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PIPELINE EXPOSURE AT RIVER CROSSINGS: CAUSES AND CURES

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ABSTRACT

Erosion is a common problem at pipeline watercourse crossings. Watercourses are naturally vulnerable to erosion but the risk is particularly acute after sub-soil and armour materials have been disturbed by trenching and backfilling during pipeline construction.

The process of pipeline exposure at watercourse crossings can be grouped into these types. One common type of erosion phenomenon is episodic exposure resulting from general and local scour. This is associated with temporary river scour during flood events. It includes general scour involving temporary lowering or the entire river bed during high flows, as well as local scour which involves development of a scour hole during high flow events at a predictable location on the river bed. River engineers have adopted various design methods to ensure sufficient pipeline burial depth which minimizes pipeline exposure due to such periodic occurrences.

A second type of erosion phenomenon causing pipeline exposure is progressive river channel bed and bank erosion. This is not a function of a single event but occurs periodically, resulting in progressive removal of pipeline cover. Progressive erosion at pipeline crossings includes riverbed degradation, bank erosion and growth of gullies. River bed degradation (progressive river bed lowering) is a complex phenomenon associated with the stage of geomorphic development of the drainage basin. Its prediction is based on a sound understanding of sediment supply, river hydraulics and river outlet conditions. Bank erosion is a common occurrence and is readily observed. It may be a continuous or episodic occurrence and is often related to the river's tendency to change its meander pattern, cross sectional shape or bed level. Growth of gullies is a very common cause of erosion at pipeline crossings and results from changes in land use, soil composition, and landscape drainage networks. Techniques for predicting progressive erosion are not well developed and widely understood. As a result, progressive erosion is a common cause of erosion and even pipeline exposure at pipeline crossings of rivers, streams, and gullies.

A third mechanism of pipeline exposure is river avulsion. This is often associated with a tortuously meandering channel, a steep braided channel with a wide flood plain or an immature channel on a delta.

Methods of avoiding or controlling erosion are based on a sound understanding of causal factors. Each river crossing location is unique and the local risks of pipeline exposure must address specific local conditions. Methods of estimating the risk of local and general scour, progressive erosion, and river avulsions are discussed. Methods of mitigating erosion at pipeline crossings include proper siting of pipeline crossings, deep burial, conventional armouring and a combination of bank toe protection and upper bank vegetation cover.

INTRODUCTION

There are thousands of kilometers of buried pipeline installed in Western Canada, resulting in numerous watercourse crossings, some on large rivers and many on smaller rivers, streams, and ephemeral watercourses. Standard specifications for minimum pipeline burial range from 1.5 m to 2 m below the invert of smaller streams and rivers, depending on the policy of the owner and on the vulnerability classification of the stream. These nominal burial depths are exceeded whenever there is a risk of significant episodic erosion of the stream bed and bank.

In Canada, watercourse crossings are subject to provincial regulations which govern the safety of the pipeline and water resource (AEP, 1994). In Alberta, for example, the crossing must be designed to avoid exposure during the 50 or 100 year recurrence interval for gas and oil pipelines respectively. These criteria are provided to protect the watercourse and to prevent deterioration of local and downstream water quality and aquatic habitat. They are also needed to avoid unnecessary disruption of the flow regime caused by pipeline exposure, breakage and replacement.

Despite government regulations and extensive experience in the design of pipeline watercourse crossings, there are numerous cases of pipeline exposure caused by erosion at pipeline crossings. Through the course of various pipeline crossing projects, the authors have inspected some fifteen exposed pipelines in Alberta and B.C. The cause of exposure is most often failure by the design engineer to understand the character and evolutionary trend of the river or stream, and failure to recognize the governing mechanism causing exposure. This paper presents a discussion of various stream bed and bank erosion mechanisms and presents general river engineering and river control methods to minimize the risk of pipeline exposure. It also presents an approach to understanding river conditions and trends so that the risk of pipeline exposure can be anticipated and properly mitigated.

GENERAL AND LOCAL SCOUR

The river bed is subject to temporary removal and replacement of bed material, depending on hydraulic conditions, and the occurrence of floods. This type of erosion can be classified as general or local scour. It occurs when the hydraulic shear stress on the stream bed exceeds the capability of the bed material to resist motion. Bed material is transported by bed load (rolling and salting along the bed), and by suspended load (bed material which is fully entrained in the fluid by turbulence). The amount of general and local scour is a function of the magnitude and duration of shear stresses which exceed the critical (beginning of motion) shear stress.

General scour refers to degradation of the channel (width and length) during peak flow conditions. General scour can lead to significant damage to a pipeline crossing because it can cause exposure of a pipeline across the entire channel width, which risks damage to the pipe if the stream channel is wide. Local scour refers to additional scour at specific locations which are subject to higher local flow velocities and turbulence as a result of an impingement, change in flow direction, obstruction and flow constriction. Local scour normally causes exposure of a relatively short reach of channel and this may not lead to excessive stresses on a pipeline. Both types of scour normally cause a temporary or long term lowering of the stream bed. The original bed profile typically recovers following the flood event.

