Mine Closure 2026 – AB Fourie, G Boggs, J Heyes & M Tibbett (eds)

doi:10.36487/ACG_repo/2615_146

Case study: geotechnical considerations for the conceptual littoral zone design supporting mine closure at the Ekati mine Pigeon Pit

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Abstract

Ekati is a diamond mine located approximately 300 km northeast of Yellowknife in the Northwest Territories in the low Arctic ecoclimate zone, Canada. The area is characterised by continuous permafrost reaching depths up to 320 m, boulder fields and numerous lakes.

The closure plan for the Pigeon Pit at Ekati involves flooding of the open pit to form a freshwater lake as part of progressive reclamation outlined in the interim closure and reclamation plan for the mine. To facilitate this, designs of an outflow channel and 3 conceptual littoral zones for fish habitat restoration were developed to enhance aquatic habitat while achieving long-term geomorphic and geotechnical stability.

Three conceptual littoral zones – the Northwest, Southwest and Ramp – were designed to provide productive shallow water habitat through a combination of bench excavation, fill placement and engineered substrate. This paper presents the technical basis for the conceptual littoral zone designs, focusing on geotechnical characterisation, stability considerations and construction requirements appropriate for mine closure in cold region environments.

An assessment of the existing pit walls, overburden slopes and bedrock domains suggests that the risk of long-term geotechnical instability is low. Current bench-scale performance in the region of the proposed littoral zones is observed to be good to very good, with minimal ravelling and intact bench crests. Stability analyses show factors of safety exceeding the target design acceptance criteria for long-term stability for both static and pseudo-static loading. Anticipated permafrost thaw during lake filling is not expected to influence deep-seated pit wall stability or compromise littoral zone performance. This integration of progressive mine closure into the mine plan demonstrates the application of hydrotechnical and geotechnical engineering design to develop stable, habitat-supporting pit lakes in cold region mining environments.

Keywords: *mine closure, cold regions, sub-Arctic tundra, low Arctic ecoclimate, permafrost, littoral zones, aquatic habitat, fish habitat restoration, progressive reclamation, geotechnical design and assessment*

1 Introduction

Ekati is a diamond mine located approximately 300 km northeast of Yellowknife in the Northwest Territories of Canada. It operates on the traditional lands of the Tłı̨chǫ Dene, Akaitcho Treaty 8, North Slave Métis and Kitikmeot Inuit, who are involved in monitoring the project. In Canada, reclamation and site rehabilitation are conducted during mining operations and follow progressive closure and reclamation strategies intended to address territorial and federal legislative requirements for the protection of the environment and surrounding communities.

Closure planning is iterative, and the interim closure and reclamation plan (ICRP) V3.1 (Arctic 2022) outlines the long-term approach for the Ekati mine. Mining at Pigeon Pit ended in 2022 and its closure plan forms one

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component of the overall ICRP. Three littoral zones – the Northwest, Southwest and Ramp – are planned to create shallow water fish habitat through bench excavation, fill placement and engineered substrate. This paper outlines the conceptual design of these zones and describes the geotechnical considerations influencing them. The technical basis for the concepts, with emphasis on geotechnical characterisation, stability and construction considerations for closure in cold regions, are summarised. A location plan for Pigeon Pit at the Ekati diamond mine is shown in Figure 1 (Tetra Tech 2024).

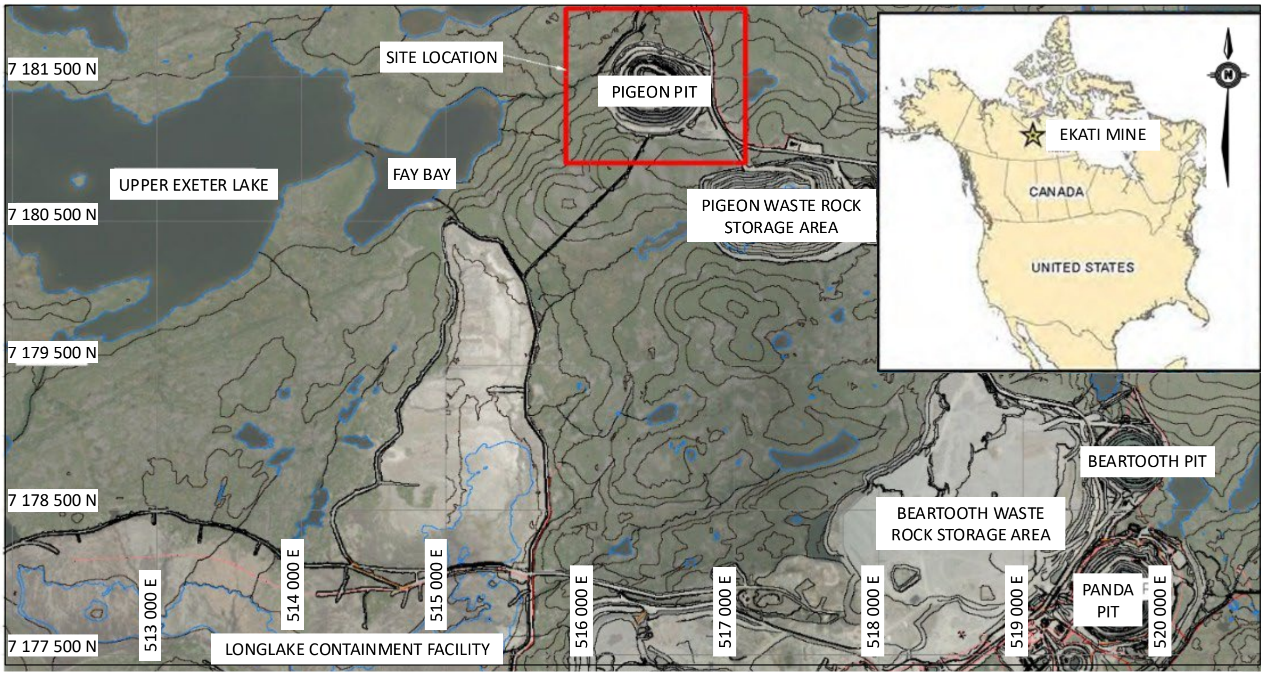


Figure 1 Site location plan for the Pigeon Pit

Pigeon Pit will be one of the first pits to be fully reclaimed during mining operations and will offer the opportunity for research and learning to refine the closure planning strategy at the other pits. An aerial view of the pit is shown in Figure 2 (Arctic 2022). Backflooding of the pits will be completed by either passive (precipitation and natural run-off) or active pumping from nearby lakes. A pipeline is to be constructed from Upper Exeter Lake to Pigeon Pit to facilitate active pumping planned during the open water season from June to October (Arctic 2022).

