Detection of landmines in peat soils by controlled smouldering combustion: Experimental proof of concept of O-Revealer

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1. Introduction to humanitarian demining

The landmine problem worldwide is rising. It is estimated that 2–5 million landmines are laid every year, while the rate of clearance is 10 times slower [1]. It matters because according to the International Committee of the Red Cross the number of casualties caused by landmines currently exceeds 26,000 persons per year [2,3]. Many landmine detection and demining technologies exist, using principles that span from mechanical and electromagnetic to biological [4], and some have been developed recently [5,6]. However, there are still very few technologies capable of achieving the high-reliability required for humanitarian demining (99.6% removal to a depth of 200 mm [7]) while maintaining an acceptable clearance rate (~100 m²/day, [8]). This is because of the very wide range of landmine types, soils types and environmental conditions encountered in humanitarian demining.

The minefields in the Falkland Islands are a particular case where the difficulty of humanitarian demining is evident. After more than 30 years since the 1982 war between Argentina and the United Kingdom, only 5000 landmines out of the original 20,000 anti-personal and 5000 anti-tank landmines have been cleared [9]. Under the Ottawa Treaty on anti-Personnel Mine Ban, the British government had the legal responsibility to remove them by 2009. However, due to the slow rate and high costs of conventional humanitarian demining, a 10-year extension was recently sought [10]. Because a large fraction of the 117 minefields in the Falklands is situated in peatlands [11], this paper studies the feasibility of a novel technology specific for detecting landmines buried in peat. Peat is a histosol [12], a soil consisting primarily of organic materials. By cross referencing world maps of minefields with maps of peatlands, we found that peat is known to be the soil type of important minefields not only in the Falklands but also in Vietnam, Burma, Laos, Uganda, Zimbabwe or former Yugoslavia, to name a few.

This landmine detection technology, which we named O-Revealer, is based on the controlled use of smouldering combustion. Smouldering combustion is the slow, low-temperature, flameless burning of porous fuels [13,14]. Because peat is an organic soil, it is prone to smouldering combustion. There is a body of scientific literature on the ignition and spread of smouldering fires in peatlands [15], but this knowledge has not been used before for the purpose of mine clearance in peatlands. The idea of O-Revealer was independently proposed in 2007 in a letter to the UK Ministry of Defence for demining in the Falkland Islands [16], although posterior investigation showed that it had been proposed before by others [9,11].

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2. **Introduction to O-Revealer**

Once a smouldering fire is initiated, it spreads horizontally along the soil surface and vertically into deeper soil layers. The fire consumes the topmost layer of soil and can remove in the order of 200 mm or more of soil, depending on the duration of the fire, the soil moisture and the wind conditions [17]. If applied to a minefield, this depth of burn is enough to meet UN requirements [7] and would expose all landmines and other solid objects, which could then be identified and removed, as illustrated in Fig. 1. The peak temperature of smouldering peat is around 500 °C and the horizontal spread rate in the order of 10 mm/h [18,19] which leads to long residence times at high temperature. This strong thermal effect raises questions regarding the burn severity on peat ecology (related to environmental impact) and the risk of triggering thermal runaway of the explosive charge (related to the risk of chain explosions in dense minefields and the scattering of residual explosive). These questions need attention in the context of O-Revealer and were initially raised by the UK Ministry of Defence in response to [16]. The question of burn severity to peat was already answered and quantified in [18], which showed that the prolonged heating rates from smouldering result in sterilization of the affected soil layer and in irreversible changes of physical, chemical and biological nature. Therefore, there could be an environmental impact to the soil in the patch of land where the technology is applied. The deployment of O-Revealer in the field will have to take this environmental impact into consideration and minimize it by working on small patches of land, by ensuring the fire does not spread beyond the working patch, and by waiting or creating the right conditions of moisture and wind [15]. The question pending is that of thermal runaway, which has never been examined before and is presented as part of this study.

