Unravelling flail-buried mine interaction in mine neutralization

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Abstract

This study attempts to explain the ground effects and effects on mines when using flails during mine neutralization. It focuses, describes, and discusses the forces at play at the flail-buried mine interface, provides an explanation using simple mechanics for previously reported observed ground effects and effects on mines, rationalises the role of individual flail components in the overall effectiveness of flail systems. The study theorises and describes stress distribution; soil movement, formation and progression of pressure field in the flail-buried mine interface. The study makes apparent characteristics that are unique to flails that may lay the foundation for specifying, screening, evaluating and/or selecting flails on a technical and rational basis for mine neutralization.

Résumé

La présente étude porte sur les effets au sol et sur les mines de l'utilisation de fléaux en neutralisation des mines. L'étude décrit et traite principalement des forces en jeu à l'interface fléaux-mines enfouies. Elle propose une explication des effets au sol et sur les mines au moyen de mécanismes simples observés et rapportés et rationalise le rôle des composants de fléaux dans l'efficacité de l'ensemble du système à fléaux. L'étude théorise et décrit la distribution des contraintes, les mouvements du sol, ainsi que la formation et la progression du champ de pression à l'interface fléaux-mines enfouies. Enfin, elle dégage les caractéristiques uniques des fléaux qui pourront servir de fondements pour une spécification, un choix, une évaluation et une sélection des systèmes à fléaux de neutralisation des mines sur une base technique et rationnelle.

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Executive summary

The neutralization of landmines is a high priority activity for both the Canadian forces (CF), and the Canadian Centre of Mine Action Technologies (CCMAT). The CF considers pressure-activated landmines as a serious threat to the movement of CF personnel and vehicles operating in current and post conflict areas of the world, whereas CCMAT (an organization mandated by the government of Canada to assist humanitarian demining activity world wide) considers mine neutralization essential prior to the commencement of economic reconstruction and the return of the land to the local people for normal every day use.

Current practices of mine neutralization centre on manual demining, a slow, labour intensive, and often a high risk and expensive process. Mechanised flail systems are often proposed to speed up the process, reduce the cost, and the risk associated with the neutralization of buried pressure activated landmines.

The concept of using flails to neutralize mines has been around for many years and a number of defence forces have some form of flail system readily available in service. In spite of this, the state of technical knowledge with respect to the mechanics of flail-soil interaction that results in the activation and neutralization of a given buried mine is limited. This limitation has resulted in the engineers having to rely on trial and error and intuition, rather than on a technical basis to substantiate the requirements for design of mechanised flail systems to address the mine neutralization issues. In recent years several prototypes of flail systems have been put together for marketing to humanitarian agencies world-wide. Independent field trials on typical systems have revealed that the performances are less than satisfactory and do not meet the needs of the international demining community. Landmines are generally buried within 150mm of the earth's surface. The commonly accepted and United Nations requirement for mine clearance is 99.6 % to the depth of 200mm from the ground surface.

This study breaks ground in its attempt to explain and provide to designers, purchasers and users of flails an insight into the happenings at and in the flail-buried mine interface during the neutralization of buried mines. It achieves this by:

a. focusing, describing, and discussing the forces at play at the flail-buried mine interface,

b. providing a technical rationale for previously observed and reported ground effects and effects on mines during the neutralization of mines using flails,

c. rationalising the role of individual flail components in the effectiveness of flails systems, and

d. using well accepted soil mechanics principles to describe at flail impact, the soil compaction and movement, and the formation and progression of pressure fields in the flail-buried mine interface that result in the activation and neutralization of a buried mine.

The study makes apparent and highlights the characteristics that are unique to flails that can help move the field of flail-making from one of trial and error to one based on science, thereby introducing some technical rationale to a field that is currently based on intuition.

The study enhances the understanding of flails and lays the foundation for improving the performance of flails. The noted characteristics need to be experimentally investigated to identify how they can be exploited to develop standard tests for measuring the intensity, regularity and depth of penetration of pressure fields created on flail impact. Also, the noted characteristics will help compare and grade on technical basis the performance of flails systems now available world wide to neutralize anti-personnel landmines.

The characteristics will assist both the user and designers to define and set flail system specification to meet demining requirements.

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Sommaire

Les Forces canadiennes (FC) et le Centre canadien des technologies de déminage (CCTD) considèrent la neutralisation des mines terrestres comme une activité prioritaire. Pour les FC, les mines terrestres à déclenchement par pression constituent une menace sérieuse pour les mouvements de leur personnel et de leurs véhicules déployés dans les zones de conflit ou pacifiées du monde. Pour sa part, le CCTD (organisme mandaté par le gouvernement du Canada pour participer au déminage humanitaire dans le monde entier) considère la neutralisation des mines comme essentielle avant que ne puisse être entreprise toute reconstruction économique ou la restitution des terres aux populations locales pour un usage quotidien normal.

Les pratiques actuelles de déminage manuel utilisées par le centre sont lentes, demandent beaucoup de personnel, et sont souvent risquées et coûteuses. Des systèmes à fléaux mécanisés sont souvent proposés pour accélérer le processus du déminage et réduire les coûts et les risques associés à la neutralisation des mines terrestres à déclenchement par pression.

