Ditch Settlement and Imported Fill Methodology Report

WP52D116-002

Work Package: 52

Imperial Oil Resources Ventures Limited
Conceptual and Preliminary Engineering for Mackenzie Gas Project

Job No. 99-C-3079

Prepared by:

Imperial Oil Use Only

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<td>Moness Mazzella</td>
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EXECUTIVE SUMMARY

The Mackenzie Gas Project (the project) is proposing to construct:

- 189 km of NPS 16, NPS 18, NPS 26 and NPS 32 gathering pipelines north of the Inuvik area facility
- a 1,194 km NPS 30 gas pipeline from the Inuvik area facility to a tie-in point in northern Alberta
- a 457 km natural gas liquids (NGL) NPS 10 pipeline to transport liquids from the Inuvik area facility to Norman Wells, where it will tie into the existing Enbridge Norman Wells oil pipeline

From north to south, the pipelines will traverse continuous, discontinuous and sporadic permafrost. Therefore, settlement associated with permafrost thawing is expected along the pipeline.

This report presents the method used to estimate the:

- settlement of the native backfill material over the pipeline, i.e., the ditch settlement
- volume of imported fill that might be required to offset the settlement. This volume was used as the basis for the preliminary designs and corresponding cost estimates.

Estimates of ditch settlement, and the imported fill quantities required to offset it, are based on:

- route soil information obtained from borehole and test pit data
- terrain mapping from interpreting air photographs

Subsurface soil information from boreholes and test pits was initially used to estimate ditch settlement fill, imported fill or both, at specific locations. These discrete estimates were then grouped and applied to the entire route, using terrain mapping information along the pipeline right-of-way.

The following were developed as part of this study:

- a computer program that estimates settlement associated with thaw on the right-of-way and local settlement over the ditch line. The program computes settlement on a layer-by-layer basis for each borehole within the engineering borehole database.

- a numerical model that estimates the amount of imported fill required to either completely or partially offset local ditch settlement. Imported fill is estimated on the basis of the average soil strain predicted from each borehole’s data. Two reclamation scenarios were considered:
  1. Leaving some fill on the trench shoulders after thaw.
  2. Transferring any stranded fill left on the trench shoulders after the roach has thawed to the ditch line.

The following activities will be considered in detailed engineering:
• Update the standard moisture content look-up tables and, where practical, fill in some of the existing data gaps using engineering judgement.

• Reassess, where practical, the assumptions related to strain development in organic materials that result from mechanical disturbance, with the objective of correlating these strains to actual northern field data.

• Refine the use of mean settlement and imported fill values to calculate imported fill demands.

• Re-evaluate the current zero allowable settlement criterion to reflect the Norman Wells pipeline experience.

• Revisit the approach for the current stranded fill reclamation model, where no re-grading of the roach or backfill conditioning is proposed following initial construction, i.e., adopt the model that transfers stranded fill to the ditch line.

• Upgrade the settlement estimates using data from additional boreholes to be either drilled, or other data sources pursued, in data gap areas in the extreme northern and southern portions of the project.

• Continue quality control of the engineering borehole database to identify and correct variations, especially with boreholes that are causing unrealistically high or low settlement estimates.

• Determine, during detailed design, the optimum time frame (construction, post-construction or both) for placing imported fill.
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1.0 INTRODUCTION

The Mackenzie Gas Project (the project) proponents plan to construct:

- 189 km of NPS 16, NPS 18, NPS 26 and NPS 32 gathering pipelines north of the Inuvik area facility
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From north to south, the pipelines traverse continuous, discontinuous and sporadic permafrost zones. Therefore, settlement associated with permafrost thawing is expected in these areas along the pipeline.

This report presents the method used to estimate the:

- settlement of the native backfill material over the pipeline, i.e., the ditch settlement
- volume of imported fill that might be required to offset the settlement. This volume was used as the basis for the preliminary designs and corresponding cost estimates.
2.0 ROUTE DATA

2.1 Overview

Estimates of the ditch settlement and imported fill quantities required to offset the settlement are based on existing route soil and terrain information. Subsurface soil information from boreholes and test pits in the general area of the pipeline route was used for an initial estimate of the ditch settlement and imported fill quantities required at a specific location. These discrete estimations were then grouped and applied to the entire route using regional terrain information along the pipeline right-of-way.

This section describes the route information used for the ditch settlement and imported fill analysis.

2.2 Engineering Borehole Database

2.2.1 Background

The project’s engineering borehole database is a compilation of subsurface soil and permafrost information that was developed using:

- historical borehole and test pit data
- previous pipeline investigation projects (from the early 1970s)
- the Mackenzie Valley Highway project data
- recent information collected specifically for the project

Of the 14,200 boreholes and test pits in the database, most were obtained directly from the Mackenzie Valley Borehole Database, compiled by the Geological Survey of Canada (GSC) (Burgess et al. 2002). However, as the format and completeness of that database was insufficient to use directly for engineering, it had to be enhanced and modified. As the GSC database had undergone several conversions since its derivation in the mid-1970s, some quality issues exist with the engineering borehole database that are considered when it is used for project design.

2.2.2 Data Sources

The current version of the engineering borehole database available for preliminary engineering contains 19 datasets (see Table 2-1).
### Table 2-1 Source Datasets in Engineering Borehole Database

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### 2.2.3 Database Structure

The engineering borehole database is a relational database consisting of the following four main tables:

- **Header** – information that pertains to the borehole as a whole and contains its identifier, location details, contractor name, drill method, drill type and vegetative cover.

- **Soil Layer** – contains qualitative descriptions of the different soil layers, contiguous with depth.

- **Samples** – contains information on the type and depth of each sample, and the results of all pertinent index testing.

- **Thermal** – contains information on the thermal state and description of ice, if any, contiguous with depth.
The three tables that contain subsurface information are independent of each other, which is one of the strengths of this database compared with earlier interpreted versions, such as the Beaufort Delta Oil project database. However, before this information can be used for thaw settlement and other end-uses, the tables must be merged to form a single interpreted stratigraphic model with unique soil and thermal properties for each layer. This combined-layer borehole model or sublayer model has been stored as an intermediate Microsoft (MS) Access database.

The sublayer database is generated from the three subsurface tables by subdividing the complete soil profile into unique discrete layers that represent the smallest units with the same set of soil type, thermal and index properties (see Figure 2-1).

