Volume 1 Annex V1-7 Type A Water Licence Applications

Package P5-3

Hope Bay Project: Contact Water Pond Berm Design

TMAC RESOURCES

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Memo

To:	John Roberts, PEng, Vice President Environment Oliver Curran, MSc, Director Environmental Affairs	**Client:**	TMAC Resources Inc.
From:	Erick Lino, Cameron Hore, CPEng, PEng	**Project No:**	1CT022.013
Reviewed:	Arcesio Lizcano, PhD Maritz Rykaart, PhD, PEng	**Date:**	November 30, 2017
Subject:	Hope Bay Project — Contact Water Berm Design		

1 Introduction

1.1 General

The Hope Bay Project (the Project) is a gold mining and milling undertaking of TMAC Resources Inc. The Project is located 705 km northeast of Yellowknife and 153 km southwest of Cambridge Bay in Nunavut Territory, and is situated east of Bathurst Inlet. The Project comprises of three distinct areas of known mineralization plus extensive exploration potential and targets. The three areas that host mineral resources are Doris, Madrid, and Boston.

The Project consists of two phases: Phase 1 (Doris project), which is currently being carried out under an existing Water Licence, and Phase 2 (Madrid-Boston project) which is in the environmental assessment and regulatory stage. Phase 1 includes mining and infrastructure at Doris, while Phase 2 includes mining and infrastructure at Madrid and Boston located approximately 10 and 60 km due south from Doris, respectively

Contact water ponds (CWPs) will be constructed at the Madrid North, Madrid South, and Boston sites to intercept contact water runoff (SRK 2017a, 2017b). The CWPs will normally be kept in a dry state with a two-week (i.e. fourteen-day) residence time for water in the pond. The CWPs are unlined ponds that use the permafrost and naturally low permeability of the foundation materials to contain the contact water on the bottom of the pond and a geomembrane acts as the impermeable layer within the berm. The contact water pond berm design hinges on the contact between the geomembrane and permafrost soil remaining frozen.

At the Boston site, within CWP #2 (internal to the CWP berm and key trench) a surge pond will be created by fully lining a section of the CWP. The surge pond is a fully lined pond and is designed to act as surge capacity for the water treatment plant to even out water treatment plant inflow rates (SRK 2017b). The CWP berm provides the final environmental containment, by the liner tied into the key trench within the CWP berm. As such, the key design feature is the CWP berm which is the focus of this memo. An outline of how the surge pond is constructed within the CWP is also provided.

All CWPs across the Madrid North, Madrid South, and Boston sites will be constructed with the same berm design.

1.2 Objectives

This memo presents the geotechnical design of the CWP Berms for Phase 2 of the Hope Bay Project. The methods, assumptions, and results of the stability analyses completed for the Berms is presented. The analysis considers overall stability along a critical cross-section of the berms for both static and pseudo-static conditions.

Thermal modelling was completed to demonstrate that the contact water ponds would thermally perform as expected, and this analysis is provided in Attachment 1.

Hydrotechnical design and an alternatives assessment of the CWPs is presented in the site-specific Water Management Design Reports (SRK 2017a, 2017b).

2 Design Concept

2.1 Approach

The overall design concepts for the CWP berms is based on the unlined pond design which uses the permafrost and naturally low permeability of the foundation materials to contain the contact water on the bottom of the pond, and a geomembrane liner acts as the impermeable layer within the berm. This design hinges on the contact between the geomembrane and permafrost soil remaining frozen. A typical design has been developed for implementation at all sites.

2.2 Components

The CWP berms will consist of a liner system, a key trench (tie into frozen foundation), bulk fill (thermal insulation) and the road surface (berms will be used as an access road).

2.3 Foundation Conditions

Detailed studies and site inspections have not been performed along the entire length of the proposed berm alignments. The Doris, Madrid and Boston areas; however, have been well studied (SRK 2017c), and it is expected that foundation conditions and geology along the berm alignments are similar. Additional geotechnical investigation will be carried out prior to detailed design.

Permafrost at the Project area extends to depths of about 570 m and are absent beneath some large lakes. The ground temperature near the depth of zero annual amplitude ranges from −9.8 to −5.6°C, with an average of −7.6°C. Active layer depth based on ground temperatures measured in overburden soil averages 0.9 m with a range from 0.5 to 1.4 m. The average geothermal gradient is 0.021°C/m.

Permafrost soils are comprised mainly of marine clays, silty clay and clayey silt, with pockets of moraine till underlying these deposits. The most prevalent rock type on site with surface exposure is mafic volcanics, predominantly basalt. The marine silts and clays contain ground ice on average ranging from 10 to 30% by volume, but occasionally as high as 50%. The till typically contains low to moderate ice contents ranging from 5 to 25%.

Overburden soil pore water is typically saline due to past inundation of the land by seawater following deglaciation of the Project area. The salinity typically ranges from 37 to 47 parts per thousand which depresses the freezing point and contributes to higher unfrozen water content at below freezing temperatures.

3 CWP Berm Design

3.1 Berm Design Criteria

Berm specific design criteria are listed below:

- The pond will be normally empty (i.e. the pond will be kept in a dry state);
- Maximum residence time for ponded water is two weeks;
- 20-year design life;
- Effects of climate change during the 2011 to 2040 time frame will be considered;
- Berms that make up the pond will be used as an access road;
- Berms will be constructed from geochemically suitable ROQ rock or ROM waste rock; and
- Permafrost damage within the pond should be minimized.

3.2 Liner System Design Criteria

Liner system specific design criteria are listed below:

- Containment liner to be textured high-density polyethylene (HDPE) liner;
- HDPE to be protected by heavy duty (12 oz) non-woven geotextile from all material except in-situ overburden (silt and clay);
- Minimum 0.3 m thick layer of bedding material (crushed and screened geochemically suitable quarry or waste rock material) between the non-woven geotextile (covering the HDPE) and ROQ or transition material;
- Maximum internal (within berm structure) geomembrane slope of 1.5H:1V (33.6°);
- Maximum external (exposed) geomembrane slope of 2H:1V (25.5°);
- Minimum of 1 m cover between the top of the geomembrane and the driving surface;

3.3 Design

The key features of the CWP berm design are listed below and shown in CWB-01 (Attachment 2):

- 8 m wide crest;
- Side slopes of 2H:1V (26.5°);
- 2.5 m minimum thickness thermal insulation to ensure the contact between the geomembrane and permafrost soils remains frozen;
- Two thermistors to monitor thermal performance of the berm. Should monitoring data indicate that temperatures within the berm are warmer than expected and the liner tie-in is in danger of thawing, additional fill material can be placed on top of the berm to provide additional insulation;
- Minimum of 1 m cover between the top of the geomembrane and the driving surface;
- Internal (within berm structure) geomembrane slope of 1.5H:1V (33.6°);
- External (exposed) geomembrane slope of 2H:1V (25.5°)
- Textured high density polyethylene (HDPE) liner sandwiched between two layers of heavy duty non-woven geotextile, except in the liner key trench; and
- Two 0.3 m thick layers of bedding material (crushed and screened geochemically suitable quarry or waste rock material) surrounding the HDPE liner, except in the key trench (bedding on upper side only).

4 Stability Assessment

4.1 Stability Criteria

4.1.1 Minimum Factors of Safety

A factor of safety (FOS) is defined as the ratio of the forces tending to resist failure (i.e. the material's shear strength) over the forces tending to cause failure (i.e., the shear stresses) along a given surface. The selection of a design FOS must consider the level of confidence in the factors that will control stability, i.e., material properties, analysis methods, and consequences of failure.

Design FOSs are generally defined through various industry best practice standards and guidelines, and for dams, the most notable guideline is the Canadian Dam Association (CDA) Guidelines (CDA, 2014). Table 1 summarizes the recommended minimum design FOSs in accordance with the CDA (2014). These values are used as guidelines for the stability of the CWP berm.

Table 1: Minimum Factors of Safety Used for Slope Stability Analysis (CDA, 2014)

Loading Condition	Minimum Factor of Safety	Slope
During or at end of construction	>1.3 depending on risk assessment during construction	Typically downstream
Long term (steady state seepage, normal reservoir level)	1.5	Downstream
Full or partial rapid drawdown	1.2 to 1.3	Upstream slope where applicable
Pseudo-static	1.0	Downstream
Post-earthquake	1.2	Downstream

The most conservative design values were used in this analysis; i.e., 1.3 for short-term static stability, 1.5 for long-term static stability, and of 1.1 for pseudo-static stability.

4.1.2 Seismic Design Parameters

The CDA (2014) provides recommended minimum seismic design criteria based on the hazard classification assigned to the structure. Assuming a hazard classification of LOW, the CDA (2014) specifies the design earthquake with an annual exceedance probability (AEP) of 1/100 for the construction and operations stage. For long-term scenarios, i.e., post-closure, the design seismic event must be increased to 1/1,000-year event. The stability analysis was conservatively undertaken using the earthquake with AEP of 1/2,475.

SRK completed a site-specific seismic assessment for determining horizontal and vertical seismic parameters to be used in pseudo-static slope stability analysis modeling on the Project site (SRK, 2016). This analysis determines the horizontal seismic coefficient by reducing the site-adjusted PGA based on slope height and allowable deformation. The method assumes an allowable deformation of 1 to 2 inches (25 to 51 mm) for a seismic FOS of 1.1. While a larger allowable deformation is unlikely to affect the stability of the facility, such criteria was thought to be appropriately conservative. The horizontal seismic coefficients for the CWPs was determined to be 0.018 g, resulting from a 1/2,475-year return period earthquake.

4.2 Stability Analysis

4.2.1 Conceptual Model

A single critical cross-section of the CWP berm was assessed for overall stability. Since the CWP berm foundations is not expected to show significant variability, the critical section was deemed to be where the CWP berm be at its maximum overall height of 4.6 m. The CWP berm will be constructed with an upstream and downstream and slope of 2H:1V (26.5°). The section of the CWP berm that includes the surge pond has an expanded footprint and flatter overall upstream slope and an identical downstream slope (CWB-01 Attachment 2). Therefore, the typical CWP berm section is the critical section to assess for slope stability.

The model includes the foundation (frozen and thawed), a run-of-quarry (ROQ), a transition material, a bedding material and a geosynthetic liner (HDPE). Figures 1 and 2 illustrate the plan view and design cross-section of the CWP berm, respectively.

4.2.2 Method of Analysis

The stability of the critical section was assessed using the finite element code PLAXIS (Plaxis, 2017) and the strength reduction technique to fully develop a failure mechanism. The assessment was completed using 2D plane-strain conditions with 15-node elements. The generated finite element model consisted of 11,291 soil elements, 92,171 nodes, and an average element size of 2.2 m. Thermal conditions at the CWP berm site were considered in the model according to the thermal modeling results (Attachment 2). The thermal conditions at year 20 presented in Figure 3 were assumed as representative to define the frozen and thawed foundation in the model. The -2°C isotherm defines the freezing temperature. The finite element model implemented in PLAXIS considers both frozen and thawed condition are shown in Figures 4 and 5, respectively.

The finite element model was analyzed using the Mohr-Coulomb constitutive model for all materials, including the ice-rich frozen soils. The analysis considered a fully coupled deformation-flow procedure with the following simulation steps:

- Construction stages;
- Flow induced by the water retained with the berm (seepage analysis); and
- Calculation of the FoS using the strength reduction technique.

The construction stages (staged construction in PLAXIS) was performed for the phases shown in Figure 7 and described below:

- Initial condition (frozen or thawed foundation);
- Construction of the transition and lower bedding material;
- Excavation of trenches;
- Placement of the HDPE geomembrane and upper bedding material; and
- Placement of the bulk fill ROQ material.

The seepage analysis was performed to evaluate the effect of the Full Supply Level (FSL) on the stability of the upstream slope, notwithstanding a filtration through the berm and its foundation is prevented with the impermeable liner and the frozen foundation. The analysis required a fictitious water head at the downstream side, which was removed once the water level in the berm was established for the analysis.

The analysis with PLAXIS was completed for both static and pseudo-static conditions with the predefined phreatic surface. Below is a summary of the conditions considered in the analysis.

Static Analysis

A static long-term analysis was performed using parameters of the drained soil. Stiffness and strength were defined in terms of effective soil properties. The frozen and thawed foundation were addressed.

Pseudo-Static Analysis

The pseudo-static analysis was completed for both frozen and thawed foundation considering a horizontal seismic coefficient of 0.018 g (Section 2.2).

Creep effects of the frozen marine silt and clay on the stability of CWP berm were not assessed. Due to the low height of the CWP berm, the induced deviatoric stresses in the frozen soils will be very low (around 30 kPa) at the end of the construction. SRK has established a threshold stress of 30 kPa to activate the creep in the frozen marine silt and clay (SRK 2017d), creep of the frozen marine silt and clay is not expected because of the very low CWP berm load.

4.2.3 Material Properties

Sub-surface investigations within the footprint of the proposed CWP berm have not yet been carried out. Material properties for the analysis were therefore based on the site wide geotechnical design properties (SRK, 2017c). Table 2 summarizes the main properties used in the analysis.

Table 2: Material Properties

Property	Symbol	Unit	Unit 01: ROQ (Thawed)	Unit 02: Marine Clay (Frozen)	Unit 03: Marine Clay (Thawed)	Unit 04: Bedding Material	Unit 05: Transition Material (Crushed Rock)
Unit weight	γ	kN/m³	20.0	17.0	17.0	18.0	18.0
Young's modulus	E	MPa	175	150	5	50	50
Poisson's ratio	v	-	0.3	0.3	0.3	0.3	0.3
Cohesion	c'	kPa	0	112	0	0	0
Angle of friction	φ'	º	40	26	30	36	36
Angle of dilatancy	ψ	º	0	0	0	0	0
Horizontal permeability	k_x	m/s	5.0E-3	4.6E-10	4.6E-10	5.0E-4	5.0E-3
Vertical permeability	k_v	m/s	5.0E-3	4.6E-10	4.6E-10	5.0E-4	5.0E-3

The HDPE-geotextile interface (Figure 6) was considered the most critical plane in the analysis. Based on published data (Stark *et al*., 1996 and Bacas *et al*., 2015), a peak friction angle of 28 degrees was assigned to the interface between a 1.5-mm-thick textured HDPE and a nonwoven geotextile made of needle-punched monofilaments with a mass per unit area of at least 500 g/m^2.

5 Results

The results of the stability analysis are summarized in Table 3. Complete details are presented in the Figures 8 to 11.

Table 3: Slope Stability Analysis Results

Condition	Foundation	Long-term FOS	Pseudo-Static FOS
		1.5	**1.1**
Without water pressures	Frozen	1.5	1.4
	Thawed	1.5	1.4
Considering water pressures (with seepage analysis)	Frozen	1.5	1.3
	Thawed	1.5	1.3

The designed CWP berm meets the stability FOS criteria of 1.5 for long-term conditions and 1.1 for pseudo-static stability.

6 Construction

All construction fill materials will be obtained from geochemically suitable permitted quarries or geochemically suitable run of mine rock. Management and monitoring of these quarries will be according to the quarry management and monitoring plan (TMAC 2017). Surfacing (32 mm minus), bedding (19 mm minus), and transition (150 mm minus) materials will be produced at an on-site crusher located within one of the proposed quarries.

Based on previous surface infrastructure construction on the Project, it is assumed that the construction fleet will consist of CAT 730 haul trucks, CAT 773 haul trucks, CAT D8 dozers, CAT C330 excavator(s), CAT CS563 compactor and a crusher.

Prior to construction, the berm alignments should be cleared of snow and ice. Near-surface massive ground ice intercepted by the key trench may be removed if detailed analysis confirms the need for it. At no time will disturbance of the tundra vegetation or soils be allowed outside of the infrastructure footprint. Initial construction fill (transition material internal berm) will be placed by end-dumping on the existing road or pad surface and pushing the dumped material with a bulldozer. Placement of bedding material and excavation will occur from adjacent to the constructed berm within the final CWP berm footprint. The liner system will only be installed once the design surface of the bedding material and key trench excavation have been surveyed and approved by the supervising engineer. Placement of bedding material of the liner system will occur from the constructed berm or from within the final CWP berm footprint. Placement of the bulk fill ROQ material will only occur once the design surface of the bedding material and key trench excavation have been surveyed and approved by the supervising engineer. Surfacing material will not be placed until the ROQ material layer is at design grade and level.

