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ANALYSIS OF CRATERS FROM LARGE BURIED CHARGES

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ABSTRACT

This paper presents the results of a series of controlled tests conducted with large explosive charges in which a number of threat parameters were systematically varied. After each test, careful measurements were made of the crater dimensions. A statistical analysis was conducted in order to relate the measured crater dimensions to the threat characteristics. The test plan examined the effects of charge size, soil type, shape of the charge, and burial depth. The results of the analysis showed that all of the threat parameters had a significant effect on the most commonly measured dimension, the crater lip diameter. As a consequence, any model that attempts to estimate charge size based solely on crater size measurements will necessarily have large predictive errors, on the order of a factor of two or more.

INTRODUCTION TO CRATER ANALYSIS

One of the most important aspects of vehicle design has to do with the protection requirements for underbelly blast. Improvised explosive devices (IEDs) have become ubiquitous on the modern battlefield, and pose a severe threat to the survivability of mounted ground combat forces. These threats are normally not standard military ordnance, but instead consist of homemade or modified explosives, packed in convenient containers, and emplaced according to local custom or procedures. As a consequence, the effective explosive load delivered to a combat vehicle as a result of a buried charge in theater is highly variable. This poses a significant challenge for requirements specification – how should we specify the underbelly protection criteria, given what we know about the actual nature of the threat?

One approach to this problem is to conduct forensic analysis of the craters generated by the blasts that occur in theater, and use this data to attempt to estimate the net explosive weight (NEW) of the charge. This involves sending a crew to the site of a blast and measuring relevant dimensions of the crater, such as the lip diameter and depth. This can be a challenging task, since the blasts generally occur in remote, potentially unsecure locations, and these measurements must be made following the removal of the damaged vehicle. The figure below shows one such crater, which was created by a blast occurring near a roadside in a more heavily populated area.

Note that the crater in this case is non-symmetric, owing (in part) to the neighboring pavement. Also, there is very little ejecta around the lip of the crater. These factors make the crater diameter measurement itself highly variable. Much of the ejecta has fallen back into the crater, which also affects the crater depth measurement. Because the blast occurred near a road, the soil conditions are likely to be much more heavily compacted than would be the case if the blast occurred in open country, and this will also affect the size and depth of the crater. Clearly, conducting crater forensic examination and measurement is a very demanding task. Just as clearly, the crater shown in the figure must have resulted from a fairly large charge, and it is important to know just how large in order to write good vehicle survivability requirements to protect mounted ground combat troops.

Figure 1. Crater from an IED blast.

One of the early works on crater analysis was produced by the U.S. Army Corps of Engineers. A technical report [1] entitled *Cratering from High Explosive Charges* details observations and measurements of data from a large number of buried blasts (over 1,800) in a wide range of conditions, including 20 different types of soil, different charge weights (covering several orders of magnitude), and different burial depths. One of the key objectives of this work was to determine the extent to which it was possible to determine a relationship between crater dimensions and charge size, especially using the common cube-root scaling law. This law says that explosive effects scale approximately as the ratio of the cube root of the explosive mass, *W*, so that we have:

$$Effect \propto W^{1/3} \qquad (1)$$

In this equation, the effect may be the pressure at a given distance, or the diameter or depth of the crater. One of the conclusions of this early work was that cube root scaling for crater dimensions was not a reliable indicator of charge size. This is not surprising, insofar as cube-root scaling was developed primarily to describe the propagation of blast waves in different media, rather than to describe the movement and dislocation of bulk materials during an event.