During the process of generating the sublayer database, if a borehole lacks key information from either the soil or thermal tables, it is rejected. In the current Revision E of the engineering borehole database, about 8,560 boreholes met the minimum requirements for sublayer generation and were suitable to be included for ditch settlement analysis. However, the actual number of boreholes used in any given analysis, is further reduced at run time, depending on the completeness of the information over the depth interval being considered.

### 2.3 Route Look-up Tables

In addition to the sublayer database, additional information is required for each borehole before the information can be used to estimate ditch settlement and imported fill quantities along the pipeline route. The most important of these route look-up tables are:

- physiographic regions
- pipeline kilometre post (KP)
- terrain group

The information is stored in tables within a Microsoft Access database and is accessed at run time by the Settlement Calculator described in Section 5.0.

### 2.4 Terrain Grouping

Ditch settlement and imported fill quantities are initially estimated on a borehole-by-borehole basis using individual borehole stratigraphy and index properties. However, because boreholes are not consistently distributed and non-continuously spaced, no subsurface information exists for some locations along the pipeline route. To address the limitation of using individual boreholes only, the borehole settlement estimates are grouped by terrain and physiographic region. The mean and standard deviation estimates of settlement are then considered to be typical of conditions within that terrain group at that general location. This approach does not account for potential variability in ditch settlement within specific terrain occurrences. However, the approach provides a statistically representative estimate of ditch settlement within terrain groups and accounts for regional changes in ground conditions.

Borehole settlement values are generally better considered together in broad terrain groups or classes, rather than individual terrain types. This is done partly because grouping boreholes:
• removes some of the difficulties associated with relating the detailed Mackenzie Gas Project terrain types to terrain groupings from previous projects

• allows broader application and inclusion of smaller terrain types that lack specific borehole information

**FIGURE 2-1 SCHEMATIC OF SLABAYER MODEL**

Terrain groups associated with boreholes in the engineering borehole database were derived by examining the actual soil layers and using generic terrain mapping from various historical sources.

Table 2-2 summarizes the breakdown of terrain group lengths, along the pipelines, encountered within the project’s 10 physiographic regions (based on Revision 4 of the pipeline alignment).
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<td></td>
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<td></td>
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</tr>
<tr>
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<td>ObA</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>0.1%</td>
</tr>
<tr>
<td>Organic blanket over Glaciofluvial</td>
<td>ObG</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
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<td>ObGM</td>
<td>0.1%</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
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<td>ObGR</td>
<td>0.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
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<td>2.8%</td>
<td></td>
<td>1.9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>1.7%</td>
</tr>
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<td>ObM</td>
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</tr>
<tr>
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<td>Op</td>
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<td>1.2%</td>
<td>12.2%</td>
<td>0.1%</td>
<td></td>
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<td>4.7%</td>
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<tr>
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<td>0.2%</td>
<td>0.3%</td>
<td>0.4%</td>
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<td></td>
<td></td>
<td></td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
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<td></td>
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<td></td>
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<td>1.4%</td>
<td>0.5%</td>
</tr>
<tr>
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<td>0.9%</td>
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<td>0.0%</td>
<td>0.7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.3%</td>
<td></td>
</tr>
<tr>
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<td>OvAR</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1%</td>
</tr>
<tr>
<td>Organic veneer over Eolian over Moraine</td>
<td>OvEM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>0.1%</td>
</tr>
<tr>
<td>Organic veneer over Glaciofluvial</td>
<td>OvG</td>
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<td>0.1%</td>
<td>0.1%</td>
<td>0.3%</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>0.6%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Organic veneer over Glaciofluvial over Moraine</td>
<td>OvGM</td>
<td>0.3%</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1%</td>
</tr>
<tr>
<td>Organic veneer over Glaciofluvial over Bedrock</td>
<td>OvGR</td>
<td>0.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0%</td>
</tr>
<tr>
<td>Organic veneer over Lacustrine</td>
<td>OvL</td>
<td>2.1%</td>
<td>1.8%</td>
<td></td>
<td>1.8%</td>
<td>0.3%</td>
<td>4.5%</td>
<td></td>
<td></td>
<td></td>
<td>8.3%</td>
<td>3.5%</td>
</tr>
<tr>
<td>Organic veneer over Lacustrine over Moraine</td>
<td>OvLM</td>
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<td>3.9%</td>
<td></td>
<td>0.6%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.7%</td>
<td>1.1%</td>
</tr>
</tbody>
</table>
## Table: Terrain Group Distribution

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic veneer over Lacustrine over Bedrock</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>OvLR</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organic veneer over Moraine</td>
<td>OvM</td>
<td>24.8%</td>
<td>2.6%</td>
<td>8.1%</td>
<td>22.8%</td>
<td>0.1%</td>
<td></td>
<td></td>
<td></td>
<td>0.3%</td>
<td>7.4%</td>
<td></td>
</tr>
<tr>
<td>Organic veneer over Moraine over Bedrock</td>
<td>OvMR</td>
<td>0.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td>0.0%</td>
<td>0.1%</td>
<td>0.3%</td>
<td>0.1%</td>
<td>0.5%</td>
<td>0.1%</td>
<td>0.2%</td>
<td>2.5%</td>
<td>5.6%</td>
<td>0.2%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>83.0%</td>
</tr>
</tbody>
</table>

**Note:**
Yellow highlighting indicates more than 2% of segment.
3.0 **DITCH SETTLEMENT**

3.1 **Method and Assumptions**

For the Mackenzie Gas Project, thaw settlement refers to settlement caused directly by the thawing and draining of excess moisture from thawing soil or bedrock. It is frequently used to describe the settlement experienced on the pipeline right-of-way, under the pipeline, or both, depending on the pipeline’s operating temperature. However, another form of local settlement common to pipelines in northern settings is ditch line or ditch settlement. Although ditch settlement often involves a component of thaw settlement, ditch settlement is a more general form of subsidence resulting from volume loss from mechanical disturbance to soil structure and self-weight settlement of the material.

Local settlement associated with the pipeline ditch is expected along the pipeline alignment in permafrost and organic terrain. Based on the experience of other northern pipeline projects, local settlement of the pipeline ditch, immediately following construction, can be greater than general right-of-way settlement. Following construction of the Norman Wells oil pipeline, where no imported fill was used for backfilling during construction, it was estimated that settlement occurred along 30% of the ditch and about 10% of the settlement was greater than 200 mm (MacInnes et al. 1989).

