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Analyzing Functionality of Landmines and Clearance Depth as a Tool to Define Clearance Methodology

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Analyzing Functionality of Landmines and Clearance Depth as a Tool to Define Clearance Methodology

Mine contamination from World War II remains in Skallingen on Denmark's western coast. Skallingen's dynamic coastal environment caused the mines to shift in the soil, and time, salt water and soil depth rendered some of the landmines inactive. Comparative digital-terrain models, in addition to surveys and analysis of fuze and detonator functionality, enabled clearance personnel to establish clearance depth and related criteria and facilitated efficient clearance efforts. As a result, the last functional mines were cleared in June 2012 after six years of effort.

by Martin Jebens [Danish Coastal Authority]

During World War II (1939–1945), German forces placed approximately 1.4 million landmines along the Danish west coast as part of the West Atlantic Wall. After the war, manual clearance and the use of tanks with rollers operated by former German soldiers under Danish and British command removed the majority of these mines. While the boundary of each minefield was known in the area of Skallingen, the mines were randomly placed within each minefield. Thus, total clearance of the area and the remaining 72,000 mines was impossible.

During the next 65 years, dynamic changes in the environment, including erosion, moved or rendered many of the mines inoperable, changing their depth and condition. In 1999, Denmark signed the *Convention on the Prohibition of the Use, Stockpiling, Production and Transfer of Anti-personnel Mines and on Their Destruction* (Anti-personnel Mine Ban Convention or APMBC). Clearance of the anticipated 10,000 remaining mines began in 2006. Since then, clearance has been carried out in three phases; the last phase ended in June 2012.

During and after the first two phases, a number of Technical and Non-technical Surveys (TS, NTS) were completed to further determine the characteristics of the minefields. In particular, the current depth and condition of remaining mines were investigated. These investigations showed that Skallingen mines in contact with salt water for more than three years do not work as originally intended. This is due to the alteration of explosives in the detonators and the corrosion of metal in the fuzes. A three-dimensional (3-D) digital-terrain model of the 1945 surface also determined the recommended clearance depth to avoid clearance of unnecessary quantities of soil.

These relatively inexpensive analyses at Skallingen resulted in the use of different clearance techniques to target each specific threat in the different geomorphologic terrain types. With the resulting information, the clearance operation was accomplished in a shorter time and at a lower cost. Clearance was also more environmentally friendly, for example, avoiding damage to sensitive marsh and beach areas by preventing unnecessary heavy machinery from entering the areas. Similar analysis of mines and soil composition in other mined areas could result in a more flexible approach to the clearance work and may reduce cost and risk.

Environment and Dynamic Processes

Due to its geomorphology, Skallingen has a unique fauna, flora and landscape. The marshlands on the peninsula's eastern part represent the largest unprotected salt marsh in northern Europe. Likewise, the dunes and beaches on the western and southern part of the peninsula are nearly undisturbed by man. The peninsula extends approximately 12 km in a southeasterly direction with a width of about 2.5 km.[1]

Aerial photo of the southern part of Skallingen in which the final mine clearance took place.
All graphics courtesy of the author.

Placed in a dynamic coastal environment, the minefield is influenced by a number of physical processes on a daily basis, including erosion caused by wind and water, dune migration, marsh build-up and marsh and dune expansion.

The beach zone (Figure 1) is a deposit of unconsolidated sand sediment that is easily influenced by aeolian (wind) and hydrodynamic (water) processes caused by the strong westerly winds from the North Sea. This results in surface changes and the rework of sediment, which can exceed 1 m a day.[1]

The beach is backed by a dune zone (Figure 1), an accumulation of sand built only by aeolian processes. Dunes are entirely composed of unconsolidated sediment and tend to be fragile, mobile and susceptible to erosion until they become vegetated, which stabilizes them. As a result, dunes can easily change shape and move into the marsh area over time. Dune elevations of up to 10–12 m are fairly common on the peninsula.[1]

