Chapter 1

Mechanical clearance

Summary

Manufacturers, research and development agencies and field operators have largely ceased to regard mechanical clearance — the use of stand-alone mechanical systems to fully clear minefields — as achievable. Yet, this sub-study has found evidence from the field to suggest that full clearance may sometimes be the result of ground preparation by certain machine systems, notably flails, mechanical excavators and tillers. Based on the record of demining machines gained since the late 1980s, machines perform best where soil is not saturated with water or as dry as dust, and where terrain is not too steep or too rough. Steep gradients pose one of the most significant limiting factors on the ability of a flail to operate. Rocky ground is also an important obstacle. However, the precise circumstances under which humanitarian mine clearance by machine may occur remain to be determined.

Introduction

Background

Since the start of humanitarian demining at the end of the 1980s, the use of stand-alone mechanical systems to fully clear minefields — mechanical clearance — has been hailed as the ultimate goal to which all mechanical development efforts should be directed. A decade and a half later, expectations have greatly diminished. Manufacturers, research and development (R&D) agencies and field operators have largely ceased to regard mechanical clearance by machine as achievable. As a consequence, mechanical systems have typically been deployed in clearance operations in conjunction with manual demining and MDDs, for ground preparation, area reduction and, as part of the quality control process, cleared area confirmation.

Terms of reference

A choice of stand-alone mechanical systems exists — flails, tillers, rollers, sifters, combined and multi-tool systems, and adapted commercial engineering machines. This chapter reviews the characteristics of these systems, their impact on the ground and mines within it, and considers their potential for mechanical clearance.

The term "mechanical clearance" is here defined as the application of machines as the primary clearance method to remove and/or destroy mines and unexploded ordnance (UXO) from a given area to the quality of clearance laid down for clearance by the International Mine Action Standards (IMAS). Manual or MDD teams may, of course, be subsequently used as independent quality assurance (QA) of the area.

Insufficient information is available on the physical consequences for the ground and any mines under or on its surface from the beating of a flail, the grinding of a tiller, or other forces exerted by various systems. Testing of machinery using live, surrogate or dummy mines has been limited. Some manufacturers, national testing agencies and mine action centres have conducted testing and accreditation of vehicles in order to gauge their level of effectiveness, but these could be further developed.

Missed mines and any possible relationship to mechanical systems are not extensively recorded. Often, they are only noted when they are the cause of an accident or incident. Independent QA is still not widely carried out, particularly outside Europe, and records that are kept may be jealously guarded, incomplete or inaccurate.

Chapter layout

Following this introduction, the remainder of the chapter has five sections.

Section 1 addresses flail systems. It describes how flails function and explains some of the physical limitations on their capability for ground processing.

Section 2 reviews tiller systems, describing how they function and the physical limitations that may affect their capability for ground processing.

Section 3 discusses mechanical excavation, giving an overview of the technique of soil excavation and subsequent treatment/cleansing of potentially mine-affected, excavated soil.

Section 4 gives a brief overview of mine rollers and steel-wheeled vehicles, describing their successful role in area reduction and the reasons for their unsuitability for mechanical clearance.

Section 5 contains the conclusions, findings and recommendations of the sub-study research and assesses the implications for the possible use of machines as the primary clearance tool in the future.

Additional empirical evidence of machines clearing to humanitarian standards is provided in Annex 1 to this chapter.

Flail systems

Introduction

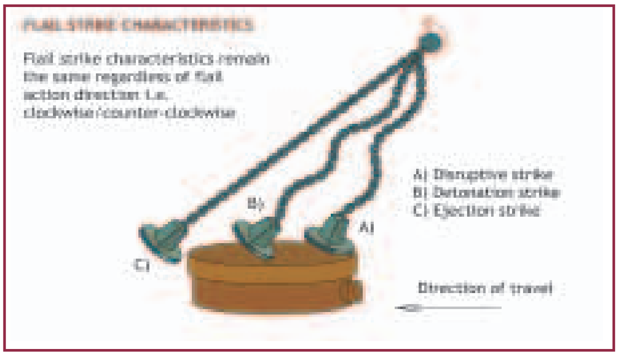
The most common type of mechanical system currently on the market is the flail. Flails have a long pedigree: prototypes saw service in the 1914-1918 war and were used extensively during the 1939-1945 war. From then until the early 1990s, however, flail systems developed slowly. It was the emergence of humanitarian demining that provided the impetus for advances in flail technology. More R&D funding has been invested in improving flails than in any other system.

Flails have largely developed as a result of market forces — improvements carried out by private mechanical engineering firms in the business for profit — but also through the work of national militaries. All operate according to the same principle: a rotating axle, shaft or drum with attached lengths of chain-link along its surface that impart violent impact to the ground when rotated at speed. Some flail designs have an advantage when encountering anti-tank mines. The stand-off provided by the distance of the chains to the flail unit axle allows the blast to dissipate somewhat before contact with the vehicle hull is made.[1] Mostly, however, flails are regarded as a tool against anti-personnel mines and small items of UXO.[2]

Flail strike characteristics

There is a lack of information on the sub-surface physical effects of mechanical clearance systems on mines. A length of chain hitting the ground at speed forms the core working methodology of all flail systems. The target is the ground and/or mines and UXO contained within it. The impact of the flail with its target is referred to as a *flail strike*. Three characteristics of flail strike are identified: a disruptive strike, a detonation strike and an ejection strike (*see Fig. 1*).

Fig. 1. Flail strike characteristics



Adapted from an original in Lower (2001).

Disruptive strike

A disruptive strike refers to a strike of the flail resulting in a mine or UXO becoming physically damaged. In the worst-case scenario, ordnance is damaged but is still functional, potentially becoming more dangerous than before it was struck. Preferably, and more usually, a disruptive strike will result in the ordnance being broken up to a point where it no longer functions. Fully functioning mines can be disrupted rather than detonated when struck by a flail so that the fuse mechanism fails to function correctly. In addition, mines that are disrupted may have become inoperative at some stage of their history since being laid and would not have functioned in the conventional manner. There is no known method to predict the ratio of mine break-ups between functional and non-functional anti-personnel mines.

It may be acceptable that when a flail is deployed to prepare ground for later clearance by other methods, mines are broken up to the extent that they are inoperable. The mine is no longer a threat to subsequent clearance personnel. The broken pieces are frequently found in a radius not significantly greater than the radius previously covered by the intact mine. Sometimes, however, random fragments can be strewn over a wide area. The spread of mine fragments may depend on the type of mine struck and the soil type and depth in which the mine was laid. The greater the depth, the less the spread of mine fragments but the less the corresponding likelihood of destroying the mine.

According to a number of operators, certain flails are capable of breaking up specific mine types into fragments no bigger than a thumb nail. If such systems are deployed across a suspect area for more than one sweep, results can be so effective that further clearance methods bear more resemblance to quality control (QC) than actual clearance. Small fragments of explosive material do, though, remain and would be signalled by MDDs, were they to be subsequently used. Metal fragments/small mine components would also be located by metal detectors. This approach has limitations, possibly dictated by mine type, soil type and topography; the parameters of these limitations are yet to be determined. The implications, though, are that given suitable conditions against suitable mine types, it may be possible to predict situations where flails could operate as a stand-alone clearance system.

Detonation strike

A detonation strike refers to a flail strike upon a mine or the soil above it causing it to detonate as a result of the impact of the chain initiating the fuse sequence. Detonation greatly helps area reduction as the presence of mines is immediately indicated. Detonations are not always complete. On occasions the fuse will function but the main body of the mine fails to explode (for example, because of moisture ingress). These are known as *partials*. Experience shows that mine type, soil conditions, engine power, ground penetration ability and the forward speed of the machine may influence whether a mine will detonate or break up when flailed.

Depending on the type of mine, a detonation may result in particles of mine casing fragments being distributed over a wide radius. Although the threat from the mine has been removed, detonation during mechanical ground preparation — where the task of the machine is to prepare the ground for primary clearance by other means — causes complications for subsequent operations over the same area for manual or MDD teams. If the mines were of a large metal content, thousands of metal splinters are indicated by metal detectors. For MDDs, explosive molecules create extensive contamination over the area to be cleared.[3] Thus, manual and MDD clearance operations over ground previously prepared by machines where the majority of mines were detonated is safer but may sometimes be more time consuming than if they had only been broken up.

Ejection strike

An ejection strike is a flail strike resulting in a mine being picked up and thrown clear of the flail unit. This effect is commonly known as a *throw-out*. In general, flail operators have found throw-outs to be a relatively rare occurrence, although the exact frequency is not known. It is likely, but difficult to prove, that throw-outs are caused by an incomplete strike of a chain link upon a mine. Instead of being broken up or detonated, the mine is raised from the ground to become briefly entangled in the mêlée of the rotating chains before being disgorged forwards in the path of the vehicle or to the side.

If the mine is thrown in front of the continuing path of the machine, it is unlikely to escape detonation or break-up a second time. Mines thrown into a previously cleared or non-suspect area pose more of a problem by creating suspect ground out of mine-free land.

Throw-outs are the principal contention among detractors of flail systems as a primary clearance tool. According to a number of field operators, mechanical engineers have made improvements to flail systems such that certain machines have almost completely eliminated the problem of throw-outs.[4]

Physical forces of flailing

A length of hammer-tipped chain link slammed onto the ground will be attended by a variety of violent physical forces, each affecting the result against a mine/UXO target in different ways. What these forces consist of, and their exact contribution towards a flail system destroying mines and UXO, is not entirely understood. In order to smooth out the problems of flail technology, it is important that the effect of these physical forces is as fully understood as possible. The impediments to flail efficiency can perhaps be negated, at least partially, by adjustments to flail power, the forward speed of the machine, hammer shape, ground depth penetration, flail shaft height in relation to the ground and flail shaft helix configuration (*see below*), to name only a few.

The features of a particular flail design may overcome some physical limitations while simultaneously accentuating the negative effects of others. It is a fine balance. A system effective in one soil may be less effective in another. The individual components that make up a flail need to be rationalised. The nature of soil mechanics may play a crucial role.

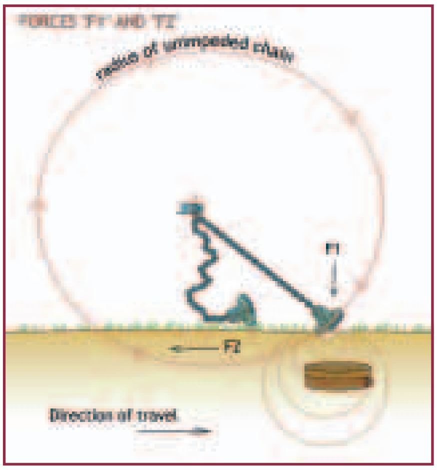
It is sensible to attempt to unravel what is happening to the chains as they hit the ground, drag through it, and continue their rotation through the next 360° cycle. Understanding of what actions occur in the ground when struck by a flail also requires investigation. To date, only limited scientific research has been conducted, notably the study by DRES (now Defence Research and Development Canada — Suffield) on behalf of the Canadian Centre of Mine Action Technologies (CCMAT).