The local ditch settlement phenomenon results from the following main factors:

- Frozen soil tends to bulk during excavation. Consequently, it is not always practical to grade or place the spoil into a roach pile within the width of the excavated ditch. When the spoil thaws, it might settle below the surrounding ground surface. Bulking is also a function of the excavation method. Backhoe spoil generally has a higher bulking factor than trencher spoil.

- Ice-rich material often exists just below the bottom of the active layer in permafrost soils, and will be penetrated during pipeline ditch excavation in some permafrost areas. This ice-rich material will become mixed with other soils, making it more susceptible to thaw settlement during the first summer after construction, than less disturbed portions of the right-of-way.

- Because backfill is porous, infiltrating surface water can accelerate thermal erosion of the backfill.

- Loss of volume occurs in peaty soils, when excavated by a trenching machine, because of the breakdown of the peat’s fibrous structure. This volume loss is caused by more than thawing alone.

- The ditch line is generally more disturbed than the rest of the right-of-way. Therefore, the freshly exposed black earth absorbs more heat from solar radiation, and tends to thaw faster initially than the less disturbed portions of the right-of-way.

Loss of material from erosion or other particle transport was not considered directly in the ditch settlement calculations.
3.2 Ditch Settlement Zone

Ditch settlement is calculated for the interval between the ground surface and the bottom of the trench. This zone is subjected to accelerated thaw compared to the rest of the right-of-way and controls the differential settlement between the ditch area and the adjacent terrain.

Mineral soils located within the active layer zone, i.e., the zone that freezes and thaws seasonally, are not included in the ditch settlement calculation. It is assumed that the soils in this zone heave and settle seasonally, similar to soils in the adjacent right-of-way, and do not contribute to differential, i.e., ditch, settlement. This assumption is based on southern pipeline experience where imported fill is not normally required to offset ditch settlement associated with mineral soil and frost depths of up to 1.2 m.

Active layer thicknesses used in calculating ditch settlement were derived from a conservative lower value, based on two data sources (AMEC 2004, Smith et al. 2004). Table 3-1 summarizes the assumed active layer thicknesses.

<table>
<thead>
<tr>
<th>Physiographic Region</th>
<th>Active Layer Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mackenzie Delta (Recent)</td>
<td>0.4</td>
</tr>
<tr>
<td>Mackenzie Delta (Pleistocene)</td>
<td>0.4</td>
</tr>
<tr>
<td>Mackenzie Delta (Caribou Hills)</td>
<td>0.4</td>
</tr>
<tr>
<td>Mackenzie Delta (Parsons Lake)</td>
<td>0.4</td>
</tr>
<tr>
<td>Anderson Plain (north)</td>
<td>0.5</td>
</tr>
<tr>
<td>Anderson Plain (south)</td>
<td>0.5</td>
</tr>
<tr>
<td>Franklin Mountains</td>
<td>0.5</td>
</tr>
<tr>
<td>Mackenzie Plain</td>
<td>0.5</td>
</tr>
<tr>
<td>Great Slave Plain</td>
<td>0.9</td>
</tr>
<tr>
<td>Alberta Plateau</td>
<td>0.9</td>
</tr>
</tbody>
</table>

3.3 Strain Correlations

3.3.1 Frozen Mineral Soils

Frozen soils will settle when they thaw if they have an initial excess amount of moisture, i.e., more than the amount that can be stored normally within their pore spaces. The amount of strain that can occur is a function of the type of soil and its moisture content. In the laboratory, thaw strain is determined by thaw consolidation tests. In such a test, a sample of frozen soil is allowed to thaw in a triaxial or oedometer apparatus. By undertaking several tests of similar samples under different applied pressures, a plot of thaw consolidation versus pressure can be produced. Figure 3-1 plots thaw strain as a function of applied pressure.
As shown in Figure 3-1, thaw strain increases with applied pressure. Although the curve is non-linear, it is common practice to estimate the thaw consolidation behaviour of a soil with a linear function, where $A_0$ is the zero intercept and the slope of the line is the coefficient of compressibility ($m_v$). For the Mackenzie Gas Project, an overburden pressure of 50 kPa was used to develop all thaw strain correlations. This pressure corresponds to the midpoint overburden pressure for a typical thaw bulb under a pipeline. The strain value coinciding with this pressure is referred to as the $A_{50}$ parameter.

A considerable amount of research on past pipeline designs and other northern projects was undertaken for the project. Consequently, the results of hundreds of thaw consolidation tests have been published. Much of this information was compiled and used to develop new or updated thaw strain correlations for various soil types in this study. Sources of data for this analysis are:


Thaw strain can be empirically correlated with either the initial frozen bulk density or moisture content of a soil sample. Early research into the thaw settlement phenomenon focused on thaw strain-frozen bulk density correlations. However, because frozen bulk density information is difficult to obtain and requires undisturbed samples, this information is rare for boreholes in any of the databases available to this project. In contrast, natural moisture content data is available for almost all of the database boreholes and, therefore, is a better choice for developing thaw strain correlations.

Natural moisture content is normally reported gravimetrically as the ratio of the weight of water to the dry weight of solids. As this definition is suitable for most non-permafrost soils, it is used worldwide and is the parameter reported in the engineering borehole database. However, in ice-rich permafrost mineral soils or organic soils, gravimetric moisture content trends towards infinity, making it difficult to establish thaw strain correlations.

This difficulty can be overcome by considering volumetric instead of gravimetric moisture content, i.e., the volume of water relative to the total volume of the sample. For example, in the case of pure ice, the volumetric moisture content is 100%, and the corresponding theoretical thaw strain value is 1. This provides a useful upper bound on thaw strain correlations. In contrast, the gravimetric moisture content of pure ice is infinity. Volumetric
moisture content has been used in previous pipeline projects to estimate thaw strain. Hanna et al. (1983) originally published data in this format.

Based on this rationale, empirical volumetric moisture content–thaw strain correlations were developed for several different basic soil types. For mineral soils, the basic types considered were:

- fine-grained silts and clays (see Figure 3-2)
- coarse-grained sands and gravels (see Figure 3-3)
- tills (see Figure 3-4)

Full saturation and a specific gravity of 2.67 were assumed in the conversion of gravimetric moisture content values to volumetric moisture content values for mineral soils.