2 Project description and physical environment

The Ekati mine operates in the low Arctic ecoclimate zone. The project area is characterised by continuous permafrost reaching depths up to 320 m, boulder fields and numerous lakes. The area is dominated by lakes and streams on a landscape shaped by multiple glacial periods ending about 9,500 years ago. The landscape consists of various bedrock types and glacial remnants, including boulder fields and eskers (Arctic 2022).

Figure 2 Aerial view of the Pigeon Pit in summer 2020

The pre-disturbance conditions at the Pigeon Pit area consisted of a small pond (Pigeon Pond) surrounded by flat, low-lying wetland underlain by organic peat and silt deposits (Arctic 2022). A thin veneer of till overlies the areas and common permafrost terrain features such as ice-wedge polygons are present. An isolated kame lies approximately 500 m north of the former Pigeon Pond. South and east of the former pond, rolling ground moraine covered with glacial till to 15 m thick characterises the periglacial terrain and landforms. Arctic grayling, burbot, lake trout and slimy sculpin were present in Pigeon Pond prior to dewatering and subsequent mining (Arctic 2022).

2.1 Regional geology and structure

The Ekati site is underlain by rock types of the Canadian Shield, which makes up roughly 50 per cent of Canada and stretches from Labrador in the east to the high Arctic in the northwest. The site is in the middle portion of the Slave Structural Province characterised by Archean granite-greenstone (Arctic 2022). The bedrock units in the Ekati site consist metasedimentary schists (metasediment), migmatite, and intrusions of granite, granodiorite and tonalite. These Shield rocks are often transected by late-stage Archaean diabase dykes.

The host rock to diamonds is kimberlite. The Pigeon kimberlite pipe is part of a broader province of kimberlite intrusions within the Lac du Gras region. Kimberlite bodies in this province are typically steep-sided and small (Tetra Tech 2024).

2.2 Permafrost and cold region engineering

The Ekati site is characterised by continuous permafrost reaching depths up to 320 m beneath the main land mass. The permafrost ground consists of bedrock, alluvial or lacustrine sediments (loose, unconsolidated soil, silt, sand, gravel or clay), glacial drift or till forming distinct landforms, organic materials (peat) and ground ice. The presence of permafrost at a mine site requires additional considerations with respect to project planning and closure as an understanding of the response of permafrost to disturbance by mining activities can help guide engineering judgement and design.

3 Traditional land use

The area around the Ekati diamond mine is a vital traditional landscape for the Tłı̨chǫ and Dene First Nations. Traditional uses focus on subsistence and cultural continuity. The area is a key migratory route for caribou, and the Arctic tundra and surrounding wetlands have been used for traditional activities such as trapping, fishing and food gathering.

4 Mine closure reclamation objectives and design considerations

The ICRP V3.1 describes the closure goal for the site to be returned to 'viable, and wherever practicable, self-sustaining ecosystems that are compatible with a healthy environment, human activities, and the surrounding environment.' Closure criteria that have been developed are science-based guidelines and studies meant to protect fish, wildlife and people, and the closure designs have been developed in consideration of traditional knowledge through engagement with Indigenous peoples who have used the area traditionally (Arctic 2022).

4.1 Closure and reclamation guidelines

In 2013 the Mackenzie Valley Land and Water Board (MVLWB) and Aboriginal Affairs and Northern Development Canada (AANDC) developed guidelines to help operators meet requirements by providing a standardised framework for ICRP and final closure plans (MVLWB & AANDC 2013). These guidelines outline step-by-step procedures, required studies and appropriate detail to ensure mining-affected lands are restored to sustainable ecosystems, community use, and long-term environmental and end land use stability.

4.2 Pigeon Pit closure strategy

Figure 3 shows the existing and proposed final configuration of the closure strategy plan for the Pigeon Pit (Arctic 2022). The plan involves back-flooding of the open pit to form a pit lake as part of progressive reclamation outlined in the ICRP for the mine. To facilitate this, designs of a diversion channel, outflow channel and 3 conceptual littoral zones for fish habitat restoration were developed to enhance aquatic habitat while achieving long-term geomorphic and geotechnical stability. The diversion and outflow channels are not the subject of this paper.

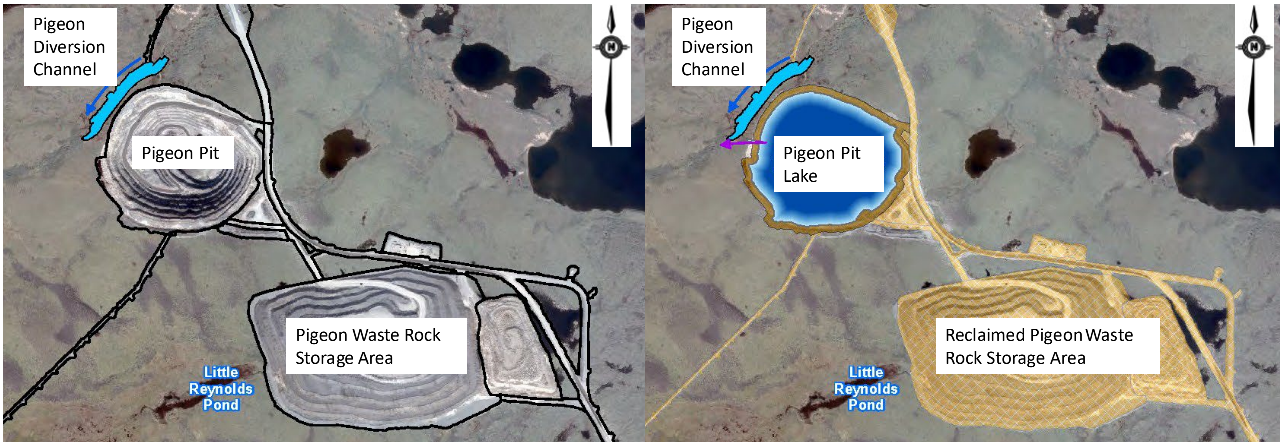


Figure 3 Existing Pigeon Pit conditions and planned final configuration

5 Littoral zones design concept

The locations of the planned littoral zones to be constructed are shown in Figure 4 (Tetra Tech 2024). The conceptual littoral zones are referred to as the Northwest littoral zone (NLZ), the Southwest littoral zone (SLZ) and the Ramp littoral zone (RLZ).

The conceptual littoral zone design consists of a bench constructed at 3 select locations around the open pit perimeter, establishing shallow zones to provide fish habitat in the pit lake. The design concept is illustrated in Figure 5 (modified from Arctic 2022).

