-analytical solutions of rigid-body water free-surface impact based on numerical (finite-element and smoothed particle hydrodynamics) simulations and improved semi-analytical von Karman and Wagner approximations.

The overall objectives of this research project is achieved through the following tasks: (1) evaluate the current predictive capability of LS-DYNA for coupled dynamic motions of submerged mines on a seabed in the marine environment; (2) identify development needs and further develop LS-DYNA for coupled fluid-structure-seabed interaction applications. Simultaneously, our group has been developing approximate semi-analytical procedures building on the von Karman and Wagner approaches; (3) calibrate the computational efficiency of LS-DYNA; (4) compare numerical predictions of resulting numerical modules developed with laboratory experiment; (5) conduct parametric studies of characteristic impact mechanics; and (6) analyze and document the research results.

WORK COMPLETED

Simulations Using ALE Finite-Element Model – Simulations using the ALE finite-element model were performed over a wide range of conditions (Challa et al a &b). The characteristics of entry speed, entry angle, and vehicle weight were varied. For each simulation, a total of 2000 data sets were created from the simulation. Displacement, velocity and acceleration of the model were recorded at each data dump. An important result from these simulations was the peak acceleration experienced by the object upon impact. Each simulation output were filtered to remove the 'noisy peaks' caused by modeling the otherwise unbounded water domain as a finite one.

Bounds on maximum acceleration due to impact of a rigid object water re-entry were obtained analytically. For a rigid object with a spherical bottom, closed form solutions based on the von Karman and Wagner approaches were correlated with the results obtained from the explicit finite element analyses. The boundary conditions for the analytical approach included the free surface kinematic boundary condition, the free surface dynamic boundary condition and the radiation boundary condition. The pressure on the body was determined according to Bernoulli equation, and the impact force on the body can be obtained by direct integration of the pressure over the wetted body surface theory.

It is important to note that the maximum radius of the base (for a $1/6^{th}$ Froude-scale model of dropped object) is 338.5mm and the radius of the conical portion impacting the water surface was 84.8mm. For a conical bottomed rigid object, the analytical results showed that there was large difference between the experimental peak impact accelerations and those obtained by von Karman and Wagner analytical estimates. The large difference could be attributed to the conical shape of dropped object bottom impacting the water surface compared to the large spherical bottom used in deriving the closed form solutions. In addition to the unique shape of the dropped object, the basic assumptions of the formulations for both von Karman and Wagner approaches also played a pivotal role in contributing to the large difference. The von Karman approach was based on the momentum theorem (using an added virtual mass) and the penetration depth was determined without considering the splash-up of the water level, thus neglecting the highly nonlinear coupled fluid-structure interaction effect. The Wagner approach, on the other hand, attempted to relax the von Karman no-splashing assumption by using a rigorous dynamic formulation and incorporated the effect of the upward splashing of the water and its effects on the object. With the upward splashing correction, the Wagner approach tended to over predict the maximum impact retardation as it neglects the water compressibility (i.e. a more yielding fluid) near the impact zone.

Simulations Using SPH Models – Smoothed particle hydrodynamics (SPH) is an N-body integration scheme to avoid the limitations of mesh tangling encountered in extreme deformation problems with the FE method (Challa et al. a & b). The main difference between classical methods and SPH was the absence of a grid. Hence, the particles were the computational framework on which the governing equations were resolved. The main advantage, however, arose directly from its Lagrangian nature, since such an approach could tackle difficulties related with lack of symmetry, large voids that might develop in the field, and a free water surface much more efficiently than Eulerian methods could. The conservation laws of continuum fluid dynamics, in the form of partial differential equations, were

transformed into particle form by integral equations through the use of an interpolation function that gave kernel estimation of the field variables at a point. The Gruneisen equation of state that was used for the ALE method was retained for simulation the water domain that was modeled using a Null material model. However, the speed of sound at the reference density was set to 100m/s as the acoustic speed is not important for the present problem. It is worthy to note that this sound speed was much lower than that of a real fluid, but much faster than any water waves in the model.