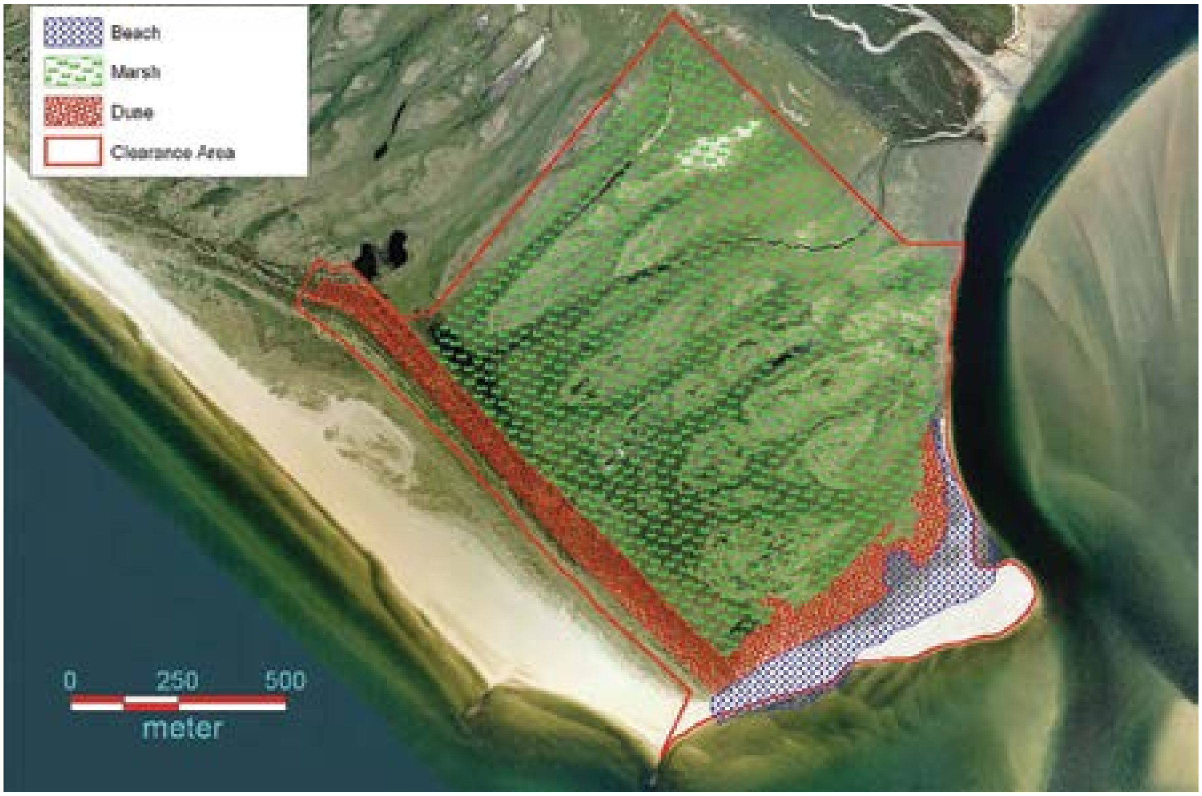


Figure 1. The three different terrain types (beach, dune and marsh) encountered on Skallingen using a geomorphologic description.

Behind the dunes is a region of marsh and tidal flats (Figure 1) where the quiet waters allow fine silt and clay to settle to the bottom of the water.[2] Because of the low energy environment, erosion does not occur.[1] Tides influence the area daily, resulting in waterlogged soils and standing water. The tide has an amplitude of 1.5 m, but in combination with stormy conditions, the tide can exceed 4 m.[1]

Changes in Terrain

From the geomorphology described above, it is evident that the dynamic character of the area changes its topography. As a consequence, mines may be buried deeper by sediment build-up or exposed by erosion. Because of these changes, the expected clearance depth prior to the start of clearance was unknown, and operating with standard clearance depths was impossible. Therefore, to target the mine-affected surface, a digital-terrain model of the surface from 1945, when the mines were laid, was made.

