Modeling Mine Blast with SPH

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Abstract

Accurately and efficiently modeling the loads applied to a vehicle by buried explosive (mine blast) is a persistent need. In this study, Smoothed Particle Hydrodynamics (SPH) was used to effectively model mine blast. The buried explosive and soil were modeled with SPH, while Lagrangian FEM elements were used for the vehicle plate. The approach was validated against a series of mine-blast experiments performed by the Ernst Mach Institute (Freiburg, Germany), in which the momentum applied to different geometries of steel plate suspended above the soil was measured. The momentum predicted from the SPH models ranged from 14% to 18% above the measured values, depending on plate geometry. Therefore, predictions from the SPH model corresponded closely with measured momentum but were conservative, as would be desired for designing vehicles. Furthermore, the SPH approach has the potential to be computationally efficient relative to an Arbitrary Lagrangian Eulerian (ALE) approach because an Eulerian solid mesh was not needed to model expansion of the explosive. This advantage is particularly important for models that include large vehicle targets, as an ALE approach would require large Eulerian meshes, significantly increasing the memory and execution time demands.

1 Introduction

Tactical wheeled vehicles are subjected to explosions from land mines and improvised explosive devices (IEDs). The design of the vehicle and armor system must be able to withstand the pressure and impulse, from the explosive as well as the explosively-driven soil if the charge is buried. Explosive tests of armored vehicles are expensive and the data contains variability due to field conditions. Additionally, data collection in actual tests is always limited to the number of sensors deployed, allowing measurement at key points that require a priori determination.

As an alternative to field testing, numerical modeling and simulation can provide valuable data in a timely and cost-effective manner and can be used as an effective design tool. In this paper, the Arbitrary Lagrangian-Eulerian (ALE) and the Smoothed Particle Hydrodynamics (SPH) approaches for modeling the detonation of the buried explosive and the momentum are examined. The results show that using SPH particles to model buried explosive can be accurate and time-efficient for determining the momentum applied to armored vehicles by buried mines.

2 Model Validation

2.1 Validation Tests

The SPH and ALE simulations discussed below were validated against a series of mine-blast loading experiments performed by the Ernst Mach Institute, Freiburg, Germany (*1*). The series of experiments consisted of detonating Comp-B explosive in a column of soil and measuring the momentum applied to steel plates suspended above the soil. The column of soil was contained by a cylindrical cardboard form, commonly referred to as Sonotube. Plate geometries included 120° (Figure 1) and 90° configurations. Dimensions are in millimeters. The plate targets consisted of two halves 800 mm x 400 mm x 60 mm, welded together at either 120° or 90°. The mass of the 120° plate target was 309.4 kg, and the mass of the 90° plate target was 308.4 kg.

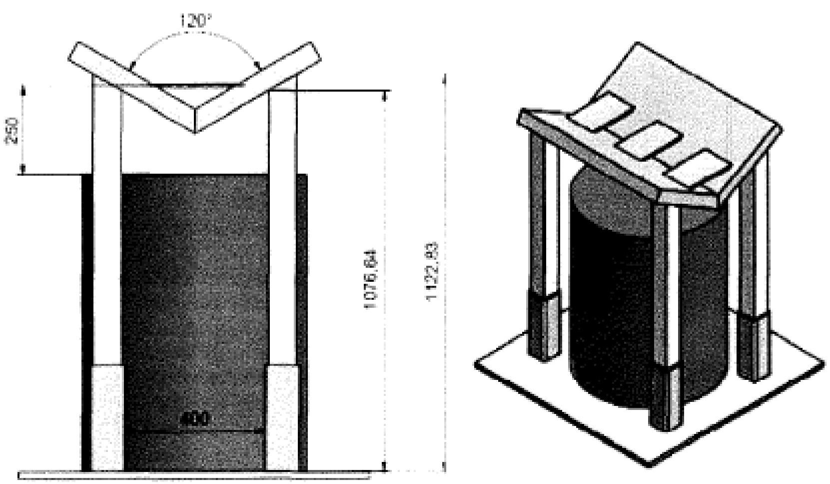

*Figure 1. Sonotube Mine Test with 120° Plate Configuration (*2*)*

The Comp-B explosive had a cylindrical shape. The charge was placed 50 mm below the top of the soil. The upward displacement of the plate target was measured using string potentiometers, and elementary energy relations were used to determine an initial velocity. This initial velocity was multiplied by the mass of the plate to determine an imparted momentum.

