Effect of Fragmenting Buried High Explosive Projectile
(152mm HE Frag OF-540) on Military Ground Vehicles

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Abstract
Simulation of Military ground vehicles subjected to buried landmines, and Improvised Explosive Devices (IED) has been carried out by many researchers, and military establishments to understand the effects in detail. But the ability to predict the effects of fragmenting IED’s on military ground vehicles is little known in simulation community. Hydrocode simulation such as Eulerian simulation and Arbitrary Lagrange in Eulerian (ALE) simulation coupled to vehicle structure is widely used methodology to characterize buried detonating IED. Fragmentation is the breakage of a body into several small pieces due to mechanical loadings. Dynamic fragmentation process between ductile materials and brittle materials goes through three phases: crack nucleation, crack propagation and fragmentation. Density and strength of materials dictates the phases of dynamic fragmentation. Fragments of different shape and size are formed when cracks coalesce. Understanding this process is crucial in estimating the number of fragments, size and its effect on impacting structures. There are several statistical and empirical formulations that are available to approximately estimate the number of fragments, but does not provide sufficient information about the velocities of the fragments. For military ground vehicles it is essential to know and understand not only the size of the fragments but also its velocities and secondary damages it can cause on the vehicle hull. In this proposed study, a 152mm High Explosive (HE) OF-540 fragmenting projectile was modelled in detail per geometry and buried 100 mm deep inside the soil. This fragmenting projectile was coupled to U.S. Army’s Ground Vehicle System Center (GVSC) developed generic hull (GH) structure to understand the impact effects of fragmenting fragments. Three different analysis were carried out Projectile buried in soil with adaptive SPH projectile casing, Projectile buried in soil coupled to GH structure with projectile casing as ALE and projectile casing as adaptive SPH methods. Results from all the three analysis were thoroughly analyzed and findings from these analysis is presented in this paper. Solid element formulation is well suited for shock waves, crack propagation and fragmentation problems was used in modeling all the structural and projectile components using commercially available structural code LS-DYNA-3D.

Keywords: Improvised Explosive Device, fragments, discrete particles, adaptive SPH, erosion

1.0 Introduction
Military ground vehicles are exposed to a wide variety of threats in theaters such as buried mines, fragmenting IED, magnetically attached IED, Projectiles and other kinetic energy threats. Most of these threats carry high explosives housed in metal casings. When these HE detonates resulting high pressure expands the metal casings and eventually ruptures and travels with very high velocities. Expanding pressure wave and the fragmented metal parts impact the military vehicles and causes damages from minimal to catastrophic depending on the size of the charge. Soldiers inside the vehicles are subjected to very high accelerative and impulse loading [1]. Several blast mitigating technologies are developed and inserted to minimize the structural damages and soldier injuries such as V-Hull, Stroking floors and seats. Most often these are developed for objective and threshold threat levels and if the threat exceeds these limits, damages are far more.

Hand calculations and empirical formulas are not suitable for highly non-linear problems of HE explosions, shock loading and fragmentation. Limited set of experimental data are available to develop empirical formulas. However, for most of the HE explosions, problems are analyzed by complex analytical technique, generally computational solvers. Experimental tests are crucial in development of computational models, without which computational models become unreliable.

Fragmentation is breaking a continuous body into several small pieces. Several researchers namely Rosin-Rammler [1933], Weibull [1939], N.F. Mott [1947], Linfoot [1943], Gilvarry [1961], Grady [1982, 2007] and many others have performed numerous expanding ring and cylinder experiments to study the fragmentation process in detail and developed several mathematical and statistical theories. [2-8]. In this paper, fragmenting 152mm OF-540 projectile was analyzed using ALE and ADAPTIVE SPH TO SOLID methods using commercially available LS-DYNA [9] non-linear solver from an application point of view. Main objective of this paper was to capture the fragmentation process computationally by Eulerian and Lagrangian with adaptive SPH methods and its effect on the military ground vehicle structures and compare the selected responses.

2.0 FEM Model of 152mm OF-540

Hypermesh pre-processor was used to mesh the OF-540 using the CAD geometry. Several models were created from 1 mm element size to 5 mm element size to understand the process of fragmentation and element erosion.

