Soil Properties Influence on Land-Mine Blast Effects

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1 Executive Summary

Land mines and other buried explosives cause significant damage to people, equipment, and vehicles every year. While the effects of explosives in rock have been well documented by the mining industry, the effects of explosives buried in soil are less developed. A buried land mine has the intended consequence of impulse loading the object directly above the blast area. The soil surrounding the buried explosive has the effect of confining the charge as well as focusing the blast energy upward. Depth of burial for a typical land mine is less than 18 in (45.7 cm) and the charge shape is flat and typically circular. Additionally, most land mines use high explosives and may use have some booster component, depending on the manufacturer. Understanding the mechanism of soil-blast interaction can lead to predictive models that would aid designers of armored undercarriages and increase crew survivability.

In the paper, the results of a preliminary study of land mine blast measurements and observations will be presented. Variables such as land mine burial depth, soil types, soil water content are investigated with respect to the effects on blast impulse loading at various standoff distances (the height of a measuring location above the ground surface). Initial impulse measurements presented in this paper show that standoff distance is a more important factor than the depth of burial of the charge.

In addition to charge-target configurations, the soil must also be evaluated for its ability to transmit blast loads. Initial experiments performed in this study indicate that soils with high percentages of clay transmit higher impulse loads to the standoff target. The effects of moisture content and compaction (void ratio) are also investigated. The influence of soil strength parameters, cohesion and friction angle, under dynamic loading conditions are still under investigation as well.

2 Introduction

While air blast explosions can be modeled with a high degree of accuracy, explosions in non-homogeneous, non-isotropic materials have not been accurately modeled. The mining industry has had success with developing empirical relationships for explosive-rock combinations, but still relies on in-the-field judgment. Researchers at the Army Research Laboratory and Sandia National Laboratory, among others, are currently working toward modeling the land mine – soil interaction problem using a combination of Eulerian and Lagrangian finite element analysis.

While soil and rock masses differ in important qualities, it is possible to use the experience and empirical equations developed by the mining community in an effort to understand the soil-blast interaction and to help develop predictive models of target impulse loading. For most mining engineering theory, the rock is assumed to be a competent whole whose strength is degraded by the presence of fractures and other irregularities (like mineral veins). Soil masses are a conglomeration of non-uniform, non-homogeneous, non-isotropic soil grains. Traditional soil mechanics extrapolates behaviors and strength properties based on a soil's behavior on the whole.

2.1 Vertical Impulse Measurement Fixture (VIMF)

The Vertical Measurement Impulse Fixture (VIMF) at the U.S. Army Research Laboratory (ARL) allows full scale experimenting of land mines and vehicle hulls. The VIMF is a structural mechanical device that responds to blast loading by measuring the vertical displacement of a fixed mass vertical guide rail, which is a direct measure of the imparted impulse. The majority of the experiments in this study were conducted with a flat witness plate attached to the guide rail bottom and the vertical displacement was measured to determine the impulse imparted by a land mine blast. For this study, the cast TNT charges were remotely detonated predominantly under the center of the witness plate with the standoff distance being measured from ground level to the bottom of the plate. The soil is prepared by compacting the area within the retaining walls and then excavating a hole in which the mine is buried. Above the charge, the soil is tamped by hand replicating land mine burial techniques. Figure 1 shows the experimental facility.

The guide rail is mechanically braked to preserve the structure and the maximum displacement and impulse can be calculated. The calibration equations and process are detailed in [1]. Additional in ground instrumentation in the form of pressure transducers can be placed radially from the charge to measure pressures along the lateral direction.

Figure 1: Vertical Impulse Measurement Fixture Overview

2.1.1 Preliminary Soil Characterization

The soil inside the VIMF can be changed to match desired experiment conditions. The preliminary soil specifications required a mixture of clay and sand at set percentages. More recent experiments have replaced the clayey soils with 100% sand. This report primarily deals with the clayey soils. The two primary mixtures are composed of an 85% clay – 15% sand mixture or a 50% - 50% clay-sand mixture. The final soil is a 100% sand sample. The soil was prepared by a contractor to have as uniform a mixture of clay and sand as possible. The soil within the VIMF facility is mechanically compacted using a backhoe attached tamper. While sheepsfoot rollers are the traditional method of compacting fine grained soils, the backhoe tamper has been reaching greater than 80% compactive effort as determined by the soils testing contractor. This level of compaction should replicate in situ conditions, although land mines buried on roads would be placed in soil having a higher degree of compaction. The VIMF is an outdoor facility so surface and depth of burial moisture contents may vary. The charge hole is dug the same day as the experiment, minimizing localized water loss. Additionally, the propensity of clayey soil to retain water helps minimize the potential for the hole to dry out.