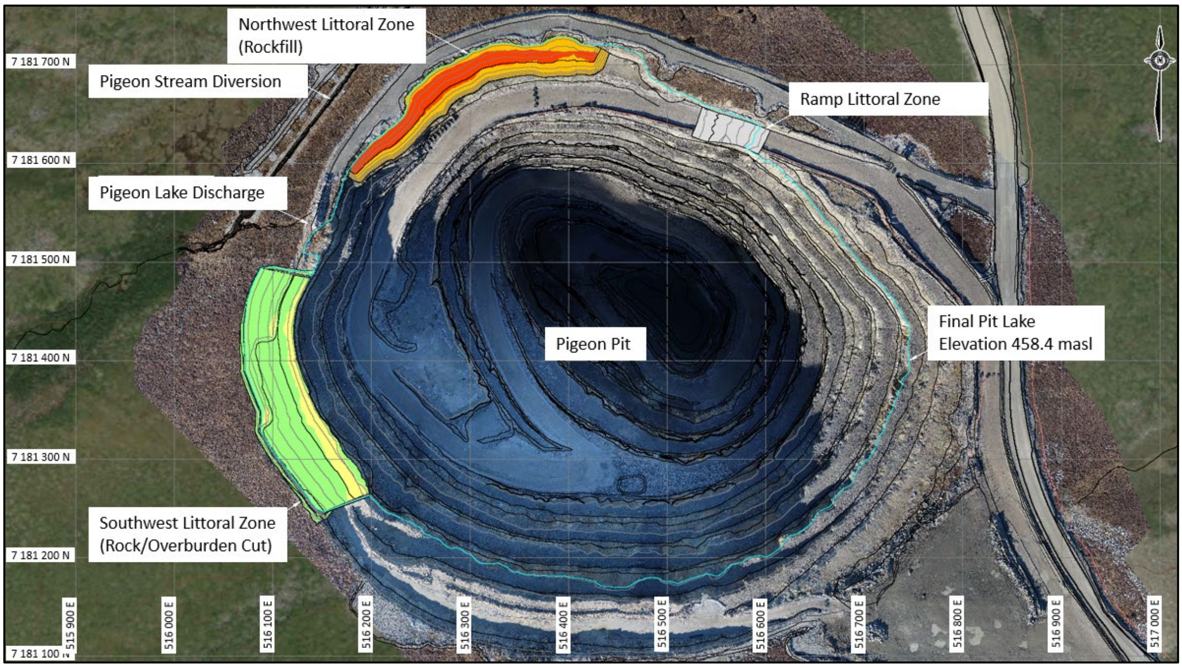


Figure 4 Pigeon Pit planned locations for fish habitat restoration

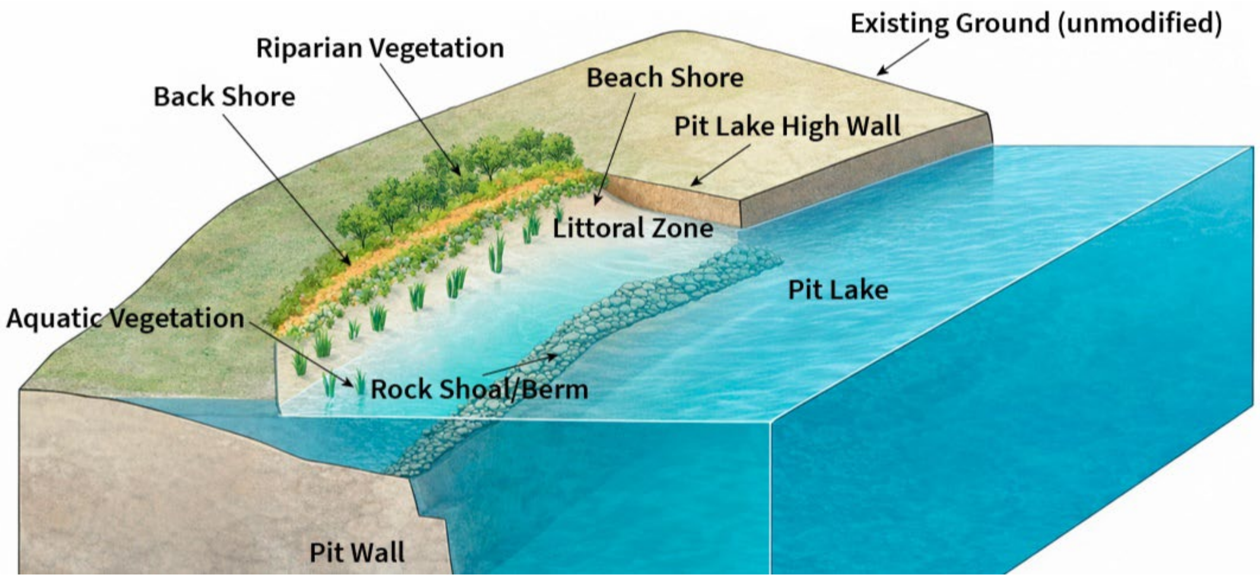


Figure 5 Conceptualisation of littoral zones established at pit crests prior to backflooding

The design is based on the following criteria:

- Littoral zones will be constructed at select locations around pit perimeters. Littoral zones will either be contained within the pit (backwall required) or intersect existing ground (no backwall required).
- The general geometry selected for littoral zones includes:
  - nominal bench width of 50 m, as applicable. Narrower or wider benches may be developed to suit existing pit geometry
  - maximum water depth of 5 m at bench crest
  - sloped bench to develop variable water depth along littoral zone.
- Substrate will be suitable to foster healthy fish habitat on excavated bench surfaces.

- Rockfill berm will be constructed at the bench crest to keep the substrate in place.
- Stable ground conditions (bench scale and overall slope scale) based on rock mass characterisation (including kinematics and long-term bench-scale and overall slope stability) are desirable where littoral zones are to be constructed, with preference given to locating littoral zones in bedrock.
- Bench cuts are limited to 10 m where possible to allow bench construction using a single blast.
- Bench cuts cannot encroach on existing infrastructure including dams, active roadways and pushbacks.
- Limited plucking of loose rock from ice scour or ice movement may occur where rock lies within about 1.5 m of the lake surface (typical ice thickness), but this is not expected to compromise littoral zone function.

A typical design cross-section through the conceptual littoral zone is shown in Figure 6 (Tetra Tech 2024).

