Natural processes of spilled oil at surface and sub-surface shoreline sediment

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Abstract

An oil spill in the marine environment the oil will undergo a number of weathering processes (e.g. dispersion, emulsification, photo-oxidation, biodegradation, evaporation, sedimentation etc.) at the water surface and in the water column, which will alter the physical and chemical properties of the oil as a function of the environmental conditions and oil type, and will have a high influence on the fate of the oil. After stranding the weathering processes continuous, together with additional processes (e.g. sediment interaction, transport, wave exposure and erosion), and that determines the ultimate fate of the oil and restoration of the shoreline ecosystem for different shoreline characteristics.

The natural weathering processes of the oil at shoreline sediment are only poorly understood and describes. These are very important both to estimate the restoration time for different spill scenarios, as well as a basis for development of new and cost-effective clean-up and restoration in-situ treatment techniques. SINTEF has therefore, partly in cooperation with CEDRE for international harmonization of methodology, established laboratory and meso-scale systems at different complexisity levels which simulates the main environmental parameters (scaled down), including; exchange of fresh seawater, tidal variation, wave exposure, temperature control (ambient and water), sediment characteristics, light exposure etc, in addition to oil quantities and weathering degree (evaporation, water content and photo-oxidation). Using these experimental systems the natural processes can be quantified (quantitative and qualitative) under reproducible and control conditions.

The paper describes the experimental shoreline systems using three different crude oil types (paraffinic, naphthenic, and waxy) and an asphalthenic heavy bunker oil, representating 3-7 days at sea prior to stranding, to quantify the major processes for different shoreline scenarios. The data from the studies shows clearly, that fate and behavior of the oil emulsions are very dependent on the properties of the oil and shoreline characteristics, both in the acute (e.g. penetration, retention, remobilization, adhesion) and restoration (e.g. erosion, oil fines interaction, washout, biodegradation) phase. The data from these studies will be used as a basis for development of in-situ treatment and restoration techniques, and to establish algorithms to be included for improvement of predictive numerical models.

Background

Based on the expansion of the petroleum industry on the Norwegian continental shelf towards exploration and development of oil fields closer to the coast, more vulnerable areas and cold climate, greater attention is paid to acute release which can threaten coastal and shoreline areas. Gaining licence to operate, including accessing the new areas, largely depends on the oil companies' ability to meet authority requirements and winning the trust of stakeholders by operating in a responsible manner. The Norwegian Government presented its integrated management plan for the Barents Sea and the Lofoten Area in 2006. This plan builds on a comprehensive set of knowledge, but it also points to areas where more knowledge and new technology is needed. One of the main knowledge gaps pointed out in this plan was related to oil spill contingency and response.

Norwegian authorities has also focus on improving the oil spill response in coastal areas and on shoreline, due to the experience with high cost and limited efficiency for cleanup operation in the last years (Rocknes 2004 and Server 2007), and the threat by increasing ship traffic along the Norwegian coast.

The need for development of oil spill contingency and response in the "new" area is challenging due to several aspects including; remote areas, infrastructure/logistics, personnel, daylight (polar nights/midnight sun), low temperature, ice, health, safety and environment, and cost effectiveness.

Several initiatives have been taken to close the gap in knowledge both from the industry and the authorities. One such initiative is a Joint Industry Project (JIP) established by Eni Norge AS, Shell and StatoilHydro ASA, which aims to increase the efficiency of coastal and shoreline oil spill response operations. Emphasis in this program is on developing more efficient alternatives to the present mechanical based cleanup and restoration techniques and strategies. This paper is mainly based on experience, findings and data from the first phase on this project on studies on the natural processes of stranded oil in the acute and restoration phases.