The following is a simplified extrapolation of the findings of the study published in 1999 by DRES.[5] Some of the terminology has been altered for ease of understanding. The DRES study is largely theoretical, based on tests carried out at their test facility and never in live minefields. The findings require further verification, and it is possible that results would be different if the principles stated in the study were put to use in real field conditions. However, the Canadian study increases our understanding of the limitations of flailing as well as its potential.

The main forces

Two main forces have been identified in attempting to rationalise the physical phenomena endured by the chain links of a flail in operation, and in the ground it strikes *(see Fig. 2 overleaf)*.

Fig. 2. Force 1 and Force 2 characteristics



Adapted from an original in Shankla (2000).

Force 1

Force 1 (F1)[6] is the physical force which describes the sequence of actions that occur the moment an individual chain impacts with the ground. These actions would change slightly, depending on the hammer shape and whether a hammer is fitted to the end of a chain. The chain has extended itself straight due to the centrifugal force imparted on it by the high-speed rotation of the shaft to which it is attached.

From the moment the ground interrupts the trajectory of the end of the chain in its circular path, F1 plays its part. F1 takes place in the ground struck by the chain, but not along the chain itself. The 'F' in F1 is impact force. It can be expressed as a function of hammer mass (or in the case of a chain without hammer, the end link or links), angular velocity, flail radius and stopping time. Stopping time is represented by the ground, which provides resistance to the path of the chain. The power of the stopping time is reliant upon the characteristics and composition of the soil, a subject dealt with below.

F1 is responsible for the positive function of a flail: the initial impact of the end of the chain causes the mine to detonate or shatter. It therefore stands that F1 should be maximised so that detonation or shattering is the result.

Force 2

Force 2 (F2)[7] refers to various forces unleashed the instant F1 is played out. The chain is still being propelled at approximately the same speed as at F1, but is no longer straight as it fights against the ground into which it has been driven, and is dragged along until continuing upwards and away from the ground in its next cycle. F2 is the horizontal drag through and across the ground that has been penetrated as a result of F1. F2 accounts for three possible consequences when flailing. All of them negatively affect flail performance.

1. Bulking

Sometimes referred to as overburden, bulking is the loosened soil created by the action of the flail dragged through and across the impacted ground. Bulking is an effect well understood by the construction engineering and agricultural industries.

The measure of the bulking factor of soil is its volume after excavation divided by volume before excavation. As the flail moves along its path, a trail of loosened soil is left in its wake. In the event of a mine being missed by the flail, overburden may serve to conceal missed mines under a depth of loosened soil, exacerbating the difficulty of locating missed ordnance after a machine has completed its sweep. The amount of overburden created varies between mechanical systems and soil types.

It has been discovered that overburden can be significant enough so that some current models of metal detector are unable to detect mines and UXO buried as a result of it. The amount of overburden created increases the deeper a machine is required to flail. A ground penetration depth of 20 centimetres will produce roughly twice the amount of overburden created by flailing to a depth of 10 centimetres.

Fig. 3. SWEDEC test area demonstrating overburden/soil bulking.

2. Throw-outs

Throw-outs have been explained above in the section describing an ejection strike. Throw-outs occur as a result of the F2 phase of flail action. A length of chain having not achieved a hit on a mine during phase F1 may contact it during its subsequent horizontal path (F2) through and across the ground, picking it up and propelling it out of the flail rotunda.

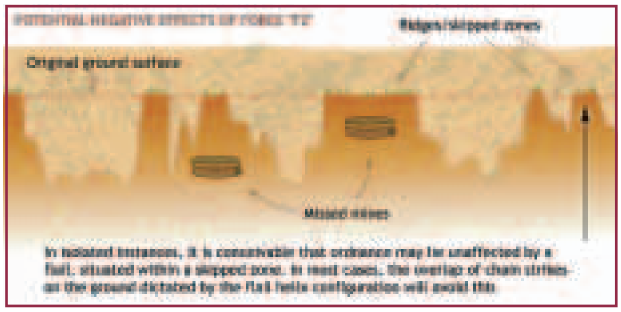
Fig. 4. Beaten zone of a flail system. Small sections of the ground show where chains may not have achieved a complete strike.

3. Ridges/skipped zones

The pattern created by the points at which chains are attached to the flail shaft is referred to as helix configuration. A flail helix configuration is usually designed so that when chains have hammers connected which are of greater circumference than chain links, all strikes upon the ground should be overlapped by adjacent hammers. The intended result is that no section of ground is missed by the flail. At reoccurring intervals, F2 defeats this aim. Once the impact at F1 has played out, the chain length buckles as the horizontal plane does not permit it to remain straight, as during its unimpeded flight prior to ground strike. The chain kinks and buckles in a snake-like motion. During phase F2, the overlap of impacting chains achieved at F1 is disrupted, allowing points of ground along the path of the machine to be skipped over.

It is conceivable that a mine/UXO could be situated within such skipped zones, which appear as ridges with an unbroken surface, islands within the trail of the machine, unless these are covered by overburden. Some flail manufacturers have minimised this effect by a combination of improvements to flail helix designs and, through increased rotation speed, achieving more strikes to the ground per metre. For certain flails, ridges/skipped zones remain a problem. On some flails, such likely shortcomings are immediately predictable due to the sparse positioning of the chains attached to a shaft.

Fig. 5. Skipped zones (illustration exaggerates effect)



Adapted from an original in Shankla (2000).

The manner in which a machine is operated will also have implications on the degree that ridges/skipped zones present a problem. Better results are recorded by machine operators when ground penetration depth selected is 10 centimetres or less. The lesser depth of penetration appears to minimise the ''snaking'' effect of chain lengths as they are dragged through and across the ground. Certain clearance contracts may dictate that systems must penetrate beyond 10 centimetres. The result may be an increase in ridges/skipped zones.

Forward speed of the machine also plays a part. In general, the slower the vehicle is driven while flailing the ground, the lesser the likelihood of ridges/skipped zones. Unfortunately, a slower-moving vehicle reduces productivity.

The DRES study argues that the increase of one of the force components leads to a corresponding decrease in the other and vice versa. Therefore, if the positive F1 is increased, the negative F2 will decrease to a corresponding degree. If this is the case, overburden, throw-outs and ridges/skipped zones can be reduced although not eliminated. Elimination of F2 would require a flail to use rigid arms instead of chains which give way when striking the ground. A stiff limbed flail (''fixed link'') would cause tremendous shock to a machine that could not possibly be absorbed by all but the heaviest chassis.

Fig. 6. Aardvark MK IV, Balkans.

DRES constructed a fixed link flywheel at their test facility. The violence imparted to the flywheel was so great that the fixed link was adapted to incorporate a ''knee-joint'' in the middle of each fixed link in order to absorb some of the shock. Currently, this design is showing high potential, achieving good results in tests against surrogate mines.

There are other means of increasing F1 at the expense of F2 for conventional chain flails. An increase of power to the flail shaft results in greater revolutions per minute, causing a much enhanced initial strike onto the ground (F1). The horizontal drag through and across the ground (F2) is curtailed. Where practicable, selection of a lesser ground-penetration depth may create advantages. Slower forward speed of the machine reduces productivity but is a preventive measure against ridges/skipped zones as it concentrates more strikes upon the soil per metre.

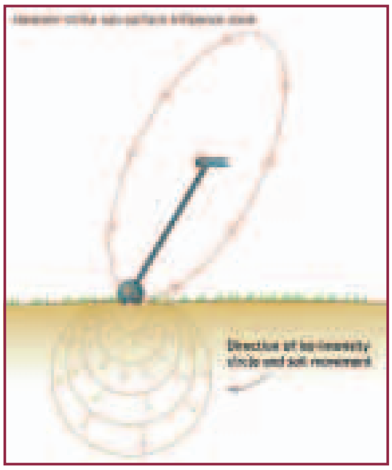
Impact stress distribution and soil movement

When the end of a chain impacts with the ground, a reaction is set off in the soil. Shock waves travel in roughly isotropic circles (i.e. equal in all directions) from the point of impact, travelling out in ever-widening but ever-weakening arcs in the manner of the ripple pattern caused by an object thrown into a pool of still water.

The area beneath the surface of the ground affected by shock waves as a result of being struck by the end of a flailing chain is referred to as the influence zone. The DRES study indicates that if the blow is delivered hard enough, ordnance within the influence zone may detonate or break up:

> *"The hammer impact forces the soil located under the hammer to give way and move. The pattern of soil particle movement depends on soil conditions. The impact of the hammer causes the soil particles located directly in front of it to move in the direction of travel with the same speed as the hammer. Hammer movement also affects the other soil particles located to the right and left side of the hammer. The cohesion and adhesion properties of the soil particles influence the relative movement of soil particles. Some of this movement is in the direction of the hammer and some towards the sides of the direction of hammer travel. Soil particles go forward and at the same time they may move to the sides until they are outside of the influence of the hammer, and finally, the hammer passes them and they come to rest."*

Fig. 7. Sub-surface influence zones



Adapted from an original in Shankla (2000).

The pattern of movement of soil particles underneath the hammer suggests the existence of an influence zone underneath the hammer. To simplify understanding, it can be assumed that the influence zone has a circular shape and moves with the hammer. The iso-intensity circles that are attached to each other at the hammer impact point create the influence zone. As the radius of the zone increases, the soil movement decreases. The smallest circle of the zone has the highest intensity as the soil particles close to the hammer have the highest tendency for movement. The largest circle that is representative of the soil particles some distance away from the hammer have the least tendency for movement.

The path of the movement of soil particles are lines drawn perpendicular to each circle's perimeter. Arrows show the path of movement of the soil particles. The magnitude and direction of the movement of each soil particle depend on its location within the influence zone. Soil particles located directly under the hammer will have the same velocity as the hammer. The velocity of soil particles would decrease towards the perimeter away from the centre of the influence zone. The points located outside of the influence zone would have no velocity and hence will not move.

Soil underneath the hammer is considered to have a semi-infinite dimension. At the start of the hammer impact, soil particles located beneath the hammer are displaced downward. After rearrangement of soil particles, when there is no margin for further soil compaction underneath the hammer, soil particles start to move to the sides. The influence zone is thought to move with the hammer. The movement of the hammer will affect soil particles located in a width equal to the largest diameter of the influence zone.