2.2 Test Results

Three replicates of each test were performed, and the results are shown in Figure 2. The mean momentums for the 90° and 120° tests, plotted with error bars at time 4.75 ms, are compared with simulations conducted by Southwest Research Institute (SwRI), San Antonio, TX using the CTH hydrocode. This figure was used as a basis for validating the SPH and ALE simulations discussed below. As the figure illustrates, the momentum curves generated with the CTH simulations over-predict the imparted momentum when compared with the dots representing the physical tests.

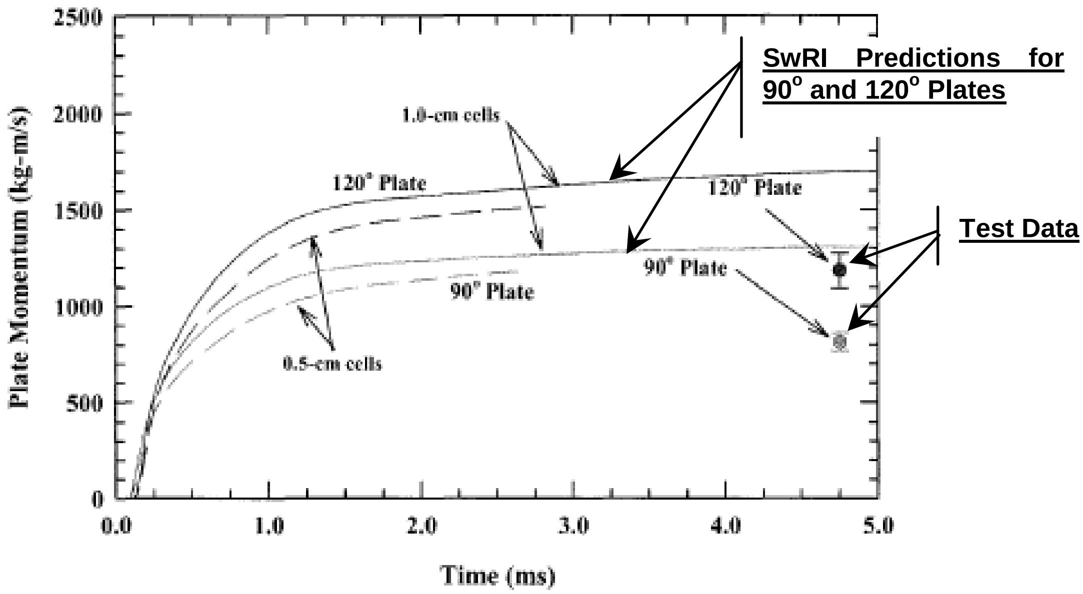

Figure 2. Comparison of CTH Predictions and Experimental Values of Plate Momentum vs. Time for 90° and 120° Plate Targets (3)

3 ALE Simulation

3.1 Geometry

Ernst Mach tests were first simulated using Arbitrary Lagrangian-Eulerian (ALE) capability in LS-DYNA. The Lagrangian geometry for the simulation is shown in Figure 3(a). Two orthogonal planes of symmetry were used, as illustrated in the figure. The Sonotube was explicitly modeled in the ALE simulation because large radial deformation of the soil was observed late in the simulation. Including the effect of the Sonotube on this radial deformation was therefore deemed necessary; however, it ultimately proved to have little influence on the results. This Lagrangian geometry was suspended in a spherical Eulerian mesh of solid elements, as shown in Figure 3(b).