Development of Semi-Analytical Approximation Procedure – The reliability of the experimentally measured maximum accelerations was calibrated with classical von Karman and Wagner approximate closed-form solutions. For a conical bottomed rigid object, the analytical results show that there is a large difference between the experimental peak impact accelerations and those obtained by these analytical estimates. The large difference can be partly attributed to the unique shape of the dropped object and partly due to the assumptions of the formulations for both von Karman and Wagner approaches. Owing to the large difference between the experimental accelerations and those provided by von Karman and Wagner approaches, an improved approximate solution procedure using an "equivalent" radius (r) of the dropped object was estimated to understand the physics of the impact (Challa et al. a & b). It could be observed that the von Karman approach tended to estimate a lower value of the radius of the conical portion whereas the Wagner approach tended to estimate a higher value of the impact radius. As the effect of local rose up of the water was significant during water entry of a rigid 3D object, the von Karman predictions for maximum impact accelerations were not significant in determining the maximum impact accelerations for the water entry of dropped object. Based on the equivalent radius approach, the approximate analytical solutions of von Karman and Wagner could be used to obtain design maximum accelerations of the dropped object model consistent with experimental results. Further, the mean equivalent radius (r*) was computed to analytically estimate the maximum impact accelerations (for varying impact velocities).

RESULTS

Finite-Element Predictions and Analysis

Effects of Vertical Velocity Variation – The vertical velocities of the dropped object at impact considered in this numerical study ranged from 10m/s to 4 m/s (with 9.8 m/s corresponds to the maximum scaled down impact velocity upon water landing). For a 5m drop height, the peak acceleration upon impact corresponded to 51.52 m/s^2.

Effects of Entry Angle Variation – The entry angles of the dropped object upon impact were varied from 15 to 30 deg to examine its influence on peak acceleration. These simulations showed that the impact acceleration could be reduced by having the dropped object enter the water at an angle. Figure 1 shows the animation images at various time steps. These plots show the fringe levels at various stage of penetration successfully demonstrated the ALE features for the impact problem.

Effects of Weight Variation – The effects of variations in the object weight were examined by varying object weights ranging from 2.5 kg to 5 kg (3.5kg corresponds to the experimental case-II involving an electromagnetic drop mechanism). The general trend showed a small advantage gained in reduced the g-force for a large increase in weight. Trends obtained from acceleration time history data for a 3.5 kg model were similar to the ones attained for case-I. The acceleration time history for a weight of 3.5kg of dropped object yielded a value of 35.48 m/s^2. The peak acceleration from the FE simulations and the experimental data for case–II were 35.50 m/s^2 and 36.50 m/s^2, respectively, showing good predictive capability of the numerical model.

SPH Predictions and Analysis

Effects of Vertical Velocity Variation – The vertical velocities ranged from 10m/s to 4 m/s, of which 9.81 m/s corresponded to the nominal scaled down impact velocity upon water landing. The elevation of the mesh impingement using the SPH formulation is shown in Figure 2. Figure 3 shows

a good comparison between the experimental results and the ALE and SPH results for maximum impact acceleration. The graph indicate that the trend of impact accelerations increased and happening must faster with an increase in the entry speed. Figure 3 also shows the plot of accelerations obtained analytically vs. drop height for the dropped object model (using the original radius of the dropped object). It is important to note the values of maximum impact accelerations are almost identical for both von Karman and Wagner solutions.

Effects of Entry Angle Variation (Pitch Tests) – To determine the effect of varying the entry angle of the dropped object upon impact, the entry angle was varied from 15 to 30 deg. As expected, the impact acceleration could be reduced by having the dropped object enter the water at an angle. It was also important to note that the SPH results match reasonably well with the ALE results for the inclined impact tests. Note that there were no experimental results to calibrate the numerical predictions (no angle variation tests were conducted). However, it was nevertheless interesting to observe the closeness of prediction results obtained by the two numerical models. This also demonstrated the usefulness of numerical simulations once the models have been calibrated by other experimental data.