Le concept de l'utilisation des fléaux pour neutraliser les mines existe depuis de nombreuses années, et nombre de forces de défense possèdent déjà un système à fléaux. Malgré tout, l'état des connaissances techniques est limité dans le domaine de la mécanique de l'interaction fléau-sol entraînant le déclenchement et la neutralisation des mines enfouies. Cette limite a incité le Génie militaire à se fier à des méthodes empiriques et à l'intuition, plutôt qu'à des méthodes techniques pour répondre aux exigences en matière de conception de systèmes à fléaux mécanisés de neutralisation des mines. Au cours des dernières années, divers prototypes de systèmes à fléaux ont été proposés aux organismes humanitaires dans le monde entier. Des essais indépendants sur le terrain de systèmes particuliers ont démontré que les performances de ces derniers étaient loin de satisfaire aux besoins de la communauté de déminage internationale. Les mines terrestres sont généralement enfouies à moins de 150 mm de profondeur. L'exigence communément acceptée par l'Organisation des nations unies en matière de déminage est un taux de réussite de 99,6 p. 100 jusqu'à une profondeur de 200 mm.

Cette étude innove en matière d'explication et d'informations pour les concepteurs, les acheteurs que les utilisateurs de fléaux et elle donne un aperçu de ce qui se passe au niveau de l'interface fléaux-mines enfouies lors de la neutralisation de ces dernières. L'étude :

a. décrit et traite principalement des forces en jeu à l'interface fléaux-mines enfouies;

b. propose une explication des effets au sol et sur les mines lors de l'utilisation de systèmes à fléaux au moyen de mécanismes simples observés et rapportés;

c. rationalise le rôle des fléaux particuliers dans l'efficacité de l'ensemble d'un système à fléaux;

d. décrit au moyen de principes de la mécanique des sols bien acceptés le compactage et les mouvements du sol survenant au point d'impact des fléaux, ainsi que la formation et la progression du champ de pression à l'interface fléaux-mines enfouies responsable du déclenchement et de la neutralisation des mines.

L'étude dégage et met en relief les caractéristiques uniques aux systèmes à fléaux qui pourrait permettre de faire passer la fabrication de ces derniers de l'approche empirique actuelle à une approche scientifique en introduisant notamment certains fondements techniques dans ce domaine de connaissance actuellement basé sur l'intuition.

En améliorant la compréhension de l'effet des fléaux, l'étude jette les fondements nécessaire à l'amélioration de leur performance. Les informations recueillies doivent être étudiées par voie d'expérimentation afin d'identifier la façon dont elles pourront être utilisées pour mettre au point des essais normalisés qui permettront d'évaluer l'intensité, la régularité et la profondeur de pénétration des champs de pression créés par l'impact des fléaux. Ces informations permettront également de mieux comparer et de classer de façon technique la performance des systèmes à fléaux actuellement disponibles dans le monde pour neutraliser les mines antipersonnel.

Enfin, les informations recueillies aideront les utilisateurs et les concepteurs à définir et à fixer les spécifications des systèmes à fléaux de façon à ce qu'ils satisfassent aux besoins en déminage.

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DRES and CCMAT funded this study to enhance the understanding of flail fundamentals and their role in mine neutralization.

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1. Background

Finding, removing and neutralising landmines is a slow, tedious, labour intensive and costly exercise. Flail systems are often proposed for the neutralization of pressure activated antipersonnel landmines. International humanitarian demining organizations, assisting in the reconstruction of the economy in post conflict areas of the world, have a need for the verification of the claims made by private venders selling demining equipment, in particular the claim of the equipment's effectiveness in neutralising antipersonnel mines to the degree claimed.

A Canadian military team assisting the Cambodian Mine Action Centre (CMAC), accepted to meet the need by field testing a typical flail system offered by Finland. The extensive and painstaking field trial revealed a number of unacceptable deficiencies that have been well documented at [1]. The study confirms that the performance of currently available flail systems is marginal and well below what is required by the humanitarian demining community for neutralization of antipersonnel mines. The deficiencies observed at [1] are common to most flail systems available today because they are very similar in design.

It is suggested that the effectiveness of current flails can be significantly improved, as their ineffectiveness can be traced back to the paucity of technical understanding of the forces at play at the flail-buried mine interface during mine neutralization. Recent studies [2, 3] carried out for the Canadian Centre for Mine Action Technologies (CCMAT) at the Defence Research Establishment Suffield (DRES) have noted that the understanding of the mechanics and dynamics of flails at the flail-buried mine interface is essential to the formulation of a rational approach to the designing and evaluation of flails.

It is the thesis of this study that the assumed potential capability of the flails to neutralize mines can either be brought to reality or disproved only when the mechanics and the controlling parameters of flails are well understood. To date the flail ground interaction in mine neutralization and the resultant effects left on the ground and on the buried mines have remained unexplored and unexplained. What follows is an attempt to provide a technical explanation, albeit in qualitative terms, for the effects on the ground and the buried mines that were well documented and reported in [1].

2. Scope of study

It is not considered realistic to presume that one demining tool or procedure can meet the varied and complex requirements of the humanitarian demining community. The subject of surface vegetation, brush removal, handling of obstacles and objects, though important issues, are separate issues requiring very different approaches and techniques and should be dealt accordingly. The issue of vegetation and obstacle clearance is therefore outside the scope of this study.

At the current stage, the flail fundamentals and their role in mine neutralization are not sufficiently understood. The state of knowledge does not permit a fair assessment of the potential of flails or their limitations to neutralize pressure activated anti-personnel mines. What is clear and well documented is that chiselling and soil movement adversely affect demining operations and need to be well managed and, if possible, avoided.

