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Geotechnical trial support

Final report

P. Dzwilewski
Applied Research Associates, Inc.

CSA: G. Coley, DRDC Suffield, 403-544-4046

This scientific or technical validity of this Contract Report is entirely the responsibility of the Contractor and the contents do not necessarily have the approval or endorsement of Defence R&D Canada.

Defence R&D Canada

Contract Report

DRDC Suffield CR-2012-136

March 2009

Canada

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Contract No. W7702-07R171/001/EDM

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GEOTECHNICAL TRIAL SUPPORT
W7702-07R171/001/EDM
FINAL REPORT

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Abstract

This work was to provide geotechnical support for the mechanical neutralization trials of heavy mine rollers, soil placement, soil sampling and testing were investigated. A soil bin was constructed and instrumented to obtain applied surface load from a loading plate or wheel, soil stress, surface displacement, and landmine simulator pressure plate force and displacement. Over fifty tests were conducted on either DRDC Prairie Soil or Gravel to evaluate soil stress gauges and to gain insight into the important physical mechanisms of wheel loading and subsequent soil and buried landmine response.

Resume

Le présent travail visait à fournir du soutien géotechnique pour les essais de neutralisation mécanique de rouleaux de déminage lourds; le positionnement du sol, ainsi que l'essai et l'échantillonnage du sol ont fait l'objet d'une étude. Un contenant à sol a été construit et équipé de façon à obtenir une charge de surface appliquée d'une roue ou plaque de chargement, des contraintes au niveau du sol, d'un déplacement en surface, et d'un déplacement et d'une force de plaque de pression de simulateur de mines terrestres. Plus de cinquante essais ont été réalisés sur du gravier ou du sol de prairie de RDDC pour évaluer les calibres de contrainte de sol et pour mieux connaître les mécanismes physiques importants du chargement de roue et la réaction subséquente du sol et des mines terrestres enfouies.

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Executive summary.

This research was performed for the Defence Research & Development Canada (DRDC), Suffield under contract W7702-07R171/001/EDM, entitled, Geotechnical Trial Support, in support of the Technology Demonstration Program (TDP) on Mechanized Mine Neutralization (MMN). This work contributes to the overall program goal of developing the scientific framework to guide counter explosives strategies, and by providing theoretical and empirical data along with a validation of capabilities and equipments to support the informed, rational selection of mechanical neutralization equipment.

The objective of this work was to provide geotechnical support for the mechanical neutralization trials, in particular heavy roller vehicles. In this effort, the important soil conditions and properties that affect landmines and soil pressures, appropriate sensors, soil placement, soil sampling and testing were investigated. The technical approach for this study was to search the literature for guidance in measuring stress in soil including the presence of structures like landmines, and to perform laboratory-scale instrumented tests in conditions as close as possible to those of demining operations.

A soil bin was constructed and instrumented to obtain applied surface load from a loading plate or wheel, soil stress, surface displacement, and landmine simulator pressure plate force and displacement. Over fifty tests were conducted on either DRDC Prairie Soil or Gravel to evaluate soil stress gauges and to gain insight into the important physical mechanisms of wheel loading and subsequent soil and buried landmine response.

Some of the important findings are:

1. When loaded directly from above, the landmine simulator bottomed out (i.e., set off) at applied loads of 5 kN, which is about half the roller load of a typical heavy demining vehicle.
2. Soil gauges that are flat relative to the diameter (i.e., “pancake”) performed well and were validated under known loading conditions; conversely square or squat gauges (i.e., aspect ratio of near one) did not perform well and over registered the stress by 50-200%. In addition, the flat gauges indicated nearly linearly response to increasing load and had a high degree of repeatability.
3. Although for a given soil, surface displacements varied considerably indicating soil stiffness and density differences, the measured soil stresses hardly varied at all for a given applied load. This indicates that the vertical stress is mainly being controlled by static equilibrium conditions and loading geometry.
4. Vertical soil stress was higher in the landmine simulator tests than in the free-field tests which indicates the landmine is restricting the downward soil motion leading to more compression.

5. The landmine simulator response (i.e., the measured pressure plate force and displacement) was virtually the same in either the Prairie Soil or DRDC Gravel.

Based on the research and testing done for this project, the following recommendations are made:

- offset wheel loading testing;
- double or multiple wheel testing;
- test different wheel diameters and widths; and
- testing on a wider range of soil density and water content Evaluate the test data by
- incorporating the variable contact area for the wheel loading Develop the in-situ soil properties from the test results.

Sommaire

La présente recherche a été effectuée pour Recherche et développement pour la défense Canada (RDDC) Suffield dans le cadre du contrat W7702-07R171/001/EDM, ayant pour nom Geotechnical Trial Support, pour appuyer le programme de démonstration de technologies (PDT) concernant la neutralisation mécanisée de mines (NMM). Ce travail contribue à l'objectif global du programme consistant à développer le cadre scientifique pour guider les stratégies anti explosives en fournissant des données empiriques et théoriques, ainsi qu'une validation des capacités et des équipements pour appuyer la sélection rationnelle et informée d'équipement de neutralisation mécanique.

L'objectif de ce travail était de fournir du soutien géotechnique pour les essais de neutralisation mécanique, en particulier en ce qui concerne les véhicules de déminage par rouleaux lourds. Dans cet effort, les propriétés et les conditions de sol importantes, qui ont une incidence sur les mines terrestres et les pressions du sol, les capteurs appropriés, le positionnement du sol, l'analyse et l'échantillonnage de sol, ont été étudiées. L'approche technique pour cette étude était de fouiller dans la documentation à la recherche d'aides pour mesurer les contraintes dans le sol, y compris la présence de structures comme les mines terrestres, et d'effectuer des essais instrumentés à l'échelle du laboratoire dans des conditions aussi près que possible de celles des opérations de déminage.

Un contenant à sol a été construit et équipé de façon à obtenir une charge de surface appliquée d'une roue ou plaque de chargement, des contraintes au niveau du sol, d'un déplacement en surface et d'un déplacement et d'une force de plaque de pression de simulateur de mines terrestres. Plus de cinquante essais ont été réalisés sur du gravier ou du sol de prairie de RDDC pour évaluer les calibres de contrainte de sol et pour mieux connaître les mécanismes physiques importants du chargement de roue et la réaction subséquente du sol et des mines terrestres enfouies.

Voici certaines des découvertes importantes :

Lorsque chargé directement à partir du dessus, le simulateur de mines terrestres s'est stabilisé (c. à d. déclenché) à des charges appliquées de 5 kN, ce qui correspond environ à la moitié de la charge (rouleaux) d'un véhicule de déminage lourd typique.

Les calibres de sol qui sont plats par rapport au diamètre (c. à d. « crêpe ») ont bien performé et ont été validés dans des conditions de charge connues; en revanche, les calibres carrés ou courts et larges (c. à d. rapport d'aspect de près de un) n'ont pas bien performé et ont surenregistré les contraintes de 50 à 200%. De plus, les calibres plats ont indiqué une réponse presque linéaire à l'augmentation de la charge et avaient un haut degré de répétabilité.

Bien que, pour un sol donné, les déplacements de surface variaient considérablement, ce qui indique des différences de densité et de rigidité du sol, les contraintes mesurées en matière de sol variaient à peine pour une charge appliquée donnée. Cela indique que les contraintes verticales sont principalement contrôlées par la géométrie de charge et les conditions d'équilibre de type statique. Les contraintes de sol verticales étaient plus élevées dans les essais de simulateur de mines terrestres que dans les essais de champ libre, ce qui indique que la mine terrestre restreint le mouvement du sol vers le bas, ce qui entraîne une plus grande compression.

La réponse du simulateur de mines terrestres (c. à d. le déplacement et la force de plaque de pression mesurés) était presque la même dans le gravier de RDDC ou le sol de prairie.

En se basant sur les recherches et les essais effectués pour ce projet, on fait les recommandations suivantes:

Décaler l'essai de chargement de roue;

Doubler ou multiplier l'essai de roue;

Tester différents diamètres et largeurs de roue;

Effectuer l'essai sur une plage plus grande de densités de sol et de teneurs en eau; and

Évaluer les données d'essai en incorporant la surface de contact variable pour le chargement de roue Développer les propriétés de sol sur place à partir des résultats d'essai.

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1 Introduction

This report summarizes the research performed for the Defence Research & Development Canada (DRDC), Suffield under contract W7702-07R171/001/EDM, entitled, Geotechnical Trial Support, in support of the Technology Demonstration Program (TDP) on Mechanized Mine Neutralization (MMN). This work contributes to the overall program goal of developing the scientific framework to guide counter explosives strategies, and by providing theoretical and empirical data along with a validation of capabilities and equipments to support the informed, rational selection of mechanical neutralization equipment.¹

1.1 Objective and scope

The objective of this work was to provide geotechnical support for the mechanical neutralization trials, in particular heavy roller vehicles (Figure 1). In this effort, the Rocky Mountain Division (RMD), Littleton, Colorado, USA of Applied Research Associates, Inc. (ARA) was tasked to identify the important soil conditions and properties that affect landmines and soil pressures, identify appropriate sensors, soil sampling and testing, advise on soil placement, support the field trials, evaluate the sensors, tools, soil sampling and soil placement procedures, and make recommendations for improvement.



Figure 1: Example of a heavy roller demining machine (courtesy of W. Roberts, DRDC).

1.2 Technical approach

The technical approach for this study was to search the literature for guidance in measuring stress in soil including the presence of structures like landmines, and to perform instrumented tests in conditions as close as possible to those of demining operations. These instrumented tests

were performed in a soil bin that was constructed in the RMD office/laboratory complex in Littleton, Colorado

2 Soil

The European Committee for Standardization has published the CEN Workshop Agreement, CWA 15044:2004, for Test and Evaluation of Demining Machines which defines three soils to use and the particle size distribution and relative density (% maximum dry density) for placement, namely, gravel (94% \pm 2% relative density), sand (90% \pm 2% relative density), and topsoil (85% \pm 2% relative density).

The soil lanes at DRDC, Suffield for the three types of soil are shown in Figure 2 and closer views of the three soils are shown in Figures 3-5.

