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EFFECT OF SOIL PARAMETERS ON LAND MINE BLAST

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ABSTRACT

Protective equipment, either for personnel or vehicles, must be designed to mitigate the effect of a landmine blast. Landmines are found in all types of soil conditions; this research demonstrates that the energy released by a mine varies greatly with the soil conditions surrounding it.

For its ease of use and repeatability, testing of personal protective equipment (PPE) is often done in dry sand. Repeatability is essential when comparing various types of equipment (e.g., various demining boots); results from dry sand tests are more repeatable than tests done in wet, silty-clay type soil, however landmines detonated in dry sand transfer much less energy than landmines detonated in wet, silty-clay type soil. It is important to identify the worst-case scenario, that is, under what conditions a landmine will transfer the most energy to a target. Once this threat is identified, equipment can be designed to protect against it, and tests done in dry sand can be related to those worst-case soil conditions.

Tests were conducted with a simulated landmine in engineered soil containers where soil conditions could be carefully controlled. A target was attached to a piston apparatus, mounted above the soil container, and the energy transferred to the target was calculated from the height the piston jumped after the landmine was detonated. Variables included standoff, overburden, soil type, moisture, and density. Over 200 trials were performed. High density, high moisture soil conditions produced seven times the energy transfer versus dry sand conditions.

INTRODUCTION

According to the 1999 Landmine Monitor report from the International Committee to Ban Landmines, estimates on the number of buried landmines worldwide range from 60 to 110 million.¹ Landmines are indiscriminate: they injure children, adults, civilians, humanitarian deminers, and military personnel.

Military and civilian organizations have different approaches, resources, methods, and timelines for demining. However, they are similar in that they support research and development for mine action, and both must protect personnel and vehicles from landmine blast.^{2, 3, 4, 5, 6} The physics of a landmine blast are the same, regardless of the victim or target.

Anti-Tank (AT) and Anti-Personnel (AP) landmines may be either blast or fragmentation mines. The nature of the threat posed by blast mines is different from that posed by fragmentation mines: blast mines are designed to injure and maim; fragmentation mines are designed to kill. AP blast mines are responsible for the majority of deminer injuries.⁷ This investigation looks exclusively at blast from landmine surrogates.

To accurately develop protection systems for personnel and vehicles from a landmine blast, it is necessary to understand and quantify the method of energy transfer from the blast to the target. Underestimating the blast energy could result in an insufficient protection system. Conversely, if the blast energy is overestimated, the protection system may unnecessarily become too costly to produce, or too bulky to use.

It is well known that different soil characteristics affect landmine blast output.^{7, 8, 9, 10, 11, 12} The objective of the current investigation was to identify and quantify which soil parameters had the most significant effect on landmine blast.

Not only is it important to accurately assess blast output, it is also important to establish a testing standard to ensure repeatability across tests and to define a metric for comparison. The International Test and Evaluation Program for Humanitarian Demining (ITEP) and NATO are examples of organizations which establish testing standards.^{7,13} In 2001, the NATO Research and Technology Organization established a new Task Group to review how various countries test PPE against AP mines, and to recommend a course of action for future testing.⁷ The Task Group recommended medium sand as a standardized test soil.⁷

Good scientific research results are consistent and repeatable. Sand facilitates consistent and repeatable results. It is cost-effective, widely available, easily and well defined by a simple sieve analysis, easy to prepare for trials, and is thus often used in experiments with landmines.^{11, 12, 14, 18, 19}

The Royal Military College in Kingston, Ontario, Canada, was contracted to recommend a soil standard that would be globally recognized. Two options arose: the first was a well-graded loamy sand subjected to a specific compaction and with a specified water content; and the second, a well-graded sand with a specified grain size distribution.¹⁵ The first option was rejected because the identified soil could vary greatly within the given range. The second option was preferred; defining sand by specific grain sizes would allow various labs to mix identical soils. However, the recommended sieve sizes did not correspond to standard sieve sizes, and manufacturing the sand for the second option was prohibitively expensive.

In search of a cost-effective alternative, commercially available sands were compared to the recommended grain size distribution. Concrete Fine Aggregate Sand (CFAS) was chosen because it matched three points on the grain size distribution, was locally available, and cost-effective.

Soil is composed of various sizes of mineral and organic particles. According to the British Standard, there are several soil types: Clay, Silt, Sand, Gravel, Cobbles, Boulders, Organic, and Peat.²⁰ Soil types are defined by characteristics such as cohesion, plasticity, and particle size. The particle size ranges are listed in Table 1.

Table 1.

Type	Sub-type	Particle Size (mm)
Clay		< 0.002
Silt	Fine	0.002 – 0.006
	Medium	0.006 – 0.02
	Coarse	0.02 – 0.06
Sand	Fine	0.06 – 0.2
	Medium	0.2 – 0.6
	Coarse	0.6 – 2
Gravel	Fine	2 – 6
	Medium	6 – 20
	Coarse	20 – 60
Cobbles		60 – 200
Boulders		> 200

Most soils consist of a graded mixture of various sizes; soil characteristics are affected by the mixture. ‘Fine-grained’ soils consist mainly of clay- and silt-sized particles; ‘coarse-grained’ soils, consist mainly of sand and gravel sized particles.

Because several reports indicate that the blast output is greater in fine-grained soil than in coarse-grained soil, and Suffield prairie soil (PS) is fine-grained and abundantly available, prairie soil was chosen to compare to the CFAS. Compaction, consolidation, water content, and tri-axial tests were performed on a sample of the prairie soil. The major component of the prairie soil was clay; secondary components included some silt and trace sand. The prairie soil was characterized as medium plastic and brown. The maximum dry density was 1623 kg/m³, and the optimum moisture was 18.1%.^{16, 17}

Compared to the CFAS trials, prairie soil trials were much more labor-intensive and much more variable. The goal of this research is not to replace all sand trials, but to define the differences, and the effect of these differences on the energy transfer from a landmine to a target. Once these differences are identified, a relationship between the landmine energy transfer in CFAS and prairie soil can be defined.

PHYSICAL SET-UP

The piston apparatus consists of a steel target plate, a target mounting plate, a frictionless shaft, a linear voltage displacement transducer (LVDT), a pressure transducer, the piston stand, a platform spacer, and ten large cylindrical soil containers.

