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NUMERICAL MODELLING OF A SIMPLIFIED SURROGATE LEG SUBJECT TO AN ANTI-PERSONNEL BLAST MINE

Jennifer Motuz[1], Duane S. Cronin[1], Mike Worswick[1],
Daniel Bourget[2], Kevin Williams[2], Gilles Pageau[2]

[1] *University of Waterloo, 200 University Ave W., Waterloo, ON, N2L 3G1, Canada*
[2] *Defence Research Establishment Valcartier, 2459 boul. Pie-XI Nord, Val-Bélair, QC, G3J 1X5, Canada*

The development of improved landmine protective footwear requires an appropriate test apparatus and an understanding of the physics and damage mechanisms associated with a close proximity blast event. A Simplified Lower Leg (SLL) is under development, which will mimic the response and failure mechanisms of a human leg under the extreme loading conditions of an AP blast mine. The surrogate SLL is intended to provide an appropriate means for testing current protective boot designs and evaluate new approaches. Numerical modelling techniques are being utilized to assist in the development of this leg.

The short duration response of the SLL to blast loading has been predicted using a Lagrangian numerical model, and compares well with experimental tests. However, it is necessary to model longer durations to determine the effectiveness of the protective footwear.

To consider the longer duration loading, a Lagrangian model of the SLL has been coupled to an Arbitrary Lagrangian Eulerian model of the explosive, soil and surrounding air. The landmine blast has been modeled separately and compares well with the experimental data within 70 cm of the blast. Short-term modelling of the effect of the expanding explosive gases on the tissue has also been successful.

INTRODUCTION

Since the Ottawa Convention in 1997 [1], several demining efforts have begun to allow agricultural and industrial development in previously “contaminated” areas. Several protective footwear designs currently exist, however there is no standard for testing their effectiveness. A surrogate leg with appropriate biofidelic response is necessary to evaluate protective footwear.

In order to support the development of the SLL, numerical models are under development. The long-term goal of this modelling is to allow the numerical simulation of various boot designs on different sized charges to screen different designs. Relatively short analyses (100 μs) have been completed using Lagrangian formulation models of the SLL subject to blast loading [2,3]. The preliminary Lagrangian models of buried 100 g C-4 charges (surrogate mines) compared well with the experimental tests [2,3], but only for a very short duration.

In the current work, an Arbitrary Lagrangian-Eulerian (ALE) formulation has been used for models that were cost-effective to run as long as 2 µs. These models have allowed the longer-term effects of AP mine blasts to be investigated. Two models will be discussed in this paper: the first includes only an explosive charge surrounded by air and soil. The second model couples the first to a Lagrangian model of the SLL.

LITERATURE REVIEW

Experimental Data

Detailed experimental data related to AP blast mines and their effect on leg structures is relatively limited. There has been some cadaver testing in the United States [4] to evaluate blasts on the human body. A preliminary SLL physical model has been developed and experimental data has been collected on its behaviour when placed on 50 g and 100 g surface-buried C-4 charges [5].

The most recent blast mine data has been obtained by Bergeron et al [6] at the Defence Research Establishment Suffield (Canada). This data contains pressure-time relationships and soil ejecta behaviour when surrogate land mines (100 g C-4 charges) are buried at three depths: surface, 3 cm below, and 8 cm below the sand surface.

Solution Techniques

Lagrangian models of the surrogate charge have been created [3] to compare with the SLL test series results [5] and blast mine results [6].

The first Lagrangian models of the blast were using axisymmetric solid elements. The use of axisymmetric elements allowed for a very fine (0.5 mm) finite element mesh to be used in the areas of interest to determine the explosive behaviour in the short-term. The SLL was coupled to the mine blast model using an automatic contact algorithm.