Installation of the liner system to create the surge pond will occur at the same time as installation of the liner system for the outer CWP berm. Within the lined base area the upper overburden will be removed. The excavated overburden materials will be placed in the overburden pile associated with a nearby quarry. Once the liner system is placed no traffic will be allowed on the liner.

All construction should be performed in accordance with the technical specifications (SRK 2011).

Wherever possible, the entire berm will be constructed in the winter to ensure the foundation materials remain frozen. Some summer construction may be required to meet development schedules. This will be limited to initial construction fill (transition material internal berm), the key trench excavation will only occur during winter. Winter and summer initial berm end-dumping construction techniques will be identical; however, summer construction will result in the use of more construction material as greater imbedding of material into the active layer will occur. Summer construction will also require screening of the site for nesting birds, and modifications to the construction schedule may be required to avoid disturbing nesting birds.

Excavation into overburden soils will not be permitted, except where otherwise specified in the design drawings (e.g., key trench). The excavated overburden materials will be placed in the overburden pile associated with a nearby quarry.

Routine visual inspections of berms will be carried out by operational staff and by the engineer of record during annual inspections and if areas are identified requiring maintenance that will be carried out using similar materials used for initial construction.

7 References

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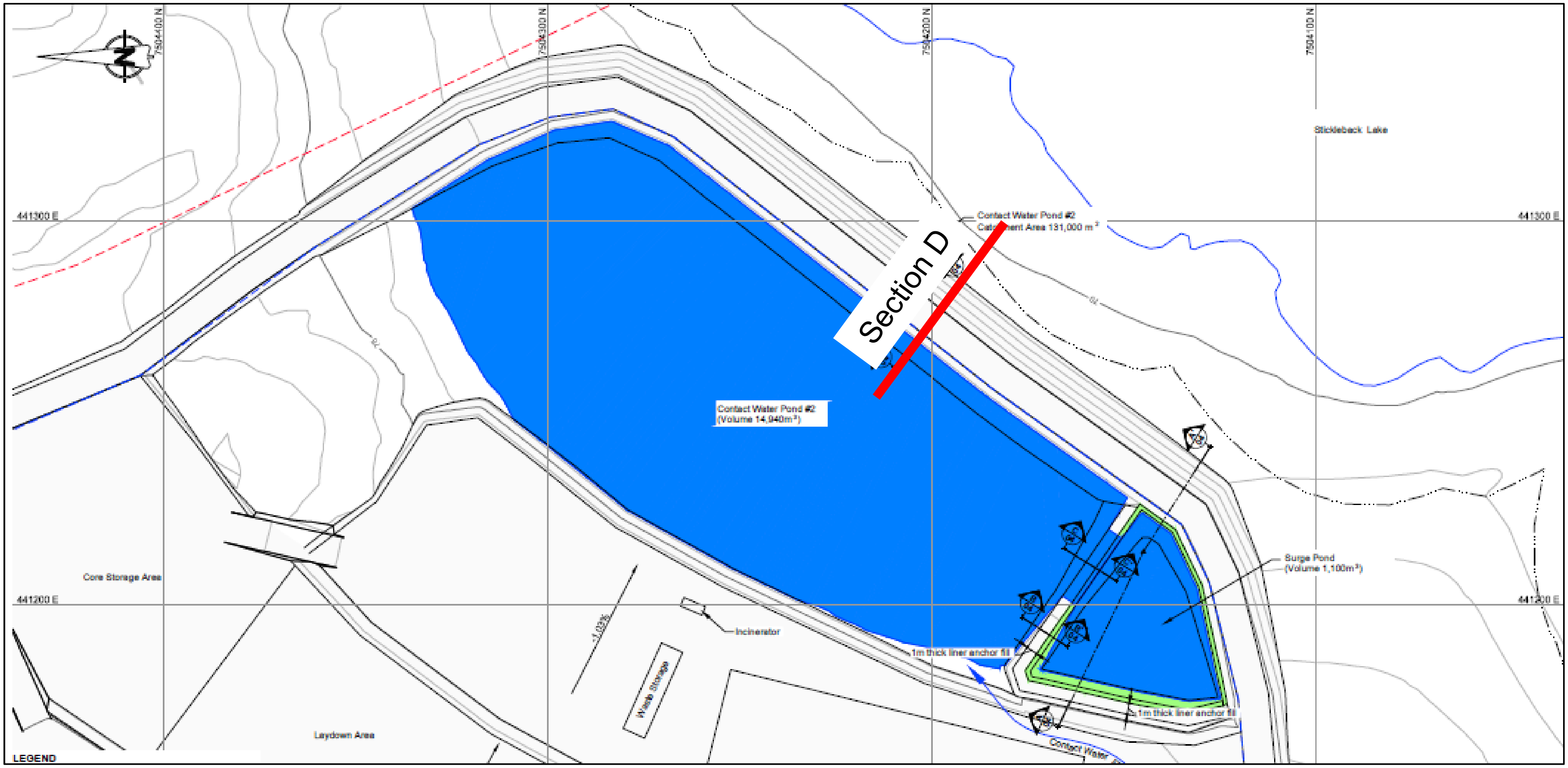
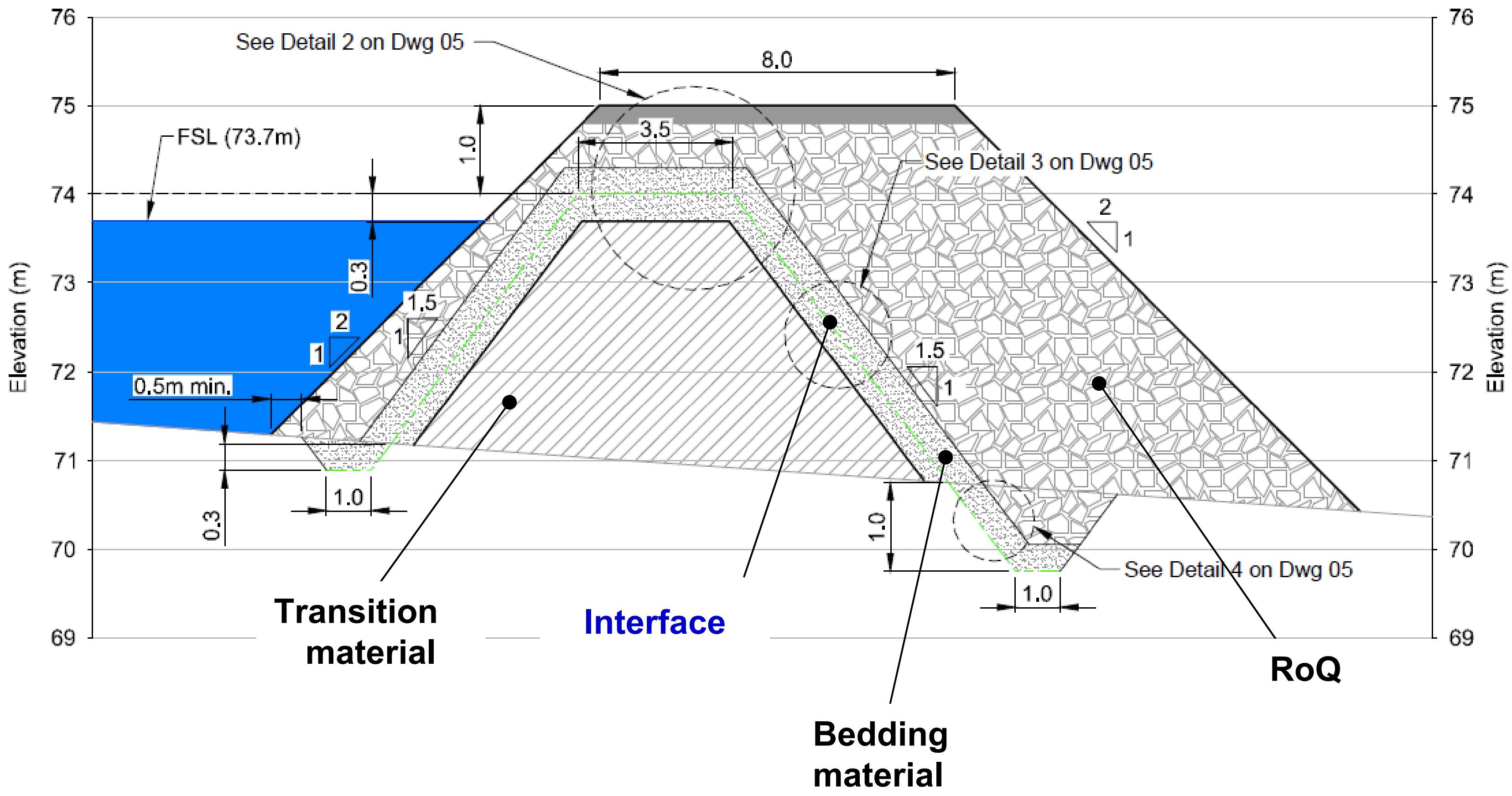
Figures



srk consulting	MAC RESOURCES	CWB Stability Analysis
		Contact Water Berm General Arrangement
Job No: 1CT022.013 Filename: Boston_CWB_StabilityAnalysis_Memo_Figures_1CT022-013_Rev01_EL_al	HOPE BAY PROJECT	Date: 11/24/2017 | Approved: EL | Figure: 1

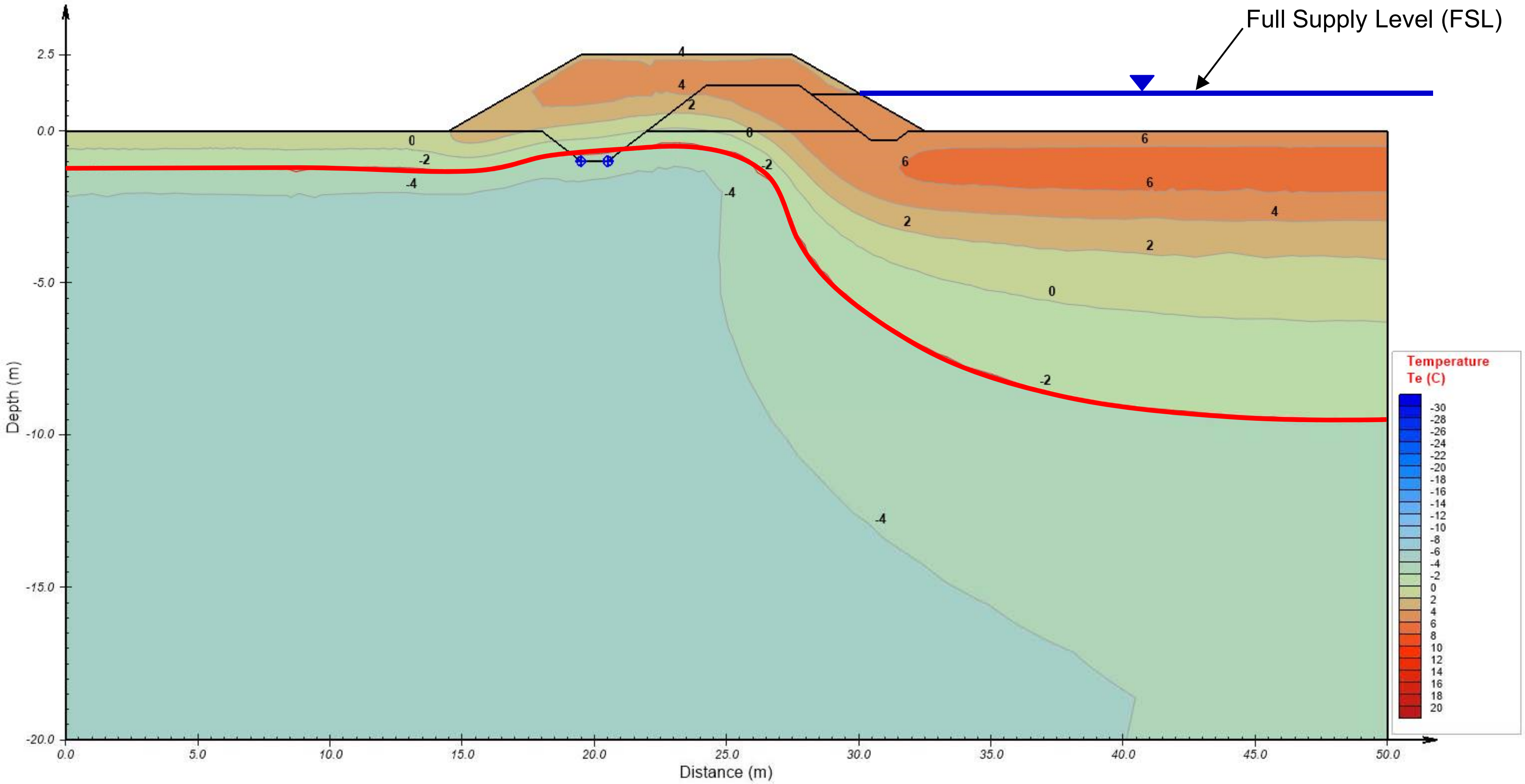
Section D-D



Notes:

1. Sections have 3x Vertical Exaggeration

srk consulting	MAC RESOURCES	CWB Stability Analysis
		Contact Water Berm Typical Section
Job No: 1CT022.013 Filename: Boston_CWB_StabilityAnalysis_Memo_Figures_1CT022-013_Rev01_EL_al	HOPE BAY PROJECT	Date: 11/24/2017 · Approved: EL · Figure: 2

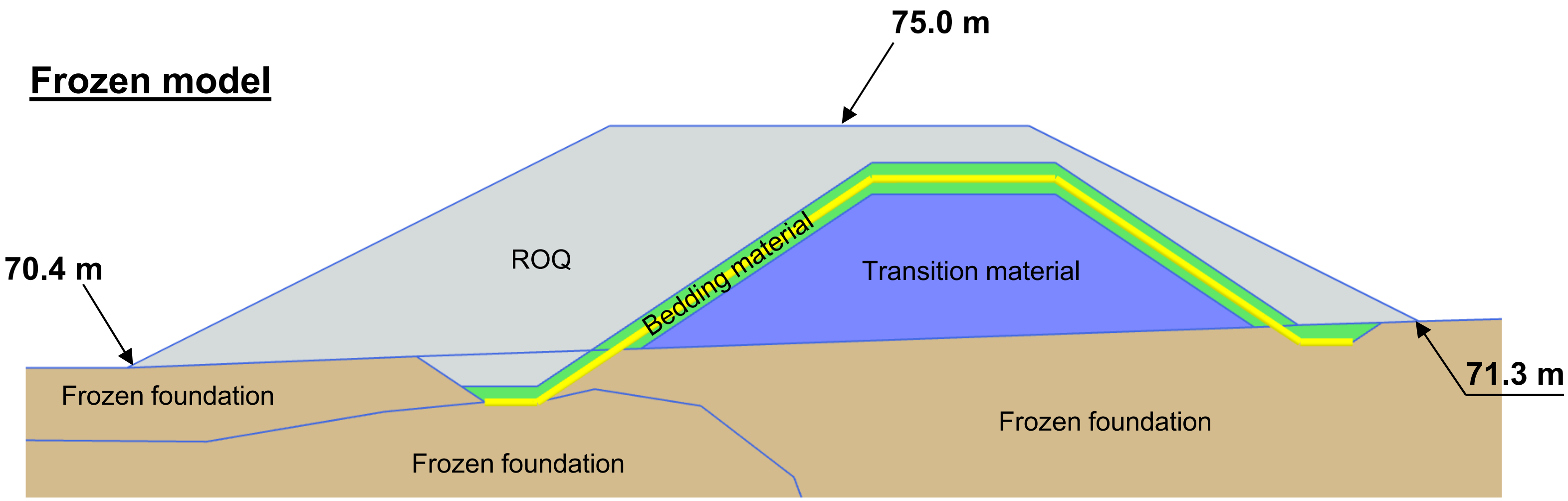


Notes:

1. Model section represents maximum position of -2°C isotherm (solid red line) during Year 20
2. Model results for minimum berm thickness of 2.5 m
3. CWP – Contact water pond

srk consulting	MAC RESOURCES	CWB Stability Analysis
		Thermal Model Results CWB (Year 20)
Job No: 1CT022.013 Filename: Boston_CWB_StabilityAnalysis_Memo_Figures_1CT022-013_Rev01_EL_al	HOPE BAY PROJECT	Date: 11/24/2017 · Approved: EL · Figure: 3

Frozen model



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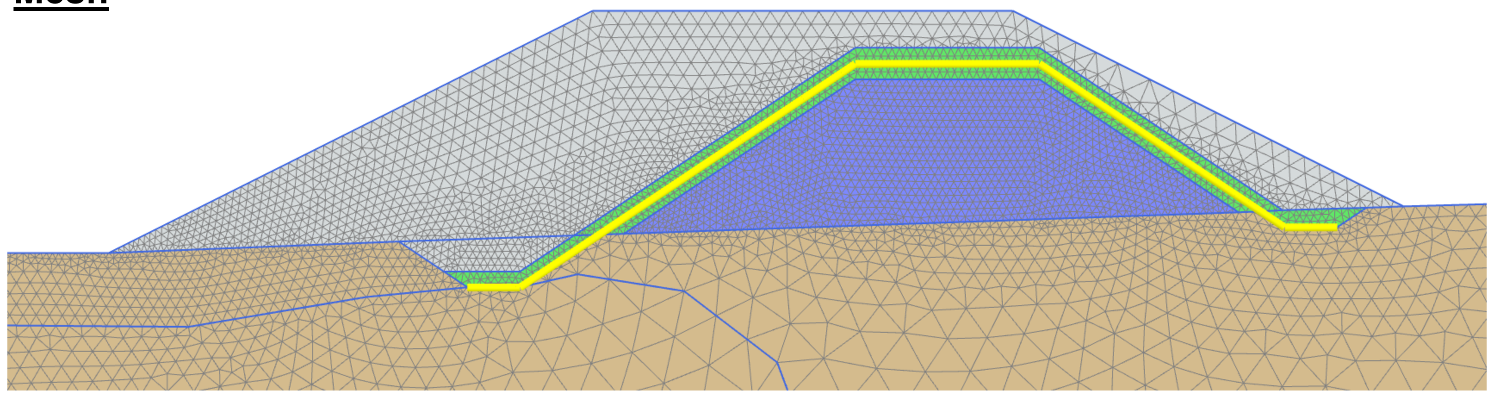

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CWB Stability Analysis

CWB Model
Frozen Foundation

Job No: 1CT022.013

Filename: Boston_CWB_StabilityAnalysis_Memo_Figures_1CT022-013_Rev01_EL_al

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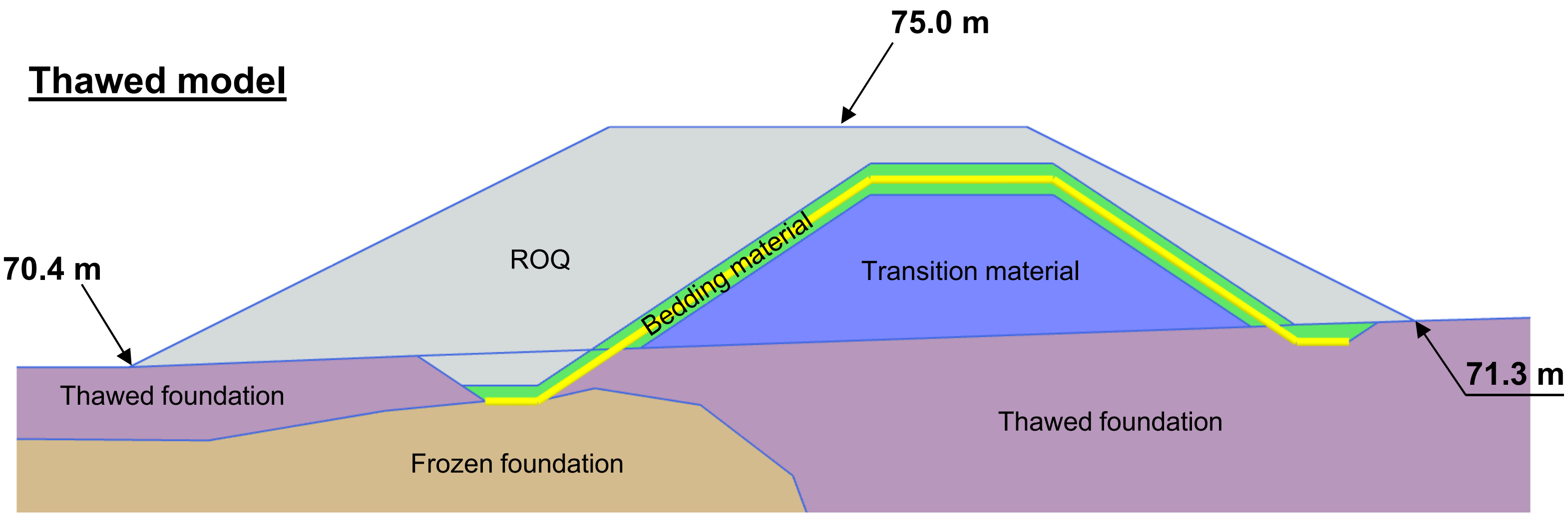
Figure: 4

Thawed model



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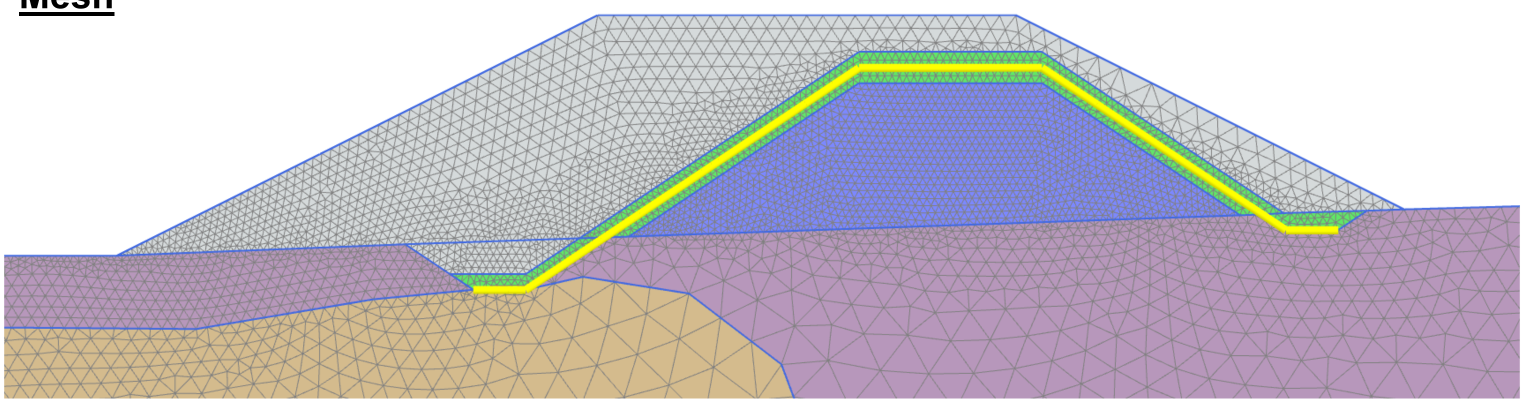

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CWB Stability Analysis

CWB Model
Thawed foundation

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Filename: Boston_CWB_StabilityAnalysis_Memo_Figures_1CT022-013_Rev01_EL_al

HOPE BAY PROJECT

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Figure: 5

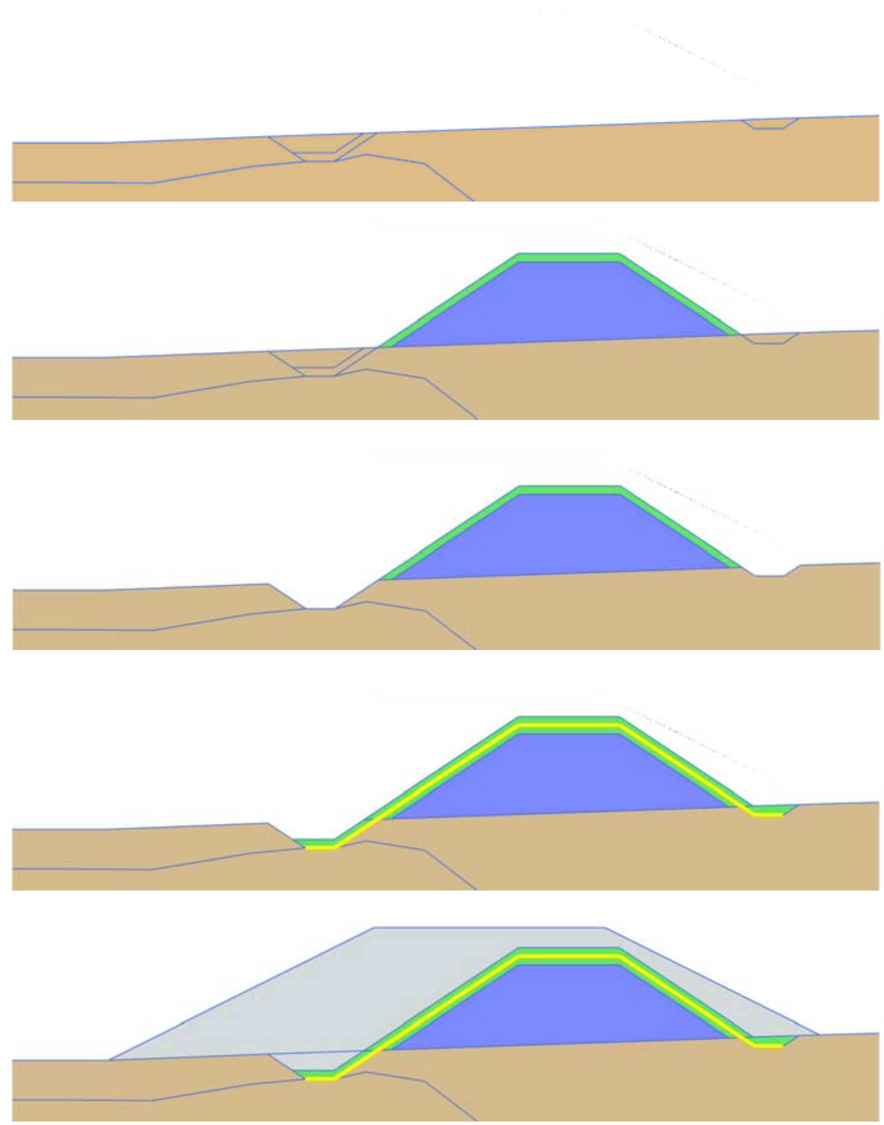
Initial phase
- Foundation

Phase 1
- Transition material and bedding

Phase 2
- Construction of trenches

Phase 3
- HDPE geomembrane and cover

Phase 4
- ROQ material



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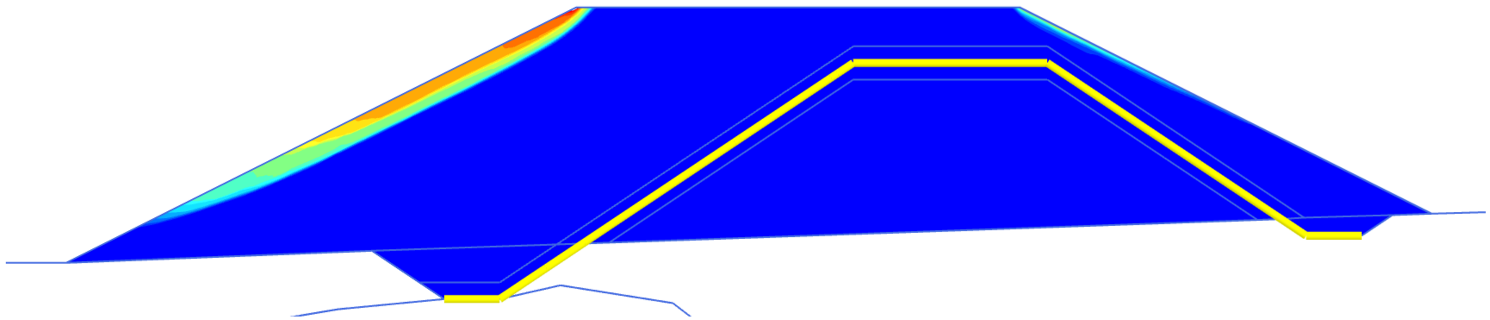
		CWB model Staged Construction
Job No: 1CT022.013 Filename: Boston_CWB_StabilityAnalysis_Memo_Figures_1CT022-013_Rev01_EL_al	HOPE BAY PROJECT	Date: 11/24/2017 | Approved: EL | Figure: 6

$$FOS_{static} = 1.5$$



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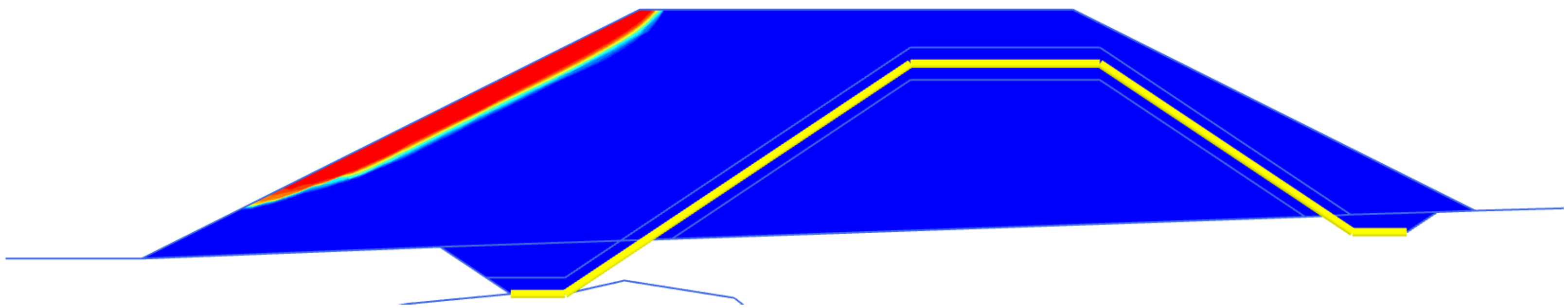

Notes:
1. Analysis without considering water pressures
2. Analysis considering frozen foundation ($\varphi = 26°$ and $c = 112\ kPa$)
3. The method of calculation is phi-c reduction with 500 steps of calculation
4. PLX model 114-2

