APPENDIX B

MACKENZIE GAS PROJECT

REVIEW OF STRAIN-BASED DESIGN – LOADINGS

Submitted to:

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Introduction – Loading Conditions

B.1 Experience from Canada, the United States and Europe shows geohazards account for between 7% and 12% of onshore pipeline incidents (e.g. Fig. 1). Although these are proportionately smaller than for corrosion and third party incidents, geohazards typically cause larger product losses, greater environmental and property damage, result in longer service disruptions, have the highest average incident cost and are second only to third party for total cost (e.g. Fig. 2; Porter et al. 2004). Not surprisingly, all geohazard impact measures worsen when data for difficult terrain and frontier areas are considered alone. One corporation with facilities traversing Andean terrain found by adopting geohazard risk management that, to its surprise, geohazards represented its highest risk exposure (e.g. Fig. 3; Esford et al. 2004; Porter et al. 2004; Sweeney et al. 2004).

B.2 For most of its history, the pipeline industry has taken a reactive approach to geohazards. Incidents were viewed as random and unpredictable, hence they were managed with investments in technology and equipment that enabled rapid response. Proactive geohazard risk management gained a foothold in the mid 1980s and was well established by the mid to late 1990s (Muhlbauer 1996, Savigny and Isherwood 2004, Nessim and Stephens 1998. The Canadian Standards Association (CSA) Oil and Gas Pipeline Systems Code Z662-03, Annex B provides guidelines for the application of risk assessment on the part of any agency designing, constructing, operating or abandoning an onshore pipeline in Canada (National Energy Board Act *Onshore Pipeline Regulations, 1999, Secs. 1 and 2*). Hazard identification is an explicit component of this process. Environmental loading mechanisms, which encompass geohazards, represent one hazard category that must be addressed (CSA Z662-03, Annex C, Sec. C.4.6).

The Proponent identifies four principal environmental loading categories:

- differential frost heave
- differential thaw settlement
- slope failure
- seismic effects.

B.3 Frost heave and thaw settlement are dealt with at some length in documents provided by the Proponent, which affords INAC an opportunity to critique the Proponent's risk assessment approach and risk control strategies, but only in relation to these two hazards. The same opportunity is unavailable for seismic effects, slope hazards, hydrotechnical events, and other possible environmental loading mechanisms. The Proponent indicates, *"the non-mandatory CSA Z662, Annex B, Guidelines for Risk Assessment of Pipelines, is not being used in design. The design process will follow standard industry practice for identifying* *right-of-way hazards … on a site-specific deterministic basis … and they will be addressed … according to acceptable design practices, which are a:*

- *factor-of-safety approach for slopes*
- *return-period design event approach for hydrotechnical events, and*
- *return-period design event approach for earthquake-related hazards.*

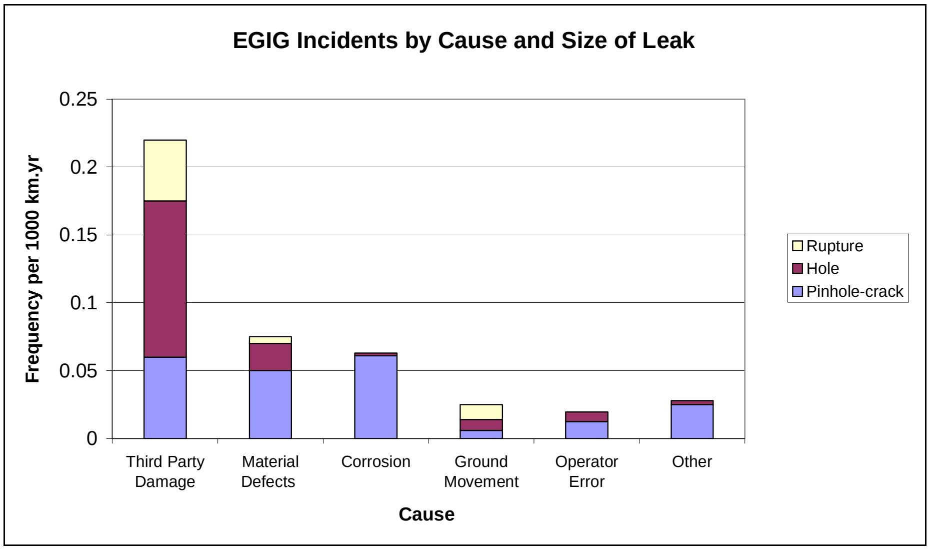
B.4 The Proponent further indicates that designs will allow for *"… appropriate combination effects, as required."*

B.5 With respect to its risk control strategy, the Proponent acknowledges that, *"for frost heave and thaw settlement, industry experience for forecasting required operational interventions is limited. The Integrity Management Plan being developed includes monitoring the pipeline and right-of-way and conducting periodic risk assessments of pipeline integrity and of right-of-way condition. Monitoring frequency, and intervention decisions made during operations, will be based on the results of these assessments."*

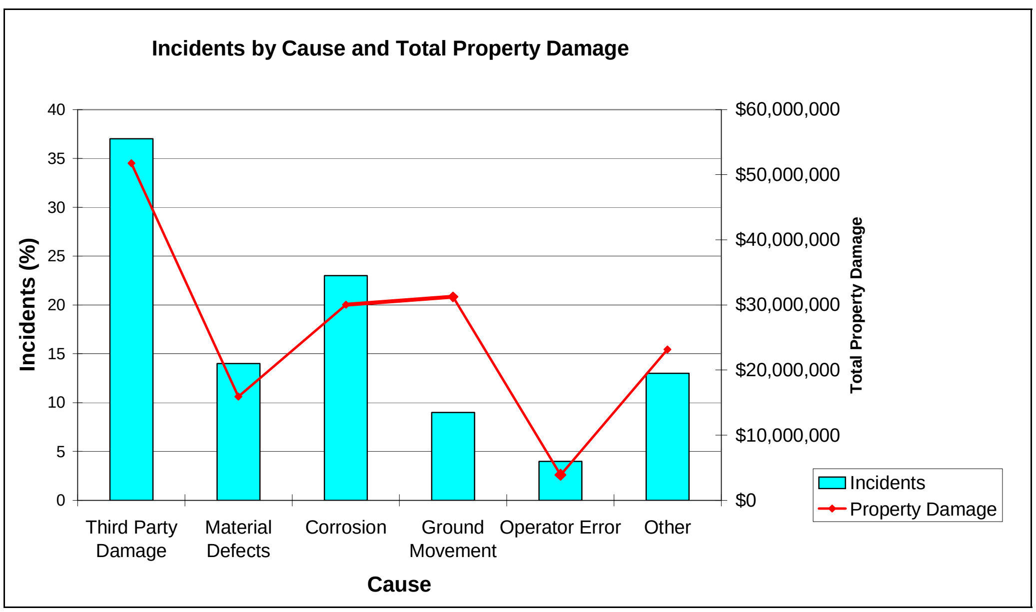
B.6 Investigation and design are ongoing with considerable additional information to be forthcoming at the end of Q3 2005, or perhaps even later. Thus, with the exception of frost heave and thaw settlement, INAC is required at this time to accept on good faith and without scrutiny that the Proponent's site-specific geohazard assessments will be though and complete. Despite the Proponent's assertion that frost heave and thaw settlement are the only uncertainties that the Mackenzie Gas Project faces, it is INAC's position that the Project is without precedent in Canada or elsewhere, and its strain-based limit states design leaves little room for error related to the magnitude and rate of strain demand as well as strain capacity of the pipeline. Thus, the Project requires risk assessment of all possible environmental loadings (singular and then combined) together with the strain capacity of the pipelines during both shut down and operation.