ALE Formulation in LS-DYNA

The finite element code LS-DYNA has two variations of the ALE method implemented [7]. The first is the Simplified-ALE (SALE) formulation developed by Benson [8], which allows internal remeshing of an area with Lagrangian (deformable) boundaries. This method was considered, however it was quickly discovered that the deformation of the explosive and soil was too large for this formulation, and the computational cost was far too high. The second formulation consists of an Eulerian code, including multi-material elements, which can be coupled with Lagrangian meshes. This formulation differs from the "Arbitrary Lagrangian-Eulerian" (ALE) formulation described by Benson [9] in that it maps all mesh deformation to the initial mesh geometry after each solution step, advecting material to the appropriate location. Thus, a single element can contain varying quantities of the explosive, soil and air materials.

Material Models

The C-4 explosive has been modeled with a JWS equation of state [8,10]. Since the experiments [6,7] used sand to bury and surround the charges, a material model for sand had to be developed. The sand pressure-volume was modeled using experimental data from a mixture of MgO and silica [11]. It should be noted that the sand was modeled as a continuous material using the soil and foam material model in LS-DYNA. A failure criterion can be specified in this model to prevent the soil from carrying tension, however we were unable to implement it in the ALE models.

A Mooney-Rivlin model was used for the rubber pad while the bone was modeled using an elastic material model. The deviatoric strength of the tissue simulant (gelatin) was neglected and the material was modeled as a viscous fluid with the equation of state of water. The air was modeled as a perfect gas using a polynomial equation of state to ensure appropriate air pressure.

NUMERICAL MODELLING OF EXPLOSIVES IN SOIL

Model Description

The ALE models used a one-quarter solid mesh consisting of 8-node quadrilateral elements. Each of the 0 cm, 3 cm and 8 cm depth of burial geometries were analysed.

Due to the nature of 3D ALE models (many elements with a higher computational cost per element than other formulations), it was imperative that the mesh be coarsened to allow for reasonable calculation times. Comparison of several mesh densities showed that a 5mm cubic element size at the explosive coarsening gradually to the edges of the mesh improved computational time significantly and did not adversely affect the results.

The ALE model consisted of three parts: explosive, sand and air. The explosive part was a cylinder of 3.1 cm radius and 2.35 cm height. The detonation point was selected 5 mm above the bottom edge of the explosive to mimic the actual detonation point in the experiments. Sand was modeled to 20 cm below the bottom of the explosive and 85 cm radially from the explosive. The air was modeled with the same outer diameter as the sand and 2 m tall to ensure that boundary reflections would not interfere with the predictions within 70 cm of the blast.

Boundary conditions were applied such that material could not flow out of the mesh. Otherwise, the air pressure leaked out of the model very quickly, reducing the accuracy of the results.

Results: Pressure-Time Relationship in Air

The peak pressures in air for the different depths of burial have been shown in Figure 1, below. The surface-buried model compares well with the experimental results, and exhibits the exponential decrease in pressure with height expected for a shock wave travelling through air. This behaviour has been highlighted by the trendline in the figure. The buried charges, however, compare poorly with extremely low peak pressure values. This is due to the containment of the explosive gases by the sand in this model.

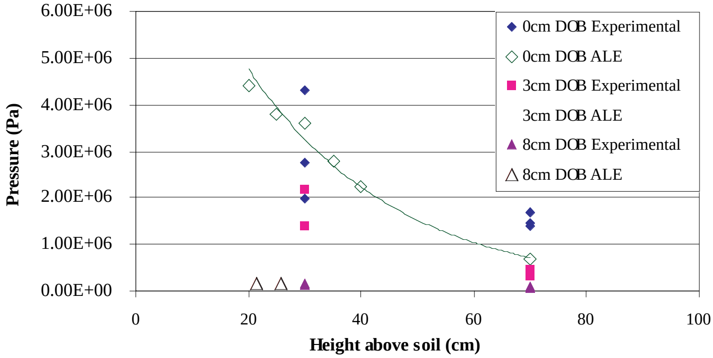

Figure 1: Peak pressures vs. height above soil for all depths of burial.

Figure 2 shows the arrival times in air for all depths of the buried-charge models. Note that all of the numerical models compared well with the experimental data.