This study describes and discusses:

a. the forces at play and the happenings at and within the flail-buried mine interface;

b. the rationale for previously documented observed ground effects and effects on mines during a flail operation;

c. the role of individual flail components in the overall effectiveness of flails;

d. using soil mechanics, the stress distribution, soil movement, formation and progression of pressure field responsible for initiating and neutralising antipersonnel mines; and

e. design changes that can contribute to increasing the overall effectiveness of flails in mine neutralization.

3. Approach

Pressure activated anti-personnel mines are solely meant to prevent persons from trespassing into protected territory. The mines are designed to actuate when the mine senses a pressure, similar to what is induced by a person walking or running on a ground surface. The overall approach of this research effort is to establish design parameters that will lead to a simple, low cost and robust mechanical equipment that will simulate in the ground layer the same pressure effects that a person does when walking or running. This study examines flails, for they offer the potential to mechanically create, maintain, and control pressure fields in the ground surface, thus offering the possibility of reproducing conditions of the same magnitude that a person produces to trigger anti-personnel landmines. The study envisages using the potential that flails offer, to neutralize anti-personnel mines and make current mined areas safe "ONLY" to walk on. The research effort is not intended to lead to a mechanical design that will neutralize all explosive ordnance lying buried in the path of the mechanical equipment. It is intended to neutralize only those explosive ordnances that have been specifically placed in a path to detonate under a person's weight and prevent him/her from trespassing. It is considered that once it is safe for a person to walk on any given mined area, then he/she can bring to bear more effective tools and procedures to detect, neutralize and/or remove other harmful buried ordnance and anti-tank mines buried in the area.

This investigation will attempt to examine the possibility of mechanically achieving a serial effect with appropriate ground coverage that closely resembles the effect in the ground layer that is produced by a running or walking person.

4. Forces at play at flail-buried mine interface

Popular flails currently available for neutralization of landmines primarily consist of a number of chains evenly spaced and connected at one end to a common horizontal power shaft. The other end of each chain is connected to a weight, often called a hammer. The shape and size of the hammer varies quite widely from one system to another. Some hammers are shaped to chisel the ground, cut and break up mines, others are shaped to transmit on impact a pressure field to trigger the buried mine, and some are shaped to do both. Rotation of the shaft at a speed higher than the critical speed, i.e., threshold speed, extends the links and hammers fully outwards in the vertical plane.

The literature does not provide any formulation as to how the height of the shaft with reference to the ground surface is to adjusted for mine neutralization. Figure 1 shows a flail configured for the neutralization of landmines, rotating at high speed with hammers fully extended and impacting the ground. As the hammers move from position A to position B, they impact the ground surface at an angle θ. The impact force *F* may be expressed, in simple terms, as two primary components:

$$F_N = F \cdot \cos\theta \quad \text{(1)}$$

and

$$F_H = F \cdot \sin\theta \quad \text{(2)}$$

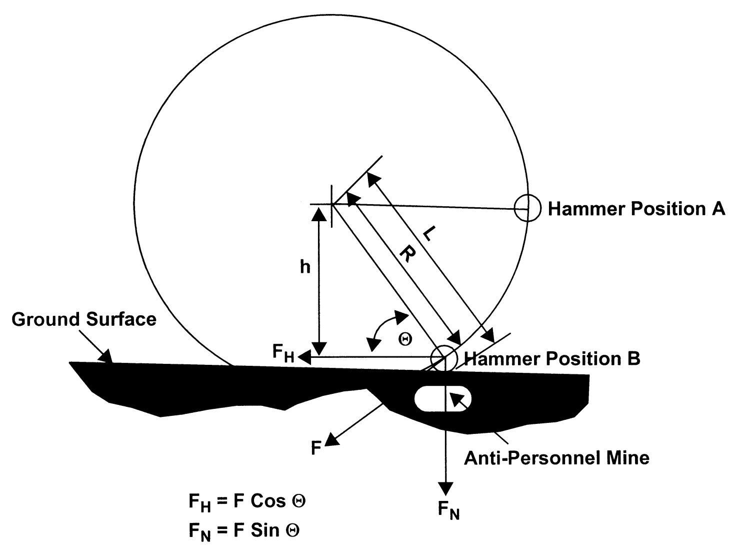


Figure 1. *Flail rotating at high speed with hammers fully extended and impacting the ground surface.*

The average impact force F may be expressed as a function of hammer mass m, angular velocity w, flail radius R and stopping time t.

$$F = mwR/t \quad (3)$$

The stopping time t in equation (3) is a function of the composition and characteristics of the surface of impact. In neutralization of buried mines using flails, the surface on which the flail hammer impacts is the ground surface. The composition and characteristics of natural ground surface is relatively quite complex, variable and unpredictable in comparison to known materials and mediums. For the purpose of this study it would suffice to say that the dynamics of natural soil under normal loading is yet not well understood. However, it is well accepted that the force imparted to the ground surface at impact and the progression of the force effects into the ground layer below are significantly affected by the composition and characteristics of the soil. On the subject flails, it can be said that soil plays a role of paramount importance, in the transfer of the load from the ground surface to the buried mine.

In this examination the soil layer covering the buried mine is idealized. It is assumed to be elastic, homogeneous, and isotropic. Although in actual practice natural soil is non-elastic, non-homogeneous, and non-isotropic material, for now the assumption aides in estimating the forces that come into play, on and in the flail-buried mine interface.