Acute oil release and weathering

After an accidental release of oil (crude or bunker) in the marine environment, the oil will undergo a number of weathering processes (e.g. dispersion, emulsification, photo-oxidation, biodegradation, evaporation, sedimentation etc) at the water surface and in the water column. These processes will alter the chemical composition of the oil and its physical properties of the oil as a function of the environmental conditions and oil type, and will have a large influence on the fate of the oil. After stranding these weathering processes continuous, together with additional processes (e.g. sediment interaction, transport, and remobilization). These processes are very complex and affected by a large number of parameters including; oil property, quantity and weathering degree, biological and chemical parameters, physical conditions, shoreline characteristics, hydrology, climatic conditions and others. These processes determines the ultimate natural fate of the oil, and thereby the choice of cleanup and restoration of shoreline ecosystem with different shoreline characteristics.

Literature and other documentation gives data on the fate, behaviour and weathering of spilled oil on shoreline from a number of real spill cases. However, very few of these studies are systematic and have been dependent of uncontrolled factors. The natural weathering processes of the oil at shoreline sediment are therefore not well understood and described. In a real spill situation the spilled oil undergoes weathering processes for several days before stranding, resulting in loss of lighter compounds and uptake of water and formation of water in oil emulsions. With a typical drifting time of 3-7days before stranding, the released oil corresponds to a residue of 250^{o}C+ with a maximum water uptake. The potential impact of photo-oxidation varies largely with time of the year. In the present study this weathering degree has been used as standard and realistic oil for the shoreline studies.

In Phase 1 of the project, focus is on studying the natural processes in the different phases after stranding of the oil and how they are affected by environmental parameters for different oil types. This knowledge can be used for development and refinement of in-situ cleanup and restoration techniques, prediction of self-cleaning rate of specific contaminated shoreline segments and development of algorithm for numerical models.

Experimental design and strategy

SINTEF has for more than three decades been involved in most aspects of acute of spill to the marine environment. Common for these activities is the successive approach including the following five steps;

- State of the knowledge/Literature review
- Laboratory/bench-scale; screening (parameter testing)
- Meso-scale studies (simulate environment parameters, under controlled and reproducible conditions, more complex studies); studies under simulated realistic and reproducible conditions
- Field studies; Verification under realistic conditions
- Experimental data used to generate algorithm for numerical model development

The same strategy has also been used for the current study on the fate, behaviour and weathering of spilled oil to the shoreline. Very central in this strategy is use of laboratory and meso-scale experimental systems. SINTEF has therefore, partly in cooperation with CEDRE for international harmonization of methodology, established laboratory and meso-scale systems (SINTEF SeaLab) with focus on simulation and downscale of the most important environmental parameters at different complexisity levels which simulates the main environmental parameters, including exchange of fresh seawater, tidal variation, wave exposure, temperature control (ambient and water), sediment characteristics, light exposure etc, in addition to oil quantities and weathering degree (evaporation, water content and photo-oxidation). Using these experimental systems the natural processes can be quantified (quantitative and qualitative) under reproducible and controlled conditions.

The experimental systems used in the experimental studies are described below, and which can be used for various studies. In addition several specially designed laboratory systems have been used.

Meso-scale shoreline basins

The meso-scale shoreline basin simulates many environmental processes including wave exposure and tidal variation. The experimental basin of 4m x 2m x 1m has a constant water level (70cm) and a constant water throughput (exchange of one volume every day). The tidal variation is control by moving the shoreline section according to a sinus curve with a period of 3 hours and is controlled by two separate motors. The properties of the shoreline section can be varied but in the present studies has a constant angle (12 degree), and is constructed of a perforated bottom covered by a geotextile. The shoreline section (3m x 2m) is divided into four sections divided by PE-plates, with different shoreline substrate characteristics. A wave generator in mounted in the lower end of the basin. The frequence and amplitude of the wave generator can be adjusted to give different wave exposure intensity. The shoreline sections are filled with sediment in a depth of approximately 10-13cm of sediment fractions. The solid substrate shale tiles (15cm x 15cm) were placed on a platform to give an equal top height as the sediment sections.

The basin is located in a temperature controlled room with air temperature control. The water comes directly from Trondheim fjord (water depth of approx. 80m) with a temperature of approximately 6-10^{o}C (seasonal dependent), and the water temperature in the basins are controlled by the air temperature. SINTEF has two basins which can be operated independent in parallel.

