

Subsurface Oil Detection and Delineation in Shoreline Sediments

Phase 1—Final Report

API TECHNICAL REPORT 1149-1
SEPTEMBER 2013



AMERICAN PETROLEUM INSTITUTE

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Executive Summary

This report summarizes the findings of Phase 1 of an American Petroleum Institute (API) Oil Spill Research and Development (R&D) Project to evaluate Current Practice and Prospective Developing Technologies for the Detection and Delineation of Subsurface Oil in Sediment Shorelines. This Phase 1 component of the project defines current practices and identifies selected developing technologies which promise to improve on the existing survey methods.

Current practice consists primarily of field surveys based on visual observations in excavated pits and trenches, in some cases supplemented by core samples and materials produced by water jet probes. These procedures can be labor intensive and time consuming, particularly when large areas are involved or repetitive surveys are necessary. In addition, typically, current practices rely on small horizontal samples, which may not be adequate to detect or define subsurface oil if the distribution is discontinuous. Developing technologies have a real potential to provide procedures that can either accelerate the collection of subsurface data or allow for continuous horizontal detection and delineation.

Attributes of the basic current and developing technology strategies, in terms of horizontal delineation, vertical delineation, survey speed, description of oil characteristics, and relative costs are summarized in Table E-1. Analysis of these attributes strongly suggests that no single technique is likely to be applicable to all situations that may be encountered and a combination of current practice and developing technology (green boxes) may be effective in providing better subsurface resolution at a quicker rate and with a more efficient commitment of resources.

This review promotes the opinion that efforts should continue to improve the efficiency of existing tactics and development of new technologies. The combined application of these tactics can significantly reduce the reliance on time-consuming practices, improve overall data quality and accelerate the collection of data. Some of the developing technologies identified herein (especially use of service dogs, electromagnetic, and surface vapor measurements) show significant potential for achieving operational status with minimal additional testing and trials and so represent a realistic potential for short-term (months to years), high value gains. The development of new technologies can proceed either through additional research or by trial applications on real-world events.

The results of this Phase 1 study form the basis for Phase 2 studies which include a *“Field Guide for Subsurface Oil Detection and Delineation in Shoreline Sediments”* (API Technical Report 1149-2, 2013) and a report which will provide recommendations for R&D studies to improve and demonstrate developing technologies.

Table E-1 Attributes of Subsurface Oil Survey Strategies

ATTRIBUTES	Existing Procedures			Developing Technology (Potential)			
	Excavation	Cores	Jetting	Push Probes	Service Dogs	Geophysical	Surface Gas
Delineation (Horizontal)	Yellow	Red	Red	Red	Green	Green	Green
Delineation (Vertical)	Green	Green	Yellow	Green	Red	Yellow	Red
Survey Speed	Red	Red	Yellow	Yellow	Green	Green	Green
Oil Character	Green	Green	Yellow	Green	Red	Red	Red
Relative Cost	Yellow	Red	Yellow	Yellow	Yellow	Green	Green

- **Green** indicates a favorable application;
- **Yellow** indicates that the strategy may be effective, depending on circumstances, and
- **Red** indicates important limitations or “not applicable”.

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Subsurface Oil Detection and Delineation in Shoreline Sediments

Phase 1—Final Report

1.0 Introduction

Oil deposited on shorelines during oil spill events can penetrate into sediments, be mixed with underlying sediments, and/or be buried by natural shoreline processes. The resulting subsurface accumulations can consist of a continuous layer or layers of solid or emulsified oil, oil-saturated sediments, or scattered discontinuous deposits. Subsurface oil is also subject to reworking and re-deposition, depending on the character of the substrate and local wave and tidal energy conditions.

Field surveys to detect, delineate and understand the characteristics of subsurface oiling are essential in the development of shoreline treatment end points and cleanup plans. Survey techniques that have been, and are currently utilized for this purpose, focus primarily on excavations. Excavations provide trained observers with the opportunity to visually assess and document both vertical and horizontal characteristics of subsurface oil. Other data collection tactics have been tested over the years, and some continue to be used, although most do not allow for the diversity of observations that can be obtained from excavations.