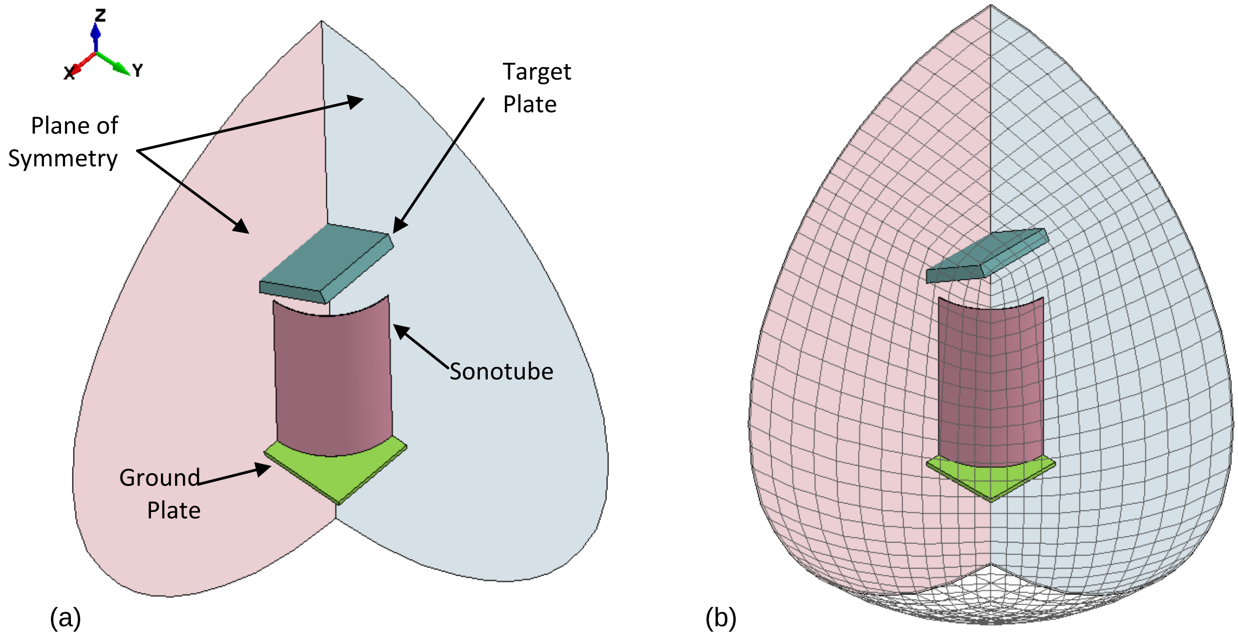

Figure 3. (a) Quarter-Symmetry Model for ALE Simulation
(b) Lagrangian Elements Suspended in Eulerian Solid Mesh

The mesh was biased toward the charge location, as shown in Figure 4(a), to maximize accuracy of the explosive burn model. The region outside the Sonotube was filled with air, while the region inside the Sonotube was filled with soil. Explosive consistent in volume and position with the Ernst Mach tests was placed within the soil. The Lagrangian Sonotube filled with soil and explosive is shown in Figure 4(b). The model is reflected about the XZ plane to provide a sectional view, and the air part is turned off for clarity.

