International Test and Evaluation Program
for Humanitarian Demining

Lessons Learned

Test and Evaluation of Mechanical Demining Equipment according to the CEN Workshop Agreement (CWA 15044:2004)

Part 2: Interpretation of Ground Penetration Depth Measurements

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(ITEP WGMAE)

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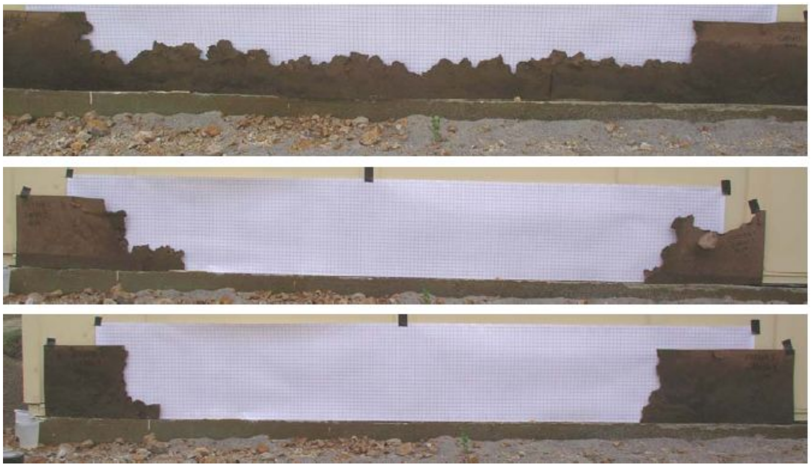
Background

The information obtained, either through direct or indirect measurement of the ground penetration depth can provide a subjective evaluation, simply through the use of photographs taken from the fibreboards (see figure 1) or from graphs plotting the measured data (see figure 2). This information will show the ground penetration capabilities of the machine tool and will allow the user to evaluate the machine for given operational conditions.

(a)



(b)

Figure 1: Ground penetration profiles determined using fibreboards (a) in topsoil with mines buried at 0 cm depth, (b) in gravel with mines buried at 15 cm depth

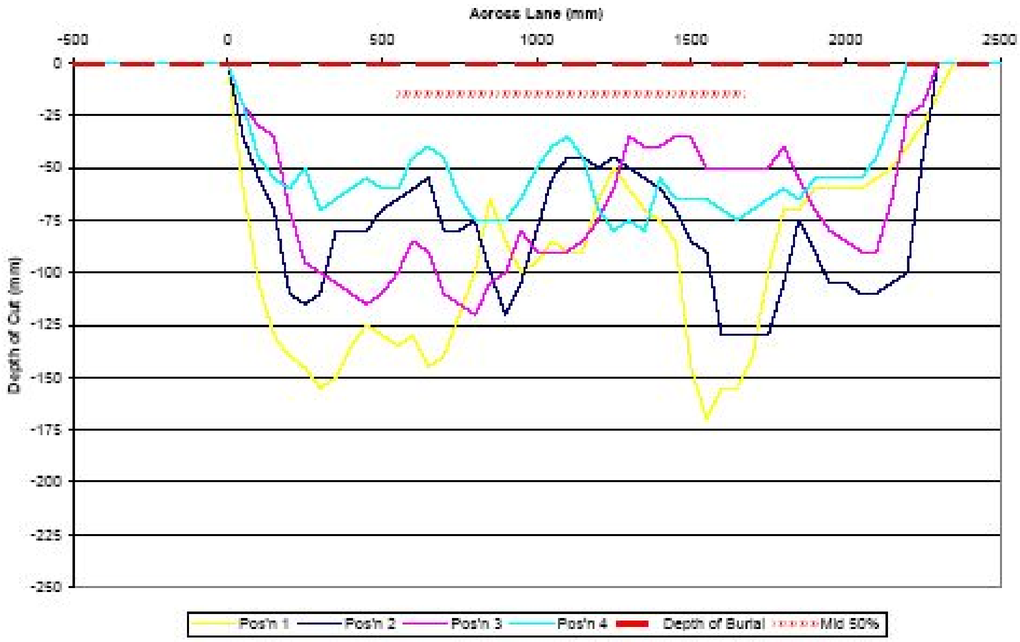


Figure 2: Ground penetration profiles determined using direct measurements. Ground penetration profiles were measured at 4 locations along the test lane.

