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DISCRETE PARTICLE METHOD IS A PREDICTIVE TOOL FOR SIMULATION OF MINE BLAST – A PARAMETER STUDY OF THE PROCESS AND APPROACH

Morten Rikard Jensen, PhD
CertaSIM, LLC
Livermore, CA

Wilford Smith
SAIC
Atlanta, GA

ABSTRACT

The modeling of a buried charge is a very complex engineering task since many Design Variables need to be considered. The variables in question are directly related to the method chosen to perform the analysis and the process modeled. In order to have a Predictive Tool two main objectives have to be carried out, the first is a verification of the numerical approach with experimental data, the second objective is a sensitivity study of the numerical and process parameters. The emphasis of the present study covers the second objective. To perform this task a comprehensive sensitivity study of fourteen Design Variables was completed which required 1000+ computational hours. The modeling approach that was chosen was the Discrete Particle Method (DPM) to model the Soil and HE and the Finite Element Method for the Structure. The basis for the study was a blast event applied to a model of the TARDEC Generic Vehicle Hull. The Response Parameter was chosen to be the Total Blast Impulse on the structure. The non-linear transient dynamic explicit Finite Element solver used for the analysis was the IMPETUS Afea Solver® which has implemented the DPM for blast simulations. The study includes soil characteristics, charge related parameters, such as size, type, geometry and location. Also the DOB, number of Discrete Particles etc. were considered. The results provide guide lines and in depth understanding of modeling buried charges with a coupled FEM and DPM approach.

INTRODUCTION

A large percentage of casualties in recent military conflicts are due to blast from buried mines, typically coming from Improvised Explosive Devices (IED). The number of Hostile Deaths resulting from "Operation Enduring Freedom-Afghanistan" between 2001 and 2014 is around 2782. Of these, 1401 deaths were caused by IED's, which is nearly 50% [1]. The design of better vehicle protection is necessary to reduce the casualties of our soldiers. At the heart of the design process is simulation technology which allows engineers to test and refine their ideas in a virtual environment before the costly step of building a prototype for physical testing. It is of vital importance to have predictive numerical tools for this process to minimize the number of physical tests. To obtain a predictive simulation tool for a specific application area, two main objectives have to be carried out successfully as shown in Figure 1. The first objective is verification against experiments, where the software is calibrated against simple tests and this is used as a base for prediction of more complicated scenarios where no experiments are available beforehand. Tuning of numerical and process parameters against already available experimental data does not make the software predictive. The second objective that must be considered is a sensitivity study of both the process parameters and the numerical parameters. This gains knowledge about the response of the numerical model and helps in the model calibration phase as well as illustration of the stability of the software.

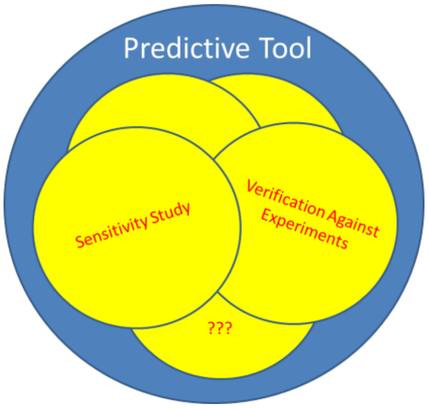

Figure 1: *Necessary objectives to consider when evaluating if a software program is a predictive tool.*

In this paper the Discrete Particle Method (DPM) provided in the IMPETUS Afea Solver®, an Explicit Non-linear Transient Dynamic FE solver is applied for modeling the mine blast event. The DPM module is described in great detail in [2, 3, 4] where the approach was verified against mine blast experiments. The module was also successfully applied in [5]. The benefit of the DPM method is further enhanced when combined with a solver that takes full advantage of the parallelization provided by GPU Technology. IMPETUS has been proved to accurately simulate mine blast during the last eight years, both by researchers and in commercial projects. An extensive number of experimental blast tests have been simulated. This means that the IMPETUS Solver satisfied the first objective of being a predictive software tool.

The benefit to using the DPM is its high degree of accuracy for modeling Soil, Air and HE. The parameters for a HE are calibrated for a particular explosive based upon a standard cylinder test [2]. Similarly the soil parameters have to be determined as well but the variation of soil type does not include a simple list as the characteristics of the soil are affected by moisture content, level of compaction and the soil make up, e.g., sand, dirt, rocks, etc. [6-11]. The procedure to calibrate the soil model requires a good understanding of how the various DPM parameters influence the resulting blast load on a structure. The best way to explain this is with a sensitivity study, which is the second objective for obtaining a predictive simulation tool and the main purpose of this study.

Recently an IMPETUS Afea finite element model of the TARDEC Generic Vehicle Hull was created. The model along with the IMPETUS Afea Hybrid III 50th Percentile Dummy model is illustrated in Figure 2. The Hull model was chosen for the parameter study omitting the dummy as it does not influence the blast loading. It is a particularly relevant structure to use for the study as it is a real structure that has been blast tested by the US Army and continues to be used by TARDEC to better understand how to protect the occupant.

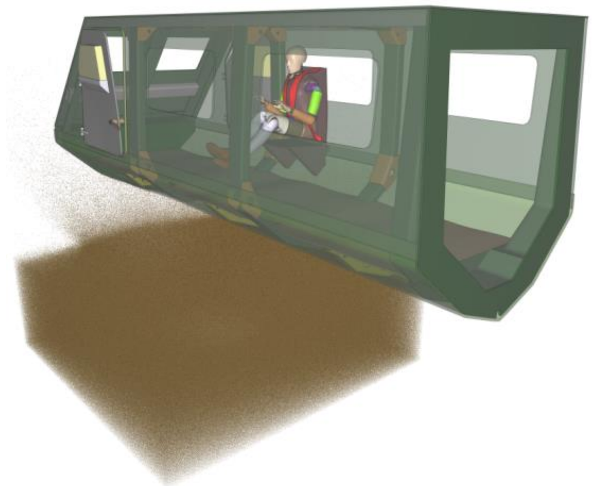

Figure 2: *IMPETUS model of the TARDEC Generic Vehicle Hull.*

By utilizing GPU technology in the IMPETUS Solver the computational time for this Base Model is approximately 9 hours. In this discussion the Blast Impulse on the structure was chosen as the Response Parameter. Note, the numerical results are compared with the "Base Model" numerical result since experimental data has not yet been publicly released by TARDEC.

BASE MODEL RESULTS AND DESIGN SPACE

Modeling blast events with the DPM is very straight forward in IMPETUS. It is done with the *PBLAST command where domains are defined for the Soil, HE and Air (if used). By simply specifying a total number of particles the solver automatically calculates the correct ratio between the domains. The solver has built-in packing algorithms for the domains in which Lagrangian structures can be embedded easily by simply including a part ID in the part set of the structural parts that interact with the particles. Furthermore, friction can be specified for the interaction between the soil and the structure. The modeling of HE is done with rigid spheres that have elastic impact for inter-particle contact. The implemented approach is described in [2]. The type of HE is easily defined, e.g., C4 or TNT, by selecting one as part of the input, but in addition a user defined HE is also available. Next, the coordinates of the detonation point within the HE domain is defined by the user.