Simulated shoreline system
A more simplified experimental systems which also simulates wave exposure, is the Simulated shoreline system which was duplicated from CEDRE. SINTEF has constructed two identical systems which each contains 12 independent reservoirs on a tilting table. Tiles with oil are placed in each of the reservoirs. The shoreline simulation system is placed with lids in a temperature controlled room.

The simulation systems generate wave energy by tilting the oscillating table from one side to another with a standard angel and frequency. For this purpose a compressed air jack along with a control unit programmed for a uniform movement is used.

The exposure degree can be varied by using different quantities of water or by changing the frequence and angle(s) of the tilting system. To quantify and study the different exposure in more detail, a numerical simulation of water flow in the reservoirs was performed using Computational Fluid Dynamics (CFD) model Flow-3D.

Sediment column
To study the fate and behaviour of subsurface oil, a sediment column system were used. This system consists of 16 columns, where a series of 4 columns can be operated individually with respect to tidal variation and water flow. A seawater reservoir is connected to the column system and the in- and output of seawater is placed at the bottom of the columns for tidal simulation. A computer program is used to simulate the tidal variation by controlling the number of tidal period and cycles.

The columns have a length of 70 cm and an inner diameter of 10 cm. The columns are made of plexiglas for possible visual observation of oil behaviour in subsurface sediment. The columns are filled with sediments to 50 cm and a vertical flux of simulated tidal water varies between 10 and 60 cm. The data program SimCol, generated by modules from LabView, control the flow of seawater in the column system.

Definitions and materials

Oil types and properties
SINTEF has over the years studied and documented the properties and weathering of a very large number of Norwegian crude oil. These can be classified according to their dominant components. In our studies three different types of crude oils from the Norwegian and North sea were used, representing different classes;

Naphtenic crude oil
Paraffinic crude oil
Waxy crude oil

In addition one bunker fuel oil was included;

IFO380 (Slagentangen refinery Norway)

The main characteristics and properties of these varied over a very wide range with respect to both e.g. viscosity and pour point. In all experiments an topped (250^{o}C+ residue) emulsion was used with close to maximum water content, representing typically 3-7 days weathering at sea.

Sediment fractions

The characteristic of the shoreline sediment in shoreline varies over a very wide range and are often a mixture of many classes. In the present study, however, sediment fraction has been used to obtain more defined conditions and reproducible results. The sediment grain size distribution used in this study was;

0,6-1,4 mm	Coarse sand
1,4-2,8 mm	Very coarse sand
2,8-6,3 mm	Very fine gravel
8-16 mm	Medium gravel
10-80 mm	Pebble
Continuous	Solid/bed-rock

Other experimental parameters

Temperature; the main focus on the present project is on cold climate, and all studies has been performed at 5^{o}C. Seawater, SINTEF SeaLab has more or less unlimited access to fresh seawater. The seawater inlet is at a depth of 80m, approximately 2km from shore. The temperature varies slightly over the year between 6-10^{o}C.
Light exposure; To simulated sun exposure an light source with the same spectre as sunlight are used, and distance adjusted to give relevant radiation dosage.

Oil spill phases

Different phases in connection to acute oil spills are defined as;

- Release: accidental release from offshore/petroleum installation
- Weathering offshore, drift and spreading on sea
- Stranding; The first tide tidal period with contact between oil and shoreline substrate. In a real situation oil can be stranded over a longer time period
- Acute phase; The stranded oil will be mobile and can be transported from the shoreline into the sea by physical exposure. Time period for this phase will vary dependent on the oil properties environmental condition, shoreline characteristics, but will be defined in this project to be 8 tidal periods.
- Restoration phase; The oil is immobile under normal situations. The time period for this phase will therefore vary over a very wide range from a few days to many years. In the present project the time period will normally be from 4 days up to 30 days.