Time is of the essence in a spill response in order to remove oil from shorelines before it can be remobilized or buried. The quicker field survey data can be collected and assessed, the faster cleanup plans can be developed and implemented. Faster methods of subsurface data collection are desirable. In addition, current strategies only provide a relatively small sample of the distribution and character of subsurface oil deposits. Better resolution of subsurface oiling is desirable.

Based on technological advances and response experience over the last decade, a variety of options have emerged that demonstrate significant potential for improving the state-of-the-art in shoreline protection and cleanup. Recognizing this factor, the API initiated an Oil Spill R&D Program to improve the overall capabilities for the Protection and Cleanup of Shorelines. One component of this effort addresses the improvement of shoreline surveys techniques for the detection and delineation of subsurface oil on sediment shorelines. The effort is divided into three phases:

- Phase 1: Description of current practice and identification of promising detection techniques (this report);
- Phase 2: Development of a *“Field Guide to the Detection and Delineation of Subsurface Oil in Shoreline Segments”*, based on current technology and practices, and assessment of prospective new technologies, including recommendations for R&D studies appropriate to advance the application of these options; and
- Phase 3: Consideration of laboratory and field tests/trials to develop and verify the applicability of high potential subsurface oil detection techniques (“Proof of Concept”).

There have been significant advances in technology over the past decade and undoubtedly there exist tools or techniques that may have an application to detect or delineate subsurface oil that are not covered in this review. Many ideas were evaluated during the Deepwater Horizon response as part of the Alternative Response Technologies (“ART”) program, some of which involved oil detection on shorelines and some of which were field tested, such as a laser fluorometer to detect sunken oil in shallow water

(Cortez, 2011). Technology will continue to improve and there is a reasonable expectation that new strategies and tactics will evolve in the coming years. This study is one step in that evolutionary process. This review focuses on those classes of developing technology which promise short-term operational application to emergency response detection of spilled oil incorporated in shoreline sediments, with the ultimate goals of significantly reducing the reliance on existing time-consuming practices, improving overall data quality and accelerating the collection of data.

2.0 Phase 1 Objectives

- Identify and document current best practices for the detection and delineation of subsurface oil in sediment shorelines.
- Identify developing technologies that have demonstrated the potential to more effectively, in time and space, detect and delineate subsurface oil in shoreline sediments (in the context of information and presentations necessary to support emergency response efforts).
- Establish a framework within which research can be implemented to progress the highest potential alternative technologies.

3.0 Background Information on Subsurface Oil

3.1 Data Requirements

The objective of this study is to identify tactics and technologies that can support emergency response operations. Spill Management Teams (SMTs) require an appropriate level of knowledge regarding the location, extent and character of surface and subsurface oil on shorelines to design, manage, and control cleanup operations. As conditions can be expected to change with time, repeated situational surveys and updates are typically necessary. To be useful, information must be available on a near real-time basis. Historical (and current) practice for subsurface oil detection and delineation, and for the monitoring of cleanup, has relied heavily on visual observations. Although subsurface visual assessments typically provide adequate levels of information to support operations, this strategy is usually slow and labor intensive, particularly with chronic reoiling and dynamic shorelines. Other subsurface observation or detection and delineation strategies have been applied to expedite subsurface observations with varying degrees of success. Technological developments in the last decade have provided the opportunity to improve current survey tactics as well as a variety of new and promising instruments and techniques.

Current shoreline subsurface detection and delineation practice in the US has generally adopted a survey methodology formalized during the 1989 T/V *Exxon Valdez* oil spill response. This methodology, the Shoreline Cleanup Assessment Technique (SCAT) procedure, allows for the standardized and systematic description of shoreline oiling conditions, both on the surface and in subsurface sediments (NOAA, 2000; Owens and Sergy, 1994, 2000). The SCAT observations are intended to be used to develop shoreline treatment recommendations for consideration by the SMT and are used for:

- Development of treatment or cleanup end points;
- Monitoring and adjustment of cleanup tactics;
- Net environmental benefit analyses (NEBA);
- Monitoring of cleanup effectiveness;

- Inspections to verify that end points have been achieved; and
- Long-term recovery monitoring.

