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THE DISCRETE PARTICLE APPROACH TO MODELING AIR, SOIL AND HE FOR BLAST SIMULATIONS

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ABSTRACT

Discrete Particles are just as they sound, individual particles that represent Air, Soil and HE (High Explosives). They are not based upon a continuum theory and should not be confused with SPH (Smooth Particle Hydrodynamics) which is a full Lagrangian continuum theory. The modeling of Air, Soil and HE (High Explosives) with discrete particles requires millions of particles to accurately model the blast event. The innovation in software coupled with the advent of GPU Technology provides an efficient and robust solution to perform the analyses. Consider that the latest GPU processor, the Tesla K40, based upon NVIDIA Kepler™ Architecture, has 12 GB of GDDR5 memory and 2880 CUDA Cores. A standard workstation with an NVIDIA Tesla GPU is all that is required to perform the calculations and the benefits are a high degree of accuracy and simplified model setup. To demonstrate the use of Discrete Particles to model the blast event and show the effectiveness of GPU computing, the IMPETUS Afea Solver®, a Non-Linear Transient Dynamic Explicit Solver, was used to perform the analyses presented in this paper. Results are compared with experimental data.

INTRODUCTION

Research efforts to understand the effects of buried and above ground landmines are well documented in the literature. The effects of both have been extensively investigated on simple structures (flat and V-shaped plates) to characterize the soil, high explosive and air blast loads. Numerous experiments have been performed in the past and continue to be performed to characterize the soil, HE, and ultimately the blast loading on a structure [1-9]. The wealth of experimental data is daunting but necessary to validate numerical results.

On the computational side there have been analytical calculations to characterize the loading mechanism [10,11], development of constitutive models for soil to capture the blast event [12-14] and in the last 15 years a wealth of numerical simulations to develop models of the entire event which may include a full vehicle with an occupant inside. The goal of all this effort is focused on the need to design a vehicle that provides the best possible chance for crew survivability.

The characterization of the blast event has many aspects which include the type of soil, level of saturation and how that influences the resulting impact on a structure. Other factors are depth of burial of the explosive, distance to the target and under what scenario the air blast affect is significant.

Experiments are always expensive but necessary as a first step to be able to determine input and validate numerical simulations. Accurate material properties are the most important ingredient to obtaining good numerical results. Obtaining this data for a blast event is more complicated than a simple tensile test and repeatability is always a concern [3] since there are so many factors in play. Most certainly, testing a simple structure such as a flat or V-shaped plate is far less expensive than testing various shield designs which require expensive prototypes to be fabricated. Add a full vehicle, with a physical dummy and the cost is enormous.

The design of a blast shield in a cost effective way can only be accomplished with the aid of numerical models. Much time and resources have been spent developing standard material models for soil that include large deformation and high strain rate effects [12,13] so that they can be used in traditional finite element solvers. These methods have shown to be either not predictive tools or require enormous computational resources and simulation time to obtain the accuracy to make them useful. It is one thing to simulate a simple structure by assuming symmetry to reduce computational cost, but the reality is that very simple structures that may be symmetric by design cannot be assumed symmetric once they are mounted to the bottom of a vehicle which is then subjected to non-symmetric loading. The consequence of which for traditional solvers is a dramatic increase in computation time.

Development of faster and more accurate simulation techniques are a necessity if we are to meet the demanding requirements to provide a better solution to the problem. Implementation of the Discrete Particle Method (DPM) in conjunction with GPU Technology reduces the computer resources that traditional solvers require and provides a robust, accurate, computationally efficient and most importantly a predictive tool.

To demonstrate the effectiveness of the DPM a comparison of experimental results found in [5,6] with numerical results using the IMPETUS Afea Solver® will be presented.

TRADITIONAL SOLVER METHODS

There are four traditional solver methods that are used to model the Blast Event. Load Blast, ALE/Eulerian and SPH. A brief discussion is warranted to understand how the various techniques differ and compare to the Discrete Particle Method which is the topic of this paper.

Load Blast Method

Load Blast is the most basic method which is based upon empirical equations and is a loading mechanism for a standard finite element solver. The blast loading is applied as an initial condition based upon the type of HE, the size of the HE and its distance from the target. This methodology was developed for an air blast scenario, where the distance to the target is large opposed to a buried mine under a vehicle. Modifications to this methodology to apply to the buried mine scenario [15] have proven to be inaccurate since it applies the load at time zero and does not take into account the time dependency of the loading due to the soil. Furthermore, it is an applied load and cannot capture the true nature of the soil impact, which is a function of the soil properties. It is not possible to correctly capture the impulse transfer of the soil to the structure especially for a non-flat structure that once mounted to the vehicle experiences a non-symmetric load.

Another attempt to apply a pressure load based empirical equation that takes into account an angled target plate and some soil characteristics was proposed by Tremblay [10], which was based upon the experimental results of Westine [11]. Implementation of this method as described by Schwer, et al [16] has not shown to be a predictive tool since the accuracy varies from problem to problem and once again the method cannot model the true nature of soil and the interaction with the structure which is a time dependent load. The relative error compared to experimental data for a simple flat plate was reported in [16] to be 53%, slightly better than flipping a coin.

