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Pipeline Rupture Under River Ice Conditions: An Assessment of Available Techniques to Mitigate Environmental Impacts

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While many measures are taken operationally to monitor, maintain, and replace aging or corroded pipe, there is always a possibility, however remote, that oil could be released into the environment. The impact and clean-up cost of a spill into a watercourse can be staggering. Under open water conditions, a response can be mobilized quickly to contain and clean-up oil that is primarily at the surface. However, if a spill occurs beneath a river ice cover, a typical response plan applicable to open-water conditions will not be effective. The most basic challenges would be determining the spill extent and accessing it, since it would effectively be confined under the ice cover.

Although research has been undertaken related to this problem, existing theories and knowledge have not been put widely into practice. The selection of models and tools capable of predicting the transport and fate of an oil spill under a river ice cover are limited in number. This paper will review the techniques available and discuss the need for improved under ice oil spill response planning. Potential winter containment and clean-up measures will be presented at a conceptual level to highlight the unique challenges introduced by the presence of an ice cover.

1. Introduction

A pipeline rupture event beneath an ice-covered river crossing presents a significant technical and logistical challenge with severe environmental consequences. While many measures are taken operationally to monitor, maintain and replace aging or corroded pipe, there is always a remote possibility that such an event might occur. The extent of oil spills occurring during the open water season can be determined visually; however, when a spill is contained beneath a solid ice cover, the affected area cannot be easily identified. Available spill response techniques therefore require *a priori* knowledge or assessment of the spread and transport of the substance beneath the ice cover.

For these reasons, a pipeline rupture event beneath an ice-covered river should be considered one of the worst-case scenarios in pipeline crossing design and spill response planning. Without detailed information on the spill extent, receiving channel hydraulics and ice cover characteristics, successful product recovery will be limited. If a spill cannot be contained and removed within a relatively short period of time, oil entrainment into the ice cover due to ice growth or breakup may disperse the spill over a far larger area.

This paper provides a brief overview of modeling methods that are capable of predicting the spread and transport of oil beneath a river ice cover and discusses some available spill recovery techniques. The need for improved winter spill response management planning is highlighted with some recommendations for future work.

2. Modeling Methods

Several analytical and numerical models have been developed to describe the spread and transport of oil under an ice cover. Most of the previous theoretical and experimental studies have been summarized by Yapa et al. (2006), including references to the earliest work which dates back to the 1970s. Included among the available model formulations are one-dimensional and two-dimensional approaches that employ a variety of simplifying assumptions and physical processes. An analytical theory applicable to the motion of oil beneath a smooth ice cover was proposed by Uzuner et al. (1979), who also conducted experiments to validate their analytical model.

Voznesensky (1979) developed a linear, one-dimensional model to describe the case of an oil spill in an open channel and also considered the case of pollution due to melting of ice containing oil. This particular application may be of interest to predict the impacts of oil that cannot be recovered from under the ice either due to extreme hazards (i.e. ice jams) or as a result of oil freezing into the underside of an ice cover over a large area.

Berry and Rajaratnam (1985) conducted laboratory experiments and developed an analytical approach to describe the behaviour of an under-ice oil slick contained by a boom. They noted that ice-covered oil slicks were thicker and shorter than those in open water, when subjected to similar approach flow velocities. These and other similar experimental observations provide data that can help refine and validate the effectiveness of various under ice oil spill countermeasures.

A comprehensive mathematical model for simulating oil slick transport beneath an ice cover, River Oil Spill Simulation (ROSS), was developed by Shen and Yapa (1988) and later extended by Shen et al. (1993) into a two-layer formulation that considers the dispersion of oil droplets in the water column, subsurface transport, and deposition of oil on the channel bottom. Yapa et al. (2006) and Girghidov (2004) both propose similar two-dimensional models for simulating the spread of oil beneath an ice cover under the influence of water current; however, the former builds on many of the processes an theories included in the ROSS model.

