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RESEARCH

In-situ Treatment of Oiled Sediment Shorelines

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Experimental oil spill studies were conducted to quantify the effectiveness of selected *in-situ* shoreline treatment options to accelerate natural oil removal processes on mixed-sediment (sand and pebble) shorelines. At each of three distinct shoreline sites, treatment test plots and control plots were established within a 40-, 80- and 143-m continuous stretch of oiled shoreline. A total of 5500 l of oil was deposited along a 3-m wide swath in the upper intertidal zone at each site. Approximately one week after oiling, a different treatment technique was applied to each plot. The treatment techniques were: sediment relocation (surf washing), mixing (tilling), bioremediation (fertilizer application), and bioremediation combined with mixing. One plot at each site was monitored for natural attenuation. The quantity of oil removed from the plots was measured six times up to 60 days post-treatment and then again one year later. Changes in the physical character of the beach, oil penetration, movement of oil to the subtidal environment, toxicity, and biodegradation were monitored over the 400-day period.

The results verified quantitatively that relocation of oiled sediments significantly accelerated the rate of oil removal from the shoreline by more than one year. Microscopic observations and image analyses confirmed that the oil–mineral aggregate formation process was active and was increased by sediment relocation. Oil biodegradation occurred in this arctic environment, both in the oiled sediments and on the fine mineral particles removed from the sediment by natural physical processes. The biodegradation of oil in sediment was significantly stimulated by simple bioremediation protocols. Mixing (by tilling) did not clearly stimulate oil loss and natural recovery in the context of this experimental design. None of the treatment techniques elevated toxicity in the nearshore environment to unacceptable levels, nor did they result in consequential alongshore or nearshore oiling.

Keywords: **Bioremediation, shoreline treatment, oil spill, fate and effects, mixed-sediment beaches, *in-situ* options**

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Introduction

This paper summarizes an experimental oil spill research study, 'The Svalbard shoreline field trials', that was the main component of the *In-situ* Treatment of Oiled Sediment Shorelines (ITOSS) Program (Sergy *et al.*, 1999a) managed by Environment Canada and sponsored by an international partnership of oil spill response and research agencies. The ITOSS Program was initiated to investigate the effectiveness of several *in-situ* shoreline treatment options to accelerate natural oil-removal processes on mixed-sediment (sand and pebble) beaches. The experimental program began with artificial beach trials, carried out in the test basins of SINTEF (Trondheim, Norway, see Sveum *et al.*, 1995) and the Shoreline Environmental Research Facility (SERF, Corpus Christi, Texas, see Kitchen *et al.*, 1997). These were followed by oil spill field trials on the arctic beaches of Svalbard, Norway. The SINTEF and SERF trials (Sergy *et al.*, 1999a,b) were mesocosm-scale studies (1 m × 2 m × 4 m and 2 m × 2 m × 33 m basins, respectively) that provided some ability to control environmental variables. The Svalbard shoreline field Trials were large-scale oil spill experiments conducted under realistic environmental conditions. The latter is the topic of this paper and a special edition of Spill Science & Technology Bulletin (2003).

In-situ shoreline treatment techniques and processes

There are a variety of options for the treatment and cleanup of oiled shorelines. Some techniques, such as washing or manual removal, remove and recover the oil or oiled material. Other treatment methods treat the oil in place (*in-situ*) without the recovery or transfer of oil or oiled materials from that location. Often these are methods that accelerate natural environmental processes that act on the oil. In principle, *in-situ* treatment options could be applied anywhere in the world and on various types of beaches and stranded oils. However, they can be particularly useful in remote areas where waste management and/or disposal are an issue. Physical *in-situ* shoreline treatment methods include mixing (also known as tilling or aeration), sediment relocation (or surf washing), and burning. Chemical and biological *in-situ* shoreline treatment methods include the use of chemical agents to alter the physical or chemical properties of the oil and the use of nutrient enhancement/bioremediation. Natural recovery, or natural attenuation, is an *in-situ* response option that allows the oiled shoreline to recover without intervention.