ALE /Eulerian Methods

ALE/Eulerian solvers fall in the category of Computational Fluid Dynamic (CFD) solvers. They are multi-material solvers and for the buried mine problem, they model the Air, Soil, HE and the Structure with an Eulerian mesh. Both methods have to cope with numerical advection problems (diffusion and dispersion). Numerical errors are inevitable when fluxing material through the element grid. Despite this, CFD methods have been developed that can conserve momentum, kinetic energy and internal energy. There are actually excellent CFD codes available, well suited for air blast simulations (both at small and large stand-off distances). Unfortunately, adding soil complicates the picture. And the interaction with a deforming Lagrangian body makes it even more difficult.

- Soil is a material that is difficult for most CFD codes to handle. For this reason it is common to accept the use of classical hydro-codes that do not conserve kinetic energy. Not conserving kinetic energy is a heavy drawback when simulating a blast event. However, the energy errors can be reduced with a finer computational grid.
- The coupling between the materials in the CFD solver (Eulerian or ALE formulation) and the deforming Lagrangian structure is often referred to as FSI (Fluid-Structure Interaction). A general coupling between two numerical grids with non-coincident nodes is hardly possible without introducing energy errors and/or numerical leakage. Once again, the errors can be reduced (but not completely avoided) with a finer computational grid.

A really fine grid can solve most problems, but the required computational resources may not be available. This is discussed in [5].

SPH Method

The SPH method is a particle based continuum method unlike the DPM which is not a continuum based approach. There are particular issues with trying to use SPH for modeling a blast event. In particular:

- The very large density ratio between HE-AIR-SOIL is a big problem for SPH, it leads to instability.
- A complex CAP material model needs extensive identification experiments to be usable.

- The SPH method has a tensile instability which makes it difficult to obtain a correct energy balance in soil.
- SPH is a continuum based theory that is really designed to model fluid flow and so it can require a large amount of computation time.

DISCRETE PARTICLE METHOD

The Discrete Particle Method (DPM) as applied to modeling the complete Blast Event was first proposed by Olovsson [17]. The implementation of the DPM in the IMPETUS Afea Solver® is described in detail in [18] and compared with experimental results in [18,19].

The HE model is based upon the Kinetic Molecular Theory for gas. The basic assumptions are presented below, but the first two are not valid for HE so modifications to the theory are necessary.

The basic assumptions for Molecular theory are:

- The average distance between particles is large compared to the particle size.
- Equilibrium exists.
- Molecules obey Newton's Law.
- Molecular collision is perfectly elastic.

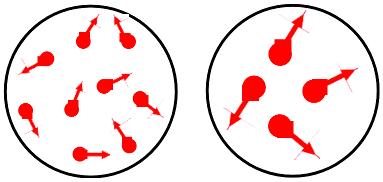

Molecules Particles

Figure 1. One Particle represents typically $10^{15} - 10^{20}$ molecules.

Calibration for specific types of explosives is accomplished by using a traditional cylinder test, as shown in Figure 2.

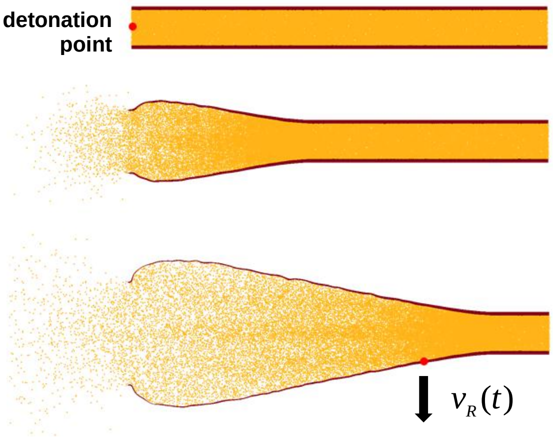


Figure 2. Cylinder Test used for HE Calibration.

Parameters that are used to characterize the HE particle model:

ρ	Density
E_0	Internal energy
D	Detonation velocity
v	Co-volume*
γ	Ratio of heat capacities*

*Optimized in cylinder test simulations

Air is also modeled with the same approach as the HE. The soil is modeled as rigid particles but includes inter particle contact for both friction and damping.

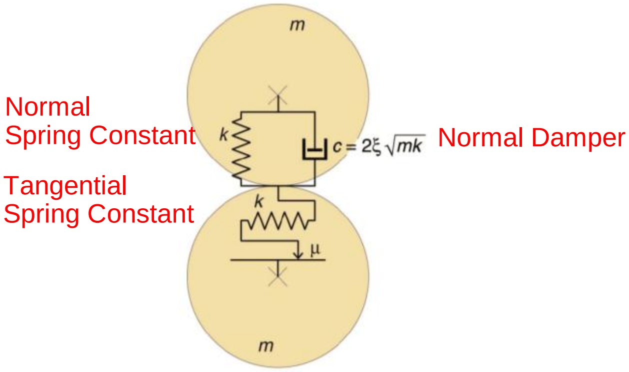


Figure 3. Rheological Model for the Soil.

