Development of a Mechanical Device for Landmine Neutralization

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Abstract
The use of mechanical devices such as chain flails for landmine neutralization and/or area reduction has the potential of greatly aiding landmine clearance. However, mechanical clearance methods have not been fully accepted in the landmine clearance community due to a lack of knowledge and scientific data concerning the actual soil-tool interaction and the landmine clearance effectiveness. The research objective was to develop a mechanical device that will deliver sufficient force to produce adequate ground deflection for detonating typical antipersonnel landmines at depths up to 200 mm. Other design parameters included design simplicity, high durability with low and ease of maintenance and flexible operation. A design matrix was employed to select an appropriate design for further analysis, resulting in preliminary testing and evaluation of a Tamper and Jackhammer. It was concluded that a tamper design resulted in superior demining capabilities. A final testing phase was designed on further evaluation of the demining effectiveness of the tamper and to determine optimal operational parameters between two shoe sizes and the number of pass applications. Tests were conducted using the Terra Mechanics Rig facility at the University of Saskatchewan. The results revealed that the small tamper shoe configuration performed better than that of the large shoe, but only marginally. Results also indicated the optimal application was two passes. It was concluded that the optimal shoe configuration would be associated with the demining environment where the device would be used.
Development of a Mechanical Device for Landmine Neutralization

**Introduction**

A mechanical demining device can be defined as a ‘machine used to mechanically treat a mined area, cut vegetation and destroy landmines up to a depth of 200 mm (Steker, 2003). Mechanical demining methods are used to enhance the demining process by increasing productivity and operator safety (Dirscherl, 2003; Griffiths and Kaminski, 2003). Typical demining machines include flail systems, tiller systems, rollers, ploughs, and combined or multi-tool systems. The use of mechanical demining devices can be divided into primary ground processing, area reduction and ground processing (Griffiths and Kaminski, 2003; Green, 1999).

The use of mechanical means of demining have a great potential, but in general, are underused (Kaminski *et al.*, 2003). Mechanical methods are severely hampered by knowledge and performance issues. A review of demining literature has exposed a general lack of research and data concerning the actual soil-tool interaction. Currently employed demining devices are hindered by performance related issues. Many devices employ high-technology components ill-suited for use in developing countries due to extreme operational and environmental conditions, a lack of a support infrastructure needed for transportation, and in field maintenance and repair (Tariq, 1998; Dirscherl, 2003; Habib, 2002; Handicap International, 2000). Many Demining organizations are poorly funded and cannot meet the cost of acquisition, operator training and maintenance of equipment (Tariq, 1998). The results of these negative attributes have led to a lack of acceptance of mechanical means in the demining community.

Recent research relating to the soil/tool interaction of demining mechanisms has been initiated, though the knowledge base is still small at this time. The impact force due to impacting devices has been theorized to be a function of the speed, impact angle and the geometry of an impacting tool. Physical soil properties such as soil compaction greatly influence the magnitude of the impact force (Kushwaha *et al.*, 2004; Stilling *et al*, 2003; Sharifat and Kushwaha, 2000, Shankhla, 2000). Researchers have modeled the pressure distribution due to impact using a modified version of the Boussinesq equation (Sharifat and Kushwaha, 2000). There is no research relating to the actual interaction between a buried landmine and a pressure wave due to surface impact. Although an extension of research relating to the interaction between buried structures and pressure wave propagation through soil can be stipulated.

The objectives of this study were to: a) develop a mechanical device for the neutralization of antipersonnel landmines; b) that the device would deliver sufficient force to produce adequate ground deflection for detonating typical antipersonnel landmines at depths up to 200 mm. Design criteria included:

- design simplicity for minimizing production and repair costs;
- high durability with low cost and ease in maintenance;
- flexible operation with capabilities of neutralizing landmines over a variety of environmental conditions; and
- low power consumption or low cost of operation

**Materials and Methods**

The development of a mechanical demining device for antipersonnel landmines followed an iterative approach involving concept generation, the development of evaluation parameters, evaluation and elimination of potential designs, and preliminary and final design testing.
Concept Generation

The design goal of developing a mechanism for neutralizing antipersonnel landmines to depths of 200 mm was used to initiate a brainstorming session. Operating parameters such as impact force and magnitude, impact frequency, power consumption and design simplicity were evaluated. Many of the initial concepts were rejected on grounds of design feasibility and simplicity that included a freefalling ballistic impact mechanism, a combination hammer/vegetation cutter, a rolling disk with internal impacting devices, a segmented roller with inner springs and a two stage impacting device. The design concepts accepted for further development included a dropping mass mechanism and a slider crank impacting mechanism.