To keep the flail-buried mine interaction issue manageable, it is assumed that for a given demining operation the distance between the centre of the power shaft and the ground surface remains unchanged. This assumption permits the impact force to be considered constant for a given demining operation.

This study finds that it is possible to explain the effects on the ground and on buried mines, resulting from flail-ground interaction in terms of:

(i) the two primary force components of the impact force F i.e., F_N and F_H;

(ii) the hammer geometry;

(iii) the type of link, linking the hammer mass to the power shaft, e.g., chain link or a fixed link; and

(iv) the soil characteristics.

Since the primary objective in mine neutralization using flails is to trigger and detonate mines where buried, it can be said that force component F_N plays a positive, helpful role and therefore its role needs to be maximised. The force component F_H contributes in the creation of ground surface disruption, overburden, ridges, and the scattering of mines. It can be said, that force component F_H plays a negative, unhelpful role and therefore its role in mine neutralization needs to be minimised to the extent possible.

It may be noted that since F_H is a function of sinθ, and F_N is a function of cosθ, the increase in the value of one component leads to a corresponding decrease in the value of the other and vice versa. Thus to increase the effectiveness of flails in mine neutralization an increase in the magnitude of F_N will simultaneously result in a decrease in the effects attributable to the force component F_H. In practise, when using flails the force component F_H can be minimised to a practical value, but it is not possible to reduce it to zero. That would jam the flail and prevent it from rotating.

It is pertinent to note here that hammer geometry and link kinematics can also add to or decrease the surface disruption effects of F_H. When hammer geometry and link kinematics are carefully selected they can help to minimise the adverse effects of F_H.

5. The role of hammer geometry

The observations reported at Reference 1 are based on flails that use a chain to link and transfer power from a power shaft to a weight. Some example of weights used in the field trials are shown in Figure 2.

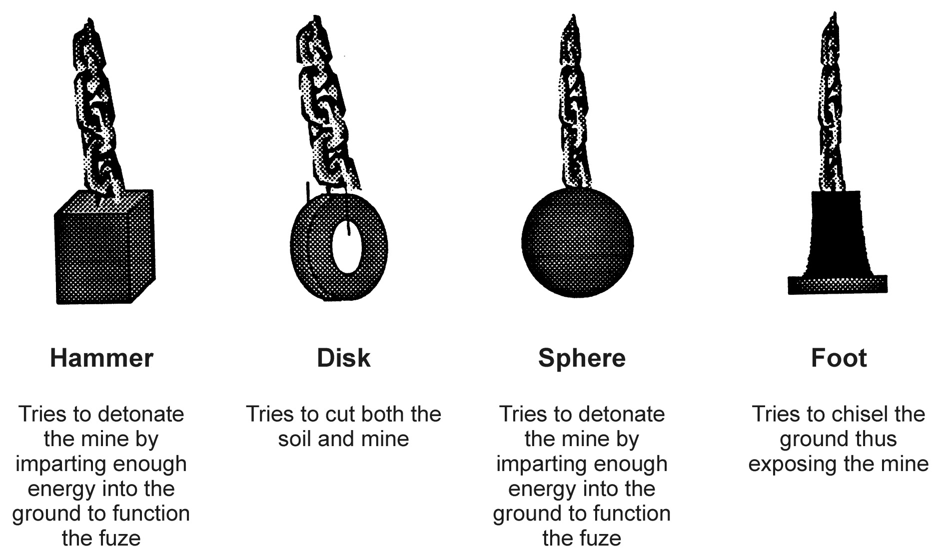


Figure 2. *Typical weight/hammer geometry, commonly used at the end of chain links.*

The essential observations attributed to chain link flails in [1] are:

(i) they create and move overburden that covers mines so deep that they cannot be detected later by using the available metal detectors, see Figure 3;

(ii) they leave ridges large enough for mines to be missed, see Figure 3; and

(iii) only a small percentage of pressure activated mines are triggered and neutralized, the rest are scattered, some still active, some in one piece, some in pieces everywhere, even into areas that have been painstakingly demined, compounding the problem at hand.

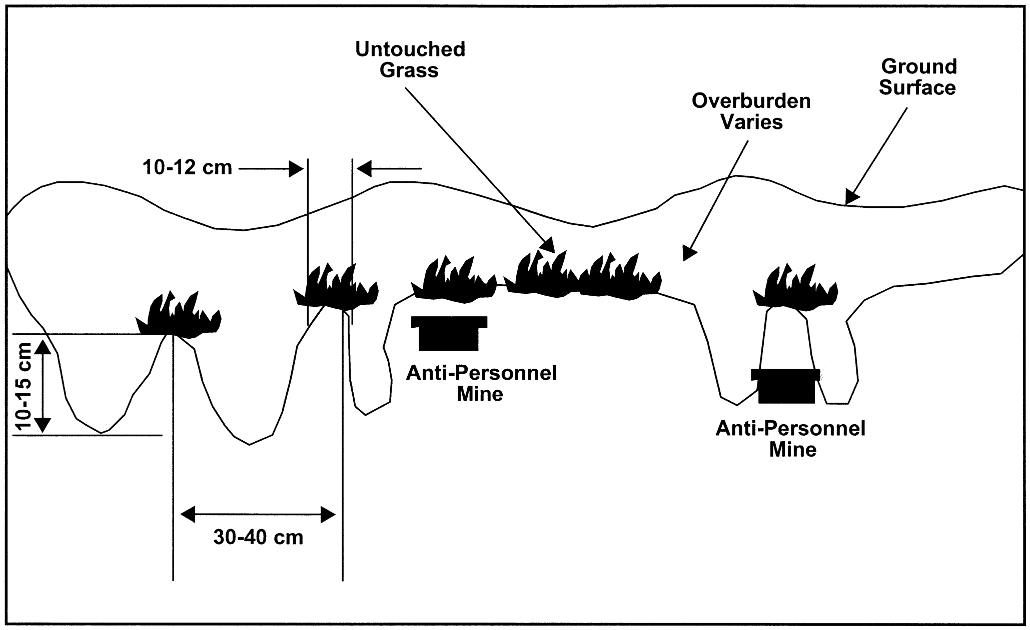


Figure 3. *Chain link flails create and move overburden and leave ridges large enough for mines to be missed.*