A team from the University of Maryland has been working on small scale (less than 5 grams of explosive) blast measurements. They have categorized the clay as expansive and have found that the moisture content of the soil plays a large role in predicting the impulse generated by the blast. As a general trend, higher moisture contents result in higher impulses. Similarly, they have found that higher clay contents result in higher impulses.

3 Predicting Soil-Blast Interaction

Any analysis of soil-blast interaction must look at the behavior of the soil under rapid, dynamic loading conditions. Factors to consider include the granular make-up of the soil, the presence of air and water in the form of voids, the relative density of the soils, as well as the strength of the soil mass. On the blast side, important quantities involve the charge size, the distance from the charge to the target, and how much material the blast must pass through before impulse loading the target.

3.1 Soil Properties Influence on Blast Effects

The interaction between the surrounding media and the explosive has significant influence on the impulse imparted to the witness plate. When considering the soil medium as a whole, simplifying assumptions dealing with soil properties and behavior are common. Despite the inherent non-homogeneity and non-isotropy of a soil, it is common to take average properties and apply them to the area of interest. While this leads to acceptable results in traditional soil mechanics, it is inherently limited when dealing with large strains and rapid loading conditions, such as those found during a blast.

Soils can be categorized as fine or coarse grained. Coarse grained soils are typified by larger individual particle size while fine grained soils have much smaller (microscopic) individual particles. This study looks primarily at clayey (fine grained) soils, with discussion to the method's applicability and possible future extension to coarse grained soils.

Clay particles are flat and plate-like. Depending on the ionic behavior of the particles, the platy particles stack in different orientations and develop different strength and other properties. The orientation and arrangement of the clay plates can form different soil fabric structures that retain a deposition and loading history. Voids between the particles are filled with water or air (under normal, non-contaminated situations) and may proportionally occupy a large volume of the soil structure. [2] The clay in the experimented soils is an expansive clay, meaning that it swells in the presence of water. [3] The expulsion of (air) voids through mechanical means is called compaction. Compaction is typically used in the context of coarse grained soils, but can provide insight into the relative density of any soil, to include fine grained clayey soils. The time dependent expulsion of water and subsequent decrease in voids for fine grained soils is the consolidation of the soil.

Observational evidence and work by the University of Maryland team suggests that explosions in clays impart higher impulse loads than in sands. From Figure 2 below, it would appear that the clay-sand makeup of the soil has a minimal role. It is important to note that experimenting occurred with clay-sand soil water contents below that of the pure sand soil. The typical clay moisture content (the ratio of water weight to solids weight) was around 10%, while the typical sand moisture content was around 20%. The outlying sand data point resulted when the plate was next to the soil (standoff distance of approximately zero) while the other data points are taken for higher standoff distances, typically 16 inches (0.4064 m) but in some cases less.

