APPENDIX 8
THERMAL ANALYSIS MODEL

Project Memo

H353004

April 19, 2018

To:	BIM	Hatch	From:	Yasmin Fakli
	Fay Pittman	Fanus van Biljon		Hani Ghiabi
	Rinaldo Stefan			Josephine Morgenroth
				Michael Yang

cc: Warren Hoyle

Baffinland Iron Mines Corporation
Mary River Expansion Project

Thermal Analysis of Proposed Rail Line Cut Sections

1. Introduction

Baffinland Iron Mines (BIM) plan to increase the Mary River Mine production to 12 Mtpa, shipping the increased output through Milne Port. This will be achieved by upgrades including the construction of a 110 km long rail line connecting the mine site to the Milne port, a new crushing and screening facility at the port, larger ore stockpiles and a second ore dock for ship loading.

Hatch Ltd. (Hatch) has reviewed the documents related to the design of the rail line along with information regarding soil conditions, climate data, and thermal properties of the materials, and performed a thermal analysis on the typical cuts to be excavated along the proposed rail line. Thermal analysis was carried out to provide recommendations for insulation requirements for cuts in areas including ice-rich and non-ice-rich types of permafrost.

This technical memorandum provides the assessment methodology, the summary of the results, and recommendations for insulation requirements for the scenarios identified in this project.

2. Background Information

2.1 Rail Design

The typical railway sections for cuts were modeled based on the recommendations provided in “Preliminary Geotechnical Recommendation for Railway Embankment - Between Milne Inlet and Mine Site” (Document # H352034-3000-229-230-0001). As a result, a slope ratio of 2H:1V was used for the side cut slopes along with a 9 m-wide base required for construction of the rail line embankment.

2.2 Permafrost and Frozen Ground Definitions

The following definitions pertain to permafrost and frozen ground regions:

Permafrost: Permafrost, or perennially frozen ground, is defined as soil or rock having temperatures below 0 °C during at least two consecutive winters and the intervening summer (Brown and Kupsch 1974).

Active Layer: In environments containing permafrost, the active layer is the top layer of soil that thaws during the summer and freezes again during the cold season.

Non-ice-rich Permafrost: defined here as permafrost that does not contain massive ground ice or ice lenses.

Ice-rich Permafrost: defined here as permafrost containing massive ground ice or ice lenses. When ice-rich permafrost is thawed under drained conditions, it undergoes volume changes and settlement.

2.3 Site Geotechnical Conditions

Between September 2016 and May 2017, Hatch carried out a two-phase geotechnical investigation program. In Phase1, which occurred in 2016, a total of 113 boreholes were drilled ranging from a depth of 1.5 m to 30 m. There were 88 boreholes drilled along the proposed rail alignment, 12 boreholes drilled at the proposed bridge abutments, 15 boreholes at Milne Port and 5 boreholes drilled at the proposed quarry locations. During the second phase of the investigation program, carried out in 2017, a total of 14 boreholes were drilled ranging from a depth of 4.6 m to 25.9 m. There were 12 boreholes drilled along the proposed rail alignment, and 2 boreholes drilled at the proposed bridge abutments.

The rail alignment, beginning at Milne Port, passes through approximately 20 km of Precambrian bedrock terrain, glaciofluvial sand, and gravel terraces. Further south, the rail alignment spans across a relatively flat lying ground comprising fine grained glacial till veneer overlying Paleozoic rocks mainly dolomitic limestone units for approximately 60 km. The final stretch of the rail alignment traverses glaciolacustrine and glaciofluvial plains, terraces, eskers and bedrock outcrops ranging from granitic gneiss to sedimentary rocks.

During this investigation, several areas with ice-rich permafrost were found including:

- A large ice body at the cut location at Km 26.7 on the proposed rail alignment 3 m below the existing ground surface elevation.
- A large ice body at the cut location at Km 47.3 on the proposed rail alignment 3 m below the existing ground surface elevation.
- Frequent ice inclusions of irregularly oriented excess ice were found at the boreholes drilled between Km 92 and Km 96 of the proposed rail alignment.

2.4 Climate Conditions

For the thermal analysis, historical mean monthly air temperatures were sourced from Environment Canada's 1981-2010 Canadian Climate Normals for Pond Inlet, NU (Table A-1 presented in Appendix A).

3. Thermal Analysis

The purpose of the thermal analysis is to predict the thermal regime of the sections including cut in permafrost zone and to provide recommendations in order to minimize the disturbance of the permafrost layers. Geostudio TEMP/W version 2012, a two-dimensional Finite Element (FE) software developed by Geo-Slope International Ltd, was used for this study.