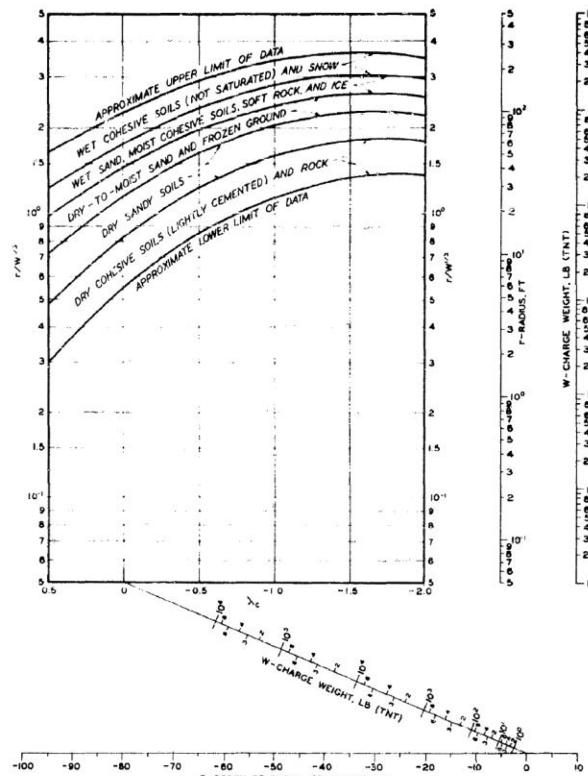

Figure 2. Nomograph for determining the apparent crater radius in various media (from reference [1]).

One of the significant charts from the report is reproduced in the figure above. This shows the approximate relationship between the scaled crater radius ($r/W^{1/3}$) and the charge weight *W*, as a function of depth of burial (*Z*), in five different types of soil, ranging from dry cohesive soils, through dry sand, frozen ground, wet sand, and wet cohesive soils (or snow). In looking at the chart, the actual values are less important than the ranges. The scaled crater radius apparently changes by nearly an order of magnitude, depending on the type of soil in which the blast occurs. Furthermore, the charge weight apparently covers three orders of magnitude. This chart shows not so much a clear relationship between charge size and crater dimensions, but rather the existence of large scatter in the experimental data as well as large uncertainties in any such relationship.

The goal of this work is to determine whether it is possible to find a more useful relationship between crater dimensions and charge size, restricting ourselves to conditions of common interest for military ground vehicles. That is, charge sizes of about 8 to 15 kg, buried in ordinary soil (no rocks or snow or frozen ground), with different soil overburdens representative of common emplacements. In addition, we looked at different charge shapes, representing the different containers that might be used for an improvised explosive device. We conducted a number of blast tests, and attempted to determine the extent to which it was possible to create a relationship that would accurately estimate the size of the charge from the measured crater dimensions.

BLAST TESTING AND CRATER MEASUREMENT

Procedures – Size, Shape, Overburden Testing

We conducted blast testing at the General Dynamics Edgefield Test Facility located at Edgefield, South Carolina. The tests were actually designed to examine the effects of different charge characteristics on target damage and total impulse. However, following each blast test, we carefully measured several crater parameters including lip diameter, apparent diameter, and apparent crater depth, to determine the relationship between the known test conditions (charge size and shape, overburden, soil type) and crater dimensions. The figures below show some of the test procedures.

Figure 3. Mine emplacement with 4" soil overburden.

Figure 4. Frame of high-speed video of blast test.

For the first set of tests, we considered only variations in charge size, charge shape, and soil overburden. All of these tests were conducted in the same type of soil. This consists of the common "5/125" soil used at Edgefield, which is approximately 125 pounds per cubic feet (wet) (2.00 g/cc) and 5% moisture content. New soil was used for each blast test, and emplaced with a vibratory soil compactor. The soil was confined in a buried steel blast box measuring 12'x12'x6' deep, providing a diagonal measurement of over 200". These tests considered two different charge sizes: 8 kg and 15 kg, two different shapes: 3:1 aspect ratio and 1:1 aspect ratio, and two different soil overburdens: 0" and 4". This provides a total of 8 different configurations, all of which were tested. Some of the tests were repeated, with a total of 13 shots conducted in this series. The table below shows the tests that were performed, with the repeated shots highlighted.

Table 1. Size, Shape, Overburden Test Matrix

Charge Size	Charge Shape	Soil Overburden
8 kg	1:1	0"
8 kg	1:1	4"
8 kg	1:1	4" (repeat)
8 kg	3:1	0"
8 kg	3:1	0" (repeat)
8 kg	3:1	4"
8 kg	3:1	4" (repeat)
15 kg	1:1	0"
15 kg	1:1	4"
15 kg	3:1	0"
15 kg	3:1	0" (repeat)
15 kg	3:1	4"
15 kg	3:1	4" (repeat)

The charges consisted of hand-packed C4 in cardboard containers. All charges were bottom-center detonated using a high-voltage electric detonator system together with a small RDX booster in order to ensure full reaction. The figure below shows two of the 8 kg charges with different aspect ratios, 3:1 and 1:1.