B.7 Following is a more in-depth discussion of the environmental loading considerations that INAC considers should be included.

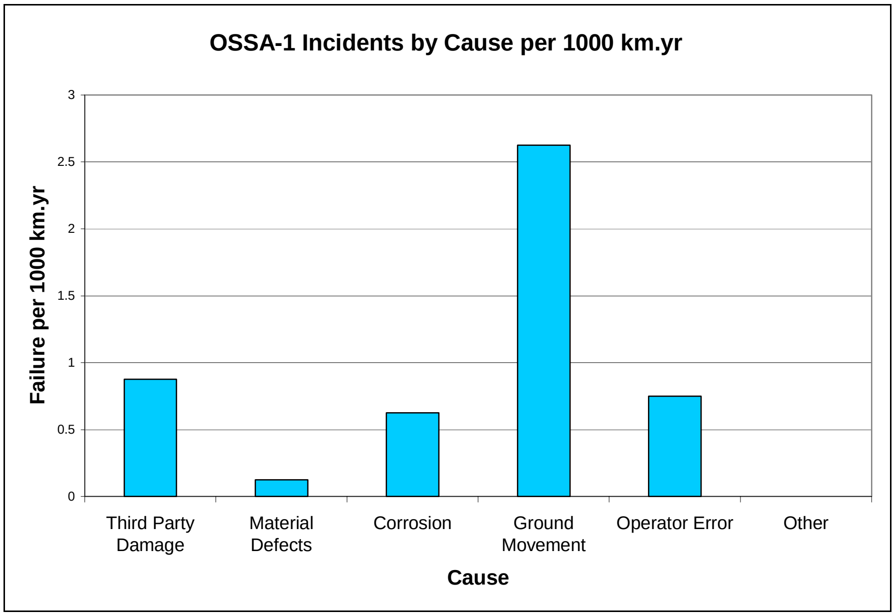
B.8 Figure 1. EGIG Pipeline Incident Data (Porter et al. 2004).



B.9 Figure 2. US DOT Incident Data for Gas Transmission Pipelines (Porter et al. 2004).



B.10 Figure 3. Incident Data for a Typical Andean Pipeline (Porter et al. 2004).



Frost Heave / Thaw Settlement

B.11 It is recognized that the MGP Proponent has conducted numerous investigations and evaluations into the potential for loading conditions associated with frost heave and thaw settlement. Regarding this issue, the following sections document issues which do not appear to have been covered or in sufficient detail as part of the submitted documentation.

Frost Blisters

B.12 Frost blisters are thought to form as the saturated active layer progressively freezes, limiting water movement within the still unfrozen region thus increasing hydraulic pressure. As freezing continues, icings may form, eventually leading to the freezing of spring outlets (van Everdingen 1982). Doming of the ground surface occurs as subsurface water accumulates under high pressure into a zone of low resistance to deformation (French 1996), while van Everdingen (1982) observed that these zones tend to occur on the outflow channel of springs.

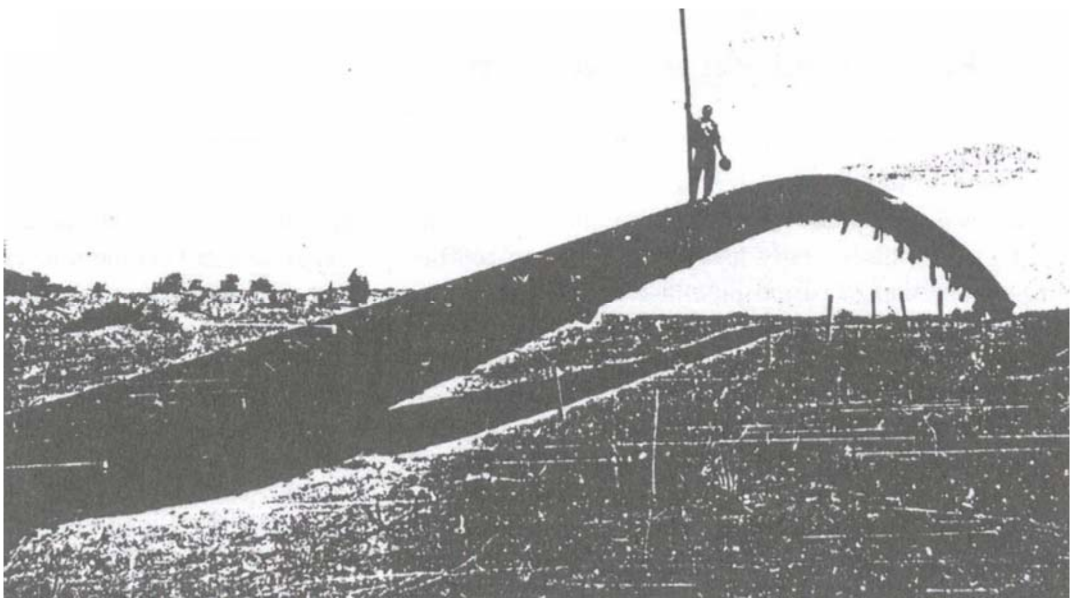
B.13 Based on van Everdingen's research conducted at Bear Rock, N.W.T. (approximately KP 545 to 550 of MGP), uplifting may occur up to a rate of 0.55m per day (van Everdingen 1982). Frost blisters ranged in size from 20m to 65m horizontally while reaching up to 4.9m vertically. Rapid uplift combined with sudden cold periods can produce contraction fractures and may cause frost blisters to rupture. Frost blisters may also experience partial subsidence as water escapes through fractures, however rebuilding may occur as new water is introduced and fractures are sealed. Through this process, a frost blister may expand and subside numerous times throughout its duration. If air becomes trapped within a frost blister after a rupture-and-resealing sequence, more powerful subsequent ruptures may result. Frost blister growth ceases and final subsidence begins when daily mean temperature reaches 0ºC. Although many frost blisters disappear during the summer, those with a good insulating mat may last a few seasons.

B.14 With respect to the MGP design, the potential for these features to occur at positions along the pipeline where heave and settlement is occurring combined with the potential of up to 4.9m vertical uplift in a matter of a few days should be accounted for in terms of limiting strain levels.