In its simplest form, a digital-terrain model consists of millions of x, y and z values, where x and y are the geographical coordinates and z is the elevation. A digital-terrain model can be acquired in a number of ways: by digitizing topographic contours from paper-based maps, photogrammetric analysis of stereoscopic aerial photos, or by airborne radar or laser scanners.[3]

Producing a digital-terrain model of a historic surface requires old aerial photographs, which have a limited use in a geographic information system (GIS) because they are not true to scale. However, if the aerial photo is geometrically corrected for distortion caused by the topography, camera optics and camera tilt, it is possible to make a digital orthophoto or a digital-terrain model.[4] The orthophoto becomes a photo map on which direct measurements of distances, areas and positions can be made.[5,6]

Aerial photos were (and continue to be) taken during a large number of conflicts worldwide. British archives hold more than 40 million aerial photos taken during WWII.[5] During the war, the British Royal Air Force passed over Skallingen several times, and photos taken during these missions generated the digital-terrain model.

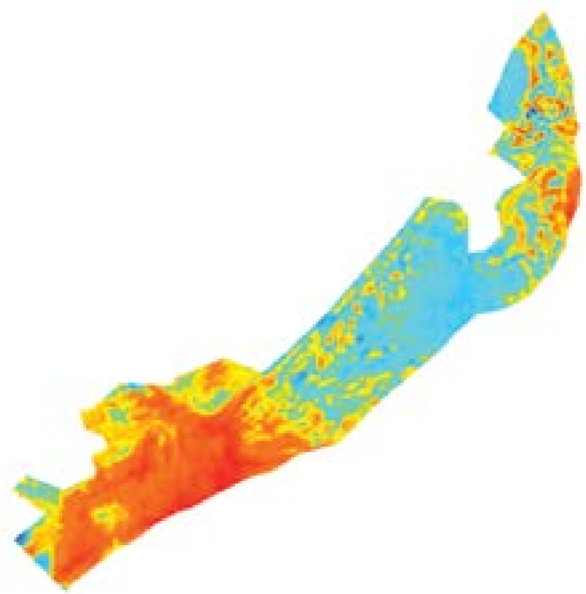


Figure 2. Digital differential model of the marsh covered with dune. Size of the area is 57,740 sq m. Red indicates areas where the hazard layer is situated inside the dune. Blue areas indicate where the hazard layer is part of the present surface. Approximately 30,000 cubic meters could be excavated without clearance.

The terrain model was created in cooperation with the Danish Consultancy within Engineering, Environmental Science and Economics (also known as COWI after the initials of its founders, Christian Ostenfeld and Wriborg Jønson) using the data software SocetSet5.3.[7]

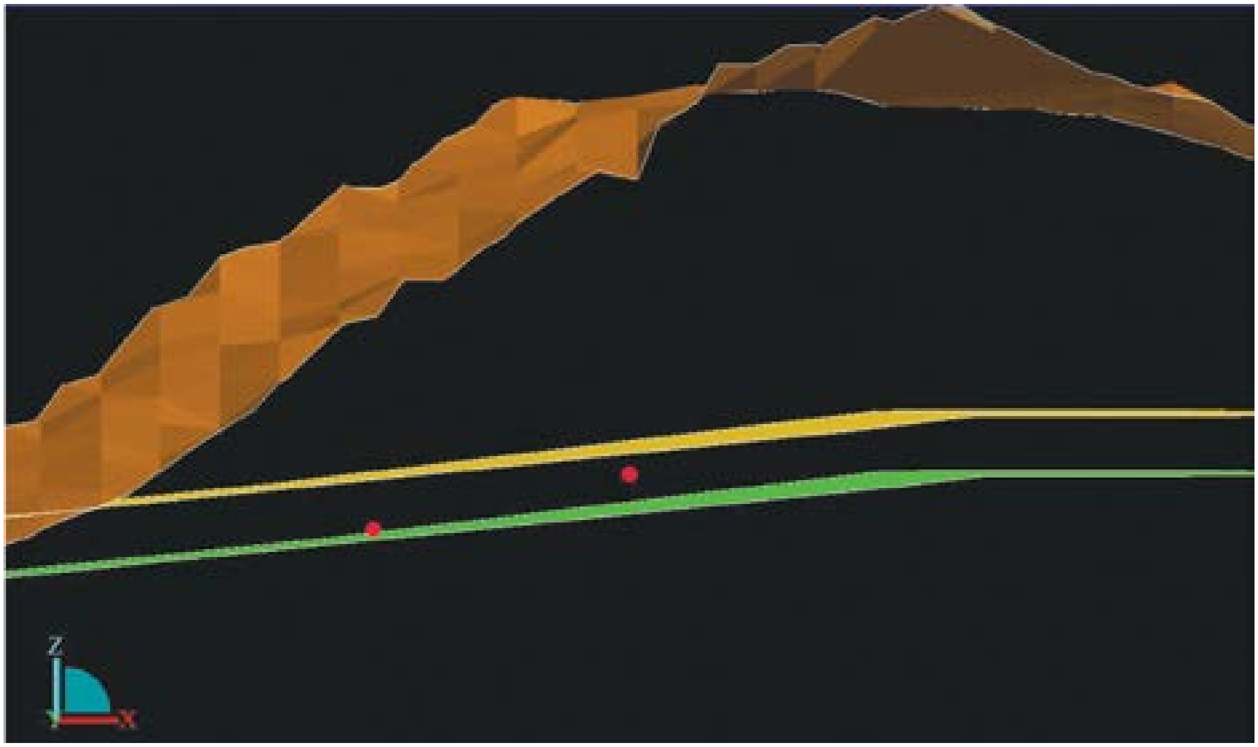
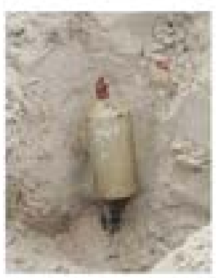