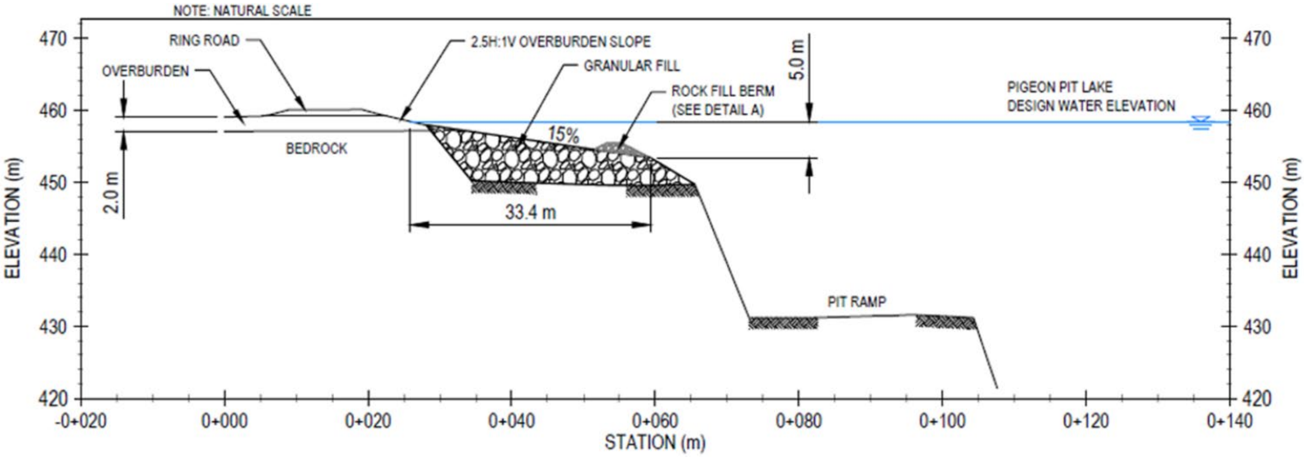


Figure 6 Typical cross-section through the littoral zone design

The base littoral zone surface will be covered with a minimum 0.5 m or greater layer of granular fill designed to achieve a maximum water depth of 5 m at the bench crest and sloped to establish aquatic ecosystems and fish habitat in pit lakes. The substrate material will provide spawning, rearing and nursery habitat for fish species found in the Ekati area. Substrate design will be completed as part of a detailed design.

Berms are designed around the littoral zone crests to retain the substrate material on the bench. The general berm design is shown in Figure 7 and consists of a 2 m-wide and 2 m-high berm with 2H:1V side slopes (Tetra Tech 2024).

5.1 Conceptual layouts

The RLZ along the top of the access ramp will develop naturally as the pit floods and will not require any modification other than placement of substrate material and construction of the substrate retention berm. The base of the littoral zone slopes down at 8.5% with a maximum width of 60 m.

The NLZ will be constructed using infill material along the upper bench. Infill material will be sourced from select blasted rock material from construction of the SLZ, for cost savings on processed granular material. The base width and grade will vary depending on the existing bench profile and height. Backslope angles are expected to be predominantly in till or overburden soils and have been designed at 2.5H:1V.

The SLZ will be constructed using a single blast approximately 5 m deep. The base of the littoral zone slopes down at 9 to 10% grade and has a maximum width of 61 m. The backslope angle will vary depending on the exposed backwall material. For cuts in rock, backslopes are designed at 0.5H:1V and will be created during blasting. For cuts in till or lacustrine materials, backslopes are designed at 2.5H:1V or shallower.

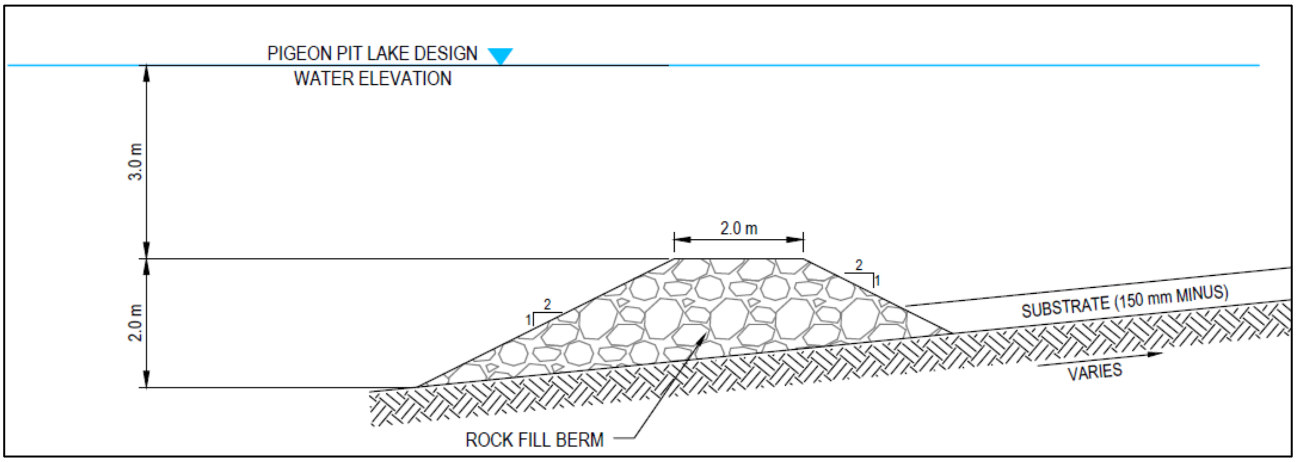


Figure 7 Typical substrate retention berm design

6 Littoral zones overburden backslope stability

Limit equilibrium stability analyses were carried out to evaluate the stability of the NLZ backslope using SLOPE/W™ software by Seequent Limited (2021), using the Morgenstern-Price method of slices on multiple slip surfaces.

Given the low consequence of failure, and the historical site design and construction experience, the minimum design factors of safety (FoS) used were 1.3 for a potential deep-seated slip surface through the overburden soils under long-term, normal post-construction conditions, and 1.1 for a potential failure under a design seismic event. These values are consistent with typical values for earthworks (Canadian Geotechnical Society 2006) and are considered appropriate for this site, given the littoral zones are largely in rock. Any instability in till will be relatively shallow and is not expected to impact long-term littoral zone performance.

A design cross-section in the NLZ was selected for stability analysis as the bench backslope is high and relatively steep, with overburden material up to 2 m in depth. The short-term, undrained case was not considered because no additional disturbance causing a sudden increase in pore pressures to the overburden layer (i.e. significant waste rock placement) is expected. The exposed overburden slopes are assumed to have thawed and stabilised after exposure for several years. Fluctuations in water elevations while in contact with the overburden layer are expected to be minimal; therefore excess pore pressures are not anticipated. Stability was evaluated for long-term normal loading and long-term seismic loading conditions.

6.1 Input parameters and backslope stability analysis results

While only limited soil index properties were available from the soil samples collected during previous drilling programs, these are considered reasonable and appropriate based on the authors' extensive site experience, work in similar northern environments with similar materials, and historical stability analyses. These are summarised in Table 1 (Tetra Tech 2024).

Table 1 Soil properties used in overburden stability analysis

Material	Unit weight γ (kN/m³)	Cohesion C (kPa)	Angle of internal friction ϕ (°)
Unfrozen till	19	0	30
Waste rockfill	20	0	42
Bedrock (impenetrable)	–	–	–

The stability of the representative overburden backslope was analysed under static and pseudo-static (seismic) limit equilibrium conditions. Table 2 summarises the results of the overburden slope stability analysis for the typical cross-section evaluated (Tetra Tech 2024). The results indicate that the calculated FoS exceeds the minimum required FoS for long-term shallow failures. Placement of a thin layer of rockfill over the exposed till slope could be considered for additional stability and protection against wave erosion.