Upheaval Buckling and Ratcheting Creep

B.15 The Mackenzie Gas Pipeline (MGP) proposes to run from the Mackenzie Valley south to the border with Alberta, passing through varied terrain and climatic conditions across its more than 1800kms of routing. Along this route, ambient temperatures will vary from as cold as approximately -26°C in the Winter north of Inuvik to as warm as +21°C in the Summer, a seasonal temperature change of 45°C, and with a similar degree of variation occurring along the entire pipeline. With these ambient temperatures occurring, the pipeline is being designed to operate at a stable temperature around the freezing point. Accordingly, the Mackenzie Valley Pipeline can be expected to experience some degree of thermal and pressure expansion once the pipeline begins operation. This expansion will occur both axially, as the pipeline attempts to increase in length, and radially, as the circumference increases. Over a pipe length of several hundred kilometres, many metres of axial expansion or extension can be expected occur. As the temperature and pressure are increased above ambient conditions and axial stress develops, the easiest direction for buckling to occur is vertically, with the pipe deflecting upwards, through the cover of soil in the direction of lowest restraint, an example of which can be seen in Figure 1.1.

B.16 Figure 4. A large overbend instability protruding free from the cover soil in Tashkent, Uzbekistan (Palmer and Williams 2003).



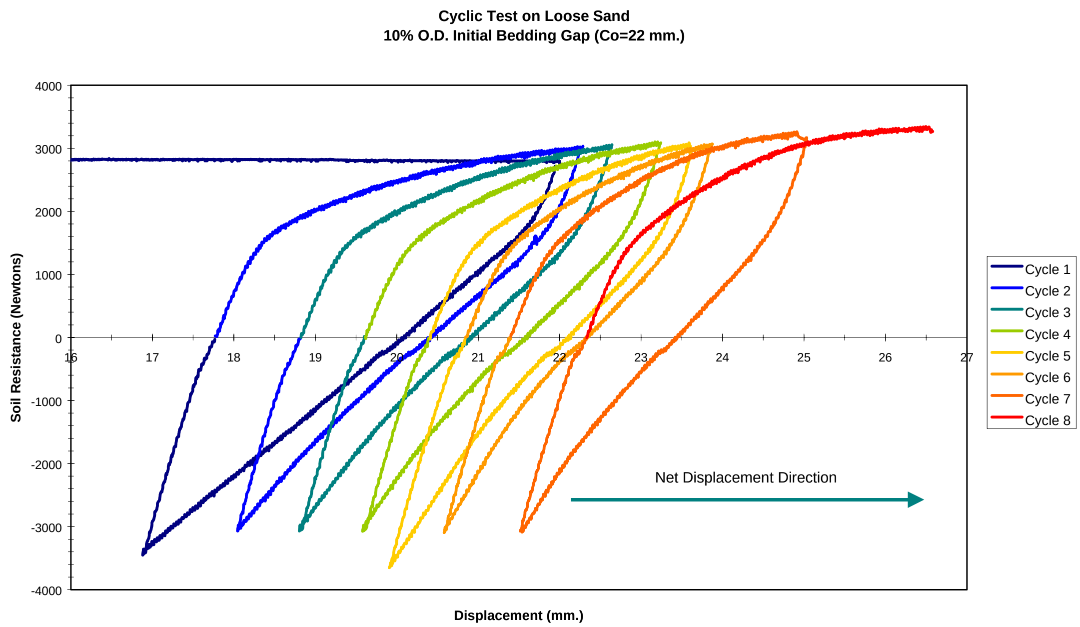
B.17 In recent years, some concern has been raised over the potential for buckles to form after repeated pipeline start-up and shut-down sequences. Several documented cases have occurred where a minimum depth of burial plus a factor of safety that should have sufficiently restrained the pipeline had been used, but with an upheaval buckle forming following such operational cycling. This has led to a variety of theories to explain why the restraint supplied by monotonic loading of cover soils may be greater than that produced during cyclic loading; such theories include particle migration, resulting in a decrease in the effective burial depth, and progressive soil yielding.

B.18 Pedersen & Jensen (1988) conducted an investigation into why buckling sometimes occurred in pipelines which had maintained temperatures below the recommended critical level, and did not appear to occur as a result of a single temperature/pressure event. They proposed that, during thermal and pressure loading of the pipeline, small displacements upward of the pipeline, known as ratcheting or non-ice related creep, could occur at locations with initial imperfections without achieving the predicted buckling conditions. During subsequent unloading of the pipeline, the uplifted vertical deflections would try to trace the same path back to the original imperfect configuration. Their principal idea regarding this ratcheting and creep theory was two-fold, 1) during the loading event, soil could creep or fall into the cavity below the uplifted pipe; and 2) a small residual compression in the pipe would arise at the site of the buckle because of axial friction effects inhibiting contraction of the pipe on cooling. Both of these effects would prevent a complete recovery to the original imperfect shape. On subsequent reloading, this cycle of soil migration and the build-up of residual compression would repeat itself until buckling initiated.

B.19 This theory was experimentally validated by Baumgard (2000) through numerous experiments both at full and reduced scales, and on various soil types, ranging from fine silts and sands to coarser media, and under both loose and dense conditions. An illustration of this migration can be seen in Figure 5. The results from this experimental research confirmed that a pipeline subjected to relatively small cycling loads could progressively work its way out from its initial burial conditions.

B.20 This change in the effective depth of burial over time poses several practical difficulties for the MGP designers. Firstly, as only a localised section of the pipeline migrates upwards as a result of this ratcheting, the net effect is to increase the imperfection required to initiate buckling of the otherwise straight pipeline. This increased imperfection height predisposes the pipeline to a vertical uplift at a lower temperature load than before, as formulated by Tvergaard and Needleman (1980). Secondly, the loss of overburden height as the pipeline begins each cycle slightly higher or with less soil cover than the previous cycle reduces the ultimate load required to initiate a buckle, as in effect there is less soil in terms of self-weight and frictional resistance to resist the buckle.

B.21 Figure 5. Creep in loose sand (Baumgard 2000).



B.22 For the MGP, the potential for ratcheting creep to occur is twofold, firstly in response to start-up and shut-down sequences forcing the pipeline to react to changes in terms of internal pressure and temperature, and secondly in response to the seasonal fluctuation in frost heave and thaw settlement (including general right-of-way thaw settlement), which will induce varying amounts of strain to the pipeline at different locations and at different times of the year. These two driving conditions can lead to the possibility that thawed ice-rich soils or conventionally loose sands and silts located along the pipeline route will migrate around the pipe during such cycles and initiate the ratcheting phenomena described above. To overcome this issue, the design should accommodate the need to ensure sufficient compaction of the backfill to minimise the movement of soils and to provide for a suitable monitoring frequency to accommodate an intervention before a buckling imperfection occurring in response to this mechanism can adversely affect the strain design of the pipeline.

