DAMAGE CAUSED BY SOIL DEBRIS EJECTED FROM BURIED ANTI-PERSONNEL MINES

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Abstract

Many traumatic upper body injuries to deminers are caused by debris generated by anti-personnel (AP) blast mines. This study better characterizes the soil ejecta threat from buried anti-personnel mines and provides an improved evaluation of light upper body protection systems by relating the threat to resultant damage to soft tissue simulants. For each tested soil type, ejecta characterization parameters include particle size distributions and velocities. Soft tissue simulant test results are presented.

1. Introduction

Injuries caused by debris from AP blast mines are common for deminers [1]. Penetrations and abrasions by debris, alone or in combination with blast overpressure, may cause infections, vascular injuries, damage to internal organs, and superficial injuries.

The International Mine Action Standard (IMAS) 10.30 [2] on personal protective equipment (PPE) recommends that, to protect against debris ejected from anti-personnel (AP blast mines), deminers' body armour must meet the STANAG 2920 ballistic limit (V_{50}) rating [3] of 450 m/s using 1.1 g (17 gr) fragment simulating projectiles (FSPs). The 1.1 g FSP, a chisel-nose steel cylinder (Figure 1), is the most common shrapnel surrogate used to evaluate the performance of military fragment resistant jackets and helmets. The recommendation should assure that deminers' PPE provides a minimum level of protection against ballistic fragmentation threats. However, penetration by the FSP through the armour does not necessarily represent the damage caused by the fragments from an AP mine blast (which consist mostly of soil and environmental debris).

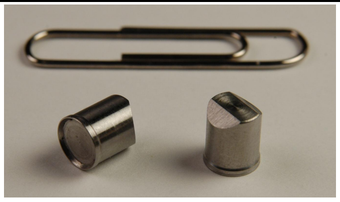


Figure 1. FSP (1.1 g)

The IMAS 10.30 also recommends that frontal PPE should protect against the blast effects from 240 g of TNT at a minimum distance of 30 cm. However, the IMAS provides no guidelines for the parameters to be used in such blast tests, yet varying some parameters could have significant effects. For example, Hlady has shown that soil conditions greatly affect test outcomes: in certain soil conditions , up to seven times more energy was transferred to the target than in standard dry sand[4]. The NATO Test Methodologies for assessing PPE performance against AP mine blast recommend standardized test parameters, including the use of Hybrid III mannequins and upper body injury criteria based on primary injury (from overpressure) and blunt trauma [5]. Tests conducted using these parameters have shown that some protective equipment does effectively reduce overpressure and receive low AIS Injury scores for blunt trauma. However, no test method exists yet that assesses the potential soft tissue injury caused by AP blast mine debris, despite the fact that many injuries caused by AP mines are from debris.

There is no sure evidence that the 1.1g FSP accurately mimics the soil ejecta threat, nor is there a defined blast test to assess penetration injuries. This study seeks to: a) better characterize the soil ejecta threat from buried anti-personnel mines and b) provide recommendations for potential evaluation methods using soft tissue simulants to assess upper body deminer protection systems against the secondary fragmentation threat.

2. Materials and Methods

For all trials in all test series, 100 g of Composition 4 (C4) – a charge size representative of larger AP blast mines – was packed in Dupont Adiprene® containers, bottom-initiated with an RP-87 detonator, buried at the centre of the soil container and covered with 20 mm overburden.

Two types of soil – dry 20/40 sand and semi-moist, compacted 20 mm crush gravel – were used for each trial series (Figure 2). Dry 20/40 sand was selected since it is used for the NATO test protocol; 20 mm crush gravel was chosen since it contains some larger projectiles and is a soil more representative of conditions found in most minefields. The 20 mm crush gravel was compacted prior to each trial, and wet densities were measured.

20/40 Sand

20mm Crush gravel

Figure 2. Charge placement in each test soil

2.1 Soil Characteristics

Two different test series were conducted to determine the size distribution and velocities of particles in soil debris ejected from an AP blast mine.

2.1.1 Size Distribution and Masses of Soil Debris

To determine the size distribution of the soil debris generated by the explosion, the charges were detonated in an enclosed, blast-resistant chamber. A clean, polyvinylchloride plastic sheet was laid on the floor's surface prior to the trials and cleaned thoroughly between each trial. A soil container was placed in the center of the chamber. Three blast trials were conducted for each type of soil. After each trial, the sand or gravel was collected for sieve analysis, hydrometer analysis, and apparent relative densities.