However, it will be useful in many cases, especially for Performance Tests, to be able to quantify the ground penetration depth characteristics of a machine tool for given conditions (soil type, target depth).There is, as yet, no widely accepted method for quantifying the ground penetration depth measurement information. Different measures, such as minimum penetration depth, average penetration depth, penetration efficiency etc. have been used in the past. In the following paragraphs some quantitative parameters are discussed, and two of them are proposed as most suitable to represent the information captured during ground penetration depth measurements.

When analysing and presenting ground penetration depth data it is further important to indicate the width of the machine tool processing path over which the ground penetration depth measurements are being evaluated.

Ground Profile Measurement Locations

CWA 15044 specifies that only the centre 50% of the machine working tool width be used for laying out the target mines during the performance test. There are two main reasons for this.

- If targets are located across the entire width of the tool, minute errors in steering can result in mines being outside of the path of the machine. In this case, it is a combination of operator performance and machine performance that is measured rather than just machine performance.
- With flails, the edges of the cut are usually not straight, but are rather curved, or show a shoulder section as shown in Figure 3. Targets that lie very close to the edges of the flail will normally be processed by subsequent passes of the machine which are always overlapped to avoid missed areas and to ensure that this boundary condition does not create a skip zone. CWA 15044 recognizes this and restricts the targets to the centre 50% of the flail width.

For consistency, it is suggested that the ground penetration depth measurements be analyzed along the same centre 50% of the machine working tool width.

Figure 3: Curved edges of flail cut

Ground profile measurement interpretation and presentation

Introduction

When a demining machine such as a flail or tiller cuts consistently and uniformly down to a certain depth, one can be reasonably sure that the mines will at least be engaged by the hammers. On the other hand, the ground depth penetration measurements depicted in Figure 4 show hypothetical cases in which the machine has failed to cut uniformly to a particular depth and hence missed mines. Clearly, all four examples point to different levels of performance, and it is important when a quantitative parameter is used that it reflects these different performance levels.

One way to quantify the performance based on ground penetration depth measurements would be to simply read off the minimum depth achieved. In this case the first two panels would result in equal performance with effectively zero depth achieved. The third panel would achieve an effective depth of 10 cm, and panel 4 would get a 1 cm rating. While this is simple, it may not be a particularly meaningful way to quantify ground penetrating performance. The maximum depth is of even less value for this purpose. Average depth is also easy to calculate and understand, but Figure 4 shows that this may not be particularly useful.

Another method might be to calculate the amount of soil that would have been removed and then to calculate the amount that remains. In panels 1, 2 and 3 of Figure 4 the maximum depth appears to be 25 cm. If we assume a total width of 100 cm, then the total amount of soil that would have been removed (as seen in this profile view) would be 2500 cm^2. In panel 1, approximately 1250 cm^2 remains, so only 50% of the soil to 25 cm depth has been removed. Panel 2 is similar but only about 30% of the soil to 25 cm depth has been removed. In panel 3 about 90% of the soil to 25 cm depth has been removed, but fully 100% of the soil to 10 cm depth has been removed. Panel 4 could be evaluated in a similar way. This is a relatively simple way to quantify the ground penetration depth measurements during a test scenario, but again, it may not be very meaningful. None of these methods gives any consideration to the possibility of mines being hidden in the surface irregularities.

Therefore two parameters, the **Maximum Effective Depth** (**MED)** and the **Penetration Efficiency (PE)** are proposed as parameters which may be more useful in quantifying the ground penetration depth measurements of the test area. Both parameters evaluate ground penetration depth performance in terms of where a mine could be hidden from the machine working tool, i.e. how well it eliminates places for mines to escape the flail hammers (or other machine elements such as tiller teeth). The parameters are relatively easy to obtain and have direct relevance to the needs of deminers and/or machine users.