Figure 3. A 3-D model of the brown present surface seen together with the position of the hazard layer outlined by the yellow and green surface inside a dune. The hazard layer is 1.9 m wide and the position of the two mines is seen inside the defined hazard layer. The sand above the yellow top of the hazard layer could be excavated without prior mine clearance.

Tellermine 42

Schütz Mine

Holtz Mine



Stock Mine

The four different mine types found on Skallingen. The Tellermine 42 and Holz mines are both anti-tank mines, whereas the Stock and Schütz mines are anti-personnel mines.

The horizontal uncertainty (x,y) of the model was found to be +/- 15 cm, whereas the vertical (z) uncertainty was +/- 60 cm.[5,6] The correlation of x, y and z coordinates in the model with the same positions and height in the present terrain confirmed the uncertainties (Figure 2).

This correlation revealed that the uncertainty of +/- 60 cm was mainly observed in dune areas where variation in topography is pronounced. Alternatively, the uncertainty of the model in flat marsh area was approximately +/- 10 cm.

By comparing the 1945 model with a laser scan of the present surface, a differential model could be created showing the difference between the present surface and the 1945 surface, thus determining required clearance depth (Figure 2). Because of the uncertainty in the model, it was only possible to confine clearance to a hazard layer (a layer of soil that may be contaminated to a certain width and a changing maximum depth), not a surface. The uncertainty of the new laser scan of the present surface was +/-10 cm.

Adding up the uncertainties gave rise to a hazard layer having a width of 1.4 meters. Finally, the width was extended due to the fact that a stock mine could stand 30 centimeters above the 1945 surface and that mines could be buried up to 20 centimeters below the surface in 1945. Therefore, the total depth of the hazard layer was 1.9 m (Figure 3).

Changes in Dune Areas

Since dunes are made of sand, the dunes do not generally exhibit any geologically recognizable features (e.g., clay layers, cross-bedding) that can be correlated with time. Therefore, the differential model was especially useful in the dune area.

The differential model, in earlier phases of clearance, showed that the hazard layer had a 1.9-m width, ranging between 0 and 10 m below the present surface. Thus, large volumes of sand could be excavated before mine clearance began (Figure 3).

In the final phase of clearance, the model showed that the mines in the dunes were placed in a hazard layer situated between the current surface and a depth of 2 m (Table 1).