2.1.2 Velocity of Soil Debris

The range of particle velocities was determined using a radar antenna unit, with a transmitter frequency of 35.463 GHz, mounted on a wall of concrete blocks (Figure 3). To minimize vibrations, the microwave reflector was attached to a rigid frame.

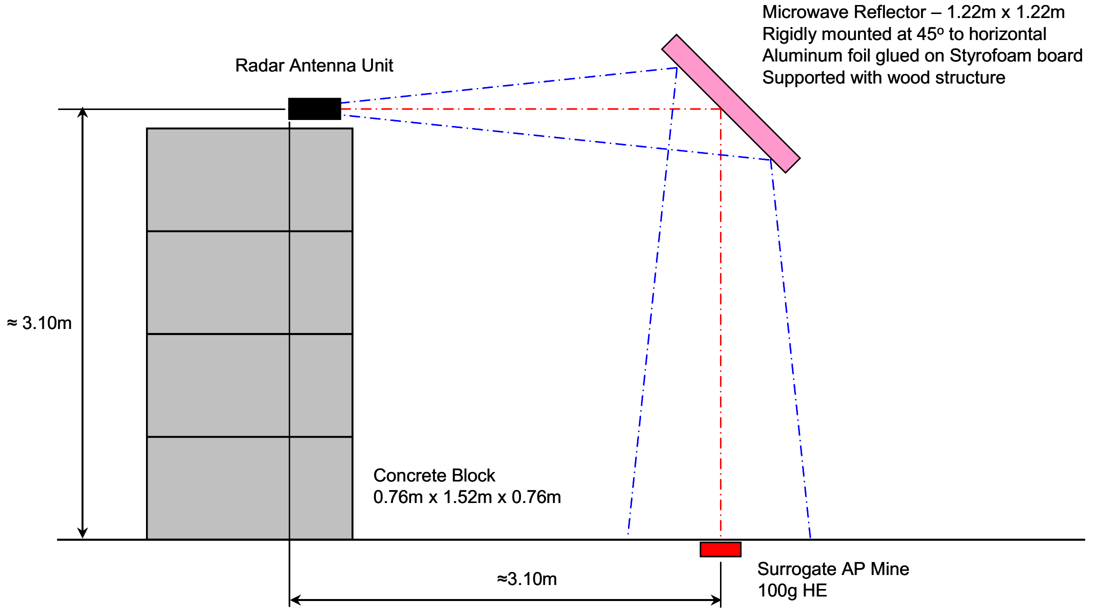


Figure 3. Radar configuration.

Doppler radar signals were analyzed using Infinition Inc. TestCenter Software Version 5.0.11 and their module of spectral analysis currently under development. A Fast Fourier Transform size of 1024 and an anti-aliasing filter were used. Each trial was also recorded with a high-speed digital camera to validate the radar measurement technique. Depending on the sunlight available, the frame rate was between 3000 and 8000 fps. Maximum upward velocities were calculated from images recorded during the first millisecond. One crush gravel trial and three sand trials were conducted.

2.2 Evaluating the response of Soft Tissue Simulants against AP mine blast

Workable test standards demand consistency, repeatability, and ease of use. Biological tissue accurately reflects reality but provides non of these, and is therefore a poor test standard. For instance, frozen tissue, tissue experiencing rigor mortis, or tissue that has decayed a great deal have different material properties from live tissue. Since injury-causing particles must encounter both skin and tissue, a test standard must include both, and must be validated with biological tissue. Over 20 synthetic materials were evaluated. While many materials may have had suitable mechanical properties, most requiring pour and cast manufacturing were not considered as there is often more variability within a given specimen and many of their mechanical properties are more temperature dependant. Three soft tissue and two skin simulants were selected. These materials, along with the biological and synthetic materials studied by Jussila [6] and Martin [7], are listed in

Table 1. The final five materials are those used in the current test series. Martin [7] suggests that the theory of rubber elasticity will be similar between neoprene rubber and human skin, so suitable neoprene materials were selected for both skin and flesh simulants to observe response against the soil ejecta threat. A vinyl nitrile was selected as an option because it offered similar mechanical properties to neoprene rubber but with a different material composition. For flesh, a silicone rubber was selected based on success obtained with this material in previous work [8]. Ballistic gelatin was also included since it is the accepted standard for flesh simulant in ballistic testing. The mixture of gelatin used was 30% (by weight) to provide a greater tolerance to temperature change in comparison with mixtures having lower gelatin content, i.e. 10% or 20% because tests were conducted outside when large temperature variations were expected (winter). 30% ballistic gelatin at 15°C has the same bloom strength as 10% and 20% mixtures at 4°C and 10°C, respectively.