The accepted design concepts were further developed such that the off-the-shelf equipment was chosen due to easy accessibility of the equipment. The commercially available designs included a pile driver, impact hammer (jackhammer), tamper and vibratory roller.

Parameterization

A set of design parameters was developed as an assessment tool for the evaluation of the initial conceptualized designs. Current evaluation protocols and the cataloguing of available landmine clearance machines served as a guideline for formulating the list of both operational and performance based parameters. The evaluation parameters included impact energy, impact frequency and forward travel speed, power requirements, design flexibility and performance, soil effects, design simplicity and maintenance, durability and strength and costs. A scoring chart was developed for each parameter and was used to assign a quantitative value for the conceptualized designs.

Evaluation and elimination

A design matrix, as outlined in The Mechanical Design Process (Ullman, 2003) was constructed using the previously discussed evaluation parameters to assess the preliminary design concepts. The weight of each evaluation parameter was determined using a paired comparison technique.

A total of five possible off-the-shelf devices were evaluated. The evaluated mechanism included

1. Blackcat Post Pounder (Production Energy Services Inc., Inez, TX),
2. Diesel hammer: APE model D1 (American Pile Driving Equipment Inc., Kent, WA),
3. Jackhammer: S 22/c (Sandvik Mining and Construction, Cleveland, OH),
4. Diesel powered tamper: LT800 (Dynapac, Mississauga, ON),
5. EXA boom mounted vibratory roller (MBW, Slinger, WI).

A comparison to existing and proven technology for mine neutralization, the Pearson Area Reduction Roller (Pearson Engineering, Walker, England), and the Aardvark MK5 chain flail system (Aardvark Clear Mine Ltd., Insch, Scotland) was made. The results of the design matrix evaluation identified the jackhammer, Aardvark MK4 Chain Flail and the tamper system for further evaluation.

In acquiring off-the-shelf mechanisms, a vibratory roller mechanism suitable for testing for the lab environment was not found. Thus, only the jackhammer and tamper were obtained for further testing.

Preliminary design testing

The objective of the preliminary testing phase was to evaluate the effectiveness of the devices for landmine neutralization before any equipment alteration and a more detailed analysis were to
be completed. The devices were compared using a secondary design matrix incorporating the following evaluation parameters: peak impact forces, maximum relative sensor displacement, impulse interaction time (duty cycle) and total impulse.

**Apparatus** The TMR test facility in the Department of Agricultural and Bioresource Engineering, (Fig. 1) was used for evaluation of these devices. The primary components of the TMR are a soil bin, carriage and soil processing tools. The soil bin is 0.76 m deep, 1.3 m long and 2 m wide. The carriage is hydraulically driven and is capable of supporting a variety of tillage tools and related instrumentation. The soil processing tools include a hydraulically driven rototiller, and rollers used for soil compaction.

![Fig. 1 The Terra Mechanics Rig.](image1)