3.1 Modelled Scenarios

The cases presented in Table 1, were modeled in this thermal analysis. These cases are representing 2 different cut depths (2m and 7m), 2 subsurface materials (Silt, Sand, and Gravel), and various insulation arrangements.

It should be noted that in Cases A-7 and B-7, a layer of crushed fill is extended on the side slopes with the purpose of protecting the slopes from sloughing for silt subsurface.

Table 1: Definition of Cases Modelled in TEMP/W

Case	Subsurface Material	Cut Depth (m)	Insulation Type
A-1	Sand and Gravel	2	None
A-2			On base
A-3			On base and slopes
A-4	Silt		None
A-5			On base
A-6			On base and slopes
A-7			On base and crushed fill on slopes
B-1	Sand and Gravel	7	None
B-2			On base
B-3			On base and slopes
B-4	Silt		None
B-5			On base
B-6			On base and slopes
B-7			On base and crushed fill on slopes

3.2 Boundary and Initial Conditions

The boundary and initial conditions are sourced from the “Geotechnical Design Basis” (Document # H353004-00000-229-210-0001). Details of the defined boundary and initial conditions are discussed in this section.

Initial Condition: The initial temperature profile was set up for the month of July, sourced from a representative thermistor installed in borehole BH2007-10 from borehole report by Knight Piesold (2008). The thermal model was then run for two weeks with exposed cuts and a mean air temperature estimated for July 2019. This was done, based on the proposed construction schedule, to calculate the initial ground temperature conditions once the construction of the railway embankment is completed.

Top boundary: It was assumed that the top of the soil profile and edge of excavation or insulation boundaries experienced a ground temperature which fluctuated in accordance with the temperature variation shown in Appendix A, Figure A-2. This temperature variation represents the estimated mean monthly temperature of Pond Inlet, NU for a 2 year period beginning at 2029 with global warming temperature increase applied starting from 2010. The temperature profile was chosen to commence at year 2029 to simulate the operation of the railway halfway in the operating period from 2019 to 2039. Temperature increases from global warming was applied to the base mean monthly temperature of Pond Inlet, NU for the periods from 1981 – 2010 to the year 2029 and beyond. An in-depth analysis of global warming scenario will be covered in Section 4.1.

There is a non-linear relationship between mean annual air temperatures and mean annual ground surface temperatures, which was accounted for by correlating the ground surface boundary conditions with the air temperature using an empirically determined function coefficient called the "n-factor". The mean monthly air temperature was modified using the freezing factor (n_f), and the thawing factor (n_t) for freezing and thawing seasons, respectively. Table 2 outlines the N-factors applied for various subsurface materials, sourced from the Geotechnical Design Basis.

Table 2: N-factors for Various Subsurface Materials

Material	N – factors	
	Freezing (n_f)	Thawing (n_t)
Sand and Gravel	0.7	1.2
Silt	0.5	1.2
Fill	0.8	1.5

Bottom boundary: As specified in the Design Basis, the temperature at the bottom boundary (depth of 20 m below existing ground) was set to -10°C.

Left and right boundaries: In accordance with the Design Basis, these were assumed to be no-flow boundaries, which is the default boundary condition in a finite element analysis (i.e., heat neither enters nor exits through these boundaries).The boundary conditions and typical meshing used in the FE models are presented in Appendix B. The boundary conditions could be established more accurately if additional ground temperature monitoring data was to be provided to Hatch.

3.3 Material Properties

The subsurface materials stratigraphy was selected based on the data obtained from 2016 geotechnical investigation and available technical references (e.g., Andersland and Ladanyi, 2004; Fillion, Cote and Konrad, 2011). The parameters used in the thermal analysis are summarized in Table 3 sourced from the Design Basis.

Table 3: Assumed and Calculated Thermal Properties

Material	Frozen Thermal Conductivity (J/s/m/°C)	Unfrozen Thermal Conductivity (J/s/m/°C)	Frozen Volumetric Heat Capacity (J/m³/°C)	Unfrozen Volumetric Heat Capacity (J/m³/°C)	Insitu Water content (%)	Insitu Volumetric Water content (m³/m³)
Fill (Types 5, 25, 8 and 12)	4.5	3.0	2,400,000	3,000,000	2	3.6
Silt	2.0	1.3	2,200,000	2,200,000	30	45
Sand/Gravel	3.0	2.0	2,600,000	2,600,000	15	25.5
Insulation	0.035	0.035	37,500	37,500	0	0

The insulation (polystyrene) layer was modelled with a thickness of 100 mm and 50 mm over the base and side slopes, respectively. It should be noted that, the thermal conductivity values used for "Ballast/subballst" and "run of quarry" are grouped within "Fill", and do not take into account the convection effect within these fill materials.