Depending on the location of the soil particles, the influence zone will be affected by one of the iso-intensity circles. The movement of the soil particles will be proportional to the intensity of the corresponding circle. Direction of movement of the soil particle will be perpendicular to the perimeter of the circle where the particles would be located. After this movement, the soil particles will attain a new position. A flail moving over a buried mine will, *depending on its forward speed*, initiate a series of impact points, each giving rise to a series of iso-intensity circles with their respective zones of influence.

Fig. 8. Soil stress distribution on a target

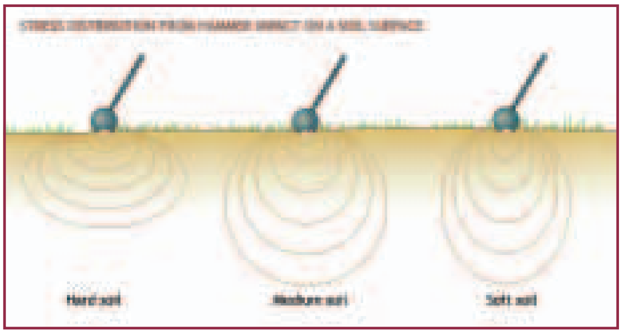
Adapted from an original in Shankla (2000).

An anti-personnel mine buried within the reach of these influence zones will experience increased pressure depending on the mine's location with respect to the point of hammer impact and the intensity of the impact. It is suggested that designers working on improving flails for mine neutralisation should focus on flails that create influence zones of the required duration and intensity, and of a diameter that is greater than the depth of ground required to be clear of anti-personnel mines.

It is the influence zone comprised of iso-intensity circles as a result of F1 that may account for the destruction of mines/UXO when a direct hit from a flail hammer (or chain link) is not achieved. A possibility exists that this indirect violence may be an effective way of destroying mines/UXO, largely because it presents an opportunity to minimise flail ground-penetration and the consequent negative effects of this as earlier identified.

Stress distribution in soil is not a new science, but not much of the knowledge in this field has been used by flail designers. Figure 9 overleaf shows soil stress distribution with contiguous and uniform iso-intensity circles. For ease of explanation, it was assumed by the DRES study that soil is elastic, homogeneous and isotropic. Actual soil is never all of these things at any given time but varies greatly in type and consistency, and can be afflicted with roots, stones and foreign objects. It can be assumed that the size and velocity of an influence zone imparted by a flail strike depends to a large extent on particular soil conditions.

Fig. 9. Effects of soil on impact zones



Adapted from an original in Shankla (2000).

Limitations imposed by soil, terrain and vegetation: extreme situations

Difficult ground and terrain are among the most limiting factors in the deployment of mechanical assets. Severe gradients, heavy vegetation, boggy ground, rocks and boulders can all determine whether a machine can be set to work in a particular suspect area. Different machines will be defeated by different levels of difficulty. Some ground and terrain limitations are related to problems suffered by the prime mover to which a flail may be attached, e.g. difficult traction or lack of power to operate uphill, and as such do not fall within the scope of this study. Other constraints may be due to the inability of a flail tool to contend with extremes of soil and terrain, factors of relevance to understanding flail action or appropriate identification of mechanical tasks.

Based on the records of demining machines since the late 1980s, machines perform best where soil is not saturated with water or as dry as dust, and where terrain is not too steep or too rough. Steep gradients pose one of the most significant limiting factors on the ability of a flail to operate. Manufacturers claim that current models of flail can move up inclines of 25º-45º (though only one machine was said to be capable of 45°). Most machines operate within the 30º-35º range, and even these figures refer more to ''hill-climbing ability'', the ability of the prime mover to drive up a hill.[8] It is doubtful that a flail tool can actually operate at gradients in excess of 30º. This restricts the use of flails over many types of terrain.

Rocky terrain is an obstacle to the effective deployment of flails. In broad terms, rocks begin to cause serious problems for flails when they are of five centimetres in diameter or more. The degree to which rocks create difficulty depends on the particular consistency of local stone, the power of the flail and the mass of the chains and hammers. Rocks and stones provide a shield to mines that lie beneath or near to them, greatly increasing the probability of a missed mine or an ineffectual, glancing blow.[9] Individual chains of the flail cannot connect with nooks and crannies protected by rocks. This problem has proved particularly acute in Lebanon, where the United Nations-coordinated operation in the south of the country has barred flails from attempting mechanical clearance.

The work-limiting parameters of soil and terrain are particular to individual machines. MDD and manual teams have similar restrictions of soil and terrain, except that their parameters are somewhat wider. When a machine is operated in a physical environment which suits its capabilities, full clearance is often achieved.

Ground penetration depth

The degree of ground penetration depth when operating a flail has significant implications on the forces at play during flailing. Currently, one of the main uses for machines in mine action is ground preparation. The ground preparation role for mechanical application is explained in Chapter 4. The sub-study on which the chapter is based concluded that machines are of more assistance to manual and MDD teams as well as more economically viable if they both cut vegetation *and* break up the ground. Currently, the IMAS state that clearance on a suspect area must be conducted to a depth indicated by a technical survey or at least down to the default depth of 13 centimetres. Many national mine action centres and commercial contracts stipulate that clearance should be conducted down to 20 centimetres.

Yet, according to a number of machine operators, maintaining a ground-penetration depth of the flail of 10 centimetres or slightly less appears to achieve better results.[10] Moreover, according to the DRES study, beating the ground with a flail with limited indentation to the ground may have a destructive effect on mines/UXO while at the same time reducing the negative effects caused by F2. It is asserted that this is a result of stress distribution and soil movement upon impact of a flail. Although not yet known, it is likely that there is an optimum ground-penetration depth at which flails are most effective. This would probably vary depending on the model of flail.

Effects of hammer geometry

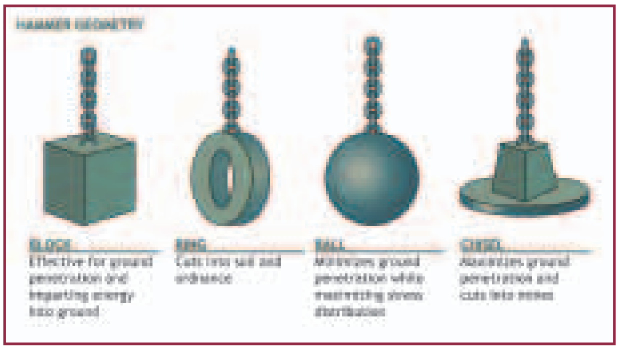
The ability of a flail to produce energy in soil sufficient to detonate or break up anti-personnel mines may be affected by hammer mass and geometry. The DRES study was based on the assumption that flail chains are fitted with a hammer. Flail chains without a hammer were not considered. Many flail operators interviewed during the research of this sub-study do not re-attach hammers onto chains, even when using systems for which hammers were part of design specifications. It appears that this omission is related to cost and wear-and-tear problems. Also, if a machine is employed purely in the ground preparation role rather than for clearance, hammerless flails appear to be effective.

The shape of a hammer may have a crucial role in flailing that is only partially understood by the demining community. It was earlier argued that the force component F2 may be the culprit behind soil bulking, throw-outs and ridges/skipped zones. This in turn was connected to the ground penetrating action of the flail. The ability of an individual flail to penetrate the ground is influenced by the shape of the hammer attached to it. Sharp-edged, chisel-shaped hammers will tend to cut deeper than rounded hammers. A blunt-edged or rounded hammer will reduce the ploughing action and surface disruption thereby minimising the effects of F2. Chisel-shaped hammers may increase the likelihood of a mine being shifted from its position without being rendered inoperable.

The DRES study argues that reduced surface indentation and penetration afforded by rounded hammers minimise the negative aspects of flails and accentuate their potential role in clearance. This has yet to be proven, and after initial field tests appears unlikely.

If, however, this concept does prove to be correct, something resembling the shape of a ball may be the optimal hammer geometry. It is not currently known if the fitting of rounded hammer shapes would have implications on a flail's ability to deal with vegetation. Hammers do play a role in vegetation cutting, but it is mainly the chain links themselves that fulfil the cutting action. The answer to this must await future test results and/or empirical evidence.

Fig. 10. Selection of hammer types



Adapted from an original in Shankla (2000).

Engine power and shaft height above the ground

The effect of engine power on a flail's ability to defeat mines has been briefly touched on. As suggested by the DRES study, in order to improve flail performance, force component F1 must be increased at the expense of F2. Theoretically, one way to achieve this is to increase the power from a prime mover to the flail attachment. The hammer or chain-link hits the ground with greater force. The influence zone is increased and thereby the potential to break up or detonate mines. A lowering of the flail shaft to the ground will also accentuate the force of a chain strike.

At the same time, though, the stand-off distance, which may be an advantage to flail systems in general, is compromised. This is due to the flatter angle between the shaft and the centre of the hammer mass at impact. However, both increase of power and decrease of flail shaft height above the ground also increase the potential for flail link to penetrate soil. This would in turn increase the negative effects associated with force component F2. To counteract this, a possible solution is a rounded hammer, which would increase the impact on the ground and reduce the ill-effects of ground penetration.

Some flail machines rely on the same power source for forward drive of the vehicle and flail shaft rotation. When a machine begins to struggle in difficult ground, power is taken away from the flail unit and given to the prime mover so that it may continue along its route. As a consequence, the flail slows down and chain impact weakens, as does its influence zone. Chains take longer in their dragging, horizontal path along the ground before the next cycle of rotation. The chances of throw-outs, overburden and skipped zones are potentially increased.

Machines with a guaranteed uniform flow of power to the flail head gain a distinct advantage. Despite difficult terrain, they can maintain rapid and powerful strikes against the ground, delivering a near-constant influence zone beneath the ground. Possibly, with an optimal hammer design, force component F2 would be reduced. High power also maintains a higher number of chain strikes per metre. A number of authorities have asserted that at least 70-80hp per metre of flail shaft must be maintained to achieve rotation speed sufficient for effective mine destruction (and reduced effects of F2). This is an approximate figure, which requires further testing.

Fig. 11. Armtrac 100.

Forward speed

Much of how a flail affects mines/UXO relies on a combination of the gearbox of the prime mover and the way it is driven by the operator. A balance must be found and maintained whereby a machine is driven slow enough to allow the flail to achieve a high number of strikes on ground within its path, but fast enough so as to maintain productivity. Too great a forward speed risks small segments of ground not receiving strikes from the flail (i.e. skipped zones). This can be partially alleviated by greater power to the shaft as the flail will turn faster and strike more often.