Effects of Weight Variation – The effect of varying the dropped object weight was obtained by testing weights ranging from 2.5 kg to 5 kg. A test for 3.5 kg corresponded to the experimental case-II involving an electromagnetic drop mechanism. It could be observed from the results that as the object got heavier the impact accelerations reduce dramatically. The general trend showed a small advantage gained in reduced *g*-force for a large increase in weight. Figure 4 shows the comparison of experimental results from the electromagnetic release mechanism with the ALE and SPH formulation. Observe that the peak acceleration decreases linearly with the successive decrease in the height of drop and the peak acceleration was reduced due to the increase in the weight of dropped object. Importantly, there was good comparison of the experimental results with both the numerical simulations. The plot of accelerations obtained analytically vs. drop height for the dropped object model (using the original radius of the dropped object) is also shown in Figure 4. The plot also depicts that the values of maximum impact accelerations (obtained analytically) are almost similar for both von Karman and Wagner solutions.

Semi-Analytical Prediction Procedure

Results from examining predictive capability of the semi-analytical predictions showed the maximum impact accelerations obtained by both the semi-analytical estimates compared reasonable well with the experimental acceleration values. In order to achieve accelerations comparable to the closed-form solutions, the analytical results showed that, for the design of a dropped object, the Wagner approach provided a correct estimate of the equivalent radius of the object. It was, however, interesting to note that the acceleration values obtained by von Karman and Wagner solutions produced accelerations that were similar ascertaining the importance of the shape of the dropped object during water impact.

To capture the proper modeling of the dynamics of the impact and to ascertain a true fluid behavior, an attempt was made to calculate an equivalent radius of the conical portion of the dropped object that would compare well with the experimental maximum impact accelerations. From the von Karman approach, the equivalent radius for Drop Test I and II were 30.0 mm and 29.3 mm, respectively. It was observed that the von Karman approach tended to estimate a lower value of the radius of the conical portion. As the effect of local rise up of the water is significant during water entry of a rigid 3D object, the von Karman predictions for maximum impact accelerations were not significant in determining the maximum impact accelerations for the water entry of the dropped object. The Wagner approach on the other hand estimated the equivalent radius for Drop Test I and Drop Test II as 107.5mm and 131mm, respectively.

To further comprehend the effect of the shape of the object (especially the conical portion of the dropped object impacting the water surface first), the values of equivalent radius (r) were plotted against different velocities of impact for both Drop Test I and II. The equivalent radius (r) was initially obtained for each drop velocity for both the experimental cases. The idea was to obtain those values of the radii that

would give the same experimental impact accelerations corresponding to the impact velocities. It can be observed that from Figure 5 the values of equivalent radius (r) of the dropped object model remain almost constant for different velocities of impact for both cases.

The next step was to compare the accelerations obtained experimentally (Drop Test I and II) to those obtained by using a mean equivalent radius (r*). The values of r* were obtained by taking the mean of all the equivalent radii obtained for different impact velocities corresponding to their respective impact accelerations. For each r* obtained for each case, the impact accelerations were calculated by varying the impact velocity. Figure 6 shows the comparison for the maximum impact accelerations and those obtained by the mean equivalent radius (r*). The figure shows that the maximum impact accelerations obtained by both the semi-analytical models seem to compare reasonably well with the experimental peak impact accelerations. It is interesting to note that the acceleration values obtained by von Karman and Wagner solutions produce accelerations that are similar ascertaining the importance of the shape of the dropped object during water impact. Based on the equivalent radius approach, it was concluded that approximate semi-analytical solutions based on the von Karman and Wagner theories could be used to obtain design maximum accelerations of the dropped object model consistent with experimental results.

IMPACT/APPLICATIONS

We have demonstrated that the arbitrary Lagrangian-Eulerian finite-element and smoothed particle hydrodynamics models developed can be applied to model practical experimental problems. With the experimental validation performed and the semi-analytical approximate procedure developed in this study, applications of these combined models can be extended to prediction of behavior of large-scale mine deployment operations in the field.