Several of the *in-situ* treatment techniques for oiled sediment shorelines rely on enhancing the oil removal processes that occur naturally in the environment. For example, biodegradation is one weathering process whereby oil-degrading microbes convert the hydrocarbons to simpler components (Prince, 1998). The treatment technique of bioremediation aims to accelerate the rate of biodegradation through the application of fertilizers. Another natural process that removes oil is wave or surf action that provides physical (hydraulic) energy for the movement of sediments and the subsequent mechanical abrasion of oil from the surface of those sediments. The purpose of a physical *in-situ* treatment action, such as sediment relocation or mixing, is to accelerate the mechanical abrasion processes by increasing the exposure of oiled sediment to these hydraulic processes (Owens, 1998). A third natural process involves the interaction between oil and fine mineral particles, and oil removal and dispersion facilitated by tide and/or wave activity (Owens, 1999). This interaction can take place in a limited wave energy environment, but may be enhanced by wave action or by treatment such as sediment relocation or mixing to make the oil more available for the formation of oil–mineral aggregates (OMAs) (Lee *et al.*, 1997b).

Purpose and objectives of the trials

The behaviour and treatment of oil stranded on coarse or mixed-coarse sediment beaches has been a feature of oil spills for many years (Owens, 1973; Owens and Drapeau, 1973) but only in the last decade has there been a focus to achieve a better understanding about treatment and natural attenuation (Hayes *et al.*, 1991, 1995; Hayes & Michel, 1995; Humphrey *et al.*, 1993; Owens *et al.*, 1994; Owens, 1998; Owens, 1999; Owens *et al.*, 2002). Despite the body of past work, questions remain on many issues, and including those on *in-situ* techniques. Thus, the studies designed in the Svalbard field trials were designed with this in mind and as part of a larger framework of investigation being undertaken by various agencies and researchers (including the authors) to gain a better understanding of the fate and behaviour of spilled oil and to enable appropriate response options to be taken.

The basic objectives of the Svalbard shoreline field trials were to

- quantify the effectiveness of selected *in-situ* shoreline treatment methods to accelerate the natural processes that remove oil stranded on mixed-sediment beaches, and
- investigate the processes that naturally remove stranded oil, such as wave-induced mechanical abrasion and the interaction between oil and fine mineral particles.

The underlying purpose was to obtain more operational and scientific information to assist decision-makers in the selection of appropriate response techniques for oiled shorelines (see Owens *et al.*, 2003). In this case, practical research questions addressed oiled sediment relocation (to the breaker or surf zone), mixing (by tilling), bioremediation (by fertilizer/

nutrient application), and natural recovery as suitable response options to oil stranded on mixed-sediment shorelines. These questions included:

- Is there a reduction in the quantity of stranded oil resulting from the relocation of oiled sediments from the high water line to the lower intertidal zone?
- Does this treatment action transfer oil to, or have an effect on, other parts of the environment?
- Does OMA formation contribute to oil removal/dispersion?
- Does mixing of the oiled layer of surface sediments in the upper intertidal zone increase the rate of oil removal from beach sediments?
- Does the application of fertilizer to the oiled layer of surface sediments in the upper intertidal zone increase the rate of oil removal from the beach sediments on arctic beaches?
- What is the natural rate of removal of oil from upper intertidal and supratidal sediments?

The objectives were addressed by the use of full-scale experimental field trials. Three shoreline sites in close proximity to each other were selected to represent different beach characteristics and oil-spill conditions. Quantitative comparisons between treatments were only made for treatments at the same site, i.e., those that shared the same set of oiling conditions.

Methodology

Experimental overview of the field trials

The Svalbard field trials spanned a three-year period. The bulk of the planning, organization, and conceptual experimental design took place during the spring and fall of 1996. Site characterization, background studies, methods development, and the oiling of a single control (no-treatment) plot were conducted at the experimental site in July and August 1996. The full-scale trials and monitoring program were carried out from July to October 1997. An option was exercised for a post-trial follow-up in September 1998 to assess the efficacy of experimental treatments relative to natural attenuation after a year.

The field experiments were conducted near Sveagruva on Spitsbergen, the largest island in Svalbard (Fig. 1). Sveagruva is located on the Van Mijenfjord, approximately 40 km from the open ocean and at approximately 77°56′N and 16°43′E. The fjord is ice-free for about three months of the year with a 1997 tidal range of ~0.6–1.8 m, nearshore water temperatures of 3–7 °C in August and salinity of 35 ppt (Guénette *et al.*, 2003).