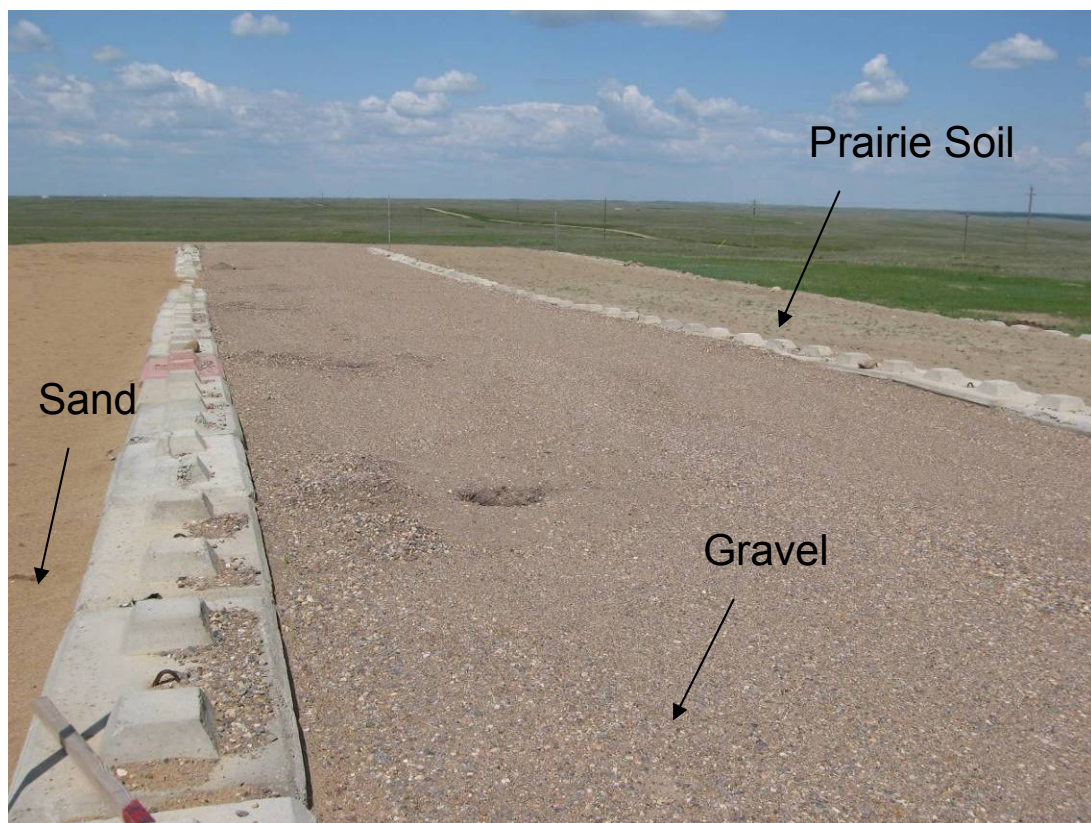


Figure 2: Soil lanes at DRDC, Suffield.



Figure 3: Sand lane at DRDC, Suffield.



Figure 4: Prairie soil lane at DRDC, Suffield.



Figure 5: Gravel lane at DRDC, Suffield.

The in-situ density and water content were measured by DRDC staff for the three soils in the June and July 2008 time period with a nuclear densitometer (example shown in Figure 6). The average and range of densities and water content for the soils in the lanes are given in Tables 1 and 2, respectively.

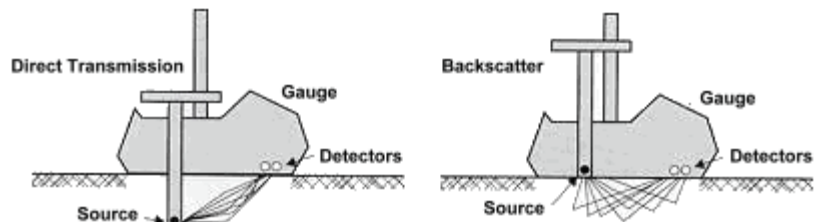


Figure 6: A nuclear density gage measures the amount of radiation emitted through soil. Once calibrated, soil density and water content can be obtained from the amount of detected radiation.

Table 1: Average wet and dry density, and water content for the three soils of the DRDC, Suffield lanes.

Soil Type	Wet Density, kg/m³	Dry Density, kg/m³	Water Content, %
Sand	1750	1697	3.1
Prairie Soil	1994	1767	12.8
Gravel	2213	2106	5.1

Table 2: Range of wet and dry density, and water content for the three soils of the DRDC, Suffield lanes.

Soil Type	Wet Density, kg/m³	Dry Density, kg/m³	Water Content, %
Sand	1690-1848	1646-1794	1.9-5.3
Prairie Soil	1853-2116	1701-1858	7.6-17.2
Gravel	2098-2307	2012-2194	3.1-7.8

Three types of soils were used in the soil bin testing for this study: dry locally-purchased Quikrete Play Sand, and DRDC Prairie Soil and Gravel. The dry sand was used to set up the initial testing and to develop test procedures. The dry sand used for this testing is not directly applicable to heavy roller demining machines because it is too weak to support the weight. However, much was learned about the stress distribution and performance differences between two different soil stress gauges. The DRDC Prairie Soil and Gravel were shipped from DRDC, Suffield to the ARA Littleton CO office. All three soils were tested drier and at lower densities than the average lane densities shown in Table 1. The lower soil densities are the result of the soils being compacted with only a manual tamper and the dryness of the soils. The tested soil densities were closer to the minimum lane densities reported in Table 2.

3 Test set-up

3.1 Test frame and soil bin

The test frame (Appendix A) was an inexpensive 20-ton shop press with a hydraulic pump, which applies the load (Figure 7). The soil bin was constructed of wood with inside dimensions of 0.92 m long by 0.52 m wide by 0.33 m deep (Figure 8). The plywood soil bin was reinforced to make it stiff to prevent stress relief due to movement. In addition, the sides of the wooden box were shimmed with steel plates placed between the outside of the wooden sides and the inside of the load frame to prevent lateral wall movement and hence stress relief.



Figure 7: 20-ton shop press used for soil loading.



Figure 8: 20-ton shop press with the soil bin in place.

The size of the soil bin was verified as being large enough using elastic theory, meaning that the stress at the bottom and sides of the soil bin are a small percentage of the applied surface load. The magnitude of the soil stress at any depth and range depends upon the size, shape and loading magnitude of the surface footprint. There are graphical solutions for elastic materials for circular, strip, and rectangular loading areas. These plots can be used to determine the size and magnitude of the stress bulbs given the loading radius and thus the required depth and lateral extent of the soil bin. It was desirable to keep the vertical stress levels at the bottom and sides of the soil bin at or below 5% of the applied surface load in order that the boundaries of the soil bin do not interfere with the stress conditions at the 0.1 m landmine burial depth. Referring to Figure 9 and using a 0.1-m wide load, typical of some demining machines, the 0.05 or 5% stress bulb goes out to 2.4X the loading radius to a range of 0.12 m whereas the wall is much farther at a range of 0.26 m from the center (at 1.5% stress level). Using a similar analysis, the depth of the bin is at approximately the 4% stress level.

To further investigate the soil bin depth effect, we used the BISAR elastic stress code to determine the vertical stress at a depth of one loading radius (in the vicinity of where soil stress measurements will be taken), which for the wheel 0.1-m width is halfway between the surface and the landmine depth of burial. If the soil bin is very shallow, the stress will increase above that for a very deep bin. As shown in Figure 10, the stress is too high by only 5% or less if the soil bin is greater than 2.5 times the loading radius. For our soil bin, the depth is 6 times the loading radius, so the vertical stress in the vicinity of the landmine burial depth will only be increased about 1% or less which is negligible.

For elastic materials, the vertical stress is independent of properties (Young's modulus and Poisson's ratio). Rectangular loading may need deeper soil bins than circular loads of the same area if the footprint becomes very long. Measurements in real soils do show deviations from elastic behavior. "There is a tendency for the compressive stress in the soil to concentrate around the loading axis. This tendency becomes more greater when the soil becomes more plastic due to increased moisture content or when the soil is less cohesive, such as a sand".³ Nevertheless, these elastic solutions provide a reliable way to begin sizing the test bed.

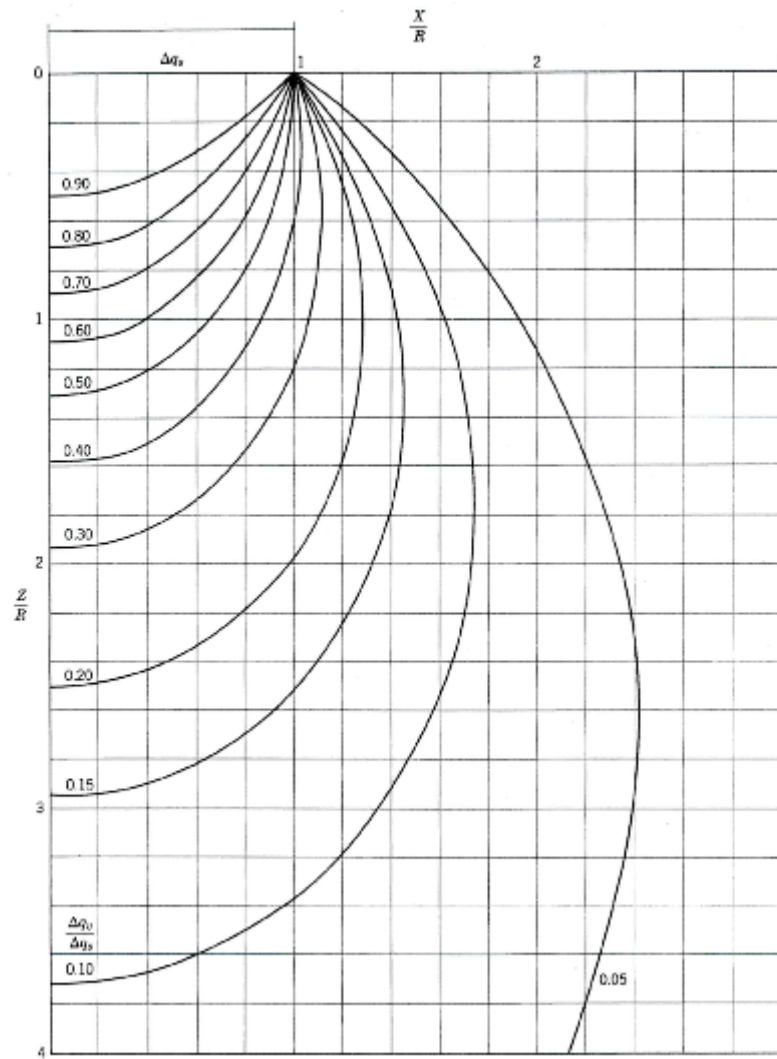


Fig. 8.4 Vertical stresses induced by uniform load on circular area.

Figure 9: Vertical stress caused by circular loading in elastic material.²
The extent of the stress bulb was used to verify the size the soil bin.