When analyzing the differential model together with aerial photos from 1945, it became clear that the southern part of the dune area had migrated across the surface of the marsh and the two had merged. This entire dune was mine-free and could be excavated before mine clearance commenced. Therefore, the dune area was further divided, giving rise

Figure 4. Figure 4 shows the new division of the area after evaluating terrain and digital-terrain model. The dune area was divided into two areas by reducing the mined volume to be cleared. See Figure 1 for comparison.

Area	Depth Analysis
Dune	The differential model indicates that the difference between the 2011 surface and the 1945 surface is a mosaic of variations between 0 and 2 m. Therefore, the clearance depth in the entire dune is 2 m below the current surface.
Marshland	Technical surveys and literature studies indicate that the mines can be found within the first 20 cm.
Beach	Experiments described in literature and experience from prior clearance phases have shown that rework of sediment by action from the sea can not bury mines deeper than 1.3 m.
Marsh covered with dune	The differential model indicates that the mines can be found around the old marsh deposit beneath the dunes. The uncertainty of the model in the flat marsh is expected to be +/-10 cm. Because of the potential larger depth AT mines could be buried in, the clearance depth was changed. Finally, a small buffer was added to the hazard layer, which therefore became 70 cm narrower.

Table 1. Review of depth analysis in the four terrain types established from the differential model.

	Lead Azide	Tetryl	Lead Carobate Hydrate (Degradation Product)	Lead Oxide (Degradation Product)	Empty
Beach		1	1		2
Dune/Marsh above 1.9 m	13		7		
Marsh below 1.9 m	3	1	12	7	

Table 2. Overview of the chemical composition of explosives and alteration products in the detonators compared to above and below 1.9 m (Danish Vertical Reference 90 [DVR90] or sea level). The chemical analysis of explosives was performed using x-ray diffraction (XRF).[3,4] The composition of explosives was analyzed using a Philips PW3020 Diffractometer with a 40-kV tension and 50mA current.

	Number Tested	Detonation Functionality Test
Marsh below 1.9 m	4	All negative
Dunes/Marsh above 1.9 meters	24	5 working

Table 3. Functionality test of 28 detonators found in the marsh and dunes. No detonator worked as intended when found in the marsh below DVR90, while approximately 20% of the detonators worked when found in the dunes.

to a new sub-area named **marsh covered with dune** (Table 1 and Figure 4).

Since mines were buried in the flat marsh area, the uncertainty of the digital-terrain model was confined to approximately +/- 10 cm. Thus, the risk layer was more limited in this area than to the rest of the dune area.

Marsh

The marsh's vertical growth is limited because of the very low sediment (clay and silt) accumulation rate. In general, the salt marsh on the west coast experiences accumulation of 2–3 mm a year.[1] Total accumulation since 1945 is therefore between 13 and 19.5 cm.[8] The differential model and a survey investigating the thickness of the top clay layer confirmed this. Finally, a TS conducted in 2008 affirmed that mines could be found only in the first 20 cm.

Beach

When mines were laid in 1945, the area presently defined as a beach was a marsh. During the last 30 years, the coastline retreated at the southern part of Skallingen, eroding the marsh and leaving behind sand. As a consequence, the only mines found in the beach area were mines that the dunes ejected onto the beach via erosion. On the beach, the locations of the mines effectively depended on the constant transformation of sediment

	Tellermine 42	Holtz-42 (AT mine)	Schütz-42 (AP mine)	Stock mine (AP mine)
Dike/dune	Could function	Unlikely to function	Unlikely to function	Unlikely to function
Low marsh	Could function	Not functioning	Not functioning	Not functioning
High marsh	Could function	Unlikely to function	Unlikely to function	Unlikely to function
Marsh covered by dunes	Could function	Unlikely to function	Unlikely to function	Unlikely to function
Beach	Could function	Unlikely to function	Unlikely to function	Unlikely to function

Table 4. The functionality of different mines in various environments on Skallingen. The chance of all components in the explosive train to work in individual mines in these conditions is very limited. The fuze and detonator in the Tellermine 42 is encapsulated behind a metal casing. Therefore, water needs time to enter the explosives inside the detonators, and the mine may still function. There is a small risk that the mines will work on the beach if they have recently been uncovered from the dunes. However, once on the beach the mines quickly decompose or break apart due to wave action.