2.1 OF-540 model

OF-540 is a fragmenting 152mm diameter projectile. Specification of the OF-540 shown in figure 1. Diameter of the charge varies from 31 mm near the fuse to 104 mm at the center. Metal casing also has varying thickness across the length of the explosive from 20 mm near the fuse to 31 mm at the far end of the fuse. Total length of the threat is 641 mm. Piezoelectric fuse is 33 mm in diameter and 35 mm in length. 8 node solid elements were used to mesh the OF-540 model. Although 4 noded shell element is easier and faster, but not recommended for blast and fragmentation problems. Meshed OF-540 model shown next to the specification has over 3 million solid elements. HE inside the projectile casing is represented as Eulerian and casing as
Lagrange with adaptive SPH. There are several meshless method options such as DEM [10] and SPG, are emerging, but SPH is widely used.

![Figure 1: Geometry and Specification of OF-540](image)

### 2.2 GVSC Generic Hull Model

Generally most of the blast events are classified in nature. This limits the accessibility of the data for research community in academia and industry partners to develop any meaningful mitigating strategies. To alleviate this, CCDC GVSC developed a generic hull (GH) structure. This GH was subjected to blast loading and the data generated can be shared with academia researchers and industry partners to collaborate and develop different blast mitigating technologies and simulation methods. Picture of GH model is shown in figure 2 has 786,000 solid elements.
2.3 Material Models

Materials used in ALE, OF-540 and GH structure are shown in LS-DYNA format

**ALE Materials**

**HE – TNT**

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*Figure 2. GVSC Generic Hull Structure*
DISTRIBUTION A. Approved for public release; distribution unlimited.
OPSEC #: 2734

*EOS_TABULATED_COMPACTION

$ Soil as adjusted (12.0% AFV content)

$ ------------ + ------------ + ----------- + ---------- + ---------- + --------- + --------- + --------- +
$#         eosid       gamma               e0             vo
11           0.000         0.000           1.00
$ ------------+ ------------ + ----------- + ---------- + ------------ +
$#            ev1              ev2            ev3            ev4               ev5
0.0001    -0.064539    0.07985  0.095161     -0.138785

Air

*MAT_NULL

$            mid            ro          pc           mu           terod        cerod          ym          pr
32    1.2985        0.0 1.8444E-5           0.0            0.0          0.0          0.0

*EOS_LINEAR_POLYNOMIAL

$           eosid           c0            c1            c2             c3             c4           c5            c6
32     0.000     0.000        0.000         0.000      0.4000    0.4000      0.000
$                e0           v0
2.533125E5        1.0

OF-540 Material

*MAT_JOHNSON_COOK_TITLE

OF- 540

$#           mid              ro              g             e             pr            dtf             vp       rateop
540     7830.00  7.75E+9 2.11E+11       0.30          0.000         1.00        0.00
$#                a                b              n             c              m           tm              tr         epso
6.18E+8      6.990+8     0.3500  0.02060      1.0300   1793.00     291.00         1.00
$#               cp              pc          spall           it             d1           d2             d3           d4
477.00  -5.270E+9            1.0       1.00        0.100    0.3020      -0.7853   0.0168
$#               d5            c2/p          erod       efmin
0.8260            0.00               0     1.00E-6

*EOS_GRUNEISEN_TITLE

OF-540

$#           eosid             c            s1            s2             s3         gamao              a             e0
54  4578.00    1.3300        0.00          0.00         1.6700     0.4300         0.00
$#             v0
1.0000

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*MAT_JOHNSON_COOK_TITLE
RHA
$#         mid             ro              g              e             pr          dtf             vp         rateop
1    7850.0  7.960E10 2.068E11        0.27         0.0             1.0              0.0
$#             a               b              n              c             m            tm             tr           epso
7.9220E8  5.0950E8         0.26       0.014         1.03      1818.0       300.0           1.0
$#            cp               pc         spall            it              d1              d2           d3            d4
448.0     -6.90010           2.0           1.0          -0.8             2.1           0.5     0.002
$#            d5           c2/p        erod        efmin
0.61             0.0             0     1.00E-6
```