The target plate is 25.4 mm thick and 254 mm in diameter. Four 19.1 mm bolts are used to attach the target plate to the mounting plate. The mounting plate is 18.4 mm thick, 152.4 mm in diameter, and welded to the shaft. The shaft is 2.13 m long and 50.8 mm in diameter. The shaft of the piston slides through a cylinder with an inner diameter of 55.88 mm, and an outer diameter of 88.9 mm. Linier bearings inside the cylinder reduce the inner diameter to 50.8 mm and ensure that the piston motion is frictionless. The total mass of the target plate, mounting plate and shaft is 47 kg.

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Ten soil containers were prepared a day ahead of the trial; each steel container was 889 mm in diameter and 762 mm tall. The containers were filled with either dry CFAS or prairie soil. Prairie soil was tamped during the filling process. When the trial matrix called for wet CFAS, water was added to the CFAS container the morning of the trial.

After the topsoil was removed, prairie soil was excavated from the Suffield Experimental Proving Ground. Unless extremely dry or wet prairie soil was required, the prairie

soil fill was taken directly from the excavated pile. Water was added to the pile before tamping to increase the moisture percentage above 18%. In order to dry the prairie soil below 10% moisture, samples from the pile were kiln-dried then bagged; the containers were filled directly from the bags. The containers were tamped in layers; approximately 300 mm of loose soil was added to a container, then tamped to approximately 100 mm. The process was repeated until the container was full. The resulting soil consistency was very hard packed.

A forklift was used to place the soil containers directly under the piston on top of the platform spacer. The maximum number of trials shot in one day was twelve. Twelve shots create a lot of ejecta, which piles up around the soil container. The platform spacer provides a level surface above the ejecta, without which, ejecta would have to be removed between each trial, thus the platform spacer speeds up trial turn-around time.

For all trials, the surrogate landmine was 25 g C4, encased in plastic, with a height-to-diameter ratio of 35%. The charge was electrically initiated with an RP-87 detonator, and boosted with 2 g of detasheet. All charges were bottom-initiated.

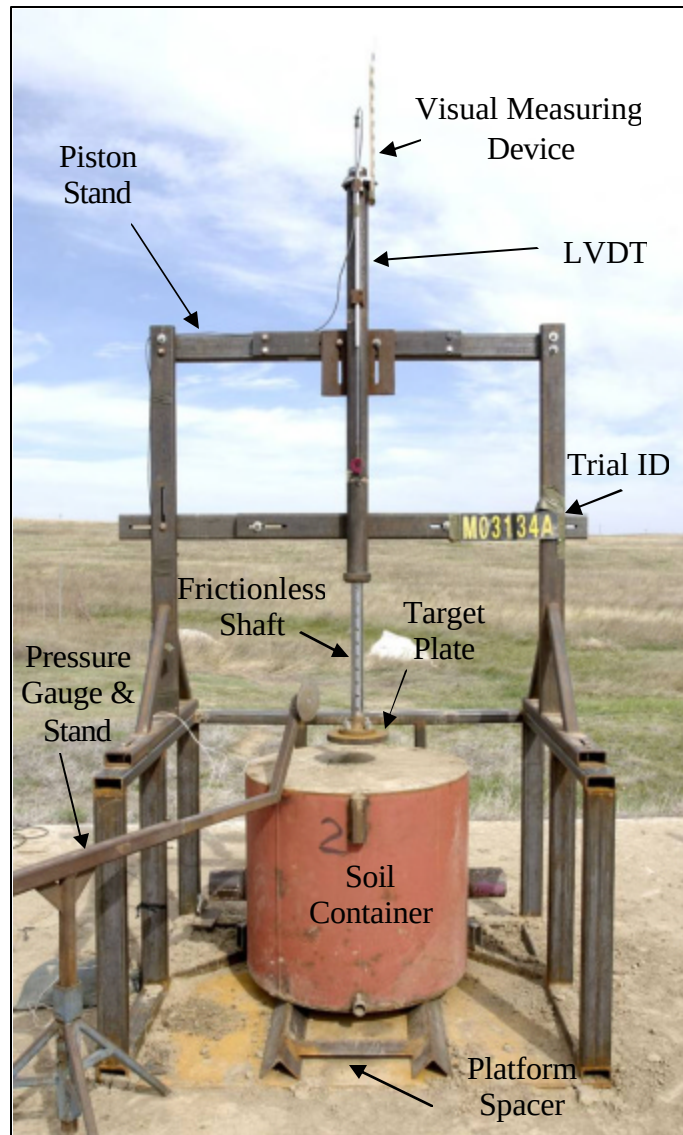


Figure 1. Piston rig

An LVDT was used to measure the height reached by the piston during the trial. A pressure transducer recorded side-on pressure of the blast.

Soil preparation for dry CFAS trials consisted of pouring dry CFAS into the soil containers and leveling it. Moving the soil containers from the preparation site to the trial site tended to compact the sand approximately 10-20 mm; when this occurred, more sand was added and leveled.

For wet CFAS trials, dry CFAS was added to the soil containers, until the level of the CFAS was 100 mm below the top of the container. The top of the soil container was then flooded with water and allowed to drain.

A water level indicator on the side of the buckets was used to measure the water table. Drainage through the sand was inconsistent. Even though all the soil containers were prepared in the same manner, with the same type of sand (often out of the same bag), the water level could not be predicted from the amount of water added. Since the water level indicator was not reliable, moisture readings were determined by a nuclear densitometer.

Two methods were used to prepare charge holes. With CFAS trials, the sand was simply dug out to the appropriate depth, the charge was put in place, and the sand replaced. The overburden (OB) was measured from the top of the charge to the top of the soil (which was level with the top of the soil container). Because the prairie soil was hard-packed, digging the charge hole was difficult. A 50 mm diameter copper pipe was used to dig the charge hole. After the charge was placed in the hole, prairie soil was used to fill the hole, however it was loosely packed. Seven different overburdens were tested: 0, 20, 50, 75, 100, 125, and 150 mm. Standoff (SO) (the distance from the ground surface to the target) was either 100 or 150 mm. In CFAS, the moisture range was 0.4 to 9.6%. In prairie soil, the moisture range was 5.3 to 22%. The ranges of dry and wet densities in CFAS were, respectively: 1361 to 1744 kg/m³ and 1409 to 1886 kg/m³. The ranges of dry and wet densities in prairie soil were, respectively: 1149 to 1867 kg/m³ and 1281 to 2092 kg/m³.