3. Mitigation and Response Measures

3.1. Spill Monitoring

Monitoring for, and detecting, a pipeline leak along a buried watercourse crossing is a critical mitigation measure applicable to all potential spills. However, under winter conditions, detection and monitoring by remote or automated means is essential to limiting the volume of oil released since visual evidence of the leak would not normally be apparent. Typically, a pipeline leak may be detected with internal monitoring systems in real time by sensing a drop in transmission line pressure or flow, rarefaction wave monitoring or real-time transient modeling (ADEC, 1999). Regulatory requirements for pipeline leak detection system performance in Alaska are based on a sensitivity of 1% of the daily volume throughput of the pipeline and it is desirable, but not required, that systems can accurately locate a leak to within 0.5% of the monitored segment length (ADEC, 2006). Since the accuracy of internal monitoring systems is based on pipeline segment length, it may be possible to locate a leak to within tens of metres to hundreds of metres, depending on the pipeline design.

Considering the risks and difficulties associated with containing an oil spill in an ice-covered river, enhancing monitoring infrastructure adjacent to critical watercourse crossings would be an effective mitigation and response measure. This may include retrofitting existing pipelines and updating best management practices in pipeline design for watercourse crossings. Critical watercourse crossings may include large, wide rivers or shallow complex reaches with winter streamflow where auguring or cutting through the ice to implement a winter spill response plan would be particularly difficult or ineffective.

The Athabasca River below Fort McMurray, Alberta, is one example of a critical watercourse. In this reach, the river’s sand bed is highly mobile with many dunes and point bars. During the winter, at any transect, a large proportion of the channel width may consist of ice on top of dry sand and locating the extent of flowing water efficiently requires specific knowledge of the local bathymetry. In addition, flow depth under the ice may be extremely shallow (less than 10 cm) over large areas, making available oil recovery techniques impractical.

3.2. Mapping Spill Extent by Remote Sensing

Technologies capable of remotely mapping spill extent beneath a river ice cover are currently very limited. Space-borne, airborne or ground-based systems could be used to map spill extent to inform a spill response plan after a pipeline rupture occurs. Ground-based acoustic technologies have shown the most promise in reference to the sea ice environment (Dickins and Buist, 1999), but none have resulted in an operational system (DF Dickins Associates, 2004). Related experience with the river ice jam detection application from Synthetic Aperture Radar (SAR) data suggests that spatial resolution and backscatter variability among different river ice types will present a significant challenge for space-borne detection.

3.3. Ice Slotting

One method of recovering an oil slick trapped or flowing beneath the ice cover is to cut an ice slot, angled upstream into the current (Figure 1). The intention of the slot is to allow oil to float to the free surface and become contained within the slot; the angle of the slot with respect to the current will direct the oil towards the bank where one or more skimmers can collect the spill from the surface.

Large blocks of ice need to be cut and removed in order to construct an ice slot, which under most circumstances can be exceedingly difficult and time consuming. In addition, selecting a location for an ice slot that will intercept the oil slick would require some prior knowledge of the transport and dispersion of the oil beneath the ice cover in order to be successful. Thin ice or an area with a hummocky ice cover could also render recovery impossible.

3.4. Diversionary Barrier and Sump

In this method, a series of closely-spaced holes are augured through the ice cover and then a thin slot is opened between them with a chain saw. A diversionary barrier, usually consisting of a series of plywood sheets can then be inserted into the slot (Figure 2). As with the ice slot described above, the slot would be aligned at an angle to the flow to direct the oil towards an open sump formed at the end of the barrier wall where the oil can be collected with a skimmer system. The success of this approach would again depend on proper site selection and favorable river ice conditions.