Grain size distribution, friction, damping and contact stiffness are adapted to match a given EOS (Equation of State). The soil is packed using a unit cell with periodic boundaries that makes it possible to repeat the geometry within the defined soil domain without creating gaps between the cells.

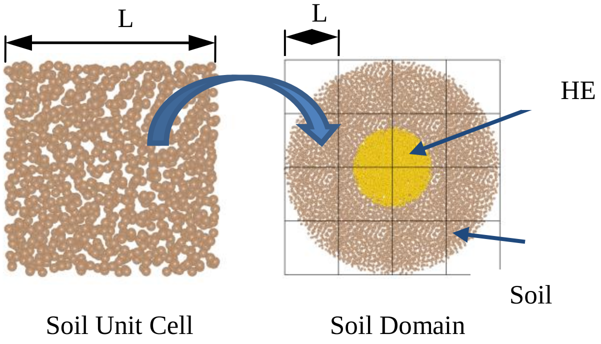


Figure 4. Soil and HE Models.

Placement of the HE in the soil domain is easily done at runtime and can accommodate the simplest configuration to the most complex as the soil is automatically filled around the shape of the HE container. This also applies to any other objects that are placed in the soil domain. Figure 5 shows a typical setup with the HE embedded in the soil and in this case a bowl shaped object placed below it. Figure 6 shows how the soil is automatically filled around the embedded object. The bowl shaped object was chosen to demonstrate that objects with complicated shapes, convex and concave surfaces are not a problem. This makes it very easy to randomly place objects at run time to simulate rocks or other debris in the soil.

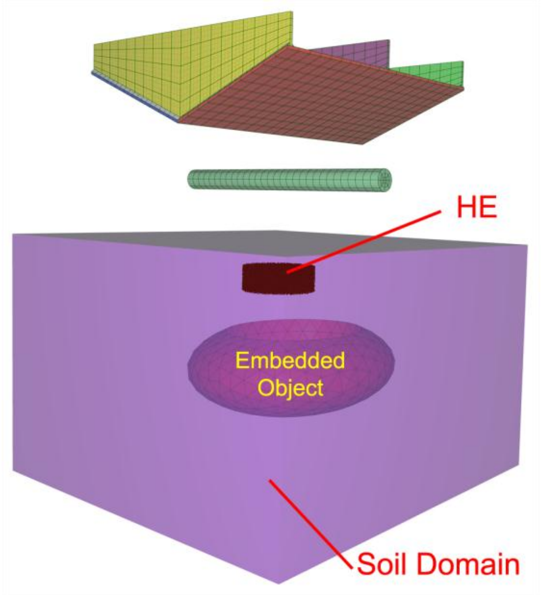


Figure 5. Placement of the HE and other objects in the Soil Domain.

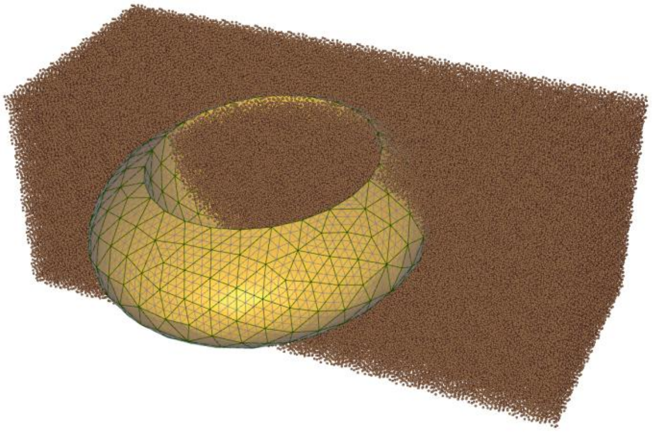


Figure 6. Close up view with the soil cut away to show how the soil is filled around a random object, in this case a bowl with both concave and convex surfaces.

Soil Calibration

Calibration of the soil for a particular scenario requires that a blast test be performed to compute the Maximum Impulse Load on the structure. Standard data collected from a blast test includes the maximum velocity of the structure and that is directly related to the impulse. From that information the following parameters can be used to calibrate the soil model.

- Soil Density
- Friction Coefficient between soil and the structure
- Spring Stiffness between soil particles
- Friction Coefficient between soil particles
- Damping Coefficient between soil particles
- Soil Particle Radius

The soil density is a parameter that can be determined by standard testing procedures. The friction between the soil and the structure is also determined from standard tests [20]. It is a straightforward process to determine the remaining parameters by simulating the blast test to optimize the values in order to match the Maximum Impulse that was measured.

Coupling with a Structure

The momentum transfer of the Soil/Air/HE to a structure is very robust as the contact is purely particle to surface. This allows the DPM to accurately model the impact on a structure as simple as a flat or angled plate to a very complicated surface like the bottom of a vehicle. As the soil impacts the structure, the “soil ejecta” breaks up and slides along the surface which may cause damage to parts of the structure that were not initially impacted [19]. With DPM the soil movement is easily handled, again because it is particle to surface contact.