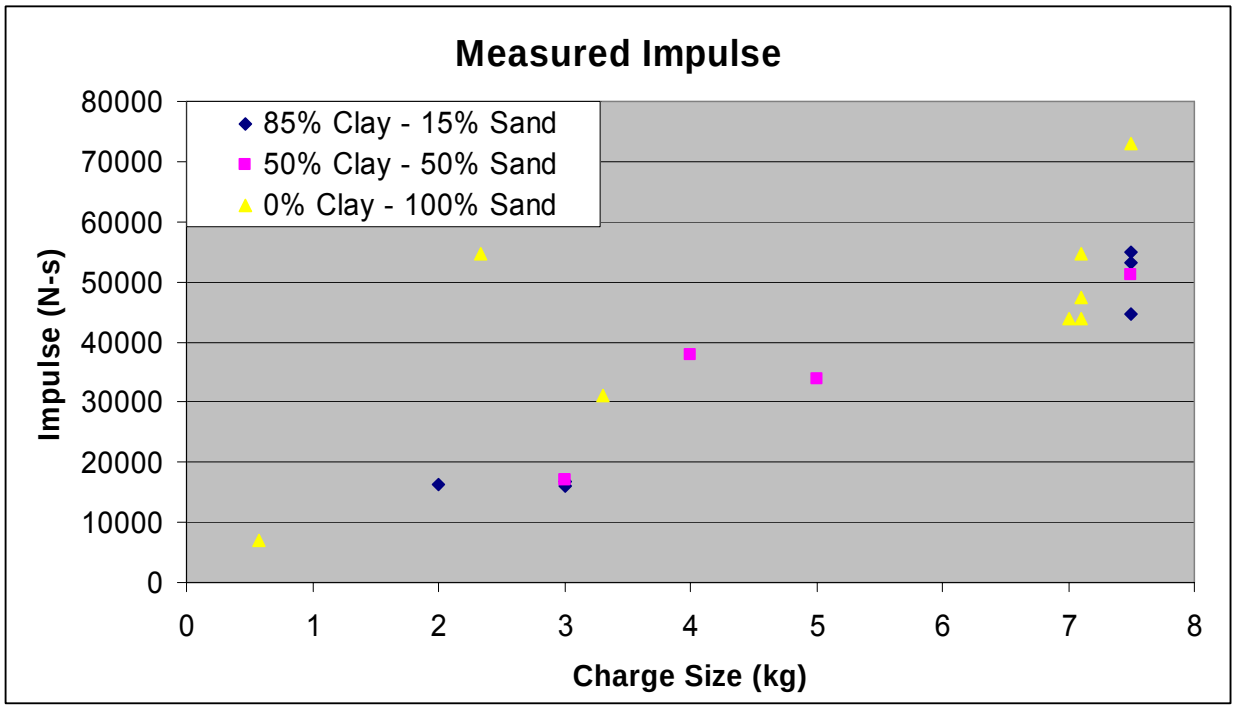

Figure 2: Measured Impulse of Varying Soil Conditions

The crater developed after the explosion also gives evidence of the influence of soil properties. By examining the geometry of the craters, a characteristic angel off vertical can be found for different soil types. Craters in clay soils have steeper side walls than craters in sands. This may be a result of the soil being expelled upwards at an earlier part of the blast, or may be a result of the clay canalizing the blast upwards. Several blasts developed two stage craters (see figure 3 for geometry), but the characteristic angle, θ, remains similar over different charge sizes and variable moisture contents. Table 1 summarizes the characteristic angles by soil type.

The steeper walls may be a result of the traditional soil mechanics concepts of cohesion and internal friction angle. Clayey soils have some internal cohesion as a result of ionic bonding that allows them to "stick together" better than coarse grained soils. Sands have typically higher internal friction angles that prevent sliding of the grains with respect to one another. The steeper wall angles may also be a result of the soil more efficiently canalizing the blast upward through other mechanisms. In either case, the steeper crater angles serve to direct more of the blast upward, resulting in higher than expected impulses on the witness plates.

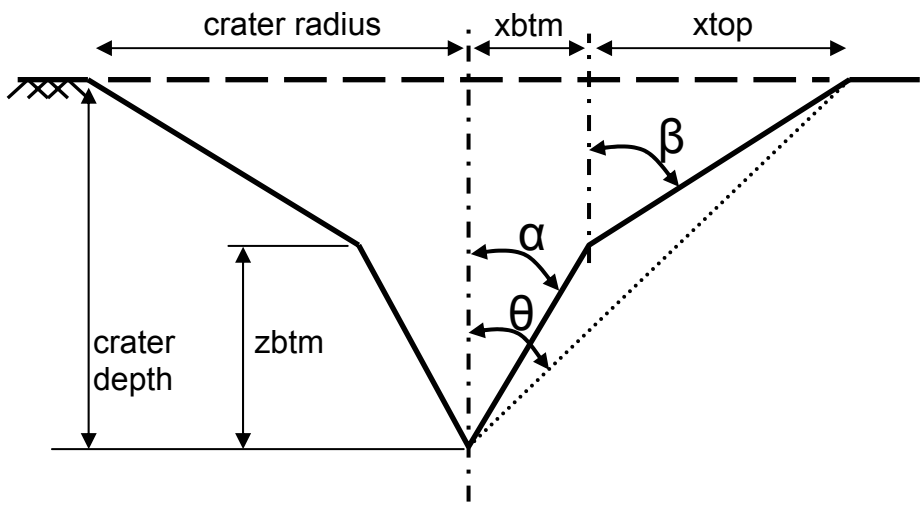

Figure 3: Crater Geometry and Characteristic Angle, θ

Table 1: Crater Characteristic Angle, θ, by Soil Type

Soil Type	Crater Angle
% C / % S	(deg)
85 / 15	56.35
50 / 50	61.17
0 / 100	65.18

From preliminary measurements into the radial dispersion of the blast loading, it appears that the pressures generated by the blast dissipate quickly in a lateral direction and that the majority of blast effects are directed upward toward the free surface.

3.2 Mining Industry Contributions

The mining industry has a long history of blasting in non-homogeneous, non-linear material. While soil and rock differ, it is possible to use the empirical relationships and equations developed by the mining industry to gain insight and predictive capability. While equations of state exist in the mining community, the empirical relationships between explosives type and rock media have been proven accurate and effective, and more popular in practice.

Cratering theory in the mine industry is similar to the principles behind a land mine blast. In its most basic form, mine cratering theory follows from a charge oriented perpendicular to a single

free surface. Beneath the free surface, the material extends "laterally in all directions beyond the point where the surrounding material would be affected by the blast." [4] A further resemblance to the land mine blast problem comes from the shape and orientation of the charge itself, "a spherical or near-spherical short charge (1:6 diameter-to-length ratio)." [5] Traditional cratering theory is based on strain energy relationships and is highly specific to explosive-rock combinations. While empirical tables exist for different rock media, no table documenting explosive-soil combinations is readily available (or may exist). Running experiments to determine the critical depth of burial for particular explosive-soil combinations will lead to additional empirical relationships and may not necessarily result in an increase in the accuracy of future work.