General and local scour are a potential but infrequent cause of pipeline exposure. Scour depth estimation is well supported by extensive research and conventional safety factor practices. Accordingly, river engineers who design pipeline crossings normally take proper account of these phenomenon so that they seldom lead to exposure and damage of pipelines.

The techniques for estimating general scour include sediment transport formulas and channel regime methods. Sediment transport models can be used to determine maximum entrainment of bed material because there is a maximum sediment load carrying capacity, which depends on the hydraulic flow condition. During flood conditions, the sediment carrying capacity rises with increasing flow velocities. General scour must be computed by continuous simulation sediment transport models, which needs to be calibrated over the entire upstream reach of river to account for sediment entrainment throughout a reach of river. This technique requires extensive bed material and river cross section data, but is vulnerable to imprecisions as a result of microscale variations along the river. To avoid the time investment and uncertainty associated with the sediment transport techniques, channel regime methods are most frequently used to determine general scour.

There are many techniques for estimating local scour, depending on the type of obstruction, constriction, impingement, or deflection of flow. Specific causes of local scour include the following:

- channel bends
- bridge or embankment constriction
- bridge pier obstructions
- channel islands
- channel confluences
- bridge abutments
- bank protection which encroaches on the river
- culvert crossings
- river bed erosion protection for buried pipelines

PROGRESSIVE EROSION AND SCOUR

River Bed Degradation

Progressive river or streambed degradation is similar to general scour in that it involves overall lowering of the streambed. However, unlike general scour, progressive streambed degradation does not result in recovery of the original streambed level after a flood event. Progressive streambed degradation leads to continued down cutting of the streambed and possible pipeline exposure. It is often associated with normal peak flow conditions and may not depend on the occurrence of extreme flood events.

Progressive streambed degradation occurs when the long term rate of erosion for a reach of river exceeds the rate of long term supply of sediment. Changes in land use causing increased runoff from the watershed can result in increased river flow and a higher capacity to transport sediment. This may lead to significant lowering of the river bed if sediment supply is unaffected. Sediment supply can be reduced by development of an upstream river control facility which traps upstream sediment or by reduced upstream erosion as a result of land use improvements and channel erosion protection. Sediment supply reduction can sometimes be caused by channelization, which reduces hydraulic roughness.

The symptoms of progressive streambed degradation are not easily recognized and therefore frequently overlooked. Progressive streambed degradation is therefore one of the more common causes of pipeline exposure. River engineers should check for progressive streambed degradation by conducting the following:

- Check for changes in the rating curve of any river level gauge on the watercourse.
- Determine if there is a robust armour layer on the streambed. The absence of an armour layer may be indicative of progressive streambed degradation.
- Check for extensive bank instability since this may be caused by the lowering of the river bed (bank instability is also associated with stream aggradation, and channel widening).
- Check for the occurrence of an entrenched watercourse flanked by high flood plains which are out of reach of typical annual floods. If abandoned terraces are present, the streambed may be in the process of degrading progressively.
- Check for upstream changes in land use, stream bank protection, channelization, and river control works which might trap sediment. These occurrences may precipitate streambed degradation.

Bank Erosion

Bank erosion is another common cause of pipeline exposure caused by progressive erosion. Like streambed degradation, bank erosion is a progressive phenomenon with no recovery or replacement of materials following a flood event. As such, pipeline exposure can occur after a series of relatively mild flood events, not necessarily as a result of an extreme event.

Bank erosion normally occurs at the outside of meander bends and sometimes along straight reaches of channels. It often takes the form of erosion at the toe of the channel bank, which reduces bank stability by undermining the slope and results in a slump or slope failure. This mode of failure occurs where the bank is composed of fine grained soils and cohesive materials. Banks composed of loose coarse grained soils such as gravels and cobbles may form an angle of repose bank slope, which erodes at a rate governed by the hydraulic capacity of the stream.

Predicting the rate of bank erosion is subject to considerable uncertainty. The best method of predicting the rate of bank erosion is by assessing the historic rate of erosion as determined from local site conditions, historic surveys and photographs, and historic air photographs.

The best method of protecting a pipeline from exposure by bank erosion is adequate burial (set back of sag bends), armouring or a combination of these methods. As a minimum, the pipeline sag bend setback should be the lessor of three times the bankfull depth or one third the channel width. The sag bend set back from the exposed bank should be at least 2 m. Sag bend setbacks should also be assessed based on a historic lateral channel stability assessment.

Erosion protection armour material should be at least double the size (diameter) of the natural bed material diameter. Design bank armour material should be based on accepted riprap sizing formulations.

Gullying

Gullying is perhaps the most common cause of pipeline exposure. Pipeline exposure caused by gullying was the most common cause of pipeline exposure during the major floods in southern Alberta during early June of 1995. Gullying is much like progressive channel degradation in that the watercourse progressively degrades, causing pipeline exposure by a sequence of lows, which may not necessarily be composed of extreme events. Unlike progressive channel degradation, gullying occurs in relatively small waterways which may be ephemeral (seasonal exposure to flow) or subject to temporary flow during rainfall of snowmelt events.