**FIGURE 3-2 THAW STRAIN CORRELATION – FINE GRAINED SILTS AND CLAYS**
NOTES:
CAGSL = Canadian Arctic Gas Study Ltd.; Foothills = Foothills Pipeline Project; ALASKA = TransAlaska Pipeline System; NWP = Norman Wells Pipeline

**FIGURE 3-3**  THAW STRAIN CORRELATION – COARSE GRAINED SANDS AND GRAVELS

NOTES:
CAGSL = Canadian Arctic Gas Study Ltd.; Foothills = Foothills Pipeline Project; NWP = Norman Wells Pipeline

**FIGURE 3-4**  THAW STRAIN CORRELATION – TILL
For the special condition of soil type Ice and Ice+ (special condition 1), the thaw strain for that layer is assumed to be unity. For the special condition where the soil type is bedrock (special condition 2), the thaw strain value is assumed to be zero. Special condition 2 might not always be a conservative assumption because weathered and highly fractured bedrock can also be ice-rich and could be prone to settlement. However, because the amount of shallow bedrock on the pipeline right-of-way is minor and because shallow bedrock normally becomes less susceptible to settlement quickly with depth, this assumption is considered appropriate.

### 3.3.2 Organic Soils

Peaty and organic soils tend to experience volume loss from mechanical disturbance and, if frozen, from thaw settlement. For the purpose of estimating ditch settlement and imported fill quantity, these soils are assumed to undergo a large strain, regardless of their thermal state. The assumption that peaty and organic soils will experience large strains, irrespective of their thermal state, is one of the most significant changes from conceptual engineering, and is consistent with anecdotal observations from the Norman Wells pipeline during inspections made in the first few years following construction. The zone of interest for organic soils is from the ground surface to the base of the pipe, not just below the active layer.

A constant strain value of 0.85 was assumed for peat and a value of 0.60 was assumed for organic clays and silts. These values are considered conservative, but have not been validated by laboratory or field tests.

### 3.4 Missing Moisture Content Values

#### 3.4.1 Interpolation and Extrapolation

When a given sublayer in the engineering borehole database is missing a moisture content value, the Settlement Calculator will try to populate that layer with a moisture content, either by interpolating from the layers above and below that layer, or using a moisture content look-up table.

The Settlement Calculator initially checks the soil group of the sublayers above and below the missing layer. If the soil in all three layers belongs to the same group, and both sublayers have valid moisture content-values, the program will compute an average value for the intermediate sublayer. If the soil group of one of the adjacent sublayers does not match the missing layer, or does not have a valid moisture content, the program will initially try to match the soil group of the sublayer above. Failing that, it will try to find a match with the layer below. A match in either of these cases would result in the moisture content of that adjacent sublayer being used for the missing value. The upper unit is queried first because it would generally have a higher moisture content than the underlying unit.

If the Settlement Calculator fails to derive a moisture content value for the missing sublayer by interpolation or extrapolation, the program will default to using a standard moisture content look-up table, described in Section 3.4.2.
3.4.2 **Standard Moisture Content Look-Up Table**

The standard moisture content look-up table is a table of average frozen moisture content values derived from all of the boreholes in the engineering borehole database, grouped by physiographic region and terrain group for specific depth intervals. If fewer than five frozen moisture content values existed at any depth interval, then that cell would not be populated.

Table 3-2 shows an example of the standard moisture content look-up used by the Settlement Calculator in support of preliminary engineering.

Water and ice content values tend to decrease with depth in permafrost soils. Table 3-2 shows that, for this example, the water and ice content declines to a depth of about 4 m and then increases with greater depths. Although this upward trend is contrary to conventional wisdom, it is not relevant to this study, because all thaw settlement calculations will be in the upper 4 m.

The standard moisture content look-up table is accessed at run time only if the Settlement Calculator program is unable to interpolate or extrapolate a moisture content value for a missing sublayer. If no valid moisture content exists in the look-up table for the depth interval that encompasses the midpoint of the sublayer, e.g., SMC = -1.0%, the Settlement Calculator will reject the borehole from the analysis because of insufficient information.

**Table 3-2 Example from Standard Moisture Content Look-up Table**

<table>
<thead>
<tr>
<th>Physiographic Region</th>
<th>Terrain Group</th>
<th>Top (m)</th>
<th>Bottom (m)</th>
<th>Standard Moisture Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Great Slave Plain</td>
<td>Moraine</td>
<td>0.0</td>
<td>0.5</td>
<td>-1.0</td>
</tr>
<tr>
<td>Great Slave Plain</td>
<td>Moraine</td>
<td>0.5</td>
<td>1.0</td>
<td>16.9</td>
</tr>
<tr>
<td>Great Slave Plain</td>
<td>Moraine</td>
<td>1.0</td>
<td>1.5</td>
<td>-1.0</td>
</tr>
<tr>
<td>Great Slave Plain</td>
<td>Moraine</td>
<td>1.5</td>
<td>2.0</td>
<td>16.8</td>
</tr>
<tr>
<td>Great Slave Plain</td>
<td>Moraine</td>
<td>2.0</td>
<td>2.5</td>
<td>13.5</td>
</tr>
<tr>
<td>Great Slave Plain</td>
<td>Moraine</td>
<td>2.5</td>
<td>3.0</td>
<td>13.5</td>
</tr>
<tr>
<td>Great Slave Plain</td>
<td>Moraine</td>
<td>3.0</td>
<td>4.0</td>
<td>13.6</td>
</tr>
<tr>
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<td>Moraine</td>
<td>4.0</td>
<td>5.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Great Slave Plain</td>
<td>Moraine</td>
<td>5.0</td>
<td>6.0</td>
<td>14.4</td>
</tr>
<tr>
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<td>6.0</td>
<td>8.0</td>
<td>18.3</td>
</tr>
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<td>10.0</td>
<td>21.9</td>
</tr>
<tr>
<td>Great Slave Plain</td>
<td>Moraine</td>
<td>10.0</td>
<td>12.0</td>
<td>-1.0</td>
</tr>
<tr>
<td>Great Slave Plain</td>
<td>Moraine</td>
<td>12.0</td>
<td>1000.0</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

**NOTE:** "1.0" denotes no data.
### 3.5 Borehole Settlement

Total settlement at a borehole is calculated by multiplying the thaw strain, estimated for each sublayer using the correlations described earlier, by the sublayer’s thickness, and then summing these individual sublayer estimates over the depth interval of interest. Total borehole settlement can be represented by the following equation:

\[
Total \_ \text{Borehole} \_ \text{Settlement} = \sum_{i=1}^{n} (\text{SubLayer} \_ \text{ThawStrain}_i \times \text{SubLayer} \_ \text{Thickness}_i)
\]  

(1)

The settlement prediction for a borehole will be zero when a borehole:

- lacks organics and is unfrozen
- is composed of soils with low ice content that is not susceptible to thaw settlement

To distinguish between these two different cases, both the percentage of the soil frozen within the thaw interval of interest and the estimated settlement are computed for every borehole.