A basic assumption of this study is that the SCAT procedure, or its equivalent, will continue to be used to support shoreline cleanup decisions and operations. To function effectively within the framework of an emergency response operation, and the continually changing environmental and oiling conditions, situational data must be easily and quickly obtained and updated. In accomplishing this strategy, SCAT relies on the examination of visual information and documentation using trained observers. The subsurface component of this process, in particular, typically is labor intensive and time consuming.

In an evaluation of modifications to existing tactics, or an evaluation of new strategies, tactics and/or technologies, the following attributes should be considered:

- ❖ **Scope:** Individual tactics may not collect all of the required data. Combinations of existing and developing tactics are acceptable as long as they contribute to improve of the speed, quality and economics of data collection;
- ❖ **Availability:** Any necessary equipment, trained operators and/or other support services should be readily available;
- ❖ **Calibration:** Calibration requirements should be minimal and, preferably, field rather than laboratory protocols;
- ❖ **Data Turn-around Time:** Observations are extremely time sensitive and should be available to the SMT on a near real-time basis (i.e. a time scale of days). Immediate data processing and presentation of summary information is crucial to the decision process;
- ❖ **Delineation of Extent:** Sufficient detail should be provided to delineate the extent and the distribution of subsurface oil deposits both horizontally and vertically. This information may include: depth and thickness of oil or oiled sediment layer(s), characteristics and distribution of oil within those layer(s), and properties of shoreline sediments (grain size, mineralogy, water content/depth to beach groundwater, presence of burrows, sediment bearing capacity, etc.);
- ❖ **Detection Levels:** Detection levels must be consistent with the requirements of each situation. At a minimum, observations should be consistent with SCAT definitions (typically visual). Some promising technologies can offer much higher detection levels. In these cases, speed, reliability and cost factors should be considered;
- ❖ **Location Control (vertical and horizontal):** Precise positioning is essential in all surveys. Current practice increasingly relies upon GPS positioning/tracking equipment and GIS data management. High precision GPS and real-time data reduction are desirable (see Section 4.2).

3.2 Subsurface Oil on Sediment Shorelines

Spilled oiled can be incorporated in shoreline sediments by a variety of mechanisms that include:

- Fluid oil deposited on the shoreline surface may soak directly into underlying sediments. This typically occurs with oils that have a low viscosity, such as distillate fuels and some fresh, light crude oils. Penetration into the sediments is dependent on: oil viscosity, sediment grain size (porosity), water

content, degree of sediment compaction, and factors such as presence of biogenic pathways (animal burrows). Normally, vertical penetration of oil stops at the beach groundwater surface. If there is sufficient available oil, the entire overlying zone may be saturated with oil and there may be a floating layer on the beach surface. A similar effect may occur when solid or viscous oil deposited on the surface is heated by the sun and decreases in viscosity sufficiently to migrate vertically. The latter effect is common when oil is deposited or stockpiled in the supratidal zone;

- Floating oil frequently is deposited on shorelines in discontinuous, irregular patterns in the swash zone or as scattered tar balls or residue accumulations;
- Oil deposited on the surface can be covered (buried) by wind-blown clean sediment or clean sand that is deposited by natural onshore or along-shore processes (accretion). Multiple layering with depth is possible;
- Surface deposits of oil can be covered by sand when dunes collapse during storms;
- Oil deposited on shoreline surfaces can be mixed with clean underlying or adjacent sediments by wave action and alongshore transport and can be re-deposited at depth and/or in adjacent locations. Downward mixing of oil may be deeper than the groundwater water level. The development of multiple oil layers is possible;
- Surface and subsurface oiling can coexist;
- Oil may flow or fall into animal burrows.

3.3 Oil Distribution

Oil on the surface or within sediments is unlikely to have a regular distribution. In most cases, oil is deposited on the mid- and upper-intertidal zones in irregular patterns by wave action, storm surges, and other processes which result in varying concentrations of surface oil. Burial processes add a vertical dimension to this irregular distribution. Understanding this typical irregular distribution pattern is critical to the design and assessment of detection equipment and evaluation techniques.