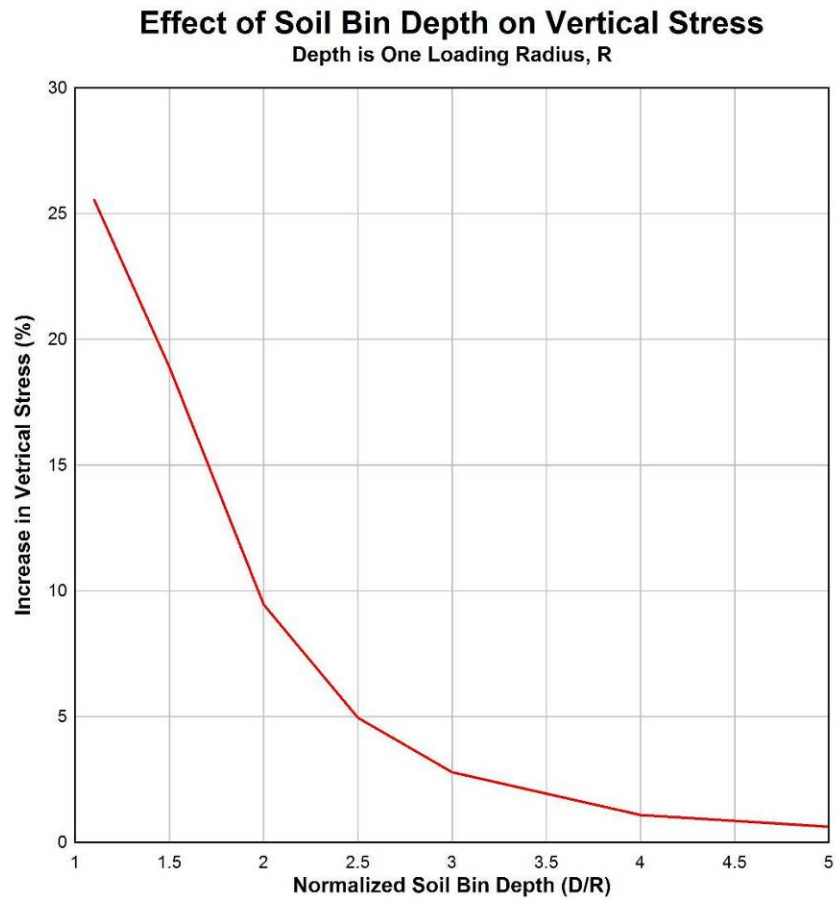


Figure 10: Effect of soil bin or test bed depth on soil vertical stress.

3.2 Instrumentation

For a typical test, the applied force, surface displacement, the soil stress at 0.1 m depth, and the force on the mine simulator pressure plate were measured. The factory supplied calibration factors were used with the exception of the M-15 mine simulator which we calibrated using the load frame with the load cell, and recording the output of the mine simulator force cell and electronics and the pressure plate displacement (Figure 11).



Figure 11: Calibration of the M-15 mine simulator. Data acquisition system and computer are visible in the left of the picture.

All measurements were recorded on a MEDAQ data acquisition system (Figure 12) from Hi-Techniques, Inc. It samples with 14-bit resolution at up to 2 M samples/s, with 2 M samples per acquisition. The MEDAQ has sixteen channels with a voltage input range adjustable from ± 10 mV to ± 50 V. The MEDAQ can be triggered from an external signal, e.g., TTL pulse, or from any data channel. Pre-trigger data can also be collected, up to the full channel memory. For these tests, we manually triggered the start of the data acquisition.

The specific MEDAQ that was used had eight channels of analog input with 1-MHz bandwidth. Another eight channels are available with 90-kHz bandwidth. The MEDAQ is controlled by a portable PC through an Ethernet interface. The MEDAQ was setup to write data files to the PC immediately after acquisition is complete, then the data was backed up manually to a USB memory stick. Data was recorded in the Nicolet Time Domain format (.wft file extension), and can be converted to many other formats post-test.

We used an uninterruptible power supply (UPS) to protect from data loss due to power interruptions and voltage transients. For these tests, the MEDAQ was configured with a sample rate of 200 per second, with a duration of 20.5 seconds.



Figure 12: MEDAQ data acquisition system.

The instrumentation consisted of the following:

- Transducer Techniques LBC-5K load cell (Figure 13 and Appendix B)
- Micro-Epsilon ILD1300-200 Laser Displacement Gauge (Figure 14 and Appendix C)
- Geokon 3500 Earth Pressure Cell (Figures 15 and 16, and Appendix D)
- Wazau Soil Pressure Sensor Type DAK (Figures 15 and 16, and Appendix E)
- M15-Simulator (Figure 11 and Appendix F)

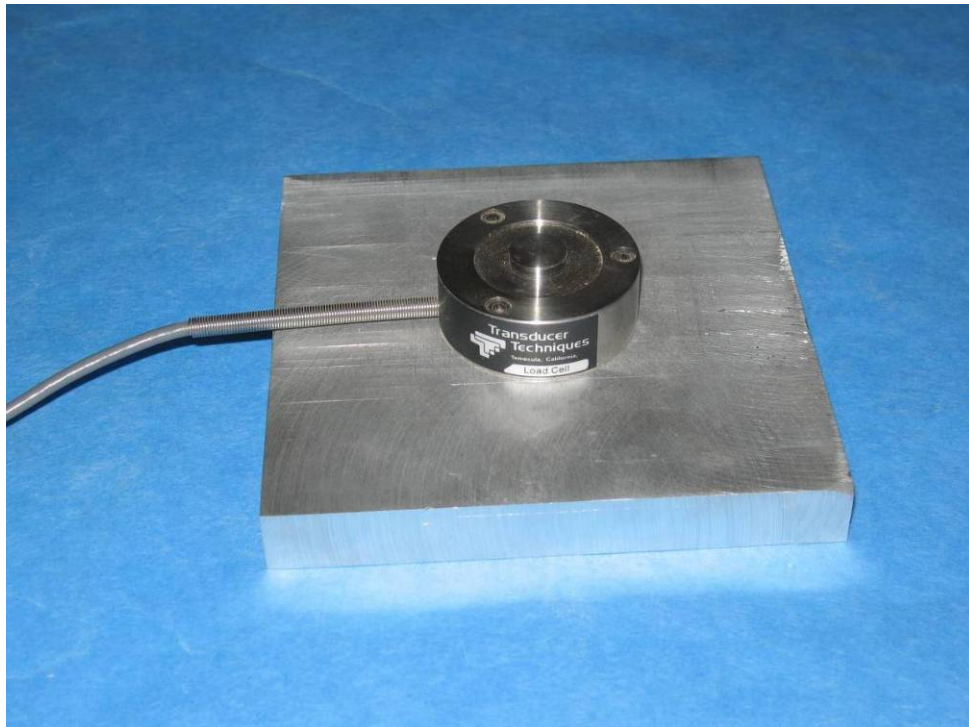


Figure 13: Transducer Techniques LBC-5K load cell mounted on a 100x100x1.27 mm aluminum plate for measuring applied load.



Figure 14: Micro-Epsilon ILD1300-200 Laser Displacement Gauge for measuring surface displacement.



Figure 15: Geokon (bottom) and Wazau (top) soil pressure gauges.



Figure 16: Closer view of Geokon (left) and Wazau (right) soil pressure gauges.

3.3 Test types

The main variations of the testing were:

Soil type: Sand, DRDC Prairie Soil and Gravel

The Prairie Soil and DRDC Gravel results are presented below. The sand tests were used to develop the initial set-up and the results showed that the soil gauges significantly over registered the actual applied pressure as expected for this type of soil and that this loose dry sand could not carry the wheel loads of interest. Therefore, the sand test results will not be presented in this report.

Plate (Figure 17) or Wheel Loading (Figure 18)

The plate (0.33 x 0.33 m square) applied the vertical loading on a constant area with maximum downward forces in the range of 20 kN (184 kPa contact pressure). This simplified loading geometry provided a straightforward way to evaluate the two soil pressure gauges.

The wheel (0.1m wide and 0.91 m diameter) loads the soil over a variable area depending on the amount of sinkage. The maximum applied load was targeted at approximately 8 kN, typical of a heavy roller demining machine.

For the all tests, the applied load, either plate or wheel, were centered over the soil pressure gauge and/or the landmine simulator.

Free-field (no landmine simulator) and Landmine Simulator Tests

Soil Pressure Gauges, either Geokon or Wazau

The effect of the geometry of the soil sensor was investigated. In the literature, it is recommended that the thickness/diameter (T/D) ratio of a stress cell be less than 1/5 to minimize error caused by cell thickness^{4,5} or even 1/10 or less⁶.

The Geokon Gauge is shaped like a pancake with a $T/D = 1/10$. The Wazau pressure sensors are almost square with T/D of about 1/1.2 which is much larger than recommended 1/5 or 1/10. It would be expected that the Wazau gauge would record a significantly higher stress than the Geokon gauge under the same loading conditions.



Figure 17: Plate loading on a sand test bed.

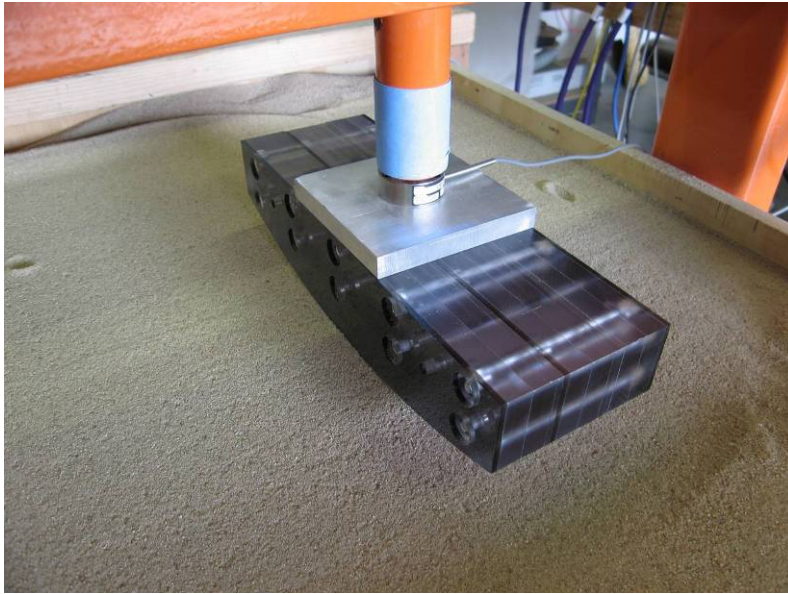


Figure 18: Wheel loading on a sand test bed.