The application of O-Revealer to a site includes a set of techniques to control the fire by combining external ignition sources (e.g. hot wire), forced ventilation (e.g., fan), active suppression (e.g., water spray) and smothering (e.g., foam application or covering with a blanket). A successful application must accommodate for the specifics of the minefield because fire behaviour in general depends on fuel type, environmental conditions, and topology. O-Revealer will be best applied under certain seasons of the year due to the variation of moisture levels of peat (e.g., dry season in tropical regions, and warm season in boreal regions). By mastering the process of smouldering acting on the spread of the fire front, we envision an inexpensive, reliable, easy-to-deploy and safe technology that excels at some of the most pressing issues of modern humanitarian demining. These issues include the detection of non-metallic landmines, avoiding false negatives, and reaching high demining rates.

In this work, we report the very first laboratory experiment designed to study the demining effectiveness and the thermal impact of smouldering fire in two types of landmines (plus an inert object) buried in peat for a range of moisture and wind conditions.

3. **Experimental methods**

3.1. Dummy landmines

Two modern and relevant types of landmines, the Italian SB-33 anti-personnel plastic landmine and the Serbian PROM-1 anti-personnel metallic landmine, were selected, and dummies were built for the experiments (Fig. 2).

The SB-33 landmine, widely present in the minefields of Falkland Islands, has a height of 30 mm and a diameter of 85 mm. Its shell and inner parts are mostly made of polycarbonate (PC) with very small amounts of metal (to avoid metal detection technologies). The SB-33 landmine is triggered via pressure which ignites the sensitive primary detonator (a few g of Lead azide [20]). This delivers a shockwave that
subsequently detonates the much less sensitive secondary explosive (35 g of research department explosive RDX [19]). Fig. 2a shows details of the SB-33 dummy, 3D-printed in PC, like the original, and following the real dimensions and design found in the literature [20]. To avoid the risk of handling explosives in the laboratory, we conducted a literature review of substances with similar thermal properties to RDX as to find a safe replacement that does not alter the heat transfer inside the dummy. We found that commercial chalk powder has the same thermal diffusivity as RDX (1.2 · 10⁻⁷ m²/s [21] vs. 1.1 · 10⁻⁷ m²/s [22]). Therefore, chalk was placed inside the dummies with the same mass at the location of the secondary explosive (mass of primary detonator is small and can be neglected).

While plastic landmines pose a challenge to traditional demining methods, the majority of current landmines are made of metal, like the Serbian PROM-1 which is one of the most representative. It is made of steel, in bottle shape buried upwards, with an inner diameter of 71 mm, a height of 140 mm, and a wall thickness of 4 mm (Fig. 2b) [20]. It includes a few g of primary detonator (Lead azide) and 439 g of secondary explosive consisting of composition B (a mixture of 60% RDX and 40% TNT [23]). For the dummy, we use a steel cylinder of the same dimensions focusing on the part of the landmine which is buried in soil and ignoring the narrower parts exposed to the open. The thermal diffusivity for composition B is 1.1 · 10⁻⁷ m²/s, which is also close to the value of chalk and hence it is used inside the dummy.

3.2. Peat experimental setup

The peat used in the experiments is sourced from commercial samples (Shamrock Irish Moss Peat, Bord na Mona Horticulture Ltd.). It is used instead of naturally sourced peat because it is readily available in large quantities, has relatively homogeneous properties and known composition, and has been used in previous experiments [19]. It has a high organic content of 98% and a dry bulk density of 140 kg/m³. To obtain the desired soil moisture content (MC), the peat was first oven-dried at 95 °C for 48 h. Then, it was mixed vigorously with the corresponding amount of water and let to rest in a sealed basket for another 48 h for homogenization. For example, 2 kg of peat at 100% MC requires 1 kg of oven-dry peat mixed with 1 kg of water. The MC values investigated correspond to conditions expected during a drought (50% MC), and conditions expected in non-flooded peatlands (100% MC). Wetter conditions above 130% do not support the spread of smouldering combustion [18,19]. After moisture treatment, the peat was not compressed in the box during packing to avoid altering the bulk density.