Results

A very large number of studies have been performed within the ongoing project, and only a very limited number of experimental data can be presented in the present paper. A more extensive and throughout presentation of experimental data and findings will be done through other journals and conferences. The results will be given as general trends rather than absolute numbers.

The weathering of the oil at sea will give an emulsion with very different properties ranging from continuous flakes to smaller individual oil lumps spread over a large area, which are a function of the physical properties of the emulsion (*e.g.* viscosity and pour point) and the exposure (wave and sun radiation) after release to the marine environment. These phenomenons are not taken into account for the laboratory studies, and restrict the studies to scenarios including continuous oil layers.

Stranding/adhesion

For studies on the fate and behaviour of oil in the initial phase, the oil was applied on the sea surface close to the shore in the basin studies. A natural stranding process was obtained after initiation of wave generation and tidal variation. The oil behaviour was very different for the various oils during the first tidal period;

Naphtenic; thin homogenous continuous oil layer
Waxy; thick lumpy inhomogenous continuous layer
Paraffinic; thick inhomogeneous in-continuous
Bunker IFO380; thicker homogenous, continuous layer

The differences in behaviour under the studied scenario are mainly due to differences in the viscosity, pour point and stickiness of the emulsion.

After the first tidal cycle the oil emulsion was remobilised for both and the Paraffinic and Naphtenic crude, whereas the Waxy crude was partly remobilised. The remobilisation took place by different mechanisms including buoyancy, washout and erosion. The bunker emulsion adhered very well to the substrate and was not remobilised during the first tidal periods. This shows clearly that the oil type behaves very differently in the initial phase after stranding, and is mainly due to different physical properties (viscosity, pour point and stickiness). A small scale laboratory test was also developed, but the experimental design does not allow comparison between the different test systems. However, the small scale systems showed clearly the importance of presence of biological film at the solid substrate surface; the crude oil emulsion did not adhere to the surface, whereas the bunker oil emulsion adhered but to a lesser extent than without biofilm. This observation was also confirmed in a meso-scale basin experiment. Small scale experiments also showed clearly that photo-oxidized oil emulsion adhered significantly better to the solid surfaces.

The fate of the oil on solid substrate after stranding varies significantly, and forms oil layers with thickness controlled by the viscosity of the oil and the angle of the shoreline substrate, whereas the Waxy emulsion was completely immobile.

Penetration – sediment

The fate and behaviour of oil emulsion during the initial phase after stranding could be similar for sediment shorelines and solid substrate, for finer sediment substrates and emulsions with high viscosity and high pour point which does not penetrate into the sediment. This phenomenon was studied both in the meso-scale basin and column experimental systems. For all emulsion some penetration was observed, and highest penetration was found for the Naphtenic emulsion which has a relative low viscosity and low pour point. The other emulsions (Waxy and Paraffinic) penetrated to a low extent during the experimental period of eight tidal cycles. Penetration increases with increasing sediment size and time. The penetration is controlled by the oil layer thickness at the sediment surface. The effect of biological film at the sediment surface is limited for sediment substrates. Photo-oxidized oil emulsion reduces the penetration into the sediment.

In the column system, with no energy exposure, a high retention was found for most situations, expect the photo-oxidized Waxy emulsion which only to a very low degree adhered to the surface. Observations and data from the meso-scale basin studies was similar for the initial penetration, but a lower retention was observed in the acute phase due to remobilised by wave action, erosion and also buoyancy.

Weathering; emulsion stability/physical properties
After stranding of the oil emulsion, the weathering processes of the oil will continue due to exposure by water, sediment temperature and light radiation. To study and document these processes for oil in the supralitoral zone a special designed system with simulated daylight exposure (summer scenario) was used in addition to the meso-scale basin system. The oil emulsion was applied as a 1mm oil layer on solid substrate and exposed to light radiation, heat and low wind. The stability of the emulsions varied over a very wide range from spontaneously break-up of the emulsion of Troll oil by light radiation, to very small changes for the bunker oil even after one month. The exposure of the oil emulsions affected the physical properties of the oil emulsion. In general, the viscosity increased significantly by a factor of 5-10 for all oil except the Naphtenic emulsion by sun radiation, which is mainly due to formation of photo-oxidation products which stabilize the emulsion. The viscosity of the Naphtenic emulsion on the other hand, decreased during the experimental period, which is mainly due to emulsion breakup.