```
*EOS_GRUNEISEN_TITLE
RHA
$#        eosid              c             s1             s2             s3          gamao              a             e0
1     4578.0          1.33           0.0           0.0              1.67          0.43          0.0
$#           v0
1.0
```

3.0 Analysis Matrix

Analysis was performed with and without structure for OF-540 threat. Five sets of analysis were performed:

1. OF-540 buried 100mm in soil, without structure coupling – adaptive SPH casing
2. OF-540 Surface laid, coupled to GH structure - adaptive SPH casing
3. OF-540 Buried 100mm in soil, ALE FSI coupling, - Eulerian casing
4. OF-540 Buried 100 mm in soil, ALE FSI coupling with Lagrange casing
5. OF-540 Buried 100 mm in soil, ALE FSI coupling with adaptive SPH casing

First OF-540 was evaluated without any structure coupling to make sure that detonation process and fragmentation are free of numerical instabilities and smooth. Second analysis was performed with OF-540 laid on ground surface and coupled to GH structure. In this analysis momentum effect of soil will be minimal on the GH structure. In the third analysis OF-540 was buried 100 mm deep inside the soil and detonated. Here OF-540 was modeled as ALE. Explosive was modeled as Eulerian in all the analysis. In this particular analysis metal casing over explosive is also modeled as Eulerian and used LS-DYNA ALE multi-material coupling. In the fourth analysis metal casing over explosive was modeled as Lagrangian. In the fifth analysis in addition to modeling metal casing over explosive as Lagrangian, ADAPTIVE_SOLID_TO_SPH was invoked to convert the failed metal casing parts into smooth particles.
3.1 Without Structure

OF-540 threat buried 100 mm deep inside the soil is shown in figure 2. Charge was detonated and fragmentation process was captured. Sequence of detonation is captured in figure 3 from detonation time to complete fragmentation process.

Crater formation of 1.6 meter in length and 1.5 meter in depth will be formed as shown in figure 4.
3.2 With GVSC GH structure

After establishing high confidence in the detonation and fragmentation process, next step was to couple the OF-540 to GVSC GH structure. All the set-up remains same as described in section 3.1 with GH structure coupled as shown in figure 5. Location of the charge was close to the center of the structure between front and mid-point legs.

Two contacts need to be defined, one between the multi-material fluid particles to the structure and another one between the adaptive SPH particles to the structure. Contact between the structure and the HE charge is activated via *CONSTRAINED LAGRANGE IN SOLID (CLIS). And contact between the SPH particles to the structure is defined via CONTACT AUTOMATIC NODES TO SURFACE. Details on how to use these cards is available in LS-DYNA user’s manual [9].