As a land mine blast ejects soil particles at high velocities from the crater as a result of an explosion, it is possible to model the explosion using flyrock empirical relationships. Flyrock is the undesirable high speed ejecta resulting from improper blasting technique. As the name implies, flyrock typically consists of boulders thrown at (typically) high velocity and to great distances. By considering the soil ejecta as a number of discrete soil "boulders," and summing the cumulative impulse effects, reasonable predictive results can be gained with a minimum of computational effort.

3.3 Predictive Model

By discretizing the soil ejecta into flyrock and calculating the cumulative effect of the soil ejecta impacting a plate, a reasonable approximation to the problem of determining the impulse effects of a land mine blast can be made. Due to the configuration of typical land mines, the flat and circular charges can be assumed to be spherical and the empirical mining engineering flyrock equations may be used. The following two equations and their derivation come directly from "Rock Blasting and Explosives Engineering" by Per-Anders Persson, et al [6]. Due to a spherical charge, the impulse density, i, is

$$\int p dt = i \propto \frac{W^{2/3}}{R} \qquad (1)$$

where p is the pressure imparted, W is the charge weight, and R is the distance from the charge. Note that in mining engineering, R is the distance from the charge to the boulder of interest. In the case of land mine blasts, allowing R to be the standoff distance from ground surface to the target has yielded the best results. Additionally, the constant of proportionality is an area that requires additional study. At present, the impulse density has been assumed to be directly proportional to the relationship above. The impulse density and the area of the flyrock (soil particle) are proportional to the force imparted to the flyrock. The total impulse, I, acting on the soil particle can be found by

$$I = \frac{\pi \cdot \phi^2 \cdot i}{4} \qquad (2)$$

where φ is the diameter of the soil particle. Further relationships exist to describe the relationships between impulse, mass, and velocity, but are not used in this case.

By finding the impulse imparted to a soil grain by a blast, a rough approximation of the total impulse of the blast can be made by summing the cumulative effects of all the soil grains. A rough approximation of the number of grains present in the apparent crater can be made by using the assumption that the grains are spheres of uniform diameter. For clayey soils, an assumed grain size 0.075 mm (the size of soil grains retained on a #200 sieve, the dividing line between fine grained soils and sands) has been reasonably accurate. The actual average size of clay particles is typically less than 0.002 mm. The number of grains can be estimated as follows:

$$NoGrains = \frac{CraterVolume}{GrainVolume} \tag{3}$$

where the Crater Volume is the measured (or predicted) volume of the crater and the Grain Volume is simply the area of a sphere,

$$GrainVolume = \frac{4 \cdot \pi \cdot r^3}{3} \tag{4}$$

The crater volume can be approximated as either a conical shape or a rotated parabola with varying effectiveness.

$$CraterVolume_{Paraboloid} = \frac{\pi \cdot r^2 \cdot d}{2} \tag{5}$$

$$CraterVolume_{Conical} = \frac{\pi \cdot r^2 \cdot d}{3} \tag{6}$$

where r is the average radius of the crater and d is the total depth of the crater.

The total predicted impulse that is imparted to the target at a standoff distance, R, above the ground is the summation of the grain impulse, I, and the number of grains, or simply

$$I_{TOTAL} = I \cdot NoGrains \tag{7}$$

Finding the total impulse due to the ejected soil particles gives a reasonable approximation of the impulse imparted to the witness plate. The model finds a larger void ratio than exists in reality as a result of the uniform, spherical grain size assumption. While this would appear to be a limitation, at the preliminary stages, it would seem to be accounting for the vaporization of soil moisture, the inter-grain collisions, and other events to give surprisingly reasonable results for such a simple model.

3.4 Model Results

Using the simplifying assumptions of spherical, uniform soil grains of 0.075 mm for the clay soils, reasonable results can be found for standoff distances between 8 and 16 inches (0.2032 – 0.4064 m). Figures 4 and 5 below show the measured impulse values versus predicted impulse values for two different crater volume approximations. Note that the 85% clay soil had the steepest characteristic angle and that the conical approximation of crater volume is valid. The 50% clay soil had a shallower characteristic angle, and the parabolic crater approximation appears to be more valid.