Table 1. Properties of biological and synthetic skin and soft tissues.

Material	Use	Density (g/cm^3)	Thick. (mm)	Hardness	Elongation (%)	Tensile Strength (MPa)
Thigh Muscle (Human) [6]	-	1.03	-	-	-	-
Skin (Human) [6]	-	-	-	-	65	18
Skin (Bovine) [6]	-	0.56	1.0		61	21
Neoprene Rubber[7]	Skin	-	-	45-55 (Shore A)	-	-
Vinyl Nitrile (VN600)	Skin	0.1	1.6	-	150	1.0
Neoprene Rubber	Skin	1.41	1.6	70 (Shore A)	200	6.9
Neoprene Foam	Flesh	0.10	9.5	50 (Shore OO)	150	0.69
Silicone Rubber	Flesh	0.20	9.5	-	150	0.34
Ballistic Gelatine (30%)	Flesh	1.03	9.5	3-5 A	-	-

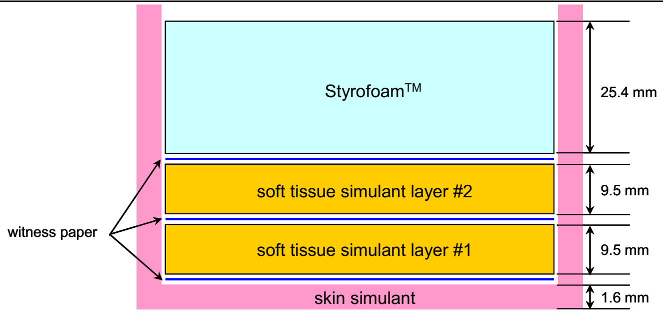


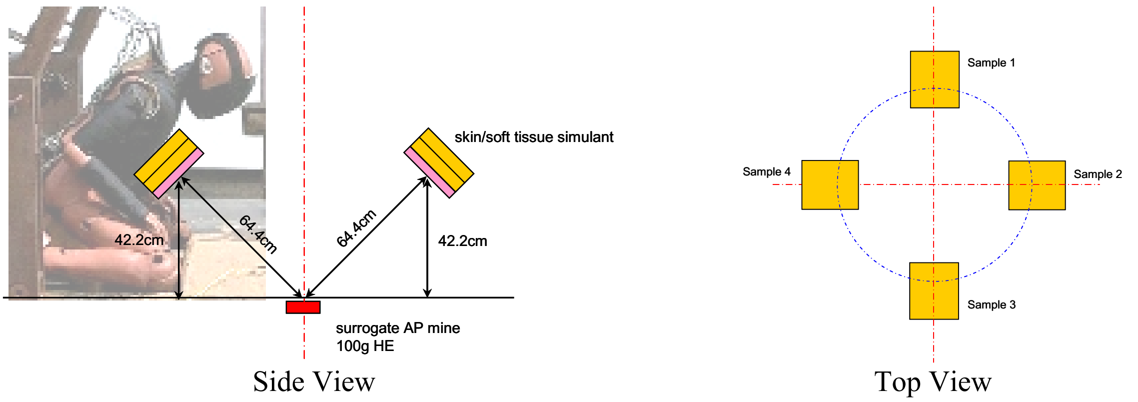
Figure 4. Sample configuration.

A skin thickness of 1.6 mm (1/16”) was selected based on bovine skin used in ballistic research. To determine whether or not particles could potentially damage internal organs, the thickness of one soft tissue simulant layer was 9.5 cm (3/8”), just over the minimum skin-to-organ distance demonstrated in the development of a test standard for stab resistant body armour [9]. Witness paper (Polyart^{TM}) was placed between several layers to record penetration at known depths (Figure 4). Each of the soft tissue simulant samples was cut into 14.6 cm squares arranged in the configuration shown in Figure 4, and held down with a tin frame bolted to the rigid support. The frame construction allowed for analysis of the center 12.1 cm x 12.1 cm area.