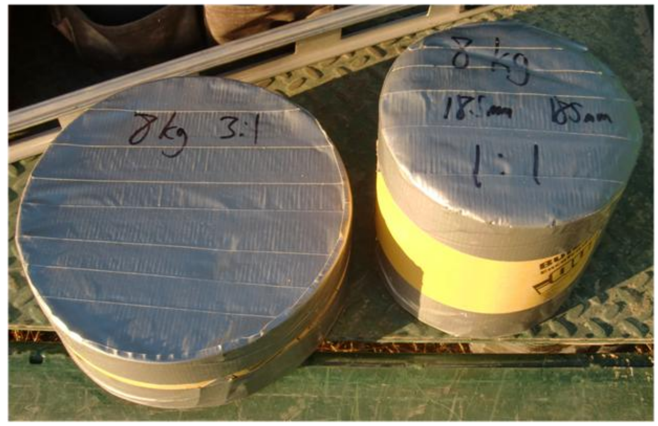

Figure 5. Hand-packed 8 kg C4 charges ready for testing.

Following each blast, the crater lip diameter, apparent diameter, and apparent depth were measured according to the standard practice described in International Test and Operations Procedure 4-2-508 [2]. The figure below shows these parameters. Note that, in practice, the apparent diameter is difficult to measure, since it presumes level, undisturbed ground, and requires the manual removal of the ejecta that forms at the crater lip prior to measurement. Similarly, the apparent depth can only be measured following removal of the ejecta. As a consequence, the most commonly reported crater dimension from theater is actually the lip diameter, which is dependent on the formation of the ejecta around the crater following the blast. In these tests, the apparent diameter and depth were measured by scraping the ejecta down to the top of the blast box.

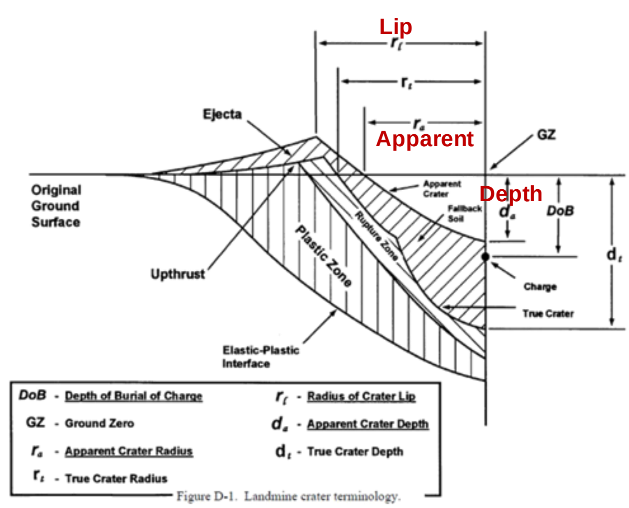

Figure 6. Crater landmine terminology from [2].

Results – Size, Shape, Overburden Testing

The results of the tests are shown in the table below, including all three crater parameters. This table is provided for the sake of completeness, to allow further analysis.

Table 2. Crater Dimensions from Blast Testing

Charge Size	Charge Shape	Over-burden	Lip Diameter	Apparent Diameter	Apparent Depth
8 kg	1:1	0"	132"	112"	14"
8 kg	1:1	4"	154"	117"	19"
8 kg	1:1	4"	148"	117"	22"
8 kg	3:1	0"	126"	104"	14"
8 kg	3:1	0"	114"	94"	17"
8 kg	3:1	4"	117"	117"	19"
8 kg	3:1	4"	133"	118"	20"
15 kg	1:1	0"	150"	115"	16"
15 kg	1:1	4"	172"	146"	29"
15 kg	3:1	0"	134"	116"	17"
15 kg	3:1	0"	135"	110"	19"
15 kg	3:1	4"	155"	123"	31"
15 kg	3:1	4"	160"	145"	26"

One way to look at this data is to simply plot the variation in a key crater dimension, such as the lip diameter, with each test parameter. This provides a simple, intuitive feel for the extent to which the parameter affects the measured result. The following figures show these plots for the case of the lip diameter versus the charge size, charge shape, and soil overburden. In addition, the data can be analyzed statistically for significance, and modeled to determine the dependence of lip diameter on each charge parameter.