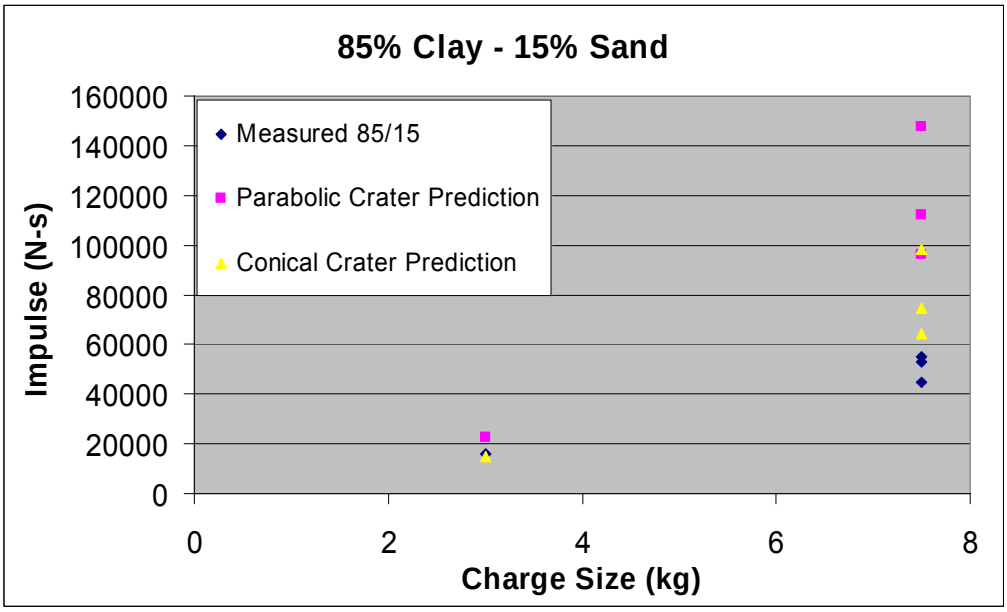

Figure 4: Measured vs Predicted Impulses using the Flyrock Model for the 85% Clay Soil

Within the flyrock model, it is critical to be able to accurately predict crater volumes based on soil type and properties. The ConWep program [7], developed by the U.S. Army Corps of Engineers Engineer Research and Development Center (ERDC) attempts to predict cratering effects of various explosives given soil conditions. Within the soil data sets, it is possible to make a prediction of the anticipated crater volume based on the explosive. For all figures below, the explosive is set to TNT, modeling the cast TNT charges in use at the VIMF.

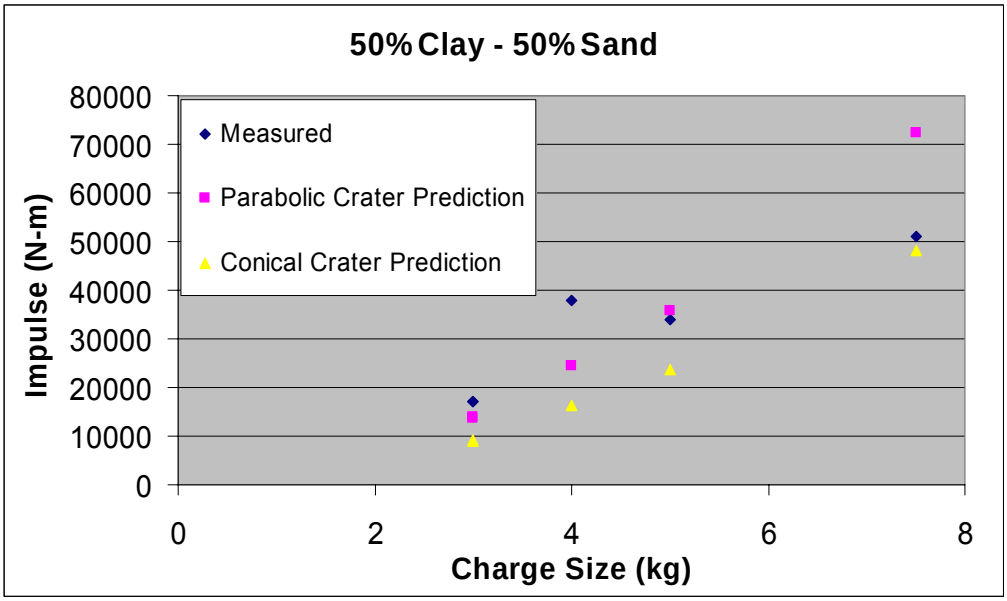

Figure 5: Measured vs Predicted Impulses using the Flyrock Model for the 50% Clay Soil

Figures 6, 7 and 8 show the relationship between the measured crater volumes and the ConWep predicted crater volumes. Note that in the figures below, the "Actual" volume is assumed to be the average of the parabolic and conical crater volumes. Figure 6 shows that the 85% clay soil is most closely represented by the clay soil set in ConWep. Figure 7 shows that wet sandy clay is a reasonable approximation for the 50% clay soil. Figure 8 shows that the wet sand data set in ConWep does not match the experimental data.

