17th Military Aspects of Blast Symposium, Las Vegas, Nevada, June 2002

Numerical Simulation of Mine Blast Loading on Structures

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Introduction

The design of vehicles to resist mine blast is of great interest to the international community who would like to provide an appropriate level of protection for vehicles and their occupants. Full size mine blast trials are expensive and time consuming to organise. However, using numerical simulations to predict the interaction of the mine blast with the vehicle can minimize the number of such trials.

This paper describes a mine blast simulation methodology that has been developed within the AUTODYN software[1]. This methodology can be used with surface-laid or buried charges and calculates both the air blast loads applied to a structure and momentum transfer due to soil or other materials impacting with that structure. The complexity of the target geometry is not limited by the methodology

The results of simulations are compared with experiments conducted by DRDC Suffield using an instrumented horizontal Mine Impulse Pendulum (MIP), as described in two papers presented MABS [2], [3].

Finally, the methodology is applied to simulating mine blast effects on a complex vehicle structure.

Mine Blast Simulation Techniques

In order to simulate mine blast effects from buried charges it is necessary to allow for both air blast effects and momentum transfer from soil material ejected as the mine detonates and the explosive products expand. We would therefore like to use a simulation methodology that can simulate both of these effects for mine blast interaction with complex structures typical of vehicles.

An initial series of simulations investigated the effects of the method used to model the explosive charge using a simple AUTODYN-2D cylindrical symmetry model with a 1kg C4 mine placed in contact with a rigid surface at ground level. The mine blast was simulated using either separate material models for the air and explosive in a multi-material Euler grid, or with both materials modelled using different state regions in a single material Euler-Flux Corrected Transport (FCT) mesh. Euler-Lagrange coupling was used to transfer the blast loads to a circular steel target plate. The charge mass and target weight used in these simulations was representative of those used in horizontal pendulum experiments conducted by DRDC Suffield and described in the next section. The air surrounding the charge was modelled as an ideal gas initially at atmospheric conditions. The explosive products in the Euler simulation were modelled using the Jones-Wilkins-Lee Equation of State (JWL EOS) and standard data for C4 and in the Euler-FCT simulations they were represented by a high-pressure air region with initial density and internal energy to represent the explosive products. An initial material location plot of one of these simulations is shown in Figure 1. In this plot the symmetry axis runs vertically through the centre of the charge and the steel target plate. The lower edge of the Euler mesh containing the air and the explosive is rigid and the other edges of the Euler mesh are open to allow the blast wave to escape from the model.

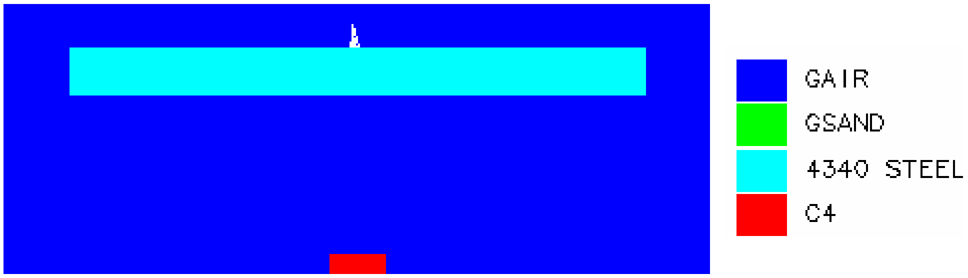


Figure 1 2D Numerical Model Used to Investigate Charge Modelling Method

The target momentum was consistent for both approaches showing that it was possible to model the charge and surrounding air as a single ideal gas (IG) material in an Euler-FCT mesh. The target momentum time histories for these simulations are shown in Figure 2, labelled 'Euler/JWL' for the two-material simulation and 'FCT/IG' for the single material simulation. Results from a 3D simulation of the same problem, that used a high pressure ideal gas region to model the explosive products, are also shown labelled '3D FCT/IG. All of the simulation results compare well with the average mine blast impulse of 2010kgm/s for this configuration measured over 4 experiments using the DRDC Suffield horizontal pendulum.