The meso-scale studies were focused on the fate and behaviour of the oil emulsion in the intertidal zone without radiation and heat exposure. During the experimental period of up to 14 days the viscosity of the emulsion did not change significantly for the oil which remained at sediment surface in the experimental system.

The water content of the oil emulsion was from an practical point of view not measured, neither on solid substrate surface nor in the sediment. But it will be expected that the unstable emulsions will break up during the transport processes in the sediment.

Remobilisation
After stranding of the oil emulsion the oil can be remobilised by several mechanisms including buoyancy, erosion, washout, dispersion, dissolution and others. These processes take place in the different phases of an oil spill, however, with different importance for the restoration process. These processes were studied both for the acute and restoration phase in the meso-scale shoreline basin and in the simulated shoreline system. The results show a large variation between the different oil types and sediment characteristics. In general the emulsions were removed from the surface either by remobilisation or transport into the sediment, with increasing rate with increasing sediment particles. However, the oils with high pour point and high viscosity stabilized the surface by binding the sediment particles to form a pavement-like scenario, which were stable during the experimental period.

The remobilisation rate and mechanism of surface oil varied with oil type. The bunker oil emulsion was less affected by wave exposure, and the surface coverage did not change during the experimental period, and the reduction in oil quantities on the surface was due to a gradually reduction in the oil layer thickness. For the oil emulsions with high pour point the oil was released from the surface and remaining oil was found as unevenly distributed lumps.

Experimental studies in the simulated shoreline studies allowed variation in environmental parameters including energy exposure, loading, and effect of biological film and presence of fine mineral particles. The result from these studies showed similar trends as in the meso-scale studies, with large variation between the different oil types. The remobilisation increased with increasing wave action. The most surprising observation for the oil emulsion on solid substrate was the limited effect by fine particles. This has over the last decades been considered as one of the main mechanisms for restoration of oil contaminated shoreline sediment. Studies with the present oil emulsions showed however little effect on oil remobilisation with presence of relevant fine particles.

Remobilisation of subsurface oil is takes place by mechanisms which includes energy exposure by either water or sediment movement. In the column studies described above, with no energy exposure, no remobilisation of oil was observed. In the meso-scale basin studies oil was remobilised either by erosion in the upper phase of the sediment given a section of clean sediment, or as washout resulting in gradually decrease in oil concentration in subsurface sediment. These processes had the highest rate for the low viscous Naphtenic emulsion, and increased with increasing energy exposure.

Conclusions/further work

The results from the laboratory and meso-scale studies under controlled and reproducible condition using three different crude oil residues and a heavy bunker oil with maximum water emulsions, demonstrated clearly that there is a very large difference in fate, behaviour and weathering of the oil in both acute and restoration phases for different shoreline characteristics. The most important factor is the chemical composition and physical properties of the oil emulsion and how they are dependent on environmental parameters and climatic conditions and seasons. The data from the laboratory studies should, however, is verified in field studies under relevant conditions as there is presently no direct link between laboratory and real case situations. The findings from cold climate conditions could also be relevant for other climatic areas through after comparative studies.

These findings, observations and data will be important both for the petroleum industry and authorities for response planning and in a real cleanup operation, for *e.g.* use of natural restoration as an active strategy. Further, the data will be used as a basis for development of cost-effective *in-situ* cleanup and restoration techniques and strategies, which could play a major role in remote areas with limited infrastructure/logistics, at low temperatures and limited daylight periods and challenging HSE conditions.

The data on the natural processes will also be used together with literature data for generation of algorithms to be used in numerical models simulating oil on shoreline processes. The data basis for predictive numerical model development would also be more robust if additional oil types were included in similar studies.

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