GPU TECHNOLOGY

A GPU is a graphics processing unit, which was originally introduced by NVIDIA to accelerate the visual output to a computer display. It offloaded computations that were traditionally done by the CPU that where then passed to the graphics display card for display on the screen. By moving the computation to the GPU it improved performance and we see that every time we use a computer. GPGPU stands for General-Purpose Computing on Graphics Processing Units. This refers to a GPU that was designed for High Performance Computing (HPC). It has a large amount of local memory, thousands of processors and supports both single and double precision. There is a specific programming language and most important of all it fits in the standard PCIe slot that is found on every motherboard currently used from standalone workstations to clusters. Figure 7 shows the current flagship GPGPU from NVIDIA, the Tesla® Kepler™ K40 which has 12 GB of GDDR5 Memory and 2880 CUDA cores.

Figure 7. NVIDIA Tesla® Kepler™ K40, 12 GB of GDDR5 Memory and 2880 CUDA Cores.

The GPU brings cluster computing to a standard workstation as well as added compute power when installed on the nodes of a cluster. It works with the CPU, but it allows for massive parallel processing without the need for a massive compute cluster.

GPU versus CPU

The GPU works in concert with the CPU, the communication is asynchronous which means that the GPU works independently of the CPU. The CPU controls the simulation process and passes data and instructions to the GPU for parallel processing. Consider a problem with 1 million particles. One of the calculations for a buried mine simulation would be to determine which particles impact other particles. The CPU sends a request to process all 1 million particles and the 2880 CUDA cores of the K40 GPU systematically performs the calculations in parallel for each group of 2880 particles until all 1 million are completed. While all this is happening the CPU is free to perform other calculations, it does not need to wait until the GPU has finished its work. It does not face the lag time that may occur with cluster based parallelization where the load balance of the CPUs is not always optimal throughout the entire simulation.

Problem Size, Performance and Scaling

The 12 GBs of memory on the K40 is enough memory to run a very large problem, e.g., buried mine impact on a full vehicle model. The concept of scaling to improve performance is not relevant when running a simulation on a single GPU, because all available CUDA cores are used by the system to their fullest extent. Also, up until now most simulations can run on a single GPU. For larger problems multiple GPUs can be used.

Performance is a function of the number of simulations that are run on the GPU at the same time. For the fastest turnaround time running 1 job per GPU is optimal. In order to demonstrate how this affects performance an identical simulation was run with the only variable being the number of discrete particles. The timings are shown in Figure 8. The first run included 1 million particles and it completed in just 18 minutes.

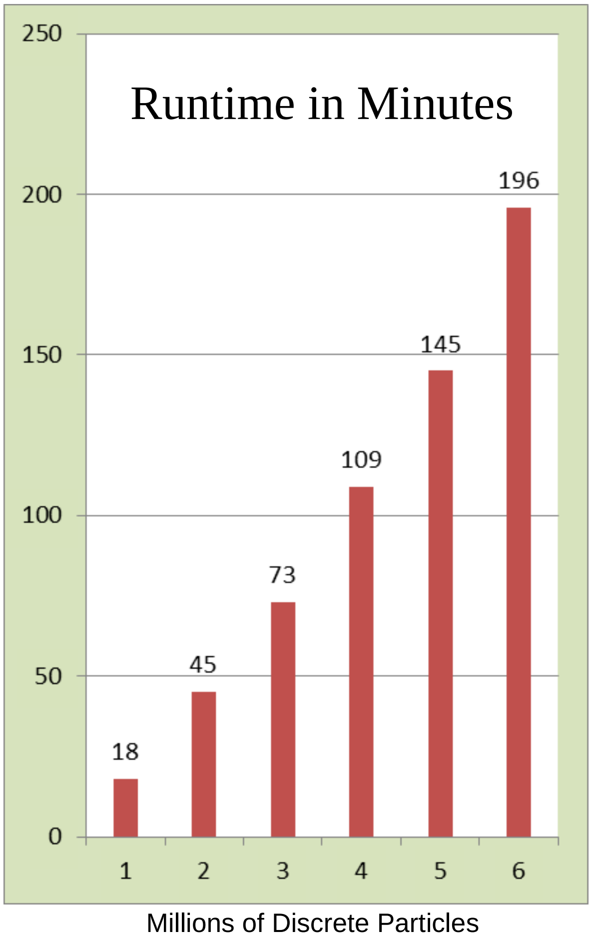


Figure 8. GPU Performance test for a Flat Plate Buried Mine Simulation.

Timing results for running multiple jobs on each GPU with different models will be discussed later in the Simulation section

EXPERIMENTAL DATA

In 2010 the Southwest Research Institute published a report [5] commissioned by the US Army RDECOM-TARDEC which provided a comprehensive set of blast test data along with simulation results for comparison using the Eulerian code CTH. Following that they published in 2011 a journal article with just the experimental data [6]. The quality of the data is very impressive and also highly praised by Schwer, et al [16].

A short description of the data presented in the report follows, the specific details can be found in the original work.