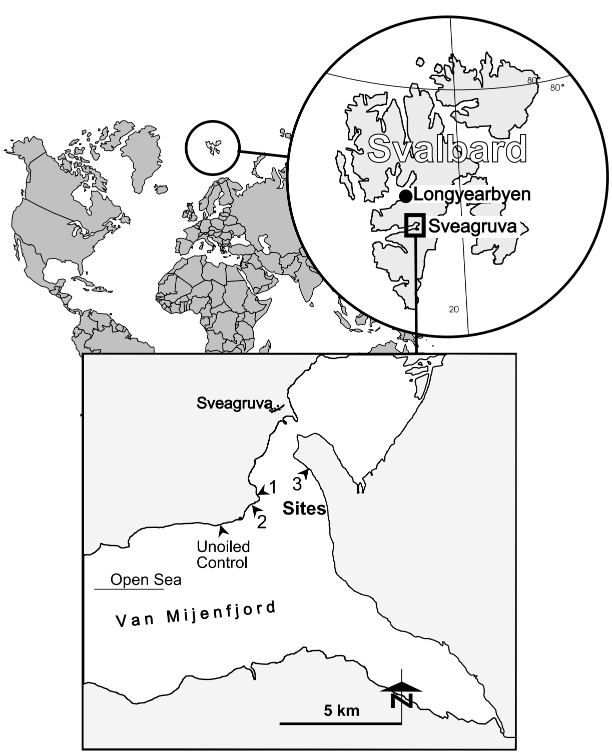

Fig. 1 Location of the Svalbard shoreline field trials.

The experimental design of the field trials is described by Guénette *et al.* (2003) and Sergy *et al.* (1999b). The basic design elements of the field trials included:

- The use of three adjacent but physically separate experimental sites with beaches of mixed coarse-grained sediments. Each site was relatively homogeneous in terms of sediment characteristics but different from each other in terms of sediment grain size ratios and wave energies (Table 1).
- One oil type, an intermediate fuel oil, that was applied evenly across the sediment surface of the upper intertidal or supratidal zone. A total of 5500 l of IF-30 oil was applied across a 3-m swath of the upper beach at the three different experimental sites. Each site received a different loading (Table 1).
- Test plots that were nested within a continuous stretch of the oiled shoreline at each of the three sites. A total of eight plots were created.
- The application of treatment options to the oiled plots after a period of exposure to wave and tidal action (about one week after oiling) in order to allow stabilization of the oiled zone.
- Five treatment options: (1) Sediment relocation was conducted at low tide when the oiled sediment in the upper intertidal zone was excavated with a small front-end loader and deposited at the waterline. (2) Mixing was carried out using a set of tines

Table 1 Experimental site parameters

Treatment option	Plot	Relative wave exposure	Sediments	Oil loading
Site 1				
Sediment relocation	B	Lowest energy site	Least coarse site	7.5 l/m^2
Natural recovery/attenuation	A	3-km fetch	41% pebble, 16% granules, 18% coarse sand, 25% sand/mud	
Site 2				
Bioremediation	C	Locally moderate energy site	53% pebble, 11% granules,	5 l/m^2
Mixing + bioremediation	D	14-km fetch	13% coarse sand, 23% mud	
Natural recovery/attenuation	E			
Mixing	F			
Site 3				
Sediment relocation	G	Locally high energy site	Most coarse site	10 l/m^2
Natural recovery/attenuation	H	40-km fetch and 30° fetch window	75% pebble, 5% granules, 2% coarse sand, 18% sand/mud	

mounted on the loader. The result was similar to that of tilling with a chisel plough. The plots were mixed to a depth of approximately 20 cm. Bioremediation was carried out using a whirligig to apply fertilizer/nutrients to (3) one of the mixed plots (after mixing) and to (4) an unmixed plot. One control site at each of the three beaches provided a measure of (5) natural oil removal rates.