The soil is also modeled with discrete rigid particles but the inter particle contact includes both friction and damping.

The rheological model for the soil is illustrated in Figure 3, showing the springs and the damper. The normal and tangential spring constants are given the same value.

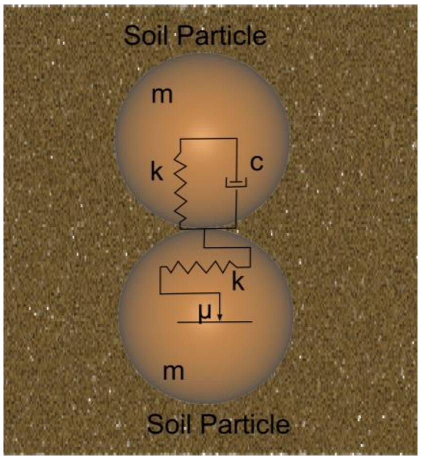

Figure 3: *The applied rheological model for the soil.*

The soil is packed using a unit cell with periodic boundaries that makes it possible to repeat the geometry to generate the Soil Bed. These unit cells are then scaled which affects the inter particle stiffness which becomes $k=L/L_0 \cdot k_0$ where L is the scaled size of the unit cell, L_0 is the un-scaled size and k_0 is the stiffness of the un-scaled unit cell. The details of the implementation are shown in [2, 3].

As for the HE, the soil can also be specified using built-in calibrated models, either as dry or wet but it is recommended to calibrate the soil based on a blast test of a rigid flat plate using the Soil Bed that is to be used for the more complicated structure. This will require using the "user defined soil option" which is straight forward to specify. It includes the soil density, the soil particle stiffness, the soil particle friction and damping. For dry soil, stiffness and friction is used and for wet soil stiffness and damping. A detailed description of the procedure for soil calibration can be found in [12]. The set-up in the command file only requires a few lines as illustrated in Figure 4.

*PBLAST
entype, enid, air, soil, he, N_p
bc_{x0}, bc_{x1}, bc_{y0}, bc_{y1}, bc_{z0}, bc_{z1}, μ
gid_{glob}, gid_{soil}, gid_{he}, x_0, y_0, z_0, t_0, t_{end}
pack, ρ_s, k_s, μ_s, ξ_s — used if soil=user
ρ_{he}, e_{he}, γ_{he}, v_{he}, D_{he} — used if type_he = user

Figure 4: *The *PBLAST command is used for defining the blast set-up [13].*

Design Space

It is always a challenge to define the experimental matrix or the Design Space when a sensitivity study or optimization is carried out. In fact, the Design Space often changes during the study due to unknown constraints on the design variables or physical limitations on the process parameters. Based on the experience and interest of the authors, 14 design variables were chosen to illustrate both approach but also process parameters. For each of the design variables between three to five or more variations where tested, leading to around 80 entities in the Design Space, each representing a numerical simulation. Less could of course have been selected but the knowledge obtained will be very helpful in future work in the field of mine blast simulations. The following characterization of the parameters illustrates the base for the Design Space:

- Soil: Density, packing routine, inter particle stiffness, inter particle friction, inter particle damping, soil domain size and friction between structure and soil.

- Charge: Charge size, geometry, HE type, orientation (angle), off center location, DOB.

- General: Total number of particles.

Each of the design variables and their settings are described in the numerical results section. The total blast impulse on the structure in the Z-direction was chosen as the Response Parameter. Blast impulse is a very common measure in a blast event, and clearly indicates the design variables sensitivity and influence on the response.

Base Model

The Base Model is the TARDEC Generic Vehicle Hull model which is modeled as a full 3D model using solid elements for all components, even for the welds and bolts. IMPETUS predominantly works with higher order elements. That is, elements with non-linear shape functions that accurately handle bending and are less prone to shear or pressure locking. All higher order elements in IMPETUS are fully integrated and, hence, do not suffer from any zero energy modes (so called hourglassing). Traditional iso-parametric higher order elements are not suited for dynamic events and explicit time integration. Extreme dispersion destroys their ability to handle propagating waves and high eigenfrequencies on the element level have a severe impact on the critical time step size. The set of higher order elements (quadratic and cubic) in IMPETUS use special interpolation functions and do not suffer from above mentioned shortcomings. The higher order elements are called the ASET™ Family of Elements. In the Base Model only Quadratic elements are specified as they are more than sufficient to accurately model the structure. A total of 24,902 elements are used. A section cut of the Base Model is shown in Figure 5, where the Discrete Particles for the soil and HE also can be seen. The total count of particles is 4,000,000 distributed as 3,977,497 for the soil and 22,503 HE particles.

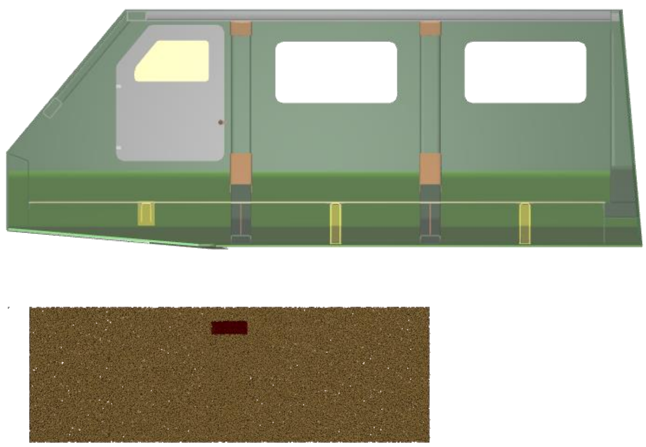

Figure 5: *Section cut of the Base Model showing the structure, soil and the High Explosive.*

The HE is a cylindrical 8 kg C4 charge with a height to diameter ratio of 1/3 and a DOB of 4 inches. It is placed in the center of the structure widthwise and in the front lengthwise as seen in Figure 5. No air particles are included in the Base Model. The simulation time is set to 20 msec. The soil density is taken from [14] and the experimental set-up from there is modeled and the soil is calibrated against their experimental Response Parameter in [12] which are the values used in the Base Model. This leads to a soil density of 2301 kg/m^3, a soil friction of 0.25 and a soil stiffness of 5e+8 N/m. The soil is assumed dry so the soil packing routine number 3 is applied which generates 10,000 soil particles per unit cell.

The result of the Base Model simulation is shown in Figure 6, where a large deformation is seen. The floor is "rippled" and the doors bend.