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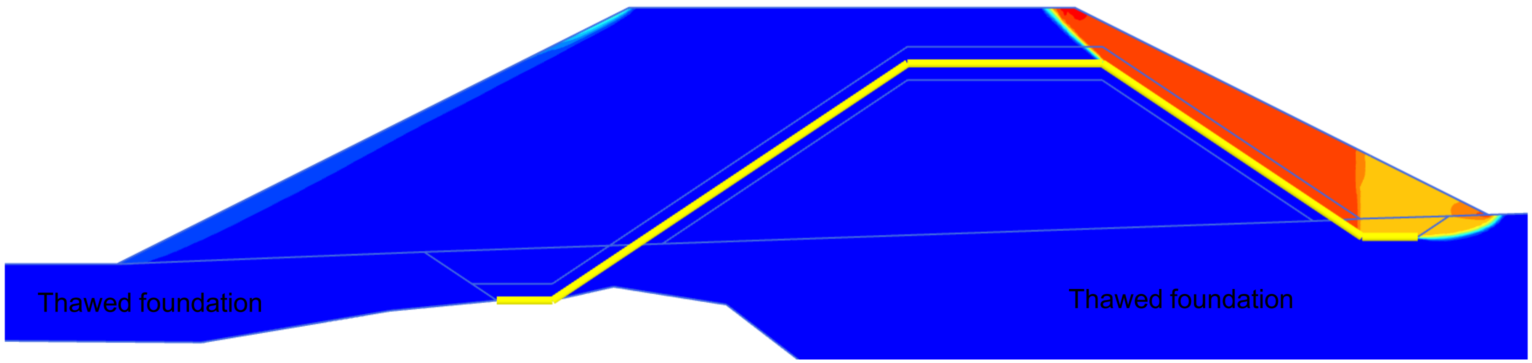
Job No: 1CT022.013 Filename: Boston_CWB_StabilityAnalysis_Memo_Figures_1CT022-013_Rev01_EL_al	HOPE BAY PROJECT	Date: 11/24/2017	Approved: EL	Figure: 7

$$FOS_{static} = 1.5$$



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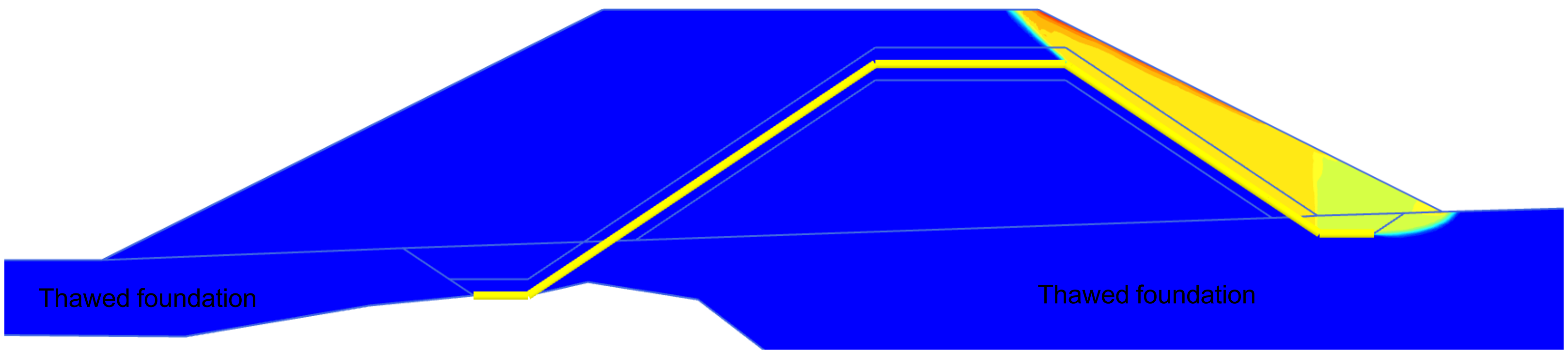

Notes:

1. Analysis without considering water table
2. Analysis considering thawed foundation ($\varphi = 30°$ and $c = 0\ kPa$)
3. The method of calculation is phi-c reduction with 500 steps of calculation
4. PLX model 118

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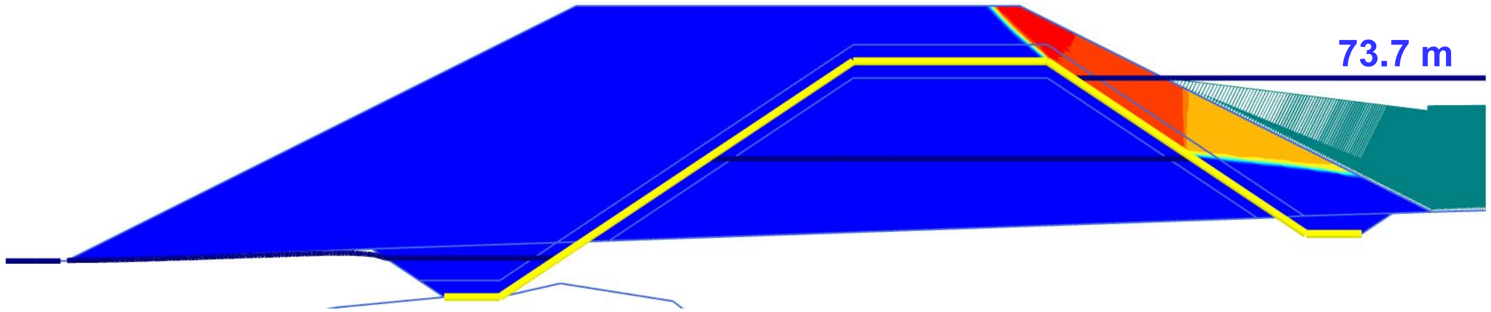
		Stability Analysis Results
Job No: 1CT022.013 Filename: Boston_CWB_StabilityAnalysis_Memo_Figures_1CT022-013_Rev01_EL_al	HOPE BAY PROJECT	Date: 11/24/2017 · Approved: EL · Figure: 8

$FOS_{static} = 1.5$



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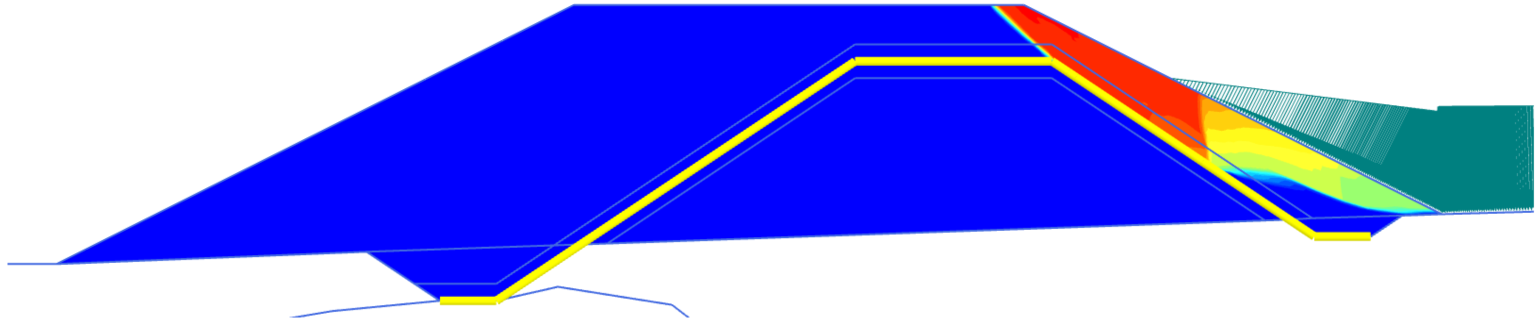

Notes:

1. Analysis considering water pressures
2. Analysis considering frozen foundation ($\varphi = 26°$ and $c = 112\ kPa$)
3. The method of calculation is phi-c reduction with 500 steps of calculation
4. PLX model 114-2

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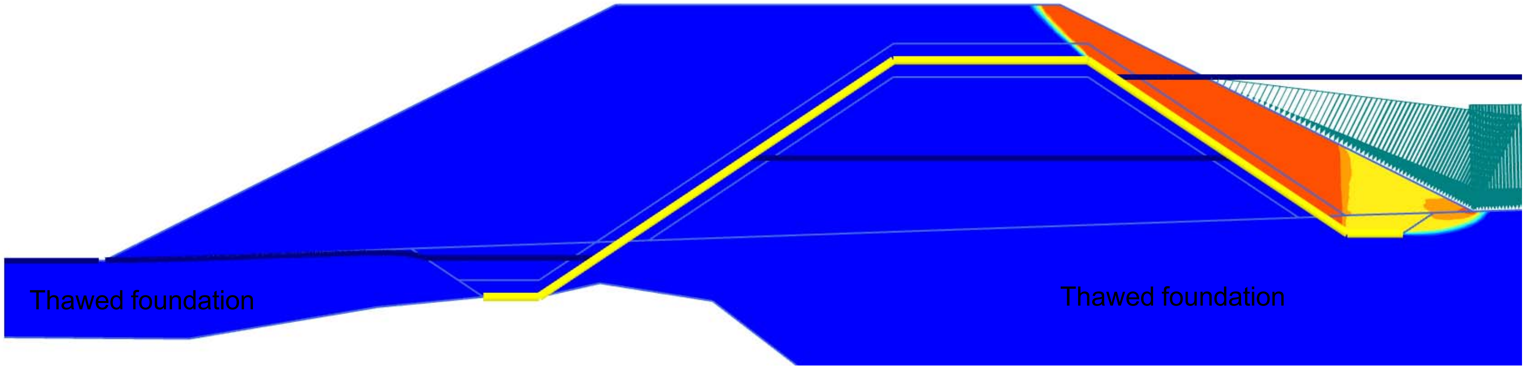
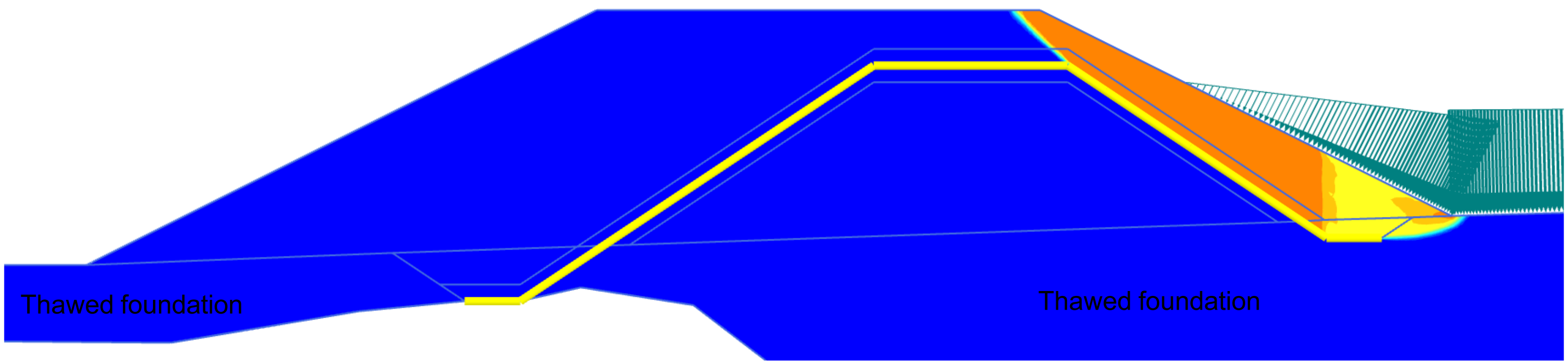
		Stability Analysis Results
Job No: 1CT022.013 Filename: Boston_CWB_StabilityAnalysis_Memo_Figures_1CT022-013_Rev01_EL_al	HOPE BAY PROJECT	Date: 11/24/2017 · Approved: EL · Figure: 9

$FOS_{static} = 1.5$



$FOS_{pseudo-static} = 1.3$



Notes:
1. Analysis considering water table
2. Analysis considering thawed foundation ($\varphi = 30°$ and $c = 0\ kPa$)
3. The method of calculation is phi-c reduction with 500 steps of calculation
4. PLX model 118

srk consulting	TMAC RESOURCES	CWB Stability Analysis
		Stability Analysis Results
Job No: 1CT022.013 Filename: Boston_CWB_StabilityAnalysis_Memo_Figures_1CT022-013_Rev01_EL_al	HOPE BAY PROJECT	Date: 11/24/2017 · Approved: EL · Figure: **10**

Attachment 1: Contact Water Pond Berm Thermal Model

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Memo

To:	John Roberts, PEng, Vice President Environment Oliver Curran, MSc, Director Environmental Affairs	**Client:**	TMAC Resources Inc.
From:	Christopher W. Stevens, PhD	**Project No:**	1CT022.013
Reviewed By:	Maritz Rykaart, PhD, PEng	**Date:**	November 30, 2017
Subject:	Hope Bay Project: Contact Water Pond and Surge Pond Berms Thermal Modeling		

Change Log

The following table provides an overview of material changes to this memo from the previous version issued as Appendix V3-2C, Attachment 1 as part of the DEIS for Phase 2 of the Hope Bay Project dated December 2016.

Changes by Section

Information Request, Technical Comment, or Other Change	Section	Comments
New contact water pond and surge pond thermal models	All	New models based on updated design
KIA-DEIS-53	All	Integrated into berm model
INAC-IR34	1, 4	Additional context for design added

1 Introduction

The Madrid-Boston Project (the Project) is a gold mining and milling undertaking of TMAC Resources Inc. The Project is located 705 km northeast of Yellowknife and 153 km southwest of Cambridge Bay in Nunavut Territory, and is situated east of Bathurst Inlet. The Project comprises three distinct areas of known mineralization plus extensive exploration potential and targets. The three areas that host mineral resources are Doris, Madrid, and Boston.

The Project consists of two phases; Phase 1 (Doris project), which is currently being carried out under an existing Water Licence, and Phase 2 which is in the environmental assessment and licensing stage. Phase 1 includes mining and infrastructure at Doris only, while Phase 2 includes mining and infrastructure at Madrid and Boston located approximately 10 and 60 km due south from Doris, respectively.

Contact water ponds (CWPs) will be constructed at the Madrid North, Madrid South, and Boston mining areas to intercept contact water runoff (SRK 2017a, 2017b). CWPs will normally be kept in a dry state with a two-week (i.e. fourteen-day) residence time for water in the pond. Permafrost and naturally low permeability foundation materials will restrict vertical infiltration of water along the bottom of the ponds.

At the Boston site, within CWP #2 (internal to the CWP berm and key trench) a surge pond will be created by fully lining a section of the CWP. The CWP berm provides the final environmental containment, by the liner tied into the key trench within the CWP berm. The surge pond is a fully lined pond and is designed to act as surge capacity for the water treatment plant to even out water treatment plant inflow rates (SRK 2017b). Additionally, in the event of a water treatment plant ‘upset’ the surge pond will be the initial storage area for contact or process water. The surge pond will be normally kept dry in the winter and will operate at varying levels otherwise (SRK 2017b). The section of the CWP that contains the surge pond will have different thermal conditions and as such has been assessed separately. For clarity this section of the CWP berm is referred to as the surge pond berm.

All ponds will require external containment berms (the berms) that will be constructed with run-of-quarry (ROQ) or geochemically suitable run-of-mine (ROM) waste rock with a design life of 20 years. The berm design includes a minimum thickness of 2.5 m with an 8 m wide crest and 2H:1V side slopes. A minimum material thickness of 1 m would be established between the top of the geomembrane and the driving surface, because the berms will also serve as access roads.

The berms will be constructed with a geomembrane liner keyed into permafrost to create an impermeable layer within the berm. The top of permafrost will aggrade upward into the berm fill and above the position of the liner within the key-trench to create a frozen impermeable seal between the liner and the natural ground.

The liner will be embedded 1 m below the natural ground in the key-trench. Ground conditions will be carefully inspected during installation of the liner to ensure massive ice is not present within the key trench, and percolation testing will be conducted to confirm saturation. The embedment depth of the liner into the natural ground will be increased as necessary should ground conditions be found to not be conducive of creating the appropriate seal.

For thermal modelling purposes, the construction of the starter berm is conservatively assumed to take place during the summer using end dumping to place ROQ or ROM material over pre-existing tundra. Key-trench excavation will commence in the fall and early winter, with remaining liner and berm construction completed over the winter. Additional design details and specific placement of each berm design is provided in SRK (2017a, 2017b).

Thermal modeling was completed to verify the minimum berm thickness required to maintain the liner frozen within the key-trench. The model inputs, assumptions, and results are summarized in this memo.

2 Methods

2.1 Approach

Thermal modeling was performed using SVHeat developed by SoilVision Systems Ltd. (SoilVision Systems 2004) with FlexPDE from PDE Solutions Inc. (FlexPDE 2014). The finite element modeling was based on conductive heat flow. Ground temperature was simulated over the 20-year design life using a maximum time step of one day.

2.2 Model Geometry

A two-dimensional (2D) model was developed with a simplified geometry for the berm design (Figures 1 and 2). Geometry of the berms include an upstream and downstream slope of 2H:1V, with a berm thickness of 2.5 m and a crest width of 8 m (Figures 1 and 2). The CWP starter berm includes an upstream and downstream slope of 1.5H:1V with a crest width of 3.5 m (Figure 3). The surge pond starter berm includes a similar geometry with exception of the upstream face of 2H:1V (Figure 3).