Landslides

B.23 Landslides occur in soil or bedrock where factors promoting slope instability overcome the strength of a hillslope. Many factors contribute to instability, but the main controls are the characteristics of the soil or bedrock, the configuration of the slope, ground ice characteristics, and the groundwater and permafrost conditions. Aylsworth et al. (2000) have documented approximately 2000 landslides in the Mackenzie Valley between Inuvik and Fort Simpson.

B.24 Several phases occur during failure, including initiation, transport, and deposition. Landslides can be triggered by gradual processes such as weathering, thaw of permafrost, or by other mechanisms such as slope undercutting, rainfall, slope vibration, or the external loading of a slope.

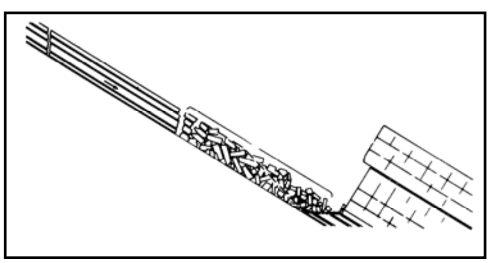
B.25 In relation to the MGP, landslides in their various configurations pose a direct threat whenever the pipeline traverses through the maximum extent of the failure or run-out path. This threat can occur as a physical impact to the pipeline, significantly denting or rupturing the line, or by deforming, bending or stretching the line when the pipeline is carried along as part of the failed or entrained materials.

Rock Slides and Rock Avalanches

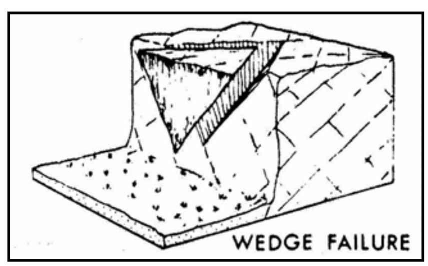
B.26 Rockslides involve the rapid translational movement of a rock mass along planar or wedge-shaped discontinuities in bedrock (Figure 6). Rockslides occur where the orientations of bedrock discontinuities intersect with the slope configuration to form detached blocks that can slide down or out of the slope.

B.27 Figure 6. Schematic sketches of (A) planar failure, (B) Wedge Failure

A.

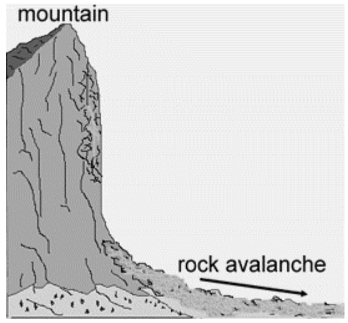


B.



B.28 Rock avalanches occur when a large rock mass breaks up following detachment and travels in an extremely rapid flow downslope (Figure 7). The flow characteristics of rock avalanches result in longer runout distances and larger destructive potential than rockfall or rockslides.

B.29 Figure 7. Schematic sketch of a rock avalanche.



Active-Layer Detachments

B.30 Active-layer detachments involve the downslope movement of only the active layer and vegetation mat. Movement may involve rotational or planar sliding of a relatively intact piece of ground on the underlying frozen sediment (sometimes known as active-layer glide), or flow of saturated sediment (also known as skin flow) (Mackay and Mathews 1973, McRoberts and Morgenstern 1974, Aylsworth et al. 2000) (Figure 8). Because active-layer detachments are difficult to detect on air photographs or they quickly evolve into retrogressive thaw flows, few are noted on the landslide distribution map prepared by Aylsworth et al. (2000). However, Dyke (2000) notes that they are probably one of the most common landslide types in the Mackenzie Valley.

Figure 8. Examples of active layer detachment in the Mackenzie Valley.

B.31 Figure 8A. Unnamed Creek near KP 657 of MGP.

B.32 Figure 8B. Landslide debris obstructing Unnamed Creek near KP 657 of MGP.

B.33 One of the characteristics of active-layer detachments is that they may occur on low slope angles. Many failures occur on slopes of less than 15º and failures on slopes as low as 3º have been recorded (Dyke 2000). These low failure angles are the result of excess pore water pressure from thawing ground ice (McRoberts and Morgenstern 1974). During the summer thaw, melting ground ice introduces water into the active layer. If water is produced quicker than it can escape to the surface, then the pore water begins to support the weight of the overlying thawed sediment and the water pressure rises. When ice is present in excess of the sediment pore volume, a rapid thawing rate can result in the pore water carrying the entire soil weight with an associated total loss of friction strength. Morgenstern and Nixon (1971) have described this process as thaw consolidation. If there is little or no cohesive strength, then the high pore water pressures can trigger slope failures.

B.34 Slope failures are most likely when high water pressures develop at the base of the active layer. During freeze-back, the active layer generally becomes ice-rich near the top as moisture from deeper levels is drawn to the advancing freezing plane. The next summer water can move from the thawing active layer into the subjacent frozen active layer and even into the top of permafrost, producing an ice-rich layer at depth (Mackay 1983). An above-normal warm summer may then penetrate to the depth of this ice-rich layer, creating favourable conditions for slope failures. Ice-rich layers can also form at depth where the permafrost is cold enough to allow two-sided freezing (Mackay 1983).

In this instance, water in the active layer is drawn both to the cooling ground surface and to the permafrost layer during freeze-up (ice segregation).

B.35 The potential for ice-rich layers to develop is dependent on the ice content of the glacial sediments that dominate the surficial materials of the Mackenzie Valley. Silts and clays tend to have the highest ice contents, with ice volumes in excess of 50% in some cases (Dyke et al. 1996). Thick ice layers are also associated with some sands. Glaciolacustrine sediments and fine-grained tills are most likely to be ice-rich, while fluvial sands and gravels are least likely to contain ice in excess of the pore volume (Dyke et al. 1996). Peats also have high ice contents but these deposits form on gentle terrain that is generally not susceptible to slope failures.

B.36 The above discussion indicates that conditions favourable for active-layer detachments are rapid and deep thaw, which increase the weight of material available to overcome cohesion and friction (Dyke 2000). In the Mackenzie Valley, however, the organic mat and overlying vegetation are effective insulators that generally resist significant permafrost degradation (Lewkowicz and Harris 2005). Furthermore, slopes are typically stable at the normal active layer thickness (Lewkowicz and Harris in press), however, pipeline trenching and backfilling operations can cause extensive disturbance to this insulation, leading to the triggering conditions promoting this form of detachments. Rapid thaw following forest fires can also trigger widespread active layer detachment slides.