RESULTS & DISCUSSION

Effect of Moisture

In CFAS, at 100 mm standoff, as evidenced by the data spread in Figure 2, moisture had little effect on the energy transferred from the landmine to the target. As noted previously, the water in the sand containers was allowed to drain; the water table was never at the top of the container.

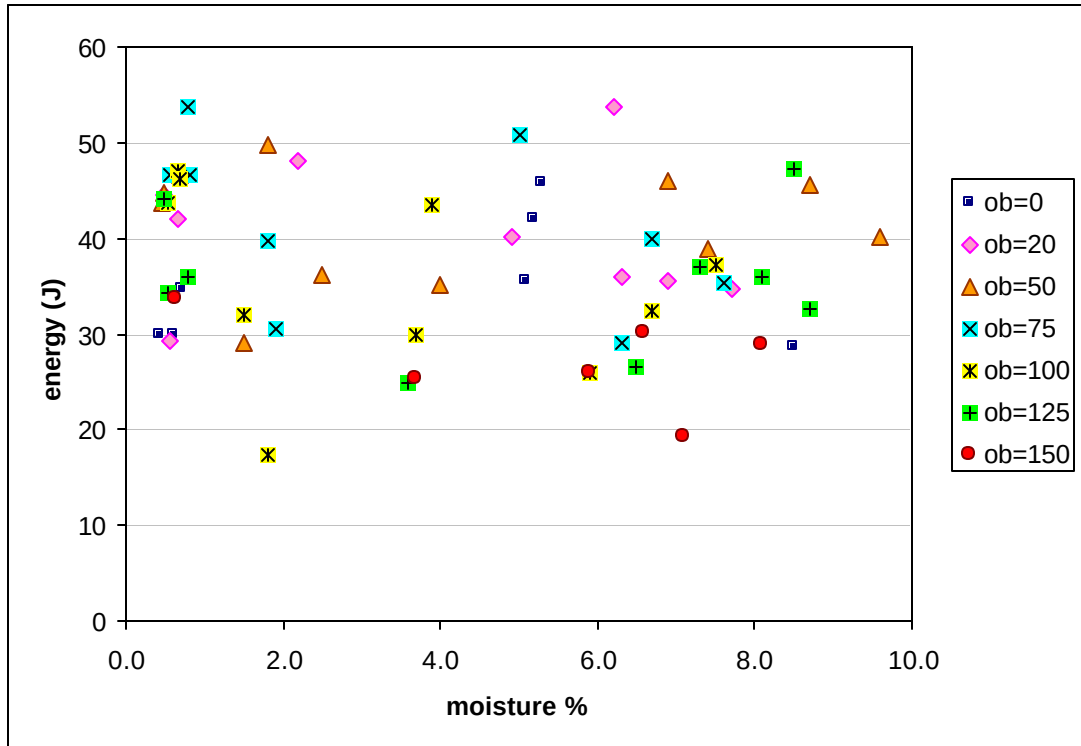


Figure 2. Effect of moisture on energy transfer in CFAS, for all overburden

In a 2002 scoping study, trials were done as a proof-of-concept for the piston rig. The main difference between the 2002 piston rig and the present version is the replaceable soil container. In 2002, the soil container was a built-in, 0.6 x 0.6 x 0.6 m cube in an existing platform. Since the container was part of the platform, the soil had to be prepared between each trial, and emptied by hand. This slowed down trial turn-around time considerably. Also, tamping of prairie soil was not possible in the 2002 rig. The small size of the soil container prohibited the use of the nuclear densitometer, thus moisture level was defined as either dried (< 1% moisture rating from the manufacturer), wet (water added but not saturated), or saturated (water pooling on the soil surface). Another reason for the modified piston rig was to increase the size of the soil container. In the original rig, as the charge was buried deeper, the energy transfer increased. It was not clear if the increase was a real effect, or an artifact of the small soil container. After a trial with an overburden of 100 mm, the top third of the soil container was empty; the container may have been focusing the blast upwards toward the target. The diameter of the new piston rig is 50% larger than the original rig. Because the small soil container may have affected the output of the 100 mm overburden trial, the data was not used for analysis.

Because the moisture readings were strictly nominal, the results of the 2002 CFAS trial show energy transferred to the target as a function of overburden rather than moisture content (Figure 3). Note: the saturated sand data point stands out; in this case, the soil container was filled with CFAS and water until the water pooled on the surface of the sand—there was no drainage. The maximum range of the LVDT was 460 mm which corresponds to 212 J. After the saturated sand trial, there was a small dent in the LVDT holder which indicated that the LVDT had been forcibly pushed past its maximum range. The actual energy transfer may have been significantly more than 212 J for saturated sand. To prevent further damage to the

rig, the saturated sand trial was not repeated. While the new piston rig is more robust, no trials have been done in saturated sand since it is too yielding to be either walked or driven on, thus saturated sand trials were deemed unrealistic. For 0 and 50 mm overburdens, average values of the energy transfer were comparable between the two piston rigs. (See Table 2.)