TRANSITIONS

Analysis and simulation capabilities developed in this research can be useful to the various units of the Navy pertinent to mine deployment, detection, burial clearance process studies.

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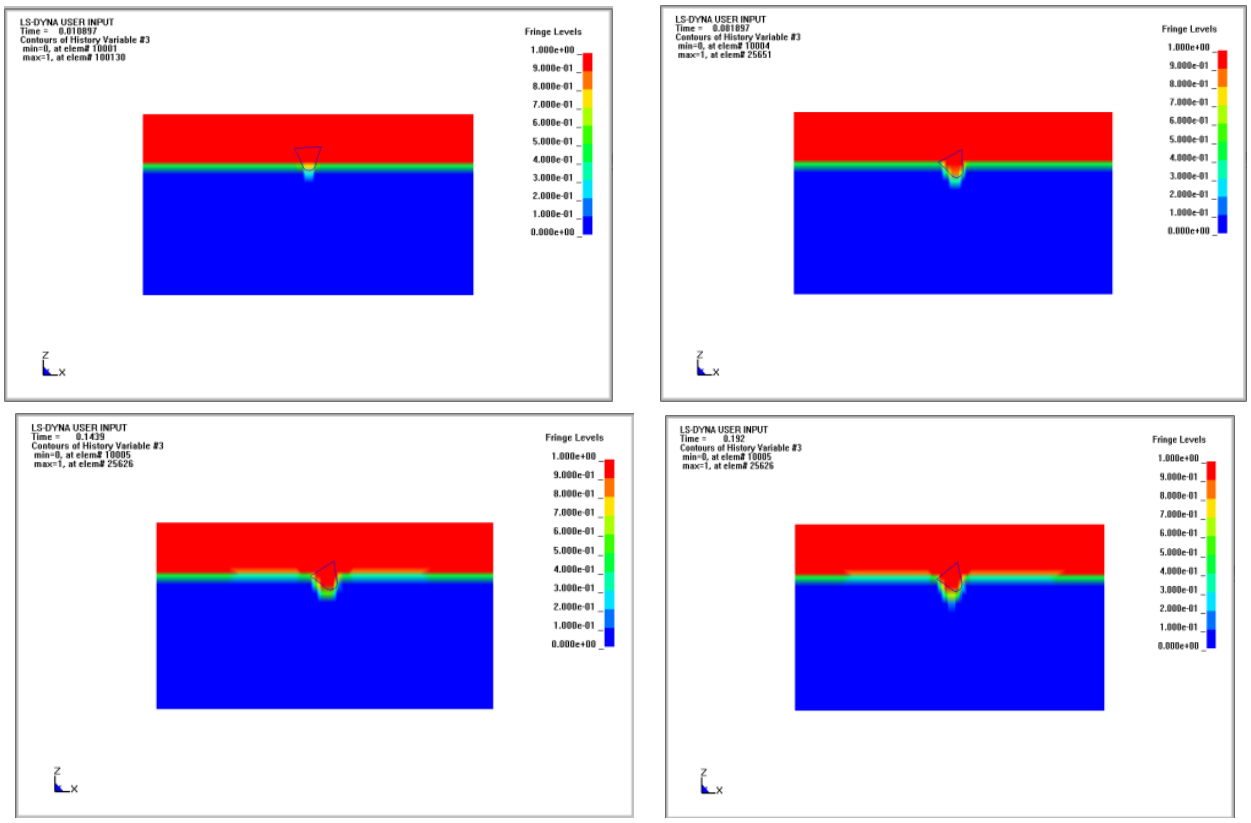