Retrogressive Thaw Flows

B.37 Also known as retrogressive thaw slumps, bimodal flows, or ground ice slumps, retrogressive thaw flows occur in ice-rich areas where massive ice bodies become exposed, such as the banks of lakes and rivers. They typically have a bimodal profile with a steep headwall and a low angle tongue (Figure 9). The headwall gradually erodes upslope as massive ground ice or icy sediment thaws in the scarp, and the resulting saturated sediment flows downslope away from the scarp (Aylsworth et al. 2000). When sufficient material has accumulated to cover the once exposed ice, the retreat stops (or slows greatly) and the slump is said to be stabilized. A very warm summer or other disturbance such as the removal of the debris at the bottom of the slope can reactivate the slump.

B.38 Retrogressive thaw flows may be initiated by any process or event that results in the exposure of massive ice or icy sediment, including detachment failures, forest fires, river erosion, cat trails, etc. Active-layer detachments commonly develop into retrogressive thaw flows due to the exposure of massive ice or icy sediments at depth (Aylsworth and Duk-Rodkin 1996; Figure 9).

B.39 Figure 9. Retrogressive thaw flow near Little Chicago (approximately KP 226 of MGP)

Deep- Seated Instability

B.40 It is well known that glaciers exhibit steady-state creep properties, which under certain loading/temperature conditions can limit to creep rupture in the form of ice falls and surging behaviour. Savigny and Morgenstern (1986) measured similar steady-state in situ creep deformations in fine-grained ice-rich soils underlaying the south approach slope to Great Bear River near the proposed MGP crossing (KP 556). These soil and permafrost conditions exist at many other approach slopes along the proposed right-of-way. Curvilinear lineaments crossing the proposed MGP right-of-way immediately south of Grat Bear River valley may be the surface expression of this deep-seated creep deformation. Large landslides encroaching on the proposed MGP right-of-way near Old Fort Point (e.g. KP 602, 630 and 643) or crossing the proposed right-of-way at KP 669 may be expressions of steady-state creep that has limited to accelerated visco plastic deformation and/or creep rupture. Warming of in situ permafrost in response to forest fires and climate change may accelerate steady-state creep rates and enhance the likelihood of creep rupture.

Permafrost and Forest Fires

B.41 In the discontinuous permafrost zone, four variables control the presence of perennially frozen ground:

- the depth of snow cover;
- the thickness of the organic horizon;
- soil moisture content; and

- the nature of the vegetation canopy (e.g. spruce forests are most effective at intercepting snowfall and reducing the depth of snow on the ground, thus favouring colder ground temperatures) (Dyke et al. 1996).

B.42 These variables control the absence or presence of permafrost more than fluctuations in the climatic regime (Smith and Riseborough 1983; Williams and Burn 1996). Not surprisingly, the most widespread changes in surface conditions that cause permafrost degradation in forested areas are wild fires. This does not result from the heat of the fire, but by:

- removal of some or all of the insulating organic layer;
- change in surface albedo; and
- removal of the shading effects of the tree and shrub canopy (Viereck 1982).

B.43 The partial or complete destruction of the vegetation allows an increased transmission of heat into the ground, resulting in deepening of the active layer and thawing of the near-surface permafrost. The most pronounced permafrost degradation occurs after intense fires that destroy the surface organic layer (Burn 1998).

Active-Layer Thickness and Forest Fires

B.44 A number of researchers have investigated the impact of forest fires on active layer thickness, including Viereck (1982), who investigated thaw depths and soil temperatures following a forest fire of moderate severity near Fairbanks, Alaska; Zoltai (1993), who investigated peat stratigraphy in a discontinuous permafrost zone in northwest Alberta and noted periodic permafrost degradation triggered by fires; Mackay (1995), who investigated over 350 km2 of forest and tundra east of Inuvik, NWT; Swanson (1996), who noted that forest fires in permafrost regions do not necessarily result in an increase in the active layer or wetter soils; and Burn (1998), who describes permafrost degradation following an intense forest fire in July 1958 about 50 km west of Whitehorse, Yukon Territory. 38 years after the fire, the active layer at the burned site was 3.8 m, a difference of 2.4 m.

B.45 A synthesis of the above studies illustrates the following points:

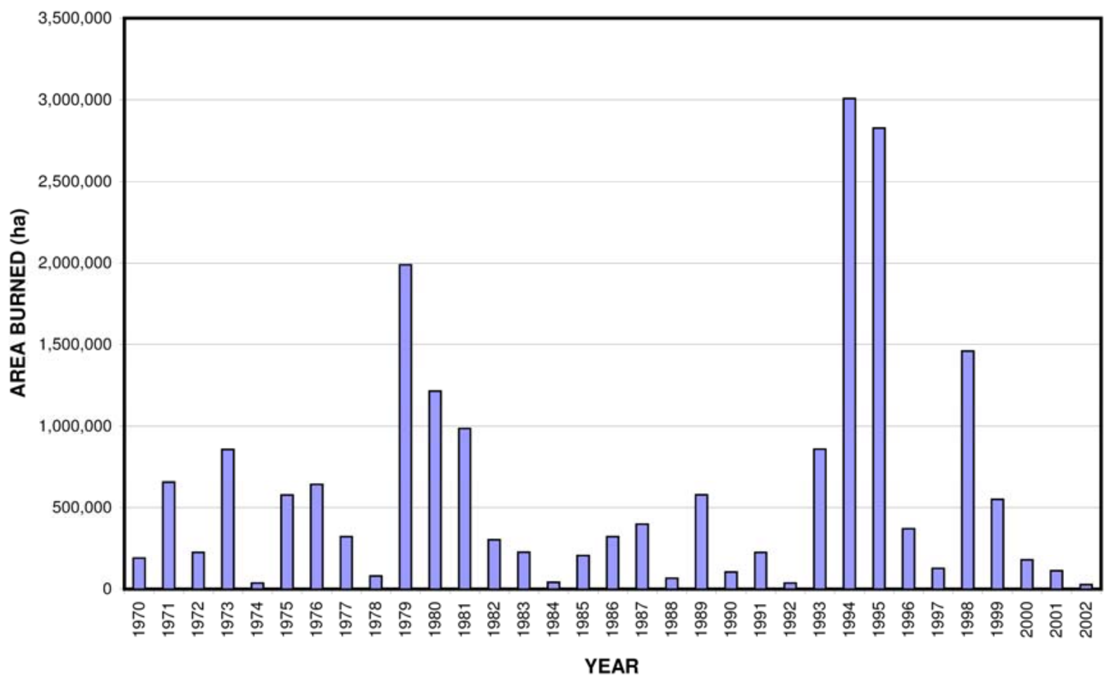
- permafrost degradation is strongly correlated with the intensity of the forest fire and the burning of the surface organic layer;
- the length of time for thaw depth to return to pre-disturbance levels is variable and is dependant on vegetation regeneration and succession;
- flatter sites tend to re-establish vegetation more quickly due to the addition of thaw water at the bottom of the active layer that produces moist conditions; and
- permafrost degradation and aggradation is probably a cyclic process that is linked to fire cycles.