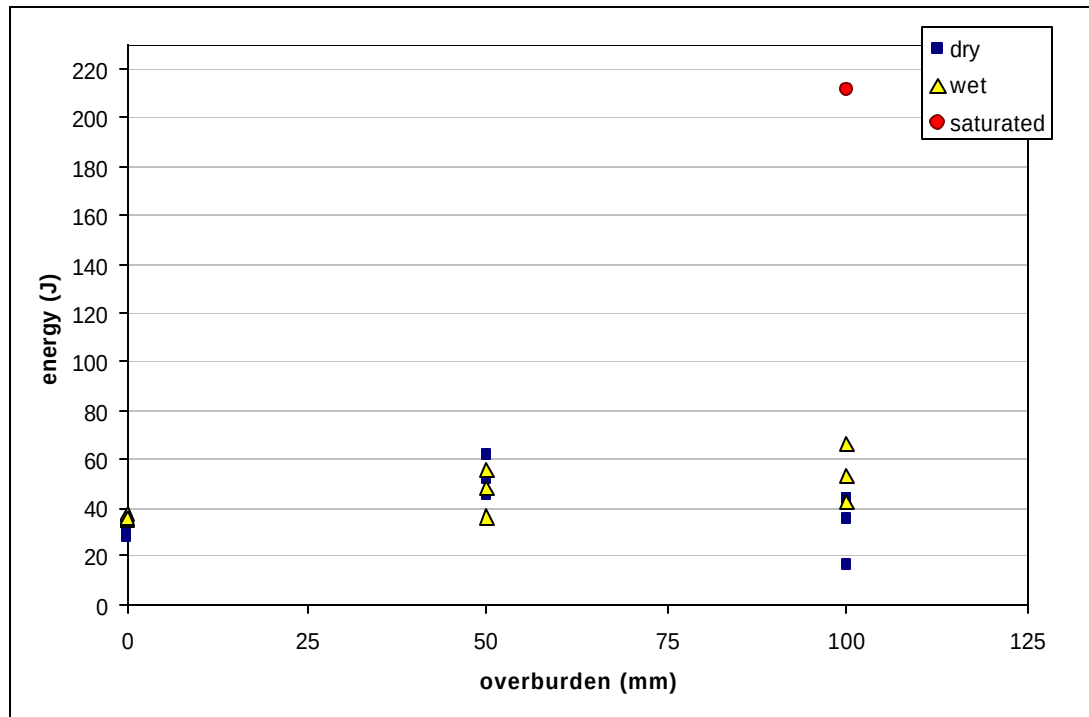


Figure 3. 2002 CFAS trial data

Table 2.

	Average Energy Transfer (J)			
	Original Piston Rig		Modified Rig	
	0 OB	50 mm OB	0 OB	50 mm OB
Dry CFAS	29	53	31	45
Wet CFAS	36	47	32	37

Effect of moisture in prairie

Unlike CFAS where the data is scattered, the effect of moisture in prairie soil shows an obvious trend of increasing energy transfer with increasing moisture. Figure 4 shows the data for selected overburden in prairie soil. This graph is presented to show the trends; the effect of overburden and moisture content are interrelated, and will be discussed shortly. The average energy transfer at 50 mm overburden and ~6% moisture in prairie soil is 36 J; at 50 mm and ~20% moisture in prairie soil, the energy transfer averages 186 J—an increase of 500%.

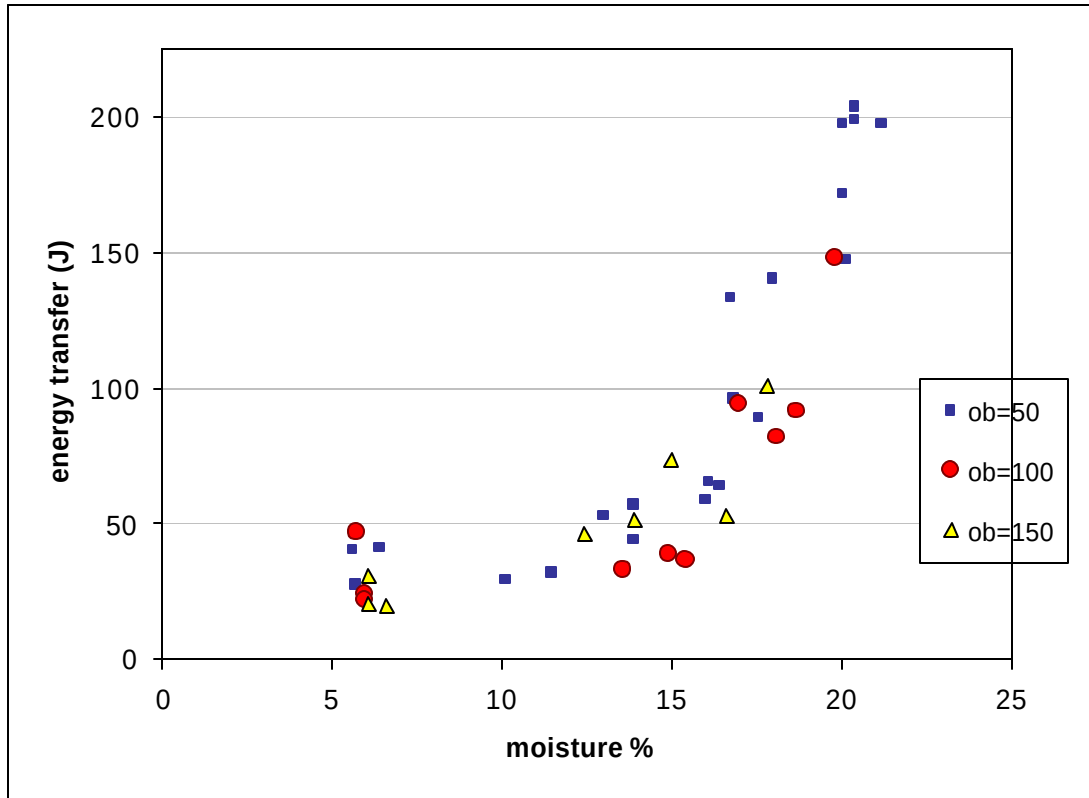


Figure 4. Effect of moisture on energy transfer in prairie soil, for all overburden

When CFAS and prairie soil are compared on the same graph, it appears that the effect of soil moisture on energy transfer follows the same trend for coarse- and fine-grained soils (Figure 5). However, this trend neglects the effects of ejecta which depend on moisture, overburden, and soil type.

Effect of Overburden

Held has done extensive research mapping the momentum distribution of AT landmines, in sand.¹⁸ Most of the damage results from momentum transfer from the sand to the target.¹⁹ Therefore the ejecta is a significant source for the energy transfer to the target.

When there is little or no overburden, the ejecta, and thus the energy transfer to the target, is reduced. Conversely, for large overburden, the soil is able to absorb a large amount of the explosive energy, and thus the amount of ejecta is reduced (in the extreme, an explosive buried deep underground does not produce any ejecta at all). Thus there exists an optimum overburden for energy transfer. The trend in Figure 6 indicates an optimum overburden, for 25 g of C4, in CFAS, to be about 50 mm.