The SCAT manual (Owens and Sergy, 2000) defines the subsurface oiled zone as “*the vertical width or thickness of the oiled sediment layer when viewed in profile by digging a pit or trench.*” Standard SCAT terminology for describing subsurface oil distribution includes:

- Saturated (Continuous: 91–100 %)
- Layers (Broken: 51–90 %)
- Patchy (11–50 %)
- Sporadic (<10 %)
- Multiple layers
- Depth of over burden
- Water level

SCAT also defines specific characteristics of subsurface oil. These characteristics include:

- ❖ **Subsurface Asphalt Pavement (SAP):** cohesive mixture of weathered oil and sediment situated completely below a surface sediment layer;
- ❖ **Oil-filled Pores (OP):** pore spaces in the sediment matrix that are completely filled with oil; often characterized by oil flowing out of the pores when disturbed;
- ❖ **Partially Filled Pores (PP):** pore spaces filled with oil, but generally does not flow out when exposed or disturbed;
- ❖ **Oil Residue as a Cover (>0.1–1.0 cm thick) or Coat (0.01–0.1 cm) (OR)** of oil on sediments and/or some pore spaces partially filled with oil. Cover/Coat can be scratched off easily with fingernail;
- ❖ **Oil Film or Stain (<0.01 cm thick) (OF)** of oil residue on the sediment surfaces. Non-cohesive. Cannot be scratched off easily on coarse sediments;
- ❖ **Trace (TR):** discontinuous film or spots of oil on sediments, or an odor or tackiness with no visible evidence of oil; and
- ❖ **No Oil (NO):** no visible or apparent evidence of oil.

It is anticipated that equipment and techniques described or resulting from this study would be used in support of SCAT surveys.

3.4 Oil Characteristics

Crude oil and petroleum products exhibit a wide variety of properties which influence their persistence, movement through the environment, and their detection, monitoring, and cleanup requirements. Once exposed to the environment, these properties can be expected to: (a) differ from MSDS product specifications, unless the oil is very fresh; and (b) continually change (often significantly) over time as weathering and other processes proceed.

Oil properties relevant to the detection, delineation and characterization of subsurface oil, and the development of response strategies, include:

- ❖ **Density:** The density of crude oil and products is dependent on their composition and temperature. Oil will sink when the density is greater than water and float if it is less. Oil density will increase as evaporation and other weathering processes occur, and some oils that initially float may ultimately sink;
- ❖ **Pour Point:** Pour point is the temperature below which oil will not flow. Many crude oils have pour points that are near or at ambient temperature, with the effect that they can change from liquid to solid and back depending on the ambient temperature range. Pour point can be expected to change as the oil weathers;
- ❖ **Viscosity:** Viscosity is a measure of the resistance of a fluid that is being deformed by either shear or tensile stress, and may be thought of as a measure of fluid friction. Simply stated, the less viscous the fluid is, the greater its ease of movement (fluidity). Oils having a high viscosity are less likely to penetrate into sediments and may require special handling procedures during cleanup;

