Numerical Modeling of a Simplified Human Leg  

to Characterize Landmine Threats  

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Abstract  

The testing and assessment of lower extremity protection for anti-personnel (AP) blast mines requires an appropriate threat. Due to the reduced availability and experimental inconsistencies in real AP blast mines, surrogate landmines with C-4 explosive are widely used. Although charge size is an important and useful characteristic, the type of explosive is also significant. It is well known that the explosive energy of C-4 exceeds that of TNT, for example, and this must be accounted for when testing protective equipment. In addition, the output of the mine is also influenced by confinement introduced by the leg and/or protection, which are located in close proximity to the mine. A numerical study has been conducted to compare various TNT and C-4 charges, evaluated with a numerical Simplified Human Leg. The results show that, based on the short time response C-4 is much more aggressive than TNT. Evaluations of damage to the numerical leg indicate that C-4 results in increased damage to the leg at a given charge size.  

1. Introduction  

The threat of anti-personnel landmines to civilian and military deminers working in many areas is significant. As such, the evaluation and comparison of protective equipment is of particular importance to many countries throughout the world, which are involved in this type of activity. The experimental testing and assessment of lower extremity protection for anti-personnel (AP) blast mines requires the definition of a threat and a means of assessing the expected trauma to the human leg. This paper is focused on investigating some common landmine threat levels, and common surrogate landmines used for experimental testing. In particular, the explosive output has been assessed using a numerical analysis approach.  

AP blast landmines are typically ranked based on explosive charge size, with charges less than 50 grams considered small, 50 to 100 grams considered medium, and greater than 100 grams considered as large mines. Although charge size is an important and useful characteristic, the type of explosive is also significant. It is well known that the explosive energy of C-4 exceeds that of TNT, for example, and this must be accounted for when testing protective equipment. In addition, the output of the mine is also influenced by confinement introduced by the leg and/or protection, which are located in close proximity to the landmine. This effect is not apparent in typical TNT equivalence for explosives which are based on mid-field pressure and impulse measurements.  

To investigate these issues, a numerical study has been conducted with various explosive charge sizes and types. The numerical model consisted of an unprotected Simplified Human Leg (SHL), modeled as a deformable structure with human material properties, coupled to an Arbitrary Lagrange-Eulerian landmine model. This model allowed for assessment of the various explosives using short-term pressure histories, and the resulting trauma to the numerical leg model. The primary benefit of a numerical approach is the reduction in scatter
associated with experimental testing, and the ability to investigate the response of the materials in great detail.

1.1. Landmine Threat

It is estimated that more than 360 different types of landmines have been deployed worldwide (Joss 1997). This study is focused on AP blast mines, which rely on the overpressure from the detonation of a high explosive to injure the victim, since they are the cheapest and most common form of landmine. Additional injuries may also occur due to environmental fragments such as soil. A typical blast mine consists of an explosive charge, detonator and a mechanical device to trigger the detonator. Blast mines may be surface or subsurface buried, and are pressure activated. They are typically designed to injure the target; however, mines with larger charges can be lethal. Buried blast mines are the most difficult to detect and are likely to remain buried for a long period after a conflict (Coupland, 1997).

The threat definition appears to be straightforward on first consideration; however the consistency of any real landmine can vary significantly in terms of explosive output (LEAP, 1999). This is due to inconsistent amounts of explosive in some mines as well as the possibility of deflagration versus proper detonation. Further, the Ottawa treaty has limited the availability and transport of real landmines making access to real mines as test devices difficult. Regardless, it is useful to examine the types of mines encountered to identify the expected threat. AP blast mines currently deployed in the world range from explosive charge weights of 28 grams to 500 grams (Jane’s 1986, NPA, 2003). The most common explosive used in blast mines is TNT, with Composition B, RDX, and other explosives being less common (NPA, 2003).