Four swine tissue samples (with skin, tissue, and ribs) were also tested in 20 mm crush gravel for preliminary validation of the surrogate materials. All swine tests were approved by the Defence Research and Development Canada – Suffield Animal Care Committee. The location of swine tissue removed (Figure 5) was selected by a swine research specialist as the location where the skin and tissue was most similar to the human chest. The samples were removed and placed in a fridge for approximately 18 hours after the swine were euthanized. The goal was to use the tissue once it had begun to relax after rigor mortis, but before much decay began.

Figure 5. Location of swine tissue removed

Four tests of each combination of soft tissue and skin simulants were performed in each soil. All tested samples were placed on rigid supports at a height of 42.2 cm and an angle of 41° (Figure 6), approximating the chest position of a kneeling deminer [8].



Side View

Top View

Figure 6. Soft Tissue Simulant Test setup.

Witness papers, skin simulants, and soft tissue simulant materials were analyzed together. All penetrations were traced onto transparencies using a 0.4 mm pen. If pieces of debris remained embedded (Figure 7), the actual size of those pieces was traced. The smaller holes – those having a minimum dimension of 1cm – were traced; in the case of larger holes, where sections of paper were completely missing, the remaining area was traced and normalized. Cracks originating from a single point indicated a penetration which was also traced. Tears were not traced. As there were no witness papers embedded in the swine samples, a plastic pipet was used to locate penetrations at depths of approximately 1.6 mm or more. Tests were discarded when most of the witness paper was missing.

All transparencies were scanned as greyscale images with a resolution of 600 dpi. Using the UTHSCSA ImageTool Version 3.0, dust and noise was minimized by filtering out objects less than 0.0127 cm (3 pixels at 600 dpi) and greytones that ranged from 131 to 255 (the lighter range), leaving traced penetration marks for analysis (the darker range of greytones from 0 to 130). Numbers of penetrations and average penetration areas were determined.

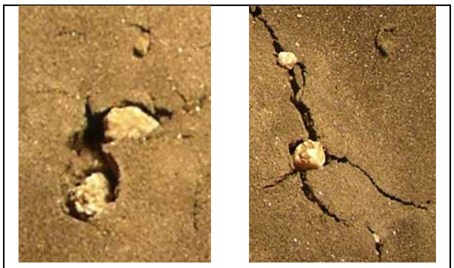


Figure 7. Examples on one sample of debris still embedded in soft tissue simulants.

In addition to the analysis described above, the swine samples were evaluated by a trauma surgeon. General observations were noted and AIS injury scores determined.

3. Results

3.1 Soil Characteristics

3.1.1 Size Distribution and Masses of Soil Debris

The particle size distributions, determined from sieve and hydrometer tests, for all 20/40 sand and 20 mm crush gravel test samples before and after blast are shown in Figure 8. Between test samples, the analyses of the 20/40 sand are more consistent than the 20 mm crush gravel as expected. In both the 20/40 sand and 20 mm crush gravel tests, there are more fine particles after blasting than before. Both before and after blasting, crush gravel contains a larger range of particle sizes, and a larger of very fine particles, than does sand.