For boreholes that contain organics, some volume reduction of the backfill will always be calculated. Whether this translates into a requirement for imported fill depends on the thickness of the organics, or on the ice-richness in the case of mineral soils. No imported fill will be required as long as the volume increase to the trench, by adding the pipeline itself (about 10 to 15% of the trench volume), exceeds the volume loss by settlement or mechanical disturbance.
4.0 IMPORTED FILL

4.1 General

Buried pipelines require a minimum depth of soil cover to meet CSA Z662-03. As previously discussed, backfill material might thaw and settle over the pipeline in ice-rich areas that thaw. One of the options being considered by the Mackenzie Gas Project proponents to ensure adequate cover over the pipelines is placing imported fill.

The following topics discuss the use of imported fill in pipeline design and how imported fill quantities are estimated.

4.2 Case Histories

Few pipelines are buried in permafrost in North America and even fewer documented cases exist of imported fill being used in pipeline construction. The Norman Wells pipeline did not proactively use imported fill in its design or construction. However, imported fill, in the form of granular borrow material, was used to mitigate areas of ditch settlement and erosion following initial construction (Geological Survey of Canada 1999). It is understood from discussions with construction inspectors, who were responsible for some of the clean-up work, that much of the imported fill was required in areas containing thick organic layers, rather than in ice-rich mineral soils.

The only documented case history where imported fill was considered during design and used during construction was the Ikhil gas pipeline (North of 60 Engineering Limited 2004). The Ikhil pipeline proponents:

- considered the potential settlement of ice-rich spoil material
- determined the amount of imported thaw-stable fill based on the field moisture content of the excavated material before backfilling

When comparing the two case histories, there initially appears to be an incompatibility between the two experiences. Settlement occurred in areas of organic soil along the Norman Wells pipeline, whereas, for the Ikhil pipeline, mitigation against settlement was mainly in ice-rich areas. However, considering the physical setting of the two pipelines, a consistent and rational explanation of these observations can be developed. The Ikhil pipeline was constructed in an area of continuous permafrost and the typical depth of the active layer (0.4 m) was small, relative to the depth of the trench (1.3 m) (North of 60 Engineering Limited 2004). In this case, the trench spoil contained a considerable amount of ice-rich soil from just below the active layer. Also, thick organic soils were mostly absent on the Ikhil pipeline.

By contrast, the active layer along the Norman Wells pipeline is deeper, and typically varies from 0.6 to 1.5 m. In comparison, the bottom of the pipeline ditch was generally less than 1.2 m deep. Therefore, in some instances, the bottom of the Norman Wells pipeline ditch likely did not penetrate through the active layer. In this situation, one would expect less ditch settlement in mineral soil than the Ikhil pipeline potentially could have experienced (had it not been mitigated). Ditch settlement was also experienced in areas containing thick organic soils. Organic soils tended to lose volume by loss of structure because of
trenching, excavation, erosion within the trench, or all three. This condition was not encountered on the Ikhil pipeline, probably because of the absence of thick organic soils.

4.3 Trench Configuration

Although the estimation of imported fill depends on ditch settlement, which is controlled by soil type, moisture content and geothermal conditions, it also depends on the size and configuration of the trench. The depth of the trench and mode of excavation, i.e., backhoe or trenching machine, are parameters in determining the volume of imported fill.

Table 4-1 summarizes the trench configuration assumptions used in estimating imported fill volumes.

<table>
<thead>
<tr>
<th>Pipeline</th>
<th>NPS</th>
<th>Pipe Diameter (m)</th>
<th>Trench Width – Bottom (m)</th>
<th>Trench Depth – Trencher (m)</th>
<th>Trench Depth – Hoe (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGL line</td>
<td>10</td>
<td>0.280</td>
<td>0.58</td>
<td>1.33</td>
<td>1.44</td>
</tr>
<tr>
<td>Niglintgak lateral</td>
<td>16</td>
<td>0.413</td>
<td>0.82</td>
<td>1.47</td>
<td>1.57</td>
</tr>
<tr>
<td>Parsons lateral</td>
<td>18</td>
<td>0.464</td>
<td>0.87</td>
<td>1.52</td>
<td>1.62</td>
</tr>
<tr>
<td>Taglu lateral</td>
<td>26</td>
<td>0.667</td>
<td>1.07</td>
<td>1.72</td>
<td>1.88</td>
</tr>
<tr>
<td>Storm Hills lateral</td>
<td>32</td>
<td>0.820</td>
<td>1.22</td>
<td>1.87</td>
<td>2.03</td>
</tr>
<tr>
<td>Mainline</td>
<td>30</td>
<td>0.769</td>
<td>1.17</td>
<td>1.82</td>
<td>1.98</td>
</tr>
</tbody>
</table>

4.4 Key Factors

In addition to imported fill volumes being a function of ground conditions and trench configuration, several other factors are also important. The two most important factors are pipeline restraint and ditch maintenance strategies.

4.4.1 Pipeline Restraint

A key factor affecting the volume of imported fill required is the amount of settlement, and its effect on vertical pipeline restraint and erosion control. If no differential settlement is tolerable, then more imported fill is required than if a nominal value were permitted.

For preliminary design, it has been assumed that backfill to the ground surface will most likely be required in select areas along the gas pipeline because of the potential for upheaval displacement.

4.4.2 Ditch Maintenance Strategies

Volumes of imported fill required to mitigate ditch settlement also depend mainly on the ditch maintenance philosophy. If the roach is not re-graded within the first few years after construction, some backfill will be left stranded on the shoulders of the pipeline trench and
will not settle back over the pipeline ditch. This material is referred to as stranded fill. If a certain amount of cover over the pipeline were required during all phases of operation, and reclaiming this material immediately after construction or during operation were not an option, then more imported fill would be required to compensate for the lost material. Consequently, volumes of imported fill would be higher.