3.4 Failure Criteria

For rail line foundation, it is assumed that the failure can be avoided when the subsurface material in the zone 1 meter below the base of the rail embankment is protected by not allowing this layer to reach a temperature above -3°C (Line A). Also, it is assumed that for cut slopes below the original active zone, slope failure can be avoided by maintaining the temperature in a zone 1 meter below the cut faces below -2°C for ice-rich layers (Line B) and below 0°C for ice-poor layers (Line C). The reference lines can be found in Figure 1.

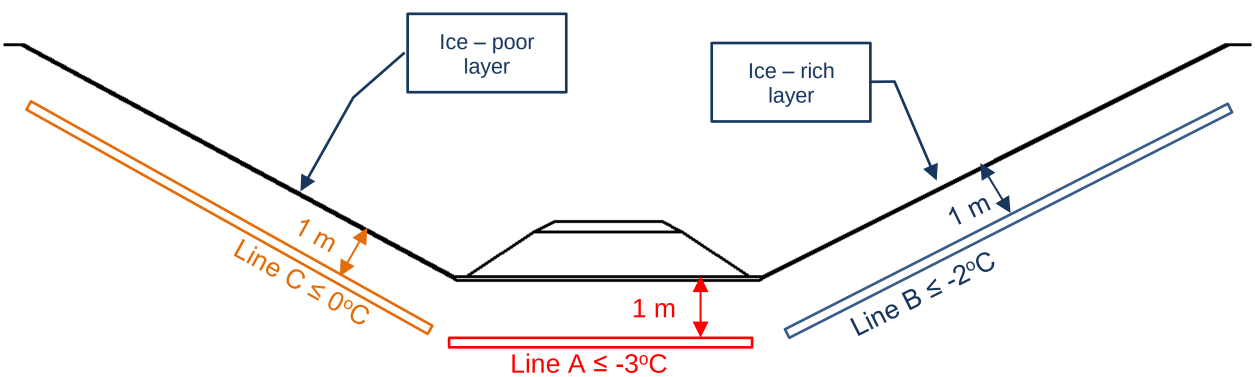

Figure 1: Temperature Threshold Zones Below Typical Railway Cut

4. Results

For each of the fourteen cases defined in this study, a transient thermal analysis was conducted for a two-year period considering the material parameters and N-factors presented in Table 2 and Table 3. The temperature profiles for the warmest ground condition are presented in Appendix C.

Table 4 summarizes the width of Lines A, B, and C with temperature <-3°C, <-2°C, and <0°C, respectively, computed for the warmest ground condition throughout the year. The results indicate that insulation is necessary to protect the foundation of the rail line from seasonal melt.

Table 4: Thermal Analysis Results

Case	Figures Appendix C	Insulation Type	Width of Line A <-3°C (m)	Width of Line B <-2°C (m)	Width of Line C < 0°C (m)
A-1	1	None	0	0	0
A-2	2	On base	8.5	0	2.6
A-3	3	On base and slopes	9	2.8	4.2
A-4	4	None	0	0	4.5
A-5	5	On base	8.1	0	3.6
A-6	6	On base and slopes	9	2.7	4.5
A-7	7	On base and crush fill on slopes	9	0	2.8
B-1	8	None	0	0	14.1
B-2	9	On base	8.4	0	12.7
B-3	10	On base and slopes	9	13.7	15.2
B-4	11	None	0	0	14.9
B-5	12	On base	8.4	0	12.5
B-6	13	On base and slopes	9	13.2	16.4
B-7	14	On base and crush fill on slopes	9	0	15.3

4.1 Climate Change Considerations

Cases B-5 and B-6 were run for a 20 year period from 2019 – 2039 to determine the risk of sloughing of the silt at the cut slopes during the operation period. The air temperature profile for this period was generated using the temperature increase increments outlined in the Design Basis and summarized in Table 5, added to the mean monthly temperature of Pond Inlet, NU from 1981 – 2010. The air temperature profile used to model the 2 week exposed cut in July 2019 and 2 year operation period starting at year 2029 is sourced from the aforementioned global warming air temperature profile.