Similar to the previous designs [18,19], a open-top reactor with internal dimensions of 200 × 200 mm² and 100 mm deep is used. This is shown in Fig. 3. The reactor walls are 12.7 mm thick and made of mineral insulation. The fire was ignited by a 200-mm coil heater at one end (buried 50 mm below the surface) with a heating power of 100 W for 30 min. A visual camera and an infrared (IR) camera were placed above the reactor to monitor the process and to record irradiation levels from the top surface. A small adjustable fan was used to generate airflows along the direction of fire spread which enabled studying the influence of environmental wind. The wind speed was measured on the plane 10 mm above the peat surface by a hot-wire anemometer to be 1.2 (± 0.1) m/s. For each experimental condition, at least two repeats were conducted, and good repeatability was shown.

The SB-33 dummy was placed on top of a 50-mm layer of peat and covered by a 20-mm peat layer on the top to fill the reactor, as shown in Fig. 3. Three thermocouples (TCs) were inserted into the dummy through the bottom of the reactor, and positioned at the fuse assembly, detonator, and secondary explosive, respectively (Fig. 3a). For the PROM-1 dummy, the bottom 100 mm of its body was covered by peat, and its neck pointed upwards out of the soil, which recreates how it is buried in real minefields (Fig. 3b). Five thermocouples were inserted from the top and into the chamber of the secondary explosive and spaced 25 mm apart one from the other (Fig. 3c). For both landmines, additional thermocouples were placed in the peat near the landmine. All thermocouples were scanned every 5 s to monitor the temperature evolution.

It is possible that, because of heating during a smouldering fire, a landmine is triggered accidentally through thermal runaway of an explosive. Thermal runaway requires the explosive to reach a critical temperature and be maintained at that level or higher for a period long enough to allow ignition to occur. It is not an instantaneous phenomena but can takes hours to manifest, especially when close to the critical temperature [14]. The primary detonator, Lead azide, has a thermal runaway temperature of 350 °C [24], but the risk of thermal runaway of a landmine is controlled by the secondary explosive because its critical temperature is lower. Once the secondary explosive melts, it becomes very unstable [25]. Therefore we chose this transition temperature as a conservative threshold for thermal runaway. The melting point of RDX depends on its composition and purity, but ranges from 185 to 205 °C [26,27]. We assume that this threshold range also applies to Composition B which consists of 60% RDX.

4. Results and discussions

Once the peat is ignited, the smouldering front spreads both horizontally along the surface and vertically in-depth. Experiments conducted in peat without a landmine measured that the horizontal fire spread rate along the top surface is 30 mm/h for wet peat (100% MC) [19]. The in-depth vertical spread rate for both MC values is around 20 mm/h. After the fire, most of the peat is consumed. The soil residue left is about 3% of the original dry mass of the sample, and consisted of a shallow layer of white ash plus a small amount of black char.

4.1. Results for SB-33 dummy

Fig. 4 shows both the visual and IR images when the fire spreads over the SB-33 dummy buried in 100% MC peat and without wind. As the smouldering front spreads, the peat is slowly converted to smoke, black char, and white ash. Meanwhile, the buried dummy is progressively revealed to the open, which could easily be identified visually (Fig. 4b). Moreover, the landmine is clearly shown in the IR imaging because the higher inertia of the plastic shows an area of substantially lower-temperatures (blue) region surrounded by the soil which is the high-temperature (red) region. During the fire, the dummy was partially damaged by heat. Its shell had deformed, partially melted and charred, leaving a small amount of chalk powder out of its body (Fig. 4c). In comparison, the inner trigger assembly and chamber showed little heat damage, indicating that the primary detonator remained intact and safe.