Test Setup and Procedures

- Excellent source of tightly controlled buried mine blast tests.

- The three test configurations are referenced by an interior angle, where 180 degrees represents a flat plate.
    - ➢ 180, 120 and 90 degrees
- 3 tests were performed for each configuration to show test repeatability.
- Detailed soil bed control with advanced data acquisition.
- The test results are clearly summarized in the report.
- The average velocity and momentum were calculated for each test configuration.
- Standard-Deviations were calculated to determine test repeatability.
- Coefficients-of-Variation were calculated to evaluate data scatter.

Data Verification

- All test series show Coefficient-of-Variation below 10%.
- There was small scatter and good control.
- The low scatter is indicative of tight test and soil bed control.

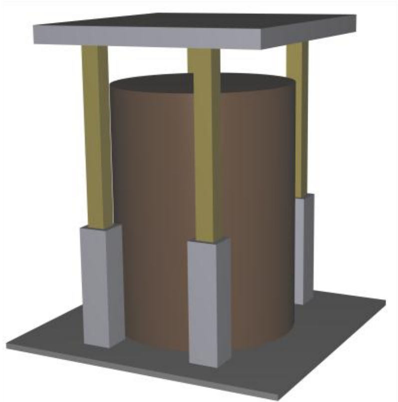
Measurements for Comparison with CTH

- **For each test reported the simulation velocities were measured at 4.75ms (steady-state lift).**
- **The average of the three velocities was used for the simulation target.**

Test Configuration

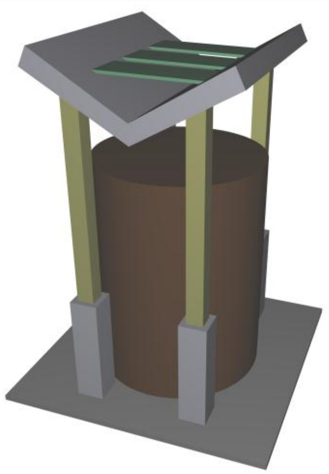
- Figure 9 shows the 3 test plate configurations, the Case ID references the internal angle.

The test configurations consist of 3 different plates, 3 variations for the soil moisture content and 3 different standoff distances. These are summarized in Table 1. Also included in the table are the Test Scatter Range and the Target Maximum Velocities for each case which was used in the report to compare with numerical results. Note, the same target values will be used to compare with the DPM results.



V180 – Flat Plate

V90 – 90 Degree Angle



V120– 120 Degree Angle

Figure 9 Test setup for 180, 90 and 120 Test Plate Configurations.

Test ID	Soil Moisture Content	Standoff Distance (cm)	Test Scatter (m/sec)	Target Maximum Velocity (Average of 3 Tests) (m/sec)
V180-07-30	7%	30	5.18-5.76	5.45
V180-07-20	7%	20	6.50-6.75	6.60
V120-07-25	7%	25	3.65-4.15	3.81
V090-07-25	7%	25	2.46-2.75	2.63
V180-14-20	14%	20	7.01-7.30	7.18
V180-21-20	21%	20	7.58-9.06	8.37

Table 1: Parameters for Experimental Setup and Target Maximum Velocity from Test Data. The target velocity was measured at 4.75 ms

SIMULATION

All test configurations are symmetric in nature and so the IMPETUS Afea® models assumed symmetry along one plane. This also allows for runtime comparisons with the results from other publications in the literature that simulated these experiments and assumed symmetry.

Because this is a buried mine at close range to the target the effect of the air blast is insignificant so the Air will not be modeled. One Million discrete particles were used in the model. The IMPETUS Afea Solver® automatically selects the number of particles to use for the Soil and the HE because there is a recommended ratio for a blast scenario and so it is done automatically at runtime by the solver. This would also be the case if Air was included.

One million discrete particles were used to model the Soil and HE, the solver automatically determines the proportion, which is 983,588 soil particles and 16,412 HE particles. For the V180 case the structure was modeled with 200 cubic hexahedron elements (64 nodes, 64 integration points and fully integrated). For the V120 plate 248 cubic hexahedron elements and 12 cubic pentahedron elements were used. For the V90 the model consisted of 324 cubic hexahedron elements. The stiffeners for the V120 and V90 plates were connected with the "MERGE" command which provides an easy way to connect dissimilar meshes.

Note the description of the V120 and V90 angled plates includes support plates between the sides. The additional mass was also reported and the position of the plates, so it was straightforward to add the plates to have a more correct model of the real structure.

Default wet and dry soil models are provided as a selected input in the IMPETUS Afea Solver®. They are calibrated models based upon blast test experiments. However, they are only provided to give the user a base line set of parameters, the user defined option is always recommended and requires that the user has blast test data to calibrate the particular soil being used for their analysis. The wet and dry soil models use two different packing schemes that are also available in user defined option. The two different types of soil use different rheological parameters:

- Dry soil: Stiffness and friction
- Wet soil: Stiffness and damping

There are 2 other parameters that are used to calibrate the model: Soil Particle Radius Scale Factor and the Friction between the soil and structure. A good description of the soil implementation can be found in [18,19].