Maximum Effective Depth (MED)

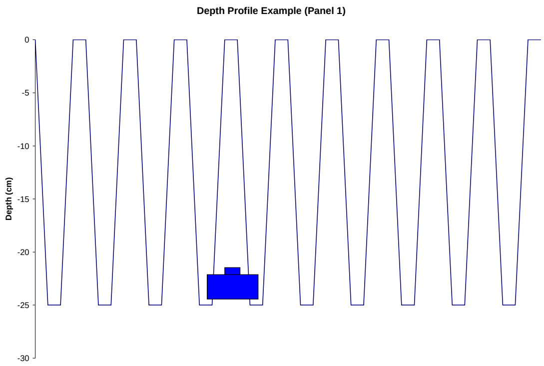
See Figure 5. Assuming a mine which meets the antipersonnel mine target sizes listed in the CWA 15044, the profile in Panel 1 would be rated to a depth of 25 cm. Any mines above 25 cm depth of burial (DOB) would be contacted by the hammer head and either triggered or damaged somehow. Below that depth, mines would escape the hammer head.

Panel 2 shows three possibilities. The blue mine begins to peek out of the skip zone at about 12 cm DOB. The red mine has the corners exposed a little more at about 5 cm DOB, and the yellow one shows 0 cm DOB where most of the mine is still hidden but where the fuze is exposed. Which of these three depths one chooses will depend on whether one assumes damage to the mine will occur with only a small slice of the mine exposed.

Panel 3 is a little easier to evaluate; the mine stays entirely hidden until the fuze pokes out at 10 cm DOB.

Finally, in Panel 4, the blue mine begins to be exposed at about 15 cm DOB, but one might debate whether it would actually incur damage with only the corner exposed. Certainly the red mine at 11 cm DOB would likely be triggered or broken.

The **Maximum Effective Depth** (**MED**) is defined as the minimum depth at which mines can be hidden in the remaining soil. In other words, if a machine processed some of the ground to 10 cm or deeper but left areas processed to only 6 cm deep, the maximum effective depth would be 6 cm. From the deminer's perspective, this is perhaps one of the most useful measures of performance as it allows the deminer to have some confidence in the results down to that depth.



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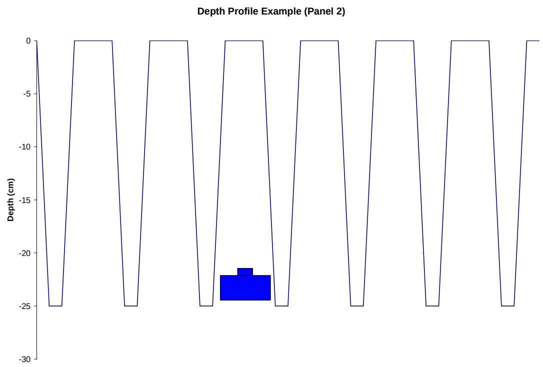

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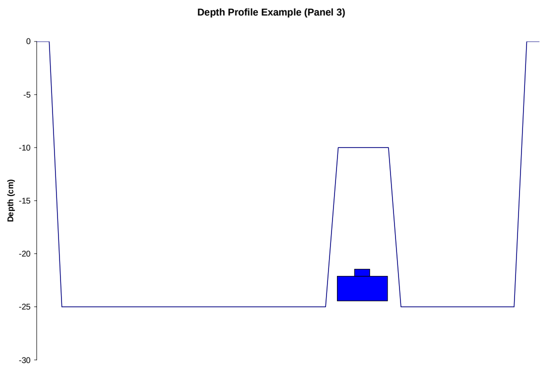

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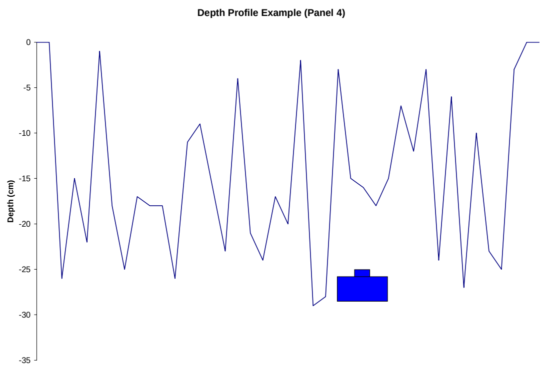