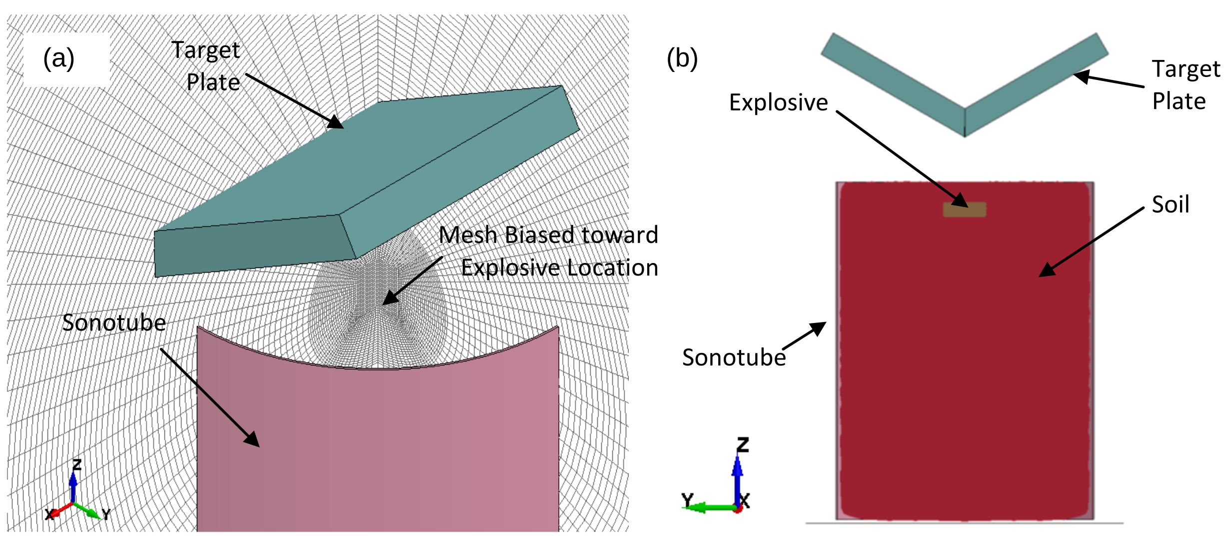

Figure 4. (a) Bias of Spherical Eulerian Mesh toward Location of Explosive
(b) Sonotube Filled with Soil and Explosive (Reflection about the XZ Plane)

3.2 Constitutive Models

The constitutive model used for the soil was *MAT_SOIL_AND_FOAM, and values used for input parameters are shown in Table 1. The curve input to define pressure vs. volumetric strain for the soil is shown in Figure 5. For all input cards discussed in this document, parameters not included in the tables were left at the default values. Prior research by Anderson, et al, indicated that predictive accuracy had a fairly low sensitivity to most constitutive soil parameters, with the exception being the density. As such, the density in the model was precisely matched to the soil used in the Ernst Mach tests.

Table 1. Input Values for Soil Constitutive Model
**MAT_SOIL_AND_FOAM*

Parameter	Description	Value	Units
RO	Mass density	1.37E-06	kg/mm^3
G	Shear modulus	3.6E-06	kg/mm-ms^2
A0	Yield function constant	2.53E-08	
PC	Pressure cut-off	-3.447E-05	kg/mm-ms^2
VCR	Volumetric crushing option	1.0	

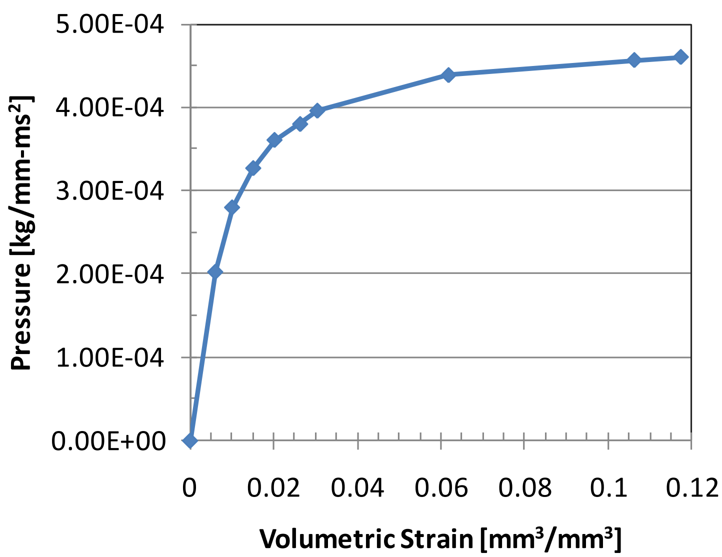

Figure 5. Pressure vs. Volumetric Strain for Soil

The explosive was modeled using *MAT_HIGH_EXPLOSIVE_BURN and the JWL equation of state, *EOS_JWL with the material constants for Comp-B. The target plate was modeled as a rigid material with the density and modulus (for time step calculation) of steel. The rigid material model was used to constrain all degrees of freedom of the plate except translation in the vertical (Z-axis) direction.

The sonotube was modeled using *MAT_PIECEWISE_LINEAR_PLASTICITY, and the input constants are shown in Table 2. These values were inferred from a review of published cardboard and wood strength and density properties.

Table 2. Input Values for Sonotube Constitutive Model
**MAT_PIECEWISE_LINEAR_PLASTICITY*

Parameter	Description	Value	Units
RO	Mass density	6.89E-07	kg/mm^3
E	Young's modulus	12.26	kg/mm-ms^2
PR	Poisson ratio	0.38	
SIGY	Yield strength	6.9E-03	kg/mm-ms^2
ETAN	Tangent modulus	1.226E-02	kg/mm-ms^2
FAIL	Failure strain	0.9%	

3.3 Contacts and Controls

The critical contact in the ALE simulation was the coupling algorithm between the Lagrangian and Eulerian elements. This coupling is governed by *CONSTRAINED_LAGRANGE_IN_SOLID, and non-default input values are shown in Table 3. The selected values were determined by trial-and-error tuning of the coupling algorithm to prevent leakage.