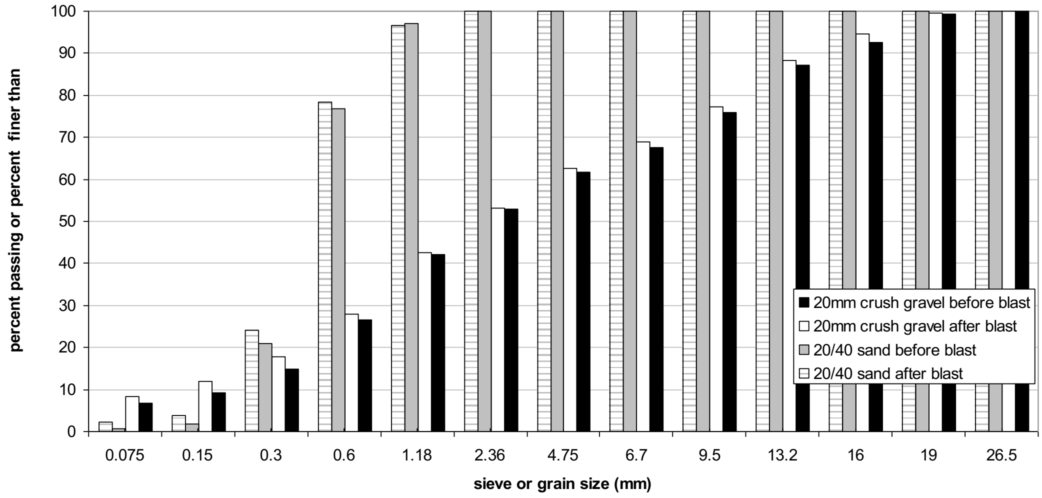


Figure 8. Particle size distributions from sieve and hydrometer tests.

On average, the total mass of sand particles ejected was 308 g whereas the total mass of crush gravel ejected was 10,351 g – 33 times more. Average particle masses in each sieve size were approximated using the average apparent relative densities and assuming all soil particles were spherical (Figure 9).

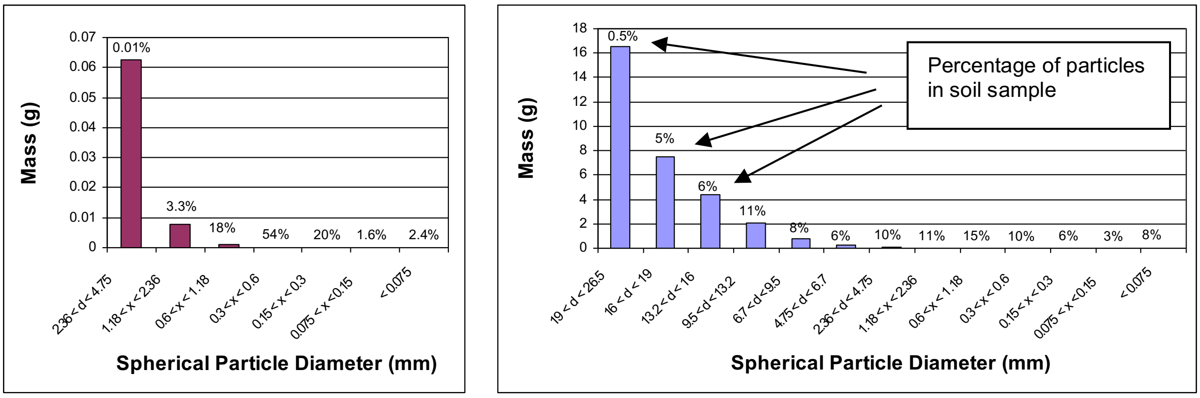


Figure 9. Approximate mass distribution of sand (left) and crush gravel (right)

3.1.2 Velocities of Soil Debris

The signal traces obtained with the radar system provide a range of velocities for the cloud of particles first launched from the blast and show a rapid decay of velocity for both soils. The maximum initial vertical velocities (just after the blast) were estimated from the intensity spectrogram (Figure 10). Values varied between 1000 and 1275 m/s for the two soil types (Table 2). As suggested by the radar manufacturer, a 50% signal strength was defined as the threshold required to estimate particle velocity . To assess the suitability of a radar system, peak velocities obtained from the radar and high speed video are compared (Figure 11). The video analysis typically over-estimated peak velocities of particles compared to the radar by 15%, on average.

Table 2. Maximum Initial Vertical Velocity

Soil type	Vertical Speed (m/s)
20/40 sand	1050-1275
20 mm crush gravel	1000-1200

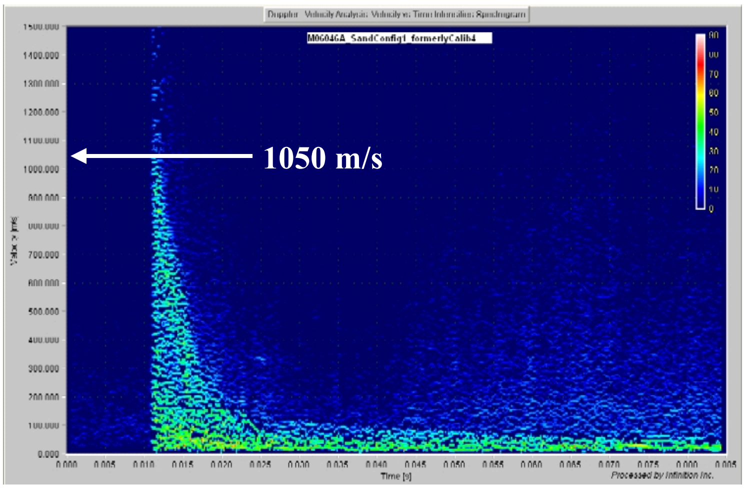


Figure 10. Intensity spectrogram, 20/40 sand.