```
*CONSTRAINED_LAGRANGE_IN_SOLID
$#      slave    master       sstyp       mstyp       nquad      ctype       direc       mcoup
1240      1111              0               0                2           5                           -12
$#       start          end        pfac            fric       frcmin       norm   normtyp      damp
0.000E+00        0.060     0.200          0.00     0.25000                                      0.00
$$#      cq         hmin      hmax           ileak        pleak      lcidpor      nvent   blockage
2         0.15
```
Fragmented particles and debris are shown in figure 5 for buried HE and figure 6 shows the sequence of fragmentation process coupled to the GH structure for surface laid HE.
4.0 Results and Discussion

4.1 Loss of mass

When projectile casing modeled as Lagrange or Eulerian, casing loses mass significantly due to erosion. This will maintain the numerical stability and continue the analysis till the termination time. This results in inaccurate conservation mass, momentum and energies. In order to eliminate the loss of mass, projectile casing was also modeled with adaptive SPH particles. By invoking adaptive SPH, failed Lagrange elements were converted into SPH particles and these particles carry the mass momentum and energy. Figure 7 shows the mass of projectile casing in time domain.

![Figure 7: Projectile casing mass](image)

To determine whether this mass loss is sensitive to element size, projectile was modeled with 2 mm and 1 mm elements sizes. Loss of mass trend did not change for finer element sizes. Table 1 shows the data from 3 mm and 1 mm element size projectiles. Figure 8 is the curve generated from table 1.

<table>
<thead>
<tr>
<th>Table 1: Lost mass from OF-540 Fragmentation</th>
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</thead>
<tbody>
<tr>
<td>Lost mass from OF-540 Projectile Casing</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Time (sec)</td>
</tr>
<tr>
<td>Coarse</td>
</tr>
</tbody>
</table>

10
It is clear from table 1 and figure 8, 80% of the projectile casing mass will be lost within 120 microseconds of detonation. Loss of mass at different time intervals are captured in figure 9.

 Projectile casing starts to expand immediately after the detonation of high explosive charge (TNT in this case) inside the casing. High pressure generated by the shock wave of the detonating products results in volume expansion. Combination of expanding volume and high pressure on the inside surface of the projectile casing generates high stresses and high strains on the metal surfaces, resulting in rupture and shearing of the casing. These ruptured materials
(fragments) fly in directions depending upon the geometry, thickness, velocity and rejection angle.

![Figure 9: Projectile casing mass loss at different time intervals](image)

**4.2 Fragment velocities**

Fragment velocities are higher for surface laid HE than that of the buried HE. This can be attributed to absence of soil resistance for fragments. Velocity-time response is shown in figure 10 for surface laid HE and figure 11 for buried HE along with sensor locations. Fragments near the detonation location travels at speed over 1000 m/s and away from the detonation location travels at a speed of 600 m/s for surface laid HE. Whereas, fragment velocities are under 500 m/s for buried HE. In case of buried HE, fragment velocities are damped by the presence of soil and fragments have to overcome the soil pressure. Smaller the size of the fragments higher the velocity and larger the fragment size lower the velocity. Even though smaller fragments size travels at higher speed with lower mass, its ability to make a meaningful impact on the target is relatively lower compared to that of the larger fragments with higher mass.
Fragments travels from 0.2 meters to over 8 meters for surface laid HE. Absence of soil resistance results in significantly higher fragment travel for surface laid HE in contrast to the buried HE where in fragment are scattered within 1.5 meters. Fragment travel are captured in figure 12 and figure 13 for surface laid HE and buried HE respectively.
4.3 Projectile casing stresses and strains

As mentioned earlier in section 4.1, expanding volume generates very high stresses and strains on the inner surface of the projectile casing, resulting in gradual rupture of the casings and fragments formed. Figure 14 shows that projectile casing volume expands for about 100 microseconds, before starts to rupture.
Figure 14: Projectile Casing – volume expansion

Stresses and strains generated on the Lagrange projectile casing captured in figure 15 and figure 16. Also in the figures 15 and 16, eroded elements and retained elements (fragments) are marked. Once the elements failed and eroded, stresses and strains reach zero for eroded elements. These failed and eroded elements constitutes as lost mass. The elements which become fragments continue to carry the mass, momentum and energy that are shown as curves with varying stresses and effective plastic strains.

Figure 15: Projectile casing – Von Mises Stresses
4.4 Energies

Internal energies of Lagrangian projectile casing for ALE, surface laid HE and buried HE are shown in figure 17 and figure 19 and kinetic energies are in figure 18 and figure 20. Internal energies of projectile casing for surface laid HE and buried HE with adaptive SPH are close to each other, whereas for ALE projectile casing internal energy is twice that. Kinetic energies of ALE and buried HE are similar, but the surface laid HE shows twice that of ALE and buried HE with adaptive SPH casing. In case of surface laid HE, absence of soil results in higher kinetic energies whereas in case of buried HE presence of soil has a damping effect which results in lower kinetic energy. In all the three cases energy component from lost mass due to rupture and erosion is not accounted.