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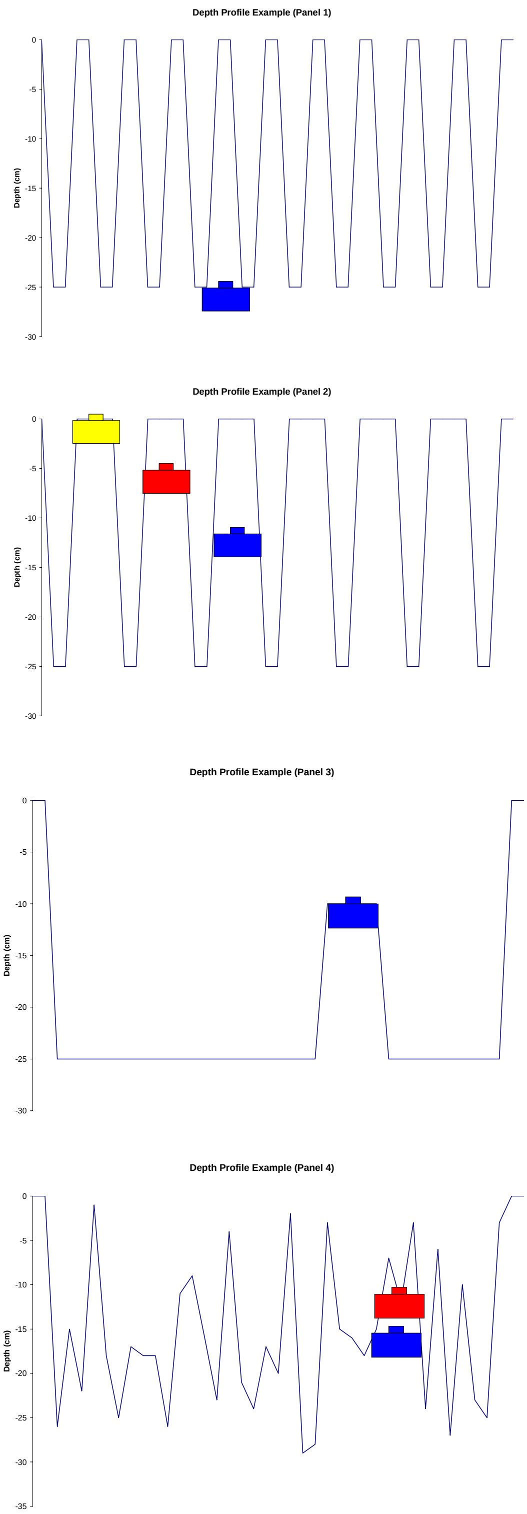
Figure 4: Hypothetical ground penetration depth measurements



1.

2.

3.

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Figure 5: Hypothetical ground penetration depth measurements – hidden mines Technique

Penetration Efficiency

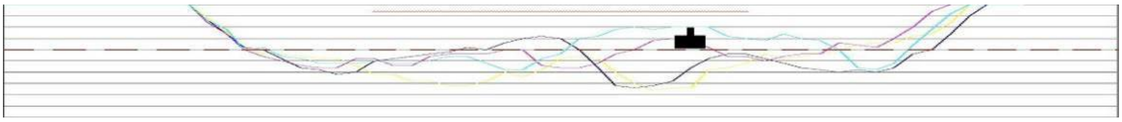
The definition of maximum effective depth is easily understood and relevant to the deminer, but it may not tell the entire story. Consider the case where three fibreboards for one machine showed three perfectly smooth, consistent, uniform profiles, each measuring to 25 cm deep, and a fourth profile which was similar except for one 8 cm wide skip zone that reached the surface. In this case the one small skip zone negates the otherwise good performance and reduces the maximum effective depth to 0 cm for the entire test. Consider a second machine which had four uniformly poor profiles, in which there were no penetrations deeper than 3 cm and where most of the ground was not penetrated at all. This machine would also be considered to have a maximum effective depth of 0 cm. Using only maximum effective depth, both of the machines would appear to have equal ground penetration capabilities.

A second, and complementary, method for quantifying and presenting the ground penetration information could be to look at how effectively the machine achieved ground penetration to a particular depth of interest. The depth might be the depth at which mines were buried for the test, or it could just as easily be some other randomly selected depth of interest. The same method is applied in either case.