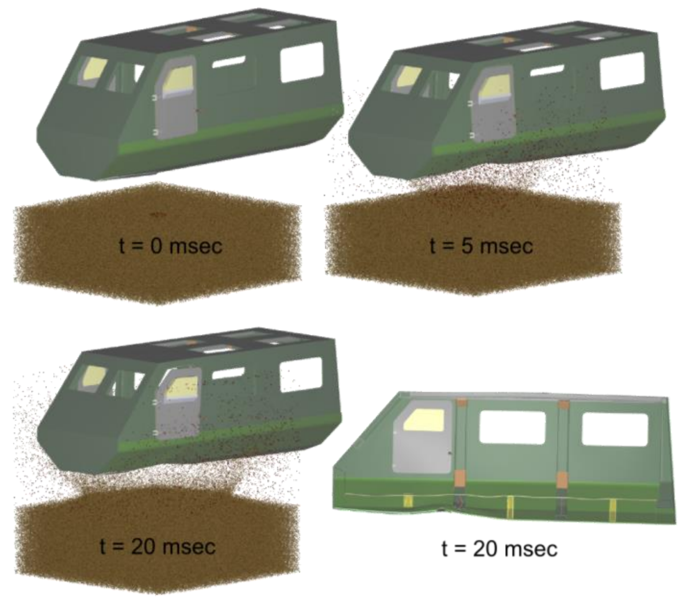

Figure 6: *Simulation results from IMPETUS. It is seen that at 20 msec the doors are bending and the floor "rippled". The last picture is a section cut to see the damage of the floor.*

A time history plot of the Blast Impulse on the structure in the Z-direction is shown in Figure 7 and it is found that the maximum value is 21,705 N-Sec. This value will be used for comparison in the sensitivity study.

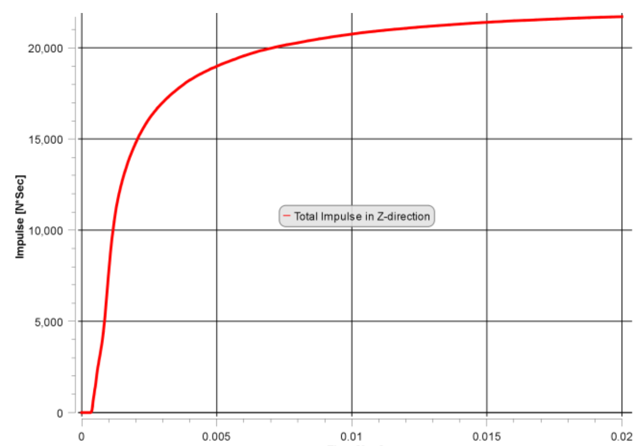

Figure 7: *The total blast impulse on the structure in the Z-direction for the Base Model through-out the simulation.*

NUMERICAL RESULTS FROM SENSITIVITY STUDY

The simulations were run on various hardware platforms which included the NVIDIA K40 GPU for parallel processing. The same version of the solver was used for all simulations. The design variables are grouped into the following three main categories: Soil, Charge and General.

Soil Parameters

The first parameter investigated is the density of the soil, the Base Model used 2301 kg/m^3. The values tested are 1370, 1620, 2020, 2500 and 3000 kg/m^3. The wet and dry built-in soil has the density of 2020 and 1620 kg/m^3, respectively. The density of 1370 kg/m^3 is listed as the density for 7% moisture soil in [15, 16]. The last two densities are specified to see the effect of heavier soil. It is expected that the Blast Impulse will increase with increasing density. The results are plotted in Figure 8 where this is verified but it is also observed that there is a linear relationship between the soil density and the total Blast Impulse on the structure. This seems reasonable when only density is changed.

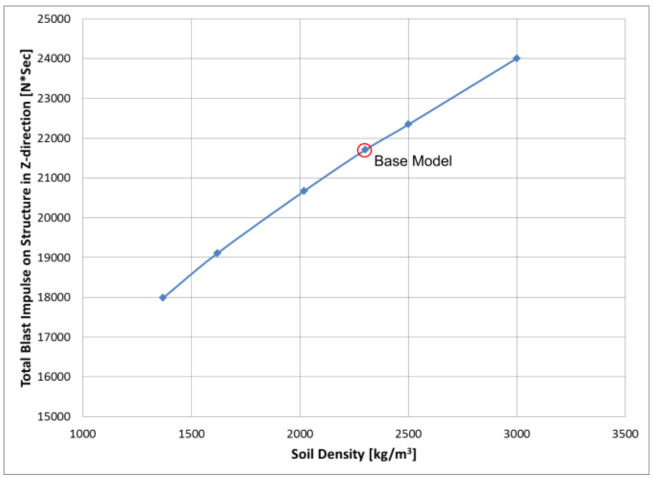

Figure 8: *Influence on the blast impulse from changing the soil density.*

The Base Model used dry soil with the soil packing method Number 3. The soil is packed in unit cells with periodic boundaries as discussed earlier and in [2, 3]. It was chosen in [12] to use a dry packing routine and calibrate based on the friction. The main difference in the packing method is the number of particles included in the unit cell and the grain radius. The older methods, 1 and 2, used 1,000 particles in each cell and the newer ones, 3 and 4, use 10,000 per cell. All include wet and dry packing options, where the wet soil option has a larger grain radius than the dry. Using 10,000 particles per cell is more accurate and is the recommended choice. It is expected that the wet soil will give the largest impulse and this is clearly verified in Figure 9. Note that there is a smaller difference between the two dry packing options than with the two wet options, which is only around 2%.

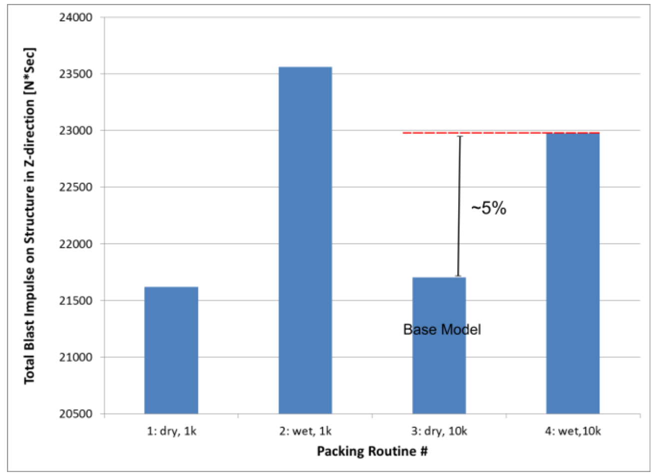

Figure 9: *Influence on the blast impulse from the different packing routines.*

It is recommended to use the newer more accurate packing options then select if the soil is wet or dry and calibrate the soil. In the Base Model, the difference between the new wet and dry packing options is around 5%.