Sub-area	Minimum Clearance Requirement	Depth	Method to be used
Dike/Dune	All explosive items which are larger or the same size as a detonator mounted on a Z.Z.42 fuze	Hazard layer between 0-200 cm below surface	Sifting
Marshland covered with dune	All explosive items which are larger or the same size as a detonator mounted on a Z.Z.42 fuze	Hazard layer of 70 cm situated around the original mined marsh surface	Sifting
Low marsh	All Tellermine 42 mines	Depth: 0-50 cm below surface	Metal detection with GPS positioning and data-logging
High marsh	All explosive items which are larger or the same size as a detonator mounted on a Z.Z.42 fuze	Depth: 0-20 cm below surface	Metal detection
Beach	All Tellermine 42 mines	Depth: 0-130 cm below surface	Metal detection with GPS positioning and data-logging

Table 5. The sub-areas defined on Skallingen compared to minimum clearance requirement, depth and clearance method to be used. In the low marsh, the clearance depth was changed to the differential model (see Table 1) because of the potentially larger depth AT mines could be buried.

caused by the sea's dynamics. Based on experiments and experience from prior work on Skallingen, mines and their components would not be buried deeper than 1.3 m and the tide would most likely remove them.[9]

Functionality

During clearance, analysis of the present quality and functionality of the mines was conducted, concluding that the quality and functionality depends on the mine type and environmental conditions.[8,10,11] A mine's functionality is understood as the mine's ability to work as intended. Namely, if an external action can detonate a mine, occurring under normal activities at Skallingen, it is considered functional. The following is a short review on how the functionality of mines was established using chemical and mechanical techniques:[8]

Mine types. The only mines found in the area on Skallingen were Tellermine 42 (metal casing) and Holzmine 42 anti-tank (AT) mines (wood casing), as well as Stock (concrete casing) and Schütz (wood casing) anti-personnel (AP) mines. Except the Tellermine 42, each mine used a Z.Z.42 fuze. Therefore, the functionality of Z.Z.42 fuzes and detonators received special attention.

Fuzes. The Z.Z.42 fuze is a mechanical fuze produced in Germany during WWII and was the standard fuze in a number of German mines.[8] A large number of Z.Z.42 fuzes were mechanically tested. The fuzes were normally corroded at the top of the firing pin, preventing them from moving freely. Further, the bakelite casing did not completely seal off the vital parts inside the fuzes. In the majority of Z.Z.42 fuzes, the oil, sand and rust had mixed together to create a hard plug between the hammer and the percussion cap. This obstruction dramatically lowered the chance of the hammer striking the percussion cap, rendering the Z.Z.42 fuze ineffectual (Figure 5).[8]

Detonators and explosives. With assistance from the Netherlands Organization for Applied Scientific Research (*Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek* or TNO), the composition of explosives was tested in 48 detonators and nine percussion caps.[12,13,14,15] All detonators were made of alumina (aluminium oxide). Primary explosives in the detonators were identified as lead azide and tetryl (Table 2). In all detonators, parts of the explosives were altered to different nonexplosive products (lead carbonate hydrate and/or lead oxide), but in many

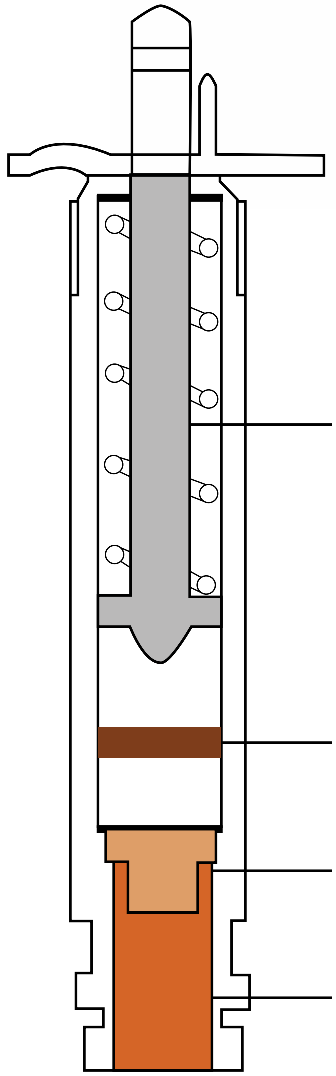


Figure 5. Schematic illustration of the Z.Z.42 fuze. The dimension is approximately 1.2 x 8.5 cm. Notice the position of the plug, which is composed of a mixture of sand grains, oil and rust.