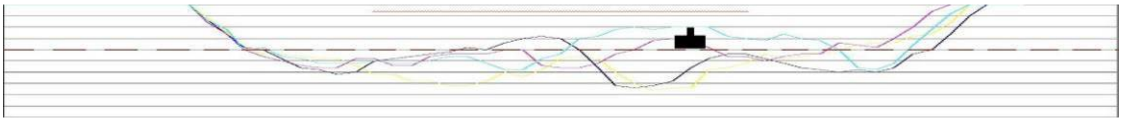
To illustrate this technique, consider the example case shown in Figure 6, which shows four penetration depth profiles from an actual machine test. In this example mine targets had been placed at 10 cm DOB, so the example will evaluate the penetration efficiency to that depth, shown by the dashed line across each profile. As noted above, to maintain consistency with the target locations defined by CWA15044, the analysis is restricted to only the centre 50% band, indicated with the top brown line across the centre of the profile. The same procedure would be followed exactly to take the analysis to the full width, or to look at a different depth.

Each panel in Figure 6 shows the four ground penetration depth profiles measured in one machine test (test lane) superimposed, and also includes the outline of a WORM-type mine target (to scale) at the maximum effective depth location.

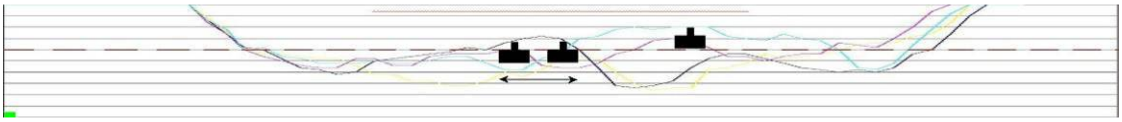
- The first panel shows the target located at the maximum effective depth (MED). The target located at the MED is repeated in the remaining panels. For each of the profiles, ask the question "is there anywhere on that profile that a mine buried at 10cm DOB would have been able to hide from the flail hammers?"
- The second panel examines the first profile of ground penetration depth measurement, shown in yellow. In this case, the ground penetration of the machine tool was deep enough all the way across the centre 50% band that no mines buried at 10 cm DOB would have escaped the flail hammers.
- The third panel shows the second profile in dark blue. In this case there is an area where mines at 10 cm DOB might have been able to hide from the hammers. One mine outline is shown at the left edge of this area and one at the right edge, with the arrow showing the complete width of the affected area.
- The third measured profile, in light blue, is shown next. In this case, there is also an area where 10 cm DOB mines could hide. The mine outline on the left is clear, and the one on the right partially overlaps the mine that shows maximum effective depth. Again, the arrow shows the width of the area.
- Finally, the fourth measured profile is seen with the light purple line in the bottom panel. Again, two mine shapes and an arrow show the affected area.



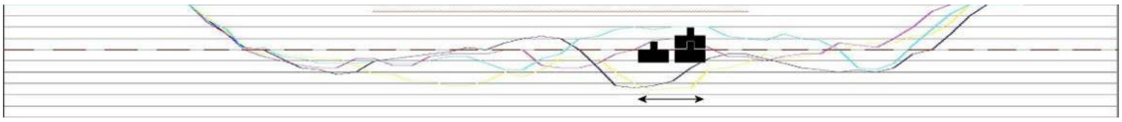
Panel 1: Target located at maximum effective depth: WORM-mine targets located less deep will be engaged by the machine tool



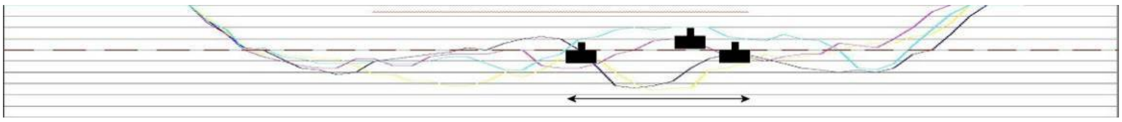
Panel 2: One target located at maximum effective depth. Moving a target buried at 10 cm depth (measured to top surface of target!) over the width of the yellow profile shows that there are no places for the mine to be hidden