The time histories for both measurement systems are compared (Figure 12). Because video measures the speed of the leading edge along the trajectory, the speed decays faster than that recorded by radar, which measures faster moving particles both behind and alongside the leading edge. As a result, it is appropriate to compare only maximum speeds estimated by each system.

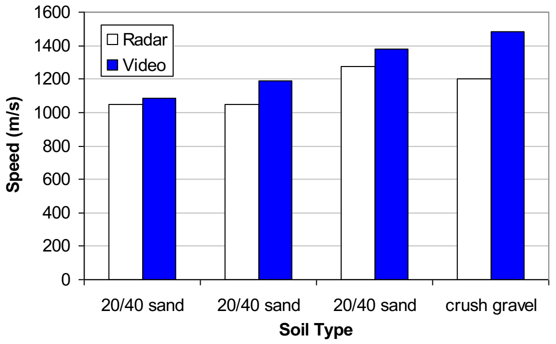


Figure 11. Comparison of initial peak velocities.

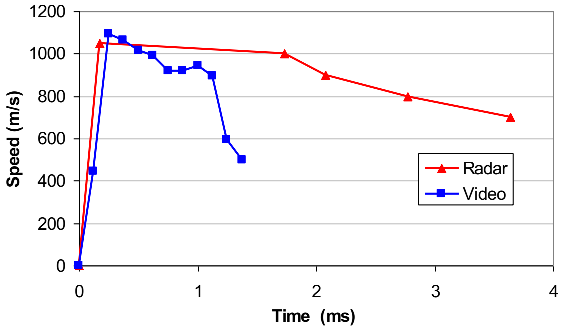


Figure 12. Comparison of velocity time history.

Signal saturation was observed for some radar tests, especially in crush gravel, which may result in an overestimation of measured velocities. High frequency signals emitted by the charge detonation may also distort initial peak velocities. However, velocity estimates obtained with high speed photography were similar to those obtained using radar, and values obtained were sufficient to estimate a range of velocities as a function of time. As only one trial was conducted for gravel, results are preliminary. Future tests with an altered test setup (to reduce signal saturation) are required.

3.2 Response of Skin/Soft Tissue Simulants

The number of penetrations and mean penetration area were determined from the witness paper analysis. The total penetration area was computed then divided by the analysed area giving a penetration value (area of penetration per total area). Penetration values for repeated tests were averaged. Figure 13 compares the response of all combinations of skin/soft tissue simulants against the different soil types. Bubble size is proportional to the penetration value. In all tests, the vinyl nitrile skin simulant had a greater penetration value than neoprene rubber, indicating that vinyl nitrile is more susceptible to damage in all conditions. For each soil type, the response of both skin simulants is dependant on the tissue simulant and vice versa. The neoprene rubber skin had very little damage (a low penetration value) in the sand trials. When combined with vinyl nitrile, the neoprene foam had penetration values that were much greater than the ballistic gelatine and silicone. Against the sand, these two materials showed little or no damage on either layer.