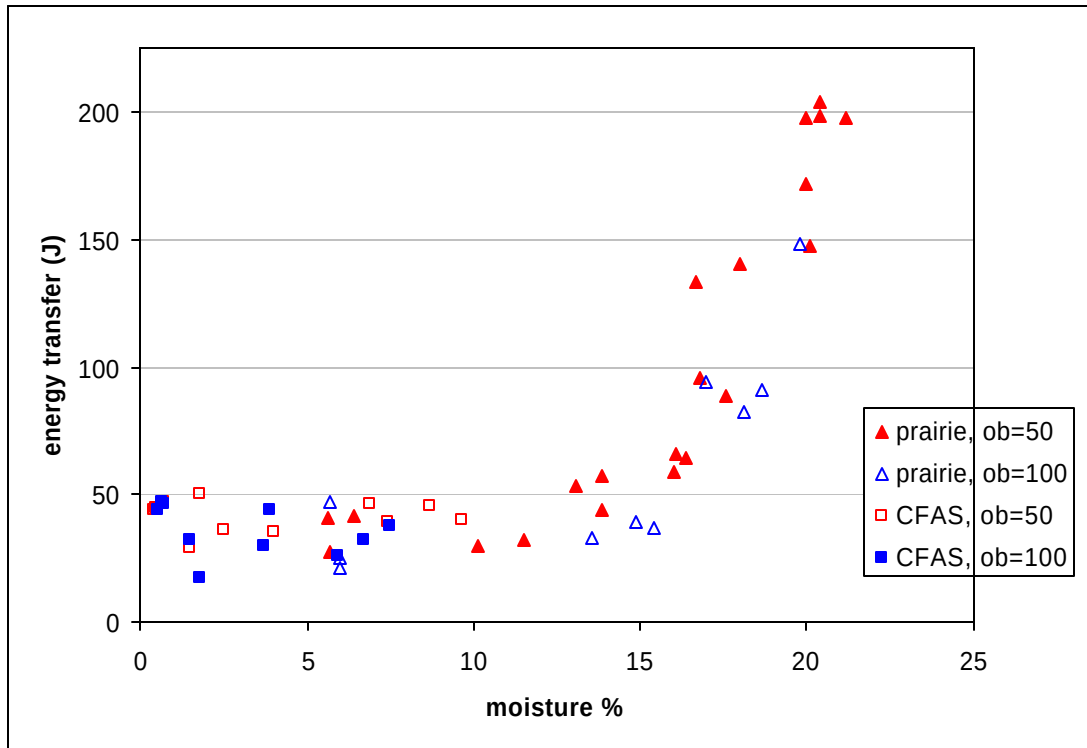


Figure 5. Comparison of moisture effects in prairie soil and CFAS

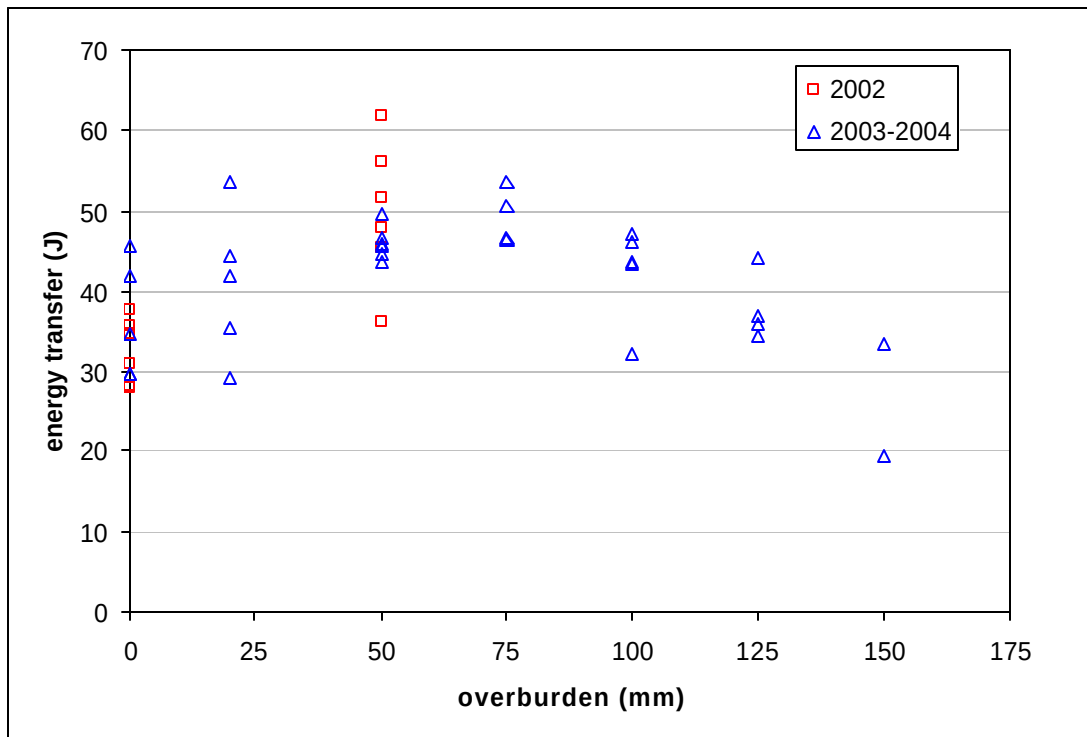


Figure 6. Effect of overburden on energy transfer in CFAS



Figure 7. Ejecta during a detonation with 75 mm overburden in CFAS

Cohesion in CFAS is very low; upon detonation of the landmine, the CFAS ejecta is fairly uniform. Comparatively, cohesion in prairie soil is much higher; as a result, large chunks of prairie soil stay together as they are ejected from the explosion. Figure 7 shows the detonation of 25 g C4 in CFAS with 75 mm overburden. Figure 8 shows a similar detonation in prairie soil—notice the large chunks of soil being ejected. In both CFAS and prairie soil trials, when no overburden is present, the detonation produces a fireball and a lot of dust, but less ejecta (Figure 9).

The amount of prairie soil available to be ejected depends on the overburden. The probability that large clumps of prairie soil will form depends on the compaction and the dry density of the prairie soil, as well as the moisture present in it. Moisture is necessary to hold the soil particles together. Without moisture, the dried prairie soil had a fine powder-like consistency. It was impossible to compact the dried prairie soil since the tamper merely blew the fine particles of prairie soil away. The majority of the prairie soil trials were compacted with a tamper; the exceptions were the dried prairie soil trials, as well as the three trials where the prairie soil was simply dumped into the soil containers. In the low-compaction prairie soil trials, the average moisture was 10.2%; this is a relatively low moisture content for prairie soil, but it is significantly higher than the 6.0% moisture content in the dried prairie soil. The relationship between prairie soil and overburden, for the standard prairie soil preparation trials, as well as the dried and low-compaction trials, is shown in Figure 10. Similar to the CFAS trials, the standard preparation of prairie soil shows an optimum overburden at 50 mm.