B.46 These studies have demonstrated the importance of forest fires in the initiation of significant permafrost degradation. However, thaw depth alone is not an indicator of potential slope instability. Active thaw depth combined with ice content, sediment texture, and slope angle will determine the likelihood of an active-layer failure (Dyke et al., 1996). Ice fabric is also an important factor. Ice characterized by visible lenses is most likely to eliminate friction because melting ice lenses are probably replaced by temporary lenses of water having no shear strength (Dyke 2000).

B.47 The importance of fire as an initiator of slope failures in the Mackenzie Valley has been recognized for at least the past thirty years. Mackay and Mathews (1973) describe active-layer detachments that followed wide-spread forest fires that burnt thousands of square kilometres north of Tulita (formerly Fort Norman) in 1968 and to a lesser extent in 1969. The fire of mid-August 1968 resulted in some failures by the end of the summer, and ongoing slumping in the next three summers.

B.48 The most significant fire seasons of the past 35 years occurred in 1994 and 1995 when about 55,000 km2 of forest was burned by wildfires in the NWT (Figure 1). Along the Mackenzie River, a number of landslides were initiated by these fires as discussed by Savigny et al. (1995), Aylsworth and Duk-Rodkin (1996), Hanna et al. (1998) and Lewkowicz and Harris (2005). These fires attracted considerable attention as they impacted the Norman Wells pipeline. The 1994 fires affected the area south of Tulita between KP-600 and KP-690, while the 1995 fires affected the immediate area of Tulita (KP-520 to KP-570).

Figure 1. NWT Forest Fire Statistics (1970 - 2002).



Potential Impacts to the MGP

B.49 Fire-induced landslide activity can potentially impact the proposed pipeline both directly and indirectly.

Direct Impact

B.50 A direct impact is the potential for an active-layer detachment to cross the pipeline right-of-way (e.g. Figure 10). If the detachment is relatively intact and crosses the pipeline on gentle slopes, the failure will be depositional, minimizing impacts to the pipeline. However, active-layer detachments can occur on slopes as low as 10 to 15º, gradients on which the pipeline route may cross at times.

B.51 Figure 10. An example of forest fire induced landslides crossing the proposed right-of-way near KP 187.

B.52 Detachment failures may also develop into debris flows on steeper slopes if large amounts of meltwater are produced by the thawing of exposed ground ice. Debris flows have considerable erosion potential, although research is needed to establish the slope where substantial erosion ends (Hungr et al. 2005). Debris flows typically become depositional on slopes less than 10º, but high clay or water content can result in runout zones of only a few degrees. Debris flows that cross the proposed pipeline have the potential to erode to or beyond burial depth and cause significant damage. This is particularly true for smaller tributaries where little or no scour is anticipated under normal hydrologic conditions, and where the subsurface consists of fine-grained, non-cohesive and unconsolidated sediments.

Indirect Impact

B.53 Indirect impacts to the pipeline are related to smaller stream crossings and the introduction of large sediment volumes to upstream reaches.

B.54 Most of the research into rivers along the Mackenzie Valley has concentrated on the Mackenzie itself or its major tributaries (e.g. Brooks 2000a, Church 1971, Church et al. 1986, Egginton and Day 1976). Further de Boer et al. (2005) observed that few studies have addressed the sediment dynamics of northern Canadian rivers. As a generalization, streams on the east side of the Mackenzie River drain relatively low relief and exhibit a spring-snowmelt dominated flow pattern classified as subarctic, nival flow regime (Church 1977).

These east tributaries generally have a less responsive discharge regime because of the presence of lakes and extensive bogs (which attenuate runoff). Also the more subdued plain and lowland topography east of Mackenzie River does not produce widespread intense rainfall (Brooks 2000b).

B.55 Church (1971) observed that many of the small gravel-bed rivers (< 100 km2) found along the front of the Franklin Mountains south of Norman Wells appeared to be relatively inactive with respect to sediment transport. He also noted that scour along these river beds is probably fairly minimal under natural conditions with bank stability enhanced by dense vegetation.

B.56 Given these conditions, many of the smaller tributaries crossed by the proposed pipeline probably appear to be benign with respect to scour potential or lateral instability. However, fire-induced slope failures have the potential to introduce significant volumes of sediment into the smaller tributaries. The introduction of large sediment volumes into a river usually results in an increase in the width/depth ratio, as the river widens to accommodate the excess bedload. Where the river is confined the primary response would be vertical aggradation, but in unconfined reaches increased bank erosion would result.

B.57 Bank erosion could also be enhanced in areas where a frozen annulus has formed around the pipeline. As gas is transported between compressor stations, it is transformed from a relatively warm state to a very cold state that is typically around -6ºC. Where the cold gas crosses wet areas, such as stream crossings, a frozen annulus 1 to 2 m in diameter can develop around the pipe. This annulus has the potential to enhance lateral instability of the channel if significant pulses of sediment have been transported to the crossing.

B.58 The proposed pipeline crosses hundreds of smaller tributaries and increased lateral instability has the potential to cause significant damage. This is particularly true as many of the smaller crossings have been proposed as shallow cut-and-fill operations that do not account for lateral instability. However, the potential impact to stream crossings is more complex than as described. For example:

- landslide activity upslope of a crossing may introduce large quantities of sediment into a small stream, but a large percentage of the introduced sediment could end up in storage without being transported a significant distance downstream (for example if the stream is poorly confined at the deposition area);
- the introduced sediment may take a period of years to transfer downstream with the rate of downstream sediment transport dependent on flood hydrology;
- the extent of bank erosion is also dependent on vegetation, permafrost distribution, and soil type, cohesion and consolidation; and

- a significant portion of the landslide material may be fine-grained material. Fine-grained material is generally transported as wash load and has little to no impact on channel morphology.