Figure 4-1 illustrates several imported fill handling scenarios, from a scenario that assumes no post-construction reclamation, to a scenario where imported fill might be needed later. Scenario 2, where sufficient imported fill is placed during construction but requires grading from the shoulders to cover the ditch centreline, is a similar approach used for the Ikhil gas pipeline and is being considered for the Mackenzie Gas Project.

<table>
<thead>
<tr>
<th>SCENARIO No.</th>
<th>SCENARIO NAME</th>
<th>SCHEMATIC</th>
<th>DESCRIPTION</th>
<th>PRIMARY DRIVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No Post-Construction; Low (No) ROW Maintenance</td>
<td><img src="schematic1.png" alt="Schematic" /></td>
<td>Zero surface settlement at all times. Requires no post-construction work. (Conceptual Engineering Approach)</td>
<td>Right-of-Way Performance</td>
</tr>
<tr>
<td>2</td>
<td>Post-Construction Reclamation</td>
<td><img src="schematic2.png" alt="Schematic" /></td>
<td>Maintain minimum cover over the pipe for stability issues (e.g. buoyancy, uplift) at all times. Post-construction reclamation not required for stability, but would be done to minimize surface settlement. (Ikhil Pipeline Approach)</td>
<td>Pipeline Integrity &amp; Right-of-Way Performance</td>
</tr>
<tr>
<td>3</td>
<td>Post-Construction Import</td>
<td><img src="schematic3.png" alt="Schematic" /></td>
<td>Maintain minimum cover over the pipe for stability issues (e.g. buoyancy, uplift) at all times. Any construction surface settlement issues will likely require additional import fill not placed during construction. (Norman Wells Approach)</td>
<td>Pipeline Integrity</td>
</tr>
</tbody>
</table>

**FIGURE 4-1 IMPORTED FILL RECLAMATION SCENARIOS**

### 4.5 Bulking Factor

Most excavated soils tend to gain bulk on excavation. During pipeline construction, excavated soil is rarely replaced in the trench to its pre-excavation density. With time, compaction or both, this temporary volume increase mostly or completely dissipates. In frozen soils, the bulking factor can be large because spoil tends to consist of large clods which, when piled into a roach, can contain many voids. When thawing occurs, these voids (which were occupied by air) collapse, resulting in settlement in addition to that associated with the ditch backfill thaw consolidation.

In estimating imported fill volumes, bulking factors need to be applied to both the excavated spoil and the imported fill. The net effect of bulking in the imported fill calculation is that it can cause a larger roach pile over the pipeline, resulting in more material being potentially stranded on the shoulders after self-
weight settlement and any thaw consolidation. All the imported fill calculations assume that the bulking phenomenon is temporary and that eventually the (ice-poor) fill will settle back to a volume similar to the in situ conditions. No time frame is placed on when, or if, this actually occurs, because the primary objective in preventing upheaval displacement is to maintain a certain density of soil over the pipeline at all times. Whether this results in a slightly elevated roach for many years is less critical. Temporary bulking is an issue only for the stranded fill model. If it is assumed that the right-of-way will be reclaimed and no stranded fill will remain on the shoulders of the trench, then bulking factors are required to be taken into consideration for only the imported fill that will arrive on site in a bulked condition and will settle on thawing.

Currently, the assumed bulking factor for native soil (spoil) is 1.3. For imported fill, the bulking factor is assumed to be between 1.1 and 1.3, which represents the range of possible imported fill, from granular to fine-grained soils. If the imported fill is also prone to thaw settlement, i.e., it is not thaw-stable, allowance for additional strain must be included in the bulking factor. This applies only to imported fill because the thaw strain for in situ soils is handled rigorously on a layer-by-layer basis for each borehole in the ditch settlement calculation.

4.6 Import Fill Model

Estimating the volume of imported fill required to completely or partially offset ditch settlement requires a model that accounts for the geometry and volume of spoil material produced, and the fact that the imported fill itself could experience some thaw settlement. Appendix A contains the derivation of the numerical model that has been developed to account for all of these factors.

By varying the geometry of the excavation, it is possible to estimate imported fill requirements for different excavation equipment, i.e., for different excavation modes. For example, imposing vertical trench walls in the model can simulate a trenching machine ditch. A backhoe trench can be represented by a slightly deeper ditch, with its walls inclined at about 1:4.
5.0 SETTLEMENT CALCULATOR

For this project, ditch settlement and imported fill quantities are estimated on a borehole-by-borehole basis using customized software developed specifically by the Mackenzie Gas Project team. The software, written in Microsoft Visual Studio (C# language), handles both the general thaw settlement problem and the special ditch settlement scenario described in this report. This software is referred to as the Settlement Calculator.

When the ditch settlement module of the Settlement Calculator is invoked, strains associated with frozen organic soils are overridden with the generalized mechanical disturbance organic strains described in Section 3.3. In addition, when this mode is invoked, imported fill volumes for each borehole are calculated and the results are extended to the applicable terrain polygons.

Figure 5-1 summarizes the overall thaw and ditch settlement and imported fill volume calculation process. The flowcharts in Appendix B document the Settlement Calculator program at the programming level.
FIGURE 5-1   SETTLEMENT CALCULATOR FLOWCHART
6.0 DITCH SETTLEMENT AND IMPORTED FILL APPLICATION

The purpose of the ditch settlement and imported fill analyses was to prepare quantity take-offs for construction execution planning and cost estimating. The information was used to estimate volumes of imported fill required along the pipeline right-of-way to offset settlement. This was done by applying the mean imported fill required per linear metre per terrain group along the route. This was also done while considering the mode of excavation, along with many other external factors that influence the trench backfill design, such as road crossings, watercourse crossings and buoyancy control.

To ensure that an appropriate volume of imported fill was considered, mean settlement values by terrain group were used in all cost estimates to date, as opposed to some statistical mean plus standard deviation value. Because of the high variability from one location to another, it would be impossible to ensure that no settlement occurs in all areas unless a conservative volume of imported fill was specified at all locations. This impractical approach would result in a perpetual above-ground roach in many areas that could hamper surface drainage.