During research in Lebanon, two operators of the Armtrac 100 flail, one from the mine clearance company, BACTEC, the other from the Lebanese Armed Forces (LAF), found that forward speed of flail machines had a significant effect on what happens to mines. Operators from both organisations report that as the vehicle is driven faster, more anti-personnel mines (mostly the Israeli No 4 and sometimes the Italian VS 50) tend to detonate than break up. At slower speed, more break-ups occur than detonations. It is not known if this is caused by the soil, which is very rocky with large boulders, or the types of mine found in Lebanon, or a combination of the two. (The speeds here referred to are not exact and were simply described as “faster” and “slower”.) This phenomenon is not recorded in any other theatre of operations using this machine. It is therefore unlikely that the vehicle itself is the cause.

Dog handlers working for the U.S. company, RONCO, indicated that when deploying dogs on clearance subsequent to a flail, mine break-ups are the preferred result as contamination covered less ground than detonations. LAF flail operators reduce forward speed in accordance with this. It is not fully understood why changes in forward speed affect the result against some anti-personnel mines. The GICHD intends to investigate this, as well as the suggestion by the Mine Action Coordination Centre for Southern Lebanon that anti-personnel mines struck by a flail but not detonated can sometimes be rendered more dangerous than had they not been flailed at all.

Mine type

Mines may be anti-personnel or anti-tank and come in different shapes, sizes and designs. The types of mine encountered, as well as their condition, affect whether or not a flail will successfully destroy them. Fuse sensitivity, for instance, can be a result of design, or the result of its conditions of storage, handling or emplacement. The amount of time a mine spends in the ground and the climatic conditions it has endured will also influence whether or not it is still functioning. Water ingress, for example, is a suspected reason why mines might fail to operate as intended. Certain mines tend to degrade faster than others. For instance, the Soviet PMD 6 has a wooden body that disintegrates particularly quickly underground. In Eritrea, a region with a fairly dry climate, local people state that it is rare to find a PMD 6 still intact 10 years after it has been laid. Often, this mine will be broken up by flail action instead of detonated.

It is generally recognised that flails do not consistently destroy thick-cased, above-surface fragmentation mines. They are usually taken up by the action of the flail, but will frequently survive intact with the increased inconvenience of being removed to a new and sometimes unknown location. On the positive side, tripwires are ripped out and fuses are usually broken off. If a flail is put to work in a suspect area where fragmentation mines are mixed with sub-surface blast mines, it must be assumed by the relevant clearance agency that back-up by alternative clearance techniques must be subsequently employed on the understanding that anti-personnel fragmentation mines are the likely residue.

A subject that has aroused much concern is the possibility that, with certain types of mine, a strike that achieves neither detonation nor complete break-up may render the mine in a more sensitive state than before the intervention. There is little evidence to support this case, but it cannot be discounted. In sum, far more research is required regarding the factors posed by mine type when flailing.

Tiller systems

Introduction

The second largest family of purpose-built demining machines is the tiller. Most tillers are based on tank or forestry machine chassis. Accordingly, tillers are often characterised by their heavy weight and large size, although lighter designs are beginning to enter the market. In general, the tiller working tool consists of a rotating drum fitted with overlapping rows of steel alloy teeth or bits. The teeth grind and chew up the ground as the tiller drum is lowered to a selected depth. Anti-personnel mines, smaller items of UXO and, for certain models, anti-tank mines, are either detonated or broken up as the steel bits impale them.

Due to the large size of most tillers, difficulties are often experienced when operating in countries where infrastructure is poor. Once working, however, clearance results appear to be good. Suspect ground is “brutalised” by these powerful machines and, if operated correctly in a suitable environment, few items of ordnance are likely to escape destruction by the bits of a tiller drum.

The majority of tiller systems are manufactured in Austria, Germany and Sweden. Currently, there are five manufacturers of tiller machines in the weight range of 14-53 tonnes. In addition, there are two combined systems: the STS MineWolf tiller/flail, which has a light tiller attachment and weighs 24.7 tonnes with the tiller fitted, and the Redbus Mineworm (part of the combined Land Mine Disposal System — LMDS) weighing 15 tonnes.

Fig. 12. Bofors Mine-Guzzler.

Limited research has been invested in understanding the physical effects unleashed in the ground and against mines by the action of a tiller. Compared to flails, there is a dearth of empirical data. In some cases, specific tillers that gave lacklustre performance in controlled tests went on to refute test results with successful application in the field.[11]

Tiller bite characteristics

Tillers work by the action of sharp blades, tines, teeth or bits fixed to a rotating drum pushed by the heavy bulk of the prime mover. The tiller unit interjects with the soil directly, taking a bite out of the ground to a depth selected by an operator from 0 to 40 centimetres. The impact with ground and ordnance within it is referred to as a *bite*. Three characteristics of tiller bite with regard to its effect on a mine/UXO are identified. These are similar to those of flail strikes and are therefore dealt with briefly:

Fig. 13. Opposite-revolving tiller drums, Rhino.

Disruptive bite

A disruptive bite on a mine/UXO from a tiller unit refers to where ordnance becomes physically damaged by involvement with the tiller bits. Items of ordnance can be broken up to the point where they are rendered harmless or only partially damaged, whereupon the item may become more volatile than before the action of the tiller. It is probable that mines/UXO are disrupted when the fuse of the item has failed to function (i.e. the mine was a dud), or the angle of attack from a tiller bit was such that direct contact with the fuse was avoided and the casing was ruptured before the ordnance was able to function correctly. Where ordnance is broken up sufficiently so that it no longer presents a threat, disruptive bites have a positive outcome.

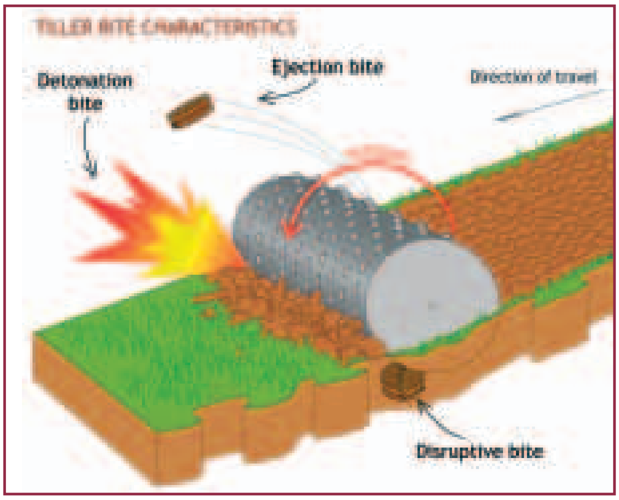
Detonation bite

A detonation bite refers to the destruction of ordnance where the item is detonated. The interruption of a tiller bit upon a mine/UXO or the pressure exerted when caught between a bit and the ground (especially hard ground) may cause the fuse mechanism to actuate. Partials, where the fuse functions but the main charge does not, are considered a detonation bite.

Ejection bite

An ejection bite describes a mine that is picked up from its position in the ground and thrown to a new location. As with flails, an ejection bite leads to a throw-out. Throw-outs with tillers are not common. Those that occur generally result in an item of ordnance being thrown in a line ahead of the machine and not to the side. The opinion from the field is that throw-outs from tillers are less of a problem than with flails.

Fig. 14. Tiller bite characteristics



A. Griffiths

Physical forces of tilling

The action of tilling is fundamentally different to that of flailing. Whereas flails not only affect a target directly, but also, potentially, indirectly through sub-soil waves of energy, the action of a tiller is direct. Beyond the physical reach of the tiller bite, the potential to destroy ordnance disappears.

Certain tiller operators have remarked on a number of negative effects of tiller action upon soil and ordnance within it. These are slipstreaming, burying, soil bulking, throw-outs and bow wave. In the main, these observed phenomena are not written down and have not been verified by scientific examination. Some of these phenomena have been noticed during machine tests conducted by the Swedish Explosive Ordnance Disposal and Demining Centre (SWEDEC), but they did not form the subject of those tests. In future, these effects may be subjected to greater technical scrutiny but, in any event, they appear to be rare. Based on available evidence from the field, they represent possible rather than probable outcomes and do not appear to seriously threaten the clearance abilities of most tiller systems.

Slipstreaming

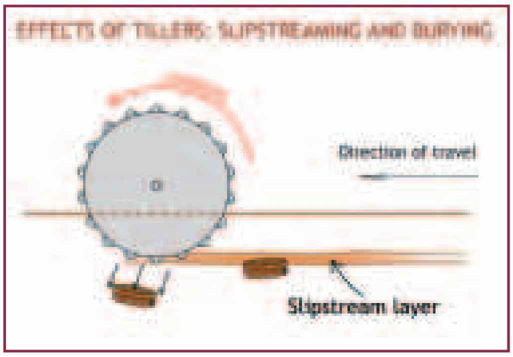
Slipstreaming refers to the theoretical phenomenon whereby the rotating action of the tiller drum creates a thin layer of free space between the end surface of the tiller bits and the surface of the ground beneath. Although as yet unproven, this space may contain aerated, loosely-packed debris such as broken-up soil, small stones and mulched vegetation. On occasions, depending on the design of the teeth fixed to the drum, the soil type being engaged and the mine type concerned, ordnance may become situated within the slipstream and escape destruction. It appears that the occurrence of slipstream beneath a tiller drum is aided by increasing rotation speed. It can resemble the effect of a vehicle tyre spinning on icy ground while remaining static.

The slipstream effect is also increased by dry, light soil conditions. Reportedly, where light to medium vegetation is present in an area worked by a tiller, slipstreaming is significantly reduced. This appears to be due to the additional "grip" on the soil provided by mulched vegetation matter. When vegetation of above-medium thickness is encountered, the performance of a tiller begins to be degraded as with any other mechanical system.

Once an item of ordnance becomes caught up in a slipstream, it may remain within the slipstream layer until the tiller drum has passed over it. Should it prove a factor at all, it should be stressed that slipstreaming does not occur in all conditions all the time. It is not known what percentage of ordnance that fails to be destroyed by tillers is due to this effect.

The factors that contribute to slipstreaming are not exactly understood. Where it occurs, its negative effects can range from severe to non-existent, depending on the size of the mine type involved. Smaller mines or fuses may escape destruction by "hiding" in the slipstream. Of the existing tiller machines, drum rotation speed varies from approximately 100 to 700rpm. As mentioned, reducing rotation speed is believed to be one method of preventing slipstreaming. It remains to be seen if drum rotation speed reduction might lead to other performance limitations.

Fig. 15. Slipstreaming and burying



A. Griffiths

Burying

The possible deeper burying of ordnance under the influence of a tiller drum may be a cause for concern. As a tiller penetrates the ground, mines located below the ground penetration depth selected by the operator may, in theory, be pushed down further by the downward force of the drum.

The design principle behind tiller systems suggests that bulk and weight are required for the performance of their intended function. The majority of tiller systems weigh between 32 and 46 tonnes. It may prove that the great mass required for tiller systems to do their job inexorably leads to some ordnance escaping destruction by becoming buried deeper into the ground. Given that a pressure-activated mine subjected to pressure from above should detonate, it is probable that such mines are inoperative. It may also be the case that mines located deeper than the tiller action were already at that depth. The question, however, remains open.