The observation (i) and (ii) can be traced back and attributed to the action of the horizontal force component F_H and the geometry of the hammer. In observation (iii) the small percentage of pressure activated mines that are triggered and detonate can be traced back and primarily attributed to the action of the normal force component F_N. The remaining mines that are scattered everywhere either in one piece or in several pieces as a result of breaking up can be traced back and attributed essentially to the geometry of the weight and the action of the horizontal force component F_H. Thus it becomes apparent that the two primary force components play completely differing roles in mine neutralization

Weight geometry can have either a positive or a negative effect on mine neutralization when using flails.

Earlier a number of negative attributes of flails such as surface disruption, creation of overburden, ridges, and haphazard scattering of mines and their components that compound the hazards and complexity of demining, was traced back to the horizontal force component F_H. It should also be apparent that before the force component F_H can play out its negative role, the weight must break the ground surface and enter it at impact, in this action the geometry of the weight i.e., its shape, plays an all important part. The weight geometry determines the extent of surface indentation and/or the depth to which the ground surface is penetrated by the weight on impact. A weight with a geometry that provides it with sharp edges will accentuate the penetration of the weight into the ground and the negative aspects of the force component F_H. A weight with blunt edges, a rounded geometry would less able to break and penetrate the ground, thus reducing the ploughing action, surface disruption, the creation of overburden, ridges, and scattering of buried mines.

This study suggests that flails designed strictly for mine neutralization should avoid weights/hammers with sharp corners and edges, since they increase weight/hammer penetration into the ground surface, augment movement of soil and increase the probability of moving a mine from its original location without fully neutralising it. A weight with rounded geometry, such as a horizontal cylinder impacting the ground, with its principal axis parallel to the impacting surface would make sense, as its geometry will minimise both indentation and surface penetration. Thus it will minimise the adverse aspects of flails and focus the process on the primary objective, that of neutralization of mines.

6. The role of flail link

In a flail system, the link plays a double role in mine neutralization:

(i) to act as a channel for the effective transfer of power from the power shaft to the hammer mass; and

(ii) to ensure an even, systematic, vertical force penetration and ground coverage, such that every inch of ground surface is covered, no zones are skipped and no mines are missed.

It is known that each flail configuration has a critical rotation rate or speed that is unique to that configuration. When the flail system rotates at a rate higher than this, the hammers remain fully extended at all times while rotating in the vertical plane. When the flail is lowered and the hammers start impacting the ground, a degree of instability is introduced in the flail system. This instability is enhanced when the hammers break through the ground surface and start to plough the ground. It was mentioned earlier that the geometry of the hammer contributes to the indentation and depth of penetration into the ground surface. To this it may be added that as the chain linked hammer ploughs through a ground layer that is non-homogeneous, has roots and is stone bearing, the hammer surface is subjected to changing force distribution, which gives a zig-zag motion to the rotating chain linked hammers. This motion was described in [1] as a snake-like motion.

It is suggested that this zig-zag hammer motion in soil results in the creation of uneven ridges and valleys large enough for mines to be missed as shown in Figure 3. The zig-zag hammer motion can be considered as a function of the degree of freedom of movement provided by the choice of link used to attach the hammer to the rotating shaft. It is suggested that if the freedom of movement of the hammer that ploughs through the ground layer is restricted to a single vertical plane by replacing the chain link by a lever link, it would curtail the zig-zag motion of the hammer and the consequential adverse side surface effects.

Furthermore, it is suggested that a lever link would ensure an even, systematic vertical force penetration and ground coverage. An example of a flail system in which the degree of freedom of movement a flail has been curtailed compared to that provided by a chain link is shown in Figure 4. In this figure the chain that normally links the hammer to the power shaft has been replaced by a rigid lever link. This modification will prevent the zig-zag/snake like motion elaborated earlier in this study, and assist in achieving the type of ground coverage shown in Figure 5, thereby eliminating the areas wherein mines may be missed.