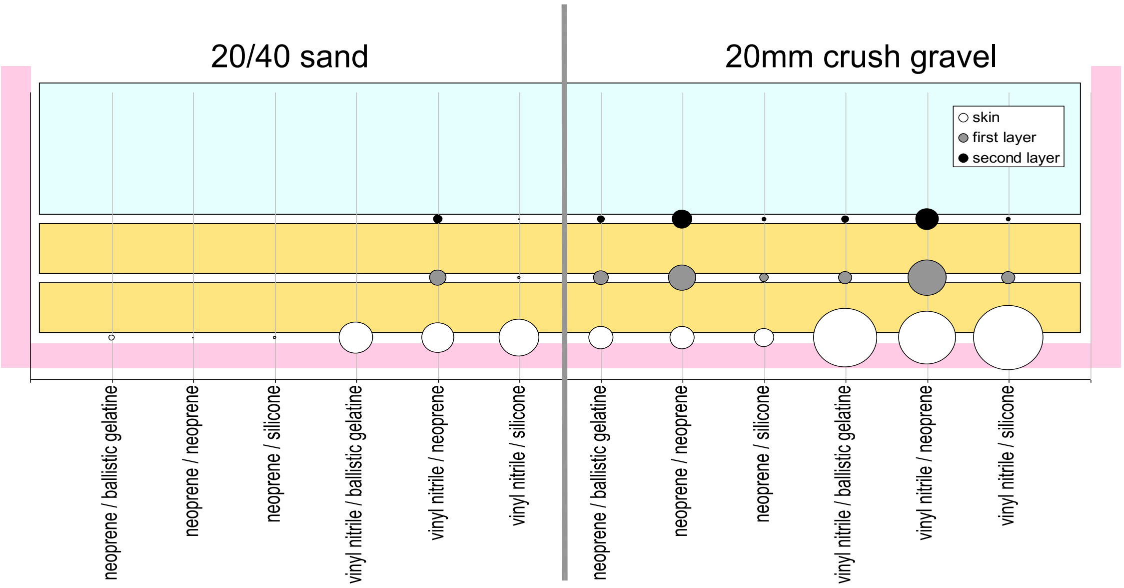


Figure 13: Relative comparison of penetration resistance for the skin/soft tissue simulants

The response in gravel of skin simulants / backing materials was compared with that of swine tissue (Figure 14). Vinyl nitrile had much higher penetration values than both neoprene rubber and swine skin, but neoprene rubber had penetration values very similar to the swine skin. However, the number of penetrations per cm^2 was slightly higher in the swine skin than the neoprene rubber, and the average penetration size was smaller (Figure 15). These results indicate that the neoprene would slightly underestimate the injury seen in swine, and the vinyl nitrile would greatly overestimate the injury.

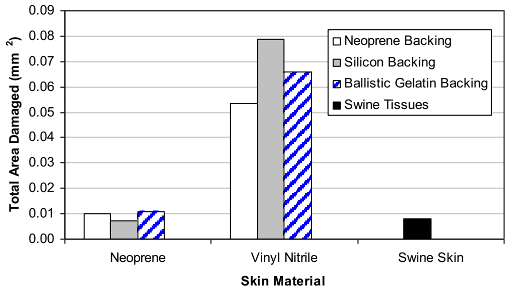


Figure 14. Comparison of skin simulant and swine tissue pe

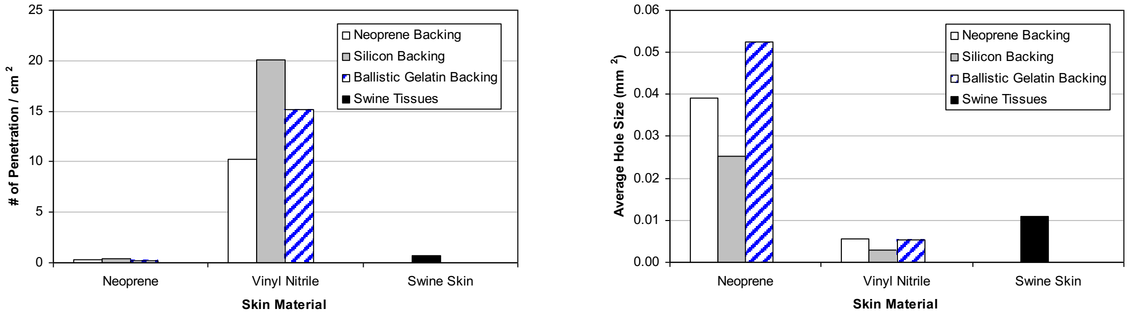


Figure 15. Comparison of skin simulants and swine tissue response to crush gravel: a) number of penetrations (left) and b) average hole size (right).

Swine tests evaluated by the trauma surgeon showed AIS scores from 1 to 3. Less severe cases were described as having much "tattooing" on the skin (like that seen in motorcycle accidents) which would not cause much, if any, infection. More severe cases showed broken ribs which would have caused internal haemorrhages. In one case, the soil ejecta penetrated the skin, tissue, and ribs, and punched a hole in the wood behind, indicating the possibility of organ damage (and possibly a higher AIS injury score).