The soil moisture content was relatively low for the test cases so a Dry soil was used. There are default parameters for the soil so all cases were run with the default parameters and no friction defined between the soil and structure. As expected it was necessary to use the User Defined Soil option and calibrate the soil parameters. Note, only the V180 (flat plate) models were calibrated. For the 7% moisture content the same soil parameters that were used for the V180 were used for both the V120 and V90 configurations. For a predictive tool this is a must as the soil parameters are only a function of the soil and not the structure being impacted by the mine blast.

All 6 models were run on a single Workstation with a Quad Core i7 processor, 32 GB of memory and 2 NVIDIA Telsa K40 GPUs. Figures 10-12 show results for the three 7% moisture content tests which included the V180, V120 and V90 configurations. The remaining 3 V180 tests only varied with the soil moisture content and so only the final computed values for the Maximum velocity are of interest as the visual aspects are quite similar to the 7% V180 case.

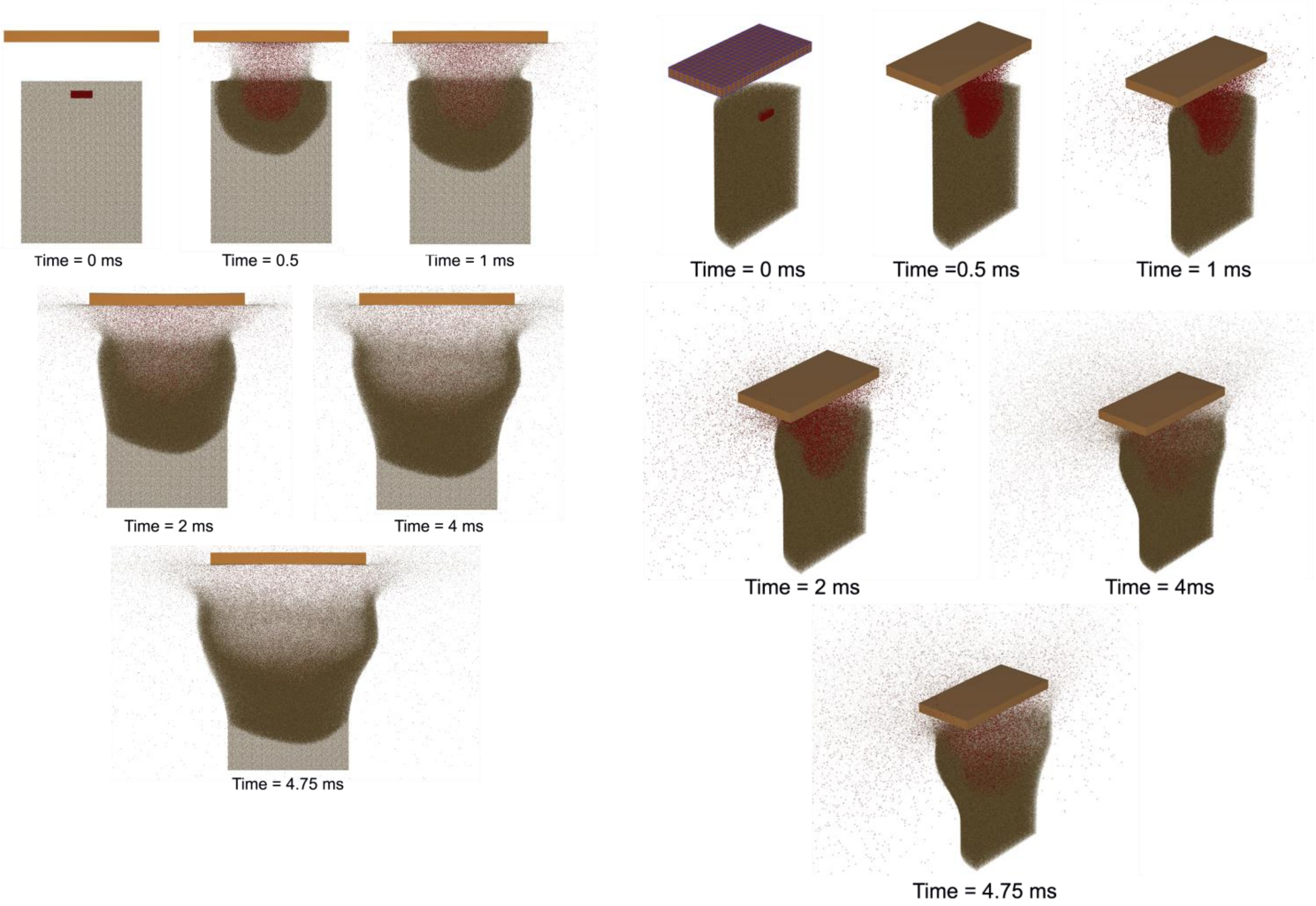


Figure 10 V180-07-20 test case with 7% Moisture Content and a 20cm standoff distance.