The observed inconsistency in explosive output of real landmines and the difficulty in acquiring them, make them generally unsuitable for experimental testing. In terms of general experimental testing, an explosive which is readily available, easy to work with and consistent in terms of detonation and explosive output is desirable. To this end, composition C-4 (91% RDX and 9% nonexplosive plasticizer by weight) has been used by several countries for experimental testing. It is important to note that there are several differences between C-4 and common blast mine explosives. Firstly, the detonation velocity of C-4 (8193 m/s) exceeds that of TNT (6930 m/s) (Dobratz, 1980) leading to a locally increased shock or shattering power, known as brisance. In addition, mid-field measurement of the explosive output of C-4 is found to be approximately 1.4 times that of TNT (Kinney 1962, Bangash 1993). This must be considered when evaluating protection with a specific C-4 charge.

It should be noted that the current study focuses on AP landmines which are surface buried (i.e. no soil overburden) for comparison purposes. However, it has been found that the depth of burial has a significant effect on the behavior of the explosive. Bergeron and Tremblay (2000) have shown that soil type and explosive confinement significantly affects the impulse from a blast mine on a target. In general, an increase in soil moisture content results in a larger amount of energy transfer from the mine to the target above the mine.

1.2. Landmine Injuries

The extent and type of injuries incurred from an AP blast mine can vary significantly and depend on many factors including soil conditions, protection worn, and variability in explosive output. Generalizing landmine injuries also presents difficulties due to differences in physiological response of the victim. Clinical experience (Coupland 1993) with typical landmine injuries indicates that the primary injuries occur in the foot, ankle and lower tibia. In particular, an unprotected leg subject to an AP blast mine undergoes stages of deformation as shown in Figure 1.

![Figure 1: AP Blast mine trauma to the unprotected human leg (Coupland, 1993).](image1)

The evaluation of injury for assessment and treatment purposes is typically accomplished through a scoring system. One example is the Mine Trauma Score (MTS)
(Lower Extremity Assessment Program, 1999), which is specific to AP blast mine injuries to the lower limb. Although MTS is suitable for the surgical evaluation of trauma, numerical approaches require the definition of failure or injury criteria in terms of mechanical parameters such as stress, pressure or deformation. The failure parameters used in this analysis are discussed below.

2. Numerical Modeling

Issues such as the interaction of detonating explosives in contact with deformable structures (boots and legs) have been successfully analyzed using explicit finite element codes, also known as hydrocodes (Cronin et al. 2000, Motuz et al 2003). These codes are typically Lagrangian in nature, with different components being modeled by deformable finite elements. However, one of the limitations of this implementation is the inability to handle large deformations. In addition, the explosive must generally be confined for the calculation to be stable. In contrast, Computational Fluid Dynamics (CFD) or Eulerian codes allow material to traverse or move through a pre-defined numerical mesh. These methods are well suited for problems involving large deformations, although there are limitations in terms of modeling a solid structure such as a boot or leg.

To address these issues, many of the current finite element hydrocodes now include a Eulerian-type analysis known as ALE (Arbitrary Lagrange Eulerian). In practice, this approach involves allowing the mesh to deform during one time step, remapping the finite element mesh back to the original configuration, and advecting material between the cells or elements as required by the remapping (Halquist 2003). The primary advantage of this technique is that an ALE mesh (explosive/air) can be coupled to a Lagrangian mesh (leg) in the same calculation. The ALE technique also has some disadvantages (Scheffler and Zukas, 2000), including assumptions related to material boundary tracking and modeling of relative slip between materials. In addition, very large displacement (i.e. propagation of an explosive through air over 15 or more charge diameters) can lead to inaccuracies. This is due to a high degree of dependence on the finite element mesh density and mesh orientation, but should not be of significant concern for close proximity blast modeling.

In general, finite element codes require geometry, material properties and boundary conditions as inputs to the problem. Geometry and boundary conditions are dependent on the simplifications and assumptions of the user. Some material properties can be found in the literature; however, many of the materials encountered in the AP mine problem have not been completely characterized at the strain rates of interest. This need has been addressed by some authors (Cronin et al. 2000, Salisbury et al. 2002), but is still an emerging area as advanced techniques are developed to investigate these areas.