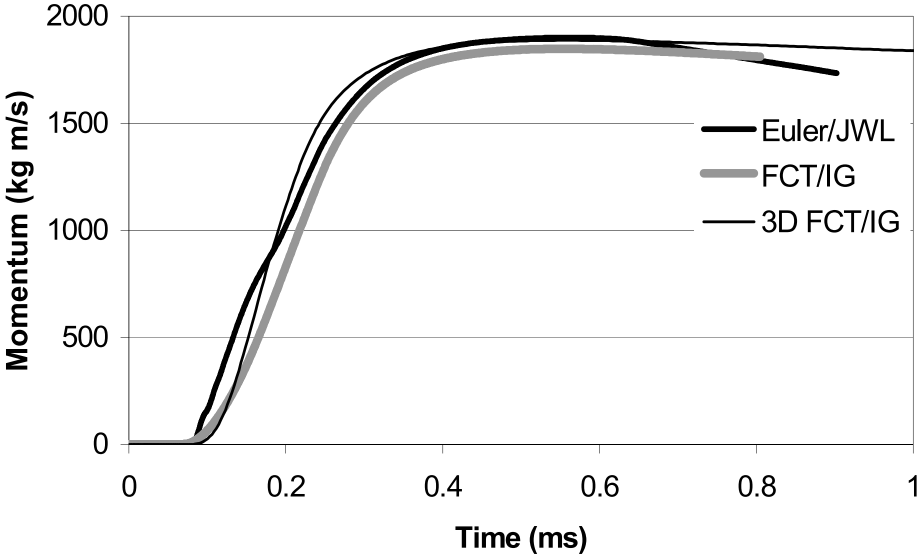


Figure 2 2D Results of Charge Modelling Method Simulations

A second set of simulations were then conducted using AUTODYN-3D to investigate the simulation of buried 1kg C4 mines. These simulations used a total of 5 subgrids as shown in

Figure 3. Two Euler-FCT grids were used. A smaller grid below the ground surface containing a high density and energy representation of the explosive products and a larger grid above the ground level that initially contains stationary air at atmospheric pressure and encloses the target plate. The ground was modelled using two joined Lagrangian grids with a cavity 50mm below the ground surface that defined the initial shape of the mine. These grids were filled with a sand material model whose material properties were taken from the literature[4]. This sand model includes effects such as volumetric crushing, yield strength dependency on pressure and shear modulus variation with density. The Lagrange cells containing the sand material were allowed to erode when they became very deformed but the momentum of eroded nodes was retained in the calculation. The target plate was modelled using a cylindrical steel block with its lower face 400mm above the ground surface. Two symmetry planes were utilised so that only a quarter of the overall geometry had to be included in the 3D numerical model. Euler-FCT coupling was used to transfer the loads from the explosive products and the blast wave to the Lagrangian ground and target plate subgrids. Lagrange/Lagrange contact was used between the ground and the target.