Table 3. Input Values for ALE Coupling Algorithm
**CONSTRAINED_LAGRANGE_IN_SOLID*

Parameter	Description	Value	Units
NQUAD	No. quadrature points	4	
CTYPE	Coupling type	4	
PFAC	Penalty factor	1.0	
ILEAK	Leakage control	2	
PLEAK	Leakage control penalty factor	0	
THKF	Shell thickness in coupling algorithm	10	mm

The time step was restricted to 10% of the calculated time step, during detonation, and increased to 67% of the calculated time step for the remainder of the simulation, as discussed for the SPH simulation.

3.4 Simulation Results

Sectional and isometric illustrations of the ALE simulation are shown in Figure 6(a) and (b), respectively.

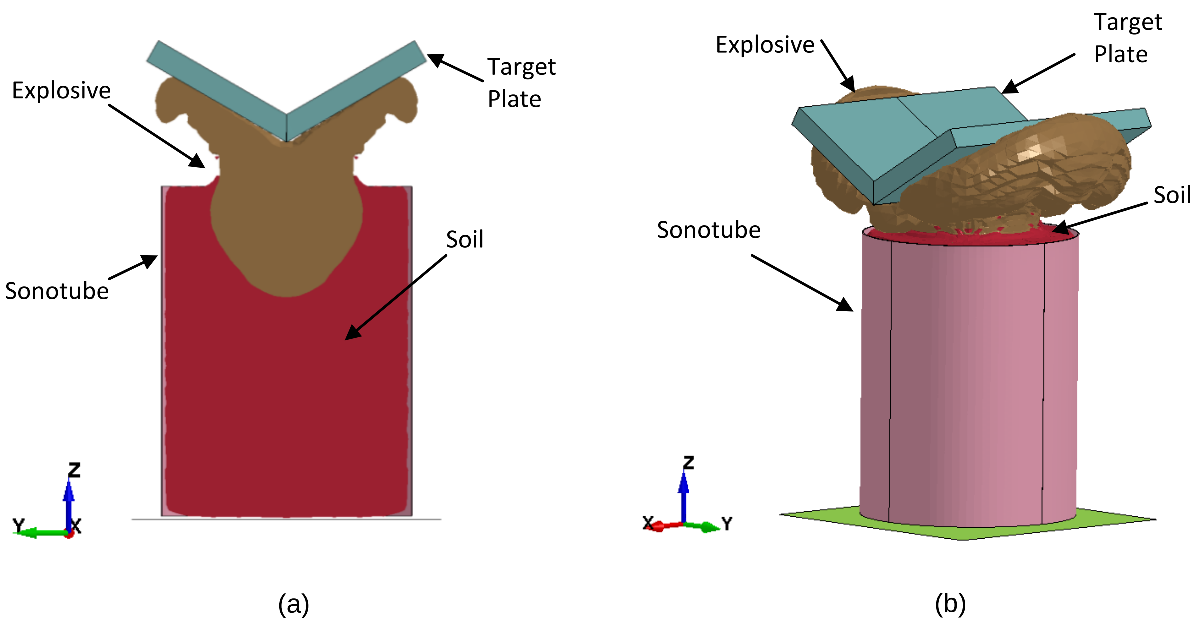

Figure 6. (a) ALE Simulation 0.68 ms after Detonation (Reflection XZ Plane)
(b) ALE Simulation 0.96 ms after Detonation (Reflection XZ and YZ Planes)

The predicted momentum from the ALE simulation for the 120° plate is compared with the measured momentum from the validation tests in Figure 7. The 90° plate experiment was not simulated. The ALE simulation predicted a momentum 70% of the measured value. This result is possibly due to leakage in the coupling algorithm, but it may also be a function of advection losses in the CFD algorithms of LS-DYNA. This result indicated that the LS-DYNA ALE method produced a closer approximation than the CTH simulation, but momentum applied to the target plate was unconservatively low.