As mentioned there are tangential and normal springs between the soil particles and the same stiffness is used for both. For the built-in soil a stiffness of 4e+8 N/m for the dry soil and 4e+9 N/m for wet soil is used. The Base Model uses 5e+8 N/m based on the authors experience and it has also been the experience that the stiffness value does not have a strong influence on the results, unless it is changed by an order of magnitude. In the sensitivity test values of 1.e+8, 2.5e+8, 7.5e+8 and 1e+9 N/m were tested. These values represent the stiffness of the unit cell, k_0, as mentioned earlier. The results are plotted in Figure 10, supporting the assumption that within the same magnitude, the soil-to-soil stiffness gives similar results. The difference between the minimum and the maximum Blast Impulse value is 7.5% where the maximum value is found at the low end of the values investigated for the stiffness.

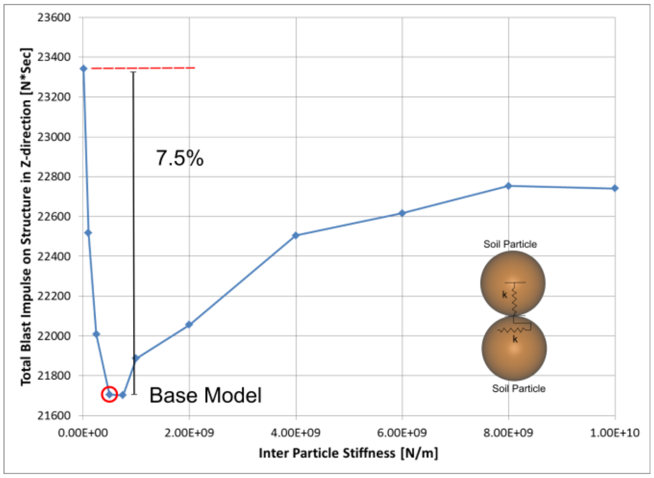

Figure 10: *Influence on the Blast Impulse from the inter particle stiffness.*

Based on these results, when calibrating the soil use 5e+8 N/m for dry soil and 5e+9 N/m for wet soil.

The friction between the particles is one of the most important parameters for the soil specification and thus often used as the main calibration variable, especially since soil density is a standard parameter that can easily be measured. For the built-in soil models, the dry soil has a friction of 0.1 whereas there is no friction applied for wet soil. The values tested here are: 0.05, 0.1, 0.2, 0.25, 0.5 and 0.75 where 0.25 is the one used for the Base Model. The influence from the setting of the friction coefficient on the Blast Impulse is seen in Figure 11. By increasing the friction the impulse is lowered and it should be noted that the maximum difference in the Blast Impulse is a decrease of 49% showing the importance of carefully setting the friction value.

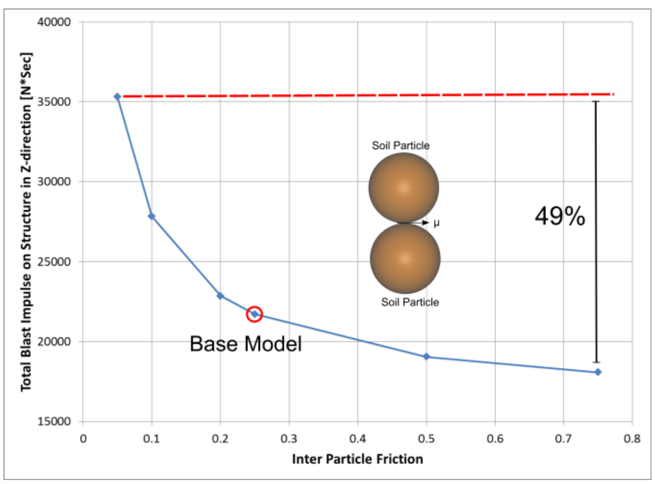

Figure 11: *Influence on the Blast Impulse from inter particle friction which has been found to be an important soil parameter.*

Experience shows that one seldom has to go outside the range that is shown in this series of runs. The number of iterations for calibrating the friction and thus the soil depends on what is an acceptable error when comparing to the target value, a small percentage error is acceptable.

As mentioned damping between the soil particles can also be applied and this is done for the built-in wet soil but not the dry option. The value used is 0.005. To test the influence from the damping coefficient, a total of six test cases were selected. They are split into two main groups, one using packing routine 3 (dry, 10k) and packing routine 4 (wet, 10k). It is expected that the results for packing routine 4 will result in a higher Blast Impulse than using packing routine 3, this is based on the study of the routines as shown earlier. This was indeed the case and it is further seen that the Blast Impulse in both cases drops with increased damping values as shown in Figure 12. The maximum decrease for packing routine 3 is 2.7% when compared with the Base Model.

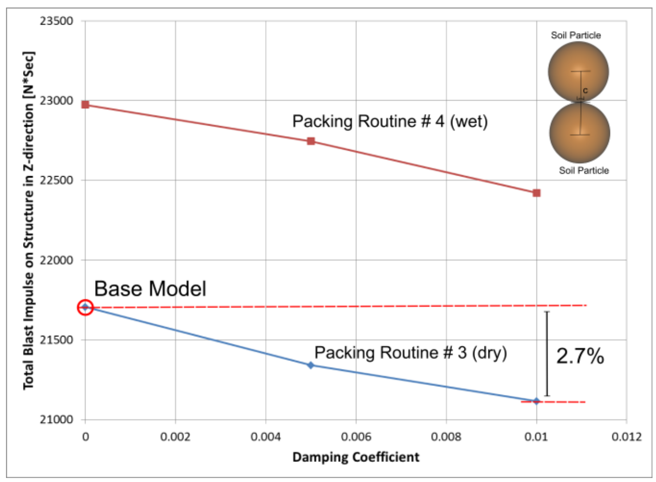

Figure 12: *Influence on the Blast Impulse from setting the damping between the soil particles for different packing routines.*

The soil particle interaction with the Lagrangian structure is treated with a contact routine that is implemented into the *PBLAST command so the user does not define a contact specification but only needs to provide which parts will be in contact with the particles. One can simply specify ALL to consider all Lagrangian parts for contact. Though there is no *CONTACT command, it is possible to set a friction coefficient for this contact and the influence of this on the Blast Impulse has been tested. The Base Model does not have any friction included for the particles in contact with the Lagrangian structure. As shown in [17], the friction coefficient can be rather large but we have often used 0.3 and the experience is that the parameter does not have a strong influence on the Blast Impulse. In this series friction coefficients of 0., 0.05, 0.1, 0.2, 0.3 and 0.5 are tested. The results are shown in Figure 13, illustrating a nearly linear relationship where it should be noted that specifying no friction and a friction coefficient of 0.5 results in only a 6% difference in the Blast Impulse.