3.4 Soil bin test preparations

The soil was placed in the soil bin in approximately 0.1-m thick layers and each layer was compacted using a manual tamper (Figure 19). The soil was leveled at the 0.1-m depth for the placement of the soil pressure gauges (Figure 20) and at the surface (Figure 21).



Figure 19: 20x20 cm tamper.



Figure 20: Leveled surface at 0.1-m depth and placement of Geokon Earth Pressure Gauge in DRDC Gravel soil bed.



Figure 21: Leveled top surface of sand soil bed.

Soil density measurements were taken for each type of soil using either a 30-cm³ Eley volumeter (Figure 22) or a 283-cm³ sampling tube (Figure 23). The larger sampling tube was particularly needed for the gravel because of the large soil particle size. Water content measurements were made on the DRDC Prairie Soil and Gravel using the standard oven-drying method. The sand was dry so no water content tests were performed.



Figure 22: 30-cm³ Eley volumeter for determining soil density.



Figure 23: 283-cm³ sampling tube for determining soil density.

4 Test Matrix

The table below lists the tests that were performed for this research.

Table 3: Test Matrix.

Test Number	Soil Type		Loading Type		Free-Field or Mine Simulator		Soil Gauge Type	
	Prairie Soil	DRDC Gravel	Plate	Wheel	Free-field	0.1 m depth	Geokon	Wazau
26-28	X		X		X		X	
29-34	X			X	X		X	
35-37	X		X		X			X
38-43	X			X	X			X
46-51	X		X			X		X
52-57	X			X		X		X
58-60	X		X			X	X	
61-66	X			X		X	X	
67-68	X			X		X	X	
71	X			X		X		X
72-73		X		X		X	X	
74-76		X		X		X		X
77-78		X		X	X		X	
79-80		X		X	X			X

5 Prairie soil testing

A total of 42 tests were conducted on the Prairie Soil. These tests will be discussed in two groups, namely, the free-field tests, i.e., no landmine simulator, and the landmine simulator tests. Both the plate and wheel loading were used for this soil, and with both the Geokon and Wazau soil pressure sensors.

5.1 Free field tests

5.1.1 Plate Loading

The free-field plate loading test (Figures 24 and 25) provides an opportunity to evaluate the soil pressure gauges because the correct vertical stress in the soil is known. The contact pressure

between the plate and the soil is equal to the applied load or force divided by the plate area (e.g., $20 \text{ kN}/(0.33 \text{ m})^2 = 184 \text{ kPa}$). At 0.1 m depth in the soil (soil gauge or top of mine location) for this plate of relatively large lateral extent, the vertical stress is close to the applied contact pressure, approximately 88%.



Figure 24: Plate load testing on Prairie Soil.



Figure 25: Surface deformation for plate load testing on Prairie

The tests were conducted by loading the plate with the hydraulic jack up to about 20 kN (the capacity of the load cell) over a period of 20-25 seconds. The surface displacement, applied load, and the vertical soil stress are recorded at 200 samples/second. The testing for a given setup was usually performed three times. The first test was performed on the newly prepared test bed and the next two were retests on the same test bed. It would be expected that the first test would have the most displacement and the subsequent tests would have less. Aside from demonstrating the capability of the soil gauges to accurately measure the soil stress for the plate loading, other important findings were observed about the soil behavior from the three plate loading testing.

As an example of the Geokon testing, the recorded time history for Test 27 is shown in Figure 26.

As the hydraulic jack is pumped up to a higher load, some load relief occurs due to the jack.

This did not significantly affect the data as when the load dropped so did the measured soil stress. The recorded time data was then manipulated to plot the results versus load and displacement. The normalized applied load is plotted versus surface displacement for Tests 26-28 in Figure 27. The first test (Test 26) has the greatest surface displacement of approximately 9.6 mm at the maximum loading, whereas the subsequent tests have only about 4 mm of surface displacement. It is interesting to note that the soil mass after the first test (Test 26) is stabilized as shown by the nearly identical Tests 27 and 28 results.

The measured soil stress is plotted versus normalized applied load in Figure 28 along with the linear elastic solution (88% of applied load). The Geokon measured stress is higher than the elastic solution by about 6% which is quite good. Of the 6% error, 4% is due to the bottom of the soil bin and the other 2% is probably caused by the soil concentrating the compressive stress toward the loading axis.³ It is interesting to note that although there are significant differences in surface displacement between the first and subsequent tests, which implies differences in density and stiffness, the vertical stress at 0.1 m depth varies very little between the tests as shown in Figure 28. This plot shows that there is a slightly more differences in measured soil stress at the lower loads when the soil is looser, but at higher loads the soil stresses are about the same. The test comparison and linearity of the soil stress versus applied load shown in Figure 28 is striking in light of the significant surface displacement differences shown in Figure 27. The soil stress being nearly the same is consistent with elastic behavior for which the vertical stress is independent of the elastic properties. Based on these results, it is concluded that the Geokon Earth Pressure Gauge will reliably measure the soil stress due to surface loading.

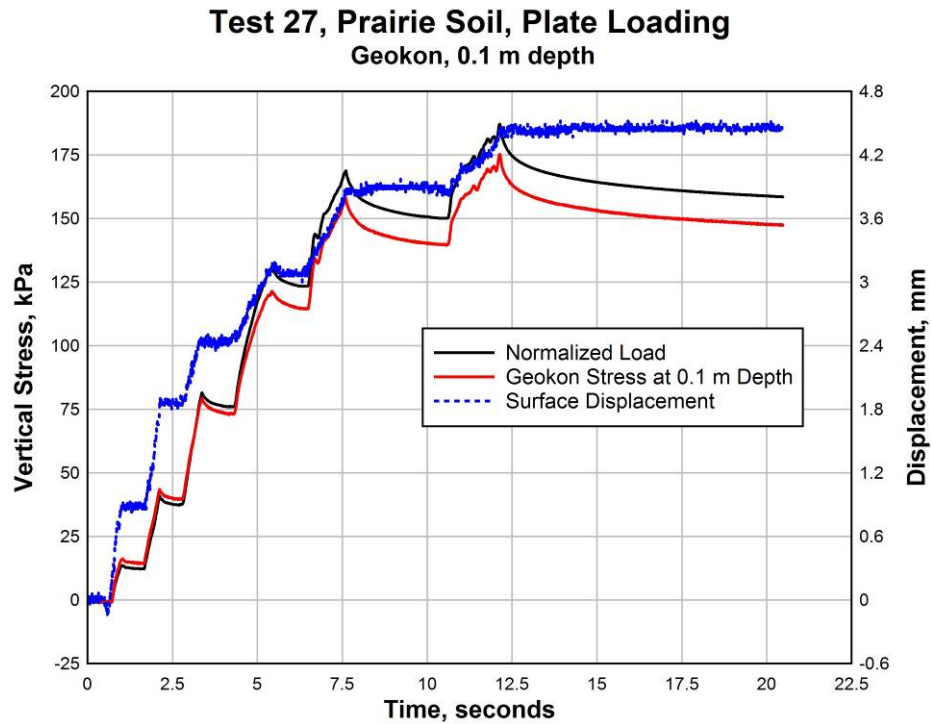


Figure 26: Recorded data time history for free-field plate load Test 27 (Geokon) on Prairie Soil.

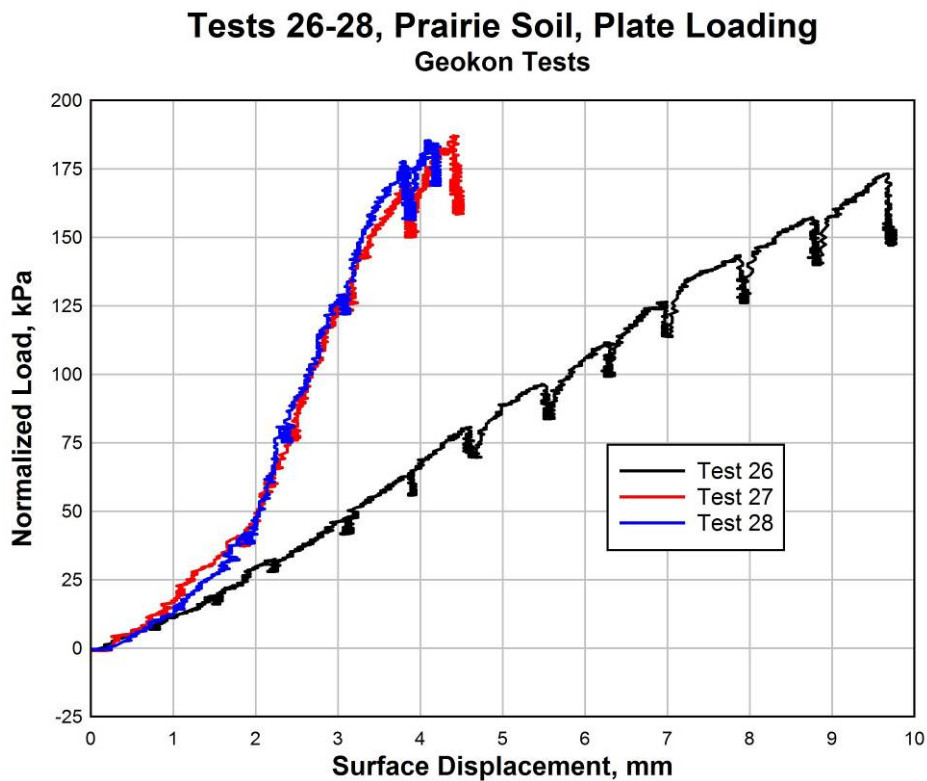


Figure 27: Applied load versus surface displacement for Tests 26-28.