There are several types of pipeline exposure caused by gullying. One is gullying in the backfill of the pipeline trench. Trench excavation and improper backfill may cause overland runoff to accumulate and to flow alongside or on top of the pipeline trench. This does not necessarily occur near a river or stream but is commonly located at these locations because of the steeper hillslopes at the edge of a river valley. This type of gullying is not related to waterway hydraulics. It is related to construction quality control during pipeline trench excavation and backfilling. It can be remedied by avoiding settlement depressions in the trench after backfill, which results in the establishment of watercourses over vulnerable area. It can also be prevented by providing suitable surface runoff crossings over top of the pipeline.

Pipeline exposure by gullying occurs when a stable waterway on a steep slope develops a headcutting nick-point as a result of soil disturbance during construction of the pipeline across the waterway. Disturbance of the local vegetation, surface soils or armour layer can initiate accelerated erosion which causes stable channels or grassed waterways to become gullies. Mitigative measures include the following:

- restoration of original conditions (this is often impractical)
- placement of a new armour layer
- development of erosion control vegetative cover. This may require the construction of temporary artificial erosion control measures designed to provide time for the establishment of a permanent vegetative cover.
- Combined toe (lower bank) rock armour and upper bank vegetation cover

Armour protection composed of riprap or cobbles should normally exceed the size of natural armour because man-made construction is often exposed to hydraulic forces greater than natural conditions.

CHANNEL AVULSION

Channel avulsion is a rare cause of pipeline exposure; however, it is an important consideration because it can potentially lead to catastrophic consequences, especially at locations where the pipeline is buried at shallow depths across the flood plain of the watercourse.

Channel avulsion occurs as a result of cutoffs on a flood plain of a meandering river, debris jams, sediment accumulation (aggradation), beaver dams, and extreme flooding. Channel avulsion commonly occurs during extreme flood conditions when overbank flow results in the development of a new preferred conveyance route.

Channel avulsion can lead to catastrophic failure of a buried pipeline because the entire pipeline across the full width of a river channel can become exposed and suspended in the river. This can lead to breakage and extensive environmental impact for polluting pipeline medium.

Methods of avoiding pipeline exposure by channel avulsion include the following:

- deep pipeline burial across the full width of an active floodplain
- prevent flow on floodplains by berms, dykes, or barriers
- beaver dam control

AVOIDING PIPELINE EXPOSURE BY UNDERSTANDING STREAM MORPHOLOGY

High risk causes of pipeline exposure and effective cures require a practical understanding of river characteristics, processes, and long term trends. This involves knowledge of fluvial geomorphology, which defines the evolutionary history of a river and the current direction of change in the characteristics of the river. A river engineer can only anticipate future behaviour of a river and its response to disturbance if the engineer understands the factors, which govern its past behaviour.

Channel Regime

Regime relationships have been developed by geomorphologists to provide a basis for assessing the natural tendencies and preferred characteristics of a river channel. Formula for width to depth ratio, channel slope, meander pattern, sinuosity, and channel depth have been developed for various geographic and climatic conditions. Depending on the availability of regime relationships for local conditions, it may be more useful to compare the local regime with nearby stable regime channels, which may be located upstream or downstream of the crossing. A significant difference in regime may be indicative of a future change to the condition such as change in river cross section or slope. This would be indicative of a strong potential for pipeline exposure.

Stream Classification

The stability of streams vary. Some types of streams are quite stable and are not subject to rapid change in the event of variable hydrologic conditions or to disturbance by pipeline construction. Other types of streams are highly vulnerable to change. Gullies and unvegetated braided channels exemplify a tendency for rapid change in cross section location, bank erosion, and level of channel bed. Channel classification is therefore a useful tool for assisting the river engineer to define potential sources of risk which may endanger the pipeline. A useful classification system has been developed by Rosgen (1996). Each category of stream has characteristic strengths and weaknesses in terms of resiliency or robustness when a channel regime is disturbed. This information has been used to identify critical issues associated with preserving the stream dimensions, pattern, and profile.

Application of Stream Morphologic Approach to Pipeline Crossings

An understanding of stream morphology assists pipeline designers to identify issues and potential solutions from the scoping study stage through engineering design specifications. From the scoping study, pipeline designers can identify general morphologic characteristics from minimal data requirements. For example, pipeline crossings at a river bend is typically ill-advised. Additionally, morphologic assessment at the scoping study stage can also estimate potential bank stability issues such as the relative importance of bank vegetation for the preservation of an existing watercourse.

At the engineering design stage, morphologic assessments supplement the available hydrologic and hydraulic information. This can be an important consideration at many crossings since most watercourses are not gauged or surveyed in detail at the crossing location. Morphologic characteristics should lend support to conclusions drawn from hydrologic and hydraulic analysis. In the absence of detailed flow analyses, morphologic characteristics can also be used to justify design requirements based on sound fluvial geomorphologic principles.

Mitigation of pipeline watercourse crossing issues also benefits from stream morphologic assessments since most mitigation measures have been rated according to stream morphology. Assessments can be used to devise a short list of feasible options for mitigation so that a cost-effective solution can be selected. Derivation of this short list is an essential element for the preparation of sediment and erosion control plans.

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