Initial tests were performed in a clay-loam soil of approximately 47% sand, 24% silt and 29% clay. Moisture content of the soil varied between 10 to 20% and was measured used the oven drying method. The tamper used for the preliminary testing was a 2.3 kW, 58 kg Wacker™ Model BS-50 gasoline engine powered Tamper (Fig. 2) (Wacker Construction Equipment AG, Munich, Germany) ™ with a 200 x 280 mm shoe. The jackhammer tested (Fig. 3) was a 1.73 kW, 30 kg Bosch™ Brute electric jackhammer (Robert Bosch Corporation, Farmington Hills, MI) with two shoes of 200 x 280 mm and a 280 x 330 mm.
Instrumentation  Two load cells were used to measure the dynamic force transferred through the soil to different depths. A 8897 N capacity shear beam MassLoad Technology™ (Saskatoon, SK) load cell and a 2227 N capacity Interface Technologies™ (River Forest, IL) load cell were used with a retrofitted interface surfaces designed with similar pressure interface areas of common landmines. A displacement sensor, with an interface area and resistive force similar to AP landmines, was used to measure the relative displacement caused by an impact. The displacement sensor was constructed by the Department of Agricultural and Bioresource Engineering in the summer of 2003 (Laturnas et al., 2003). A 2300 System strain gauge conditioning amplifier™ (Vishay Americas, Shelton, Connecticut) was used to condition and amplify the signals from the load cells and displacement sensor. Data were collected using a computer and A/D board, supported by LabVeiv™ (National Instruments Corporation, Austin, Texas) software. All data were collected at 1000 Hz. A cone penetrometer was used to measure the soil compaction to depths of 300 mm.

Procedure  The soil was rototilled and levelled. A trench of approximately 1.5 m x 0.25 m x 0.3 m was dug for placing the load cells. The bottom of the trench was lightly compacted to a value of 100 to 150 kPa. Force transducers and the displacement sensor were placed within the trench at prescribed depths, spaced approximately 0.38 m apart. The trench was filled with the removed soil and the area was levelled manually. The initial soil height and soil compaction were measured and recorded. The tests were performed using three passes of the each test equipment. After each pass, the force transferred to depth, the sensor displacement, the top soil displacement and soil compaction were measured and recorded. Sensors were buried at 100 mm, 150 mm, and 200 mm depths per test series. Sensors were buried at 100 mm, 150 mm and 250 mm depths for the Tamper.

Method of Analysis  The jackhammer and tamper devices were compares using a secondary design matrix. Evaluation parameters included maximum relative sensor displacement, maximum interaction pressure, total impulse and duty cycle. The mathematics and data analysis software Matlab® (The Mathworks Inc., Natick, Massachusetts) was used to calculate the evaluation parameters.

1Photograph reproduced from Wacker Construction Equipment AG, www.wackergroup.com
**Preliminary test results** The magnitudes of each measured parameter are shown in Table 1. The results of the secondary design matrix are shown in Table 2. It must be noted that the sensors used for the tamper were buried at a depth of 250 mm, 5 mm deeper than the jackhammer tests.

**Table 1 Summary of evaluation parameter magnitudes**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Jackhammer Big Shoe Pass</th>
<th>Jackhammer Big Shoe Pass</th>
<th>Jackhammer Small Shoe Pass</th>
<th>Tamper Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Max Average Pressure (kPa)</td>
<td>43</td>
<td>48</td>
<td>49</td>
<td>56.6</td>
</tr>
<tr>
<td>Total Average Impulse (N·s)</td>
<td>31.1</td>
<td>20.3</td>
<td>22.0</td>
<td>30.6</td>
</tr>
<tr>
<td>Total Displacement (mm)</td>
<td>0.67</td>
<td>0.93</td>
<td>0.71</td>
<td>0.99</td>
</tr>
<tr>
<td>Duty Cycle (%)</td>
<td>11.0</td>
<td>8.5</td>
<td>7.9</td>
<td>13.3</td>
</tr>
</tbody>
</table>

**Table 2 Secondary design matrix scores**

<table>
<thead>
<tr>
<th>Device</th>
<th>Pass 1 Score (%)</th>
<th>Pass 2 Score (%)</th>
<th>Pass 3 Score (%)</th>
<th>Average Score (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tamper</td>
<td>48.15</td>
<td>43.70</td>
<td>40.00</td>
<td>43.95</td>
</tr>
<tr>
<td>Jackhammer Small Shoe</td>
<td>17.78</td>
<td>17.78</td>
<td>30.37</td>
<td>21.98</td>
</tr>
<tr>
<td>Jackhammer Big Shoe</td>
<td>17.78</td>
<td>13.33</td>
<td>13.33</td>
<td>14.81</td>
</tr>
</tbody>
</table>

The tamper system displayed significantly higher magnitudes in each evaluation parameter compared to the jackhammer configurations during the first pass. This was reflected in the resulting score of 48.2% compared to 17.8% for each jackhammer configuration. The second pass also resulted in the tamper scoring higher than both jackhammer configurations. Both the tamper big shoe jackhammer scores dropped 4.45% due to a drop in the duty cycle. The tamper again resulted in the highest score for the third pass, though the small shoe jackhammer score raised significantly from 17.8 to 30.4%. Thus, the tamper was selected for further development and analysis. The results of the design matrix showed that the tamper consistently scored higher in each test pass, with the largest score difference between passes 1 and 2.