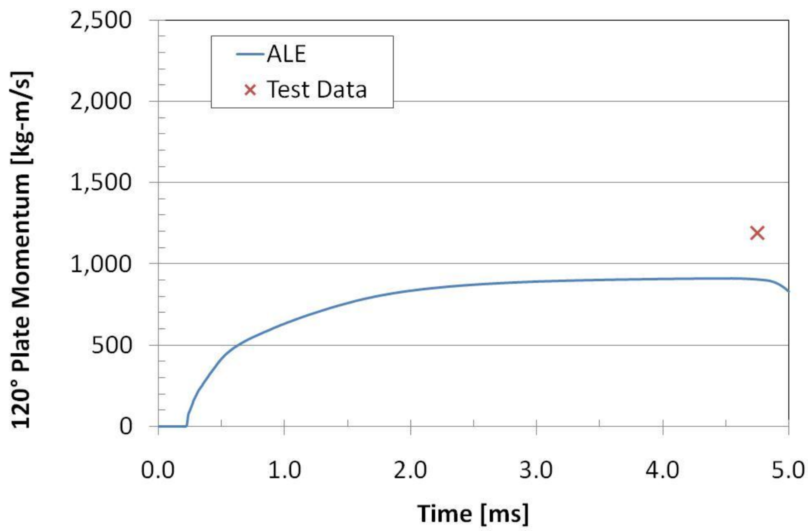

Figure 7. Results from ALE Simulation for the 120° Plate

4 SPH Simulation

4.1 Geometry

The Ernst-Mach tests were further simulated using SPH particles for the soil and explosive and Lagrangian FEM elements for the plate target. The SPH particles were 10-mm in diameter and were used for both the explosive and soil. The typical target plate element was 12.9 mm x 12.9 mm x 30.8 mm. To reduce complications from boundary effects, no planes of symmetry were used, and the entire cylinder of soil and explosive was modeled. The explosive had a volume and position consistent with the Ernst Mach tests.

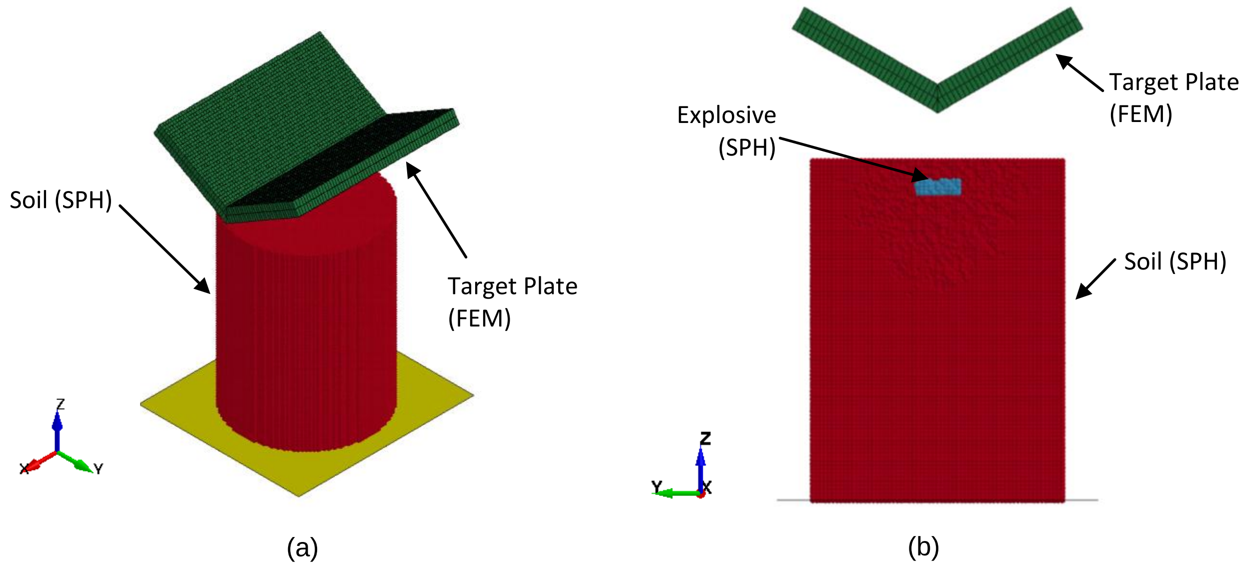

Figure 8. (a) Isometric View of SPH Sonotube Mine Model with 120° Target Plate
(b) SPH Sonotube Mine Model Section through Middle YZ Plane

4.2 Constitutive Model

The constitutive models for the Comp-B explosive, soil, and target plate were identical to those used for the ALE model. The sonotube was not included because it was found to have negligible effect on ALE simulation results.