- Systematic monitoring was conducted over a 400-day period (August 1997 to September 1998) to quantify changes in oil concentrations in the sediments of the plots and to document changes in beach physical character, oil penetration, oil loading, movements of oil outside the plot and to the subtidal environment, biodegradation, toxicity, and to validate OMA formation.

The three experimental sites were chosen based on significant differences, and each treatment was quantitatively compared only with other treatments at that site. Within this relatively low-energy fjord environment, a locally high-energy and a locally low-energy site were used to assess separately the treatment technique of sediment relocation and to compare this technique against the (control) option of natural recovery at that same site. The third site was used to assess bioremediation, mixing, and mixing combined with bioremediation. The response option of natural recovery (the control) was individually assessed at three different sites each with different wave energies and sediment types.

Mixed-sediment beaches: An experimental design challenge

Mixed-sediment beaches are composed of sediments of greatly different sizes and shapes that present different surface areas and different interstitial void space volumes that in turn affect oil retention. Moreover, the individual sediments themselves are distributed non-uniformly. When oil is applied to this type of beach, this heterogeneity of the substrate causes a high spatial variability in oil quantity, concentration, and distribution, and makes it extremely difficult to obtain an accurate determination of overall oil loading or oil concentration, i.e., the exact amount of oil in a given section or volume of beach (Sergy *et al.*, 1991). For this reason, considerable effort was spent in the design of the field trials to overcome this problem and to ensure the accuracy of the results from monitoring.

Each of the three experimental sites was selected to ensure a relatively homogeneous sediment type within the site to reduce variability of the data (Guénette *et al.*, 2003). Very large sediment samples were collected for oil-in-sediment analysis and a special extraction technique was developed for the collection of these samples to further override potential mixed-sediment heterogeneity errors. A systematic sample collection strategy and technique further reduced sampling error and provided an accurate representation of the experimental plots. Care was taken to collect a vertical profile of equal proportions of the entire oiled layer during sampling so that oil loading rather than spot concentration values could be calculated. Accretion of surface sediments (clean sediments) was measured and excluded in the determination of the sample zone. Samples were collected along a relatively narrow alongshore band within the intertidal zone to avoid across-beach differences in oil removal, and buffer zones were maintained within the oiled plot to minimize edge effects in the sampling area.

Summary of Results

A concise compendium of the results of the Svalbard shoreline field trials is presented in individual manuscripts of the Spill Science & Technology Bulletin special issue (2003). Further details are contained in a series of four technical reports (Sergy *et al.*, 1999a,b; Prince *et al.*, 1999; Lee *et al.*, 1999). A summary of the results is provided below.

The effectiveness of sediment relocation

Sediment relocation of the oiled shoreline significantly accelerated the rate of oil removal (Owens *et al.*, 2003). This technique reduced oil persistence by at least one year in this sheltered (40-km fetch) wave-energy environment where oil was stranded on the beach face in the upper intertidal and supratidal zones, above the level of normal wave activity. Sediment relocation accelerated the short-term rate (weeks) of oil loss from the intertidal sediments on the relatively low wave-energy shoreline, where the stranded oil was located in the zone of wave action.

Secondary effects of sediment relocation

Sediment relocation resulted in a significant increase in the generation of oiled sediment-fines, and OMAs were detected in the nearshore waters during the first tide following treatment (Lee *et al.*, 2003a). No detectable toxicity was observed in nearshore waters using the Microtox® test. The toxicity of samples from sediment traps on the nearshore sea bed and from nearshore subtidal sediments were within Environment Canada's acceptable limit for ocean disposal of dredge spoils (Lee *et al.*, 2003b). Relatively small quantities of oil were deposited in nearshore subtidal sediments as a result of the shoreline sediment relocation treatment. Sedimentation rates of the oil and mineral fines in subtidal sediments were highest immediately following relocation treatment. There is conclusive evidence of oil biodegradation within the subtidal sediments (Lee *et al.*, 2003b).

Mixing

Under the conditions of this experiment, the technique of mixing/tilling did not clearly contribute to removal of oil within the intertidal sediments (Owens *et al.*, 2003). The changes in total oil loading caused by treatment were small and were unlikely to have accelerated natural recovery. However, the results do suggest that mixing/tilling made the shoreline sediment substantially more permeable to seawater and air for at least 10 days after tilling, which could lead to enhanced microbial activity (Prince *et al.*, 2003).