Bulking (overburden)

As with flails, the grinding and churning action of tilling creates a layer of loosened, aerated soil referred to as bulking (overburden). Some of the overburden is swept under and behind the vehicle, some pushed ahead of the tiller unit in the form of bow wave and some deposited to the side from the bow wave into windrows. As with flails, non-destroyed ordnance may be buried within the bulked soil invisible to the naked eye. Due to aeration, the depth of soil is increased, further concealing ordnance that may have remained within the original soil bed beyond the ground-penetrating ability of the machine.

Throw-outs

Like flails, tillers may potentially pick up items of ordnance within their path and throw them to a new location. Unlike flails, tiller throw-outs tend to be in a line in front of the path of the vehicle and seldom to the side. The rotating bits cannot move in random directions as occurs to the chains on a flail. This is an advantage as it can be reasonably expected that such ordnance will be neutralised at the second opportunity. With most tiller systems, drum rotation is often of a clockwise direction. This means that the teeth of the drum bite into the ground from above. Anti-clockwise rotation is understood to be where the teeth come up from underneath, in opposition to the direction of travel of the vehicle. (Clockwise rotation is taken as the direction of flail/tiller rotation when observing the right-hand side of the vehicle.)

Most tillers rotate in a clockwise direction although some tillers that combine a double roller configuration rotate the drums in opposing directions. It is logical that where tiller throw-outs occur, they are most frequently as a result of anti-clockwise tiller drum rotation, although this is unsubstantiated. If correct, the already-infrequent occurrence of tiller throw-outs could be further reduced by a preference for clockwise tiller drum rotation. However, some operators believe that clockwise drum rotation increases the possibility of mine burying. The Minebreaker 2000/2, for example, was designed with an anti-clockwise rotating drum in order to avoid compaction of mines into soil. As with the problem of slipstreaming, throw-outs may also be lessened by the reduction of tiller drum rotation speed. Conceivably, the greater the rotation speed, the greater the propensity for ordnance to be flung out from the ground.

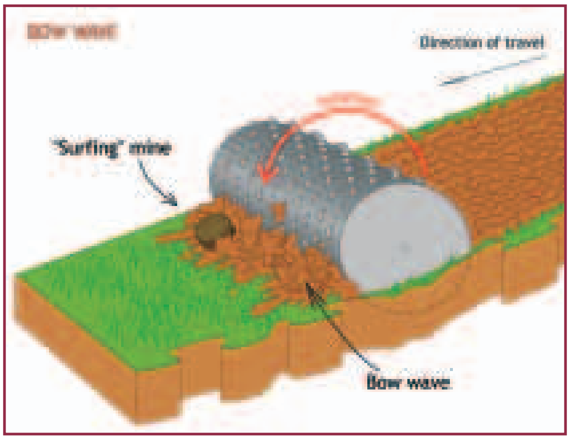
Bow wave

Bow wave refers to the loosened earth moving slightly forward of the rotating tiller drum as the machine moves forward. The soil in a bow wave is produced by the bulking effect. The assertion that bow wave may be a tiller problem is not universally accepted. Within the demining industry, some contend that it is marginal and is not a factor affecting safety. However, bow wave has been identified as a concern by tiller operators in Bosnia and Herzegovina and Croatia.

Bow wave has the appearance of water pushed in front of a ship at sea. Ordnance may be situated within the bow wave at the front of a tiller drum. On occasion, ordnance caught in this position may roll continually within the bow wave and never end up between the jaws of the tiller teeth and the ground surface, thus escaping destruction even though the soil particles that comprise the bow wave are ever changing; the ordnance acts like a surfer, always keeping slightly ahead of the breakpoint. As a machine finishes a sweep in a suspect area, ordnance within the bow wave may be pushed to the edge of the area to be deposited and left there as the machine changes direction to begin a fresh path.[12]

The amount of bow wave may increase the greater the ground penetration depth selected by an operator. However, some operators claim that mines and other ordnance located at 10 centimetres or more below the surface are less likely to escape destruction due to bow wave than items closer to the surface. This seems to be supported by tests of the Mine-Guzzler conducted by SWEDEC, which was found to be more effective against mines at 10 centimetres and 20 centimetres than those nearer the surface. Potentially, items placed at greater depths are less afforded the opportunity to rise up and become caught within the bow wave.

Fig. 16. Bow wave in front of a tiller



A. Griffiths

As the soil builds up ahead of the tiller drum, the excess tends to spill out to the sides of the path of the vehicle, leaving small windrows either side of the machine wake. Mines that have been displaced by the tiller but that have avoided destruction by moving with the bow wave may be deposited to the sides within these windrows. Where this occurs into the path of the next sweep, it can generally be assumed that the item will not escape destruction with the next line of clearance followed by the machine. If the mine is contained within the windrow deposited on the cleared side of the vehicle path, a problem is presented.

Limits of soil, terrain and vegetation

Like flails, tillers are at the mercy of particular conditions of topography and soil. As with flails, in steep or close terrain tiller machines are restricted more by their heavy prime mover than by the efficacy of the tiller tool. Of the five tillers on the market at the time of writing, hill-climbing ability claimed by manufacturers ranges between 24° and 30º. Tillers tend to be bulky and difficult to manoeuvre over extreme topography. When it comes to soil type, it is the tool itself which is subject to limitations.

Tillers do not perform well in sodden conditions, possibly as the backstop provided by harder soils does not come into play. Nor do they function impressively in rock-strewn soil. Large stones and rocks tend to protect mines/UXO from the intrusions of an oncoming tiller bit. Where the rock type is hard, damage to tiller bits can be expected. As claimed earlier, the presence of light to medium vegetation possibly enhances tiller performance, allowing the bits to grip the soil reducing slipstreaming. Most tillers operate less effectively in vegetation of 10 centimetres in diameter or more. The restrictions on tiller performance presented by soil, terrain and vegetation are similar to those experienced by flails.

Ground penetration depth

As tillers cannot be expected to affect buried ordnance through indirect energy (F1) and beyond the actual reach of the bits attached to the rotating drum, the maximum effective ground penetration depth achieved by three of the five tiller systems available on the market is 50 centimetres (in soft soil). Of the remainder, none achieves less than 20 centimetres.

Where survey has not indicated the likely depth of ordnance, all tillers on the market can achieve the required IMAS default clearance depth of 13 centimetres. All tillers also achieve sub-surface ground preparation (*see Chapter 4*), which both cuts vegetation and breaks up the ground. As noted above, tillers appear to perform better when ordnance is found at depths of 10-20 centimetres. Other tests and statements from users suggest that the optimum performance of most tillers is achieved when mines/ UXO are cleared at between 10-30 centimetres, with the tiller drum set at penetration depth of 30 centimetres. However, where mines are found at deeper than 20 centimetres, performance begins to deteriorate. It is not known whether this deterioration is uniform to all ground conditions and against all mine/UXO types. There may be exceptions.

Engine power

As a generic type, tillers are heavyweight tools assisted by mass to bite into ground at greater depths than most other mechanical mine clearance solutions. Intrinsically, such weight requires considerable engine power to drive both the prime mover and the tiller drum. Large mass helps a tiller to absorb the shock wave of detonations.

A massive prime mover is also needed to counteract the forward (or backward) drag imparted by the rotating tiller drum. Without great size, the machine would be propelled or retarded by the tiller attachment as well as its own engine and gearbox. This need for resistance to the propulsion effect of a churning tiller drum is in part the reason all tillers employ caterpillar tracks, giving them greater contact with the ground.

Unlike the chains of a flail, tiller drums are forced into direct contact with ordnance and cannot rely on the stand-off and force-absorbing flexibility enjoyed by flails. Without greater mass, a tiller might suffer unacceptable damage.

Tiller machines currently on the market are able to drive tiller drums at 190-700rpm in light to medium soil — an achievement requiring considerable power when penetrating ground at 20 centimetres or more. If such power is the goal of tiller manufacturers, large size is an inescapable feature.

As experience with tiller systems increases, it is becoming more apparent that a high speed of tiller drum rotation may not be as crucial as had been thought. Higher tiller drum revolutions per minute may even be a significant contributing factor to occasional throw-outs and the potential for slipstreaming. The destructive action of a tiller bit upon a mine/UXO may not actually require great speed, as the mass behind each bit should ensure penetration of a mine/UXO casing or the pressure activation of a serviceable fuse.

Optimal engine power is specific to each machine. Whether there may be scope for the reduction in engine power and therefore rotation speed remains to be seen. Reduction of revolutions per minute may reduce slipstreaming and throw-outs, but may also introduce other, as yet unknown drawbacks.

Forward speed

Forward speed is largely dependent on the speed of tiller drum rotation. If tiller drum revolutions per minute are low, so too must be the forward speed. This would reduce cost-effectiveness. Despite other possible negative effects mentioned above, faster revolutions per minute of the tiller drum allow greater forward speed and therefore increased productivity. Like flails, the helix configuration of the tiller bits attached to the drum is positioned in such a way that the optimal forward speed must be found and maintained in order that each centimetre of ground is affected by a tiller bit and that skipped zones do not occur. According to tiller operators in Bosnia and Herzegovina and Croatia, limited fluctuations in forward speed do not appear to affect the ratio of break-ups to detonations, as occurs with flails.

Mine type

With the exception of one machine, existing tillers are designed to destroy anti-personnel mines but are able to survive anti-tank mine blasts. The Rheinmetall Landsysteme Rhino and STS MineWolf both employ a tiller attachment for suspect areas where anti-personnel mines alone are expected, but use a flail attachment for areas where anti-tank mines may be present. The ability to engage with anti-tank mines using a tiller drum is largely due to the significant mass of most tiller systems, enabling them to absorb greater explosive blast pressure.

As with flails, mines/UXO encountered by tillers will be destroyed by actuating fuse mechanisms, or by breaking up ordnance that fails to detonate. With regard to anti-personnel fragmentation mines (e.g. the POM-Z), no evidence has been obtained to suggest that tillers are more effective than flails. Since tillers destroy mines and UXO by the direct contact of the tiller bits with ordnance, the efficacy of tiller systems is less connected to the factor of mine type than is the case with flails. When a mine is situated beneath the physical ground penetration ability of a flail chain, indirect energy in the form of influence zone may destroy only some types of ordnance. A tiller relies on the physical contact and pulverising power of its hardened steel bits, discriminating less between the varying fallibilities of mine/UXO types.

Mechanical excavation

Introduction

Of all the mechanical ground processing options, excavation of soil from suspect land is arguably the most tried-and-tested method of ensuring that suspect ground is rendered clear to a stated depth. The method involves moving suspect soil for subsequent inspection for mines/UXO, leaving the optional return of cleared spoil to its original location.

