Introduction

In October 2006, the International Test and Evaluation Programme for Humanitarian Demining (ITEP) undertook an in-country side-by-side trial of two COTS flail machines, the DOK-ING MV-4 and the WAY INDUSTRY Bozena 4. Participants from Canada, Sweden, the United Kingdom and Belgium carried out the trial at the premises of the International Mine Action Training Centre (IMATC) in Nairobi, Kenya, which also provided all logistical support.

Both light flail machines used in the trial have already been tested extensively, and are currently deployed in a variety of demining operations around the world. The performance numbers for the “new machines” in “standard operating conditions”, as published by the manufacturers, are well known and have been confirmed using, amongst others, the standard testing procedures recommended by the CEN Workshop Agreement on Test and Evaluation of Demining Equipment (CWA 15044, July 2004).

However, environmental conditions in demining operations are not necessarily as they are in a standard test environment and new machines undergo wear and tear during deployment. Therefore, it was decided to organise a trial in which the performance of two widely used machines was evaluated for the particularly difficult environmental conditions local to the IMATC, and similar to those in Southern Sudan. The trial was further conceived so that it would be possible to assess the effects of flail hammer wear on the performance. Finally the trial was also intended to be a test case as to whether the performance testing guidelines of the CWA 15044 were applicable for testing in-country, outside specialised and purpose-built test facilities.
Trial design

All tests were initially based on the methodology for performance testing as specified in the CEN Workshop Agreement on Test and Evaluation of Demining Machines (CWA 15044). The details of this methodology can be found in the CWA 15044 document which is publicly available at the ITEP website (www.itep.ws).

In summary, standard performance testing is executed in specially prepared test lanes consisting of well defined soil types (specified soil texture, soil compaction and moisture content) without vegetation cover. Each test lane contains a minimum of 50 mine targets buried at the same depth, and at least three different burial depths (flush, 10 cm, 15/20 cm) are considered. The mine targets comply with a number of specifications and are placed creating minimum disturbance to the surrounding soil. Furthermore, it is recommended to determine the clearance tool penetration depth and the variation of this penetration depth across and along the clearance path, which is generally done using 3 fibreboards inserted in the test lane. These fibreboards are intended to act as witness panels to record the depth of penetration of the flail hammers.

From the onset of the trial, it had been the objective of laying out the test lanes maintaining the local conditions, i.e. no soil preparation according to the standard conditions described in the CWA 15044 and no removal of the (albeit sparse) vegetation. This would allow the test team to judge if certain standard conditions could be sacrificed without compromising the results. Hence, the preparation of the test lanes consisted mainly of target and witness board insertion. The mine targets used in the trial were those specifically developed by the Canadian Centre for Mine Action Technology to be compatible with the performance test target guidelines described in the CWA 15044. They are known as Wirelessly Operated Reproduction Mine (WORM) targets. The WORM system is an easily transportable inert testing system, and specific targets can be traced and evaluated electronically as being live, triggered or damaged.

However, the particular difficult soil conditions at the IMATC resulted in the need for further deviations from the standard test protocol. The soil at the IMATC appears to be a type of vertisol and is locally referred to as “black-cotton” soil. Black-cotton soils have a high content of expanding and shrinking clay and are very hard with deep cracks when dry. The trial was carried out at the end of the dry season which consequently presented extremely hard soil conditions with deep cracks running randomly through it (Figure 1). Due to the soil constraint and without some of the specialised equipment that is available at test centres, it was not possible to install either the mine targets or the fibreboards in the manner prescribed by CWA15044. The mine target holes as well as the soil slit created to insert the fibreboards were generally larger than recommended.
Figure 1. General and detailed view of the cracks in Black Cotton soil. Below, a WORM target in an excavated hole.
Tested machines

Both machines used in the demonstration trial are classified as light flail machines. Further machine details can be found in the GICHD Mechanical Demining Equipment Catalogue and on the manufacturers’ websites (DOK-ING MV-4, WAY INDUSTRY Bozena 4).