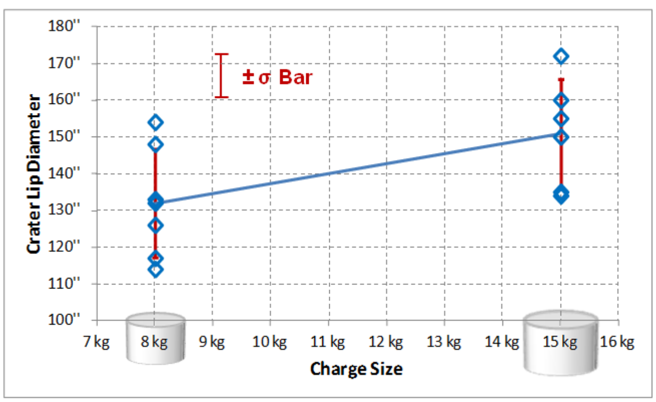

Figure 7. Dependence of lip diameter on charge size.

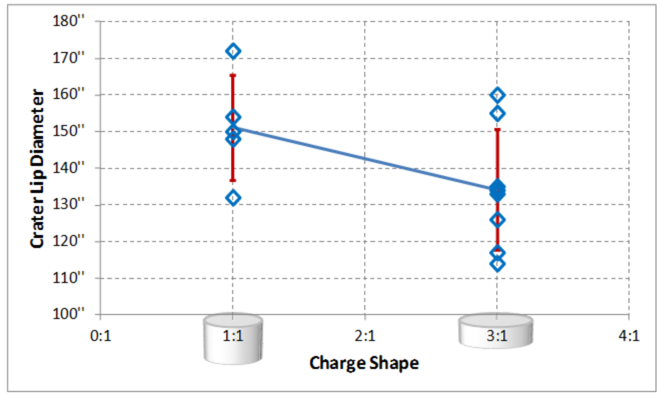

Figure 8. Dependence of lip diameter on charge shape.

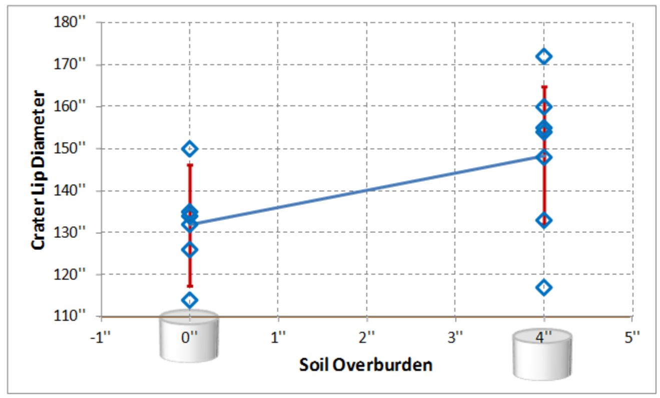

Figure 9. Dependence of lip diameter on overburden.

The figures indicate an apparent relationship of lip diameter to all three charge parameters. In order to test this relationship, we can conduct an Analysis of Variance of the data to estimate the significance of these results. In this case, because we have an unbalanced experimental array, we analyzed the data using a “Type II” ANOVA (although the results are not greatly different using a “Type I” or “Type III” analysis). The object of the ANOVA is to determine the likelihood that the null hypotheses are true. In this case, the null hypotheses are that the charge size, charge shape, and soil overburden do not affect the crater lip diameter. Intuitively, from the charts, we would expect these hypotheses to be rejected. The ANOVA procedure calculates a numerical value indicating just how likely it is that the data produced by the tests would be consistent with the null hypotheses. This likelihood is called the p-value, and is the result of an F-test on the data. From the Type-II ANOVA of the data shown above, the likelihoods that the null hypotheses explain the experimental results are about:

Charge Size: $p = 0.0003$
Charge Shape: $p = 0.002$
Overburden: $p = 0.002$

What this means is that it is extremely likely that the crater lip diameter is dependent on the size of the charge, which makes perfect sense. However, it means that the lip diameter is dependent on the shape of the charge as well, and also on the burial depth. Note that typically, in a real engagement, the burial depth and charge shape are not known beforehand. The charge shape often depends on the container which happens to be available for packing the homemade explosive, including perhaps a pickle barrel, or a palm oil container, or whatever else is close at hand. The soil overburden depends on the training and determination of the emplacer, as well as on the length of time in the ground, erosion and settling, traffic, and other factors.