4. Discussion

Blasted soils contain similar particle sizes to unblasted soils, but the blasted soils generally have more of the small particles. Such particles are so fine that they could pass through the weave of typical protective fabrics, like aramid fibers. This is an important aspect since standard body armours are not optimized against this type of projectile. Fall [10] showed that sand penetrated past several plies of Kevlar when tested against buried 100 g C4 surrogate mines. The addition of a backing material to the PPE in a blast test would allow evaluation of whether or not damage has occurred from small particles. Two types of backing materials could be selected – one that is easy to penetrate but remains intact so that penetrations past the PPE will be visible, or one that reacts like human skin and tissue so that injury can be predicted. Of the materials tested here, the neoprene foam as a soft tissue simulant and vinyl nitrile as a skin simulant showed the most damage and could indicate whether or not soil debris penetrated past the PPE. The neoprene rubber skin simulant showed many similarities to swine skin in its response to gravel although it slightly underestimated the damage. This shows promise for pinpointing a synthetic material that will accurately mimic the response of biological tissue. However, the comparison of skin and tissue simulants needs to be further validated with biological tissue in a variety of soil types to predict secondary fragmentation injury in blast tests using synthetic materials.

In the case of gravel, about 22% of the soil particles ejected weighed more than the standard FSP used for testing PPE. Assuming that a portion of these particles travel at the maximum velocities found with the preliminary radar and high speed video results, they should initially strike the head of a kneeling deminers' (with his head directly over the mine) at velocities between 500 m/s and 1000 m/s since soil first strikes the deminers' head within the first millisecond. It is likely that the particles would strike the chest at slightly lower velocities as the chest is located in a less severe position within the blast cone. Yet, Mah showed that no compacted semi-moist crush gravel penetrated chest armours having V_{50} ratings of 311 m/s and 402 m/s for the 1.1 g FSP [11]. If the V_{50} rating was applicable to gravel, some of the particles should have penetrated. This indicates that the 1.1 g FSP used to test deminer PPE does not accurately mimic soil ejected from AP blast mines, and raises questions about its ability to provide a realistic assessment of the protective capabilities of the PPE being tested against soil ejecta. As a result, current deminer PPE designed to meet the 450 m/s V_{50} rating is likely over designed for prevention of penetration of soil debris ejected from an AP blast mine. Multiple simulating fragments that produce similar damage to that produced by soil particles or multiple standard projectiles, with correction factors for more representative V_{50} values, may be more appropriate to evaluate PPE.

5. Conclusions

Blasted soils have more of the small particles that could potentially pass through the weave of some fabrics. The addition of a backing material to PPE in blast tests are recommended to evaluate particles penetrating past the PPE. One of two backing materials are suggested: one that is easy to penetrate so that penetrations past the PPE will be visible, or one that reacts like human skin and tissue so that injury can be predicted. The vinyl nitrile skin simulant and neoprene foam soft tissue simulant were easy to penetrate and could be effective backing materials if an evaluation based on fragments penetrating past PPE. To relate to injury, the synthetic materials need to be further validated by biological tissue tests. Preliminary tests show that the neoprene rubber skin simulant responds to gravel similarly to swine tissue, although it slightly underestimates the injury. Based on some of the crush gravel tests conducted, there is a clear indication that the current 1.1 g FSP used to test deminer PPE does not accurately mimic the soil ejected from AP blast mines. Multiple projectiles and modifications of the V_{50} rating are suggested so that the test will be more applicable. It is possible that protection equipment designed to protect against the damage of soil ejecta, rather than high severity ballistic threat, will be lighter and less expensive than conventional systems and will likely have a better chance of being adopted by the humanitarian demining community.

6. Acknowledgements

The work presented here was supported by the Canadian Center for Mine Action Technologies. The authors wish to thank Russ Fall, Jim White, Les Eagles, Dan Roseveare, Gerry Rude, Dave Ewing, Lawrence Chesson, Ted Ostrowski, and Bob Martin from DRDC Suffield for the support provided during the experimental trials. Thanks to AMEC Earth and Environmental, Hamilton and Infinition Inc. in assisting with data analysis. Many thanks to Dr. Ira Hill, Dr. Ian Anderson, Dr. Thomas Sawyer, and Capt. Charlene Fawcett for their assistance in swine tests and evaluation. Thanks also to Kent Hocevar, Krista Munroe, May Mah, Julian Lee and others we couldn't mention – for without their support, the work would not have been possible.

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