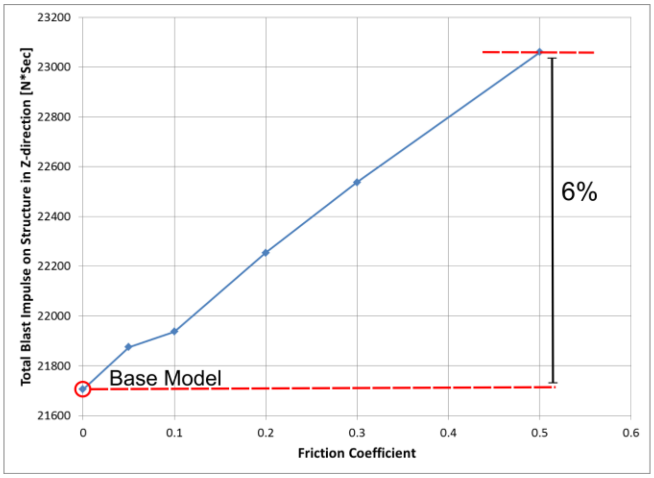

Figure 13: *Influence on the Blast Impulse from setting the friction between the soil particles and the structure.*

One parameter that not is mentioned often in the literature is the size of the Soil Bed. In [18] the recommendation is a minimum of 2x2 m of soil around the charge for the given charge but no information is given about the depth. In [19] a Soil Bed of 2x2m with a depth of 1.6 m is applied for a 2 kg TNT cylindrical 1:3 charge. In the Base Model a 3x3x1 m Soil Bed is used. Five other tests where done with different dimensions, these are shown in Figure 14. A special version of IMPETUS was compiled for this sensitivity study since the number of HE particles should remain the same and the size and mass of the soil particles should be similar. Thus, the ratio between the volume of the tested dimensions and the volume of the Base Model was used to find the number soil particles that should be specified. The special version of IMPETUS allowed the input of individual input to be specified for the number of particles for Air, HE and Soil. Of course by doing this, there is a risk of violating the distribution functions between the different particle domains. Also, the global domain needed to be changed to capture the new soil domains. The results of changing the Soil Bed dimensions are shown in Figure 14. The difference in Blast Impulse from the smallest value (2x2x1 m) to the largest value (6x6x0.5 m) is approximately 7%. The 2x2x1 m domain is probably too narrow, having fewer particles impacting the structure and hence a lower Blast Impulse, especially considering that the width of the Generic Hull is around 1.5 m. The 6x6x0.5 m domain gives the largest Blast Impulse which could be due to the use of the Rigid Reflecting Boundary option at the bottom of the Soil Bed which indicates that the depth is too small. Visually, this was shown by observing the soil deformation. If these two cases are omitted, 2x2x1 m and 6x6x0.5 m, the difference between the maximum and minimum values is 1.6%. The results show that the applied Soil Bed for the Base Model (3x3x1 m) is the minimum recommended dimensions for the investigated set-up.

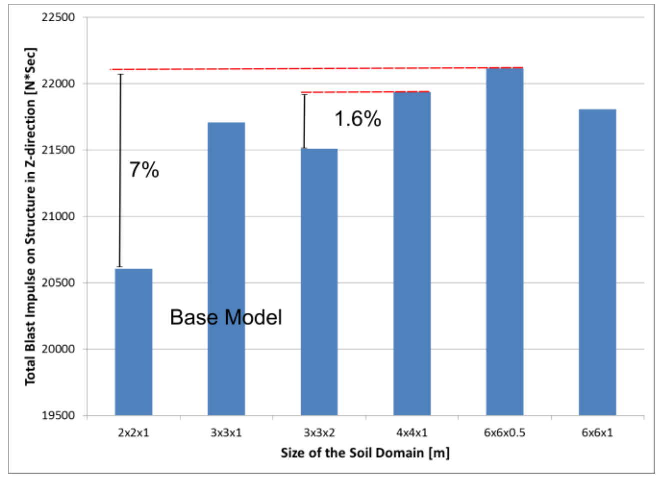

Figure 14: *The different tested Soil Bed dimensions and their influence on the Blast Impulse.*

Parameters for the Charge

The charge size used in the Base Model is 8 kg C4 which is the size given as a STANAG 4569 Level 3 threat type in [20]. In this standard the charge sizes for the different threat levels are 6, 8 and 10 kg. These are also the charge sizes listed in [18], though for both standards the charge type is TNT. In the Defense Community there seems to be a need for modeling larger charge sizes, mainly due to the use of more powerful IED's. A major problem in the numerical simulation of large charges is the high deformation of the Lagrangian structure since traditional linear elements cannot withstand this large deformation. Thus, by applying a large charge size it shows the influence on the Blast Impulse but it is also a good validation of the ASET™ Element Technology. Five different charge sizes were tested besides the Base Model: 6, 8, 10, 15, 20 and 30 kg. This means that the largest charge tested is three times the maximum threat level defined by the NATO standards. The DOB was kept the same as well as the diameter to height ratio. The buried 6 kg and 30 kg charge geometry is illustrated in Figure 15.

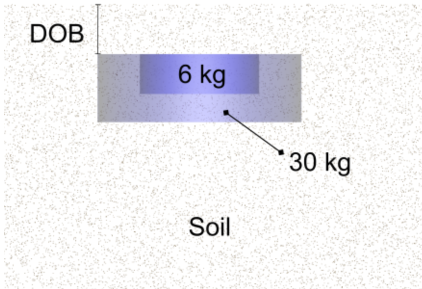

Figure 15: *The smallest (6 kg) and the largest charge (30 kg) applied in the test series. The DOB is kept the same in all cases as is the diameter to height ratio.*

The impulses are plotted in Figure 16 where it is seen that the Blast Impulse varies linearly with the charge size.

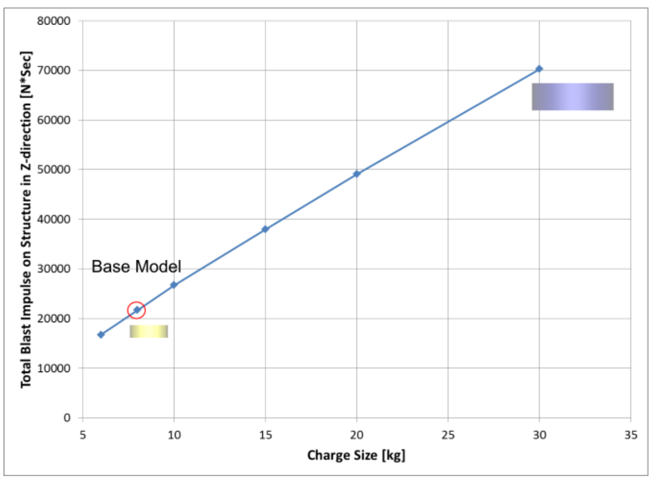

Figure 16: *Influence on the Blast Impulse from the size of the charge. The smallest charge is 6 kg and the largest is 30 kg, all HE are C4.*

All models ran succesfully to normal termination and there where no problems with the elements, even for large structural deformations. The Base Model has no Damage or Failure specified so the Hull simply bulges up as shown in Figure 17 which is the result for the largest charge size of 30 kg C4. It is seen that the integrity of the elements are intact.