In the charts shown above, there is a red bar labeled "± σ". In this case, sigma is the standard deviation of the data collected under those test conditions. The span of the bar is a reasonable measure of the variation to be expected in the measured lip diameter when other significant factors are ignored. The size of this variation can be compared with the size of the effect attributed to each factor, which can be found from the linear model of the data. So, for example, the difference between the lip diameter of an 8 kg charge and a 15 kg charge is about 22" (a little more than the slope shown in Figure 7). In contrast, the ± σ variation to be expected in the data covers about 29". This means that the variation in relating lip diameter to charge size is larger than the effect of the charge size, if no account is taken of the shape or overburden. Again, the shape of the charge and the overburden are typically not known in battlefield conditions.

Models of Charge Size

The blast test data can be used to generate a model that attempts to estimate the charge size based on the measured lip diameter. The nature of this model depends on the assumptions about how much knowledge is available about the blast. In the best case scenario, we would know the charge shape and overburden, and use the model to back out only the charge size. So the model would have the form:

$$W = f(D_L, A, O_S) \qquad (2)$$

where W is the charge size (kg), D_L is the lip diameter (inches), A is the aspect ratio, and O_S is the soil overburden (inches). Simple linear analysis produces the following:

$$W = -26.52 + 0.2486 \cdot D_L + 2.2472 \cdot A - 1.0495 \cdot O_S \qquad (3)$$

When applied to the test data, the model produces predicted values for charge size that can be compared with the actual values. The figure below shows this comparison. The red icons represent 8 kg test data and predictions, while the blue icons represent 15 kg test data and predictions. Although the 8 kg data shows a couple of outliers, the 15 kg data is very good, within about 2 kg of the actual charge size.

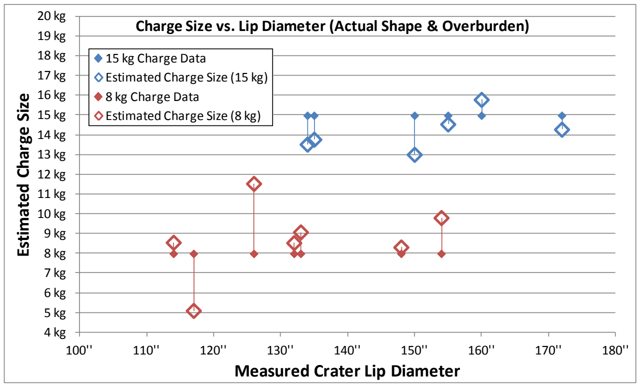

Figure 10. Comparison of measured and predicted charge size from lip diameter – best case.

Of course, as mentioned previously, the aspect ratio and overburden of the charge are not typically known when doing post-blast forensics. As a consequence, the only parameter that may be available is the lip diameter. A more real-world scenario would create a model that depends only on this single parameter, recognizing that the other parameters will not be available. In this case, the simple linear model takes the form:

$$W = -5.683 + 0.12015 \cdot D_L \qquad (4)$$

The figure below shows the correlation between measured and predicted values of charge size when using this more realistic model. In contrast to the "best-case" scenario shown above, this model has large errors in several test predictions, both over-estimates of the 8 kg charges, as well as under-estimates of the 15 kg charges. Using this model, at least four of the thirteen tests would be mis-characterized, in the sense that two of the 8 kg shots produced craters more consistent with 15 kg blasts, while two of the 15 kg shots produced craters more consistent with 8 kg blasts.