Fig. 5 shows temperature measurements in the peat near the shell of the dummy, as well as inside the dummy. The glass transition point of the PC shell is 155 °C [28], above which the material deforms and melts, which is marked in Fig. 5a as a benchmark value for shell damage. The range of critical temperatures for RDX is shown as reference in Fig. 5b as a benchmark value for thermal runaway.

Outside the landmine (Fig. 5a), the peak temperature during fire spread ranged from 450 °C to 570 °C, and is similar between different MC values. These values are in agreement with previous measurements in smouldering peat [18,19]. Thus, the landmine presence does not affect the fire significantly. The fire sustained temperatures higher than the damage threshold for 3 h, which explains the observation of damage to the shell after the experiment (Fig. 4c).

Comparison of measurements outside (Fig. 5b) and inside (Fig. 5a) the dummy shows that temperatures inside were up to 350 °C lower than those outside. The error bars, evaluated as maximum and

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Footnote: Text to be inserted as a footnote when color is referred to in text:
minimum from the temperature measurements at three different locations, are larger than expected. This is because the thermocouples shifted position during the experiment due to deformation of the shell (seen in Fig. 4c). The mass of the secondary explosive reaches temperatures above the runaway threshold only for the case of dry peat (50% MC), a situation that if sustained for long enough could lead to thermal runaway.

To quantify the thermal severity experienced inside the landmine, we measure the average residence time above a given temperature value following the methodology explained in [18]. The results are shown in Fig. 6, where the error bars indicate standard deviation for multiple thermocouples and repeats. For peat MC of 50%, the residence time above the critical value is 30 min, for which we judge the chance of RDX thermal runaway as moderate. However, it is important to note that a moisture condition of 50% or lower is very rare for peatlands and has only been observed in the field under severe drought conditions. Under a normal value of moisture expected in peatlands, such as 100% MC, the residence time above the critical value is very low, in the order of a few min, indicating a very low risk of thermal runaway.

As the wind increases, both the spread rate and the peak temperature in the peat increase. Accordingly, Fig. 6 shows that the wind significantly increases the thermal severity inside the landmine, thus increase the risk of thermal runaway. For 50% MC with wind, the thermal severity increases to 3 h, 6 times greater than the case without the wind. Similarly, for 100% MC, the thermal severity increases to 1 h. We judge the chance of RDX thermal runaway under wind conditions to be between moderate and high.

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Fig. 3. Photos of the experimental setup before ignition. The dummy of an SB-33 landmine is shown: (a) partially buried in peat, (b) completely buried in peat, and (c) the buried dummy of a PROM-1 landmine.

Fig. 4. (a) Diagram for the location of the SB-33 dummy; (b) visual and infrared photos of spread over the dummy for moisture content of 100% without wind; and (c) comparison of the landmine conditions before and after the fire.

Fig. 5. Thermocouple measurements for the experiments of a SB-33 dummy landmine buried in peat with moisture contents of 50% and of 100%, without wind: (a) location of the peat near the dummy shell (single experiment in each curve) and (b) location inside the dummy (average of 3 repeats with the maximum and minimum as error bars).
4.2. Results for PROM-1 dummy

Fig. 7 shows both visual and IR images of fire spreads around the PROM-1 dummy landmine buried in 50% MC peat without wind. The dummy is progressively revealed to the open, which could easily be identified visually (Fig. 7b). As in the previous case, this landmine is clearly shown as well in the IR imaging because of the temperature contrast between the landmine and the soil. The steel body of the dummy was left undamaged and the primary detonator and secondary explosive remained intact and safe.

Fig. 8 shows temperature measurements in the peat outside the PROM-1 dummy and the average temperature inside the dummy for 50% MC and without wind. The peak temperature outside the dummy is around 500 °C, similar to both the cases without any dummy and with the SB-33 dummy (Fig. 5a). The temperature inside the PROM-1 (Fig. 8b) shows low error bars, indicating high uniformity across different locations compared to the SB-33 (Fig. 5b). Arguably, it is because the metal dummy is not damaged and the thin steel wall is a good heat conductor. All peak temperatures inside the dummy were found to be below the critical values for thermal runaway.