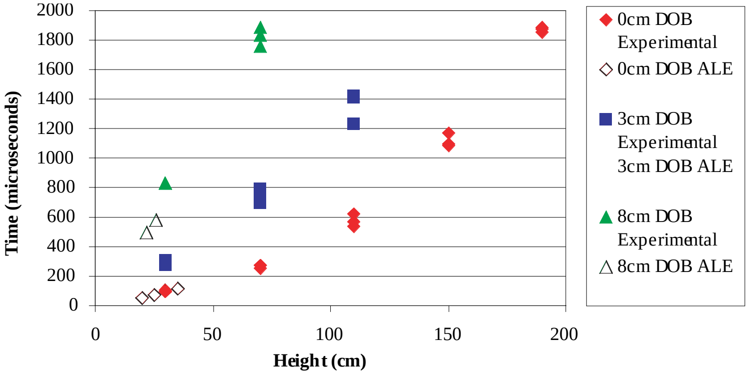

Figure 2: Peak pressure arrival times vs. height above soil for all depths of burial.

Results: Pressure-Time Relationship in Soil and Soil Ejecta Behaviour

The soil pressure magnitudes have not been compared with the experimental data due to issues regarding the damage to in-soil pressure transducers in the experimental study [6]. The peak pressure arrival times in the soil were compared with the experimental data and the numerical results are reasonable for all charge depths.

The soil deformation compared well with the experimental data for both of the ALE predictions of 0 cm and 8 cm depth of burial models. Figure 3 shows the output of the numerical model compared with a photograph from the experimental series for the surface buried charge at 50 µs after detonation.

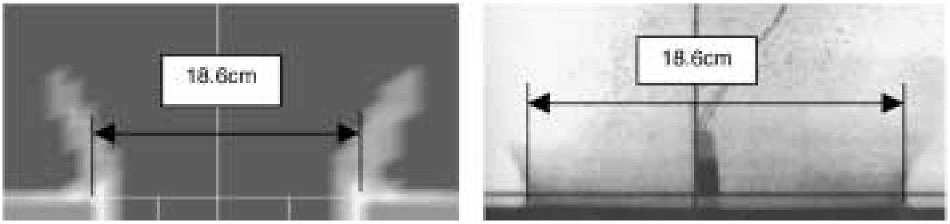

Figure 3: Soil deformation for the 0 cm depth of burial charge, 50 µs after detonation.

Figure 4 shows a similar comparison for the 8 cm depth of burial charge, 250 µs after detonation.

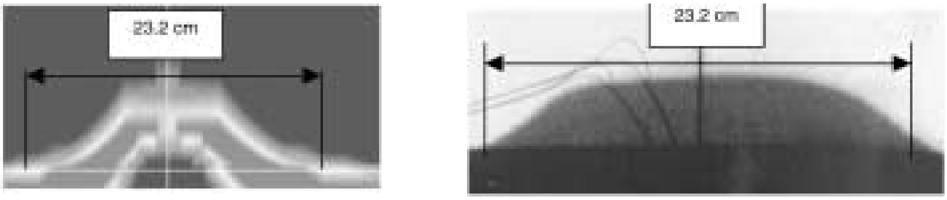

Figure 4: Soil deformation for the 8 cm depth of burial charge, 250 ms after detonation.

MODELLING OF EXPLOSIVE INTERACTION WITH THE SLL

Model Description

The surface-buried explosive mesh from the previous ALE mine only model was included in this model to ensure that the explosion would be modelled correctly. To mimic the experiments [5], a rubber pad 2.54 cm tall and 20 cm in diameter was placed immediately above the explosive to simulate a normal boot. The bone was modeled as a cylinder 4 cm in diameter and 70 cm tall, with the tissue surrounding it as a tube 4 cm inside diameter and 20 cm outside diameter and 60 cm tall.