Panel 3: One target located at maximum effective depth. Moving a target buried at 10 cm depth (measured to top surface of target!) over the width of the dark blue profile shows that there are places for the mine to be hidden



Panel 4: One target located at maximum effective depth. Moving a target buried at 10 cm depth (measured to top surface of target!) over the width of the light blue profile shows that there are places for the mine to be hidden



Panel 5: One target located at maximum effective depth. Moving a target buried at 10 cm depth (measured to top surface of target!) over the width of the purple profile shows that there are places for the mine to be hidden

Figure 6: Penetration efficiency, example for targets buried 10 cm deep

The widths of each of the areas of interest are measured and compared as shown in Table 1. In this case, the measurements are in pixels as they were taken directly on the digital images from the fibreboard photographs. They could as well have been measured directly in metres, inches or any other convenient unit since the final values are not dependent on the units used.

In this example, there was the possibility that mines at 10 cm DOB could have escaped the flail hammers across 22% of the centre band area. However, the machine in this test lane achieved sufficient ground penetration to ensure that, for 78% of the centre band, none of the specified mine targets at 10 cm DOB would be missed by the flail hammers. Hence PE_{10}=78% for this test lane. Again, the same analysis could be done for the full width or for other depths of interest on this same set of profiles, and because the final rating is a percentage, it does not matter what units are used to measure the widths.

Table 1: Penetration Efficiency – Example – 10 cm (from Figure 6)

Profile #	***Centre 50% Band Width (pixels)***	***Missed Area Width (pixels)***	***Percentage of Width Missed (%)***
Profile 1	845	0	0%
Profile 2	845	177	21%
Profile 3	845	150	18%
Profile 4	845	409	48%
Overall Width	3380	736	22%
PE_{10}=78%			

The **Penetration Efficiency** at some depth 'x' (**PE_x**) refers to how much of the processed path would actually have allowed the machine to engage mine targets at that depth. Hence, if a profile showed that 20 cm depth had been reached across a total of 80% of the width of that profile, the penetration efficiency would be given as PE_{20}=80%. With the basic profile measurement data the penetration efficiency at any other depth can easily be determined.

Methods for Calculating MED and PE

Assuming that fibreboards have been used in a test, the simplest way to evaluate MED and PE is to use a full-sized paper cutout of the mine profile. Finding the shallowest depth at which the mine can hide is quick and easy and can be measured right off the fibreboard, giving Maximum Effective Depth (MED). Placing a straightedge across the fibreboard at the depth of interest for Penetration Efficiency, the paper cutout can be moved to locations where the mine can hide. The width of each location can be measured and tabulated as shown in the example above to give Penetration Efficiency for that depth.

If many tests or profiles are to be evaluated, it may be useful to be able to evaluate them electronically. In principle, this can be done quite easily:

- take a digital photograph of the fibreboard
- using any of a number of image processing programs, trace the cut edges of the fibreboard, and capture the x-y pixel locations along the cut edges.
- Create a spreadsheet with the necessary functions (equations) to compare the x-y pixel values with the size of the mine to give both MED and PE.
- Import the x-y pixel locations into the spreadsheet.

A detailed procedure for this has been worked out and used on at least two occasions [1] [2]. Experience in these cases shows that all of the photo processing, data capture, and spreadsheet analyses can be done in under five minutes per fibreboard. Any software engineering student could probably create a quicker, easier, single-package program which would do in a fraction of the time, but this has not been pursued. Interested parties can obtain the spreadsheet and procedures from the ITEP website and/or Defence R&D Canada – Suffield (Geoff Coley +1-403-544-4046; William Roberts +1-403-544-4756; Russ Fall +1-403-544-4769).

[1] **Demonstration Trial of Bozena-4 and MV-4 Flails,** G. C. Coley, D. J. Roseveare, P.G. Danielsson, T.T. Karlsson, S. M. Bowen, L. M. Wye, F. C. A. Borry, 2007.Available at http://www.itep.ws/pdf/NairobiFinal.pdf

[2] **Machine Demonstration Analysis and Preliminary Results,** G. Coley, 2007. Available at http://www.itep.ws/pdf/MachineDemoSibenik2007_Coley.pdf