Table 2 Summary of overburden backslope stability

Section evaluated	Loading condition	Minimum calculated Factor of Safety (FoS)	Minimum required FoS	Comments
Northwest littoral zone	Long-term, Static	1.5	1.3	Potential shallow failure through unfrozen till in inundation zone; low risk of failure
Northwest littoral zone	Long-term, Pseudo-static	1.3	1.1	Potential shallow failure through unfrozen till in inundation zone; low risk of failure

6.2 Seismic considerations

The pseudo-static analyses were completed using the peak ground acceleration (PGA) for an event with 2% probability of exceedance in 50 years (1 in 2,475-year event), where the seismic shaking is represented by a static, horizontal force that is equal to the PGA. A PGA of 0.0383g was used for pseudo-static analysis, based on the seismic hazard calculation (Natural Resources Canada 2020). The design return event is considered in relation to the criticality of the component and the impact of failure. The littoral zone back slopes are considered low consequence, and failure is not expected to have long-term impact on littoral zone performance. Higher seismic return periods are not considered warranted at this stage of design

7 Littoral zones rock mass quality and rock slope stability

The geotechnical considerations and conclusions relating to long-term stability of the littoral zones described in the following sections are based on previous design studies completed by Tetra Tech EBA (2013) and Zostrich (2014, 2016) for Pigeon Pit, coupled with observations of the current Pigeon Pit wall and overburden slope performance.

7.1 Geotechnical subsurface investigations

The geotechnical data used to develop the pit slope design criteria were collected over a period of several years from a variety of studies. These included: 10 oriented (clay imprint) boreholes drilled in 2007 and geotechnically logged using Laubscher's Mining Rock Mass Rating method (Laubscher 1977), and with geologic structures measured; 8 geotechnical boreholes drilled in 2012 and geophysically logged to collect acoustic and optical televiewer (ATV and OTV) data used to orient geologic structures, and geotechnically logged following the Rock Mass Rating 1976 (RMR76) methodology (Bieniawski 1976); and laboratory strength testing of selected samples of drill core to determine uniaxial compression, triaxial compression, discontinuity shear strength and tensile strength.

7.2 Slope design process and general slope design criteria

The operational pit slope design was developed using standard industry-accepted methods generally following the slope design process as outlined in Read & Stacey (2009).

7.3 Geological zones and geotechnical domains

The geology and structure are divided into geotechnical domains based on areas with similar rock mass quality, structural characteristics such as jointing, foliation or major structural trends. A plan map showing both the as-built pit, general geology and the defined geotechnical domains relative to the location of the planned littoral zones is shown in Figure 8 (Tetra Tech 2024).

During selection of conceptual NLZ, SLZ, and RLZ locations, geotechnical domains were reviewed to identify lower long-term stability risks. Table 3 summarises the key geotechnical hazards associated with each area (Tetra Tech 2024; Zostrich 2016).

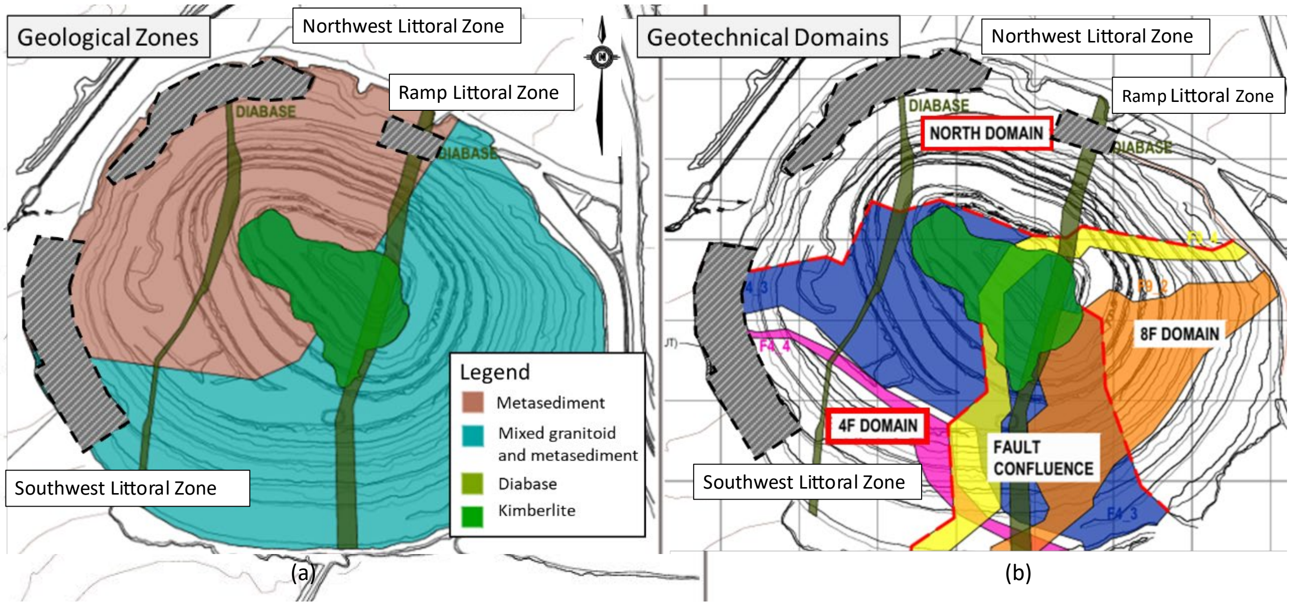


Figure 8 Pigeon Pit geological and geotechnical domains. (a) Geological zones; (b) Geotechnical domains

Table 3 Geotechnical domains, key hazards and qualitative risk of bench instability

Zone	Domain/ geology	Key hazards (kinematic assessment)	As-built bench face angle (°)	Observed bench and wall performance	Qualitative risk of bench instability impacting littoral zone
Northwest littoral zone Ramp littoral zone	North/ metasediments	Planar instability along south-dipping systematic joints if undercut Potential toppling Possible ravelling if intersecting diabase dyke or 5F_4 structure Potential wedges formed by intersecting joint structure	65–80	Very Good No toppling observed Absence of accumulated rockfall at toe and relatively intact bench crests indicative of long-term stability	Low
Southwest littoral zone	4F / Mixed granitoid and metasediments	Persistent discontinuities associated with F4-3 and F4-4, but sub-perpendicular to wall strike Steep east-dipping systematic structure. Potential toppling Potential wedges formed by intersecting joint structure	55–67	Good No toppling observed Absence of accumulated rockfall over time at toe	Low

7.4 Rock mass rating and geomechanical properties

Table 4 summarises the geomechanical properties based on laboratory testing (Tetra Tech EBA 2013).