The HALO Trust employed the technique using adapted front-end loaders and tractors throughout the 1990s in Afghanistan, Cambodia, Eritrea, Georgia (Abkhazia), the Russian Federation (Chechnya), and the Federal Republic of Yugoslavia (Kosovo). A similar technique was adopted in Bosnia and Herzegovina by Norwegian People’s Aid (NPA), using a front-end loader, and by European Landmine Solutions (ELS), using an excavator. Menschen gegen Minen (MgM) has also been at the forefront of the excavation method, particularly in regard to soil sifting. Other systems using the excavation technique are the Mineworm (as part of the Redbus LMDS), Armtrac Sifter, MgM Rotar Mk-2, and the Night Vision & Electronic Sensors Directorate (NVESD) Floating Mine Blade.

Fig. 17. Converted (armoured) Russian RABA front-end loader conducting rubble clearance, The HALO Trust, Kabul, 1998.

The HALO Trust programme in Afghanistan is evidence of the tangible benefits of mechanical over manual clearance. HALO estimates that from the moment a manual deminer encounters a buried mine until the moment the mine has been destroyed by a charge placed *in situ*, an average of 25 minutes will have elapsed. The HALO programme operates in cycles of 21.5 days.

HALO calculates that the number of mines destroyed by mechanical means per cycle would take manual deminers 6.8 cycles to match.

Often, the inspection of potentially contaminated soil is carried out in an area prepared for the purpose. Some machines process soil on the move, with cleared soil released along the path of the vehicle. Most machines employed in the excavation role are specially adapted commercial engineering vehicles, upgraded with add-on armour plate and transparent armour (reinforced glass). These typically include front-end loaders, tractors, excavators and bulldozers. They represent an effective alternative to the purpose-built mechanical systems sold on the market as specific mine clearance vehicles. In demining tasks among rubble and destroyed infrastructure in built-up areas, excavation is the only mechanical clearance process that has met with success.

The excavation and processing technique

Mechanical excavation involves the removal of suspect soil to a depth indicated by survey that mines are expected to be found. The general method for mechanical excavation has four main stages:

1. The parameters of a minefield are established using minefield maps, general survey, technical survey, area reduction by MDD/manual/mechanical system or by any other method that will reveal the border between a safe and a mined area (*see Fig. 18*).
2. Potentially mined soil is excavated. If the excavation method is by tractor or front-end loader bucket, the bucket should only be three-quarters full in order to avoid possible spillage of suspect soil when the machine is moving (load capacity for a typical loader bucket is around 2.5 cubic metres). Some specialised mined soil excavation systems process and clear soil picked up *in situ* while moving along a clearance path within the suspect area.

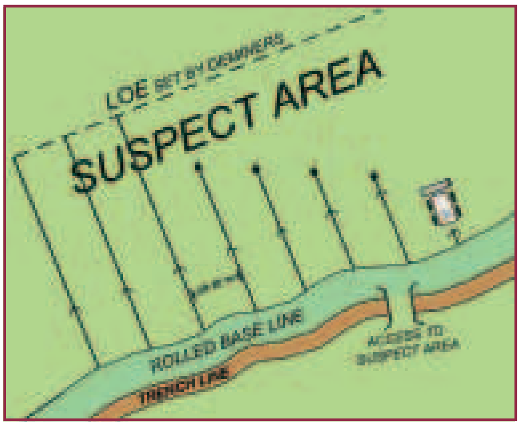
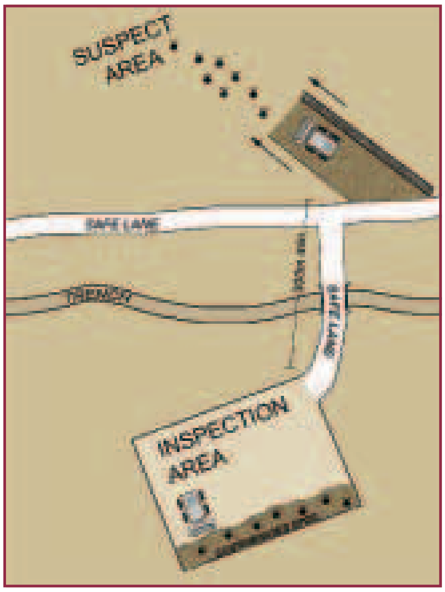


Fig. 18. Locating the true mined area

Starting from a safe base line, the true area affected by mines should be delineated prior to mechanical excavation in order to save significant time.

Fig. 19. Suggested positioning of inspection area in relation to suspect area



3. Suspect soil is processed to separate mines/UXO from soil. Once this is achieved, ordnance is destroyed by explosive ordnance disposal (EOD) staff. The method of soil excavation and processing depends upon the machine used:
   - **Sifting *in situ***: soil is sifted through the machine separating earth from solid objects as the machine moves along a path of excavation.
   - **Manual inspection area**: a flat, open area with a hard surface is prepared where suspect soil is spread out for visual examination and check by metal detector. The inspection area needs to be outside the danger template of the adjacent suspect area where soil is being excavated (*see Figs. 19 and 20*).
   - **Sift inspection area**: an area separate to the excavated area where soil is put through a sifting mechanism, separating loose soil from ordnance.
   - **Crushing**: suspect soil can be fed through an industrial rock crusher of the type used in rock quarrying. The crushing chamber is robust enough to absorb the detonation of anti-personnel blast mines. Larger UXO or anti-tank mines are located by an on-board metal detector, warning the operator of a possible mine/UXO. Ordnance is removed from the conveyor belt for subsequent disposal before entering the crushing chamber. Mine-free, loose soil emerging from the chamber is fed into a pile for later redistribution in the original suspect area.
4. Soil free of ordnance can be left at the point of processing (if in a separate inspection area) or preferably redistributed to the original suspect area (automatic in the case of on-board, *in situ* soil processors).

The machines

Mechanical excavation and sifting operations are carried out by a variety of machine types. Many are commercial engineering vehicles, adapted for work in mined areas. Some adapted commercial vehicles are fitted with special-to-task demining

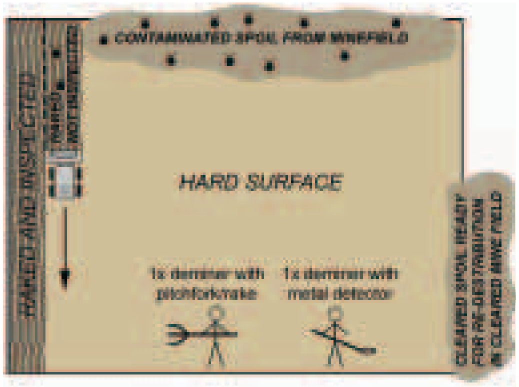


Fig. 20. Inspection area

As contaminated soil is being raked by loader bucket, deminers should remain under protection or situate themselves out at an appropriate safety distance. They return to inspect soil once the machine has raked one row of one-bucket width.

Fig. 21. Deminer inspecting excavated soil in inspection area, Cambodia.

attachments. Mechanical excavation is also conducted by machines exclusively designed for the role, as described below.

Commercial engineering vehicles

The workhorse of excavation ground processors is the front-end loader. Excavators are also extensively used, particularly in rubble clearance. With its hydraulic, extendable arm, an excavator can reach over obstacles such as walls, ditches and earthworks in order to excavate in suspect spot locations where it would be physically impossible or damaging to infrastructure to deploy a full-size bucket. Commercial excavators can be employed where conditions are too tight for front-end loaders and tractors such as in built-up areas.

Fig. 22. A "gill" in operation.

Front-end loader buckets have been adapted by HALO with the addition of a steel grill, which it calls "the gill", so that machines can operate in suspect areas where anti-tank mines may be present. As seen in Fig. 22, soil is sifted through the gill, allowing soil and objects up to the size of common anti-personnel blast mines through but retaining any anti-tank mines or large UXO encountered at the surface of the gill where it can be easily seen by the operator and subsequently dealt with. It is not the aim to deploy gill-fitted front-end loaders into anti-tank minefields, but where the mine situation is unclear, machines so-equipped can be deployed with greater confidence.

Clearance method

Once an area is confirmed as mined, the vehicle moves into the suspect area from an established safe line. The driver contacts the ground with the bottom front blade of the bucket and drives forward. Using manual controls, the bucket is angled to skim off soil to a desired depth. With a half- to three-quarters-full bucket-load of suspect soil (in order to avoid spillage), the vehicle reverses down its own track to a safe route previously established between the suspect area and the pre-prepared soil inspection area.

To avoid wasting time, the soil inspection area should be as close to the suspect area as possible while observing a calculated safety distance. The machine dumps its load of potentially contaminated soil at one end of the inspection area. Various local, cheaply-made devices have been developed to assist the spread of contaminated soil in an inspection area. The spreading of soil into thin layers for ease of visual inspection can also be achieved by skimming, using the bottom blade of a loader bucket (*see Fig. 20*).

Sifting and crushing

Once suspect soil is excavated, one option of processing it so that it is rendered free of ordnance is to sift it and then feed it through a crushing mechanism. Two systems have been used: the Redbus Land Mine Disposal System (LMDS) Mineworm which sifts and crushed debris *in situ*, and industrial rock crushers which are static, fed with suspect soil from a separate location.

Fig. 23. Redbus LMDS, Bosnia and Herzegovina.

The Mineworm is the follow-up vehicle of the two-machine Redbus LMDS. Mineworm follows in the wake of the ground-beating Bigfoot machine. The remote-controlled Mineworm excavates soil to a pre-selected depth (to a maximum of 55 centimetres) using a front-mounted soil-breaker and root-cropper. This feeds loosened soil into a rotating blade excavator which lifts soil up and onto an on-board conveyer leading to an industrial fragmenter.

Before the fragmenter, a magnet removes larger metal objects for later inspection. UXO tend to be captured by this, whereas smaller metal items such as detonators, or objects of limited metal content such as anti-personnel blast mines, should be fragmented. Cleared spoil is then deposited at the back of the machine. The entire process is conducted in the suspect area as the machine moves along its path.

Mineworm has undergone trials and development in Bosnia and Herzegovina. The system began full-scale operations there in 2003 (along with Bigfoot).

Industrial crushers have been used for the processing of excavated suspect soil. The HALO Trust operates crushers adapated from the quarrying industry. Soil is fed into a hopper/sifter where small particles are dropped before larger particles and fed into a crushing chamber. The size of crushed debris released from the chamber is adjustable. This is usually set to enable destruction of the smallest known anti-personnel mine types. Crushers have been fitted with metal detectors producing audible alarms so that when larger metal particles such as UXO or metal-cased mines are encountered, the crusher conveyor belt stops and reverses in order to prevent the item from entering the crushing chamber. Such items are dealt with by EOD staff. The crushed, hazard-free soil is eventually returned to the site from where it was originally excavated.