The AP landmine problem presents some unique challenges for numerical modelers:
• High rate material properties for biological, polymeric, soil and explosive materials must be measured and modeled.
• Large deformations of materials at very high rates must be considered.
• The behavior of the explosive is coupled to that of the lower leg and must be modeled correctly. This generally requires the use of multiple numerical techniques to achieve an accurate representation of the problem.
• The actual geometry of the structure (leg and protective boot) is very complex. This includes the global geometry, such as the shape of the leg and bone structure, as well as smaller structures such as arteries and nerves.
• Increased detail in terms of geometry and numerical techniques requires significant increases in computing resources.

In general, it has been found that a coupled ALE-Lagrangian analysis technique, to analyze the explosive/soil/air and leg/protection respectively, provides an accurate representation of a close-proximity blast event (Cronin et al. 2000, Motuz et al 2003). This technique has been used to investigate various explosive types and charge sizes.

2.1. Simplified Human Leg Model

A Simplified Human Leg (SHL) model has been developed for the purposes of evaluating the effect of various types and sizes of explosive on an unprotected human leg. The SHL (Figure 2) was designed with axial
symmetry to reduce computation time, while still being representative of the geometry and energy absorption characteristics of the human lower leg. The geometry of the leg was designed based on anatomical measurements from the Visible Human Project (Chang, 1998). Although the leg is axially symmetric, a quarter model was analyzed using solid three-dimensional finite elements. This allowed for the future incorporation of non-symmetric components such as boots, and for non-symmetric failure of materials.

![Figure 2: Numerical model of the SHL](image)

The SHL consisted of a calcaneous (heel bone), talus (ankle bone), and combined representation of the Tibia/Fibula as indicated in Figure 2. The bone structures were surrounded with soft tissue. This structure was treated as Lagrangian or deformable in the numerical model. The material properties for each component were defined based on available properties for human tissues (McElhaney 1966, Cowan 1989, Currey 1984, Cronin et al. 2000). Specifically, the bones were treated as elastic-plastic materials, with the onset of yielding (plasticity) corresponding to damage or fracture. The soft tissue was treated as a compressible viscous fluid with appropriate properties. Previous analyses have shown that the strength of the soft tissue is negligible in close proximity to a mine. Erosion criteria were introduced to simulate the failure and loss of materials during the blast, and to maintain numerical stability.

The soil, explosive, and air were modeled using an ALE approach, such that the material could flow through the mesh and accommodate the corresponding large deformations. This type of approach for modeling a deformable structure subject to AP blast mine loading has been validated experimentally (Motuz, 2003).

### 2.2. Numerical Model Results

Detonation of a landmine in contact with the bottom of the SHL results in an initial shock wave, which is transmitted through the soft tissue and bone. This high-pressure wave dissipates as it travels up the leg and is followed by additional stress waves as the mine gases expand. This second phase (high-pressure gas expansion) lasts on the order of 50 microseconds and is followed by a third phase, corresponding to venting and redirection of the explosive gas by the structure (leg). In general, analysis with this model predicts that structural damage to an unprotected leg occurs within approximately 300 microseconds after detonation. It should be noted that additional damage due to environmental fragments and erosion may occur over longer periods of time.

Figure 3 shows the deformation of the SHL and contours of pressure when subjected to a 50-gram C-4 charge. When compared to Figure 1, this model displays the expected tissue stripping and bone crushing for this level of insult.