In order to evaluate the effect of hammer wear on the flail effectiveness, each machine was run with new hammers and also with a set of artificially worn hammers. The wear was artificially applied by grinding new hammers, emulating worn hammer samples provided by the manufacturers. The machines were also run without hammers, which ought to be considered as a purely theoretical test, as neither of the manufacturers recommends running their machine without hammers. The hammer wear/no hammer tests were carried out with mine targets buried at 10 cm depth only.

Both manufacturers were given the freedom to “tune” their machines as they saw fit to best deal with the hard, dry soil. There were no restrictions on what the machines could do with respect to depth control of the machines. The manufacturers were asked, though, to select a constant speed for a particular test. Then, if desired, different speeds could be selected for subsequent tests/test lanes.

Trial results

Machine performance

Details of the performance of the two machines are contained in the final trial report, soon to be released through the CCMAT website (www.ccmat.gc.ca) and the ITEP website. The tests did not reveal any real differences in the performance of the two machines. Both machines had difficulty dealing with the soil conditions at this test site, which is not surprising given the characteristics of the vertisol soil. Indeed soil experts cite difficulty in working vertisols, even with heavy machinery.

It was not possible to draw firm conclusions about the effects of hammer wear on effectiveness, except to state that it appears that you can compensate for worn hammers by driving the machine more slowly and thus giving the worn hammers more time to work. The trial could not reveal the point at which it becomes impractical to drive slowly enough to compensate for wear. More details on this topic are also available in the final trial report.
Lessons learned

Conduct of the trial

While this trial did not show any significant differences between the two machines, it demonstrated several things about the way trials should be conducted, and about how certain trial data should be treated.

First of all it showed that trying to apply the CWA 15044 standard performance guidelines during acceptance or in-country trials will inevitably lead to compromises of the prescribed standard conditions, which may frequently result in incomparable and/or invalid final data. In the case of this trial, it seemed that important standard conditions were lost so that, in all but one test, the mine target data was discarded as invalid and misleading. An important lesson learned was that performance tests should be restricted to facilities where CWA15044 conditions can be met in order to avoid the collection of performance data that are either only applicable to the very local conditions in which they were obtained or are misleading and invalid.

Second, it was agreed that there would be merit in complementing the CWA15044 test guidelines by an improved description of the CWA15044 acceptance tests. The current CWA15044 is primarily focused on the performance and survivability tests of machines for demining operations. By comparison, it deals with acceptance tests, or in-country tests in a much briefer and more general manner. The current trial showed clearly that the soil condition is a very important factor influencing the potential of a demining machine to reach its (quoted) optimal performance and that there is a need to better describe/quantify these soil conditions in order to allow the results of performance tests to be translated into the local conditions where acceptance tests are conducted.

Last but not least, the trial pointed out that carrying out side-by-side tests of two competing machines can cause some real problems with how the machines are operated, and with how the tests end up being run. It became clear that any such comparative test should require the two teams to be completely segregated from each other, and access to ‘the other team’s’ test data should be restricted.

Trials in hard soils

The procedures outlined in the CWA15044 performance test concentrate on the use of mine-like targets, with the use of in-ground fibreboards to show how uniformly a machine penetrates the ground.

Mine targets and hard soils – A misleading combination

To illustrate the encountered problem, consider the imaginary example, shown in Figure 2, in which mine targets have been encased in a large block of concrete. At one spot, a mine target has been placed in a hole in the concrete, which has been backfilled with a layer of soft leaves. In the first panel of Figure 2, a single flail
hammer approaches the hard concrete surface. When it hits the surface, it bounces as shown in the second panel, perhaps chipping the surface, and is pulled around for another strike. With the very hard surface, the hammers have limited surface penetration, and the effectiveness against the mine targets is minimal. In panel 3 the hammer has reached the soft, leaf-filled hole. Of course it plunges deep into the hole, and triggers or breaks the mine target. If the hole is very deep or very narrow, it is more difficult for the hammer to reach the mine target, but it is a very easy target if the hole is relatively large and shallow. Finally, in the fourth panel, the hammer has moved on and is prepared to resume the chip-and-bounce process as it hits the hard surface again. Very clearly, the results with the mine target in the soft hole are not representative of what the machine is doing to the mine targets under the hard surface.