Outstanding Issues along the MGP Route

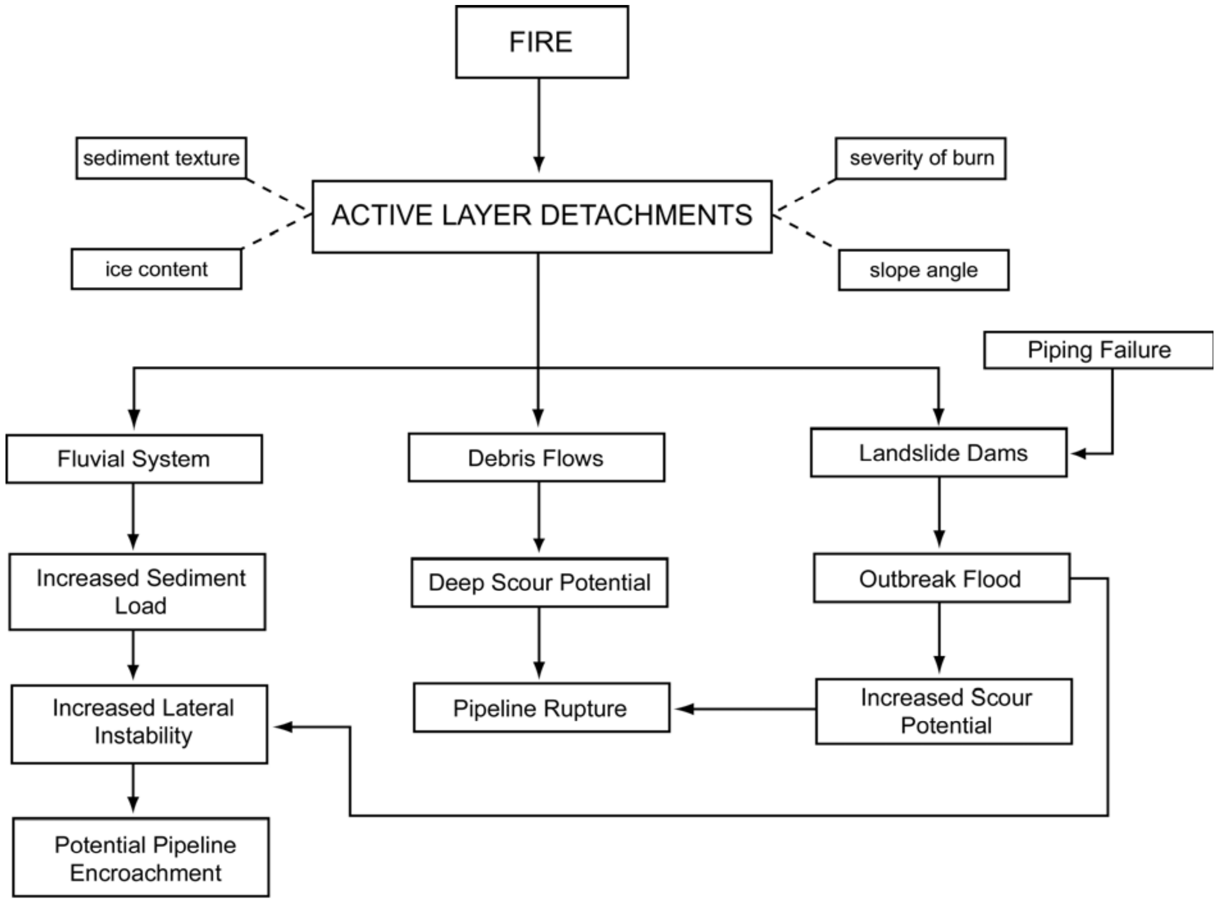
B.59 Based on the above discussion, there are a number of measures that should be taken to anticipate and evaluate potential hazards and risks posed by fire-induced detachment failures, as indicated below:

B.60 To successfully anticipate these hazards, an evaluation of what areas along the proposed pipeline route have burned in the past forty years, and what areas have the potential to be impacted by forest fire over the next several decades should be conducted. This evaluation should include what stage of permafrost recovery these sites are in for those that have experienced forest fires, and areas currently suffering spruce beetle infestations with and an evaluation of how these infestations change fire frequency and severity.

B.61 For those sites where the proposed pipeline route is determined to have the potential to be impacted by forest fire over the next several decades, a further evaluation should be conducted to include what terrain types exist in the vicinity of the pipeline route, whether the slopes are steep enough for active-layer detachments to initiate and directly impact the pipeline or into a tributary that is crossed by the pipeline, and if excessive sedimentation of tributaries lead to significant channel changes or avulsion potential.

Figure 11 illustrates an example of a flow chart that summarizes the potential impacts of fire-induced slope failures in permafrost terrain on pipeline crossings.

B.62 Figure 11. Potential Impacts of Fire-Induced Detachment Failures.



Ground Displacement and Seismicity

B.63 It is widely recognised that the Northwest Territories are situated in a seismically active region, less so than perhaps Alaska or the Yukon, but still subject to many historically significant earthquakes. For example, the Nahanni 1985 earthquakes (M6.9 and M6.7) produced high accelerations and led to rock falls and rock avalanches in the Mackenzie Mountains (Figures 12A and 12B) and a liquefaction failure at Little Doctor Lake, a location within 80 kilometres of the pipeline right-of-way (Figure 12C). The significance of these earthquakes and the high likelihood of the occurrence of further significant earthquakes necessitates that their direct and indirect effects be accounted for in the design of the Mackenzie Valley Pipeline and its associated structures and facilities.

B.64 Figure 12A. Large rock falls in the North Nahanni River valley caused by the 1985 North Nahanni earthquakes.

B.65 Figure 12B. The English Chief rock avalanche caused by the 1985 North Nahanni earthquakes.

B.66 Figure 12C. The Little Doctor Lake landslide, believed to be a coseismic liquefaction failure of till-like colluvium caused by the 1985 North Nahanni earthquakes.

Direct Effects

B.67 The direct effects of such seismic activity can influence pipe stress modeling in which forces are applied to the theoretical pipe, the deformed shape is assessed, and a critical strain threshold developed. The inclusion of a seismic load can affect the results from this modeling, with the potential of reducing the maximum allowable operating strain. While it is imperative that seismic forces be accounted for in the pipe-strain analyses, these assessments should not be limited to the evaluation of single event, but should allow for the combined effects of multiple events, as occurred for the two large earthquakes making up what is referred to as the Nahanni Earthquake. This multiple earthquake assessment would represent a scenario where the strain criteria would be exceeded during the first event and whereby insufficient time for mitigation or an occurrence during an inaccessible season prevents mitigation between events.

Secondary Effects

B.68 Accounting for secondary effects is equally important to assessing the direct impact of an earthquake on the pipeline. Seismicity has the potential to initiate several ground displacement phenomena, including rockfalls, debris slides, rock avalanches, liquefaction and seismically induced slope failures, many of which have historically occurred in the vicinity of the MGP proposed route.

Rockfalls, Rock Avalanches and Debris Slides

B.69 Rockfalls, rock avalanches and debris slides triggered by earthquakes have been documented within the Mackenzie Valley within the last 25 years (e.g. Savigny et al. 1992, Figure 12C). These failures typically form in oversteepened ground where weathered, wedged or jointed bedrock is exposed, as described in the previous section on slope stability. Seismicity plays a role in further fracturing this rock, or through the induced acceleration, providing sufficient momentum to overcome the static stability to trigger the fall, avalanche or flow. Depending upon the proximity of the MGP to such steep bedrock exposures, impact from this form of failure has the potential to directly rupture or damage the pipeline.