Model geometry of the berms represents a typical section with the minimum berm height to be constructed; and therefore, the most conservative section with the greatest expected thaw.

2.3 Model Inputs

2.3.1 Material Properties

Three materials were defined in the thermal models: ROQ material at 30% saturation, ROQ material with 100% saturation, and natural overburden consisting of clay. Table 1 summarizes the thermal properties for each material.

The thermal properties for ROQ material were taken from previous work completed by SRK for granular pad design (SRK 2017c). The ROQ material was modified to account for unfrozen saturated thermal conductivity and heat capacity of the material located on the upstream side of the CWP liner (Figure 1). The unfrozen properties for this material were also estimated for 100% saturation (Table 1).

The thermal properties for natural overburden clay were based on average soil properties and a freezing point depression of -2°C. The porewater freezing point was based on average site-wide conditions which is reported to be -2.1°C (SRK 2017d). There is a negligible difference between the position of these two isotherms, and -2°C is presented for clarity of the results. An unfrozen water content curve for clay was included in the model with consideration for the freezing point depression in accordance with Banin and Anderson (1974).

Table 1: Material Thermal Properties

Material	Degree of Saturation (%)	Porosity	Thermal conductivity (kJ/(m·day·°C))		Volumetric Heat Capacity (kJ/(m³·°C))	
			Unfrozen	Frozen	Unfrozen	Frozen
ROQ Material	30	0.30	104	117	1,697	1,509
ROQ Material, Unfrozen 100% Saturated	100	0.30	141	117	2,576	1,509
Overburden Clay[1]	85	0.52	112	187	2,842	2,038

Notes:
1. Overburden clay includes a freezing point depression of -2°C and unfrozen water content curve

2.3.2 Boundary Conditions

The surface boundary conditions applied to the upper surface of the model were divided into three areas; the natural ground surface along the base of ponds and along the upstream face of the berms to the full supply level (FSL), the natural ground surface downstream of the berm, and the exposed berm surface (Figures 1 and 2). Thermal forcing along these boundaries was based on a sinusoidal function of temperature and time (Equation 1) using the parameters shown in Table 2:

$$T = \max(nf * \left[MAAT + (C_A * t) + Amp * Sin\left(\frac{2\pi + (t+182.5)}{365}\right)\right], \mathrm{nt}\left[MAAT + (C_A * t) + Amp * Sin\left(\frac{2\pi+(t+182.5)}{365}\right)\right] \quad \text{Eq.1}$$

Where:

- T *is the ground temperature measured in °C*
- nf *is the surface freezing n-factor*
- nt *is the surface thawing n-factor*
- $MAAT$ *is the mean annual air temperature measured in °C*
- Amp *is the air temperature amplitude measured in °C*
- C_A *is the air climate change factor in °C* d^{-1}
- t *is time measured in days*

Mean annual air temperature and amplitude are based on average values for the baseline period of 1979-2005 (SRK 2017e). Seasonal n-factors are applied as multipliers of air temperature to estimate the ground surface temperature.

The ROQ material n-factors were based on average published values for the freezing season (*nf* = 0.86) and thawing season (*nt* =1.52) (SRK 2017c). For naturally vegetated ground surfaces, the n-factors were based on values calibrated to shallow ground temperatures measured at the

Project site (Figure 4). The calibration process included adjustment of the n-factors to simulate reasonable minimum, maximum, and mean annual ground temperature for measurements collected within overburden. The calibrated n-factors for vegetated overburden were determined to be 0.65 for the thawing season and 0.55 for the freezing season. These values are consistent with published values for similar environments and allow modeled temperature to closely match field measurements (Figure 4). The active layer thickness estimated using the n-factors for naturally vegetated overburden was 0.9 m.

Table 2: Surface Boundary Parameters

Surface Boundary Parameter	Value
Mean annual air temperature (MAAT)	-10.7°C
Air temperature amplitude (Amp)	21.5°C
Air Climate Change Factor (°C d^{-1})	0.000203
Natural Surface, Thawing n-factor	0.65
Natural Surface, Freezing n-factor	0.55
ROQ Surface, Thawing n-factor (nt)	1.52
ROQ Surface, Freezing n-factor (nf)	0.86
CWP water temperature	Annual temperature cycle based on SRK (2017f)

Climate change is considered in Equation 1 using the air climate change factor. This factor allows for a daily increase in air temperature in the model. Air temperature is projected to increase by 0.74°C per decade at Doris and 0.58°C per decade at Boston between the periods of 1979-2005 and 2011-2040, respectively (SRK 2017e). The higher rate of change in air temperature for Doris was applied to the model and is conservative for expected conditions at Boston. The air climate change factor applied to Equation 1 was 0.000203°C d^{-1} which is equivalent to an increase of 0.74°C per decade.

A geothermal gradient of 0.021°C m^{-1} was applied to the lower boundary of the model which is consistent with average conditions measured at the Project site (SRK 2017c). The sides of the model space were set to zero flux with the lower boundary set to a constant flux 3.93 kJ/(m^2·day·°C) which was calculated from the average geothermal gradient (0.021°C m^{-1}) and the thermal conductivity of the clay overburden.

A background water temperature cycle based on SRK (2017f) was applied along the bottom of the pond and against the upstream face of the liner. The CWP berm model water temperature cycle was modified to include an increase of water temperature to +16.5°C for a 14-day period that annually occurs at the end of August around the period of maximum active layer thaw to simulate elevated temperatures of water entering the pond. The temperature cycle was applied in the model to the FSL for the 20-year design life, which is conservative as the CWP will normally be kept dry.

For the surge pond berm model, the water temperature boundary was modified to include an increase of water temperature to +16.5°C for a 14-day period that annually occurs near the end of the thawing season and start of winter to simulate additional heat brought in by process water caused by potential upset of the water treatment plant. The temperature cycle was applied in the model to the FSL for the 20-year design life, which is conservative as the surge pond will normally be kept dry in the winter. It is estimated that the annual temperature of an exposed black liner with a low surface albedo would be -1.5°C, assuming a freezing n-factor of 0.55 and a thawing n factor of 2.50. The annual temperature of the water temperature boundary applied to the surge pond model is +5.1°C, making the boundary condition conservative when compared to an exposed liner.

2.4 Model Sequences

Two model sequences were developed to simulate ground temperatures for the CWP and surge pond berms and included:

- Starter Berm Model Sequence – to simulate summer construction of the starter berm (Figure 3)
- Final Berm Model Sequence – to simulate construction key-trench and final berm, followed by operation of the ponds for the 20-year design life (Figures 1 and 2).

Figures 1 through 3 show the general location over which the transient boundary conditions were applied for each model sequence; the natural ground surface along the base of the contact water pond and along the upstream face of the berm to the FSL, the natural ground surface downstream of the berm, and the exposed berm surface. The time-dependent ground temperature function was applied using Equation 1 and values from Table 2.

2.4.1 Starter Berm Model Sequence

Starter berm construction is assumed in the model to take place at the start of the summer. Initial ground temperature for the clay overburden was set to -7.6°C which is representative of average permafrost temperatures at the Project site (SRK 2017c). ROQ materials at the time of starter berm construction is assumed in the model to be 18°C which is conservative and based on a maximum air temperature of 12°C with a n-factor of 1.5 applied for exposed rock surfaces. The starter berm model is run for 180 days: a 120-day period of summer thawing and a 60-day period for active layer freezeback.

2.4.2 Final Berm Model Sequence

The initial conditions for the final berm model sequence are based on ground temperatures from last time step of the starter berm model day 180. An initial temperature of the final ROQ material was set to -5°C and is assumed to thermally adjust to the ambient air temperature during winter construction. The final berm model sequence simulates immediate operation of the ponds at the FSL which is 1.3 m below the crest of the berm and along the bottom of the pond for the 20-year design life. See Section 2.3.2 for differences in the water temperature boundary applied to the CWP berm and surge pond berm models.

3 Results

3.1 CWP Berm

Over the 20-year period, the position of the -2°C isotherm is observed to increase in depth due to the increase in ground surface temperature defined by Equation 1 and the water temperature boundary applied to the upstream berm liner. The maximum position of the -2°C isotherm for year 20 is shown in Figure 5. The key-in trench remains below the -2°C temperature threshold that is based on the average site-wide freezing point of the overburden. Deeper thaw is observed along the upstream and downstream toe of the berm due to water temperature applied at FSL for the duration of the design life. Thaw based on the -2°C isotherm does not penetrate below the liner at the critical location of the key-trench. Seasonal thaw beneath the contact water pond is estimated to be 9.5 m below the surface using the conservative model boundary conditions.

The change in temperature for the 20-year design life is tracked for two positions along the liner, referred to as Monitoring Point 1 and Monitoring Point 2 (see Figure 1 for locations). The critical monitoring point for ensuring containment is Monitoring Point 1 based on the geometry of the thawing front with respect to the position of liner (Figure 5).

The time-series of modeled temperature at Monitoring Points 1 and 2 is shown in Figures 6 and 7, respectively. Ground temperature is estimated to increase over the design life, but remain below -2°C. Over the 20-year period, the maximum ground temperature at Monitoring Point 1 is -2.8°C.

3.2 Surge Pond Berm

The maximum position of the -2°C isotherm for year 20 is shown in Figure 8. The key trench remains below the -2°C temperature threshold that is based on the average site-wide freezing point of the overburden. Deeper thaw is observed along the upstream and downstream toe of the berm due to water temperature applied at FSL for the duration of the design life. Thaw based on the -2°C isotherm does not penetrate below the liner at the critical location of the key-trench. Seasonal thaw beneath the contact water pond is estimated to be 9.8 m below the surface using the conservative model boundary conditions.

The change in temperature for the 20-year design life is tracked for two positions along the liner, referred to as Monitoring Point 1 and Monitoring Point 2 (see Figure 2 for locations). The critical monitoring point for ensuring containment is Monitoring Point 1 based on the geometry of the thawing front with respect to the position of liner (Figure 8).

The time-series of modeled temperature at Monitoring Points 1 and 2 is shown in Figures 9 and 10, respectively. Ground temperature is estimated to increase over the design life, but remain below -2°C. Over the 20-year period, the maximum ground temperature at Monitoring Point 1 is -3.2°C.

Figure 11 shows the sensitivity of the maximum temperature over the 20-year design life as the CWP berm thickness is increased from 2.5 m to 3.5 m. The temperatures measured at the liner decrease as berm thickness increases, resulting in a decrease of the depth of -2°C isotherm.

4 Conclusions

The thermal model results confirm that the minimum berm design thickness of 2.5 m is suitable to maintain the geomembrane liner frozen at the base of the key trench. The temperature monitored at the liner decreases as berm thickness increases, which also results in a decrease in the depth of the -2°C isotherm. This finding indicated that additional fill could be added to reduce thaw depths if warmer than expected conditions are observed in the berm and the liner tie-in is at risk of thawing. If required, additional mitigation techniques may also include placement of screened geochemically suitable ROQ rock or ROM waste rock along the berm side slopes that allow for increased heat loss from natural air convection in the winter. Thaw beneath the bottom of the pond is not expected to thaw through the existing permafrost. Ground temperature cables will be installed below and up through the liner embedment depth to ensure frozen conditions are maintained during operations. Visual seepage surveys will be carried out downstream to confirm no water is lost.

5 References

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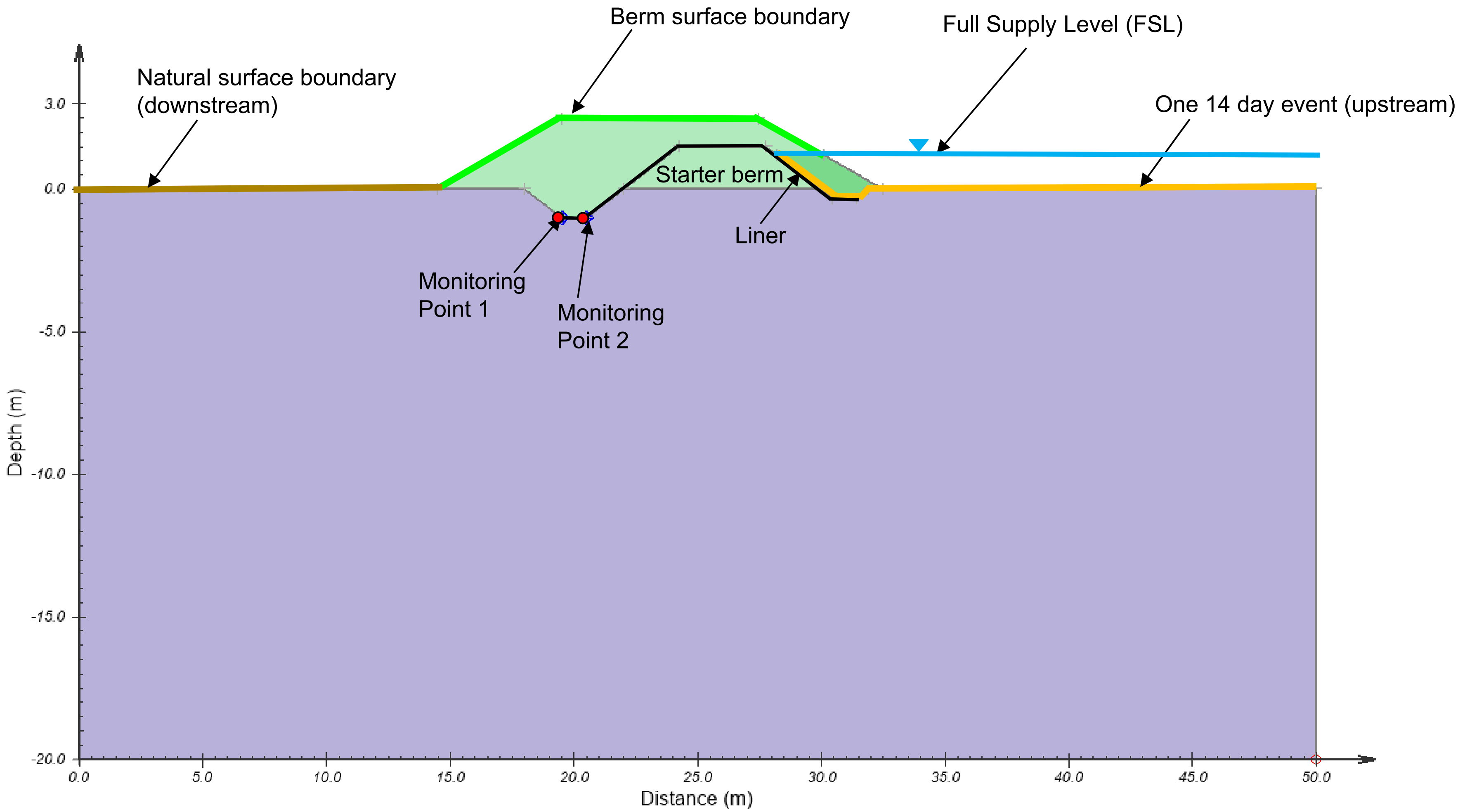
Figures