cases the degradation was pronounced (Table 2). Notably, a few detonators were empty.[13,14,15]

Percussion caps also were analyzed regarding their functionality and chemical composition of explosives. According to these tests, no percussion cap worked when found in the marsh below 1.9 m (Danish Vertical Reference 90 [DVR90] or sea level).

To establish their detonation ability, the detonators were tested mechanically, which was done by conducting a functionality test of 28 detonators. The detonator functionality test was performed at TNO by placing a squib in the open side of the detonators (Table 3). The functional detonators would ignite from the generated flame.[13,14,15] The test showed that approximately 20% of the detonators found in the dunes and marsh above DVR90 were functional, while all detonators from the marsh below DVR90 were not (Table 3).

Figure 6. According to functionality and quality of mines, the marsh area could be divided into a high and a low area. Using the depth analysis and functionality analysis it is therefore possible to divide the area into five sub-areas.

The analysis above led to the conclusion that no percussion caps or detonators worked as intended in marsh areas lower than DVR90, and that Z.Z.42 fuzes decompose and become inactive when in contact with water, wet soils and dust. Additionally, lead azide, the primary explosive used in all detonators, will dissolve and react with salt in ocean water, creating different nonexplosive alteration products.[8,13,14,15] In this case, the lead azide will likely completely alter or dissolve after three years of contact with salt water.[13,14,15]

Because explosives used in the detonators on Skallingen react and decompose after three years of contact with water, an analysis of water levels on Skallingen during the last 65 years was conducted. Based on water-level data measured during the last 50 years, the analysis showed that marsh areas below 2.0m DVR90 would have been in contact with water for more than three years and therefore the mines were nonfunctioning. This was supported further by the fact that no detonators or percussion caps in the marsh area were functional when found lower than 1.9m DVR90.

Using this information, the marsh was further subdivided (Figure 6) into low marsh, which was lower than 1.9m DVR90 in the present terrain, and high marsh, which was above 1.9m DVR90. Each had different minimum-clearance criteria and clearance depth.

Clearance Criteria

By knowing the mines' depth and functionality, the area could be divided into five different sub-areas while targeting the specific threat inside each area (Table 4 and Figure 6). This also enabled the employment of environmentally friendly clearance methods that were quicker and cheaper than if the clearance depth and functionality was unknown.

In the dune and marsh areas covered with dunes, sifting was the chosen clearance method due to the large volume of sand that needed clearing from the mines (approximately 420,000 sq m). A differential global-positioning system (DGPS), in which the clearance depth was recorded, guided the excavators and sifters. Furthermore, the machinery continuously data-logged their respective positions. Therefore, the depth was known at all times and saved for later quality control (Table 4). After clearance work, the digital-terrain model of the present surface was used to rebuild the area.

According to the findings from the functionality and depth analyses, it was possible to move freely on the beach and low marsh surfaces. In those areas, the Förster magnetometer, which was attached to a DGPS system, recorded the clearance method, making it possible to ensure that the entire surface was covered. Potential mines were found by processing data and selected anomalies with the same size and magnetic strength as defined by capacity tests (Table 4).

In the high marsh, manual mine clearance was conducted. This method was ideal due to the size of the minimum-clearance criteria and the expected depth (Table 4).

In total, approximately $50,000 was spent on this research. Use of the 1945 digital terrain model cost approximately $20,000, and the research on the functionality of mines cost approximately $30,000. This research may have saved the entire project up to $1.7 million because it was able to define the clearance depth and thus reduce unnecessary clearance efforts. The heavy machinery used for the DGPS system may have increased the total contract sum slightly.