4.3 Contacts and Controls

Shooting particle instability is a numerical artifact of the SPH formulation that introduces non-physical high-speed particles into the simulation. These particles must be deactivated from the constitutive model to prevent them from affecting results. However, at the onset of this effort, there was no way to exclude such shooting particles from the target plate contact. The result was overestimation of momentum applied to the target plate from the spurious kinetic energy of the high-speed particles.

This limitation was brought to the attention of LSTC, who modified the solver code to include a contact exclusion for shooting particles. With the shooting particles excluded from the contact, *CONTACT_NODES_TO_SURFACE was used to couple the FEM elements and SPH particles. This permitted normal part-to-part interaction in a low-maintenance and straightforward manner.

Many particles of the SPH part must be included in the contact definition, not just those near the contact surface. This is required because the particles can slip past each other and move to the region of contact (*4*).

To improve the accuracy of the simulation during explosive detonation, the time step was reduced to 10% of the calculated time step for the first 0.03 ms. The time 0.03 ms was selected because it was greater than the time required for the detonation wave to travel from the center of the charge to its extreme perimeter of the charge. After 0.03 ms, the time step was restricted to 67% of the calculated minimum time step.

4.4 Simulation Results

Sectional and isometric illustrations of the SPH simulation are shown in Figure 9(a) and (b), respectively.

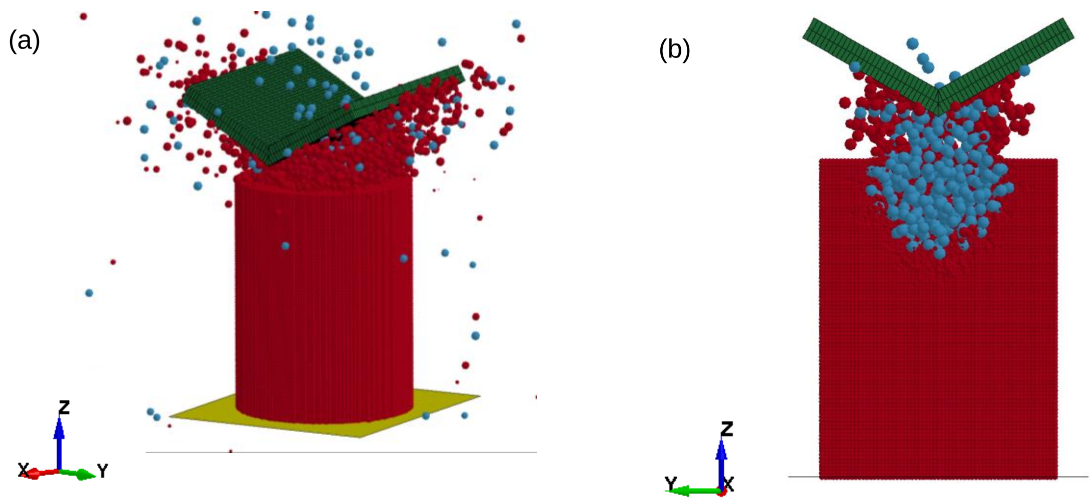

Figure 9. (a) SPH Simulation at 0.86 ms after Detonation
(b) 0.35 ms after Detonation Section through Middle YZ Plane

Simulations were performed for the 120° and 90° target plate, and results are shown in Figure 10 and Figure 11 respectively. Results for the 120° plate prior to removing shooting particles from the contact and refining the other contact parameters (default contact) are included in Figure 10, for comparison. The SPH results for the 120° simulation show excellent agreement with the plate momentum measured in the validation tests. The predicted value from the simulation was 14% above the measured momentum. For the 90° plate, the predicted value was 18% greater than the measured value. In both cases, the LS-DYNA SPH predictions are much closer than the CTH hydrocode predictions and conservatively over-predict applied momentum, in contrast to the ALE simulation.