- ❖ **Emulsification:** Crude oil tends to form emulsions which, in most cases, consist of small drops of water incorporated in the oil as a result of mixing energy, such as wave action or turbulence associated with a well blowout or pipeline release. Formation of emulsions (mousse) typically increases the volume and persistence of the spilled oil and can impact behavior and cleanup requirements. Emulsions typically do not flow, although they may exhibit measurable viscosity. As a result, they tend not to penetrate into sediments when grounded on shorelines, although some emulsions have limited stability and may collapse into oil and water phases over time or when heated (as by the sun). Relatively stable emulsions were generated following the Deepwater Horizon response and these emulsions retained sand when they were deposited on beaches. Although originally friable in composition, these sand-oil emulsions typically did not collapse and became more cohesive over time, allowing their effective recovery by screening. Emulsion formation may reduce the rate of evaporative loss of the lower molecular weight hydrocarbons;
- ❖ **Asphalt/Paraffin Content:** Crude oils and residual fuels associated with refining, contain varying percentages of asphaltic and paraffinic (waxy) components, which can impact their behavior and persistence. Crude oils that contain significant amounts of asphaltic compounds tend to be viscous, sticky, and persistent. Conversely, paraffinic oils tend to be less viscous, slippery and less persistent;
- ❖ **Hydrogen Sulfide:** Hydrogen sulfide gas is present in some crude (sour) oils and residual fuels. It has the odor of rotten eggs and is detectable by humans to levels of approximately 1 ppm. This gas quickly deadens the sense of smell and may not be detectable (to humans) following short exposure. Hydrogen sulfide can be dangerous or fatal following short exposures at relatively low concentrations. In air, it is slightly denser (heavier) than air and may persist and be detectable in subsurface sediments for extended periods;
- ❖ **Weathering:** The term weathering is used to describe a variety of phenomena which degrade spilled oil. These processes include evaporation, photo-oxidation, biodegradation, and other degradation processes. Typically, these processes remove volatile low molecular weight hydrocarbons rapidly, although burial, formation of emulsions, and the development of weathered crusts on oil accumulations may slow weathering, allowing, for example, off-gassing of detectible volatiles over extended periods;
- ❖ **Color:** Crude oils, emulsions and refined products exhibit a wide variety of colors ranging from black, brown, tan, green, red, orange, and so on. Color is often an important criterion in the description and delineation of subsurface oil. Color can also be misleading as spilled and weathered oil frequently resembles natural shoreline materials (diatom and dinoflagellate blooms, seaweed, peat, heavy mineral deposits, decomposing organic material, etc.). Light products are often difficult to detect visually in sediments, particularly in lower concentrations; and
- ❖ **Friability:** Friability refers to the cohesiveness of accumulations of oil and sediment. This characteristic describes the ease with which residues or accumulations crumble. Cohesive accumulations can be recovered using techniques such as screening, whereas more friable material breaks into smaller particles which may require other tactics.

3.5 Beach and Sediment Character

Shoreline character can impact the implementation of subsurface oil detection and delineation techniques. The characteristics can include:

- ❖ **Access and Trafficability** (the ability to support foot and equipment operation) are critical for some field operations and cleanup techniques, particularly those involving machinery;
- ❖ **Surface Topography** can impact the performance of some detection tactics. Flat surfaces may be necessary for the deployment and operation of some technologies, in particular geophysical measurements;
- ❖ **Sediment Stability** affects excavation on a beach. The angle of repose of some beach materials is so low that excavations cannot be kept open long enough to complete observations. This commonly occurs with dry, coarse sands. Slumping of material into pits and trenches dug below the water table is typical. Slumping can also occur during coring operations; and
- ❖ **Environmental, Cultural and Political Sensitivity** of the area to be surveyed can impact the selection of techniques, with intrusive and high activity techniques often being problematic.

4.0 Historical and Current Practice

4.1 General

Historical and current practices for the detection of subsurface oil on sediment shorelines were examined by reviewing case histories and other literature on oil spills that impacted sediment shorelines. Document sources examined included the following:

- Proceedings of the International Oil Spill Conference (1969 to 2011);
- NOAA Summaries of Significant US and International Spill – Oil Spill Case Histories 1967–1991;
- Proceedings of the Arctic Marine Oil Spill Program (AMOP) Technical Seminars;
- CEDRE – Major Oil Spill Summaries;
- International Tanker Owners Pollution Federation, Limited – Oil Spill Case Histories; and
- A range of Internet locations.

The first section (4.2) deals with the basic positioning current Geographic Positioning System, (GPS) technology, which is an important and applicable component for all strategies and tactics to provide location data.

In general, subsurface oil surveys and detection procedures are poorly documented in the literature. However, based on available information and experience of the reviewers, current detection and delineation tactics can be grouped into the following general strategies:

- Pits and Trenches (Section 4.3);
- Core Sampling (Section 4.4);

- Water Jet Probing (Section 4.5); and
- UV Fluorescence (Hand Held) (Section 4.6).

The following discussion of these strategies is based on available literature and augmented by the professional experience of the authors and reviewers of this document. Approximate costs for different techniques are based on 2011–2012 US dollar estimates.