Table 4 Summary of design geomechanical properties and rock quality for the major rock types

Lithology	Intact rock				RQD	RMR76	Classification
	UCS (MPa)	Tensile strength (MPa)	Cohesion (MPa)	Internal angle of friction (°)			
Granite	115.9	13.4	21.9	52.3	94.1	74	Good quality
Metasediment	131.9	13.2	27.6	46.9	95.1	74	Good quality
Diabase	207.6	–	73.0	17.7	66.5	73	Good quality

7.5 Rock Mass Rating 1976 block model

An RMR76 block model was developed using data collected from the geotechnical boreholes completed in 2007 and in 2012 (Tetra Tech EBA 2013). The block model was developed using Gemcom GEMS™ software version 6.3 (Dassault Systémes 2011).

Figure 9 shows illustrative cross-sections through the block model at the proposed littoral zone locations (Tetra Tech EBA 2013). The figure shows that all proposed littoral zone locations have rock mass classifications of good to very good quality rock, based on the RMR76 classification system.

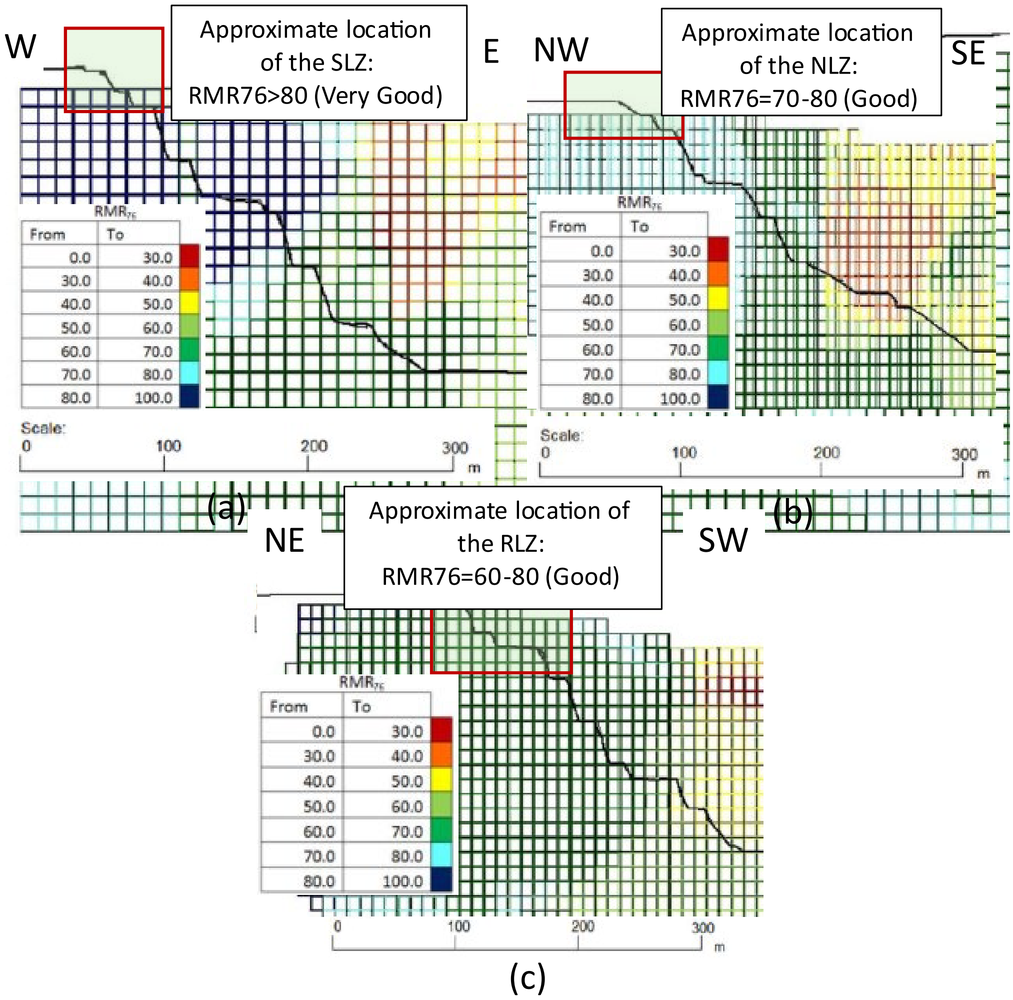


Figure 9 Rock mass rating (RMR) relative to proposed littoral zone locations. (a) Southwest littoral zone (SLZ); (b) Northwest littoral zone (NLZ); (c) Ramp littoral zone (RLZ)

8 Littoral zone geology and structure

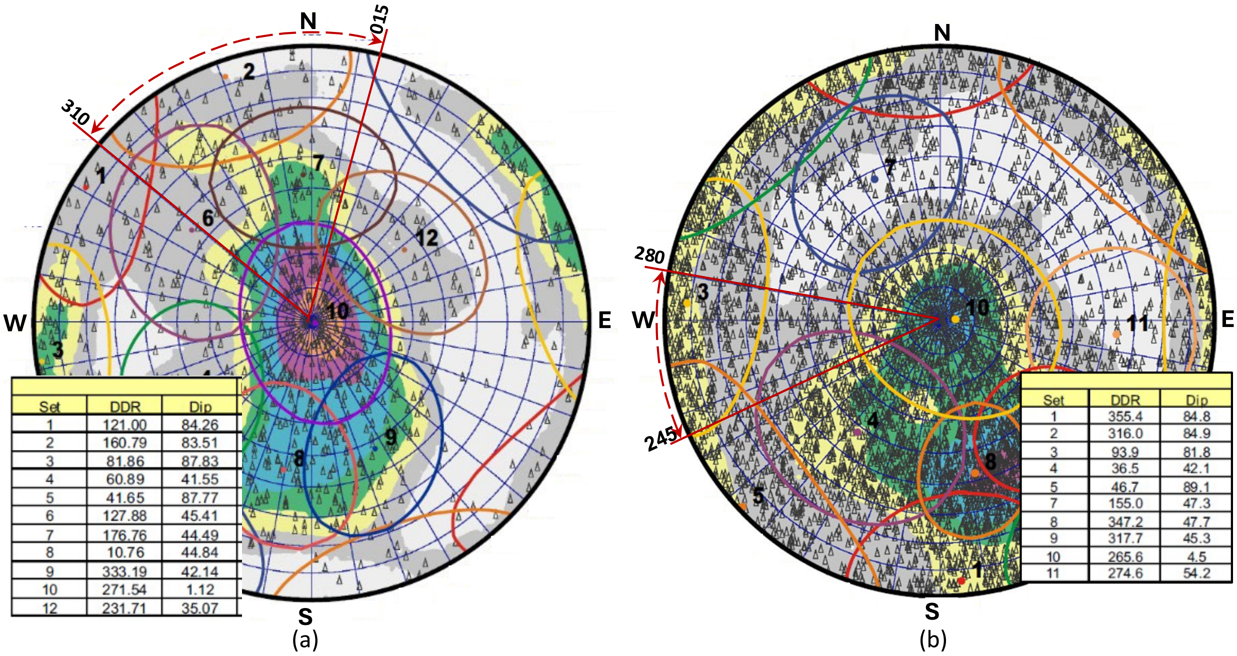
The host rock in the northwest half of the pipe is comprised of fine- to medium-grained biotite gneiss and schist. In the southeast half of the pipe the host rock is less clearly defined, with interbedded granitoids and metasediments forming the pit walls.