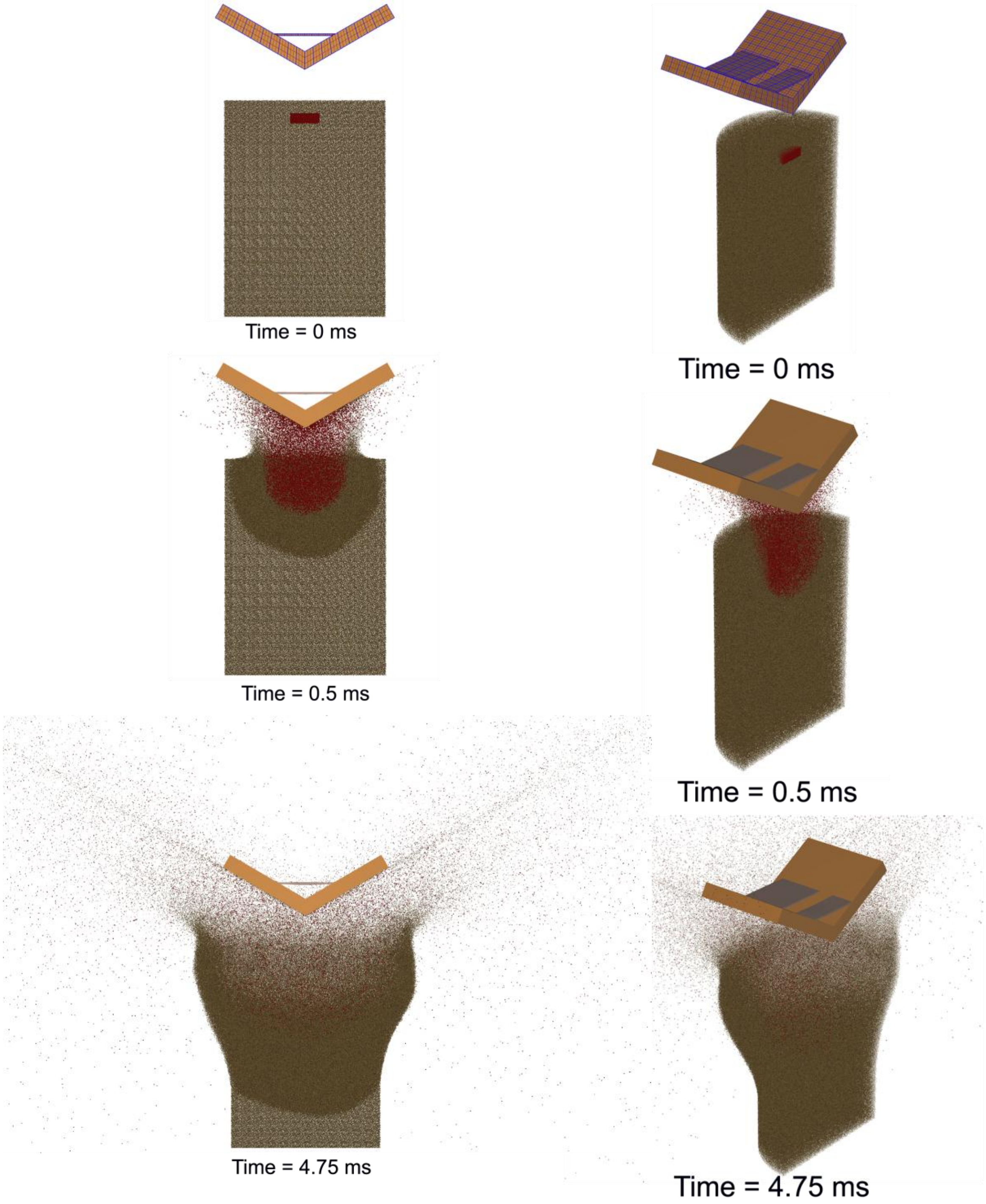


Figure 11 V120-07-25 Test Case with 7% Moisture Content and a 25 cm Standoff Distance.