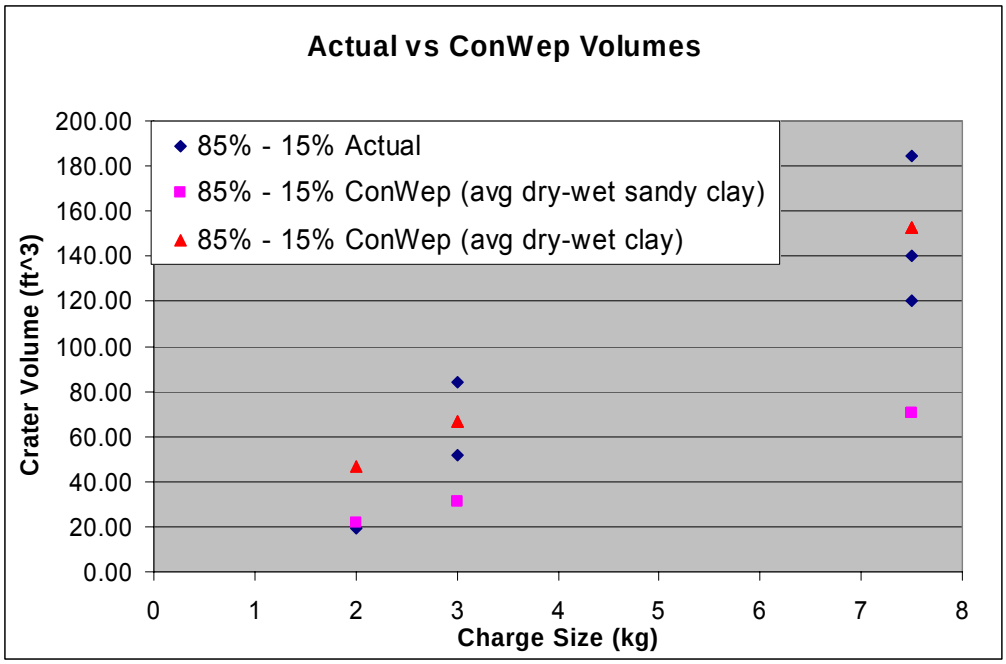

Figure 6: Measured Crater Volumes vs ConWep Predicted Volumes for 85% Clay Soil

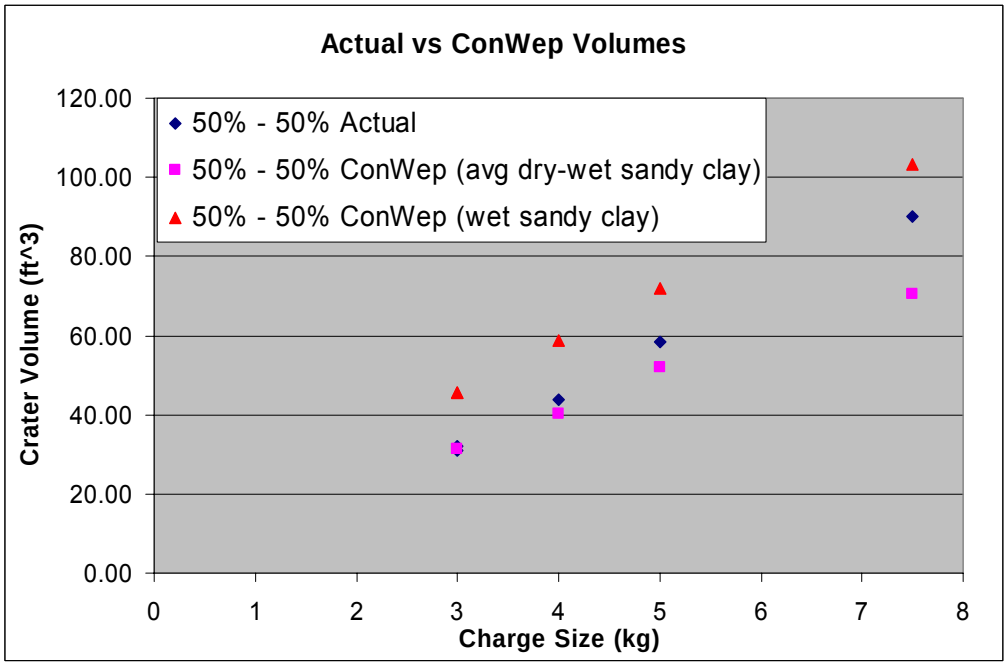

Figure 7: Measured Crater Volumes vs ConWep Predicted Volumes for 50% Clay Soil

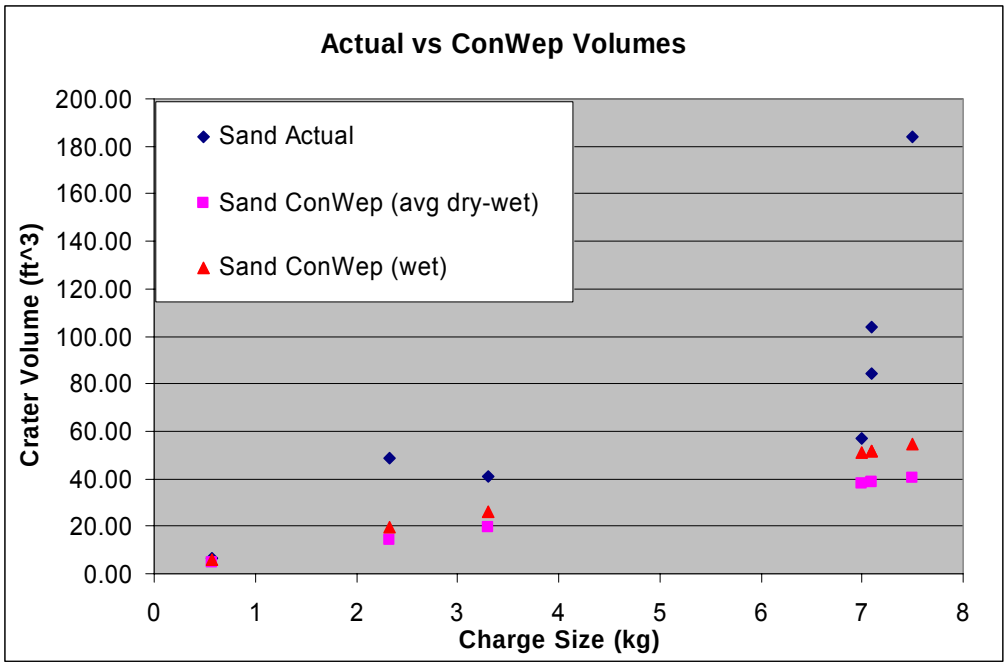

Figure 8: Measured Crater Volumes vs ConWep Predicted Volumes for Sand Soil

By coupling the ConWep predicted crater volumes with the basic flyrock model, it is possible to develop a rapid, reasonably accurate tool to predict the impulse loading of a witness