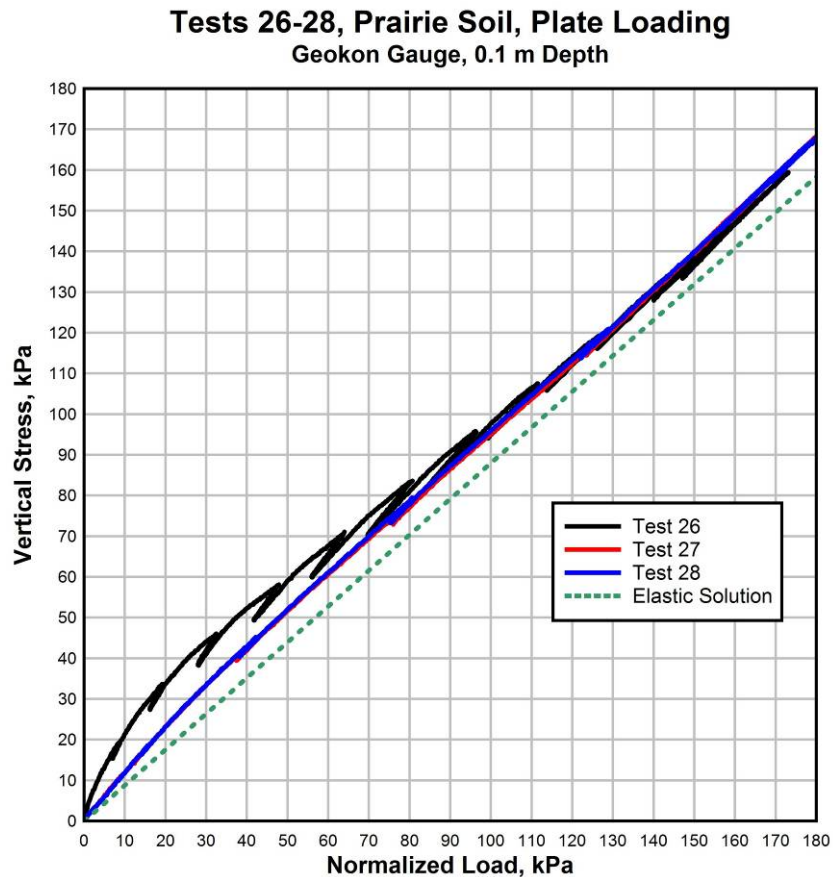


Figure 28: Comparison of Geokon vertical stress versus applied load for Tests 26-28.

The recorded time history for Wazau Test 37 is shown in Figure 29. This plot which shows that the Wazau measured stress at 0.1-m depth is significantly higher than the applied load gives the first indication of the differences in performance between the two soil stress gauges. The differences in performance is clearly seen in Figure 30, which presents the Wazau, Geokon, and elastic solution results. While the Geokon cell is recording stresses just slightly below the applied normalized load over most of the range of loading as it should, the Wazau gauge over registers the applied load by 200% at low loads and by 65% at the higher loads. The amount of error is a function of the T/D ratio and the soil-cell stiffness ratio.⁴ Based on the research in the literature⁴, these results are not a surprise as it would be expected that a gauge with the Wazau aspect ratio could over register by 50-60%.

As the Wazau over registration was consistent for all tests conducted, it was decided not to present that data in this report as the differences are significant and it is best not to draw conclusions about the important physics based on the Wazau results. Instead the Geokon gauge results will be presented in more detail and observations about the physics will be drawn on this much more reliable data. It should be noted that we contacted Wazau via email and asked about the design of their gauge. Thomas Reinheimer of Wazau replied that the gauge was designed at

the Christian-Albrechts University. We sent an inquiry email to a professor at the Christian-Albrechts University, who appeared to work in that area but may not be the correct contact person, but did not get a response. Based on the literature and our testing, we concluded that the Wazau gauge is not appropriate for this application.

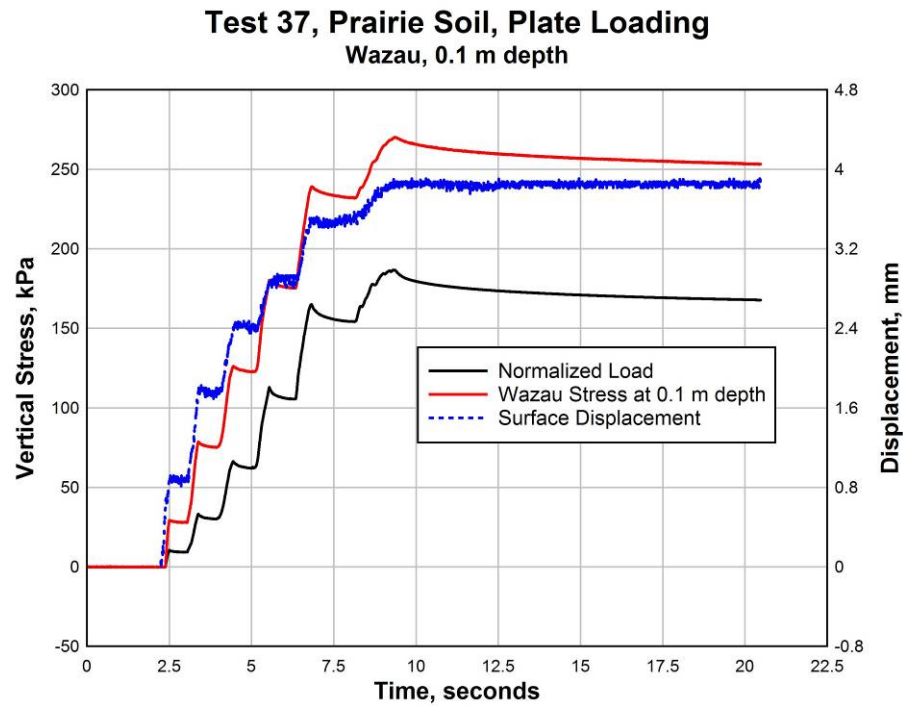


Figure 29: Recorded data time history for free-field plate load Test 27 (Wazau) on Prairie Soil.

Tests 27 and 37, Prairie Soil, Plate Loading Geokon vs Wazau Gauge, 0.1 m Depth

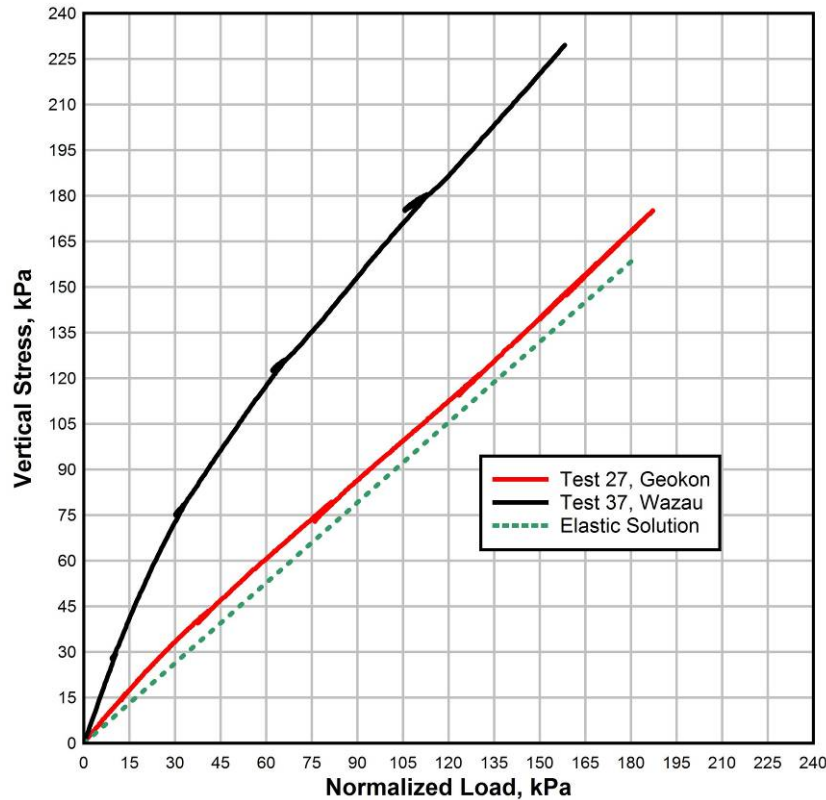


Figure 30: Comparison of Geokon (Test 27) and Wazau (Test 37) vertical stress versus applied load.

5.1.2 Wheel loading

The wheel loading test (Figures 31-33) provides an opportunity to evaluate soil pressure gauges under simulated loading conditions for a heavy roller demining vehicle. The contact pressure between the wheel and the soil varies as the load is increased and the contact area increases due to the sinkage of the wheel into the soil. The applied load was targeted to be at least 8 kN, typical of a heavy roller demining machine. Most tests were run to higher loads, approximately 10 kN.



Figure 31: Free-field wheel load (longitudinal to soil bin) testing on Prairie Soil.



Figure 32: Free-field wheel load (transverse to soil bin) testing on Prairie Soil.



Figure 33: Surface deformation for wheel load testing on Prairie Soil.

The results for Tests 29-31, which are wheel loading tests with the Geokon pressure gauge are presented in Figures 34 and 35. The applied load is plotted versus surface displacement for Tests 29-31 in Figure 34. As with the plate loading tests, the first test has the greatest surface displacement of approximately 15 mm at the maximum loading, whereas the subsequent tests have only about 6 mm of surface displacement. Once again as with the plate loading tests, it is interesting to note that the soil mass after the first test (Test 29) is stabilized as shown by the very similar Tests 30 and 31 results.

The measured soil stress is plotted versus applied load in Figure 35. It is interesting to note that although there are significant differences in surface displacement between the first and subsequent tests, which implies differences in density and stiffness, the vertical stress at 0.1 m depth varies very little between the tests as shown in Figure 35. The test comparison demonstrates the repeatability and linearity of the soil stress versus applied load. Based on these results, it is concluded that the Geokon Earth Pressure Gauge will reliably measure the soil stress due to surface loading.

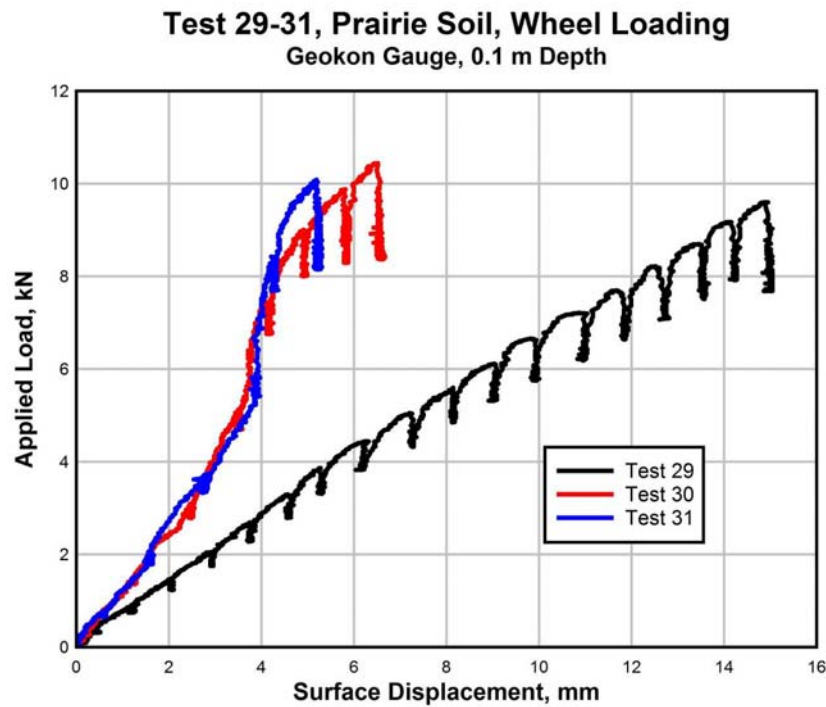


Figure 34: Applied load versus surface displacement for free-field wheel load Prairie Soil Tests 29-31.