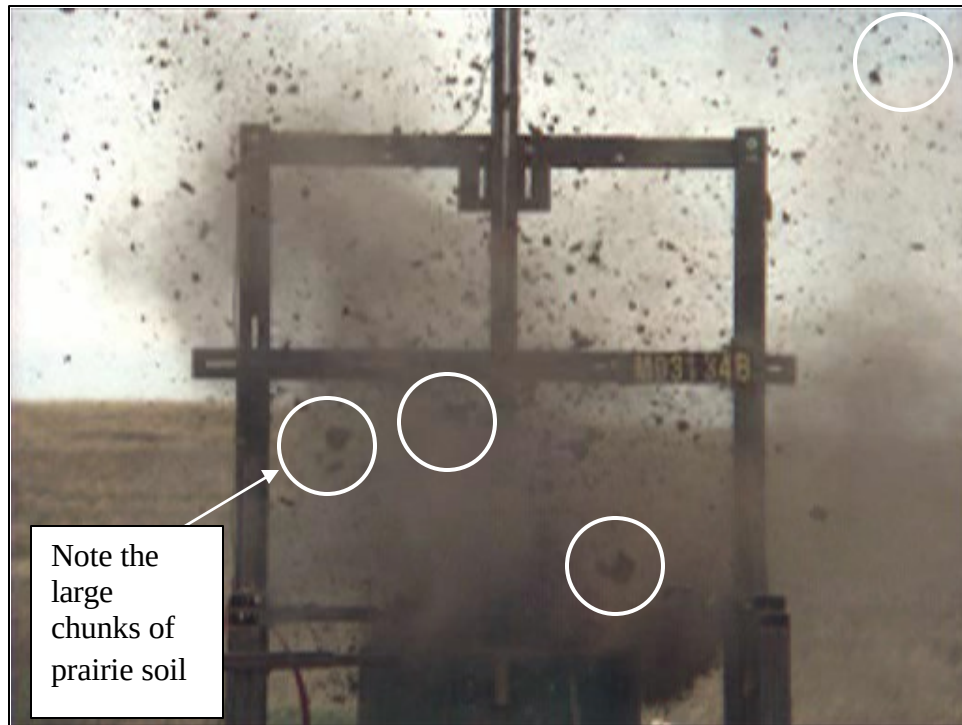


Figure 8. Ejecta during a detonation with 75 mm overburden in prairie soil



Figure 9. Fireball and dust cloud during a CFAS trial (0 OB, 150 mm standoff)

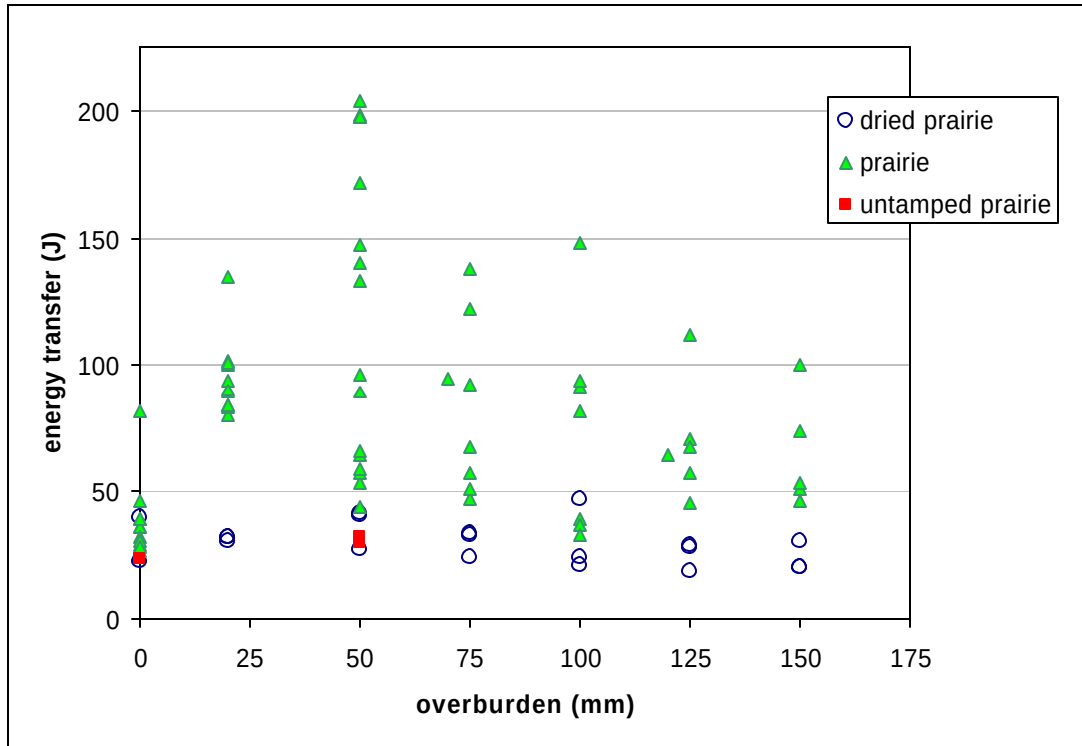


Figure 10. Effect of overburden on energy transfer in prairie soil

Dried and low-compaction prairie soil samples transfer very little energy to the target. Since energy transfer is a function of momentum, the low dry densities mean that there is less mass available to generate momentum. The average dry density of the standard prairie soil is 1517 kg/m^3 ; for dried and low-compaction prairie soils, it is much lower (1324 kg/m^3 and 1168 kg/m^3 respectively).