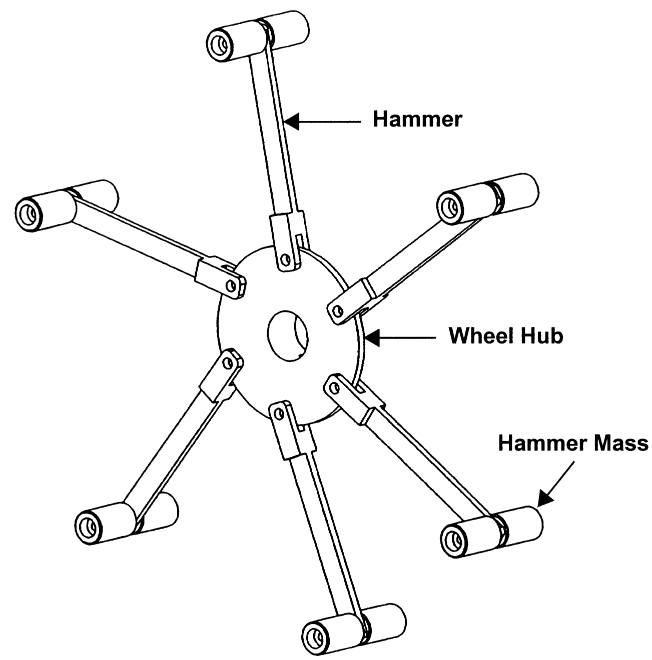
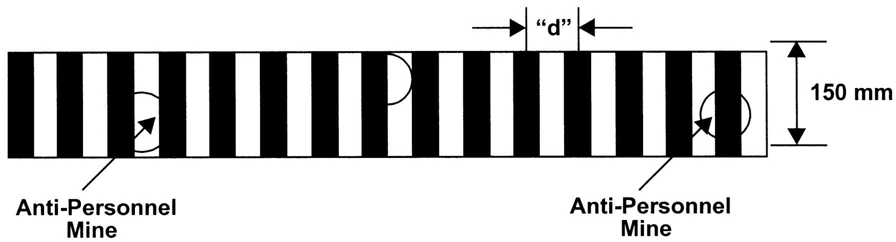


Figure 4. *An example of fixed link flail and superior hammer geometry.*



Note:

1. **The impacted areas using superior hammer geometry are shown in black**
2. **"d" is the distance between two consecutive impacts**
3. **The round circles depict buried mines in the path of a fixed linked flail**

Figure 5. *A fixed link flail offers superior and effective ground coverage.*

Recent laboratory tests in a soil bin, funded by CCMAT and DRES, on a system very similar to the one shown in Figure 4, indicate that replacing the chain link with a rigid lever link does eliminate the zig-zag motion, and provides more consistent, systematic and repeatable ground coverage as shown in Figure 5. However, a single lever in place of a chain link transmitted excessive forces and vibrations to the drive mechanism. This was corrected by cutting the single lever link into two parts and introducing an additional joint using a pin to join the two parts. The new "knee-joint" added an additional degree of freedom in the system and has proved very effective. The experimental study is still in progress and the results are yet to be published.

7. The role of power shaft height

The angle at which a flail hammer impacts the ground is a function of the power shaft height above the ground, which can be expressed as:

$$h = R \cdot \sin\theta + r \quad \text{...}(4)$$

where in R is the distance between the centre of the power shaft and the centre of the hammer mass, r is the hammer radius and θ is the angle that the flail makes with the ground surface at impact. Since both R and r are fixed for a given flail, it can be noticed that the value of h is directly prelated to the value of θ, which increases as the power shaft is raised and decreases as the shaft is lowered.

From equations 1 and 2, it can be noticed that the horizontal force component F_H increases in magnitude as θ is increased by raising the power shaft and the normal force component F_N decrease correspondingly. Vice versa is also true.

Thus it can be concluded that the variation in power shaft height *h* affects both the force components F_H and F_N differently, one positively and the other negatively. This determination would indicate that when using flails of a given length *l* where:

$$l = R + r \quad (5)$$

That the way to maximise the normal component F_N and thereby the principal surface stress that comes to bear on the buried pressure activated landmine is by lowering the centre of the power shaft and maintaining it at the lowest feasible height. This would maximise the mine neutralization capability of the flail system by maximising the normal force component F_N. Maximising F_N would also result in maximising the ground surface indentation caused by the hammer mass, which could increase ground surface disruption. The overall effect may or may not be that significant and will depend on the soil strength and may require some compromise.

The ideal situation that needs to be aimed at is one where the hammer mass makes an indentation on the ground surface without breaking through it. The hammer is then dragged until it leaves the ground surface again, ideally avoiding ground penetration and ploughing action whenever possible.

8. Stress distribution and soil movement in flail hammer-buried mine interface

On flail hammer impact, the soil surface indents due to the action of impact force, and soil particles move in various directions. The hammer geometry, hammer mass, impact speed and soil physical properties are important factors that effect stress distribution and soil movement.

Stress distribution under vertical loads, considering elastic soil behaviour, has been studied for decades. Several methods for estimation of stress distribution have been reported. Boussinesq, [5], used vertical point-load method on a semi-infinite elastic medium for approximating stress distribution. A small cube was considered at a position represented by radial vector r. The vector r is perpendicular to one side of the cube (Figure 6). It was concluded that there were no stresses on any side of the cube except on the side perpendicular to the radial vector r. The normal stress on this side, which is a principal stress, is given by:

$$\sigma_r = \sigma_1 = \left(3P / 2\pi r^2\right)\cos\theta_1 \quad (6)$$

Using Equation 6, the principal stress σ_1 at any point of the soil can be calculated. The direction of the stress will be the same as vector r. Equation 6 is based on elastic soil behaviour and the same stress distribution for all soils. Since soil behaviour is not elastic, which affects stress distribution in soil, Fröhlich modified Equation 6 to include a factor ξ that relates to soil condition, [5]. The modified equation becomes:

$$\sigma_r = \sigma_1 = \left(\xi 3P / 2\pi r^2\right)\cos^{\xi-2}\theta_1 \quad (7)$$

The factor ξ is called the concentration factor. As soil becomes softer, the value of ξ increases. Suggested values of ξ are 3 for hard soil, 4 for normal soil and 5 for soft soil. These effects are shown in Figure 7.