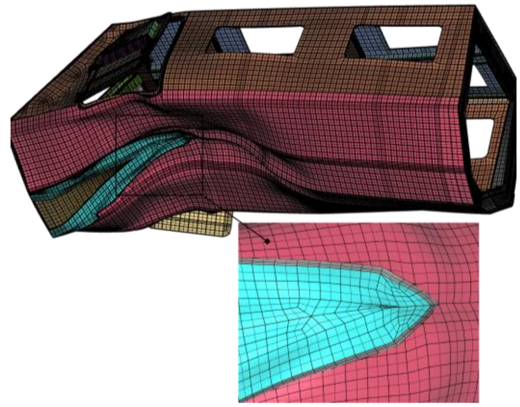

Figure 17: *The smallest (6 kg) and the largest charge (30 kg) applied in the test series. The DOB is kept the same in all cases as is the diameter to height ratio.*

In IMPETUS there are four pre-defined choices for the type of HE: C4, TNT, Petn and m46. In addition a user defined HE can be specified, e.g., if LX 17 or Comp B is used. Petn is the most powerful of the pre-defined HE but is seldom used in large quantity. After Petn is C4 the most powerful HE, followed by TNT. M46 is a Swedish HE that is similar to TNT. Simulations has been done with all four types where the only parameter changed is the "*he*" in *PBLAST which means that the volume is the same in all four cases and since the density is different for the different HE, the total mass is different. The Blast Impulse results are shown in Figure 18 verifying the order of efficiency for the varies types. Petn gives the largest Blast Impulse, followed by C4 with around 10% difference to Petn. The impulse for C4 is approximately 7% larger than the impulse for TNT which is very close to the response of m46.

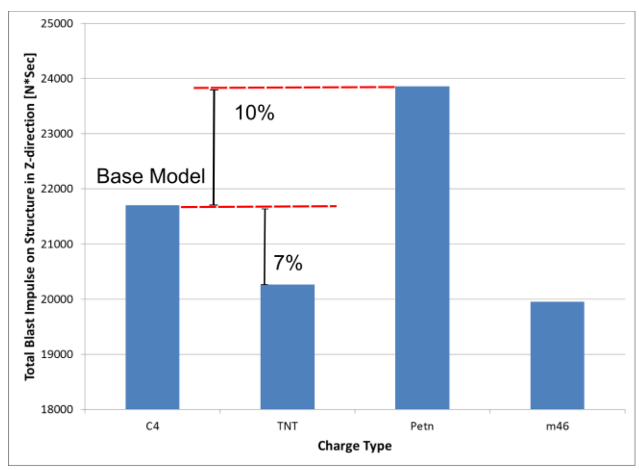

Figure 18: *Influence on the Blast Impulse from the type of High Explosive. Petn is the most powerful HE, followed by C4 and TNT.*

In the Defense Industry it is very common to use a cylindrical charge with a Height to Diameter ratio of ⅓. This is also what is applied in the Base Model. However, it would be natural that the shape of an IED would differ from a cylindrical geometry, though the cylindrical ratio is assumed to give a rather large Blast Impulse compared to other shapes. In [21] a spherical shape is prescribed which is in contrast to [18]. In addition three others geometries were tested. These are a cylinder with a larger height which is the same as the diameter, a sphere and a box. They are created such that the volume is the same as the cylinder for the Base Model, thus the same charge size is applied. The detonation is at the center of the geometry which is shown in Figure 19, together with the geometries.

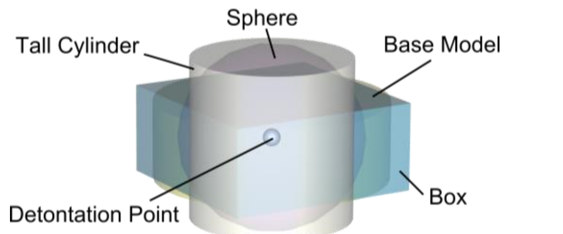

Figure 19: *Geometrical shapes tested for the HE. The volume for all geometries is identical and the detonation point is at the center.*

The results are shown in Figure 20 where it is seen that the largest Blast Impulse is for the Base Model and the smallest impulse is when using a cylinder where the diameter is the same as the height. The difference between the two impulses is approximately 17%. Thus, it is shown that the shape can have a significant influence and it is important to choose the worst case scenario, which in this case is the Base Model.

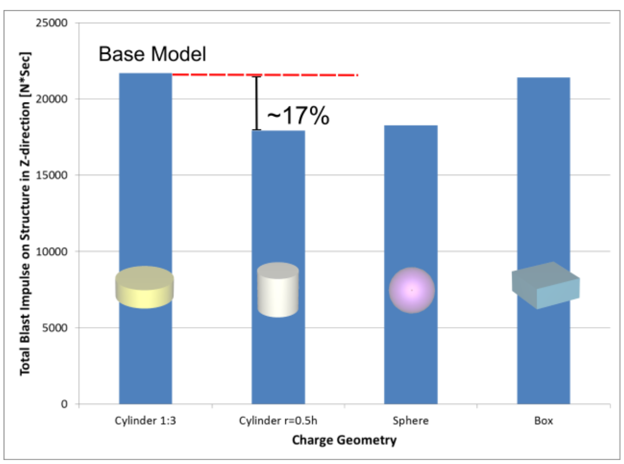

Figure 20: *Influence on the Blast Impulse from the geometric shape of the HE. The volume for all geometries is identical and the detonation point is at the center.*

The traditional orientation of the cylindrical charge in mine blast simulation is to have the largest surface parallel with the ground surface. This is expected to have largest Blast Impulse on the structure. To test this the charge has been rotated by 22.5° between 0° and 90° so a total of four additional sensitivity runs were made. The orientations are shown in Figure 21, where the results also are plotted. It is confirmed that 0° gives the largest Blast Impulse and a vertical placed charge (90°) gives the lowest. The difference from the vertical to the horizontal charge (0°) is an increase of 18%.