Effect of standoff

Compared to the distribution of prairie soil ejecta, CFAS ejecta is quite uniform. The distribution of prairie soil ejecta is composed of all sizes of particles, randomly distributed in the ejecta cloud. Using high-speed video, two large pieces of prairie soil were tracked. One piece had a volume of approximately 0.000024 m^3 , and had an estimated velocity of 9 m/s ; the other piece was 0.000048 m^3 , with an estimated velocity of 57 m/s . Estimating the prairie soil density at 1500 kg/m^3 , the mass of the first piece was 36 g , and the second was 72 g . The kinetic energy of each piece was 1.5 J and 117 J . The pieces of prairie soil ejecta carry significant energy, however not every piece strikes the target, thus there is variability in the data for the prairie soil trials. The ability to track large pieces of the prairie soil was a serendipitous discovery. As it was unplanned, and due to the random nature of the prairie soil, the velocity tracking data are qualitative only. A quantitative study could be undertaken to precisely determine the velocity of a wide number of prairie soil ejecta pieces, and then compare this velocity to the expansion velocity of the sand ejecta. (For evaluating the importance of standoff when designing PPE, this information would be invaluable.)

The effect of standoff (SO) in CFAS is shown in Figure 11. Regardless of overburden, all but two of the trials at 100 mm standoff transfer more energy to the target than any of the trials at 150 mm standoff. Increasing the standoff by 50% results in an average of 60% less energy transferred to the target.

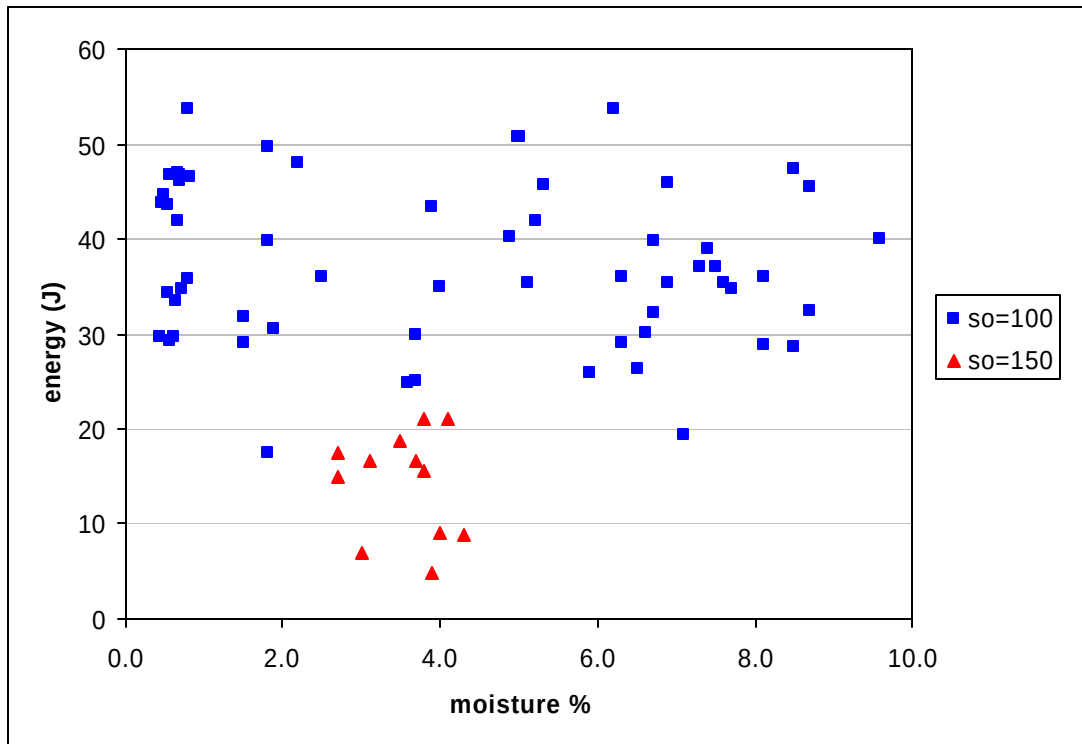


Figure 11. Effect of standoff in CFAS

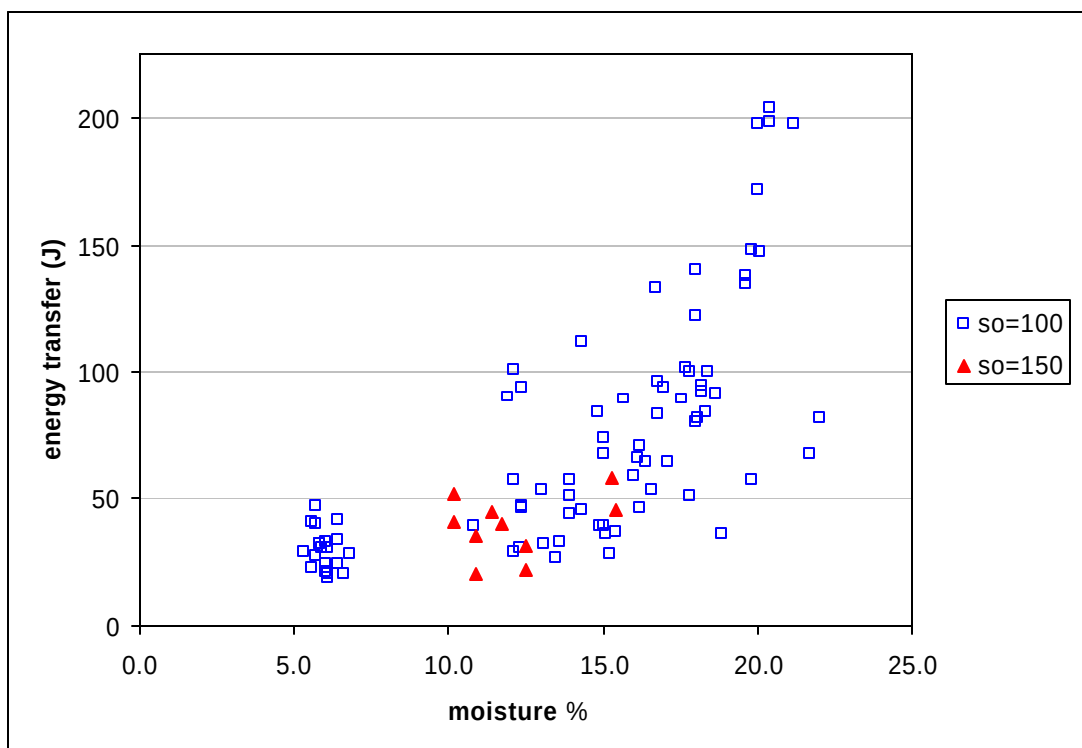


Figure 12. Effect of standoff in prairie soil

Unlike the obvious effect of standoff in CFAS, increased standoff in prairie soil does not result in any difference to the energy transfer. In Figure 12, the data from the prairie soil trials at 150 mm standoff are embedded in the midst of the data from the 100 mm standoff trials. While only 10 trials have been completed at 150 mm standoff, and in a limited moisture range in prairie soil, the result is significant. Standoff is generally considered to be the most important criterion when designing PPE; nonetheless, this result indicates the importance of defining a testing standard that considers all types of soil, particularly soil types that contain clumps and stones that could become deadly projectiles. Further tests are required to establish trends across all moisture levels.