Fig. 1 Animation images at various time steps for 15 deg impact

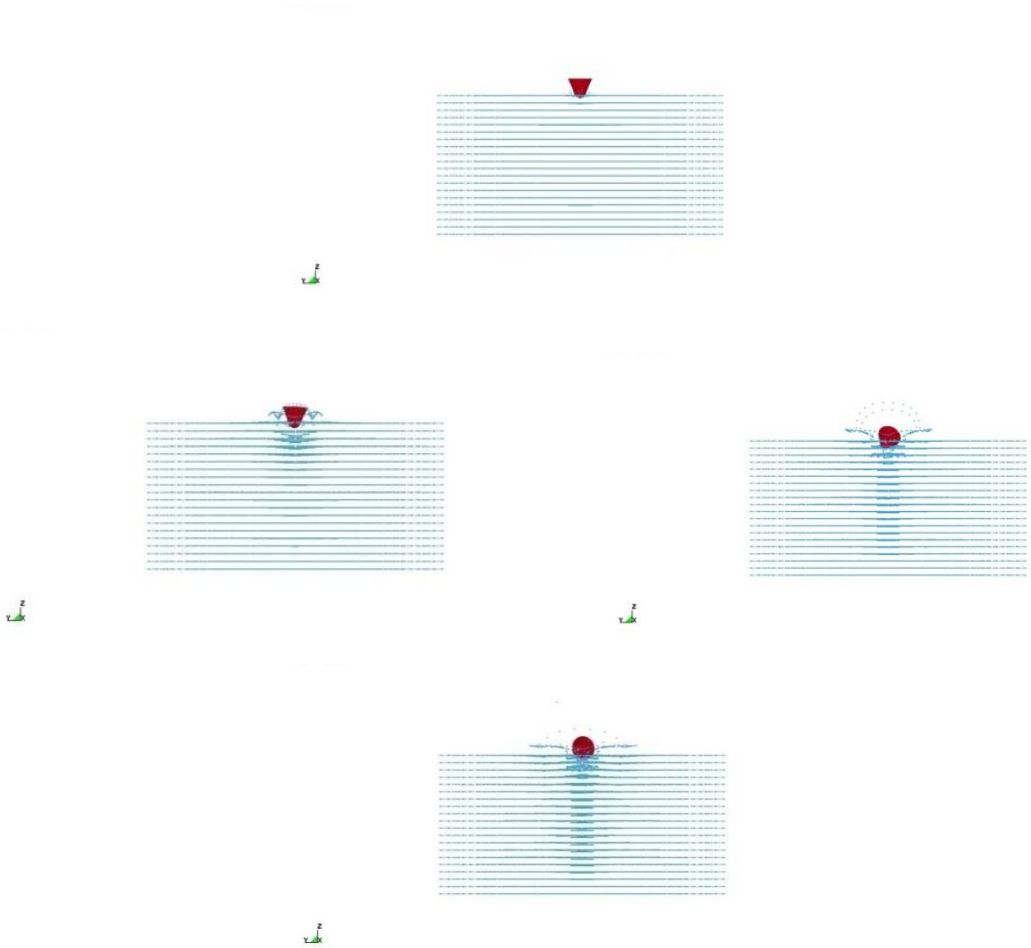

Fig. 2 Elevation view of the particle mesh impingement using the SPH method

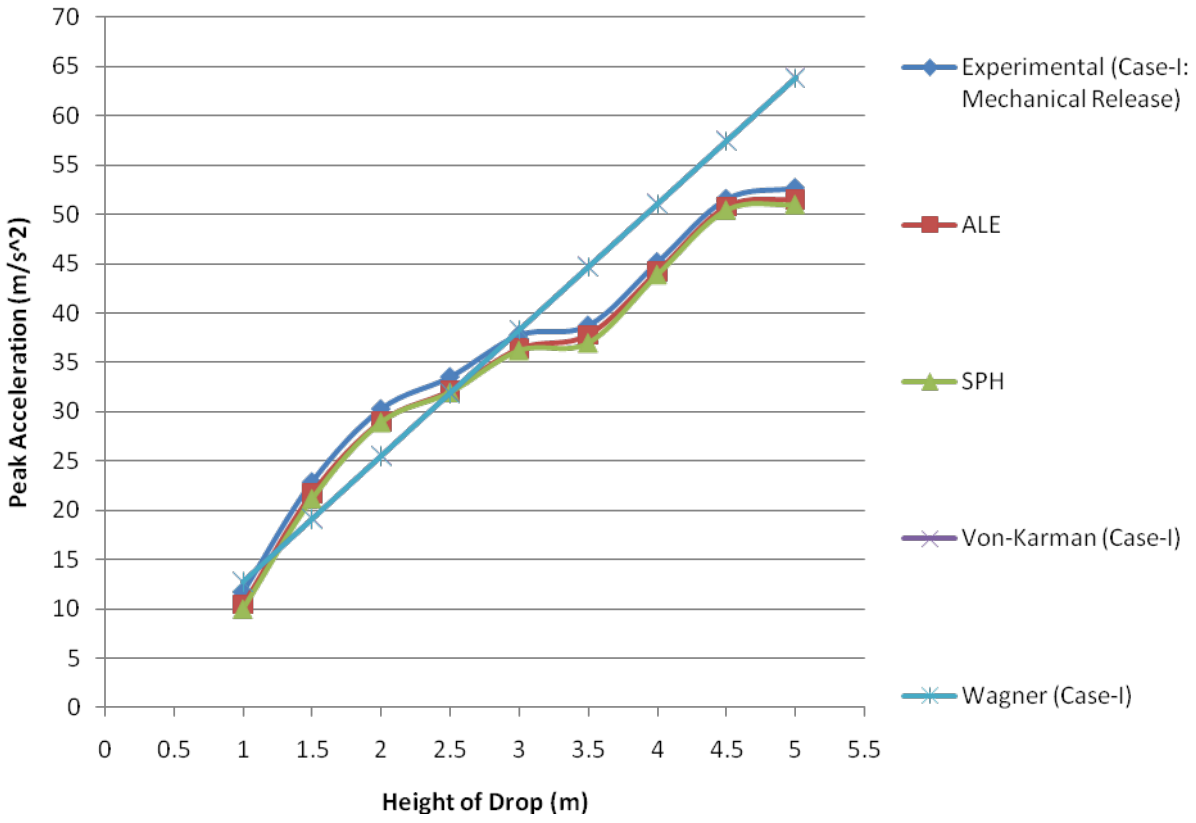