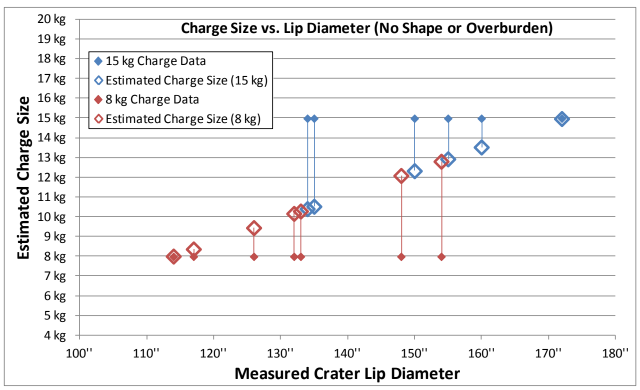

Figure 11. Comparison of measured and predicted charge size from lip diameter – real-world case.

Finally, consider the option of using our "best-case" model with "average" data. That is, use the model that takes into account all three parameters – lip diameter, aspect ratio, and overburden, but use only the measured value of lip diameter, and average values for the other two. This might be a tempting option if, for example, we thought that the aspect ratio and overburden were restricted to a fairly narrow range, so that average values might be appropriate. The figure below shows the comparison between measured and predicted charge size using this approach, assuming the aspect ratio is 2:1, and the overburden is 2” of soil.

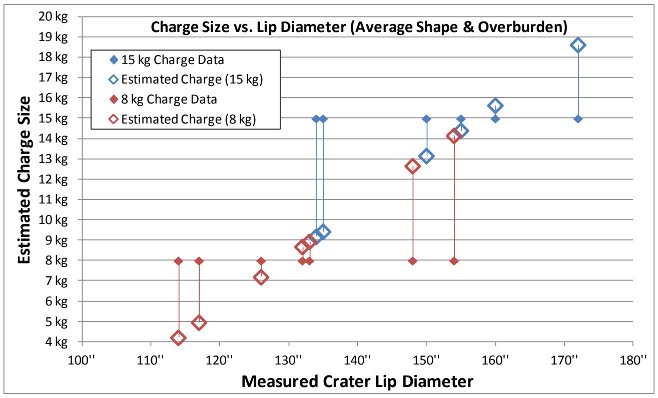

Figure 12. Comparison of measured and predicted charge size from lip diameter – worst case.

This figure shows the hazards associated with improperly using a model for a problem it was not intended to address. The errors in this case actually become worse than those associated with the simple one-parameter lip diameter model. The predictions associated with the 8 kg charges now range from about 4 to 14 kg, and those associated with the 15 kg charges range from about 9 to 19 kg.

Additional Models

Using the data provided in the table, it is possible to do similar analyses of the relationship between apparent crater depth and charge size, and between apparent crater diameter and charge size. These show similar results to the lip diameter analysis, with some differences. It appears that the charge shape is not significantly related to the apparent crater depth or apparent diameter, despite the fact that it is significantly related to the measured lip diameter. Also, the soil overburden appears to be the dominant factor in determining the apparent crater depth, with the p-value falling to 0.00002 for the null hypothesis. The figure below shows the plot of apparent crater depth versus soil overburden for the thirteen shots in the array. Note the tight ± σ bars, especially at 0” overburden. The 0” overburden data includes three shots at 8 kg and three at 15 kg, and this near factor of two difference in charge size produces very little difference in apparent crater depth.

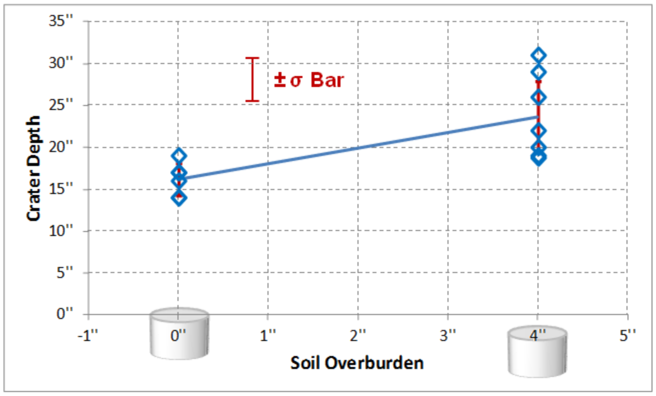

Figure 13. Dependence of crater depth on overburden.

As before, it is important to note that the apparent crater depth and apparent diameter are much more difficult to measure following a blast than the lip diameter. The measurement involves excavating the ejecta surrounding the crater down to the original bare ground on both sides. Then a straightedge has to be extended over the crater, and a vertical measurement taken down to the presumed deepest part of a ragged hole filled with debris to find the apparent depth. This is much easier to do on the range than in the field.