Bioremediation

Oil biodegradation was observed in the intertidal sediments in this arctic environment (Prince *et al.*, 2003; Garrett *et al.*, 2003). The rate of biodegradation was increased by the application of soluble and slow-release fertilizers. Changes in the chemical composition of the oil demonstrated that biodegradation was significant and that this bioremediation protocol effectively doubled the rate of biodegradation.

Natural oil-removal processes

The rate of removal by natural processes of oil stranded in the active intertidal zones of sites 1 and 2 was relatively rapid in the initial 10 days after oiling. Thereafter, the removal rate slowed dramatically, and oil residue levels did not significantly change for some months, i.e., natural removal ceased to be effective, and some degree of 'stabilization' of oil-in-sediment residues occurred. Low-level oil residues (4–5% of the original oil) still remained in the active intertidal zone after one year (Owens *et al.*, 2003; Sergy *et al.*, 1999b).

Monitoring of the oil stranded in the upper and supratidal zones of site 3 produced dramatically different results. This oil had been placed above the daily tidal influence and it had penetrated deeply into the coarse-grained pebble sediments. About 30% of the oil was lost in the first five days, but no further reduction occurred over the next year and significant quantities remained, despite the relatively high local wave-energy levels on this beach.

OMA formation, which was confirmed by direct microscopic observation, was active in the removal of oil. This process occurred naturally at the water line prior to sediment relocation. Following treatment, the quantity of oil bound in oil-mineral aggregates increased threefold as a result of the increased availability of fine mineral particles (Lee *et al.*, 2003a). It is evident that this process did occur naturally on oiled beaches and was enhanced following sediment relocation.

Validity of field experimentation

Quantitative monitoring and detection of changes in oil concentration and quantitative assessment of countermeasure effectiveness are often difficult tasks in the dynamic and complex coastal environment. In this regard, experimental oil spills provide more control over the variables than spills-of-opportunity, although care must be taken to ensure the element of reality. The Svalbard field trials recreated typical real-world spill conditions and provide a realistic simulation of the conditions that would be expected during actual oil spill response operations. The oil was applied evenly to the upper intertidal zone of the beaches where it would be expected to strand in the event of a spill. Oil loading rates were in the range commonly encountered during spills. Relatively long sections of beach were oiled and relatively large experimental plots were used to avoid the problems of many previous experimental oil spills with "edge effects" caused by the use of small plots. The treatment methods were carried out, based on operational experience, in a manner similar to those typically used for actual response operations in terms of mixing depth, equipment used, fertilizer application, and placement of relocated sediment. The time between oiling and treatment (one week) was within the range of response times experienced in past spills and that vary from a few days to many weeks.

The trials employed a sound methodology to sample and quantify oil in mixed-sediment (pebble–sand) beaches. The findings are representative as a result of careful attention to the details of experimental site selection and oiling, sample size, and sample collection strategy and technique. The data support the evaluation of the effectiveness of cleanup techniques in mixed-sediment beaches. Comparisons were made within and between plots at the same site, and statistically supported differences were clearly evident.

Implications of Field Trial Results

In the Svalbard trials, the *in-situ* treatment technique of sediment relocation had a distinct and verifiable effect on the rate of oil removal from intertidal sediments. Oil persistence was reduced, and secondary effects appeared minimal as sediment relocation did not elevate toxicity in the nearshore environment to unacceptable levels, nor did this treatment method result in significant alongshore or offshore sediment oiling. The Svalbard trials verified that sediment relocation accelerated the removal of oil from the shoreline and that OMAs were formed. From the perspective of a shoreline response operation, this qualitative verification of the role of OMA formation has confirmed how and why sediment relocation is effective. The results permit an improved ability to apply sediment relocation appropriately as a treatment method. Since the trials, a field procedure has been developed to identify OMA formation in the field (Stoffyn-Egli *et al.*, 2000a,b).