Table 5: Temperature Increase for the Period Spanning 2010 – 2039

Period	Temperature Increase (°C)
Dec – Feb	3.8
Mar – May	2.7
Jun – Aug	1.9
Sept – Nov	3.5

The warmest temperature profiles (for Cases B-5b and B-6b) with the climate change consideration are associated with summer 2039 and are presented in Figures 15 and 16 of Appendix C. The results of this analysis are summarized in Table 6.

Table 6: Thermal Analysis Results – Climate Change Considerations

Case	Figures Appendix C	Insulation Type	Width of Line A <-3°C (m)	Width of Line B <-2°C (m)	Width of Line C < 0°C (m)
B-5b	15	On base	7.3	0	14.2
B-6b	16	On base and slopes	9	12.0	15.4

An increase in the average monthly temperatures results in a decrease in the width of Line A below -3°C and overall increase in temperature of the excavation surfaces. However, when compared to the cases run for a 2 year period starting at year 2029, the changes in the width of Lines A, B, and C are minimal for the Case B-6b in which the insulation layers were placed on the base and side slopes.

5. Conclusions and Recommendations

The conclusions and recommendations from this study are summarized below:

- This thermal analysis was performed based on some typical thermal parameters extracted from literature and historical information from the Mary River site. This analysis can be reviewed when additional data is made available with respect to thermal conditions (e.g. new data from thermocouples installed at port).
- There are a number of local factors which were not modelled in this analysis that could impact the subsurface thermal regime of any individual location. Possible local factors include elevation, slope direction, groundwater conditions, and the presence of surface water.
- Following the review of the construction schedule, for this assessment, it is assumed that the construction and installation of insulation will take place within a 2-week period in July. This will not result in excessive thawing of the permafrost and sloughing of the subsurface and foundation. However, It is recommended that special care to be taken during construction and installation of insulation in the permafrost to minimize ground disturbance and melting during the construction phase.
- For cut sections where polystyrene insulation be modelled over the base (100 mm-thick insulation), the 9 m-wide zone on Line A (1 m below the base of the cut) practically remains at a temperature below -3°C throughout the year. For uninsulated side slopes, the temperature will generally be below 0°C at 1 m below the cut surfaces. For the side slopes insulated with 50 mm-thick insulation, the temperature will practically remain below -2°C at 1m below the cut surface.

- 100 mm-thick insulation is strongly recommended beneath the railway embankment for all soil conditions (e.g. silt, and sand and gravel foundations) to avoid thawing and deformation of the embankment and foundation.
- For cut slopes in ice-poor layers, no sub-excavation or insulation layer is recommended.
- For cut slopes in ice-rich layers, a 300 mm of sub-excavation is recommended followed by placement of 300 mm of fill. A 50 mm-thick insulation layer is recommended to be placed over the slopes.
- The insulation layer should be protected and secured from uplift in winds by placement of a minimum of 200 mm-thick soil cover acting as a ballast.
- Drainage ditches are recommended at the toe of the cut slopes with a minimum longitudinal slope of 0.2% to drain the water from the toe of the slopes and, subsequently, minimize water infiltration into the permafrost.
- Further analysis should be performed if the geometries or the boundary conditions of the cut sections vary from those modelled herein, including cases where:
  - the trench base is designed wider than 9 m
  - the trench depth is greater than 7 m
  - a heat source is identified adjacent to the area; or
  - soil conditions vary from that modeled.

6. References

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Lunardini, V. J., 1978. Theory of n-factors and correlation of data. In Proc. 3rd Int. Conf. on Permafrost, Edmonton, Alberta. Ottawa: National Research Council of Canada, vol. 1, pp. 41–46.