Sifting

Various earth sifting mechanisms are deployed to process suspect soil. Most are adapted agricultural sifters such as that used by the Pearson Survivable Demining Tractor and Tools (SDTT) or the Armtrac Sifter. Some sifter attachments are purpose-built for mine clearance operations, notably the MgM Rotar Mk I and II and the Mine Collector.

Fig. 24. MgM Rotar Mk 1 sifting

Initial excavation of suspect soil can be executed in a variety of ways before being deposited into and processed by a sifter unit. Excavation and sifting to extract mines and UXO from soil is done *in situ* as a vehicle moves along a path within a suspect area, or suspect soil is excavated by tractor/front-end loader and brought to a sifter system for processing at a location outside the area. There are numerous ways to achieve the same aim, which is to remove suspect soil, process it through a sifting system to separate soil from mines and UXO, and dispose of the ordnance.

Mine rolling

Introduction

Although not exclusively aimed at defeating mines, the first rollers were mounted to British Mk IV tanks in the 1914-1918 war. Current designs of anti-mine rollers have retained the simplicity of their predecessors. Anti-mine rollers were most widely employed by the Red Army of the Soviet Union. The design of rollers used in present-day humanitarian demining owe much to these.

"Rolling" could also be said to include the use of mine-protected vehicles fitted with steel wheels (no tyres) which have been used in a similar manner to conventional rollers.

Fig. 25. Armoured Terex front-end loader with Pearson roller. Eritrea - Ethiopia border, 2001.

Operational methodology

Anti-mine rollers

Rollers used in humanitarian demining have generally been mounted to adapted front-end loaders and tractors. Rollers are usually used in the area reduction role. The aim is to speed up the process by which manual clearance teams reach the real perimeter of a suspect area. Locating mines/UXO constitutes the greatest amount of time spent in any clearance operation when conducted by manual or MDD teams.

Anti-mine rollers are intended to activate sub-surface mines that are in a live, serviceable condition. They cannot influence mines which have, for whatever reason, become non-operational. As a result, anti-mine rollers do not have the same potential to destroy mines as do flail or tiller systems. Anti-mine rollers capable of withstanding blast from an anti-tank mine exist in military service, but have not yet been fully employed in humanitarian demining. Pearson Engineering and NVESD are in the process of developing anti-tank mine rollers for humanitarian demining.

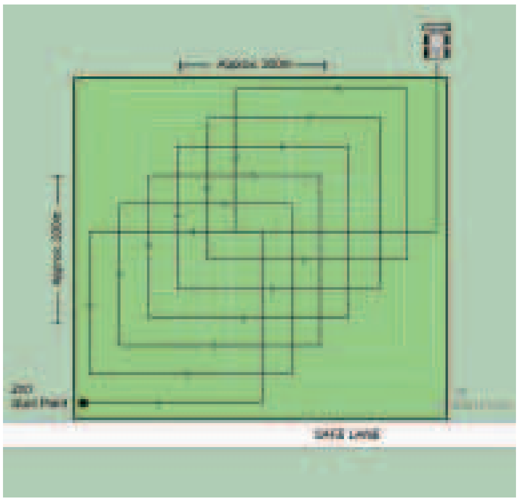
Rollers are not suited for mine clearance as they can destroy functioning mines only, and these only where conditions allow. Even fully-operational mines cannot be guaranteed to activate under the weight of a roller disc. The depth of ground in which a roller is likely to detonate a mine is determined by the weight of the roller, soil types and conditions. It cannot be conclusively determined.

As well as for area reduction, rollers are useful for post-clearance verification, and establishing confidence in a community by demonstrating the absence of live mines. Rollers typically used in mine clearance consist of segmented, heavyweight discs, each turning on a central axle. As the prime mover goes forward, the individual discs of the roller contact the ground. To a degree, the discs conform to undulations, bumps and rises in the ground.

For best results, a roller should be used in a set pattern over a suspect area. Patterns that have been used include rolling four times in four different directions. Rolling an area repeatedly is likely to be more effective than rolling just once. This is likely due to the soil compacting after each pass. At least this is supported by Pearson Roller trials conducted by the CCMAT and the Thailand Mine Action Centre (TMAC) in March and April 2003.

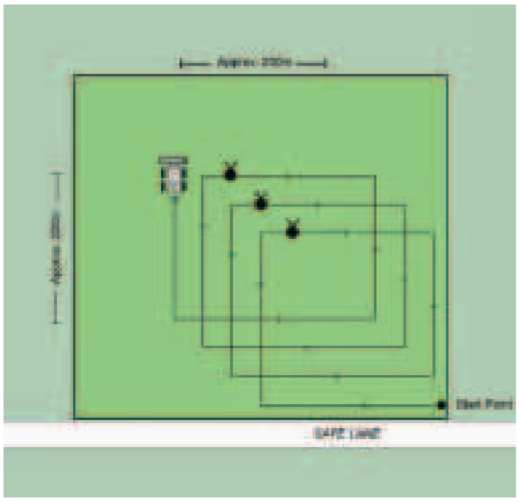
In situations where information as to the location of mines is accurate, a roller need not be used for locating mines by detonation. A roller can cover the ground close to the expected safe clearance start line in order to help corroborate that the land is truly clear of live mines before deploying manual or MDD teams. Once the presence of mines has been verified, direct clearance assets can be deployed into the reduced area where mines are actually located.

Fig. 26



Phase 2 of HALO Trust rolling operation. Grey lines are pattern from first roll. Concentric box pattern ensures that the middle of the area is rolled four times from four directions.

Fig. 27



Rolling area using concentric box pattern where mines were not expected but were subsequently encountered. In this example, an approximate mine pattern is revealed. Rolling should stop and clearance assets take over.

Rollers have been "home-made" using available local components in various programmes worldwide, particularly in Afghanistan. The only commercially produced anti-mine roller in common use in humanitarian demining is the Pearson Engineering segmented Area Reduction Roller (ARR). The ARR weighs one tonne per metre of width, available up to a width of 3.5 metres. Each individual disc exerts a ground pressure of 50 kilograms. It has been used by TMAC and The HALO Trust, which has area-reduced more than four million square metres using it.

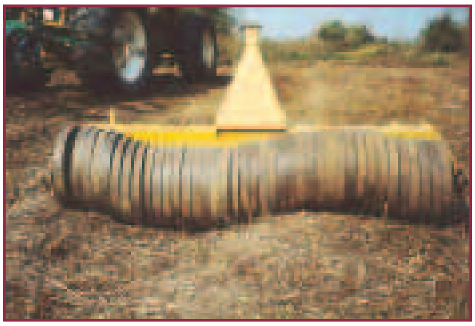


Fig. 28. Pearson Engineering anti-personnel mine roller.

The U.S.-produced Armadillo anti-mine roller has not yet been widely used in mine clearance programmes. Its ability to conform to bumps and undulations in terrain is good. Each weighted disk is mounted to an individually mounted suspension system.

Steel wheels

The attachment of steel wheels to mine protected vehicles evolved in the 1970s and 1980s, mainly in Namibia, South Africa and Zimbabwe (then known as Rhodesia). Specifically, steel wheels have been fitted to the South African Casspir MPV, developed by Mechem.

Steel-wheeled Casspirs have been used in a similar manner to anti-mine rollers; the vehicle drives in a pattern within a suspect area with the aim of detonating live mines to indicate mine patterns or sporadic presence. Covering ground in overlapping patterns without missing areas is more of a challenge than with anti-mine rollers. The wheels do not form a contiguous width beneath the vehicle but are spaced as with any standard wheeled machine.

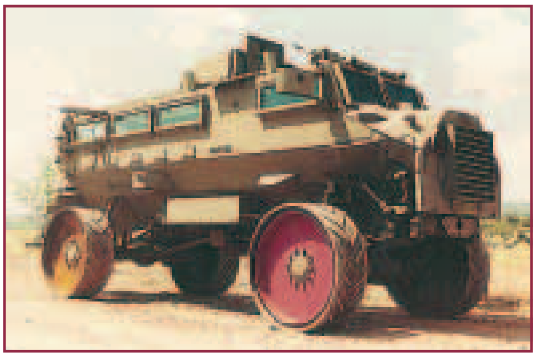


Fig. 29. Casspir MPV.

The steel wheels are an optional extra and can be fitted to Casspirs employed for mine clearance. When used to pressure-activate mines, the effectiveness of the steel-wheeled Casspir depends on the type of mine encountered. In recorded clearance tasks in Mozambique, the South African clearance organisation Mechem tended to detonate 89-96 per cent of PMN-1s and PMN 2s, 70-76 per cent of OZM-72s, 7-8 per cent of PMD-6s (they tend to become non-operational very quickly and were often merely crushed) and approximately 2 per cent of POM-Zs.

Fig. 30. Pearson Engineering SDTT. The Pearson Roller is attached to the tractor. Used in Thailand.

Conclusions, findings and recommendations

Conclusion 1.

There is scope for stand-alone mechanical systems to be used for clearance to humanitarian standards.

Findings

Although there is limited data to back up the assertion that machines achieve primary clearance of land contaminated by anti-personnel mines to humanitarian standards (as set out in Annex 1 to this chapter) it is supported by growing empirical evidence from implementing agencies as well as testing regimes. Evidence from the field suggests that few anti-personnel blast mines are left behind in a functional condition after treatment by certain machines in suitable terrain. Manual and dog teams are thereby relegated to picking up fragments.

Flails and tiller systems have set precedents for use as stand-alone, primary clearance assets: but this is by coincidence. These were set by machines employed in the ground preparation role where follow-up clearance assets did not encounter functional mines after a machine. There exists no official international proscription of using machines in the primary clearance role. It is simply that a culture of “not doing it ” has developed within the demining community. Machines are often allocated to working where mines are not expected. This approach should be carefully reconsidered. The demining community is not trying hard enough to extract the clearance potential of machines in order to use their speed and potential cost-efficiency.

With regard to flails and tillers, it is difficult to exactly understand from existing research the interrelationship between a ground penetrating tool, its force, soil types and mine/UXO types. If further research is not conducted, a time may come when enough real-time, empirical data comes to the fore to accredit some machines as a choice for primary clearance. A development that must precede such an outcome is that more stringent and comprehensive data collection for recording clearance performed by machines be made. To date, most clearance data lacks detail, making the extraction of comparative analysis difficult at best.[13] Without improvements in this field, empirical support for greater use of mechanical systems cannot be marshalled.