It is well known that increased distance or stand-off from an explosive charge reduces the blast loading. This effect was investigated by changing the offset distance between the leg and explosive charge (Figure 4). For comparison purposes, the pressure at the bottom of the foot (in closest proximity to the mine) has been plotted. It is evident that the peak pressure decreases rapidly as the offset distance increases, as expected.
2.3. C-4 and TNT Charges

The SHL was subjected to 50, 75, and 100-gram C-4 and TNT charges. A 240 gram C-4 charge was also considered. In each case, the level of initial insult was determined by monitoring the pressure at the bottom of the leg in closest proximity to the explosive. The explosives were described using the JWL equation of state (Dobratz, 1981). The results, shown in Figure 5, indicate that the initial pressure peak depends primarily on the explosive type. The average ratio of C-4 to TNT peak pressure is 1.33, corresponding to the higher detonation velocity in C-4. This result agrees with the noted higher brisance of C-4, and corresponds to damage induced in close proximity or contact to the explosive during the first phase of detonation.

The second phase of the explosion, involving initial expansion of the explosive gases, creates significant damage to the bone structure and soft tissue. As the explosive begins to flow around the leg, the loading levels decrease until no further damage occurs. In all cases analyzed, the close proximity of the landmine to the bottom of the leg resulted in crushing of the calcaneous, talus and varying levels of damage to the tibia. This result is in agreement with experimental testing at similar charge levels (LEAP, 1999, Bergeron, 2001).
Bone damage was predicted by identifying the level of fracture in the SHL tibia as a percent of the total tibia length. The results are shown in Figure 6 and indicate that the C-4 charge is slightly more aggressive for a given charge mass. A trend for increased damage with increasing explosive charge is also noted, as expected.

Additional visual examination of the models indicated that the calcaneous was completely destroyed for all C-4 and TNT charges. In contrast, the talus was partially destroyed at a C-4 charge mass of 100g but was only partially crushed at a similar TNT charge mass. This also suggests that C-4 is more aggressive in terms of injury level for a given charge size.

Injuries in the soft tissue were investigated, with the criterion for damage based on the magnitude of the pressure wave in the tissue. It should be noted that a relatively low threshold pressure (1 MPa) was selected. Thus the level of damage (in terms of SHL tissue length) corresponds to potential damage, and expected to correspond to recoverable injury for the most part. Understanding these limitations, this does provide a consistent means for assessing insult to the soft tissue. The results are shown in Figure 7 and follow a similar trend to the bone data.

![Figure 7: Soft tissue damage in the SHL](image)

Although the damage predictions suggest there are only small differences between C-4 and TNT, based on bone damage, visual observation of the material damage suggests that 75 grams of C-4 is approximately equivalent to 100 grams of TNT. The soft tissue data (Figure 7) also supports this relationship.

It should be noted that the 240 gram TNT charge corresponds to a PMN AP blast mine in size and dimension. Although actual detailed data regarding particular mines and resulting injuries is difficult to acquire and assess, available data (approximately 30 incidents) for lower extremity damage resulting from PMN mines have been identified. The level of foot protection was not available, but the consistent result was a below knee amputation. In cases where details were available, it was noted that the leg was destroyed to above the ankle. Although brief, these findings are in agreement with the numerical model predictions for a 240 gram TNT charge.

3. Conclusions

A simplified model of the human lower leg has been developed and used to compare various charge sizes, representing AP blast mines, for both C-4 and TNT explosives. The goal of this study was to compare the resulting loading and predicted injury from the various charges to identify any differences. This is important since C-4 is commonly used for experimental testing, while a large number of real AP blast mines contain TNT.

The higher detonation velocity and explosive output of C-4 leads to higher initial pressures in the SHL, by a factor of 1.33. The longer term response of the SHL and resulting damage were evaluated by monitoring stress and pressure in the bone and soft tissue respectively. It was found that the level of injury increased with increasing charge size, as expected. Although the difference between C-4 and TNT for similar charge sizes appears small from the numerical injury criteria, visual inspection of the SHL models shows a significant increase in material damage resulting from C-4 charges. It is suggested that a 75 gram C-4 charge is comparable to a 100 gram TNT charge.

The conclusion is that C-4 presents an increased level of loading compared to a similar-sized TNT charge, and this must be accounted for when selecting charges for testing. Further development of the SHL injury criteria and comparison to available data will be the focus of future research in this area.
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References