Fig. 3 Comparison of results for maximum acceleration with ALE and SPH

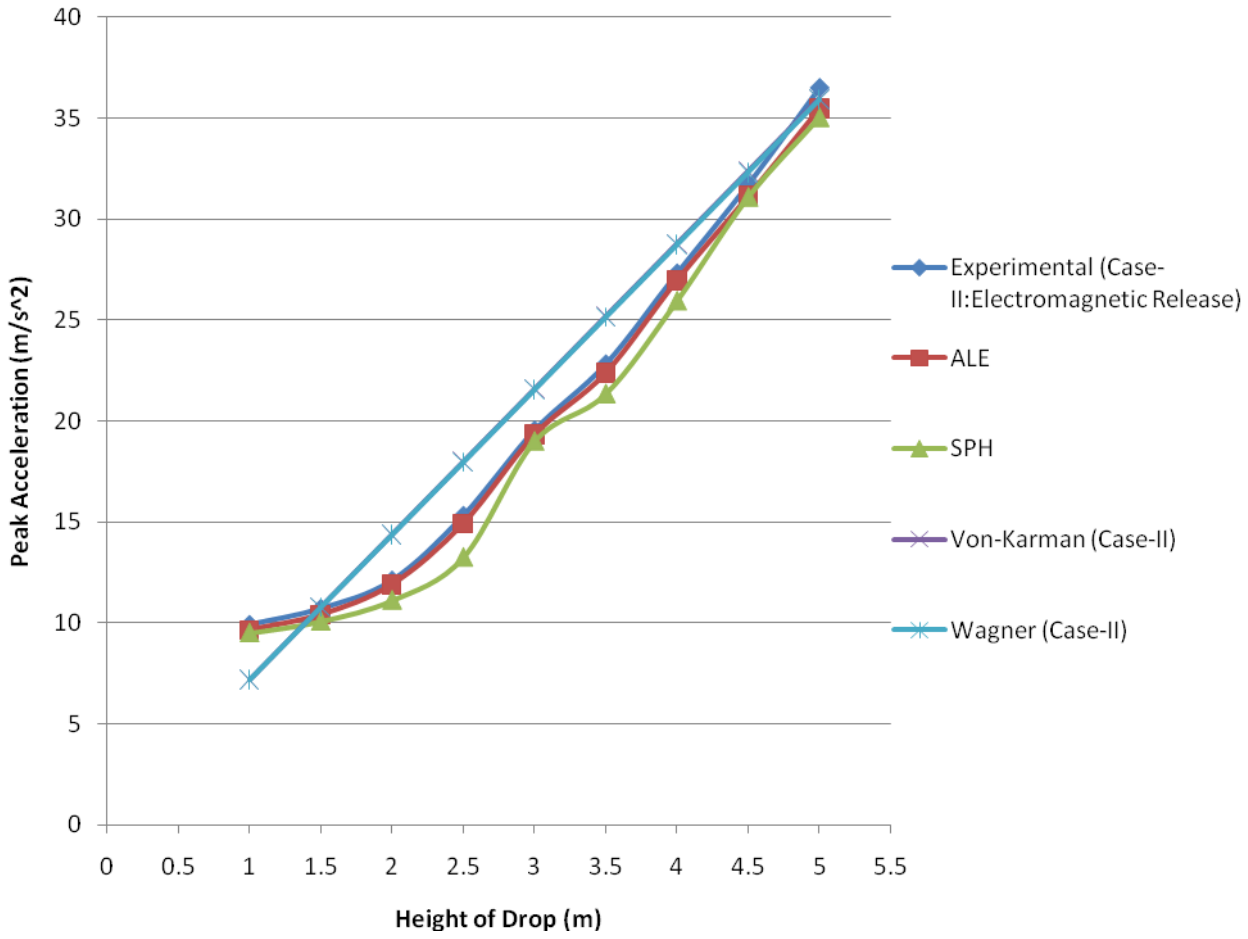

Fig. 4 Comparison of results for maximum acceleration with ALE and SPH