8.1 Faults

Tetra Tech EBA (2013) recognised 34 major potential faults and constructed a 3D fault model for the Pigeon Pit. The fault model indicated the southeastern part of the pit to be more affected by faults than other areas, and the northwest pit area where the NLZ and RLZ will be situated remained virtually unaffected by faults.

8.2 Rock fabric

A stereonet showing the rock fabric and structural orientations relative to the range of wall sector azimuth for the NLZ, RLZ and SLZ is shown in Figure 10 (after Zostrich 2016, Figure 4.1).



Set	DDR	Dip
1	121.00	84.26
2	160.79	83.51
3	81.86	87.83
4	60.89	41.55
5	41.65	87.77
6	127.88	45.41
7	176.76	44.49
8	10.76	44.84
9	333.19	42.14
10	271.54	1.12
12	231.71	35.07

Set	DDR	Dip
1	355.4	84.8
2	316.0	84.9
3	93.9	81.8
4	36.5	42.1
5	46.7	89.1
7	155.0	47.3
8	347.2	47.7
9	317.7	45.3
10	265.6	4.5
11	274.6	54.2

Figure 10 Kinematic controls showing structure dip and dip direction (DDR) and range of wall sector azimuth for the littoral zones (LZ): (a) Northwest LZ and Ramp LZ North domain; (b) Southwest LZ 4F domain

The main kinematic consideration for bench stability for the proposed NLZ and RLZ is the steeply (~80^{o}) south to southeast dipping set 2. Subordinate discontinuity sets (sets 6 and 7) also exist and could present the potential for planar sliding. The main kinematic consideration for bench stability for the proposed SLZ is a steeply east-dipping discontinuity set (set 3), inclined approximately at 82° towards 094° azimuth (Zostrich 2016). The observed performance of the benches below the proposed littoral zones suggests the bench design criteria used for mining are appropriate for longer-term bench-scale stability.

8.3 Overall slope stability

Tetra Tech EBA (2013) completed 2D limit equilibrium slope stability modelling to assess overall slope stability using SLOPE/W software. The results of the modelling indicated FoS ranging from 3.1 to 5.0.

The site is considered to have low seismic risk, with minimal likelihood of pit slope instability due to seismic activity. *The Mine Health and Safety Act* of Nunavut does not specify seismic design criteria for open pit rock slopes, and there is limited evidence of seismic-induced failures in hard rock conditions (Read & Stacey 2009). As such, seismic loading was not assessed.

Two-dimensional finite element analyses were completed by Zostrich (2014, 2016) to assess the overall slope stability under gravitational strain conditions. The analyses were completed using Rocscience's Phase 2 (Ver. 8.024) finite element modelling software. The results are summarised in Table 5 (Zostrich 2024,2016).

Table 5 Summary of finite element numerical modelling slope stability results from previous studies along relevant cross-sections

Littoral zone	Range in wall sector azimuth (°)	Geotechnical domain	Study year	Reference cross-section from previous study report	Strength reduction factor
Northwest Littoral Zone	310–000	North	2014	Section 330	5.09
			2016	Section 9	2.15
				Section 10	3.28
Ramp Littoral Zone	015	North	2014	Section 017	4.24
			2016	Section 11	2.77
Southwest Littoral Zone	245–280	4F	2016	Section 7	2.10–3.62

The currently observed post-mining stability of the pit walls and the absence of any significant bench-scale, multi-bench or inter-ramp slope instability in the areas of the proposed littoral zone developments suggests that long-term stable slope conditions can be expected.

8.4 Current bench performance

Figure 11 below shows the west wall of the Pigeon Pit and the outline of the proposed SLZ (Tetra Tech 2024). A steeply dipping diabase dyke intersects the pit wall at the south end of the SLZ and is not considered to be adversely oriented for wall stability. The benches directly below the proposed SLZ were well cleaned during mining and there is little to no accumulation of additional material, indicating good wall performance. The bench crest is intact.

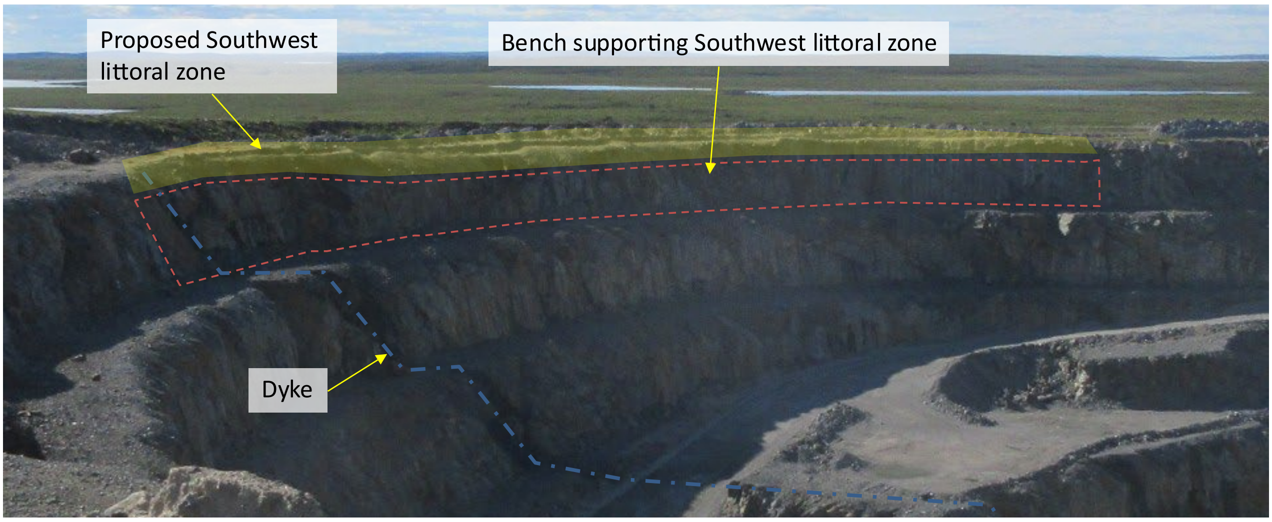


Figure 11 West wall showing the proposed Southwest littoral zone

Figure 12 shows the proposed NLZ outline, current bench performance and the overburden backslope to the ring road (Tetra Tech 2024). Little to no material has ravelled from the backslope onto the upper bedrock bench, which was well cleaned during mining. No material has accumulated on the ramp below and the bench crest is intact. The ring road also appears stable, with no signs of thermokarst or subsidence. However, once the pit is flooded, prolonged ponding against the ring road might eventually lead to surface subsidence.