With the few examples provided in this paper, it can be seen that — provided a machine is up to the task and that conditions of soil, terrain and mine type are favourable — mechanical demining systems exist that are able to clear areas where no hazardous ordnance remain to threaten follow-up MDD or manual teams. ‘’Full’’ clearance is being achieved, certainly by mechanical excavation, but also with flail and tiller systems in some cases where mine type and conditions are suitable. One outstanding aspect of these examples is that primary clearance was not the expected result. Full clearance has sometimes been achieved where the sole aim was to prepare ground for subsequent clearance methods. “Full” clearance of land occurred as a fortuitous by-product. A significant problem lies in recognising what conditions are most favourable for machines to succeed as primary clearance systems.

It is known that topography, soil mechanics and mine type together with the choice of mechanical system play a critical role in the success or failure of a system to achieve full clearance. What is not known is specifically what the most favourable conditions are. Until these factors are better understood, it will be impossible to gain full control of whether or not a machine consistently succeeds as a primary clearance asset: success or failure will be more a result of random circumstances rather than controlled certainty.

Demining operations conducted by mechanical excavation and sifting currently serve as proven examples of successful primary clearance. To the depth penetrated by a front-end loader bucket, clearance is as good as guaranteed. If the quality of this method of clearance were ever to come under scrutiny, it is more the subsequent treatment options of contaminated soil that might benefit from fine tuning.

Despite the apparent success and ease of the mechanical excavation and/or sifting process, it remains an underemployed clearance technique. The reasons for this are not exactly known; it could be that this methodology has somehow escaped wide notice within the demining community. A more likely cause is the comparatively low productivity that this technique affords. A tractor could not hope to excavate contaminated soil at the rate a tiller or flail can process land, despite the proven efficacy of the former over the remaining doubts about the latter. Assumedly the operational advantages of mechanical excavation and sifting will be continuously reduced as tiller and flail designs improve and their optimal conditions are better understood. It is likely, however, that excavation will remain a good option in more extreme conditions, particularly in built-up areas.

Recommendation 1.

If a particular machine or mechanical system can demonstrate that, given suitable conditions against an appropriate target (ordnance type), it can be used as the primary clearance tool, it should be so used. Manual or MDD team follow-up can be streamlined in order to compensate for the likely residual threat left by that machine.

Conclusion 2.

Machines are rarely, if ever, deliberately employed in the primary clearance role.

Findings

Examples are scarce where machines have been used as a primary clearance system and followed by a dog team or a small team of manual deminers intended to compensate only for a known residual threat left by the machine. Residual threat refers to specific ordnance that a specific system has a tendency to be unable to destroy. The residual threat particular to a machine should be stated by the operator. Remains of these mine types should be cleared by subsequent demining methods — manual or MDD teams.

The aim of using machines is typically not to clear land, but to prepare ground for post-machine full clearance by manual and MDD teams. However, clearance sometimes appears to be the inadvertent result.

Yet, at the same time, there are numerous cases where machines repeatedly fail to adequately destroy even the easier target of sub-surface anti-personnel blast mines. This may be because a particular machine is simply not up to the job, or that it is not being operated correctly. The comparative efficacy of different machines varies widely. Another cause may be extremes of soil or terrain. For example, the soil can be very hard and on occasion mines are apparently protected from the blow of a flail hammer by large rocks. There is much to be gained from a better understanding of the physical limits imposed upon a demining machine by its operational environment.

Recommendation 2.

Further efforts should be made to understand the optimum physical conditions in which particular machines can be expected to act as the main, primary clearance asset. This would include factors of topography, soil, ordnance type and machine.

Conclusion 3.

In general, throughout the industry, machine clearance data is poor.

Findings

Detailed data gathering on the effectiveness of mechanical clearance is the exception rather than the rule. Records of clearance statistics, post-clearance accidents and missed mines are difficult to secure. Tests using an adequate number of live or surrogate mines to establish a machine's true clearance potential are few, and those that do exist do not explore a wide range of scenarios where terrain, soil and mine type may be a critical issue. This has been a major handicap for the research carried out for this study. Even where they are collected, statistics and clearance data from different organisations can be of widely ranging reliability. Furthermore, care must be taken that statistics are not manipulated to support a particular line of argument.

Recommendation 3.

The mechanical demining community would benefit from a coordinated, standardised method of recording mechanical clearance data. This data could enable machine operators to argue for the expanded employment of mechanical assets.

Endnotes

1. For example, the STS Minewolf and RLS Rhino employ interchangeable flail and tiller attachments but both use the flail attachment when operating in areas where anti-tank mines are expected.
2. Typically for ordnance up to an 82mm mortar shell.
3. Phelan and Webb (2003).
4. For example, the Armtrac 100 has addressed the problem by introducing extended cowling over the flail unit. Engine power, flail rotation speed and suggested adjustments to vehicle forward speed are also intended to decrease the possibility of throw-outs.
5. Shankla (2000).
6. Referred to as FN in the DRES study.
7. Referred to as FH in the DRES study.
8. SWEDEC (2002).
9. According to an Armtrac 100 operator for the organisation BACTEC, working in southern Lebanon in 2002: "*Rocky soil tends to quickly degrade chain links and hammers, requiring them to be replaced more often*".
10. Based on interviews with machine operators in Bosnia and Herzegovina in May 2002 and in southern Lebanon in August 2002.
11. SWEDEC 7/2001, Eksjö, Sweden.
12. This occurrence was observed by Håvard Bach, GICHD, during operation of the MgM Rotar in Namibia in 2001.
13. CROMAC, for instance, serves as an example to the industry for full and comprehensive clearance data. Worldwide, there is significant disparity of quality of operational statistics.

Annex 1.

Examples of machines achieving clearance in demining operations

The following are a few examples of where machines have cleared land leaving little or nothing to be found by subsequent clearance methods.

ELS supporting NPA in Bosnia and Herzegovina

In Bosnia and Herzegovina (BiH), European Landmine Solutions (ELS), a commercial mine clearance company, provides mechanical mine clearance support for other organisations that deploy MDD and manual teams. ELS has mainly used the Armtrac 325 and 100 in the ground preparation role.

From April 2000 to the end of 2002, NPA contracted ELS to conduct ground preparation on many of its clearance sites. In general, the terrain in BiH is a mixture of rolling and steep hills, interspersed with agricultural plains and forest. The climate is temperate European and the soil is of medium consistency, seemingly well-suited to flails. Patterned, intensive minefields are not common in BiH.

Fig. 1. Armtrac 325.

During the NPA/ELS contract period, one apparently functional mine was found after the preparation of ground by flail. This was a Yugoslav PMA-2 anti-personnel blast mine, believed to be in working condition. It was discovered by an NPA deminer during the follow-up clearance of an area following ELS machine preparation. NPA believes it probable that the mine was never contacted by a chain from the Armtrac as the machine passed too far to one side of the mine, located near the base of a large tree. This is the only known missed mine incident as a result of ELS preparing 781,634 square metres of ground for NPA. All other mines were detonated or broken up before manual deminers or MDD teams conducted final clearance.

NPA in Angola

Beginning in 1998, the NPA programme in Angola has carried out mechanical ground preparation using Aardvark and Hydrema flails. These machines were used on suspect ground where survey produced unreliable information. The suspect areas dealt with were believed to be of low mine content. Since 1998, approximately 2.5 million square metres of suspect land have been mechanically prepared by the NPA machines in Angola. Of this area, one throw-out is recorded. No incidents of missed mines as a result of deminer clearance or civilian accidents have been recorded.

Fig. 2. Hydrema MCV 910 (series 2).

Aardvark Project Afghanistan 1990-1995

The United Nations Mine Action Programme for Afghanistan (UNMAPA) employed Aardvark flails in an attempt to speed up the rate of clearance and improve cost-effectiveness. Neither of these aims was met due to problems of management, logistics and operating procedures. Large areas were, however, mechanically prepared. UNMAPA stated that: ''*Flails are most effective against anti-personnel blast mines, achieving virtually 100 per cent detonation*''.[1] This is probably an exaggeration as there must have been incidents of anti-personnel blast mines being broken up, however the technique of flailing minefields obviously impressed those involved in the programme. Unsurprisingly, the Aardvark flails were not consistently successful against thick-skinned anti-personnel fragmentation mines such as POM-Zs, a common problem among tiller and flail systems.

Minebreaker 2000 in Afghanistan

The German military (Bundeswehr) engineer contingent in Afghanistan employed a Minebreaker 2000 to clear ground in the area of Bagram Airbase in support of U.S. military operations (not as part of the International Security Assistance Force). From 17 November 2002 to 23 April 2003, the Bundeswehr Minebreaker mechanically prepared roughly 38,000 square metres of ground. Soil was of clay quality and vegetation consisted of mainly thick, high grass.

Fig. 3. Tiller drum configuration – FFG Minebreaker 2000/2.

The area was later manually cleared by Polish Army engineers who confirmed that the Minebreaker had detonated or broken up approximately 80 sub-surface anti-personnel blast mines. All items of UXO were detonated or broken up. Two Iranian YM-1 anti-personnel mines were located that had escaped destruction. This mine type requires sustained

1. Handicap International, 2000.

pressure of at least one second in order to activate. The tiller rotation speed of Minebreaker was unable to apply this.

The HALO Trust mechanical excavation

HALO mechanical operations began in Kabul, Afghanistan in 1996. Since then, HALO has operated machines in mine clearance programmes in Abkhazia, Afghanistan, Angola, Cambodia, Chechnya, Eritrea, Kosovo, Mozambique, Nagorno-Karabakh, Somaliland, Sri Lanka and Sudan. As of March 2003, HALO has used mechanical application in a total of 11,804,416 square metres of land. No accidents occurred to demining personnel. No missed mines have been recorded by subsequent users of the land.

Croation Mine Action Centre (CROMAC) clearance projects for the year 2002

The GICHD commissioned CROMAC to provide clearance data for all demining activity within Croatia from January to December 2002. Clearance operations were conducted in a total of 232 suspect areas, and machines were employed to prepare areas by breaking the surface of the ground in 167 tasks (concurrently clearing vegetation). Of these, 104 were to prove free of mines and were cancelled out. In 63 tasks, machines encountered anti-personnel mines. Of these 63 sites, no mines were found intact by follow-up clearance methods (manual or MDD). The 63 sites covered 5,530,192 square metres. All mines had been detonated or broken up. Remaining fragments were cleared by manual or MDD teams.

Lebanese National Demining Office (LNDO)

Demining operations in Lebanon are carried out by engineers of the Lebanese Armed Forces (LAF), coordinated by LNDO. Confidence in the clearance capacity of flails (in this case an Armtrac 100) is sufficiently high that LAF demining standards allow for full clearance in order to reduce casualties. They use the flail for full clearance only in scattered minefields where the threat is higher than that in uniformly distributed minefields, as experience has shown that, in general, in Lebanon, it is quicker to clear patterned minefields manually.