The decision to use mean settlement values is further supported by the Mackenzie Gas Project proposal of a Geotechnical Verification Program. In this program, additional shallow subsurface soil information will be collected before construction begins, which will allow for more refined and location-specific adjustments to be made for the required quantities of imported fill. Data from the Geotechnical Verification Program will help to calculate the correct fill distribution within a given construction spread. However, the total imported fill requirements, estimated from mean values using Revision E of the engineering borehole database, are still believed to be reasonable.

The output from the ditch settlement and imported fill calculation is a look-up table of imported fill quantities per linear metre of trench for each terrain group encountered along the pipeline route, for both backhoe and trenching machine ditch configurations. Table 6-1 is an example of a partial imported fill look-up table.

Along the pipeline route, where little or no borehole data is available, some terrain occurrences did not always have a corresponding imported fill estimate. As a result, in areas where fewer than five boreholes existed in a terrain group, a representative value was obtained based on the following rules, which are listed in order of priority:

- from a similar terrain group with boreholes in same physiographic region
- from the same terrain group and from the adjacent physiographic region
- from similar terrain groups and from adjacent physiographic regions

As ditch settlement can occur in unfrozen thick organic soils, boreholes with organic sublayers are not discriminatingly screened for being in permafrost or non-permafrost areas, as they would be in a pure thaw settlement analysis. The distribution of boreholes along the pipeline is assumed to be random. As a population, boreholes have not been overly biased thermally in either frozen or unfrozen areas relative to organic content.
# TABLE 6-1  PARTIAL IMPORTED FILL LOOK-UP TABLE

<table>
<thead>
<tr>
<th>Line ID</th>
<th>Physiographic Region</th>
<th>Terrain Group</th>
<th>Number of Holes</th>
<th>Imported Fill – Backhoe</th>
<th>Imported Fill – Trencher</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Imported Fill (m³/m)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Stranded</td>
<td>Reclaimed</td>
</tr>
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<td>M</td>
<td>21</td>
<td>0.02</td>
<td>0.01</td>
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</tr>
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<td>0.33</td>
<td>0.24</td>
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<td>GM</td>
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<td>0.00</td>
</tr>
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<td>45</td>
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<td>0.93</td>
<td>0.70</td>
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<tr>
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<td>ObL</td>
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<td>1.15</td>
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</tr>
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<td>0.81</td>
</tr>
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<td>1.37</td>
<td>1.11</td>
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<tr>
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<td>OvA</td>
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<td>1.94</td>
<td>1.59</td>
</tr>
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<td>1.14</td>
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<td>2.29</td>
<td>1.90</td>
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</tr>
<tr>
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<td>Anderson Plain (North)</td>
<td>X</td>
<td>5</td>
<td>0.50</td>
<td>0.37</td>
</tr>
</tbody>
</table>
7.0 Closure

The following study objectives were met:

- A computer program was developed that can estimate settlement associated with thaw on the right-of-way and for local settlement over the ditch line. The program computes settlement on a layer-by-layer basis for each borehole within the engineering borehole database.

- A numerical model was developed that can estimate the amount of imported fill required to either completely or partially offset local ditch settlement. Imported fill is estimated on the basis of the average strain predicted for each borehole. This permits three scenarios to be considered:
  
  - Scenario 1. Some fill is left on the trench shoulders after thaw, with no settlement below the adjacent ground surface.
  
  - Scenario 2. Reclamation will occur after the roach has thawed and no imported fill will remain on the trench shoulders. Temporary stranded fill will be used to top up ditch backfill.
  
  - Scenario 3. Reclamation will occur after the roach has thawed. No imported fill will remain on the trench shoulders, and fill will be imported during reclamation.

Regardless of which reclamation scenario is selected, some long-term ditch settlement is acceptable.

As boreholes are not consistently distributed, or continuous along the pipeline alignment, settlement or imported fill volumes are best applied to the pipeline route using statistical values based on terrain groups rather than individual boreholes.
8.0 FUTURE STEPS

To improve the quality of the ditch settlement and imported fill models and their output, the following measures should be considered:

- Enhance the standard moisture content look-up tables, if practicable, using additional engineering expertise and judgement to complete some of the existing data gaps.

- Revise the assumptions on organic strain resulting from mechanical disturbance to match local northern experience, where practicable.

- Reaffirm the use of mean settlement and imported fill values to calculate imported fill demands.

- Revise the current zero allowable settlement criterion.

- Consider adopting the recovered fill model instead of the current stranded fill reclamation model, where no re-grading of the roach or backfill conditioning is proposed following initial construction. During detailed design, determine the optimum time frame, i.e., construction, post-construction or both, for placing imported fill.

- Drill additional boreholes or pursue other data sources in data gap areas, particularly in the extreme northern and southern portions of the project.

- Refine the engineering borehole database where errors are encountered, especially with boreholes that are causing unrealistically high or low settlement estimates.
REFERENCES


APPENDIX A. IMPORTED FILL MODEL

Definition of Variables

Thaw Settlement Inputs

Ts – average thaw strain (from ditch settlement analysis for each borehole)

Xset – allowable settlement (m) (user defined)

BFspoil – bulking factor of spoil; independent of thaw strain (assumed 1.3)

BFimported – bulking factor of import; must include thaw strain, if applicable (range 1.1 to 1.3).

Pipeline Dimension

D – pipe diameter (m)

Trench Configuration

See Figure A-1 for an illustration of trench geometry.

B – trench width (m)

H – ditch depth (height) (m)

β – roach pile angle (degrees)

α – trench angle (degrees)

Intermediate Calculated Dimensions

b – width of base of roach pile (m)

b1 – as shown (m)

b2 – as shown (m)

b3 – as shown (m)

b4 – as shown (m)

h – height of roach (m)

h1 – as shown (m)
Aroach – area of roach pile (m$^2$)
Aallow – area of allowable settlement (m$^2$)
Atrench – area of trench (m$^2$)
A_waste – area of waste (m$^2$)
A_pipe – area of pipe (m$^2$)
A_backfill – area of backfill required (m$^2$)
A_unfactored – area of available spoil (bulked) (m$^2$)
A_available – area of available spoil (un-bulked) (m$^2$)

**FIGURE A-1  TRENCH GEOMETRY**
Imported Fill Calculations – Stranded Fill Scenario

The stranded fill scenario assumes that material outside of the width of the trench will not settle back into the trench when thawed and will be left stranded-on the shoulders of the trench. The solution for the required imported fill volume in this scenario is iterative. The following summarizes the equations and steps used in the calculation.