Yasmin Fakli
Hani Ghiabi
Josephine Morgenroth
Michael Yang

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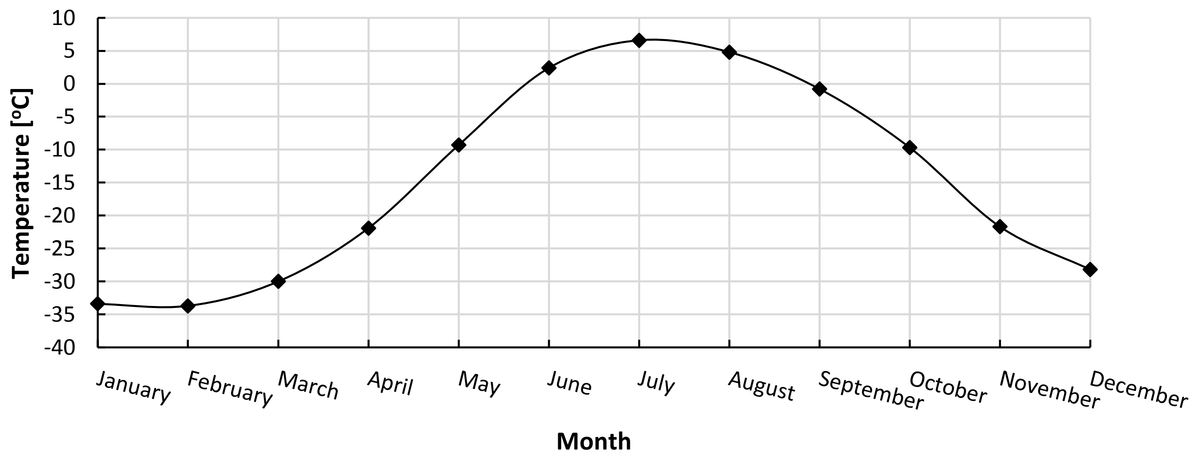
Appendices:

Appendix A – Climate Data
Appendix B – Finite Element Model Details
Appendix C – Results of Finite Element Analysis

Appendix A: Climate Data

Table A-1: Mean Monthly Temperatures - Pond Inlet, NU, 1981-2010 Climate Normals

Month	Mean Daily Average Temperature (°C)
January	-33.4
February	-33.7
March	-30.0
April	-21.9
May	-9.3
June	2.4
July	6.6
August	4.8
September	-0.8
October	-9.7
November	-21.7
December	-28.2



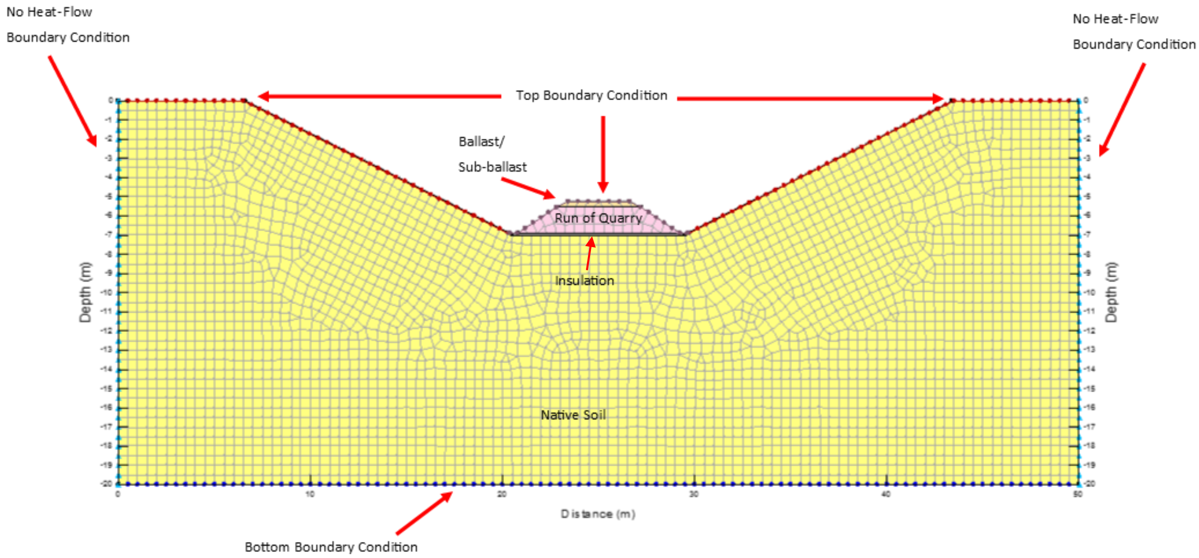
Graph-1: Mean Monthly Temperatures for Pond Inlet, NU (1981-2010)

Table A-2: Mean Monthly Temperatures from years 2029 to 2031

Year	Month	Mean Daily Average Temperature (°C)
2029	July	7.84
	August	6.04
	September	1.49
	October	-7.41
	November	-19.41
	December	-25.71
2030	January	-30.78
	February	-31.08
	March	-28.14
	April	-20.04
	May	-7.44
	June	3.71
	July	7.91
	August	6.11
	September	1.61
	October	-7.29
	November	-19.29
	December	-25.58
2031	January	-30.65
	February	-30.95
	March	-28.04
	April	-19.94
	May	-7.34
	June	3.78
	July	7.98
	August	6.18
	September	1.73