For normal soil conditions, the stress distribution in soil has been considered to have a circular shape, [6]. Although the actual stress distribution may not follow an exact circular pattern, but for estimating purposes a circular pattern is commonly used.

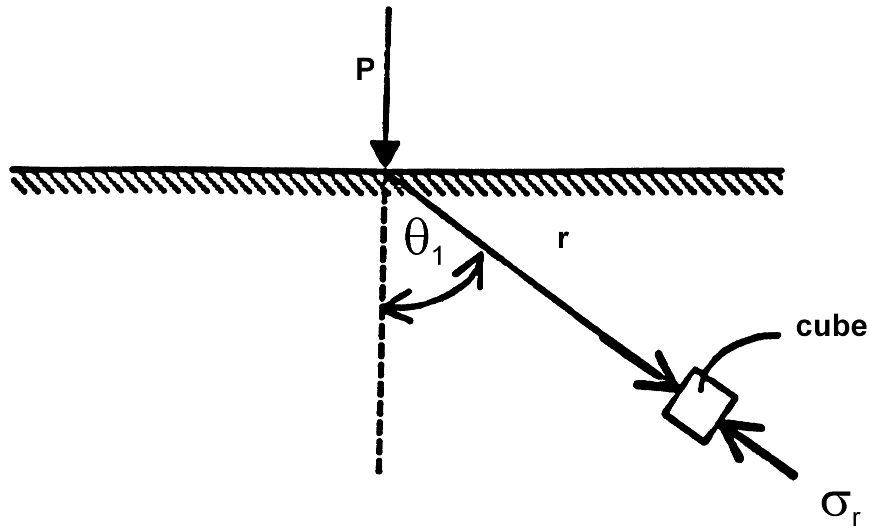


Figure 6. *Soil stress due to a vertical point load (Reference 7).*

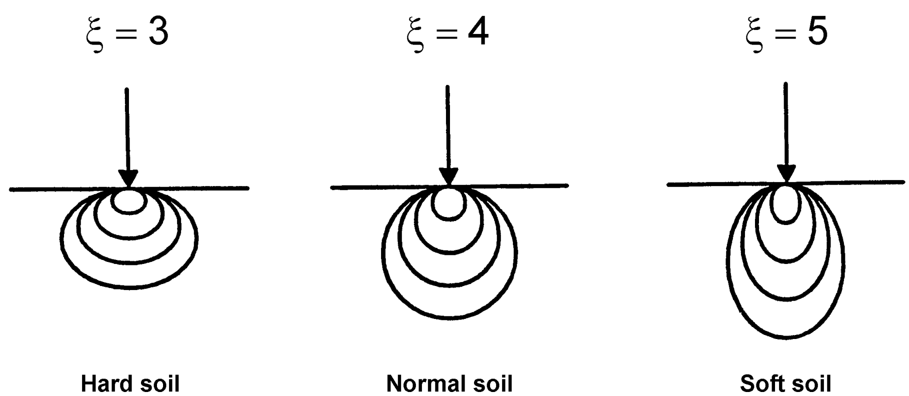


Figure 7. *Schematic representation of stress distribution under a point load in different soil conditions.*

9. Influence zone and iso-intensity circles

The hammer impact forces the soil located under the hammer to fail 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 till they are outside of the influence of the hammer and finally, the hammer passes them and they come to rest. 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 at some distance away from the hammer, would have the least tendency for movement. The path of movement of soil particles are lines drawn perpendicular to each circle's perimeter as shown in Figure 8. Arrows show the path of movement of the soil particles. The magnitude and direction of the movement of each soil particle depends on its location in 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 re-arrangement of soil particles, when there is no margin for further soil compaction underneath the hammer, soil particles start to move to the sides, Figure 9. The influence zone is assumed 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, it 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.

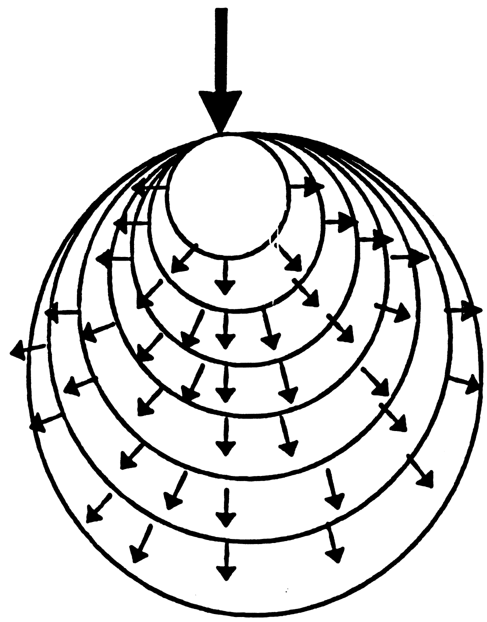


Figure 8. *Influence zone and iso-intensity circles.*

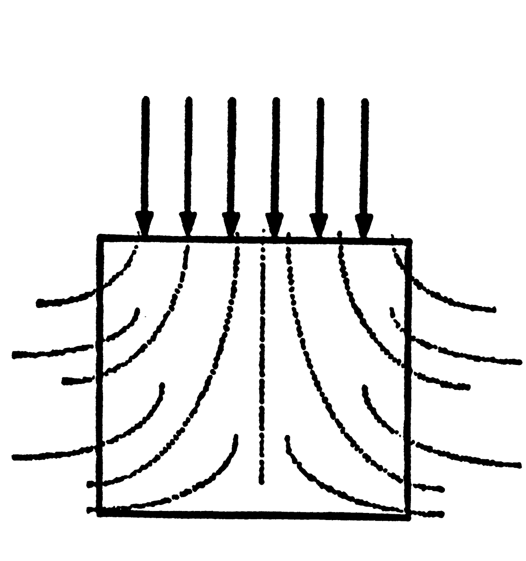


Figure 9. *Soil movement under hammer impact.*

A high speed 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, Figure 10, and creating their respective zones of influence. An antipersonnel mine buried within the reach of these influence zones will experience increased pressure with the intensity of the 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 neutralization 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 cleared of antipersonnel mines.