Due to the nature of the model, two element formulations were required. An ALE mesh was necessary to model the explosion for long periods of time without increased computational cost due to element distortion. In order to model the failure of the rubber, and the damage to the bone and tissue, a Lagrangian formulation was required. Consequently, the SLL parts were modeled using a Lagrangian formulation and coupled to an ALE mesh of the explosive, sand and air. Since there was negligible shear force transmission, coupling was done in the normal direction only.

Results: Mesh Coupling

The ALE model predicted that the shock wave impinged on the bottom of the SLL approximately 10 ms after detonation, agreeing with the experimental results [5].

Pressure transducers and strain gauges measured the pressure-time history in the bone 23.75 cm and 43.75 cm from the distal end of the leg. Photos taken every 100 µs tracked the shock wave in the gelatin (the gelatin turns opaque under shock).

The ALE model predictions are compared with the experimental data in Figure 5. Note that the pressure-time history in the bone compares well. The wave speeds in the gelatin also compared well (1940 m/s experimental, 1850 m/s numerical).

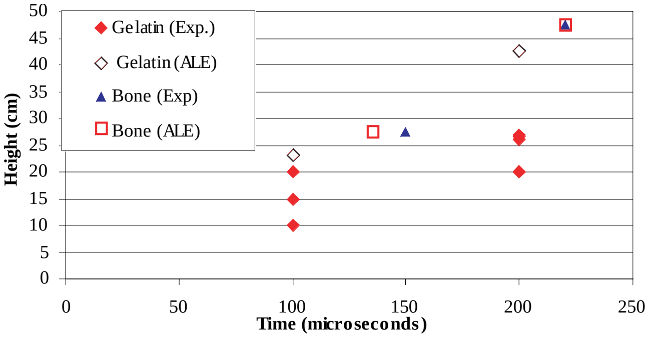

Figure 5: Shock front location in SLL tissue and bone simulants.

The ALE-Lagrangian mesh coupling appeared to work well. One issue that has not been satisfactorily resolved is that of mesh leakage; after 10 µs, the explosive material begins to leak through the rubber pad. Fortunately, density plots have shown that only 6% of the material leaks out; indicating that this is not a significant problem, although it will be addressed in future studies.

Figure 6 compares the experimental and numerically predicted deformation of the SLL 200 µs after detonation. Sections of the SLL not visible in the experimental photo have been sketched in with dashed lines. Note that the rubber material model in the ALE model does not consider failure and has deformed to an unrealistic strain state at this time.

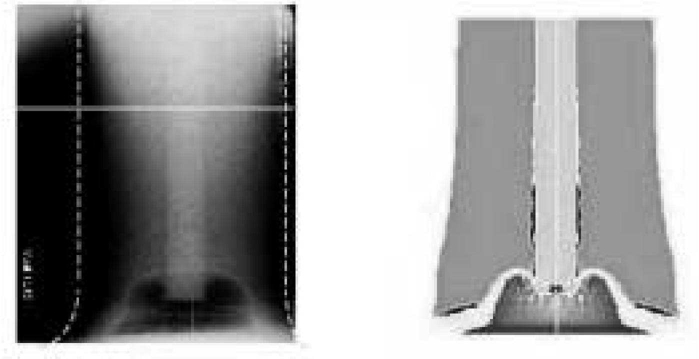

Figure 6: Deformation of the SLL 200 µs after detonation.

CONCLUSIONS

1. The surface-buried ALE models provided acceptable results within 70 cm of the explosive. This is adequate for determining the effects of AP mine blasts on the leg.
2. The buried charge ALE models predicted reasonable peak pressure arrival times in the air and soil, but the pressures were far too low. The sand model is containing and directing the explosive gases, which is not realistic.
3. The SLL model behaviour has compared well with the results obtained by Bourget [5], within 200 μs of detonation. The distortion of the Lagrangian mesh in the coupled ALE model limits the run. Future research will investigate the use of Simplified ALE meshes for the SLL to extend the run-time to 1.5 milliseconds.

ACKNOWLEDGEMENTS

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