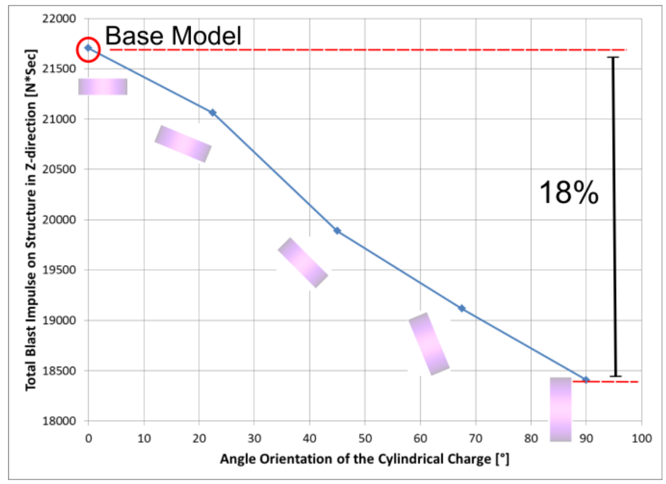

Figure 21: *Influence on the Blast Impulse from the orientation of the HE charge.*

As mention earlier, the charge in the Base Model is placed along the centerline, lengthwise and within the first 1/3 of the structure. Three other locations of the charge were tested. Two of them are along the side and the last one is close to the center but offset a little. All charges are kept in the same Z-plane and only moved in the X-Y plane in order to keep the same DOB. The detonation point is changed so it reflects the new position. The locations are shown in Figure 22, where the results are plotted. It is seen that the two outer placed charges, 1 and 2, give a similar response, where the values only differ by 0.25%. Furthermore, it is seen that the Base Model center charge results in the largest Blast Impulse which is approximately 45% larger than the effect from the two side blast tests, 1 and 2.

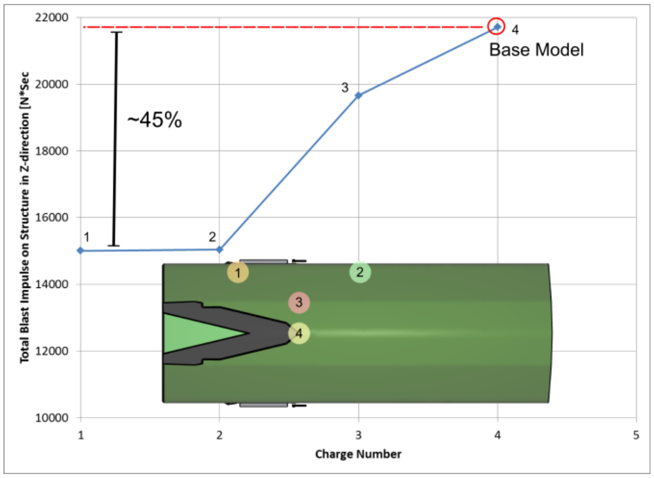

Figure 22: *Influence on the Blast Impulse from the location of the HE charge.*

The charge depth is one of the main parameters in the mine blast event. The DOB affects how much soil will impact the structure and since the soil is the major part of the Blast Impulse for a buried mine, changing DOB can significantly change the damage. Eleven different distances have been tested as shown in Figure 23 where the definition of DOB also is shown. The results show that for the cases investigated a maximum effect is obtained for DOB's between 4-6 inches. A smaller DOB results in less soil hitting the structure and thus a smaller impulse. For a mine where the top is flush with the ground level air needs to be included. After the maximum range, the charge is too deep to move the soil for impact with the structure. The difference between the smallest Blast Impulse and the largest is around 17%.

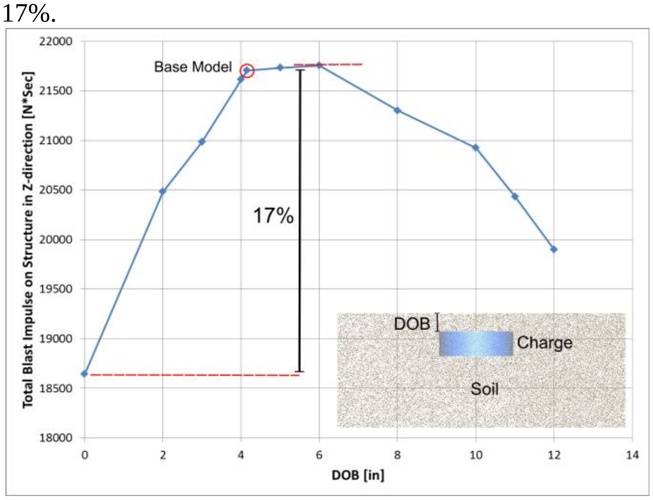

Figure 23: *Blast Impulse results for different DOB of the charge.*

General Parameters

IMPETUS only requires input for the total number of particles which then covers all three DPM domains, Soil, HE and Air (if necessary). IMPETUS automatically distributes the particles between the domains. The number of particles can significantly change the results but in general the number is not changed often once it is determined for a specific application. It of course depends on whether the model uses symmetry and Air. If the latter is used, a larger amount of particles will need to be specified since the Air domain typically is large. The Base Model has 4,000,000 particles specified which is a common number used for a full model but notice that the domains do not cover the whole structure. The domains are shown in Figure 24.

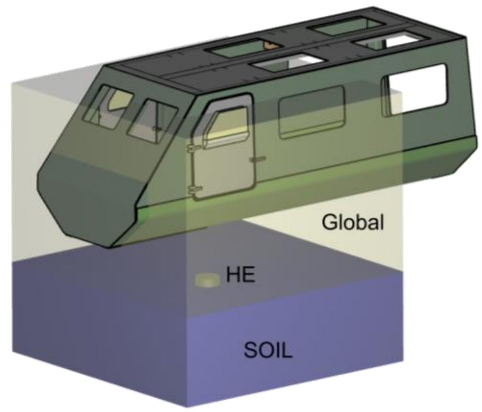

Figure 24: *The domains for the Base Model. Global, HE and Soil domains are given. Notice that the Global domain includes the other domains and only covers the necessary part of the structure.*

As a mesh convergence study always should be done for a Lagrangian mesh when simulating a new set-up, a convergence study of the number of particles should also be done. If too few particles are used, heavier particles are impacting the structure and thus a larger Blast Impulse is generated. It is also very useful to see a Contour Plot of the Blast Impulse on the structure, if it shows spots as opposed to a smooth surface, then the number of particles should be increased. In this study eleven different values were used, ranging from 500,000 to 10,000,000 particles. The results are plotted in Figure 25. A clear convergence is seen when increasing the number of particles. The difference from the Base Model to the Blast Impulse result for the 10,000,000 particles is approximately 5%. If 6,000,000 particles is used, the difference is 2.5% and for 8,000,000 it is around 0.5%.