4. Under-Ice Spill Response Planning

4.1. General Spill Response Planning

A General Oil Spill Response Plan (GOSRP) is developed by pipeline operators for major pipeline projects. These projects cover large geographic areas and involve a large number and broad range of watercourse crossings. GOSRPs, such as the one for the Enbridge Northern Gateway Project (Enbridge Northern Gateway Pipelines, 2011), are risk-based, framework documents that consider the impacts and appropriate response measures for spills on land, watercourse and marine environments.

Although a GOSRP may give special attention to critical spill scenarios and key watercourse crossings, there is often minor mention of river ice effects as an environmental or site constraint affecting a response. Enbridge Northern Gateway Pipelines (2011) discusses ice slotting as a containment technique for an oil spill under an ice cover; however, they caution that this method has limited effectiveness and is likely to require additional remediation work during spring and summer conditions.

4.2. Ice Considerations

To ensure an under-ice spill response plan can be implemented in the event of a pipeline leak, special consideration should be given to the local river ice regime and the potential range of ice conditions expected from freeze-up through breakup. Response measures that may be effective in mid-winter at a location with a smooth, stable ice cover are likely not feasible during freeze-up when the reach may have a partial ice cover or heavy concentrations of ice floes.

Near the onset of breakup, safety concerns are likely to prohibit any oil recovery activities on the ice cover. A response plan for unrecoverable oil spilled during breakup may place the most emphasis on tracking ice floes to map the extent of oil transport along the downstream reach. Alternatively, methods involving the release of dispersants below the ice cover may be viewed as having the lowest impact when the oil cannot be recovered by other direct means. During the onset of freeze-up, special boating equipment, temporary ice booms and skimmers may prove effective in limiting the amount of oil becoming entrapped beneath the ice cover and enable a response measures similar to those for an open water spill to be effective.

4.3. Modeling Scenarios

Predictive modeling of oil transport and spreading under a river ice cover is a critical component in mitigating environmental impacts of an accidental pipeline rupture in winter. Ideally, simulations for breech scenarios should be conducted for critical pipeline watercourse crossings in advance of a spill so that an effective response and cleanup can be initiated quickly. The appropriate use of one-dimensional, two-dimensional or a combination of these models, will depend on the reach hydraulic characteristics and volume of oil spill under consideration. In any case, data describing the channel bathymetry, local hydrology and river ice regime would be required to generate accurate spill extent mapping. Real time transient modeling could also inform a response plan and increase the success of containment and recovery efforts in the event of a pipeline leak.

4.4. Field Response Training

River ice conditions are extremely variable from year to year, week to week and site to site. For these reasons it is important to have access to response teams that are familiar with the unique features of each specific site before a spill occurs, as it will be particularly difficult to orient oneself with river characteristics such as bed forms and substrate, active and inactive flow areas and possible hazards without first seeing the site under ice-free conditions. Ongoing field training under all conceivable ice conditions should be an integral part of a site spill response plan to ensure responders are prepared to safely and quickly conduct their work.

5. Conclusions and Recommendations

Existing research into the behaviour of oil spills in rivers dates back to the 1970s, and more recent studies give consideration to the effect of an ice cover on the transport and spread of oil. Although some numerical models and analytical techniques exist to predict the extent of an oil spill in an ice-covered river, these have not been widely used in practice or adopted as a best management practice in the engineering design or environmental impact assessment for pipelines crossing critical watercourses, despite the difficulties associated with clean-up of an under-ice oil spill.

Spill response planning and training should give detailed consideration to river ice conditions, particularly where available techniques to intercept and recover oil under an ice cover would have limited success. Numerical modeling techniques provide the greatest opportunity to inform a successful response to an under ice oil spill; however, remote sensing technologies such as acoustics to detect spill extent from the surface should be further investigated.

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Figure 1. An ice slot designed to intercept an oil spill under a river ice cover.
(Photo source: Dowcar Environmental Management, Inc.)

Figure 2. A diversionary barrier made of plywood sheets and a sump to contain an oil spill underneath a river ice cover. (Photo source: Dowcar Environmental Management, Inc.)