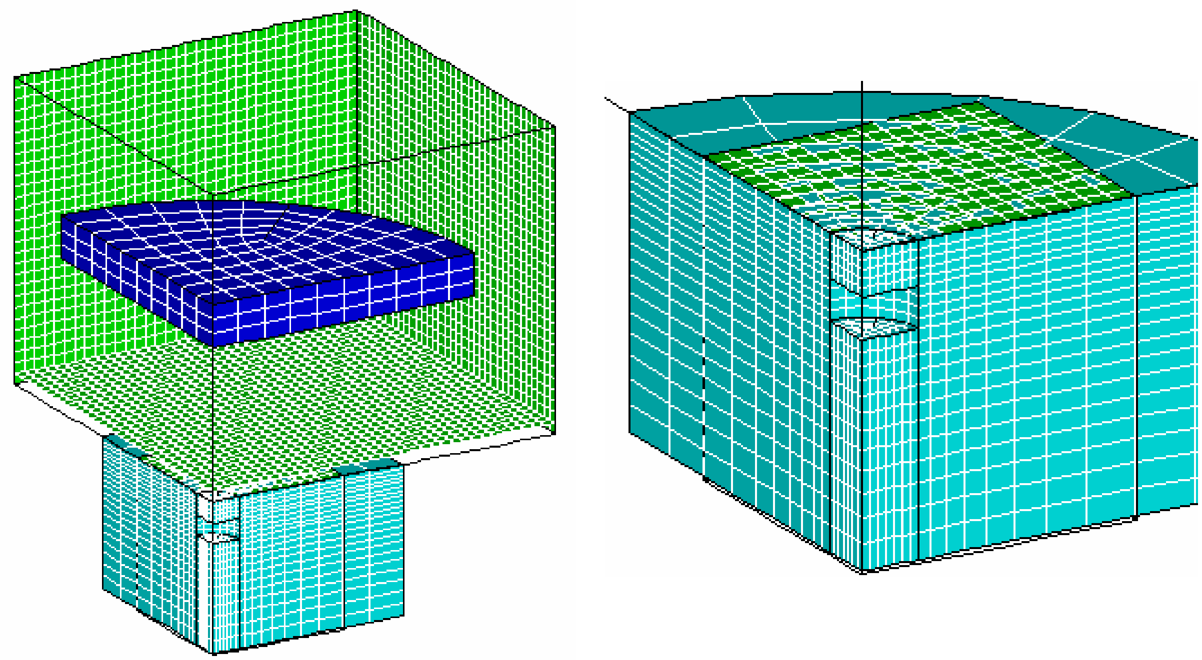


Figure 3 3D Buried Charge Modelling Methodology

The target momentum for this simulation is shown by the black line in Figure 4. The light grey curve labelled ‘Blast Only’ shows the target momentum caused by the mine blast without any momentum transfer from the sand. This shows that for this configuration about 38% of the final target momentum is caused by blast loading and 62% is caused by momentum transfer from the sand. The final target momentum is 8% higher than the experimental result for Prairie soil and 30% higher than the experimental target momentum with dry sand, see next section.

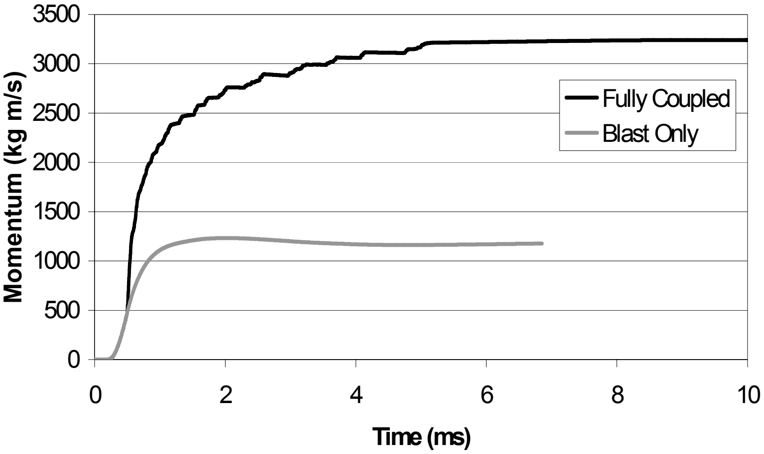


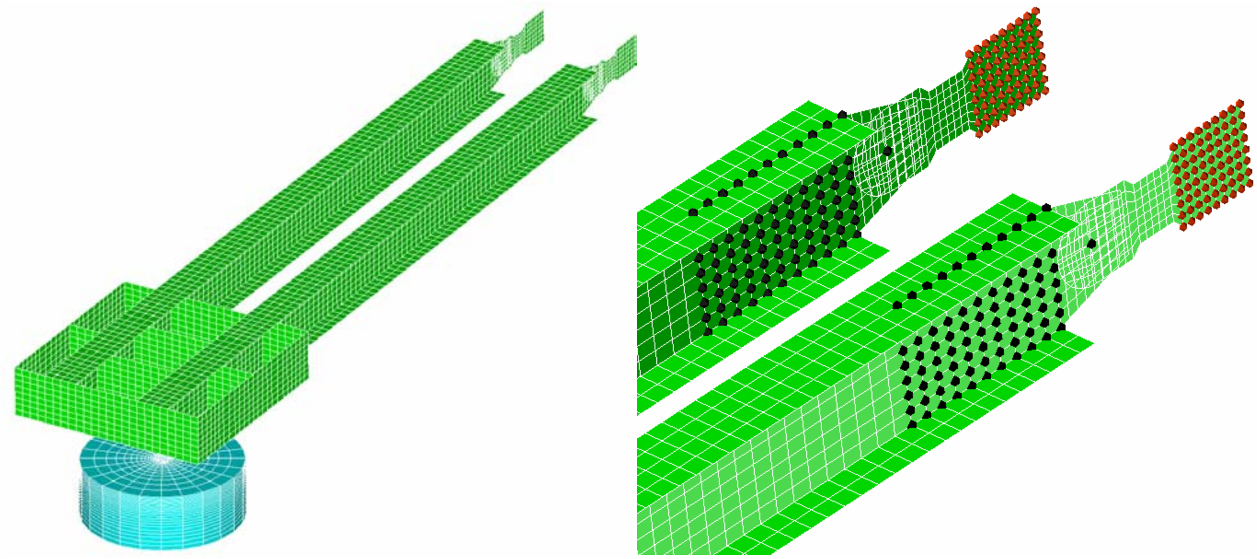
Figure 4 Simulation Results for Buried 1kg C4 Mine