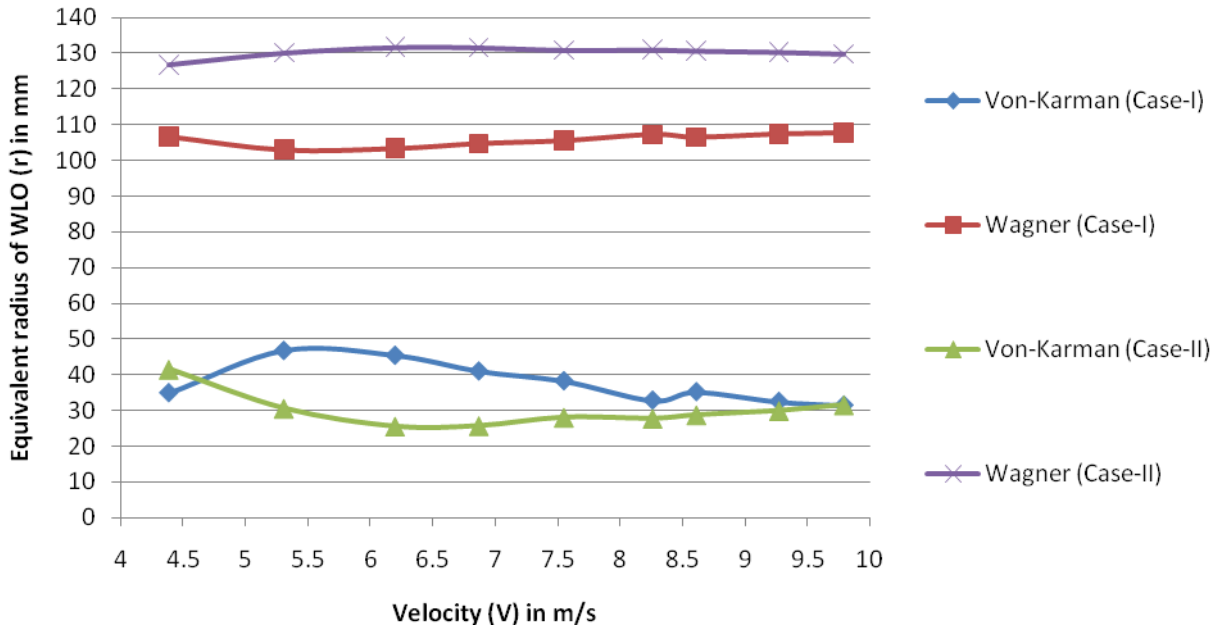

Fig. 5 Equivalent radius (r) of the dropped object for different velocities of impact for Drop Test I and II using von-Karman and Wagner approaches

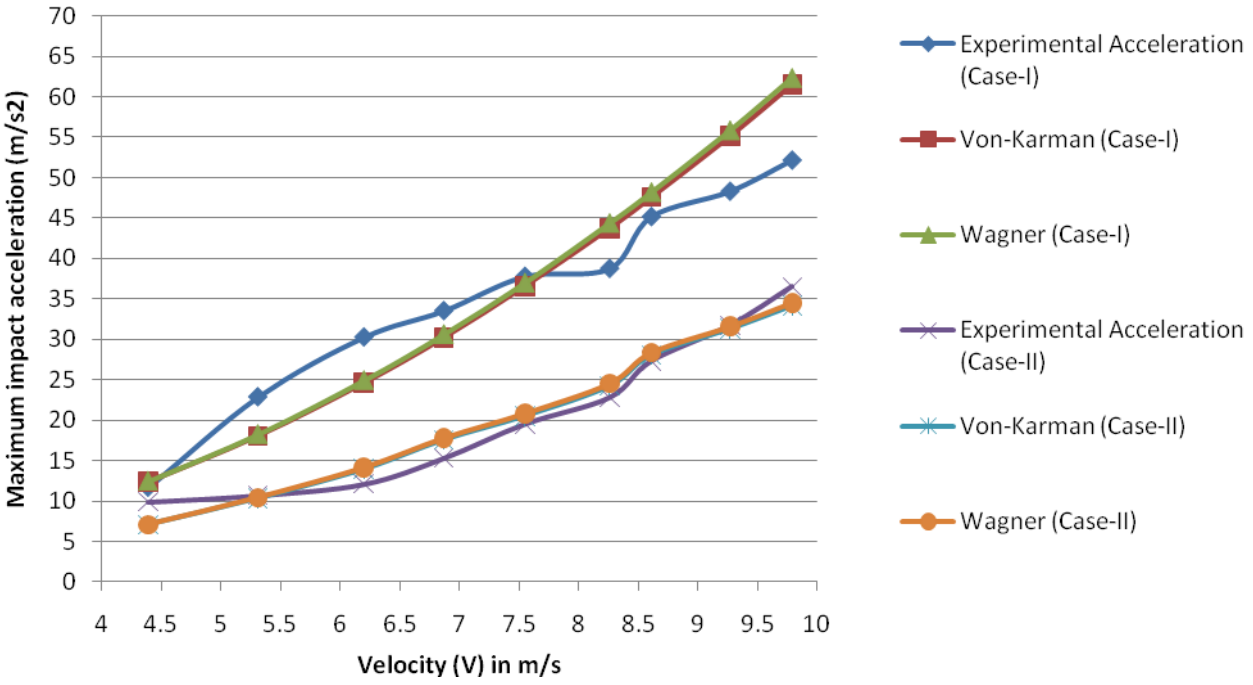

Fig. 6 Mean equivalent radius (r*) of the dropped object for different velocities of impact for Drop Test I and II using von-Karman and Wagner approaches

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