**Final Testing**

The purpose of the final test phase was to further test and assess the demining effectiveness of the tamper mechanism selected in the preliminary test phase and to determine optimal operational parameters.

**Apparatus** The tamper used for the final testing was a 2.3 kW, 62 kg Wacker™ BS-60 tamper (Wacker Construction Equipment AG, Munich, Germany). Two different sized tamper shoes were used during the testing of 200 mm x 280 mm and 280 mm x 330 mm dimensions. To
To achieve repeatable tamper operation between test runs, a rig was designed and fabricated to fasten the tamper to the carriage of the Terra Mechanics Rig (Fig. 4).

![Fig. 4 The tamper, test rig and TMR carriage apparatus.](image)

The TMR carriage essentially pushed the test rig that held the tamper along the soil surface. The rig contains a pivot point allowing tamper motion similar to the designed, human, hand-held operation mode. The test rig was designed to permit vertical tamper motion during impact without changing the impact angle and retained the ability of the tamper to rotate about the pivot point between the handle and tamper.

**Instrumentation** Four Interface Technologies™ 11.1 kN capacity load cells based on a shear beam design were used for the final testing phase to measure the dynamic force transferred through the soil. The load cells were equipped with customized top and bottom interface to replicate the geometry of common AP landmines. Three load cells were equipped with a circular interface area of $4.42 \times 10^{-3}$ m² and the base area was $8.63 \times 10^{-3}$ m². The displacement sensor, cone penetrometer, signal conditioner, soil type and data acquisition system were the same as those used in the preliminary testing phase.

**Procedure** The soil was rototilled, levelled and compacted twice using a flat roller before each test sequence. The test lane was prepared by digging six square holes, measuring approximately 0.25 m and 0.30 m depth. The holes were spaced 0.75 m apart and 0.75 m from the soil bin wall. Sensors were placed in each hole, at the removed soil returned and lightly compacted. Sensor depths were maintained at 200 mm below the soil surface with respect to the sensor surface. Tests were performed using three consecutive passes.

Travel speed was maintained at 0.5 km/h. Measurements were taken on the initial and final top soil height and compaction, interaction force profile, displacement profile and soil moisture content.

**Method of Analysis** The tamper shoe configurations were evaluated using a final design matrix in conjunction with a set of evaluation parameters that included maximum interaction pressure,
sensor deflection, duty cycle, total impulse and an additional evaluation parameter; force threshold. As a demining device passes over a buried landmine, each impact produces a pressure wave that interacts with the landmine. If the interaction pressure is above the detonation threshold, the landmine may actuate and detonate. Multiple pressure peaks interacting with the landmine may increase the probability of detonation. Two threshold levels were used, a 53.3 kPa threshold and a 110.6 kPa threshold. A top score was assigned to magnitudes above 80 hits.

A paired comparison was used to determine weights associated with the evaluation parameters. The mathematics and data analysis software Matlab® (The Mathworks Inc., Natick, Massachusetts) was used to calculate these evaluation parameters.

A statistical analysis of the measured parameters was performed to determine the effects of the operational parameters pass, load cell base area and tamper shoe size. The analysis of variance was performed per pass, using a one-way ANOVA at a 5% level of significance level.

Results and Discussion

The average magnitudes and standard deviation of each evaluation parameter are summarized in Table 3 and Table 4. The results of the Design matrix are shown in Table 5.