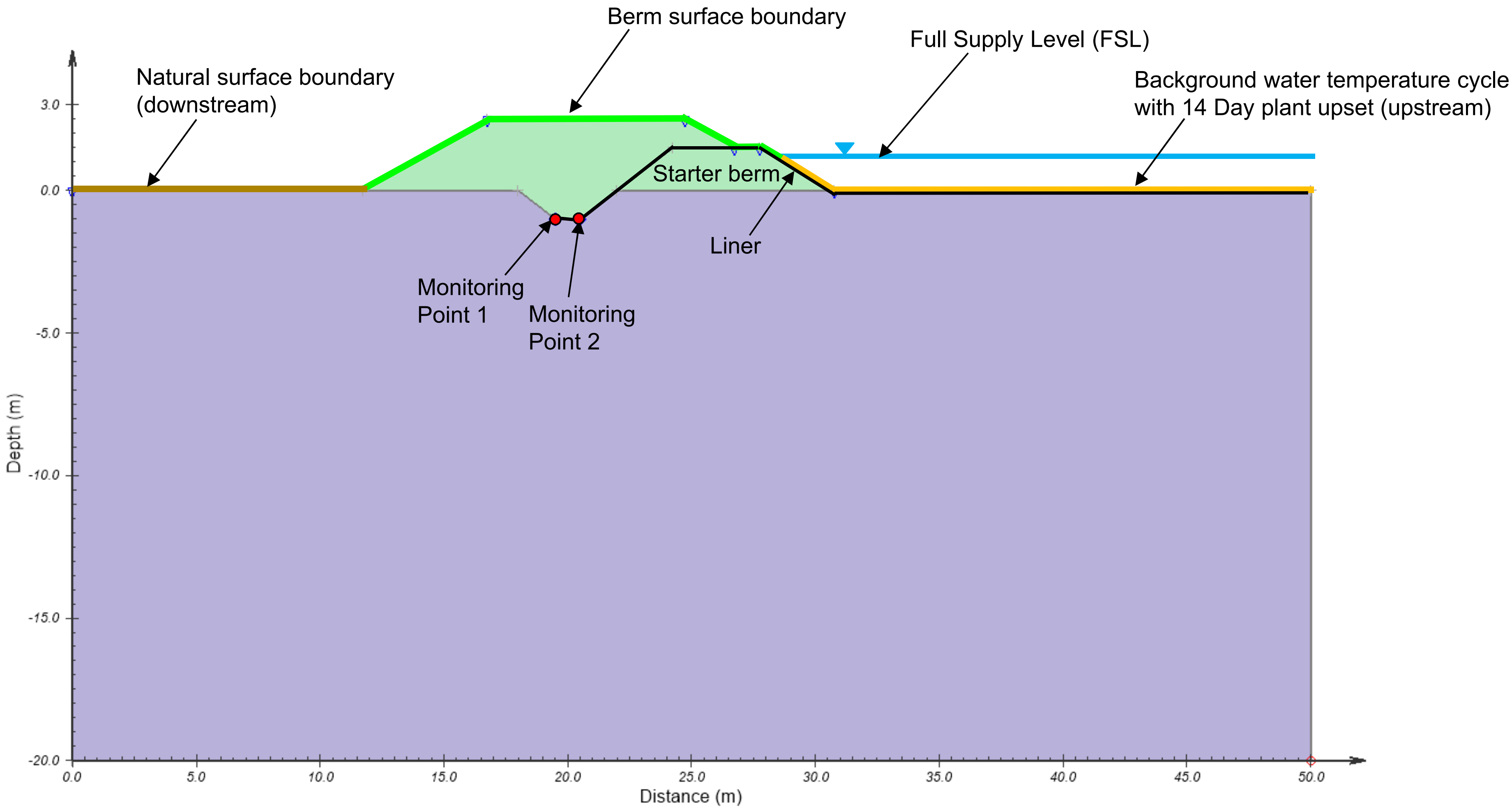
Notes:

1. ROQ – Run-of-Quarry material or geochemically suitable run-of-mine (ROM) waste rock
2. CWP – Contact water pond

Materials

- Clay
- ROQ
- ROQ Saturated

srk consulting	MAC RESOURCES	Contact Water Pond and Surge Pond Berms Thermal Modeling **Thermal Model Geometry – CWP Berm**
Job No: 1CT022.013 Filename: ContactWaterPondBermModelFigures.pptx	HOPE BAY PROJECT	Date: 9/20/2017 | Approved: cws | Figure: 1



Notes:

1. ROQ – Run-of-Quarry material or geochemically suitable run-of-mine (ROM) waste rock

Materials

- ROQ
- Clay

srk consulting

MAC RESOURCES

Job No: 1CT022.013

Filename: ContactWaterPondBermModelFigures.pptx

HOPE BAY PROJECT

Contact Water Pond and Surge Pond Berms Thermal Modeling

Thermal Model Geometry – Surge Pond Berm

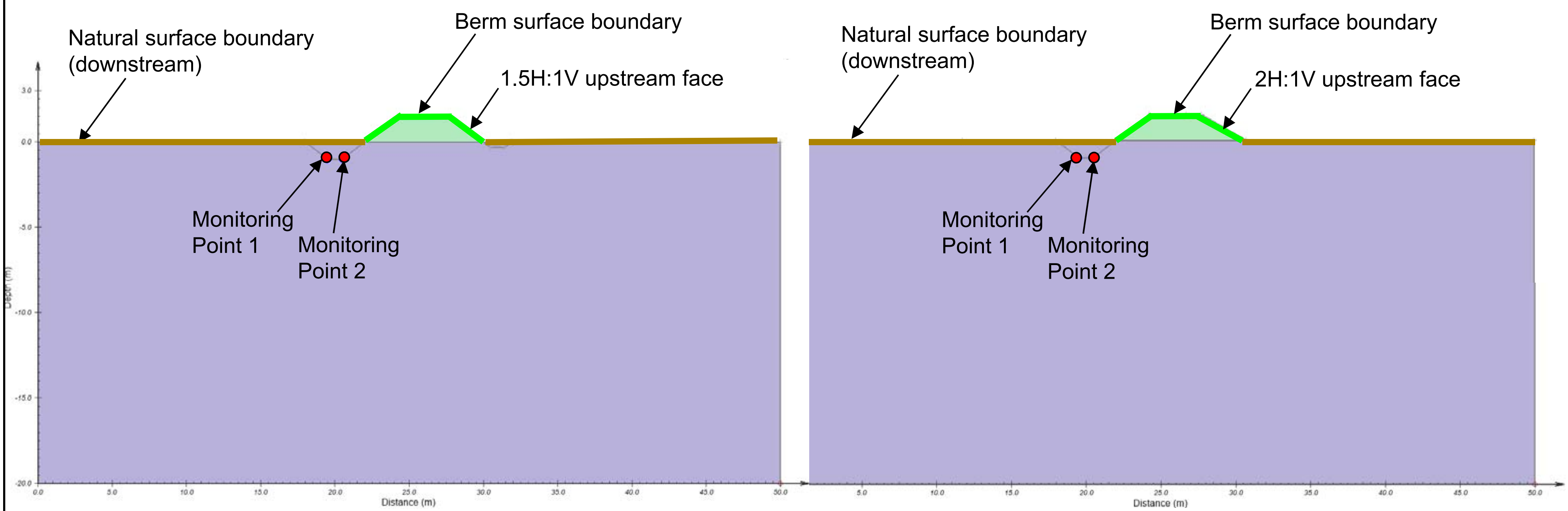
Date: 9/20/2017

Approved: cws

Figure: 2

Contact Water Pond Starter Berm

Surge Pond Starter Berm



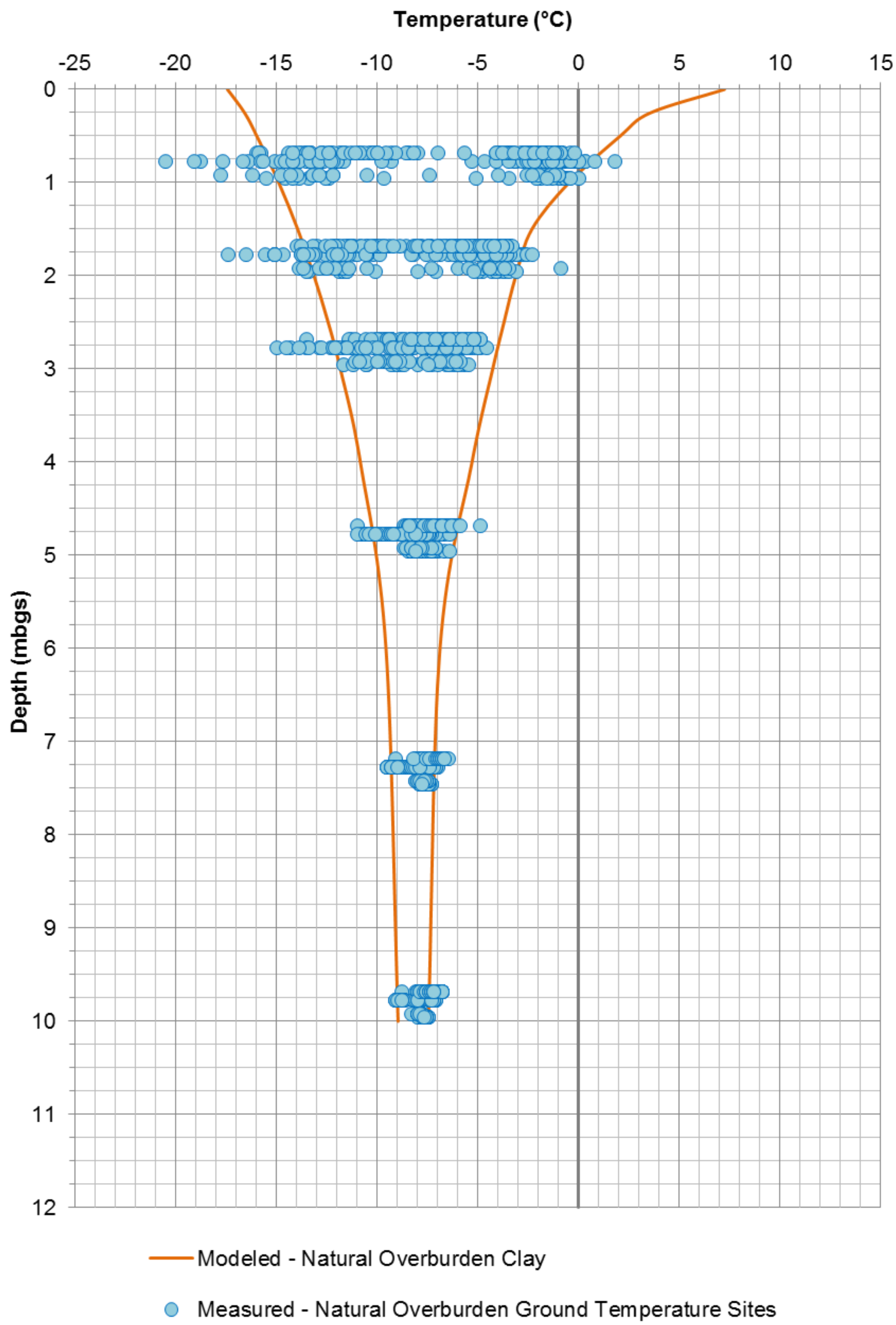
Notes:

1. ROQ – Run-of-Quarry material or geochemically suitable run-of-mine (ROM) waste rock

Materials

- ROQ
- Clay

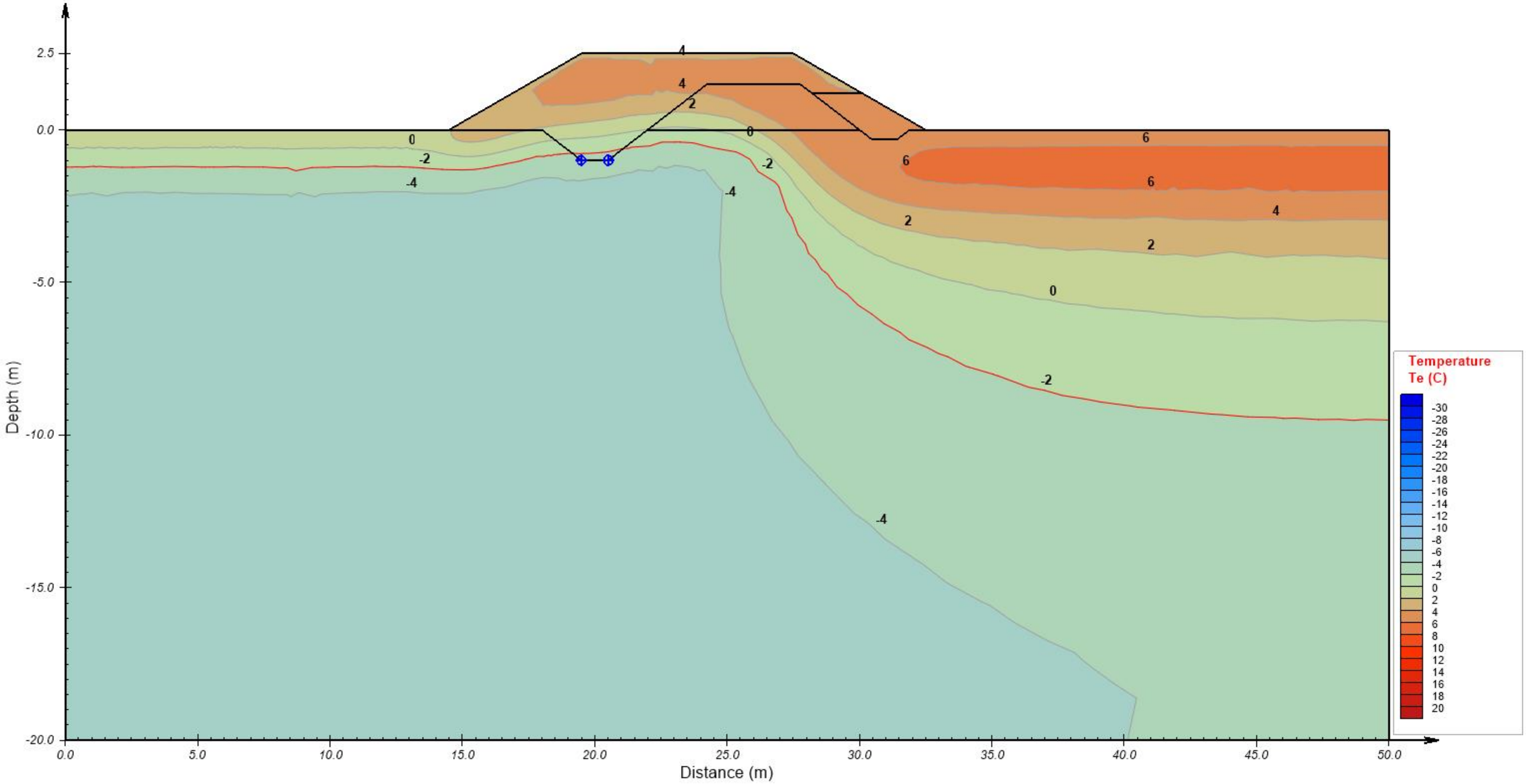
srk consulting	MAC RESOURCES	Contact Water Pond and Surge Pond Berms Thermal Modeling
		Thermal Model Geometry – Starter Berms
Job No: 1CT022.013 Filename: ContactWaterPondBermModelFigures.pptx	HOPE BAY PROJECT	Date: 9/20/2017 · Approved: cws · Figure: 3



Notes:

1. Depth expressed as metres below ground surface (mbgs)
2. Measured temperature for baseline site with natural overburden (site: SRK-19, -20, -22, -23, -24, -26, -28)
3. Model results shown for minimum and maximum annual ground temperature (solid orange lines)
4. Model n-freezing factor of 0.55 and n-thawing factor of 0.65 for natural terrain