Procedures – Soil Variability Testing

In addition to testing conducted in the standard “5/125” soil, we conducted blast tests in carefully prepared NATO Stanag soil. Again, the main purpose of these tests was to look at damage and impulse, but these tests also provided an opportunity to examine the effect of soil variation on measured crater parameters.

The NATO Stanag 4569 [3] calls out protection levels for combat vehicles, including against mine blasts. The procedures specified for blast testing are called out in the associated document AEP-55 [4], which describes various methods of conducting the tests. The most relevant procedure calls out the creation of a carefully controlled soil pit with a specified level of density and moisture in order to ensure repeatable results that are representative of what occurs on the battlefield.

The Edgefield Test Facility routinely conducts testing using AEP-55 soil beds. This involves using controlled soil packed into a 12-foot square steel blast box buried under the ground. The soil is packed in 8” lifts, with the density and moisture carefully controlled to achieve the specified conditions. In the AEP-55 specification, the soil is specified as a sandy-gravel mix with a wet density of 2.20 ± .10 g/cc, and a moisture content of between 5% and 7%. This soil has less air-filled porosity than the standard “5/125” soil, and therefore produces more damage and impulse for a given charge. We were interested in determining whether this different soil also had an effect on the crater dimensions produced by the blast.

We used the same test procedures described previously, with only two parameters in our experimental array: the size of the charge and the type of soil. The shape of the charge was held constant at a 3:1 aspect ratio. The soil overburden was also held constant at 4”. The test array is shown in the table below, together with the results of the measurements of the lip diameter, apparent diameter, and crater depth.

Table 3. Soil Variability Test Matrix

Soil Type	Charge Size	Lip Diameter	Apparent Diameter	Apparent Depth
AEP-55	15 kg	190"	147"	26"
AEP-55	15 kg	195"	143"	22"
AEP-55	8 kg	143"	117"	21"
AEP-55	8 kg	136"	118"	16"
AEP-55	8 kg	165"	127"	18"
AEP-55	8 kg	138"	114"	25"
AEP-55	8 kg	168"	136"	21"
SD	15 kg	155"	123"	31"
SD	15 kg	160"	145"	26"
SD	8 kg	117"	117"	19"
SD	8 kg	133"	118"	20"

In the table, “SD” refers to standard “5/125” soil, while “AEP-55” refers to the more severe Stanag soil. We conducted a shot at each test condition at least twice, and the 8 kg AEP-55 shot was done five times. Note that the data for the “SD” tests is not new – it comes from the testing described earlier and can be found in the initial test matrix.

Results – Soil Variability Testing

Because of the simple nature of this test matrix, the results are easy to display in the single figure shown below. This shows the measured lip diameter as a function of charge size for both the 8 kg and 15 kg shots. The AEP-55 soil tests are shown with blue icons, while the SD soil tests are shown with red icons. It appears from the figure that the AEP-55 craters are consistently larger than those in the SD soil.

As before, we can test our intuition by performing ANOVA (Type II) of the data in the table to determine our confidence that the soil type does in fact have a significant effect on crater size. The results are as expected, with the following p-values on the null hypotheses:

Charge Size: $p = 0.002$
Soil Type: $p = 0.008$

This indicates that both soil type and charge size have a significant effect on the measured crater lip diameter, as expected. As before, we can put together a model that takes into account both the charge size and soil effects. Note that in this case, soil type is a categorical variable rather than a numeric one, so there is no “slope” associated with the factor. The effect of going from SD soil to AEP-55 is approximately 29” in measured diameter, whereas the effect of going from 8 kg to 15 kg is about 38”. This means that knowledge of the soil is yet another important factor that needs to be added to any model that attempts to predict charge size from measured crater dimensions.