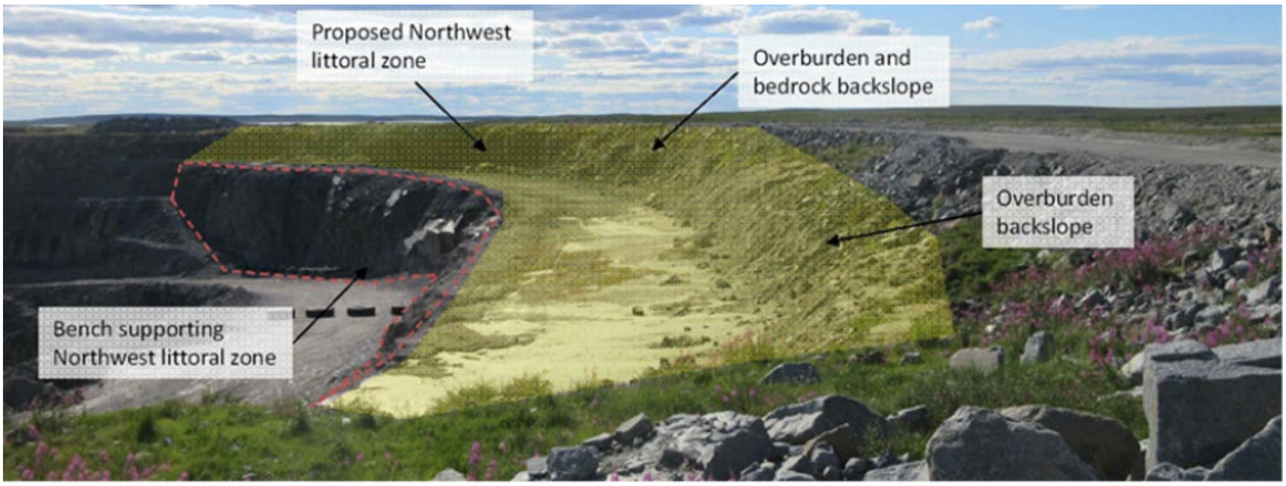


Figure 12 West facing view and the proposed Northwest littoral zone

Figure 13 (facing northeast) shows the location of the proposed RLZ, which will use the existing ramp at an elevation suitable for the fish habitat (Tetra Tech 2024). The ramp enters the pit near natural ground level, and the diabase dyke intersects the wall at a high angle without stability concerns. Current ramp and bench performance is good, with no notable debris accumulation below the ramp, indicating continued stability of the proposed littoral zone.

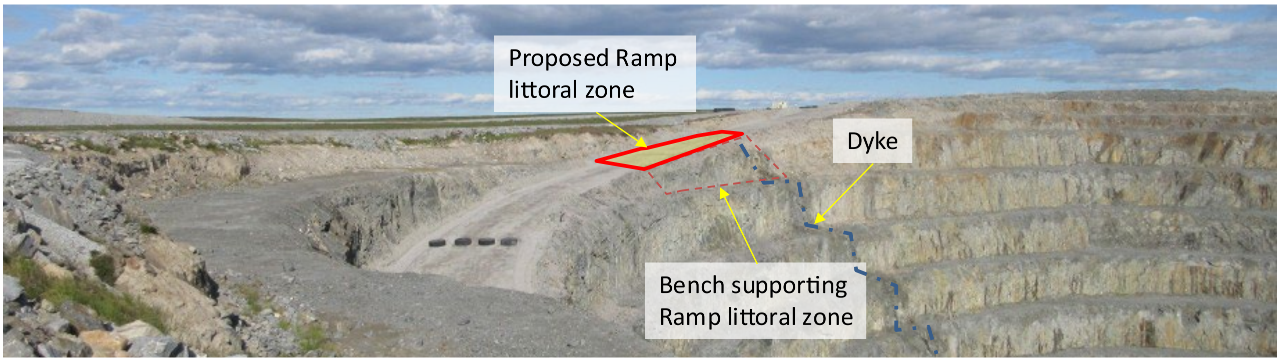


Figure 13 Northeast facing view and the planned Ramp littoral zone

8.4.1 Expected bench performance during lake filling

As the pit fills, heat transfer from the lake will modify the existing permafrost regime, creating an estimated 30 m-deep thaw zone that extends into the pit walls. This may loosen shallow blocks and cause minor, localised instability, but deeper-seated stability is not expected. These conclusions are supported by the stability analyses along cross-sections corresponding to the littoral zone areas, as well as current post-mining observations at the bench, inter-ramp and overall slope scales. Collectively, the evidence indicates long-term stability during and following filling will be satisfactory, with any instability limited to shallow block loosening during filling or ice-related plucking near the water surface.

9 Conclusion

The existing pit walls, overburden slopes and bedrock domains present a low risk of long-term instability. Bench performance near the proposed littoral zones is good, with minimal ravelling and intact crests, and stability analyses indicate factors of safety that exceed the design criteria under both static and pseudo-static conditions. Expected permafrost thaw during lake filling is not anticipated to affect pit wall stability or the performance of the littoral zones. As the pit fills, heat transfer from the lake will modify the existing permafrost regime, creating an estimated 30 m-deep thaw zone that extends into the pit walls and may loosen shallow blocks and cause minor, localised instability. Overall, the closure approach reflects sound hydrotechnical and geotechnical design for establishing a stable, habitat-supporting pit lake as part of the progressive reclamation activities outlined in the interim closure and reclamation plan for the mine and is consistent with current industry standard practice.

Current observations in the Northwest , Ramp and Southwest littoral zones indicate that the likelihood of bench-scale or overall slope instability during pit filling or long-term operation of the flooded pit is low. Bench conditions remain strong, with intact crests, minimal ravelling and no meaningful accumulation of rockfall at bench toes or loss of catchment width in areas planned for littoral zone development. Similar performance is expected following flooding. Limited plucking of loose rock from ice scour, or ice movement, may occur where rock lies within about 1.5 m of the lake surface (approximate ice thickness), but this is not expected to compromise littoral zone function.

Some settlement of the ring road may occur as lake levels rise but this will not affect closure activities as no further traffic is planned. Any sediment introduced by future rockfall would disperse naturally and is not expected to impact water quality.

Acknowledgement

Tetra Tech would like to acknowledge the support of Burgundy Diamonds’ Chris Auld, Tania Robitaille and Gibran Lopez for making this paper possible by providing review and comments. Tetra Tech thanks the management of Burgundy Diamonds for permitting this experience to be shared with the mining community.

Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used Microsoft Co-Pilot M365 (Version 19.2604.33131.0) to improve the clarity of writing certain paragraphs to assist with reducing the overall paper length. The authors have reviewed the content and edited it where required and take full responsibility for said content.

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