Table 3 Summary of evaluation parameter magnitudes for the big shoe.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Big Shoe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pass 1</td>
</tr>
<tr>
<td></td>
<td>Mean S.D. N</td>
</tr>
<tr>
<td>Peak Interaction Pressure (kPa)</td>
<td>274 304 15</td>
</tr>
<tr>
<td>Sensor Displacement (mm)</td>
<td>7.6 1.0 3</td>
</tr>
<tr>
<td>Duty Cycle (%)</td>
<td>9.5 1.2 12</td>
</tr>
<tr>
<td>Total Impulse (N s)</td>
<td>156 52.6 15</td>
</tr>
<tr>
<td>Pressure Threshold (53.3 kPa)</td>
<td>70.7 6.90 11</td>
</tr>
<tr>
<td>Pressure Threshold (110.6 kPa)</td>
<td>59.3 16.5 14</td>
</tr>
</tbody>
</table>
During the first pass, the small shoe produced the highest score of 67.6% compared to 62.9% for the big shoe. The scores for the small and big shoe were equal for Pass 2. For the third pass, the small tamper shoe scored the highest at 56.2%, compared to 55.2% for the big shoe. The average score over all three passes was 61.1% for the small shoe and 59.1% for the big shoe.

The results of design matrix indicated that the small tamper shoe out performed the big shoe configuration. The difference between the scores for the two shoe sizes was marginal. The mean values for the small tamper shoe configuration were higher for many of the evaluation parameters during each pass, with the exception of the sensor displacement. The difference in means between the shoe sizes was not statistically significant except for the total impulse. Thus, the statistical analysis supports the conclusions of the design matrix. It was concluded that the optimal shoe configuration should be selected according to the demining environment where the device would be used.

The design matrix and statistical analysis also indicated that the tamper device was best applied in two passes. The design matrix scores showed that the effectiveness of the tamper system decreases per pass. While the difference in scores was significant between the first and second pass, there was a marginal decrease between the second and third pass. The statistical analysis supported the results of the matrix, as in most cases the difference in the evaluation parameter
means was significant between the first and second pass, but not between the second and third pass.

The performance of the test rig surpassed expectations. The rig was based on a simplistic design, while allowing for interchangeability between different tamper types and sizes. The system also allowed the tamper to adjust to terrain changes such as soil undulations and obstacles (up to 0.1 to 0.15 m in height) during forward travel. The rig was not able to correct situations where the tamper becomes restricted or embedded in the soil.

A design flaw with the current rig was that if the tamper shoe becomes obstructed (as observed when the big shoe started digging into the soil), the present rig did not have a mechanism to correct this. A mechanical trip mechanism could be used to rectify the design problem. A mechanical trip mechanism would be capable of quickly raising the tamper system allowing the tamper to overcome the obstacle. The mechanism could be similar to the spring loaded system used in agricultural cultivators.

The response of the tamper to a blast from an AP landmine was not known and further research into the area, specifically live tests are needed.

**Conclusions**

In quantifying the performance of the tamper systems, the mechanism produced sufficiently high peak interaction pressures and sensor deflection magnitudes to trigger common AP landmines.

- The tamper system was based on a commonly found, off-the-shelf commercial system used in industrial construction. Thus, improving the availability of the tamper and accessibility of replacement components. The tamper design is based on a simple slider crank mechanism, self-powered by a two stroke engine. The mounting rig was fabricated from materials found both in-shop and from local metal shops. The rig design was simplistic in nature and required no special manufacturing, aside from general welding and cutting.

- The combined tamper and rig system was able to conform to terrain changes such as terrain undulations and the ability to overcome obstacles, while maintaining an optimal impact strike angle in various terrains. The modular design also lends flexibility in application for terrains such as roads, paths, urban areas and forests.

Applications in demining:

- The selection of optimal shoe size depends on the suitability of the shoe for a given situation. Environmental issues, terrain and land use should be used to determine the optimal shoe configuration for a given demining situation.

- It is recommended that the main use of the tamper and rig system be for area reduction or for area verification purposes. Though the tamper system preformed well during testing, it is not expected that the system will be 100% effective in all situations.

Some limitations of the current research:

Performance of the tamper system in differing soil composition, larger variations of soil moisture content, and the effects of overlying vegetation is needed.

Additional consideration as the effects of an actual blast from AP landmines or surrogate charges on the tamper and rig system are needed.

The dynamic characteristics of the sensors and their relation to actual AP landmines must be investigated.
References