DRDC Suffield Horizontal Pendulum

In order to investigate the output from a mine blast event and the loads applied to a structure DRDC~~E~~ Suffield has been using an instrumented horizontal pendulum, as described in a previous MABS symposia. The pendulum consists of a horizontal steel arm with a 1200mm square measuring 'pan' placed 400mm above the ground. The arm is about 5m long and is attached to a base assembly through a horizontal pivot at the opposite end to the measuring pan. The charge configuration of interest is placed under the centre of the measuring pan and the mine is detonated. The resulting rotation of the pendulum is measured and assuming that there is little pendulum movement while the load is applied, the impulse applied to the pendulum by the mine blast can be calculated using a simple formula[1]. The effects of mine burial in sand and Prarie soil, soil moisture, charge configuration, target stand-off and overburden have been investigated.

A numerical model of the pendulum geometry was constructed using approximately 50mm square shell elements to represent the various components. A vertical symmetry plane running along the middle of the pendulum was used to reduce the size of the numerical model. The different parts were joined where the real components were welded together. The pivot point between the arm and the base was modelled using a single joined node at the pivot location. Figure 5 shows the layout of the pendulum model. The pivot points connecting the pendulum arm to its base and some of the other joins between components are shown by black points. The boundary condition applied to fix the structure is shown by the grey points at the right hand end of the pendulum arms. Most of the pendulum was constructed from commonly available mild steel structural components. In early experiments some of the target area initially suffered plastic deformations and so a 600mm square section was replaced by a 50mm thick rolled homogeneous armour plate.

The head of the pendulum was surrounded by an Euler-FCT grid containing 74,000 cells. A region of uniform cubic cells with dimensions of 25mm was placed around the pendulum. For the case with the mine placed on a rigid surface a high density, high-energy region was initialised to model the charge. For the buried mine case a second Euler-FCT grid filled with high pressure gas to model the explosive products was introduced below the ground surface. The mine shape was defined using a cavity within a Lagrange model of a cylindrical region of soil similar to the approach described above. The effects of the mine blast on the pendulum were calculated using Euler/Lagrange coupling with the blast wave in the Euler-FCT grid and Lagrange/Lagrange contact between the ejected soil and the base plate of the pendulum.

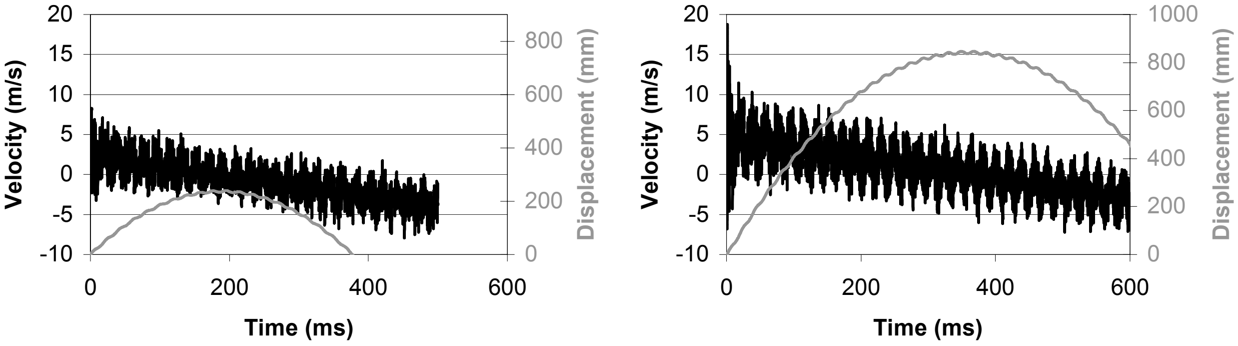


a) Overall View including Lagrange Soil Model

b) Some joins and Fixed Boundary Condition

Figure 5 Pendulum Model

The pendulum was initially at rest at the start of the calculation, with gravity acting vertically downwards. After 10ms of each simulation the Euler-FCT grids, and for the buried mine the Lagrange soil grids, were removed as the blast pressures had dissipated and the soil had finished interacting with the pendulum. The vertical velocities and displacements at the end of the pendulum furthest from the pivot point are shown in Figure 6.