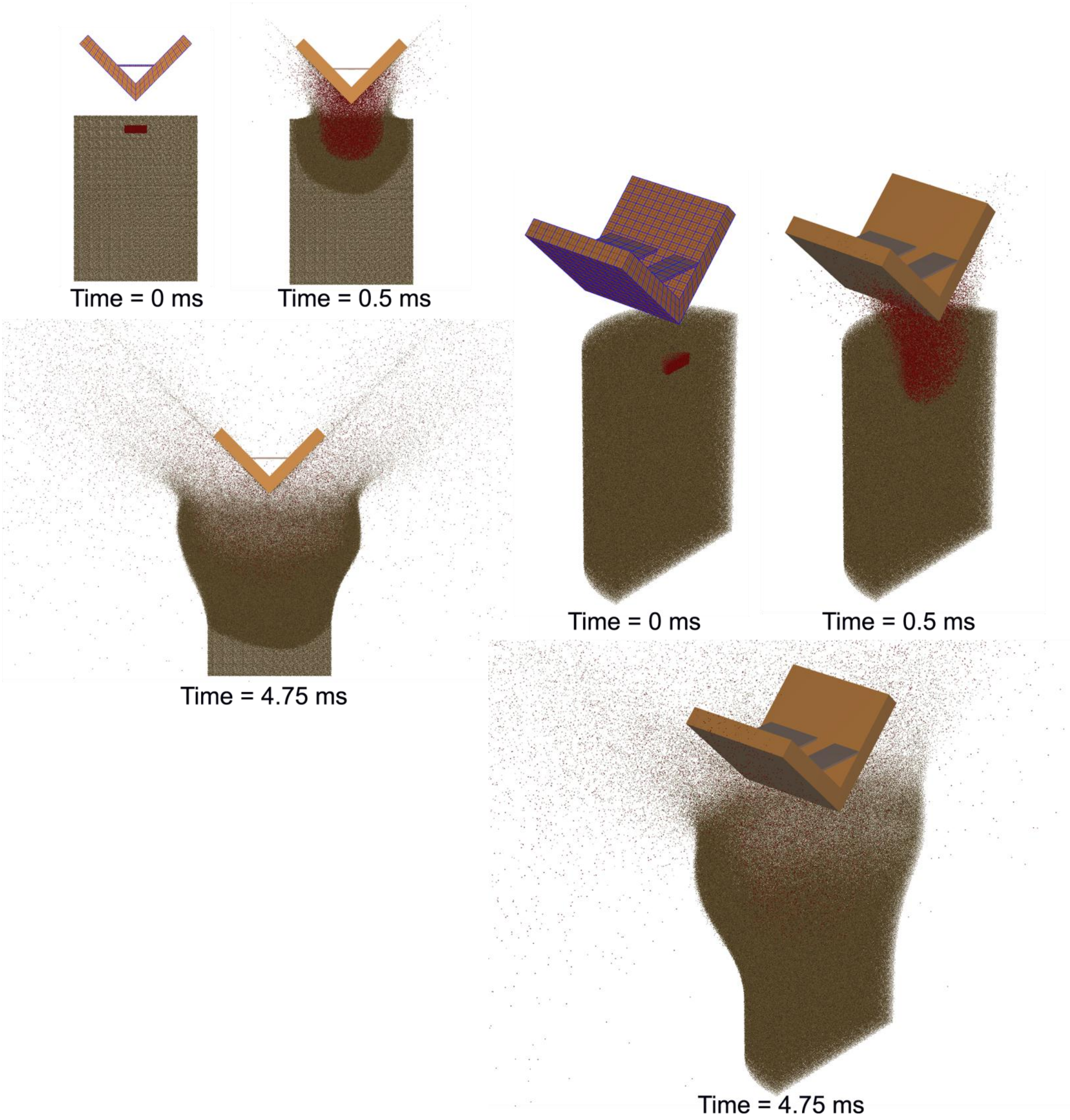


Figure 12 V90-07-25 Test Case with 7% Moisture Content and a 25 cm Standoff Distance.

NUMERICAL RESULTS

Table 2 shows numerical results for all 6 simulations including the run times. The simulation results were compared with the experimental data at t=4.75ms.

Accuracy

The most important column of results table is the "Test Scatter Range", note that **all simulation results** fell within the max and min of the test results. Recall that the soil was calibrated only for the V180 test results and that the identical soil characteristics were used for all four 7% moisture content cases: V180-07-30, V180-07-20, V120-07-25 and V90-07-25.

Peformance

All simulations were completed within 20 minutes for the case of 2 jobs running at the same time but one on each GPU. This means that all 6 simulations were completed in less than 1 hour. To test performance of the GPU 3 jobs were run on both GPUs and the last job finished in less than 1 hour. So the average time for each job was similar to running them sequentially, with the only difference being when they finished.

Test ID	Soil Moisture Content	IMPETUS Afea Results Maximum Velocity (m/sec)	Relative Error from Average Target Maximum Velocity	Within Test Scatter	Runtime (mins)
V180-07-30	**7%**	**5.54**	**1.7%**	**YES**	**19**
V180-07-20	**7%**	**6.51**	**-1.4%**	**YES**	**18**
V120-07-25	**7%**	**3.99**	**4.7%**	**YES**	**20**
V090-07-25	**7%**	**2.57**	**-2.3%**	**YES**	**20**
V180-14-20	**14%**	**7.00**	**-2.5%**	**YES**	**17**
V180-21-20	**21%**	**7.58**	**-9.4%**	**YES**	**17**

Table 2: IMPETUS Afea Simulation Results for ½ symmetry model using the Soil Parameters Calibrated for the V180 Test Results.

CONCLUSIONS

It is clear from the simulation results that the Discrete Particle Method is an accurate tool for modeling mine blast scenarios. It has also shown to be a predictive tool as well since the soil model was only calibrated for one blast test, the V180-07-20 (flat plate) and then subsequently used to accurately model the remaining structures, the V180-07-30, V120-07-25 and the V90-07-25 with the same soil model.

The DPM in combination with GPU Technology has shown extremely good run times for the simulations. Although it is not possible to share results from proprietary customer data, the authors can tell you that the runtimes for commercial users of the IMPETUS Afea Solver® for real vehicle structures are also very good.

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