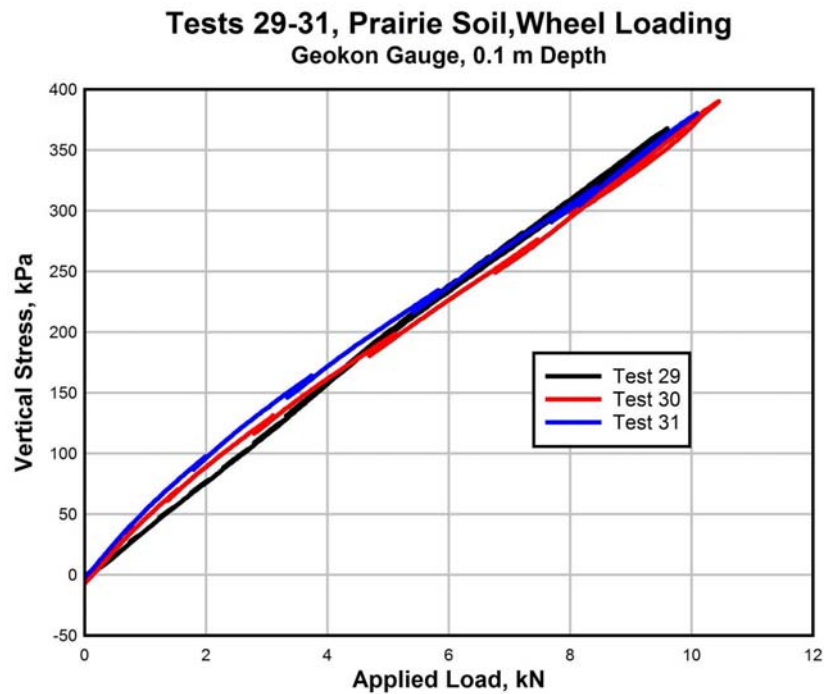


Figure 35: Comparison of Geokon vertical stress versus applied load for free-field wheel load Prairie Soil Tests 29-31.

5.2 Landmine simulator tests with wheel loading

The landmine simulator tests (Figures 36-39) provided a reasonably high-fidelity but basic simulation of the loading of soil by a heavy roller demining vehicle. These tests were similar to the free-field tests with the addition of the landmine simulator which provided the force on the pressure plate and indirectly the pressure plate displacement through the calibration. Based on the calibrations, the pressure plate moves down about 10-12 mm before bottoming out (i.e., when the internal stops restricts the displacement) at a load of approximately 2200 N. The wheel loading was applied to match the weight of a heavy roller (~10 kN) which was more than sufficient to bottom out the pressure plate.



Figure 36: Placement of the landmine simulator in the soil bin for the Prairie Soil testing.



Figure 37: Placement of the Wazau Soil Pressure Sensor on top of the landmine simulator.



Figure 38: Landmine simulator test sinkage caused by wheel load on Prairie Soil.



Figure 39: Landmine simulator surface deformation for wheel load testing on Prairie Soil. The transverse cracks in the soil are caused by the downward displacement of the pressure plate.

Each landmine simulator test was performed on a test bed that was reworked and recompacted above the landmine simulator. This was done because we found that the cracks in the soil formed due to the downward displacement of the pressure plate would affect subsequent load tests.

The landmine simulator test results will be illustrated with the Test 67 data, which is a wheel loading test with the Geokon pressure gauge placed on the top of the landmine pressure plate. The Test 67 data plotted versus applied wheel load are presented in Figure 40. There is a wealth of information on this plot.

In Figure 40, the applied wheel load is plotted up to 10 kN (heavy-roller load). The pressure plate force and displacement level off at approximately 5 kN or about half the applied load. This bottoming out is caused by internal stops in the landmine, which are there to prevent overloading and damaging the internal force gauge. The bottoming out occurs when the pressure plate force (blue curve, right axis) is around 2200 N and 1.1 cm of displacement (green curve, right axis). The landmine would be set off at these conditions. The corresponding surface displacement at an applied load of 5 kN is 1.7 cm, which is about 55% higher than the pressure plate downward movement. The measured soil stress on top of the pressure plate at the 5 kN load is 250 kPa, which is about 25% higher than the free-field stress. This higher compressive stress is due to the presence of the landmine simulator (Figure 35). It is interesting to note that the soil stress begins to increase more rapidly with increasing load (i.e., slightly steeper slope) above the bottoming-out load of 5 kN. This is caused by the restricted pressure plate downward movement.

The landmine simulator test results were quite reasonable, repeatable, and understandable. The measurements taken and the test procedures are quite adequate for laboratory-scale testing and for extension to field testing.

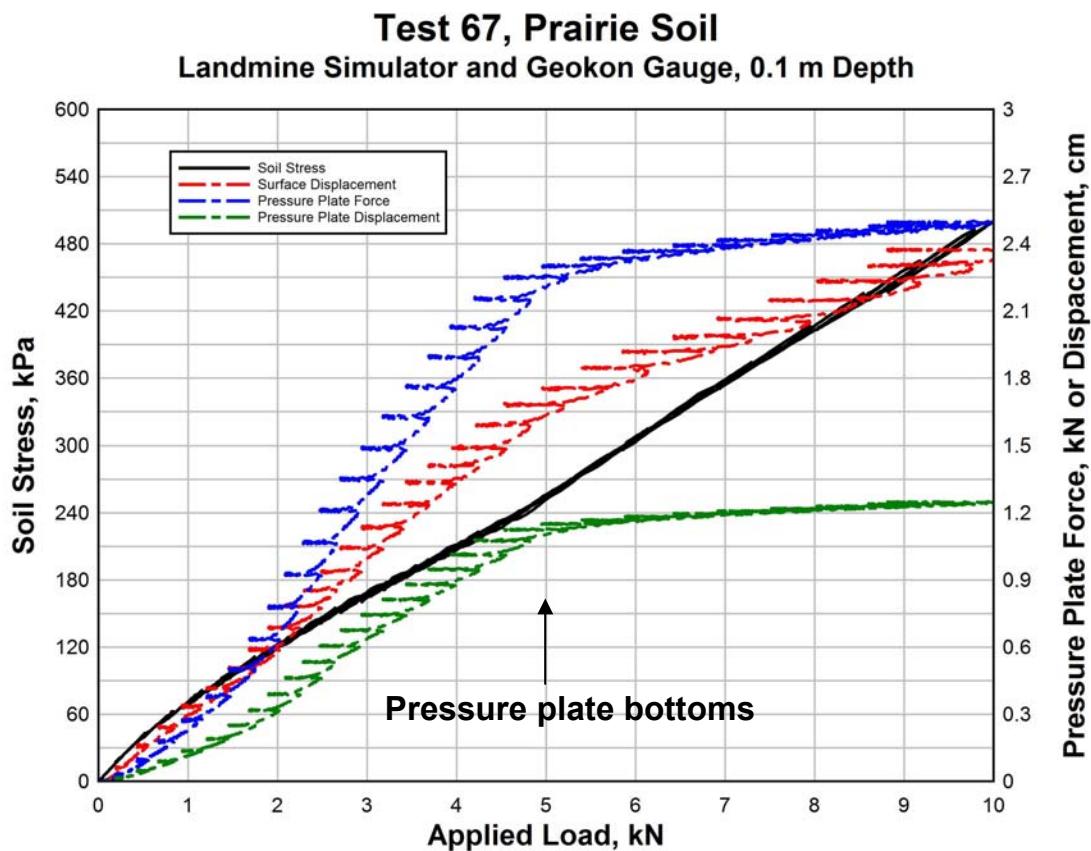


Figure 40: Prairie soil landmine simulator Test 67 results plotted versus applied load.

6 DRDC gravel testing

A total of ten tests were conducted on the DRDC Gravel. These tests will be discussed in two groups, namely, the free-field tests, i.e., no landmine simulator, and the landmine simulator tests. Only the wheel loading was used for this soil with both the Geokon and Wazau soil pressure sensors. Only the Geokon test results will be presented here.

6.1 Free field tests with wheel loading

Free-field tests (no landmine simulator) were conducted on the DRDC Gravel with the wheel loading. Some setup pictures are presented in Figures 41- 43.



Figure 41: Placement of the Geokon Soil Pressure Sensor in the DRDC Gravel at 0.1 m depth for the free-field tests with the wheel loading.



Figure 42: Wheel loading on DRDC gravel during free-field test.



Figure 43: Soil deformation for the free-field wheel load testing on DRDC Gravel.

The results for DRDC Gravel Tests 77 and 78, which are wheel loading tests with the Geokon pressure gauge are presented in Figures 44 and 55. The applied load is plotted versus surface displacement in Figure 44. As with the Prairie Soil tests, the first test has the greatest surface displacement of approximately 27 mm at the maximum loading, whereas the subsequent test had only about 17 mm of surface displacement.

The measured soil stress is plotted versus applied load in Figure 45. The measured soil stresses at the 0.1-m depth for the two tests are about the same at low applied loads (≤ 2 kN) and within 10-15% at the higher loads. Variations in the soil bed can account for these 10-15% differences which are in the reasonable range for geotechnical testing.