Gupta has numerically investigated the loading on a vehicle floor plate from a 10 kg TNT landmine explosion.¹¹ To define the widest possible range of the influence of the soil, Gupta used two different soil types, saturated tuff and dry sand. Findings indicated a peak differential in the momenta transfer 25-30% higher in wet tuff than in the dry sand.

To find the widest possible range in the piston data, the maximum and minimum energy transfer trials for each soil, at each overburden, are plotted in Figure 13. Defining the range is very important for scaling. At 50 mm overburden, the minimum energy transfer in CFAS was 30 J, and the maximum energy transfer in prairie soil was 204 J. The output in wet prairie soil was 6.8 times higher than in CFAS.

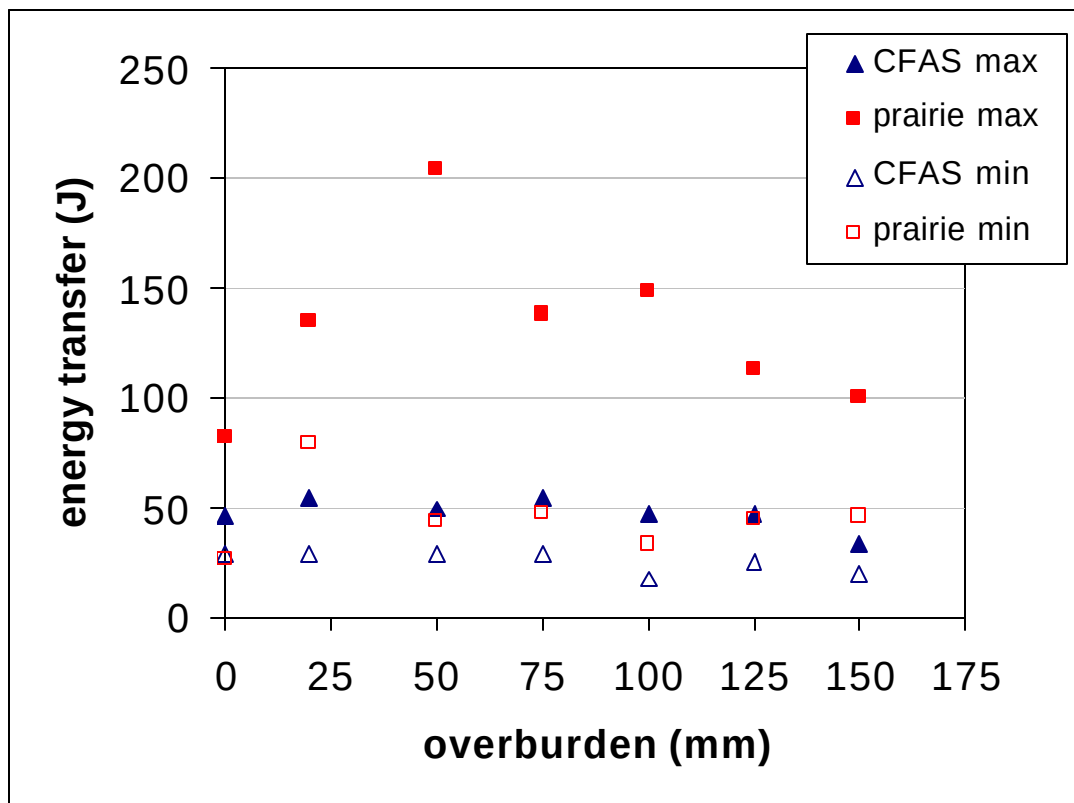


Figure 13. Maximum and minimum energy output in prairie soil vs CFAS

CONCLUSIONS

The data indicate that the loading resulting from the detonation of a landmine buried in a high moisture content, silty-clay, is significantly greater than the loading resulting from the detonation of a landmine detonated in dry sand. Fine-grained soil preparation is labor intensive, and results obtained when using such soil are more variable than those obtained using well-defined, consistent, sand.

The charge size—25 g of C4—is at the low end of the range for AP landmines, and is considerably smaller than the average size of an AT mine. The optimum overburden for both CFAS and prairie soil trials was 50 mm. Other charge sizes should be investigated to determine scaling laws.

Through high speed video, it was possible to track large pieces of prairie soil ejecta and thus estimate the mass and velocity of the ejecta. Future work should compare the velocity of the ejecta of different soils. A more accurate method for estimating the mass of the particles is required. Due to the dusty nature of a landmine explosion, video is often obscured. Bergeron had success using a flash x-ray technique to map out the explosive cap.⁹

Future research should include more standoff distances across a wider range of moisture contents. The present study showed that standoff was effective in CFAS; a 50% increase in standoff produced a 60% reduction in the energy transfer. In prairie soil, increased standoff offered little benefit because the velocity of the pieces of ejecta did not decay as quickly as the velocity of the blast wave.

Prairie soil was used as the representative fine-grained soil. The major component of prairie soil was clay. Other soil ratios and mixtures (e.g., sand-silt, sand-gravel, etc.) may facilitate a different energy transfer than either sand or clay. For example, the high density of the large gravel pieces in roadbeds, could result in ejecta particles with considerable kinetic energy.

This study indicated that a landmine detonation in wet prairie soil transfers five times as much energy to a target than a detonation in dry prairie soil. A landmine detonation in wet prairie soil transfers seven times as much energy to a target than a detonation in dry CFAS. Because it is easy to use and facilitates repeatability, sand will likely continue to be the medium of choice in landmine blast trials. In order to define a correlation between blast output in fine- and coarse-grained soils, more research is required.

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