plates due to a land mine blast. Note that only the two clayey soils will be modeled. Additional work on predicting the crater volume produced in land mine – sand explosions is required. While the results do not look significantly more accurate than those shown in Figures 4 and 5, it is important to note that figures 9 and 10 below are purely predictive and do not rely on measured crater volumes.

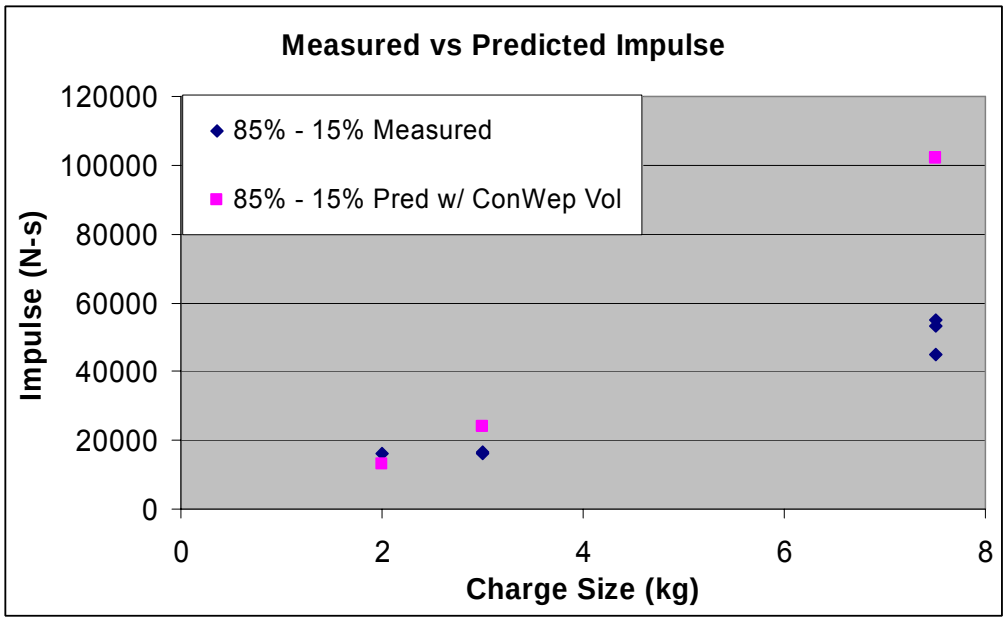

Figure 9: Measured vs Predicted Impulses using the Flyrock Model with ConWep Volumes for the 85% Clay Soil