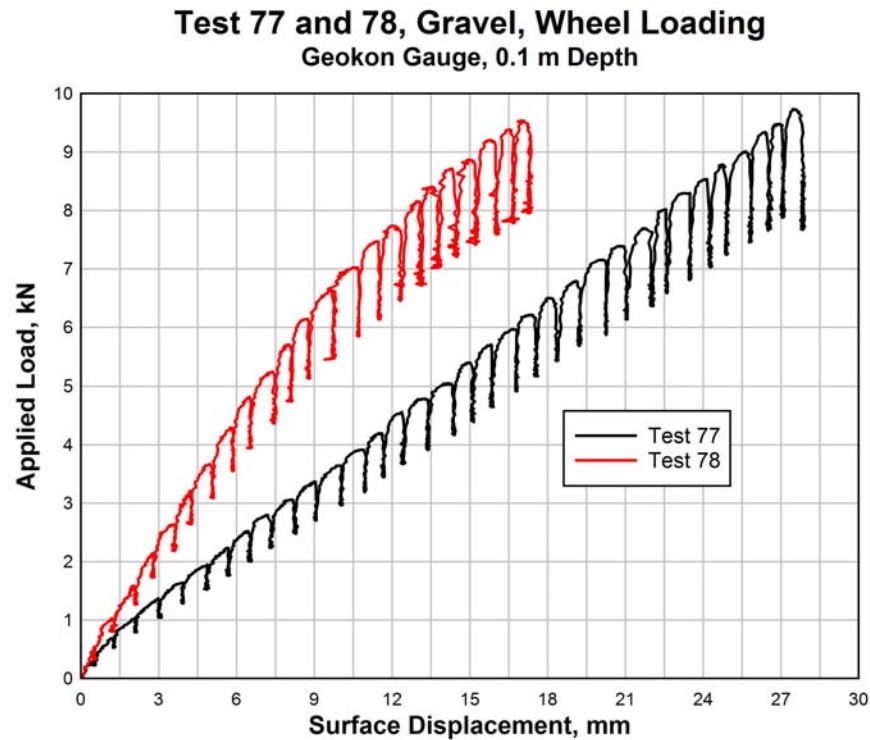


Figure 44: Applied load versus surface displacement for DRDC Gravel Tests 77-78.

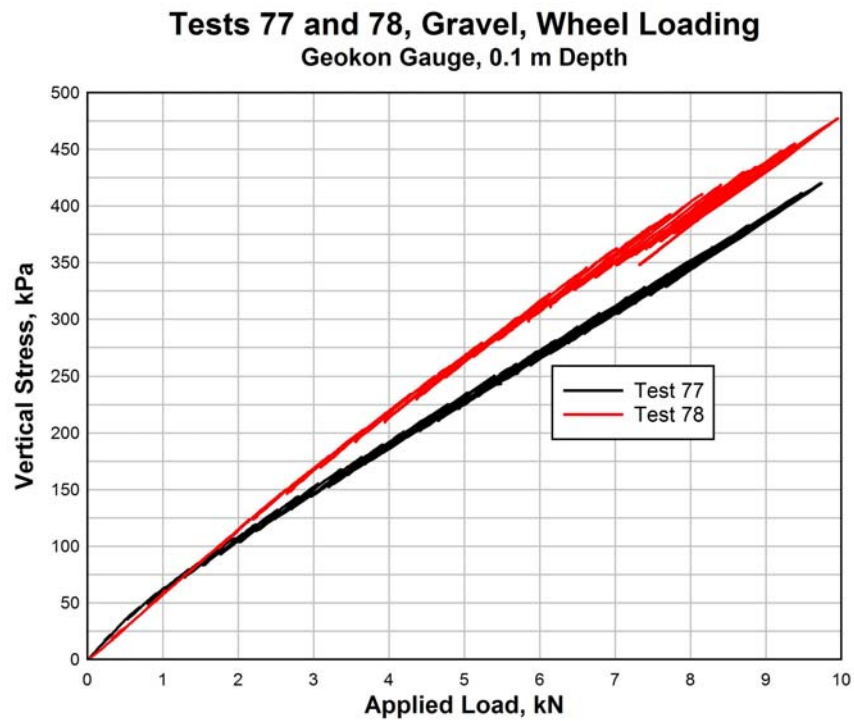


Figure 45: Comparison of Geokon vertical stress versus applied load for DRDC Gravel Tests 77 and 78.

6.2 Landmine simulator tests with wheel loading

Landmine simulator tests were conducted on the DRDC Gravel with the wheel loading. Some setup pictures are presented in Figures 46- 48.



Figure 46: Landmine simulator test setup with wheel load on DRDC Gravel.



Figure 47: DRDC Gravel being loaded by the wheel in a landmine simulator test.



Figure 48: Surface deformation caused by the wheel load in a landmine simulator test.

The landmine simulator test results will be illustrated with the Test 72 data, which is a wheel loading test with the Geokon pressure gauge placed on the top of the landmine pressure plate. The Test 72 data plotted versus applied wheel load are presented in Figure 49. These results are very similar to the Prairie Soil results shown on Figure 40.

In Figure 49, the applied wheel load is plotted up to 10 kN (heavy-roller load). The pressure plate force and displacement levels off at approximately 5 kN or about half the applied load. This bottoming out is caused by internal stops in the landmine, which are there to prevent overloading and damaging the internal force gauge. The bottoming out occurs when the pressure plate force (blue curve, right axis) is around 2200 N and 1.1 cm of displacement (green curve, right axis).

The landmine would be set off at these conditions. The corresponding surface displacement at an applied load of 5 kN is 1.8 cm, which is about 60% higher than the pressure plate downward movement. The measured soil stress on top of the pressure plate at the 5 kN load is 310 kPa, which is about 20% higher than the free-field stress. This higher compressive stress is due to the presence of the landmine simulator (Figure 45). As with the Prairie Soil, the soil stress begins to increase more rapidly with increasing load (i.e., steeper slope) above the bottoming out load of 5 kN. This is caused by the restricted pressure plate downward movement.

The landmine simulator test results were quite consistent between the Prairie Soil and the DRDC Gravel.

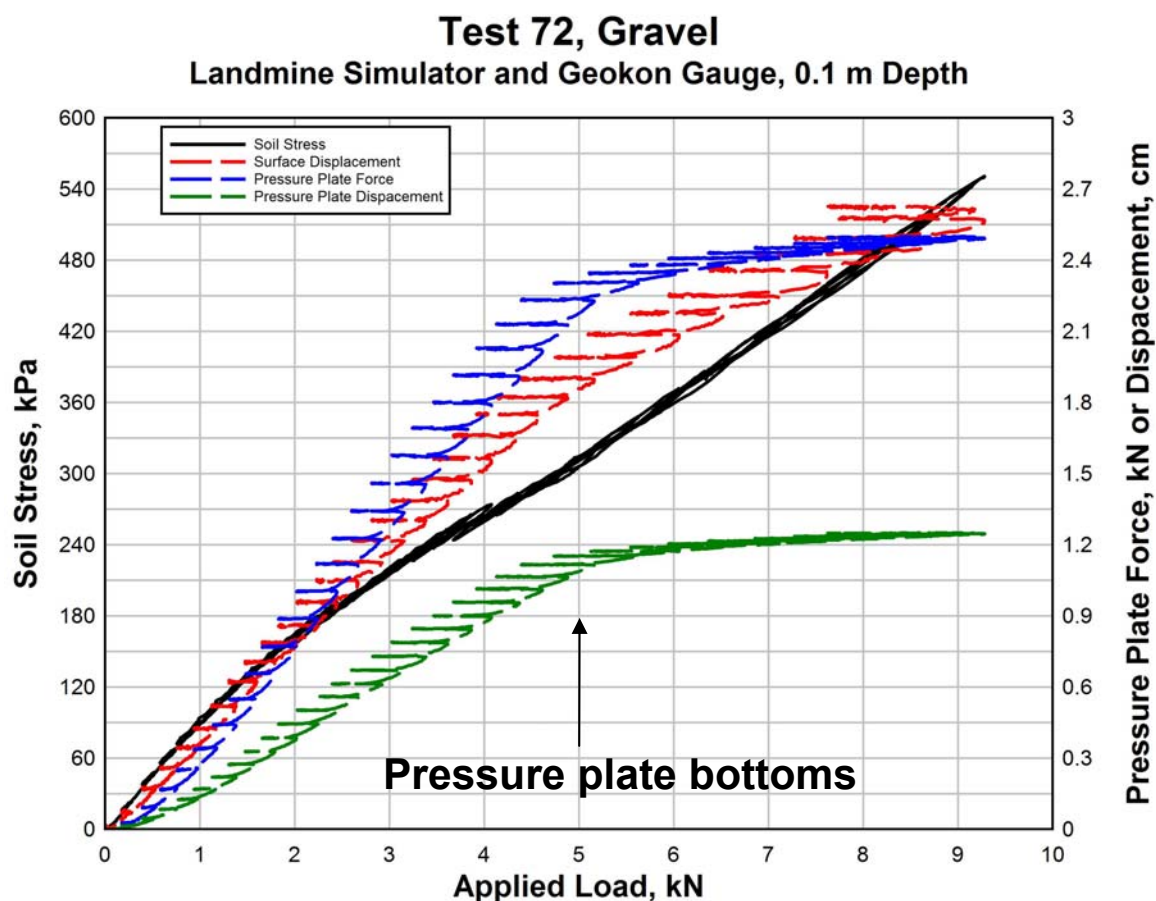


Figure 49: DRDC Gravel landmine simulator Test 72 results plotted versus applied load.

7 Comparison of results

The following three figures compare the measured soil stress as functions of soil type, and free-field vs landmine simulator conditions. It can be observed that the soil stress is higher when the landmine simulator is present as illustrated in Figure 50 for the Prairie Soil and in Figure 51 for

the DRDC Gravel. In addition the measured soil stress for both the free-field and landmine conditions is higher in the DRDC Gravel than for the Prairie Soil for a given applied load. These higher soil stresses in the DRDC Gravel are illustrated in Figure 52 for the landmine simulator tests. For example, the DRDC Gravel stress is about 20% higher than in the Prairie Soil at the 5-kN loading level.

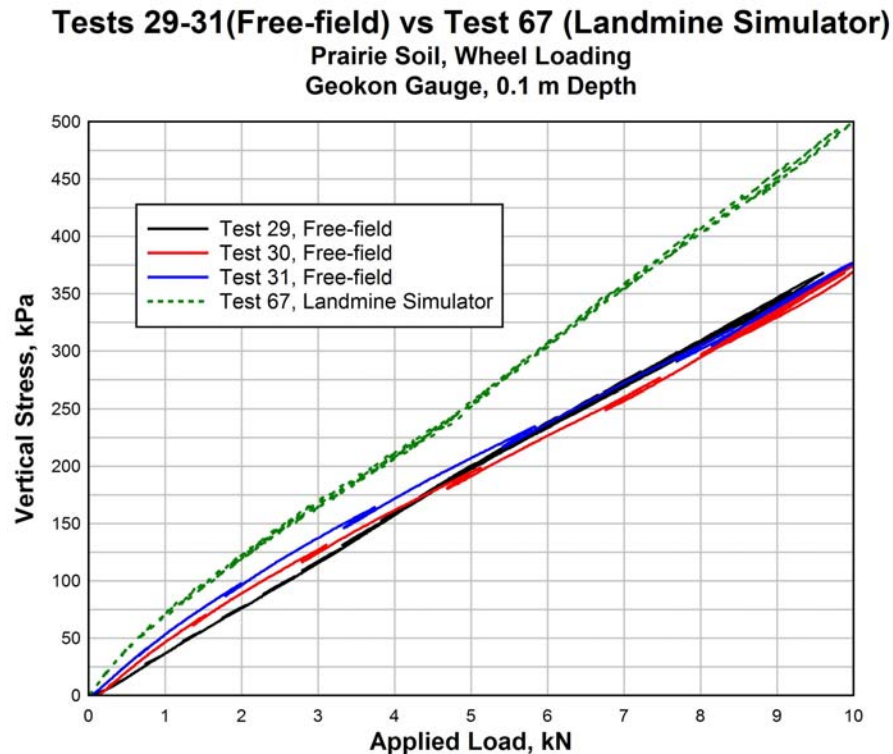


Figure 50: Comparison of Geokon vertical stress versus applied load for Prairie Soil Tests 29-31 (free-field) and 67 (landmine simulator).