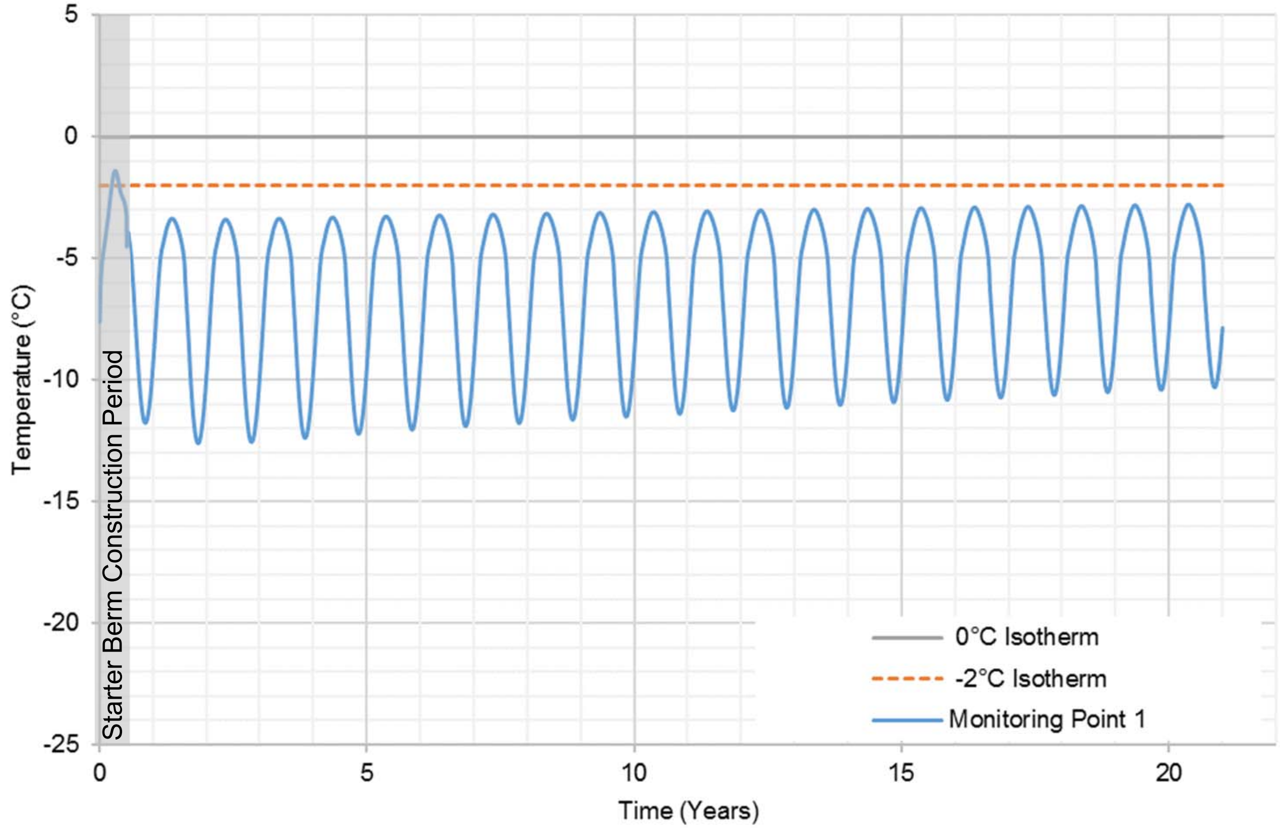
srk consulting	TMAC RESOURCES	Contact Water Pond and Surge Pond Berms Thermal Modeling **Measured versus Modeled Ground Temperature**
Job No: 1CT022.013 Filename: MeasuredModeledTemperatureComparison.pptx	HOPE BAY PROJECT	Date: 9/20/2017 · Approved: cws · Figure: **4**



Notes:

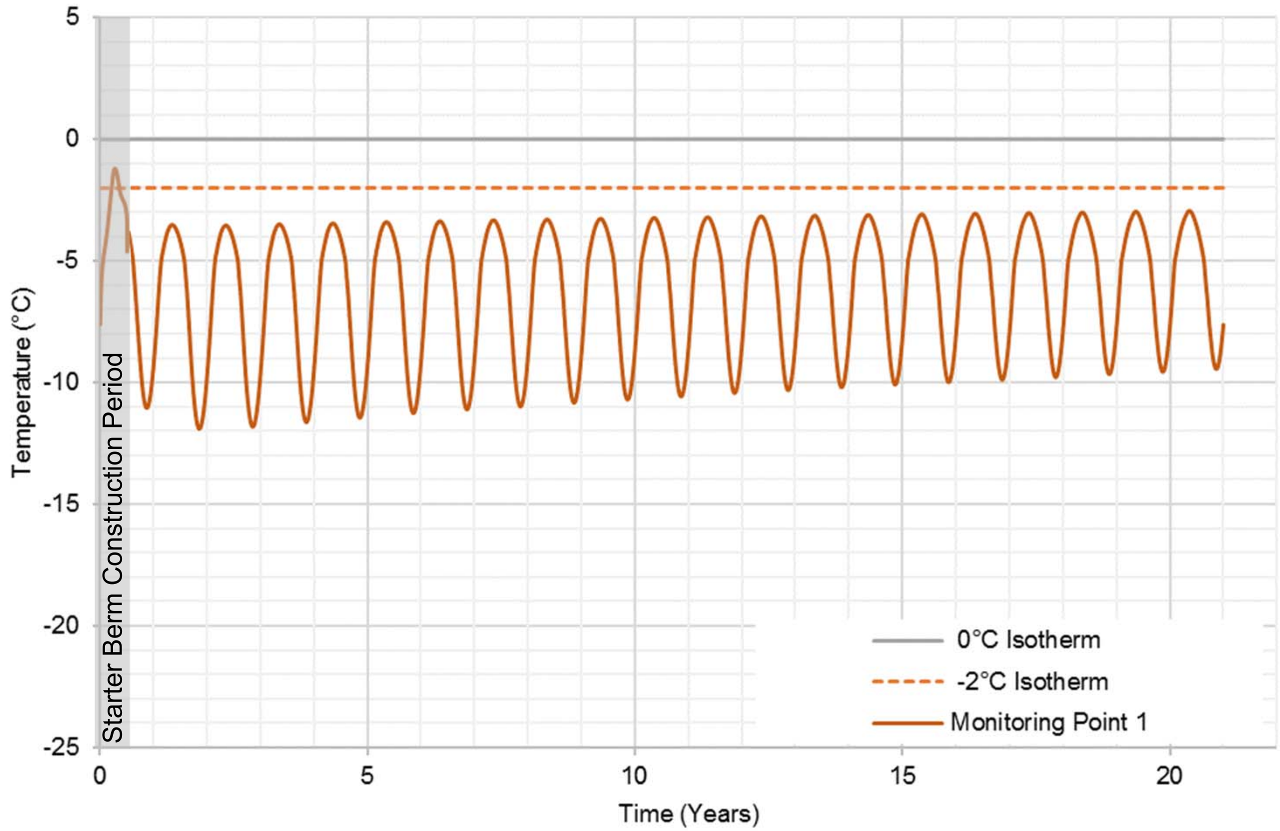
1. Model section represents maximum position of -2°C isotherm (solid red line) during Year 20
2. Model results for minimum berm thickness of 2.5 m
3. CWP – Contact water pond

srk consulting	MAC RESOURCES	Contact Water Pond and Surge Pond Berms Thermal Modeling **Thermal Model Results – CWP Berm (Year 20)**
Job No: 1CT022.013 Filename: ContactWaterPondBermModelFigures.pptx	HOPE BAY PROJECT	Date: 9/20/2017 · Approved: cws · Figure: **5**



Notes:
1. See Figure 1 for location of Monitoring Point 1
2. Model results for minimum berm thickness of 2.5 m
3. Starter berm construction period indicated with grey bar
4. CWP – Contact water pond

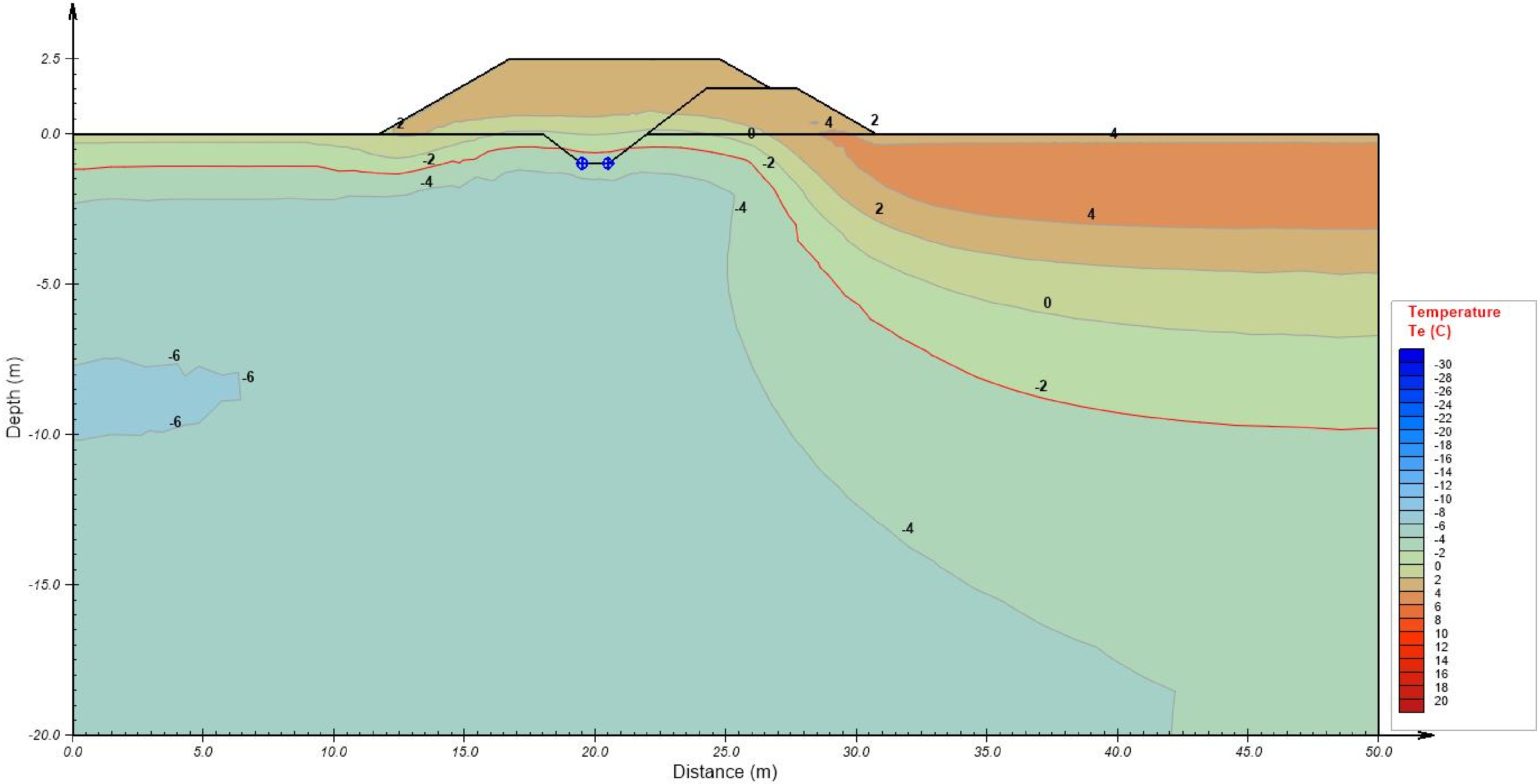
srk consulting	MAC RESOURCES	Contact Water Pond and Surge Pond Berms Thermal Modeling
Job No: 1CT022.013 Filename: ContactWaterPondBermModelFigures.pptx	HOPE BAY PROJECT	**Temperature Time Series – CWP Berm, Monitoring Point 1**
		Date: 9/20/2017 · Approved: cws · Figure: 6



Notes:

1. See Figure 1 for location of Monitoring Point 1
2. Model results for minimum berm thickness of 2.5 m
3. Starter berm construction period indicated with grey bar
4. CWP – Contact water pond

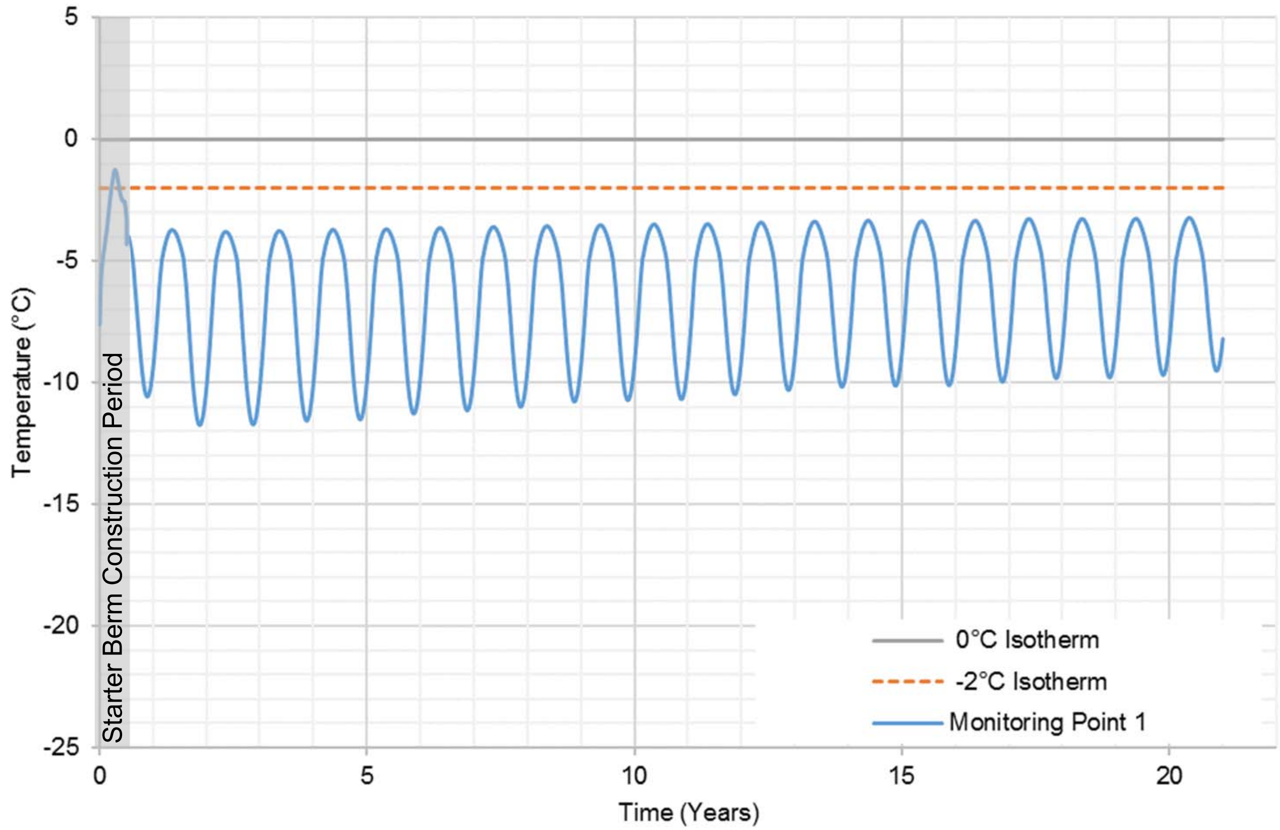
srk consulting	TMAC RESOURCES	Contact Water Pond and Surge Pond Berms Thermal Modeling **Temperature Time Series – CWP Berm, Monitoring Point 2**
Job No: 1CT022.013 Filename: ContactWaterPondBermModelFigures.pptx	HOPE BAY PROJECT	Date: 9/20/2017 Approved: cws Figure: 7



Notes:

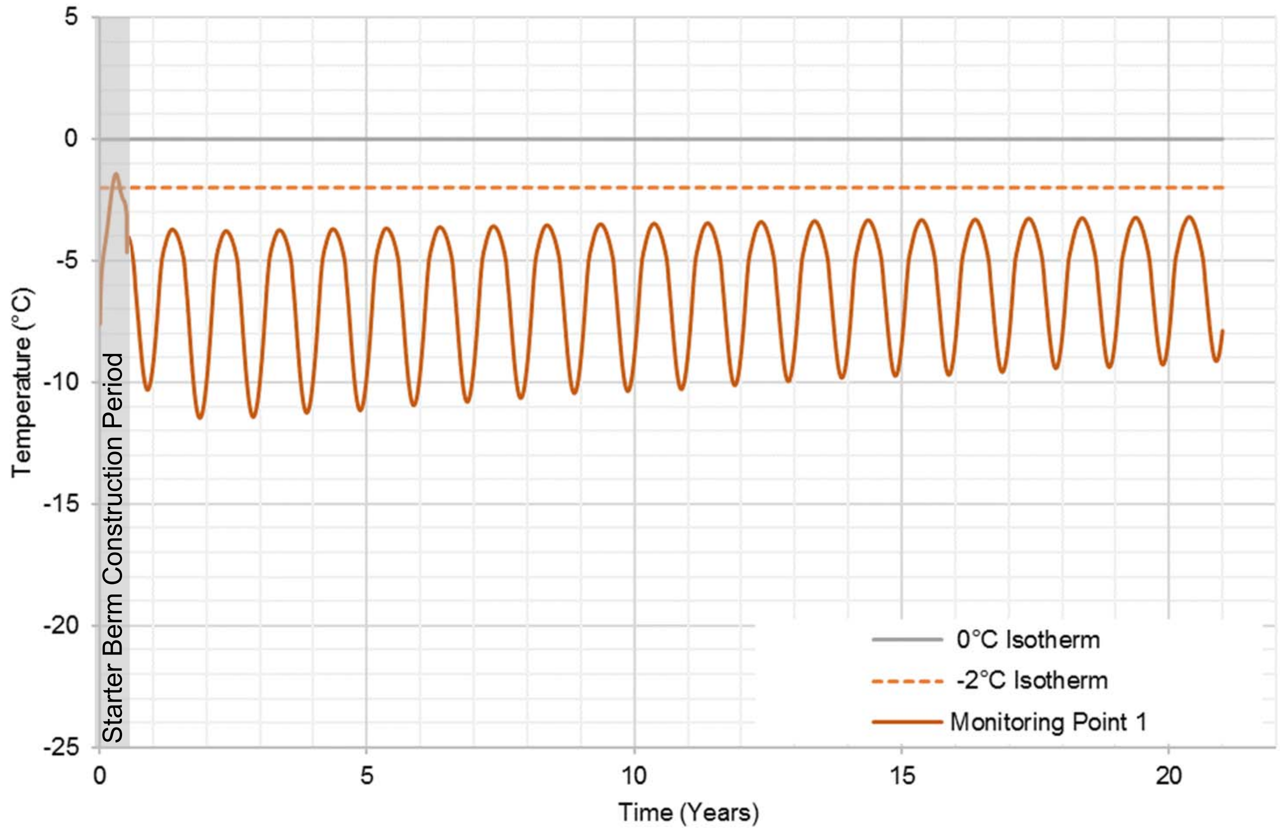
1. Model section represents maximum position of -2°C isotherm (solid red line) during Year 20
2. Model results for minimum berm thickness of 2.5 m

srk consulting	TMAC RESOURCES	Contact Water Pond and Surge Pond Berms Thermal Modeling
		Thermal Model Results – Surge Pond Berm (Year 20)
Job No: 1CT022.013 Filename: ContactWaterPondBermModelFigures.pptx	HOPE BAY PROJECT	Date: 9/20/2017 | Approved: cws | Figure: 8



Notes:
1. See Figure 1 for location of Monitoring Point 1
2. Model results for minimum berm thickness of 2.5 m
3. Starter berm construction period indicated with grey bar

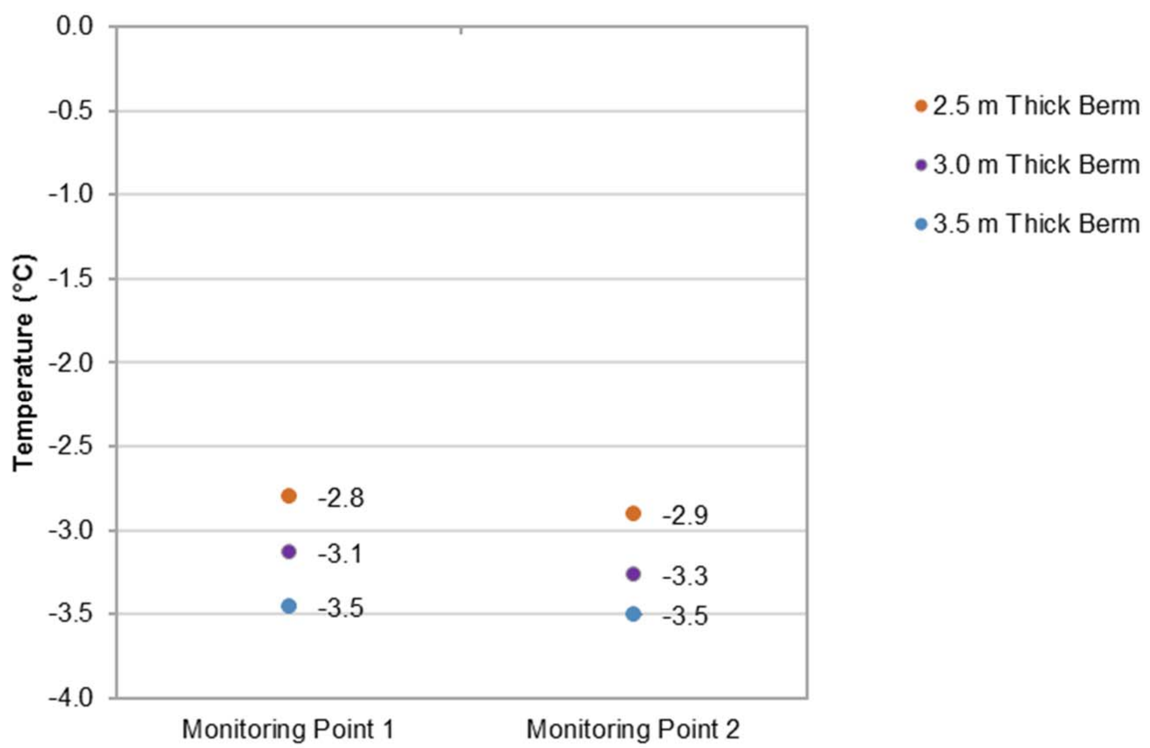
srk consulting	TMAC RESOURCES	Contact Water Pond and Surge Pond Berms Thermal Modeling
		Temperature Time Series – Surge Pond Berm, Monitoring Point 1
Job No: 1CT022.013 Filename: ContactWaterPondBermModelFigures.pptx	HOPE BAY PROJECT	Date: 9/20/2017 · Approved: cws · Figure: 9



Notes:

1. See Figure 1 for location of Monitoring Point 1
2. Model results for minimum berm thickness of 2.5 m
3. Starter berm construction period indicated with grey bar

srk consulting	TMAC RESOURCES	Contact Water Pond and Surge Pond Berms Thermal Modeling
		Temperature Time Series – Surge Pond Berm, Monitoring Point 2
Job No: 1CT022.013 Filename: ContactWaterPondBermModelFigures.pptx	HOPE BAY PROJECT	Date: 9/20/2017 | Approved: cws | Figure: **10**



Notes:

1. Maximum ground temperature over the 20 year design life for monitoring points
2. Event pond berm thickness of 2.5 m, 3.0 m, and 3.5 m
3. See Figure 1 for location of monitoring points
4. CWP – Contact water pond

srk consulting	MAC RESOURCES	Contact Water Pond and Surge Pond Berms Thermal Modeling **Sensitivity to Change in CWP Berm Thickness**
Job No: 1CT022.013 Filename: ContactWaterPondBermModelFigures.pptx	HOPE BAY PROJECT	Date: 9/20/2017 · Approved: cws · Figure: **11**

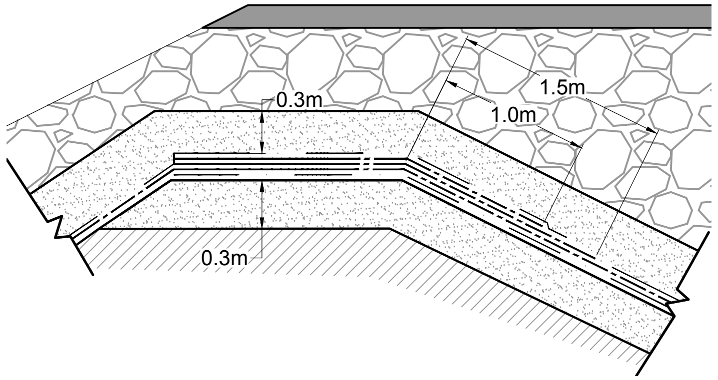
Attachment 2: Engineering Drawings for Contact Water Pond Berm Design

Engineering Drawings for the Contact Water Pond Berm Hope Bay Project, Nunavut, Canada

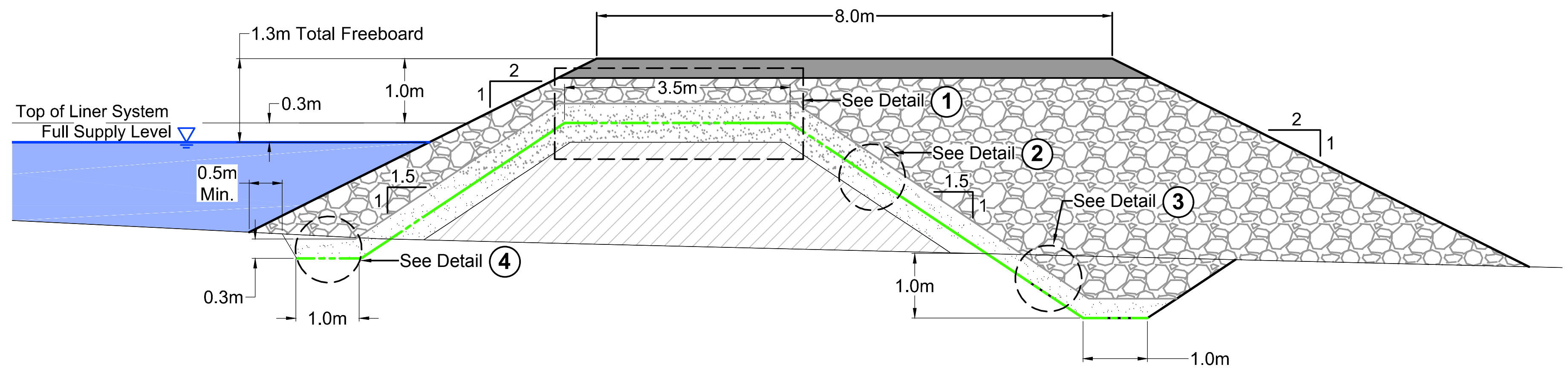
ACTIVE DRAWING STATUS

DWG NUMBER	DRAWING TITLE	REVISION	DATE	STATUS
01	Contact Water Berm Typical Section and Details	A	Nov. 29, 2017	Issued for Discussion

Project No: 1CT022.013
Revision A
November 29, 2017



1 **Typical Liner System Under Driving Surface**
NOT TO SCALE



Typical Contact Water Berm Section

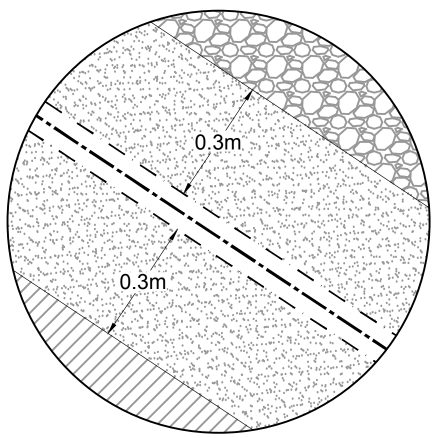
0m 0.5 1.0 1.5 2.0

LEGEND

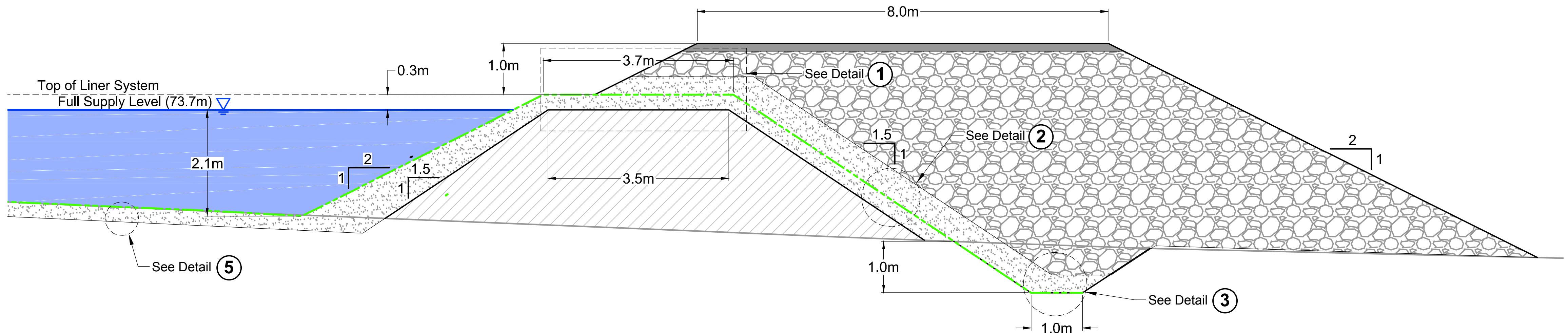
- Non-woven Geotextile
- HDPE Liner
- Liner System
- Existing Ground
- Surfacing Material
- Bedding Material
- Run of Quarry Material
- Transition Material

NOTES

1. Dimensions in metres unless noted otherwise.

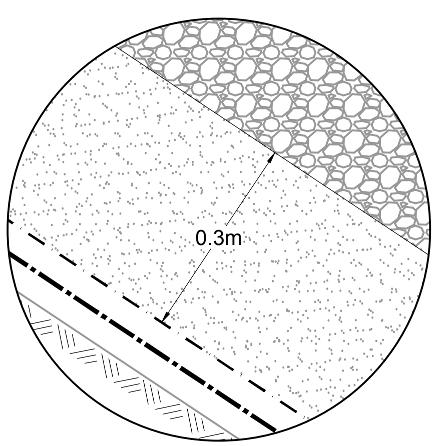


2 **Typical Liner System in Berm Core**
NOT TO SCALE

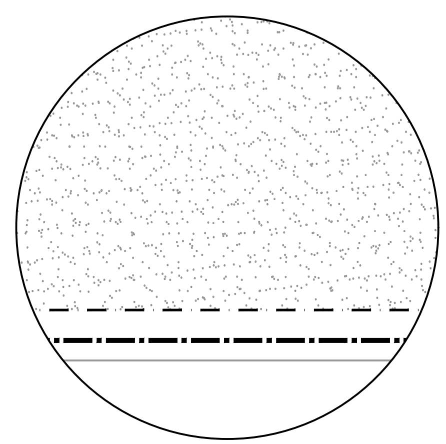


Surge Pond Typical Section

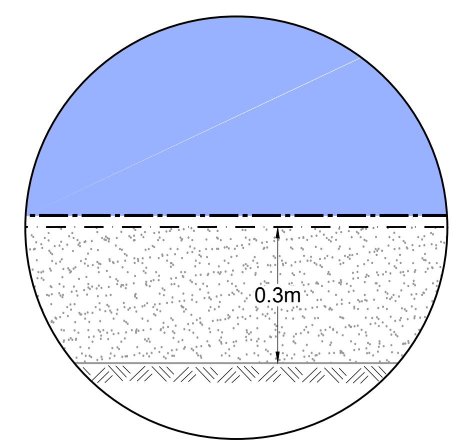
0m 0.5 1.0 1.5 2.0



3 **Typical Liner System in Keytrench**
NOT TO SCALE



4 **Typical Liner System in Liner Anchor Area**
NOT TO SCALE



5 **Typical Liner System on Surge Pond Floor**
NOT TO SCALE

DRAWING NO.	DRAWING TITLE	DRAWING NO.	DRAWING TITLE
REFERENCE DRAWINGS			

NO.	DESCRIPTION	CHK'D	APP'D	DATE
A	Issued for Discussion			

REVISIONS

PROFESSIONAL ENGINEERS STAMP

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DESIGN: CH	DRAWN: NV / TH	REVIEWED: CH
CHECKED: CH	APPROVED:	DATE: 17/12/05

FILE NAME: 1CT022.013 - CWP Berm.dwg

TMAC RESOURCES

HOPE BAY PROJECT

SRK JOB NO.: 1CT022.013

Contact Water Pond Berm Design

DRAWING TITLE:
Contact Water Berm
Typical Sections and Details

DRAWING NO. CWB-01 | SHEET 1 of 1 | REVISION NO. A