Figure 2. Hammer Strikes on Hard Surface - Example
While the mine targets in the Nairobi trial were not encased in concrete, this example is actually reasonably close to the situation encountered in this trial. Consider the image in Figure 3. It is quite obvious that the flail hammers have achieved inconsistent and only relatively shallow penetration in the hard surface. Figure 4 demonstrates that at least some of the apparently deeper hammer penetration is due to the mine burial holes themselves. The deepest part of this particular profile still has the remains of the sand used to fill the hole.

Figure 3. Poor hammer penetration in hard surface

Figure 4. Deep Hammer Penetration in Soft Holes
While the example of Figure 2 is admittedly extreme and unrealistic, the photographs shown in Figure 3 and Figure 4 demonstrate that the example actually tells the story in an accurate way for very hard soils.

One might reasonably ask whether all trials conducted in which the mine targets are placed in holes which are soft, relative to the surrounding soil, are therefore suspect. The answer is that it will depend on the capability of the machine and how hard the surrounding soil is. If the soil is hard enough that the machine cannot reliably cut to the depth necessary to engage the mines, then yes, the data at that depth of burial might be suspect if it shows an apparently good rate of mine neutralisation. On the other hand, if the machine is able to penetrate the surrounding soil, then one can conclude that the machine is actually engaging the mine targets and the mine target data is valid.

This all means that when the surrounding soil is extremely hard, and the mine targets are covered with soft soil in oversized holes (as was the case for these tests), they will be prone to give artificially high performance indications. It is critically important to evaluate the ground profile to see whether the machine is indeed penetrating uniformly, and to the necessary depth. If the profile is smooth and shows a consistent ability to dig to a given depth, then the data from the mine targets is probably realistic. If the ground profile is uneven, it suggests that the soft holes are compromising the mine target data. In this case, the ground profile provides the more valid measurement of performance.

This discussion applies whether one is using the WORM targets, inert mines, or any other mine or mine simulator; the problem is not the mine target itself, but rather the hole needed to bury the target.
Ground Profiles – What do they mean?

The CWA 15044 recommends the use of three fibreboards during the performance test to evaluate the penetration profile across the clearance path of the machine (Figure 5).

Installation of the fibreboards in the Nairobi trial was hampered by the hard vertisol soil, in much the same way as the installation of the mine targets. It was not possible to create very narrow slits in the soil, and the resulting trenches were wide enough that they acted just like the soft holes in concrete in the hypothetical example shown in Figure 2. Happily, with hard, dry soil conditions, it was possible to simply brush away the loose soil without disturbing the bottom of the cut, and measure directly down from a straight edge (Figure 6). It would be difficult to do this in soft or wet soils, but it worked well in this case.
Although CWA15044 recommends the use of fibreboards to illustrate the cutting ability of machines such as flails, it does not offer any guidance on how to quantify the information provided by the fibreboards. As the Nairobi trial showed that it is critically important to evaluate the ground profile in order to assess the validity of the mine target performance results. Two separate measures to quantify the ground penetration have been developed by the ITEP test team: the Maximum Effective Depth (MED) and the Penetration Efficiency (PE). Both are based on the measurements of ground penetration whether measured directly as done during this trial, or through fibreboards.

Maximum Effective Depth (MED)

From a deminer’s perspective, perhaps one of the most useful measures of performance of a flail, or other ground penetrating machine, might be the maximum depth to which the machine can be counted on to cut uniformly and reliably. 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. This parameter allows the deminer to have some confidence that, down to that depth, it is unlikely that mines might be able to hide from the effects of the flail hammers.