a) Bare Charge

b) Buried Charge

Figure 6 Pendulum Velocities and Displacements for Bare and Buried Charge Cases

With the bare charge the pendulum starts to move after 0.2ms and at the location considered reaches a peak velocity of 8.3m/s after 1.4ms. The start of the pendulum movement is delayed to 0.5ms with the buried mine and reaches a peak velocity of 18.7m/s after 1.6ms. Both velocity-time histories show a strong oscillation corresponding to a bending mode in the main beams of the structure with a period of about 19.2ms and a frequency of 52Hz. Higher frequency vibration, presumably of other parts of the structure, is also evident. For the buried mine case the amplitude of the vibration is about 1.5 times greater than with the bare charge. After 10ms the pendulum head had moved 24.7mm and 41.8mm for the bare and buried mine cases respectively which confirms that the pendulum movement is small while the mine blast loads are acting.

Using the formula described earlier the impulse applied to the pendulum by the mine blast event can be calculated. For the bare charge case the pendulum rotates by a maximum angle of 3.2° and the calculated impulse is 1730kgm/s. For comparison, the average momentum from 4 bare charge experiments was 2010kgm/s. With the buried mine the pendulum rotates 10.1° and the corresponding impulse is 3080kgm/s. For experiments with a charge buried in dry sand (less than 0.5% moisture) the average pendulum momentum was 2478kgm/s (3 experiments) while with low moisture (average 7.5%) Prarie soil, the average impulse was 2982kgm/s over 4 experiments. The sand model used in these simulations is based on material tests with an average water content of 6.6% and an initial density of 1674kg/m^3. The average density of the dry sand in the experiments was 1550kg/m^3 and for the Prarie soil it was 1420kg/m^3.

The pendulum momentum calculated using the pendulum rotation in the buried charge simulation is 9% lower than that calculated using the simple target model described in the previous section.

One marked difference in the pendulum response to the bare charge blast loads and the buried mine can be seen in the local material velocity in the pendulum face directly above the charge. The vertical velocity at this location for these two cases is shown in Figure 7. For the bare charge case the pendulum is gradually accelerated and over the first millisecond of the simulation reached a peak velocity in 6.2m/s. For the buried charge there is an initial gradual rise in velocity as the first blast wave reaches the pendulum followed by a sudden jump to a velocity of 27m/s as the first soil ejected by the mine strikes the pendulum after 0.55ms.

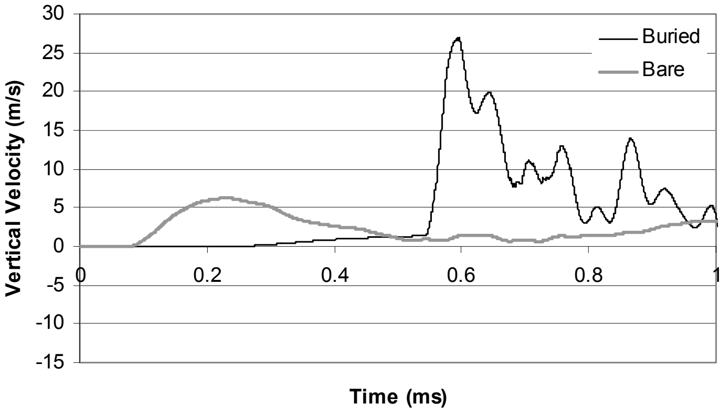


Figure 7 Vertical Velocities in Pendulum Face Directly Above Mine

Vehicle Simulations

The objective of the simulation comparisons with experiments described above was to generate sufficient confidence that the predicted mine blast loads were realistic and could usefully be used to assess mine blast effects on real vehicles.

The techniques described in the previous section were applied to the simulation of a light armour vehicle. This work was conducted for Patria Vehicles Oy of Finland. Confidentiality restricts what can be shown from these simulations but the principles used in the analysis and some generic results are described.