Assume a value for imported fill:

\[ A_{\text{import}} = \text{assumed} \quad (1) \]

By geometry:

\[ \tan(\alpha) = \frac{b_2}{H} \quad (2) \]

Solve for dimension \( b_2 \):

\[ b_2 = \tan(\alpha) \times H \quad (3) \]

Area of trench:

\[ A_{\text{trench}} = H \times (B + b_2) \quad (4) \]

Area of spoil:

\[ A_{\text{spoil}} = A_{\text{trench}} \times BF_{\text{spoil}} \quad (5) \]

Area of pipe:

\[ A_{\text{pipe}} = \pi \times \frac{D^2}{4} \quad (6) \]

Area of roach (area available):

\[ A_{\text{roach}} = A_{\text{spoil}} - (A_{\text{trench}} - A_{\text{pipe}} - A_{\text{import}}) \quad (7) \]

Area of roach (by geometry):

\[ A_{\text{roach}} = \frac{1}{2} \times b \times h \quad (8) \]
Height of roach:

\[ h = \frac{1}{2} b \times \tan \beta \]  
(9)

Substituting Equation 9 into Equation 8:

\[ A_{roach} = \frac{1}{2} \times b \times \frac{1}{2} b \times \tan \beta \]  
(10)

Solving for \( b \):

\[ b = \sqrt{\frac{A_{roach}}{0.25 \times \tan \beta}} \]  
(11)

Dimension \( b \):

\[ b = B + 2(b_2) + 2(b_1) \]  
(12)

Rearranging Equation 12 and solving for \( b_1 \):

\[ b_1 = \frac{b - B - 2(b_2)}{2} \]  
(13)

By geometry:

\[ \tan(\beta) = \frac{h_1}{b_1} \]  
(14)

Solving for \( h_1 \):

\[ h_1 = \frac{\tan(\beta)}{b_1} \]  
(15)

Area of waste:

\[ A_{waste} = 2 \times \frac{1}{2} b_1 \times h_1 \]  
(16)

Available spoil (bulked):

\[ A_{unfactored} = A_{spoil} - A_{waste} \]  
(17)
Available spoil (unbulked):

\[
A_{\text{available}} = \frac{A_{\text{unfactored}}}{BF_{\text{spoil}}}
\]  

(18)

By geometry:

\[
\tan(\alpha) = \frac{b_3}{X_{\text{set}}}
\]  

(19)

Solve for \(b_3\):

\[
b_3 = \tan(\alpha) \times X_{\text{set}}
\]  

(20)

Dimension \(b_4\):

\[
b_4 = b - 2(b_1) - 2(b_3)
\]  

(21)

Allowable settlement area:

\[
A_{\text{allowable}} = \frac{1}{2} \times X_{\text{set}} \times (b_4 + B + 2b_2)
\]  

(22)

Backfill area required:

\[
A_{\text{backfill}} = A_{\text{trench}} - A_{\text{pipe}} - A_{\text{allowable}}
\]  

(23)

Net imported fill required (iterate with Equation 1 until \(Net_{\text{imported}} < 0.001\)):

\[
Net_{\text{import}} = A_{\text{backfill}} - \frac{A_{\text{import}}}{BF_{\text{import}}} - A_{\text{available}} \times (1 - T_s)
\]  

(24)
Imported Fill Calculations – Reclaimed Fill Scenario

The scenario where material on the shoulders of the trench, which did not settle back into the trench upon thawing, will be reclaimed and pushed over the ditch line in the early operational years of the project is referred to as the reclaimed fill option. The solution for imported fill volume in this scenario is non-iterative. The following summarizes the equations and steps used in the calculation.

By geometry:

\[ \tan(\alpha) = \frac{b_2}{H} \]  \hspace{1cm} (25)

Solve for dimension \( b_2 \):

\[ b_2 = \tan \alpha \times H \]  \hspace{1cm} (26)

Area of trench:

\[ A_{\text{trench}} = H \times (B + b_2) \]  \hspace{1cm} (27)

Area of pipe:

\[ A_{\text{pipe}} = \pi \times \frac{D^2}{4} \]  \hspace{1cm} (28)

By geometry:

\[ \tan(\alpha) = \frac{b_3}{X_{\text{set}}} \]  \hspace{1cm} (29)

Solve for \( b_3 \):

\[ b_3 = \tan(\alpha) \times X_{\text{set}} \]  \hspace{1cm} (30)

Dimension \( b_4 \):

\[ b_4 = B + 2(b_2 - b_3) \]  \hspace{1cm} (31)

Allowable settlement area:

\[ A_{\text{allowable}} = \frac{1}{2} \times X_{\text{set}} \times (b_4 + B + 2b_2) \]  \hspace{1cm} (32)
Available spoil:

\[ A_{\text{spoil}} = A_{\text{trench}} \times (1 - T_s) \]  \hfill (33)

Backfill required:

\[ A_{\text{backfill}} = A_{\text{trench}} - A_{\text{pipe}} - A_{\text{allowable}} \]  \hfill (34)

Imported fill required:

\[ A_{\text{import}} = \left( A_{\text{backfill}} - A_{\text{spoil}} \right) \times BF_{\text{import}} \]  \hfill (35)
APPENDIX B. SETTLEMENT CALCULATOR FLOWCHARTS

Figure B-1  Calculating Thaw Settlement and Imported Fill Requirements

Notes:
Numbers reference off-page flowcharts. Appendix flowcharts contain variable names (for example, "terrainGroup", "numberOFlayers" and "importFill") used in the Off computer program that calculates ditch settlement. For consistency, the same variable names that are used in the Off computer program are also used in these flowcharts.
FIGURE B-2  DITCH SETTLEMENT (3 OF 3)
FIGURE B-3  THAW SETTLEMENT (1 OF 3)
Figure B-3  Thaw Settlement (2 of 3)
FIGURE B-4  COMMON SETTLEMENT
FIGURE B-5  MOISTURE CONTENT
FIGURE B-6  GROUPING SUBLAYERS BY TERRAIN GROUP

Notes:
Numbers reference off-page flowcharts.
Appendix flowcharts contain variable names (for example, “terrainGroup”, “numBoreHoles” and “importFile”) used in the C# computer program that calculates ditch settlement. For consistency, the same variable names that are used in the C# computer program are also used in these flowcharts.
FIGURE B-7  APPLY RESULTS TO ROUTE