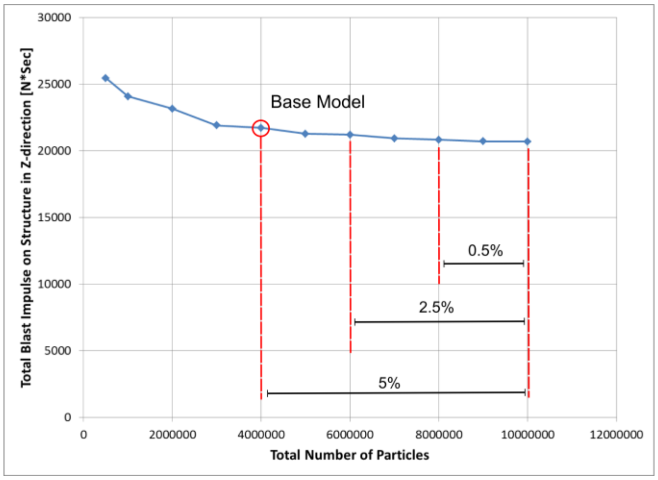

Figure 25: *Influence on the Blast Impulse from total number of particles given. A clear convergence is obtained.*

CONCLUSION

Over 80 simulations were performed to generate a Design Space for a buried mine blast event of the TARDEC Generic Vehicle Hull applying the IMPETUS Afea Solver®. Fourteen different Design Variables were considered both approach and process parameters. The Response Parameter chosen was the Total Blast Impulse on the structure in the global Z-direction. All 80 simulations ran to normal termination, illustrating the stability of the software over the estimated 1,000+ computational hours. On an overall level, the trend in the results seems to match what was expected.

For the soil related parameters it was seen that the Blast Impulse increased linearly with the density and that there is a small difference between the dry 10k soil packing routine and the dry 1k soil packing routine, whereas the difference in Blast Impulse for the dry and wet packing routines is around 5% for the current values. It is recommended to use the newer 10,000 particle packing routines since they are more accurate.

The Soil Bed is modeled with Discrete Particle Method (DPM) where there is a normal and a tangential spring (soil-to-soil stiffness) in the inter-particle contact as well as damping and tangential friction can be included. The sensitivity study on the stiffness shows that the value has little effect on the Blast Impulse when the soil-to-soil stiffness is changed within the same magnitude. It is suggested in general to use 5e+8 N/m for dry soil and 5e+9 N/m for wet soil. The soil-to-soil damping was tested for both the dry and wet 10k packing routines. In both cases the Blast Impulse decreased with increased damping coefficient. For the dry packing routine the Blast Impulse dropped by 2.7% going from the Base Model with no damping to an applied damping of 0.01.

The tangential inter-particle friction coefficient is one of the main parameters when calibrating the soil. The results were as expected, the Blast Impulse drops with an increase in the friction coefficient. In this case the difference in the Blast Impulse is 49% as the friction coefficient is increased from a value of 0.05 to 0.75. When the soil impacts the structure it can slide along the structure as it would in reality and so a friction coefficient for this contact can be specified. For the range of friction coefficients that were tested a nearly linearly relationship between the Blast Impulse and the friction coefficient is seen. The impulse increases with an increase in the coefficient and the increase is 6% between the maximum of 0.5 and no friction being applied, as is the Base Model case. This indicates a rather low influence from the friction between soil and structure when considering the Blast Impulse. The dimensions of the Soil Bed are an often overlooked and undocumented parameter in the buried mine blast literature which is why it was chosen to be investigated. It was found that the 3x3x1 m Soil Bed that was used in the Base Model is the minimum dimensions for this set-up. Less height (6x6x0.5 m) gave a larger Blast Impulse, related to the use of a Rigid Reflected Boundary at the bottom of the Soil Bed and a more narrow Soil Bed (2x2x1 m) gave a lower impulse, due to the lack of enough soil particles. The difference between the maximum and minimum Blast Impulse is 7% when including the 2x2x1 m and 6x6x0.5 m test cases and only 1.6% when excluding them. This shows that if the dimensions for the Soil Bed are realistic the change has little influence on the results.

Other Design Variables are related to the charge and one of the parameters considered is the size of the charge. All models ran to normal termination without any inverted elements, etc., even with the charge size of 30 kg and this attributed to the robust nature of the ASET™ Elements. The result shows that Blast Impulse increases linearly with increased charge size. A study of the different pre-defined HE types showed that Petn gives a larger Blast Impulse then C4 and TNT, where the latter gave the smallest impulse of the three. Different geometries of the charge where also tested, showing that the cylindrical charge in the Base Model gave the largest Blast Impulse and a sphere gave a much lower impulse. The cylindrical charge in the Base Model was rotated over a range from 0° (horizontal) to 90° (vertical) to demonstrate the effect on the impulse. Changing the charge to the vertical position gave a drop of 18% in the Blast Impulse compared to the horizontal orientation, which shows that the charge orientation does indeed matter. An even larger influence is seen when the charge is placed at different locations but with the same DOB. The Blast Impulse drops as the charge is moved away from the "Under Belly" position used in the Base Model.

The maximum drop is ~45% for the chosen configurations. Different settings of the DOB are also tested and it was found that a DOB of 4-6 inches results in the maximum Blast Impulse on the structure and lower impulses are obtained for both deeper and more shallow buried mines. The smallest impulse is for a charge located flush with the soil surface which differs by 17% from the maximum impulse obtained but in this case air should probably be included as it plays a role for this situation.

When using the DPM to model the buried mine blast event, the total number of discrete particles has to be specified by the user. In the Base Model this was selected to be 4,000,000 particles and a large number of different settings were tried. The largest number of particles tested was 10,000,000 which gave a 5% lower Blast Impulse than the Base Model, 0.5% lower than 8,000,000 and 2.5% lower impulse than using 6,000,000 particles. A very clear converge is observed with increasing number of particles which is expected.

Future research will include calibration of the soil when experimental data is released for the TARDEC Generic Vehicle Hull. It would be interesting to do a new sensitivity study against experimental data where the Design Variables are the ones found in current study to have the largest influence on the Blast Impulse. Different Blast Test Sites can have vastly different Soil Beds and it would be interesting to carry out calibration of these soils on simple Blast Tests of Rigid Plates and then apply the different soils for the TARDEC Generic Vehicle Hull Model. Other areas of research considered for future work is investigation of: the effect of multiple charges, include the IMPETUS Afea Hybrid III 50th Percentile Dummy, a Soil Bed with gravel, stones and rocks, and multiple layered Soil Beds.

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"Many unclassified studies from past researchers have utilized fictitious vehicle geometry due to the non-availability of realistic information. Due to the sensitive nature of the work performed by the Department of Defense, data generated from testing military vehicles is usually classified, making it difficult to share data in the public domain. In order to increase the operational relevance of studies performed by the wider scientific community, the US Army Tank Automotive Research, Development and Engineering Center (RDECOM-TARDEC) has fabricated a generic vehicle hull to help evaluate blast mitigation technologies, and also shared an FEA model of the same for purposes of this research." It was necessary to develop a new model for the IMPETUS Afea Solver® and the authors would like to thank TARDEC, in particular, Dr. Ravi Thyagarajan, Mr. Madan Vunnam and Dr. Bijan Shahidi for supporting the effort to develop the model.

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