4.2 Geographical Positioning Systems (GPS)

4.2.1 General

Shorelines often exhibit dynamic sedimentary changes, particularly in response to storm wave action. Changes can include rapid erosion, accretion, and the redistribution of sediments and subsurface oil. Understanding these processes and the accurate location of subsurface features is essential. Historically, the location of observations has been plotted manually on maps or air photos, with depths of subsurface features measured with tapes. Beach profiles have been developed with the use of hand levels and chains or tapes and in some cases by instrumental surveying. Current GPS technology allows the collection of accurate both horizontal and vertical locations and recording of survey track lines and way points. Survey grade GPS equipment can also provide computerized profiling and 3-dimensional mapping capabilities.

4.2.2 Hand Held GPS

Hand held GPS units typically contain track logging capability which records movements of the unit over time. Units can be time synchronized to SCAT observations and photography. Data can be downloaded to a GIS system for data management and map production on a daily basis.

4.2.3 Beach Profiles

Subsurface observations are evaluated in the context of shoreline elevations, or profiles, perpendicular to the shoreline. Historically, profiles were surveyed using tapes stakes and hand levels, and in some cases using surveying equipment, such as levels. Current technology permits rapid and highly accurate profiling and development of 3-dimensional maps using Real Time Kinematic (RTK) satellite surveying technology. This technology can provide centimeter-level accuracy. Ideally, a control point (benchmark) with a fixed geodetic location (latitude, longitude and state plane coordinates) is established and a known elevation or datum (e.g. NAVD 88) is established for each survey location. A portable transceiver is set at each sample point, with data transmitted back to the base unit (Figure 4.1). The ability to quickly resurvey and compare profiles can be extremely valuable. Representative data presentations are shown in Figure 4.2.

Advantages:

- An existing technology that provides accurate horizontal and vertical positioning;
- Hand held units are relatively easy to learn to use; and
- Some equipment collects continuous position data and can be time synchronized to automatically track surveys and downloaded to a GIS for data management.



Figure 4.1 GPS Satellite Survey Equipment

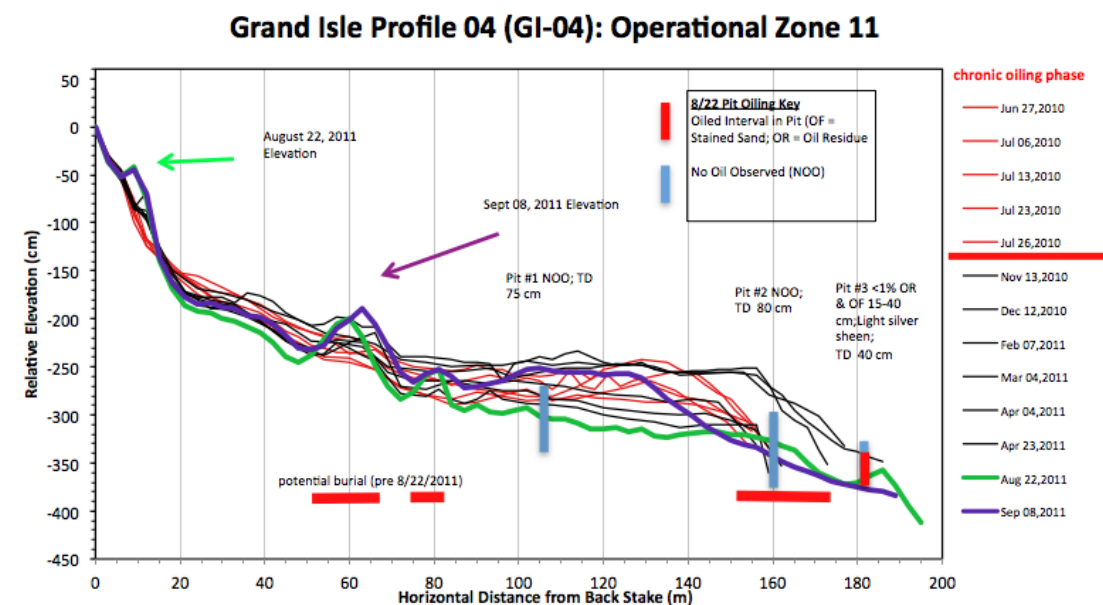


Figure 4.2 Combination of Time-series Beach Profile Data and Pit Information