Liquefaction and Dynamic Settlement

B.70 Seismically induced liquefaction occurs in loose fine sediments where re-arrangement of soil particles leads to a collapse of the soil structure and an elevation in pore pressure. This elevation in pore pressure results in a reduction or total elimination of shear strength in the soil. With this reduction in shear strength, the ability of the soil to resist pipe movement is diminished and the strain in the pipe accordingly permitted to increase. While extremely fine grained sediments such as clays have been shown to be somewhat resistant to liquefaction, saturated silts and sand have been found to be very susceptible, and are present along the route of the MGP. As part of the MGP proposal, soil resistance is proposed to act as one of the principal strain controls for the limit-states design. In areas where liquefaction and the resulting loss of soil resistance can be expected to occur, this principal strain control may prove insufficient, and alternative design features may be required.

B.71 In addition to the issues associated with liquefaction, when loose soils are disturbed, the particle re-organisation described in the previous paragraph typically leads to settlement. Depending upon the pipeline burial conditions, this settlement can place a considerable skin friction loading, occurring as downdrag, on pipeline. Along the pipeline route, areas which may be susceptible to thaw settlement, and for which a pipeline has been designed to accommodate that level of settlement, may endure additional forces and resulting strains above this initial estimate should such downdrag occur. This downdrag effect can be extremely significant when associated with long directional drill crossings and high valley slopes, where the installed pipe rests within comparably loose soil within the borehole annulus. In these directionally drilled situations, the installed pipeline is typically in tension at the top of the slope and in compression at the bottom resulting from its self-weight attempting pulling itself down the slope. If downdrag occurs, this additional compression force may lead to unacceptable strain and buckling or wrinkling at the base of the slope.

B.72 Material that has thawed as a result of the advancing thaw bulb may be particularly susceptible to liquefaction and settlement despite their prior resistance when previously frozen. Ice-rich materials that would otherwise be too dense or with insufficient saturation may thaw leaving a loose and saturated soil skeleton. This loose skeleton may be potentially prone to collapse under even minor disturbance.

Seismic Slope Instability

B.73 The loading effects resulting from slope stability failures has already been addressed as part of this document in prior sections, however, the impact of additional seismic loading to influence slope stability should not be neglected. Around the world, there are countless cases where slopes that have remained stable for thousands of years have been activated by even relatively small seismic events. In the Mackenzie Valley, this seismic activation of otherwise stable slopes has been observed following the Nahanni earthquake. Earthquake magnitude and duration both play critical roles in affecting the stability of slopes, the former governing the acceleration and thereby momentum the slope's mass is subject to, and the latter controlling the residual condition of the soil or rock as a result of the seismic event.

B.74 With the proximity of the MGP route to known seismic epicentres, it is highly likely that slopes exist which would be characterised as typically stable under static conditions, but will sufficiently lose strength during a seismic event failing either during or shortly after the event occurs. This failure may be of the conventional type, occurring as a landslide, rock avalanche, debris slide or flow, or may occur as a non-conventional type, such as a liquefaction induced lateral spread or flow failure, features that have been shown to frequently occur in slopes as flat as 3º and rarely in slopes as flat as 1º (Ziony, 1985).

B.75 As is the case for the liquefaction susceptibility of ice-rich permafrost soils, in areas where these soils are thawing, the loose saturated nature of this material has the potential to de-stabilise slopes during seismic events. This de-stabilisation can occur through several routes including the increased weight of the soil acting on the slope as it becomes saturated, or by the looser nature of these materials permitting liquefaction and flow-failure to occur (e.g. Figure 12C).

Ground Displacement Conclusions

B.76 Initiation of any of the forms of ground displacement described above has the potential to apply considerable loads onto the pipe through dragging and/or physical impact from the ground onto the pipe. For pipes that are buried, liquefaction, slope failures and high energy rock avalanches have the potential to drag or pull the pipeline out from its original alignment, increasing the level of strain in the pipe and potentially initiating buckling or tensile failure. For pipes remaining on the ground surface, the significance of the aforementioned effects is diminished as the soil is readily able to move beneath the pipe relatively unimpeded, however the protection supplied by burial emphasises their exposure to impact damage. The significance of these secondary effects needs to be assessed and incorporated into the design of any pipeline and structure located in susceptible areas. This assessment is especially important for areas where ice-rich permafrost is or will be thawing as a result of global warming or as a result of the operation of the MGP. In these cases the ground may initially act as stable material, but once the thaw progresses, the saturated and loose soil may behave adversely affect this initial stability, triggering or exacerbating ground movements, and increasing the strain on the pipeline. While the MGP submission has indicated that direct impact on the pipeline from has been assessed and that some of the secondary effects have been addressed or will be once the geotechnical investigation program is completed, it is important ensure that addressing each of these secondary effects individually is completed, as is the potential for the interaction of several effects or multiple seismic events to occur in short succession.

B.77 Recommendations

1. There exists the potential for the interaction of several loading effects or multiple events to occur in short succession, and which could have a significant effect on to the strain-based design. The potential of multiple effects should be evaluated in light of the details provided from the completed geotechnical investigations, including the effects of an increase in the number and distribution of unfrozen spans, or a change in the predictions relating to frost heave and/or thaw settlement. The Proponent

should be required to satisfy the Board that its final design is capable of accommodating multiple loading effects.

2. The Proponent should satisfy the Board that the design will account for the potential for increased strains due to frost blisters at locations along the pipeline where heave and settlement are also occurring.

3. Slope stability failures can occur as a physical impact to the pipeline, significantly denting or rupturing the line, or by deforming, bending or stretching the line when the pipeline is carried along as part of the failed or entrained materials. The Proponent should identify potential slope stability failure sites and demonstrate that the maximum extent of the failure or run-out path for all forms of slope stability failures are incorporated into the project design.

4. Forest fires have the potential to remove the insulating cover which will induce terrain degradation, permafrost thawing, slope instability and increased sedimentation to water bodies. The Proponent should identify which areas have been previously impacted or have the potential to be impacted by forest fire over the expected life of the project and demonstrate that appropriate mitigation measures have been included in the project design.

5. The occurrence of earthquakes could impose significant environmental loads and subsequent strain on the pipeline. Therefore, the Proponent should satisfy the Board that the direct and indirect effects of earthquakes are accounted for in the pipeline design and appropriate mitigation measures.

Conclusions

B.78 The preceding discussion highlights several issues relating to the loading conditions that a pipeline operating in the Mackenzie Valley may encounter. Many of these issues will directly impact the pipeline, and require that site specific geotechnical information is required before a detailed, or even in some cases a reasonable assessment can be conducted. Other issues described occur as secondary effects, where one particular event triggers a situation that can then in turn impact the pipeline. For these situations, the likelihood of the triggering event and the possibility of breaking the link between the triggering and subsequent events should be assessed.

B.79 These issues discussed as part of this report have been presented as individual scenarios, but it must be emphasised that many of these issues can, and often will, occur in combinations and at multiple locations simultaneously. Hence, an evaluation of the possible combinations of issues that can occur should be undertaken as part of comprehensive design process, and in situations where mitigation or intervention will be required as part of the MGP design, the reasonable expectation that mitigation or intervention can be supplied at one or multiple locations simultaneously should these issues occur.

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