Fig. 9 shows the thermal severity inside the metal dummy for two values of peat MC, with and without wind. In general, without wind the risk of thermal runaway is very low, with a residence time above the critical value in the order of minutes. Similar to SB-33, the wind increases the risk of thermal runaway. However, even with wind and low-moisture peat, the chance of thermal runaway is still very low.

The wind increases oxygen supply which in turn increases slightly the smouldering peak temperature and increases substantially the spread rate [15,17]. Thus, wind tends to decrease substantially the residence time at lower temperatures but increase slightly it at higher temperatures. This trend is observed in all cases expect for dry peat and the SB-33 dummy (Fig. 6a), for which the reason the residence time increases with wind is related to burning peat particles that fall thought the damaged shell.

4.3. Detecting other bodies buried in soil

Other bodies like tree roots, stones or debris buried in the soil typically interfere with traditional demining methods and often cause false detections. However, smouldering fire can burn the peat down to a significant depth, revealing these buried objects to the open. In order to examine how O-Revealer can help identify these bodies that are not...
landmines, a spherical stone of 8 cm diameter was buried in the peat and tested under the same conditions as the landmine dummies. Fig. 10 shows both the visual and IR images when the fire spread over and around the stone in 50% MC peat without wind. In IR images, the stone can be seen just as the dummy landmines were previously seen (Figs. 4 and 7). However, once the peat is consumed, from visual inspection the stone can be easily distinguished from any landmines. Therefore, the possibility of false detection during demining with O-Revealer is low.

5. Conclusions

We study a novel landmine detection technology, called O-Revealer, which uses controlled smouldering combustion and is valid for minefields in peat soils. We have conducted laboratory experiments with two types of dummy landmines buried in peat, the plastic SB-33 and the metal PROM-1. In all experiments, the smouldering fire burned across the peat, leaving the dummy completely exposed to the open for easy identification and quick demining. The spread rate and peak temperature decrease with increasing soil moisture but increase with increasing wind speed. Moisture and wind are found to be the main environmental parameters of O-Revealer that allow burn severity and thermal runaway to be minimized: high moisture and low wind are preferred, noting that the moisture has to be below the critical value for smouldering ignition [18].

Investigating the issue of thermal runaway, the results show that the chance is high for plastic landmines like the SB-33 in dry peat and wind conditions, but very low for metal landmines like PROM-1. Investigating the issue of the burn severity to peat shows that deployment of O-Revealer in a minefield can have a local detrimental effect on the affected peat layer and patch of land where it is applied. Environmental impact can be minimized by waiting or creating the right condition of moisture and wind.

By mastering the process of smouldering ignition and spread, we envision an inexpensive and reliable technology that is easy to deploy, and that excels at the most important issues of humanitarian demining including detection of non-metallic mines, avoiding false negatives and reaching high demining rates.

O-Revealer will be inexpensive because the equipment needed to control a smouldering fire would be low cost and consists roughly of electric wires, battery pack to power the igniter, large portable fans for forced ventilation, sand and water to set fire breaks around the patch under treatment, and a portable water system for active suppression. O-Revealer will be reliable because it guarantees that all solid objects buried in the soil down to the depth of burn will be exposed. Once the technique and the tools have been developed and optimized to a particular location (landmine type, weather, and soil conditions), O-Revealer can easily be applied by trained but unskilled personnel with minimum oversight.

This laboratory investigation serves as the proof of concept for the technology at the small scale and justifies a pilot study in larger peat areas and real minefield sites, such as the Falkland Islands.
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References


Fig. 10. (a) Diagram for the stone and (b) visual and infrared photos of fire spread in peat with a moisture content of 50% without the wind.