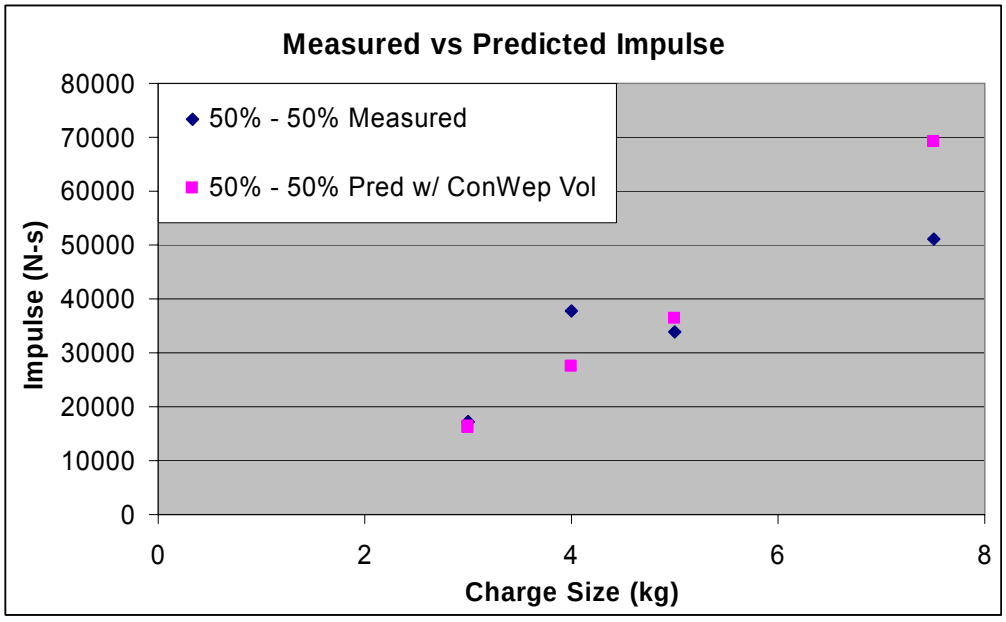

Figure 10: Measured vs Predicted Impulses using the Flyrock Model with ConWep Volumes for the 50% Clay Soil

Refinement of the model is clearly necessary. At high charge weights, the predicted impulses tend to overestimate the impulse generated. At higher charge weights, it may be necessary to use the distance from the charge to the target (standoff distance plus depth of burial) as opposed to the standoff distance alone. At low charge sizes, the charge may be more coupled with the soil creating measured impulses higher than predicted values. The charge-soil coupling has the effect of increasing the explosive effects due to a matching of explosive properties and the amount of soil confining the charge.

3.5 Limitations of the Model

The model is by design simplistic. It attempts to make a conservative estimate of the impulse transmitted to a witness plate without taking into account the myriad variable inherent in such a problem. At the most basic level, it appears to be a functioning model that requires refinement. Additional experimentation and experimenting is required in several areas.

Within the realm of the soil, the model does not account for moisture content, already identified as an indicator of impulse magnitude. The variability of soil grain size is an area that requires additional work. The distribution of grain sizes and shapes may be dealt with probabilistically as a future refinement.

The influence of the depth of burial on lower charge weights and the potential coupling effect of a soil-explosive configuration should be investigated. The model does not account for the fact that not all of the soil ejecta will be directed directly toward the witness plate or that the mine may not be placed directly below the center of the target. Additionally, the constant of proportionality between the impulse density and the charge weight and standoff distance has been left at unity. This is most likely an oversimplification. The only explosive currently experimented has been cast TNT; additional explosives need to be investigated. Also note that the model is only valid for bare explosives. Shaped charge type mines are beyond the scope of the flyrock model.

4 Conclusion

The problem of soil-blast interaction is a complicated one that must account for soil variations, charge configuration and placement, as well as explosive variations and strengths. As a simple model of a complex problem, the flyrock model does reasonably well at approximating the impulse loading of a target plate above a cast TNT charge. Understanding the mechanism by which the soil is expelled and the explosive energy is released will aid in the development of future land mine blast models. More accurate models can lead to the improved survivability of vehicle crews in blast resistant or blast survivable vehicle hulls.

References

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[2] Budhu, Muni, *Soil Mechanics and Foundations*, Wiley, New York, NY, 2000.
[3] Ibid.
[4] Persson, Per-Anders, Roger Holmberg, and Jaimin Lee, *Rock Blasting and Explosives Engineering*, CRC Press, Boca Raton, FL, 1994.
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[7] U.S. Army Corps of Engineers Engineer Research and Development Center (ERDC), Geotechnical/Structures Laboratory, *ConWep Release 2.1.0.1*, Conventional Weapons Effects Software.

Additional Resources

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