Determining maximum effective depth, or MED, is relatively straightforward. A mine, or a profile image of the mine is simply laid on the ground profile and moved to find the shallowest depth at which it can remain hidden in the undisturbed soil. There is the question whether the entire width of cut should be considered or if allowance should be made for overlapping passes which will eliminate shortcomings in the shoulder regions of the profile. Figure 7 shows an example of MED. In this example, four separate profiles were taken in the test lane; each is shown in a different colour. This example clearly shows that, although the machine did manage to penetrate more
deeply in certain places, it was possible for mines to remain hidden in undisturbed soil to a very shallow depth at other locations. With the horizontal lines spaced at 25mm intervals, the top of the mine (not the top of the fuze) is at about 45mm depth. Hence, in this case, the deminer could only be confident that mines down to 45mm would be engaged by the flail hammers on a reliable basis.

![Figure 7. Maximum Effective Depth Example](image)

**Penetration Efficiency (PE)**

The definition of Maximum Effective Depth (MED) is easily understood and relevant to the deminer, but it may not tell the entire story. Consider the case where one machine had three perfectly smooth, consistent, uniform profiles, each measuring to 25 cm, and a fourth profile which was similar except for one skip zone, 8 cm wide and 10 cm long that reached the surface. In this case the single skip zone reduces the maximum effective depth to 0 cm. 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, and so, according to MED, both machines would be considered equal.

A second method for quantifying and presenting the profile information was developed which looked at how effectively the machine achieved ground penetration to a particular depth. The depth in question might be the depth at which mines were buried, or it could just as easily have been a randomly selected depth of interest.

Figure 8 shows an example of the Penetration Efficiency (PE). In this example, the mine shape in the upper left corner is at the MED location, at a depth of only about 3cm. This example looks at the penetration efficiency at a depth of 15cm for the dark blue profile. Placing the shape of a mine at a 15cm depth of burial (measured to the top of the mine, not the top of the fuze), it is clear that there is an area on the left side of the profile where mines at 15cm could lie untouched. This area extends about one quarter of the way out from the left edge of the cut before the flail hammers would have encountered mines at 15cm. There is also a small area on the far right side where a single mine might lie untouched. Finally, near the right side there is an area where a few more mines at 15cm could be unaffected by the flail hammers where the dark blue profile was measured. For the dark blue profile, about 45% of the width had places where mines at 15cm could lie untouched by the flail hammers. Conversely, about 55% of the blue profile was deep enough to ensure that the hammers would encounter mines at 15cm, so for this one profile PE\textsubscript{15}=55%. The same procedure was
used to measure each of the other profiles in this test lane and then the values averaged to give a PE\textsubscript{15} value for the entire lane.

![Figure 8. Penetration Efficiency Example](image)

Penetration efficiency is also straightforward and easy to determine, but, unlike maximum effective depth, PE needs to be determined for each profile, and is dependent on what depth is being discussed. It is therefore more time consuming to determine if it is being done manually.

*Ground Profiles – The Big Picture*

While some might question whether it is appropriate to quantify the performance of a machine based on only three or four profiles, each of the profiles represents several dozen individual depth readings. In the case of this trial, each test lane was characterized by up to 180 separate measurements.

With MED giving the worst-case scenario and PE quantifying the degree of success a machine had in reaching a given depth, the ground profile can be a useful measure of machine performance for a flail or some other ground penetrating machine. In certain cases, such as the Nairobi trial, these two parameters may well provide a more valuable indicator of performance than the use of mine targets.

A detailed discussion of the ground profile data collected during the Nairobi trial and the MED and PE obtained at different depths can be found in the final trial report.

**Conclusions and recommendations**

The in-country trial of the Bozena-4 and MV-4 mini-flails showed that, based on the data that could be obtained, there was little performance difference between the two machines under the test conditions. Certainly it is possible that differences in operating procedures might show some differences, but it was beyond the scope of the trial to do an exhaustive evaluation of this effect. Similarly, a glimpse of the effects of hammers wear on performance was obtained, but more detailed testing of this effect will be needed before definitive statements can be made.

Despite the complications in the in-country trial of the Bozena-4 and MV-4 mini-flails, the trial was successful in several ways. Valuable insight into the conduct of future trials was gained, and meaningful ways to quantify ground penetration were developed.