Sediment relocation has been used during the *Exxon Valdez* spill (Owens *et al.*, 1991), the Tampa Bay spill (Owens *et al.*, 1995), the *Sea Empress* spill (Lee *et al.*, 1997a), and the *Apollo Star* (Molden, 1997) and visual observations indicated that the technique was successful in reducing oil residues. The Svalbard field trials now add the quantitative data on effectiveness that was not previously collected from the field. Sediment relocation is a viable treatment technique that dramatically accelerates natural processes in the removal of stranded oil from a shoreline. As a shoreline treatment response option it can be considered under various spill conditions and scenarios. These include:

- When oil is stranded high on the beach above the zone of normal wave action. As it is well documented that oil, especially fuel oil, tends to persist for many years in sheltered energy environments, e.g., the *Arrow* and *Metula* spills and Baffin Island Oil Spill experiment (Owens *et al.*, 1994, 1999, 2002), the implications of long term persistence must be considered in the shoreline treatment decision process.
- When oil has penetrated deeply into the beach sediments below the zone of normal sediment reworking. This situation can occur where the sediments are relatively permeable and penetration is not constrained by either the water table or the presence of fine-grained material that fill the interstitial spaces.
- When natural attenuation would take an unacceptable length of time. The oil persistence was reduced at the Svalbard site 3 from years to a few days. In other circumstances, e.g., Svalbard site 1, where oil was laid down in an active intertidal zone, sediment relocation only resulted in a short-term acceleration to the natural rates of oil removal. Nevertheless, there are situations where rapid or immediate removal of stranded oil by sediment relocation is warranted, e.g., Tampa Bay spill (Owens *et al.*, 1995).
- When bulk oil has been removed and cleaning or polishing of the remaining residue is desirable or required, e.g., recreational or tourist beaches.
- Prior to storm events, in order to expose oiled sediments to the predicted high wave-energy levels, e.g., *Exxon Valdez* (Ushagat Island: Owens *et al.*, 1991), or to prevent deep burial of surface oil on sand beaches as was observed at the *San Jorge* spill in Uruguay (personal observation of Sergy, 1998).
- When *in-situ* techniques are appropriate because sediment removal is undesirable due to a lack of natural replenishment and/or waste transfer and/or disposal is an issue, or where there are logistical constraints in remote areas or at inaccessible locations.

With respect to the other treatment techniques tested, bioremediation and mixing, the implications of the trial results are less dramatic, but none the less important. The application of slow-release fertilizer proved to be an effective method to stimulate oil-degrading microbes on an arctic shoreline, therefore, bioremediation should be considered as an option even in such cold conditions to speed up the processes of nature. The trials demonstrated that simple test kits and portable instrumentation can be used to monitor the effectiveness of fertilizer application on site to allow application protocols and rates to be amended during spill-response operations. This would substantially simplify using bioremediation as a routine response option.

Mixing or tilling of oiled sediments did not appear to have a major effect, at least under the conditions evaluated in this study. The operational use of mixing would not be recommended for a scenario similar to this study. Mixing could be appropriate in other situations, as in the case of oil burial or penetration of the oil to depths beyond the reach of effective wave action. A more aggressive mixing technique where the sediments are 'turned over' might be more effective than simply using the tines to mix as was tested in this experiment, but this remains in the realm of speculation.

In addition, the results from the Svalbard trials support a practical recommendation that oiling conditions should be monitored and shoreline response plans re-evaluated as the spill grows older and cleanup proceeds. Observations on the behaviour of the oil remind us that we cannot necessarily predict the fate and persistence of oil and that attention must be paid to feedback from real-time observations such as from SCAT teams (Owens & Sergy, 2000) especially in the early stages following a spill. The long-term persistence of large quantities of oil on the site 3 control plot was not predicted. Although the site was located in a zone of relatively low wave-energy, it was thought that winter storm activity would have had more effect. The sites 1 and 2 results identified another important consideration, namely, the timing of the treatment in relation to the natural removal cycle. Treatment may be more effective at a later time when this activity would accelerate the loss of the low-level oil residues that remain in the long term. Such a two-stage *in-situ* cleanup process, natural removal of the majority of the oil followed by later treatment to accelerate the removal of the residues, might have resulted in a more-effective treatment at both sites. A further extrapolation is that relocation could be of benefit in locations similar to sites 1 and 2 that have not undergone significant natural attenuation within a reasonable period of time.

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