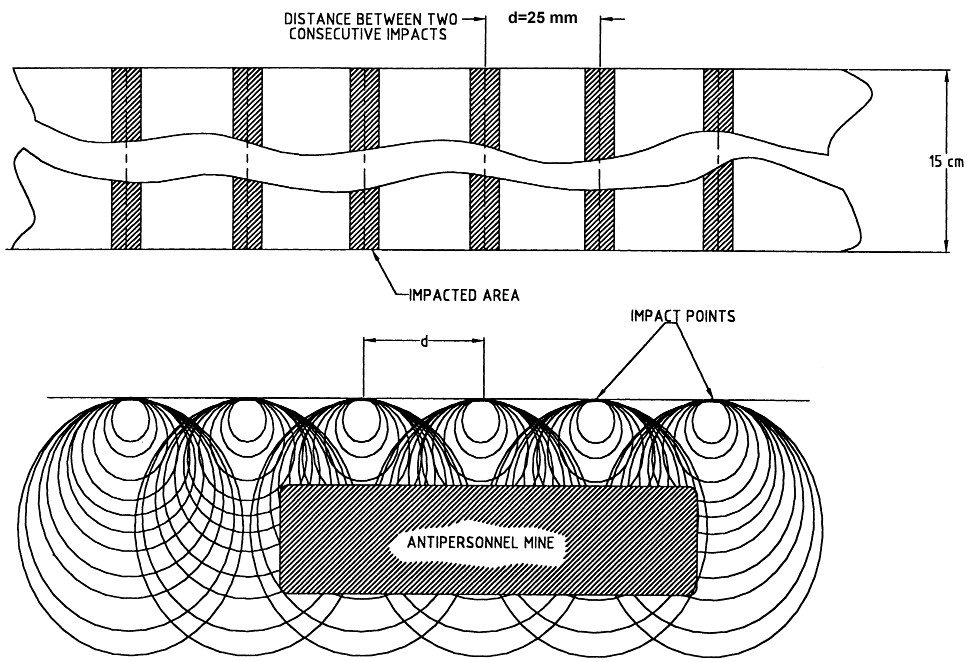


Figure 10. *Schematic representation of stress distribution over buried mines in the path of a fixed link flail.*

10. Evaluating flails

Currently there are no universally recognised common test procedures for evaluating and screening flails. The need to make a beginning exists. This study suggests that each flail configuration has characteristics that are unique enough to be identified and measured. These can form the basis for screening, evaluating and/or selecting flails for mine neutralization. These characteristics for a given flail configuration and design are:

(i) maximum principal surface stress inducing capability F_N;

(ii) hammer geometry and link type that minimise ground surface disruption; and

(iii) the depth and intensity of the influence zone.

11. Conclusions

1. Observed flail effects on the ground and on mines can be traced back and explained in terms of force components at play at the flail-buried mine interface.

2. Flail configuration, component selection, design and geometry all contribute significantly to the overall effectiveness of flails in mine neutralization.

3. Hammer designs that focus on the creation of requisite pressure fields at impact to neutralize anti-personnel mines may be more appropriate than those that focus on sharp edges and corners for breaking ground and mines using brute force.

4. Flail movement that is restricted to a single vertical plane may offer superior and effective ground coverage.

5. Each flail configuration has a unique power shaft height (above the ground) that determines the maximum principal stress inducing capability for the given flail system.

6. Flails have characteristics that can be exploited to establish specifications and common universal tests for comparing and evaluating flails, now available the world over.

12. Recommendation

It is recommended that common test procedures be developed for flails that would make it feasible to measure and compare flail systems in terms of their real mine neutralization capability. The test results will make it possible to rate flail equipment, and thereby enable designers, users and purchasers to compare the effectiveness of current and future flails, before making investment and purchase decisions. This would significantly reduce the current expensive practice of buy and try in far away areas of the world.

13. References

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List of symbols/abbreviations/acronyms/initialisms

F	impact force, kg.
F_N	normal component of force F, kg.
F_{MN}	maximum normal component of force F, kg.
F_H	horizontal component of force F, lbs.
h_c	power shaft critical height corresponding to force F_{MN} for a given flail system in meters.
θ_f	angle of flail hammer impact.
θ_c	critical angle of flail hammer impact corresponding to force F_{MN} for a given flail system.
m	hammer mass in kg.
R	radius of flail in meters.
n	flail rpm.
w	angular velocity in rad/s.
t	stopping time in seconds.
l	length of flail in meters.
N_c	flail hammers fully extended, flail critical rpm.
r	hammer radius
θ_1	angle made by radial vector r with the vertical
σ_1	principal stress
ξ	concentration factor