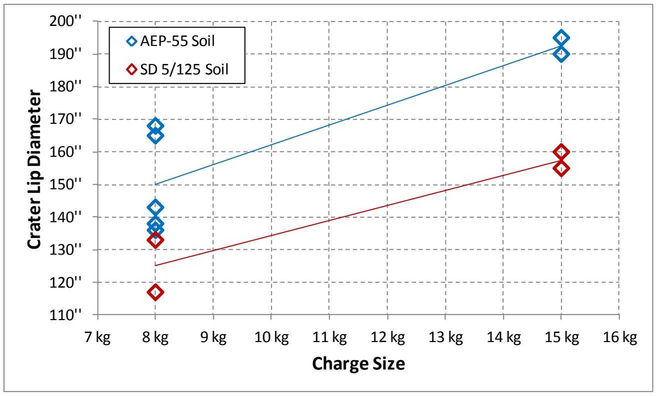

Figure 14. Summary of charge size/soil type test data.

CONCLUSION AND IMPLICATIONS

The data presented in this paper indicates that measurement of the crater lip diameter does not provide an accurate estimate of the size of the charge. Other factors are also important, including the type of soil in which the blast occurs, the depth of burial of the charge (soil overburden), and also the shape of the charge. Although estimates of the average values of these other parameters may be available, the fact is that without knowledge of the actual encounter parameters, an attempt to estimate charge sizes from measured lip diameters will likely have very large errors. These errors could amount to a factor of two or more.

Naturally, the data shown here represent a fairly small sample of blast tests – less than two dozen in all. It is certainly possible to create better models with more data. However, the fact remains that however well-developed the model, it is unlikely to provide an accurate estimate of charge size from crater diameter measurements in the absence of good information about the many factors that can affect the measurement in addition to charge size.

Note that the parameters described here are not comprehensive – that is to say, things may be even worse. We have not taken into account such factors as the type of explosive, or detonation method. In our tests we used a reliable electric detonation system with a booster, whereas it is known that improvised devices may use anything from simple blasting caps to knotted Detcord to anti-personnel landmine boosters. In addition, where we used C4 explosive, most events in theater use homemade explosives (HME). While HME has somewhat less explosive energy than C4, its softer equation of state should make it more efficient at coupling to the soil. This would be expected to result in a different relationship between explosive energy delivered to the target and that delivered to the crater, resulting in a different explosive efficiency [5,6]. These factors were not examined here, but would be expected to complicate the relations even further.

This is a somewhat disturbing conclusion, insofar as it flies in the face of assumed common knowledge. After all, it is known that the size of the crater is affected by the size of the charge. The work presented here absolutely confirms that fact. Why then, can't we estimate the size of the charge from the crater measurement?

An example may help to illustrate this problem. It is known that atmospheric temperature is strongly dependent on latitude – the farther north one goes, the colder it gets. However, that does not mean that it is possible to determine one's latitude by looking at a thermometer. Other factors, such as time of year, altitude, proximity to a coastline, and time of day also play a role. Knowing that the outside temperature is, say, 50° F, does virtually nothing to help determine one's latitude, unless all of the other factors are also known, in which case it's possible to put together a model that provides a reasonable estimate. Without knowledge of all the other parameters, the model is very inaccurate.

Note that such a model is not, at that point, useless – it is far worse than that. A useless model would provide no information. So, for example, given the measured crater lip diameter without associated data on charge shape, burial depth, and soil conditions, a useless model would decline to offer an estimate of the charge size. But a model that is used improperly would, instead, *provide an inaccurate estimate*. Keep in mind that these estimates are used to drive protection requirements for combat vehicles which need to survive in the current threat environment. Both over-estimates and under-estimates of charge sizes are hazardous in different ways. One can lead to a failure to deploy significantly improved vehicle designs (on the assumption that they're still not good enough), while the other can lead to acceptance of unsuitable vehicle designs.

Furthermore, such models can take the place of better estimates. In theater, for example, good statistics have been accumulated on "found and cleared" IEDs. This data shows the most prevalent charge size, and also the distribution of sizes and shapes, and the types of explosives and detonation mechanisms. The figure below shows one such collection of found and cleared threats, indicating the wide variety of charge sizes and shapes typically encountered.

Figure 15. Pile of found and cleared IEDs.

With this wealth of explosive resources, it would be straightforward to conduct simple testing to estimate the most common effective net explosive weight, and the effects of these different charges on a target. However, the existence of a charge size/crater diameter model obviates the need for the relatively simple testing of these found and cleared charges that would generate this valuable information. As a consequence, vehicle protection requirements may instead depend on a potentially inaccurate model.

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