When the projectile casing was modeled with adaptive SPH, lost mass due to erosion will be retained and converted into SPH particles and carries material properties. Internal energies and kinetic energies of the adaptive SPH projectile casing are presented in figures 17, 18, 19 and 20. It is obvious to expect higher kinetic energy for fragmented particles in case of surface laid HE than that of the buried HE and the curves in figure 20 shows that. Conversely the internal energies are in opposite trend i.e., higher for buried HE and lower for surface laid as in figure 19.
Table 2 summarizes the internal and kinetic energies plotted in figure 19 and 20.

**Table 2: Internal and Kinetic Energies of projectile casing**

<table>
<thead>
<tr>
<th>Projectile Casing</th>
<th>High Explosive Location</th>
<th>Internal Energy (Joules)</th>
<th>Kinetic Energy (Joules)</th>
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</table>

4.4 Coupled to GH

Fragments coupling to GVSC GH structure are shown for buried HE and surface laid HE in figures 21 and figure 22. Picture clearly shows how the fragments differ significantly for HE locations whether surface laid or buried deep in soil. Number of fragments, velocities and distance travelled are uniquely different.
Impulse is calculated by multiplying the global vertical velocity of the GH structure to the mass. Global velocities of the GH structure is shown in figure 23 for all the three cases, surface laid, ALE and buried HE. Surface laid HE has the least global velocities compared to that of ALE and buried HE. ALE and buried HE projectile results in higher global structural velocities augmented by the soil pressure and ejecta, whereas in case of surface laid HE it is purely the projectile
casing and explosive pressure. Lower global vertical velocity will result in lower total impulse for surface laid HE.

![Figure 23: Global velocities of GH structure](image)

### 5.0 Conclusion

Numerical simulation of fragmentation process of OF-540 projectile was successfully carried out by positioning the OF-540 projectile on the soil surface and buried 100 mm deep inside the soil. Numerical simulation was carried out first with projectile buried in soil without coupling to any structure to establish the numerical stability and fragmentation process. Having established the confidence in simulating the fragmentation process, projectile was coupled to the GVSC developed GH structure. Projectile casing was modeled with Eulerian, Lagrangian methods shows loss of mass due to rupture and element erosion. This resulted in inaccurate conservation of mass, momentum and energy as measured by the global velocities of the structure. To overcome the loss of mass, projectile casing was modeled as an adaptive SPH particles and simulated for surface laid and buried deep inside soil initial boundary conditions. Simulation shows that, this method converts the failed Lagrange elements into SPH particles and these particles carries the mass, momentum and conserves the energy. The overall simulation attempted to show, the detailed analysis of fragmentation process, lost mass, stresses & strains, fragment velocities & displacements and how the explosive energy transforms into internal and kinetic energies of projectile casing and its effects on the GH structural response. Simulation also shows that loss of projectile casing mass is not element sensitive. In summary

- Surface laid HE with adaptive SPH projectile casing produces
  - more fragments, less impulse load on the GH structure
- ALE with Eulerian projectile casing produces

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Element deletion from computation due to erosion in Lagrange and Euler methods, leads us to explore different meshless methods such as DEM, SPH or SPG. Although these meshless methods are computationally intensive and take up too much memory, but they provide deep insight into the physical phenomenon that happens inside the projectile which is extremely difficult to capture by physical testing. Also from a physical test point, it is challenging to count all the fragments from the failed projectiles as they are scattered all around the field. Only visible fragments can be counted. Analyzed method here in this research provides valuable information and better understanding of the fragmentation process, damage mechanisms and its effect on structure.

Acknowledgements

Terminologies

**Surface Laid HE** = Projectile laid on soil surface – Projectile casing as Lagrange with adaptive SPH particles

**ALE** = Projectile buried 100 mm deep inside soil - Projectile casing as Eulerian

**Buried HE** = Projectile buried 100 mm deep inside soil – Projectile casing as Lagrange with adaptive SPH particles

Abbreviations

ALE – Arbitrary Lagrange in Euler

ALE FSI – Arbitrary Lagrange in Euler Fluid Structure Interaction

CLIS – Constrained Lagrange in Solid

CCDC – Combat Capability Development Center

DEM – Discrete Element Method

GH – Generic Hull

GVSC – Ground Vehicle System Center

HE – High Explosive
IE – Internal Energy

IED – Improvised Explosive Device

JWL – Jones-Wilkins-Lee

KE – Kinetic Energy

SPH – Smooth Particle dynamics

SPG – Smooth Particle Galerkin

RHA – Rolled Homogeneous Armor

References