Tests 77-78 (Free-field) vs Test 72 (Landmine Simulator)

Gravel, Wheel Loading
Geokon Gauge, 0.1 m Depth

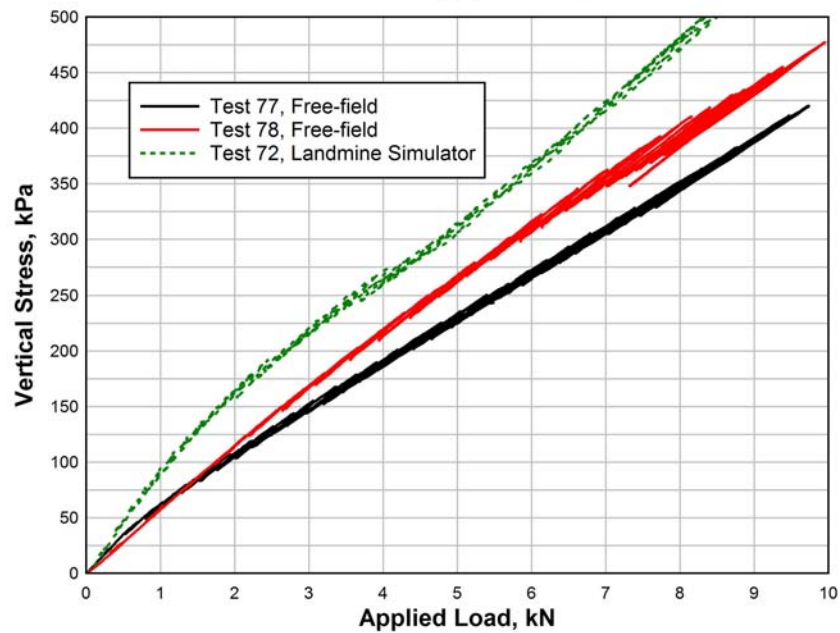


Figure 51: Comparison of Geokon vertical stress versus applied load for DRDC Gravel Tests 77-78 (free-field) and 72 (landmine simulator).

Test 67 (Prairie Soil) vs Test 72 (DRDC Gravel)

Landmine Simulator, Wheel Loading
Geokon Gauge, 0.1 m Depth

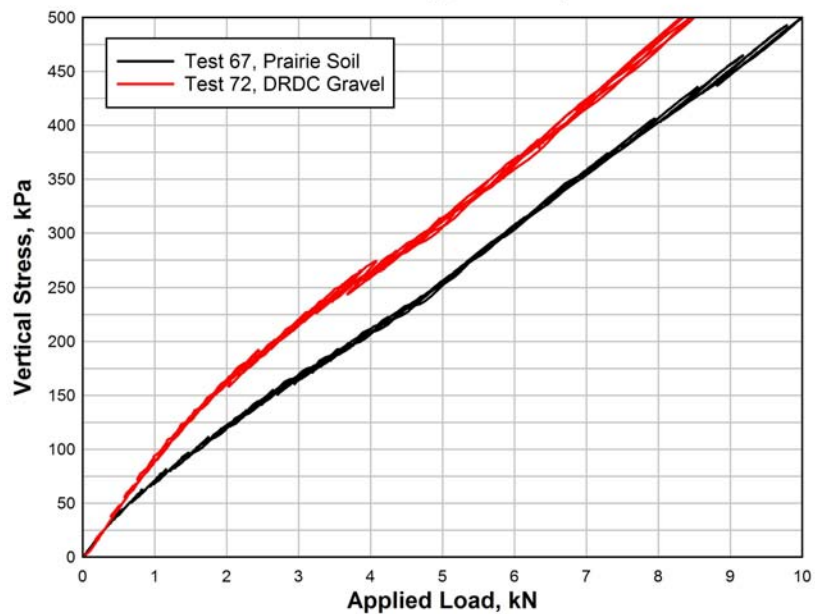


Figure 52: Comparison of Geokon vertical stress versus applied load for landmine simulator Tests 67 (Prairie Soil) and 72 (DRDC Gravel).

Lastly, the landmine simulator tests in the two soils are compared in Figure 53. The measured pressure plate force and derived downward vertical displacement, and surface displacement are plotted versus the applied load for Prairie Soil Test 67 (black) and DRDC Gravel Test 72 (red). While there are some differences in the surface displacement, the pressure plate force and displacement overlay each other.

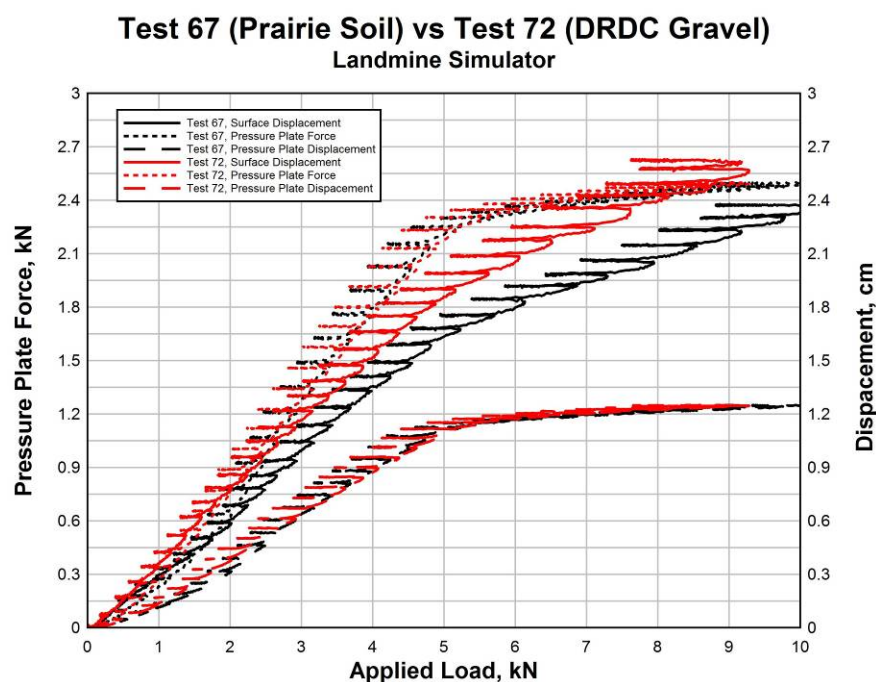


Figure 53: Comparison of pressure plate force and displacement, and surface displacement versus applied load for landmine simulator Tests 67 (Prairie Soil) and 72 (DRDC Gravel).

8 Summary and conclusions

This research was performed for the Defence Research & Development Canada (DRDC), Suffield under contract W7702-07R171/001/EDM, entitled, Geotechnical Trial Support, in support of the Technology Demonstration Program (TDP) on Mechanized Mine Neutralization (MMN). This work contributes to the overall program goal of developing the scientific framework to guide counter explosives strategies, and by providing theoretical and empirical data along with a validation of capabilities and equipments to support the informed, rational selection of mechanical neutralization equipment.¹

The objective of this work was to provide geotechnical support for the mechanical neutralization trials, in particular heavy roller vehicles. In this effort, the important soil conditions and properties that affect landmines and soil pressures, appropriate sensors, soil placement, soil sampling and testing were investigated. The technical approach for this study was to search the

literature for guidance in measuring stress in soil including the presence of structures like landmines, and to perform laboratory-scale instrumented tests in conditions as close as possible to those of demining operations.

A soil bin was constructed and instrumented to obtain applied surface load from a loading plate or wheel, soil stress, surface displacement, and landmine simulator pressure plate force and displacement. Over fifty tests were conducted on either DRDC Prairie Soil or Gravel to evaluate soil stress gauges and to gain insight into the important physical mechanisms of wheel loading and subsequent soil and buried landmine response.

Some of the important findings are:

When loaded directly from above, the landmine simulator bottomed out (i.e., set off) at applied loads of 5 kN, which is about half the roller load of a typical heavy demining vehicle.

Soil gauges that are flat relative to the diameter (i.e., “pancake”) performed well and were validated under known loading conditions; conversely square or squat gauges (i.e., aspect ratio of near one) did not perform well and over registered the stress by 50-200%. In addition, the flat gauges indicated nearly linearly response to increasing load and had a high degree of repeatability.

Although for a given soil, surface displacements varied considerably indicating soil stiffness and density differences, the measured soil stresses hardly varied at all for a given applied load. This indicates that the vertical stress is mainly being controlled by static equilibrium conditions and loading geometry.

Vertical soil stress was higher in the landmine simulator tests than in the free-field tests which indicates the landmine is restricting the downward soil motion leading to more compression.

The landmine simulator response (i.e., the measured pressure plate force and displacement) was virtually the same in either the Prairie Soil or DRDC Gravel.

9 Recommendations

Based on the research and testing done for this project, the following recommendations are made:

- Offset wheel loading testing
- Double or multiple wheel testing
- Test different wheel diameters and widths
- Testing on a wider range of soil density and water content
- Evaluate the test data by incorporating the variable contact area for the wheel loading
- Develop the in-situ soil properties from the test results

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This work was to provide geotechnical support for the mechanical neutralization trials of heavy mine rollers, soil placement, soil sampling and testing were investigated. A soil bin was constructed and instrumented to obtain applied surface load from a loading plate or wheel, soil stress, surface displacement, and landmine simulator pressure plate force and displacement. Over fifty tests were conducted on either DRDC Prairie Soil or Gravel to evaluate soil stress gauges and to gain insight into the important physical mechanisms of wheel loading and subsequent soil and buried landmine response.

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Landmine; roller; soil; load; stress; pressure force; displacement; depth.

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