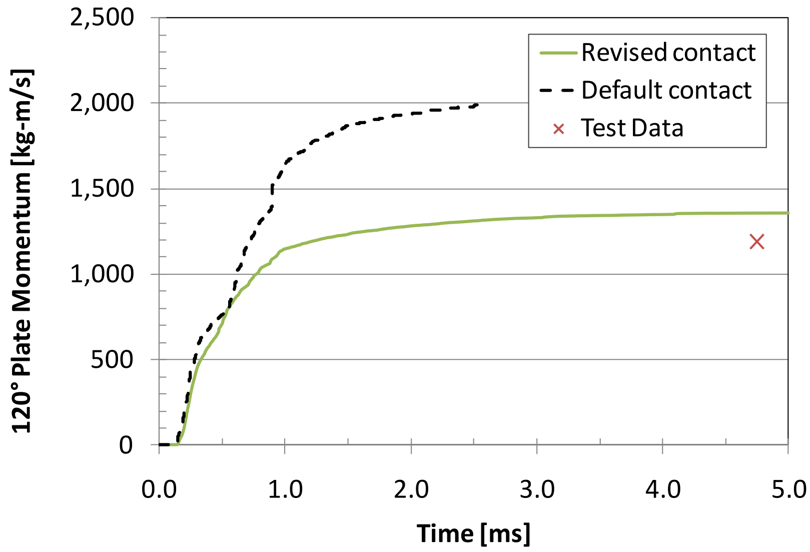

Figure 10. SPH Results for the 120° Plate

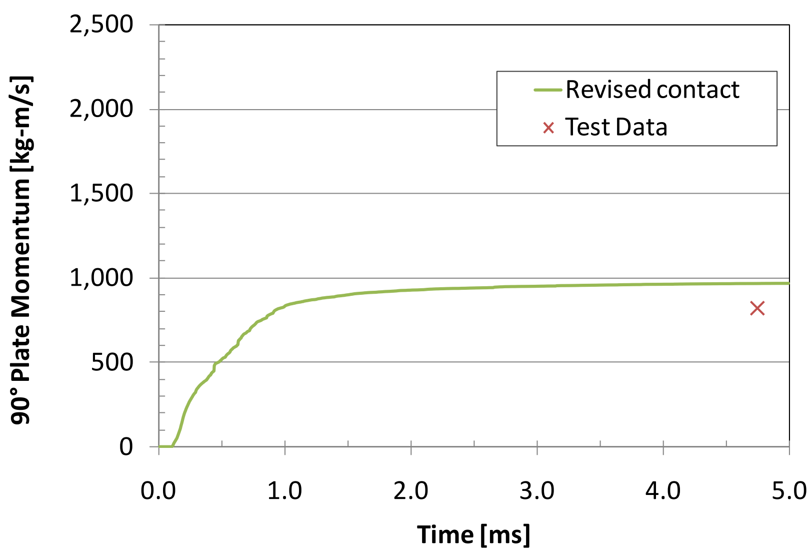

Figure 11. SPH Results for the 90° Plate

5 Conclusions

Predictions from the SPH simulation corresponded more closely to measured momentum from validation tests than ALE, and they were conservative in that they over-predicted the applied momentum. The ALE method under-predicted momentum and was less accurate in the 120° plate case. This result was likely caused by either leakage in the ALE coupling algorithm or advection losses in the CFD algorithm.

Another limitation of the ALE method is that any target, including a large vehicle, must be included in the Eulerian solid mesh; larger targets at greater distances necessarily require larger

Eulerian meshes covering the intervening space. The Eulerian solid meshes required for large vehicle targets will suffer a significant computational burden not shared by the SPH approach.

These two limitations of the ALE method and the better results observed in the SPH model suggest that the SPH method is more effective for modeling buried-mine blast.

References

1 Anderson, Charles E., Jr.; Behner, Thilo; Weiss, Carl E.; Chocron, Sidney; Bigger, Rory P. *Mine Blast Loading: Experiments and Simulations*. Southwest Research Institute. April, 2009.

2 ibid, p. 13

3 ibid, p. 48

4 Barsotti, M; Puryear, J; Stevens, D. Airport Cooperative Research Program Report 29, *Developing Improved Civil Aircraft Arresting Systems*. Transportation Research Board. 2009.