For these simulations a complete model of the vehicle structure, suspension system and wheels was created. This was considered necessary to ensure a realistic response to a mine detonation under one of the vehicle wheels and to extract local velocity measurements from various parts of the vehicle. The vehicle hull was constructed from various grades and thicknesses of steel plate. The hull geometry was modelled by transferring IGES surface data from the CAD model of the vehicle into True*Grid*[5] mesh generation package where the geometry was meshed primarily using shell type elements. Other bulky and heavy components such as the engine/gearbox and differentials were modelled as Lagrange blocks. The suspension leaf springs and axles were represented using beam elements. The shock absorbers were modelled using non-linear damping elements and the suspension bump stops were represented using non-linear spring elements. The wheels and tyres were also modelled using shell elements with boundary conditions applied to simulate the internal pressure in the tyres. Detail was added to the model until the overall weight and centre of gravity location were well represented.

A new capability was implemented to allow the pressures in the air and the explosive products to interact with the shell model of the vehicle structure, in addition to the Lagrange soil grids, using Euler-Lagrange coupling. The momentum in the Lagrange soil grids was transferred to the vehicle components using AUTODYN's Lagrange/Lagrange contact algorithm.

The simulation was run in five stages:

- Load suspension from its initial unloaded position with vehicle deadweight
- Static damping of vibrations caused by first step
- Initial buried mine blast simulation covering a small volume a with fine Euler-FCT mesh
- Remap state at end of initial blast simulation to coarser Euler-FCT mesh engulfing entire vehicle
- Remove Euler-FCT/soil meshes at end of loading phase and allow vehicle to move and deform under the applied mine blast loads

A plot of the vehicle suspension and wheels in their loaded position is shown in Figure 8. The location of the mine in the soil below one of the vehicle wheels is shown in Figure 9.

The simulation results included the deformation of the structure, the displacement and acceleration at key locations within the vehicle such as the seat locations and the overall movement of the entire vehicle.

Some of the simulation results will be shown in an animation during the presentation of the paper.

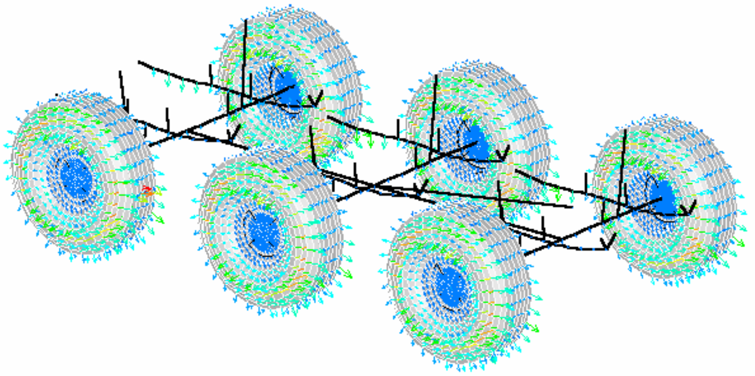


Figure 8 Model of Vehicle Suspension and Wheels

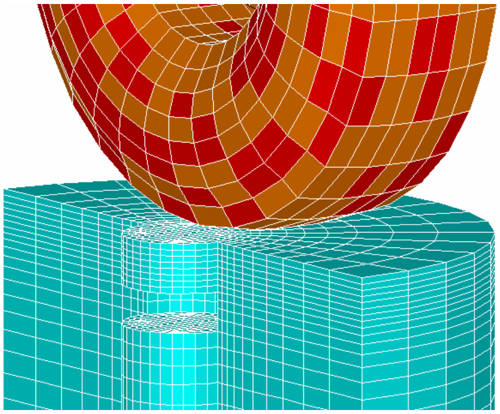


Figure 9 Mine Location

Conclusions

A hydrocode simulation methodology that can be used for both buried and bare charge mines has been developed. This methodology gives impulse loads that agree well with experimental data for 1kg C4 charges measured by DRDC Suffield using a horizontal pendulum.

For the configuration considered here the pendulum impulse was 78% higher for the buried mine compared with the bare charge case. The buried mine also produces much more localised deformations in the pendulum where soil ejected by the mine strikes the structure.

The methodology has been used to simulate mine blast effects on complex geometry models of a full vehicle.

Acknowledgments

The authors are indebted to Patria Vehicles OY for permission to include a description of some of the vehicle simulation work done on their behalf by Century Dynamics.

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