Future Potential and Conclusion

Overall, this review describes a flexible response to mine clearance operations in which survey procedures play a crucial role in establishing the minimum-clearance requirement and clearance depth. Skallingen is not a geomorphologically unique area. Shifting sand dunes are found worldwide in coastal and desert areas. Coastal and delta areas also have comparable marshland globally. As in Skallingen, in similar environments the use of geomorphologic and terrain analysis can increase the efficiency and improve the results of clearance operations.

The two approaches—analyzing clearance depth and mine functionality—used here are, in combination, excellent tools in areas where mines were buried deeper or relocated since the time of placement. Moreover, the two approaches can be used individually. In general, using old aerial photos in mine clearance operations has benefits. In arid areas or areas subject to large degrees of sand drifting, like Skallingen, a digital-terrain model of the surface at the time the mines were buried makes clearance safer, more efficient and less expensive since the clearance depth will be known. In minefields placed in open areas, old aerial photos and orthophotos could help define the minefield perimeter.

Analyzing mine functionality and quality could be important in all minefields depending on age and environment. Most environments appear to affect the functionality of mines.[8,10,11] Only functionality of mines in the low marsh areas is described in more detail in this paper. The chance of all components in the explosive train to work in individual mines in Skallingen is very limited because of aging and the environmental conditions.

Leaving explosives behind after clearance should only be done with with great care and only after conducting a detailed investigation of functionality, terrain and future land use. Ideally, this should also be done in cooperation with international clearance advisors (e.g., the Geneva International Centre for Humanitarian Demining and the United Nations Mine Action Service). Through chemical and physical investigations, we have inferred and proven that the mines in the low marsh on Skallingen do not work as originally intended. Although the area is part of a national park where the public will not likely come into contact with the remains, these explosives could still pollute the area through passive decomposition. Over time explosives will slowly dissolve and evaporate, releasing chemicals into the environment. Prior to and at the end of the clearance operation, therefore, the soils in the Skallingen areas were analyzed to identify potential pollutants. No traces of explosives were found.[16,17]

Finally, the erosion of mine-contaminated areas can spread into areas that were previously mine-free.[18] In Skallingen, the marsh is not eroding, and as a result this is not an issue. Determining the potential for a mined area to spread into another area via erosion is achievable if the geomorphologic conditions are analyzed with topography.

As seen in Skallingen, spending more time on NTS and TS can make mine clearance more efficient, save funds, protect the environment from unnecessary invasive clearance procedures and result in cancellation of suspected hazardous areas. In order to achieve a mine-free world, these flexible, creative methods should be utilized without restriction to traditional standard mine clearance methodology.

See endnotes page 66

The author would like to especially thank explosive ordnance disposal technician Johnny Rankenberg Thomsen for his extensive work analyzing detonators and fuzes.

Martin Jebens is the geographic information systems manager at the Danish Coastal Authority's demining project at Skallingen, where his work includes analyzing coastal morphology, detection techniques, topographical models and the functionality of landmines. He has a Master of Science in geology from the University of Copenhagen (Denmark) and experience working as an exploration geologist, focusing on diamond, nickel and gold deposits in Scandinavia and Greenland. He previously worked at the Geological Survey of Denmark and Greenland, and also at a Danish exploration company.

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News Brief

New Human Rights Safety Bracelet Designed

~*Blake Williamson, CISR staff*

In 2009 Russian human rights worker Natalia Estemirova was abducted in front of her home in Grozny, Chechnya and murdered in Ingushetia, Russia. In response to her murder the organization Civil Rights Defenders (CRD) created the Natalia Project—a bracelet that sends out a distress signal when the wearer is in danger. Designed for those working in conflict areas, the bracelet is one component of a comprehensive security program using satellite navigation technology to send signals to the smartphones of those in close proximity (who are previously assigned by the bracelet-wearer to receive alerts) and CRD's headquarters in Stockholm, Sweden.[1,2,3] CRD verifies the alarm and ensures appropriate messages are posted to social media in accordance to a predefined, customized security protocol. ...

Photo courtesy of Civil Rights Defenders.

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ENDNOTES

Analyzing Functionality of Landmines and Clearance Depth as a Tool to Define Clearance Methodology by Jebens [from page 57]

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