Year	Month	Mean Daily Average Temperature (°C)
	October	-7.17
	November	-19.17
	December	-25.45

Appendix B: Finite Element Model Details



Typical Model Setup, Meshing, and Boundary Conditions for FE Analyses

Appendix C: Results of Finite Element Analysis

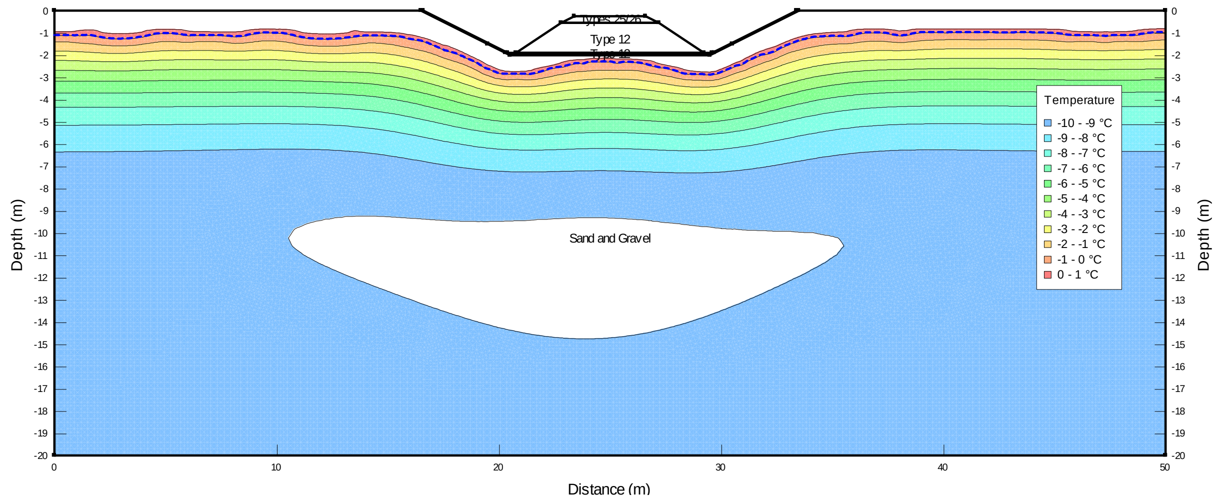


Figure 1: Results of Case A-1

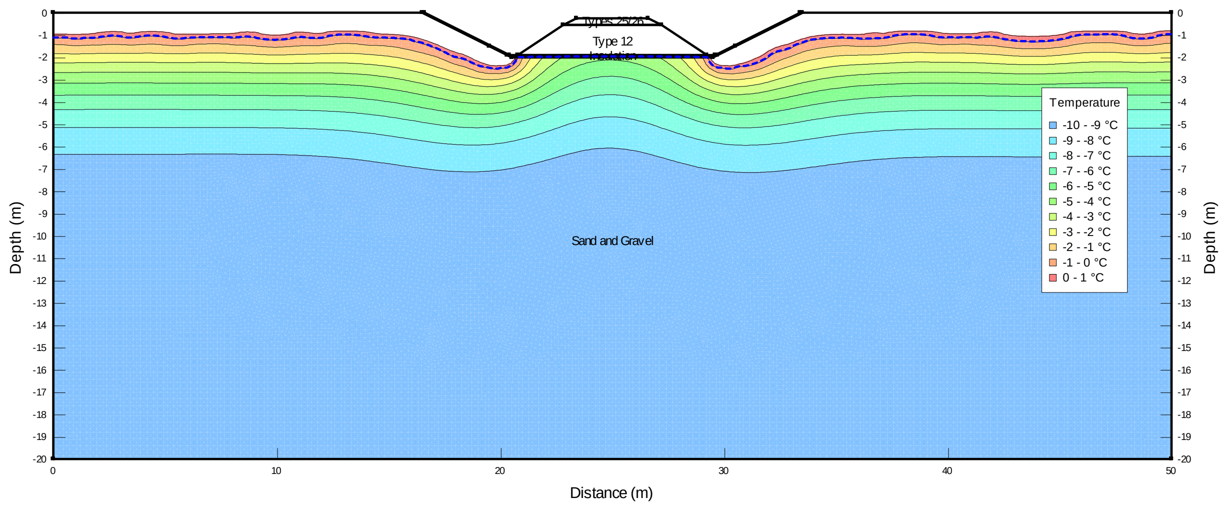


Figure 2: Results of Case A-2

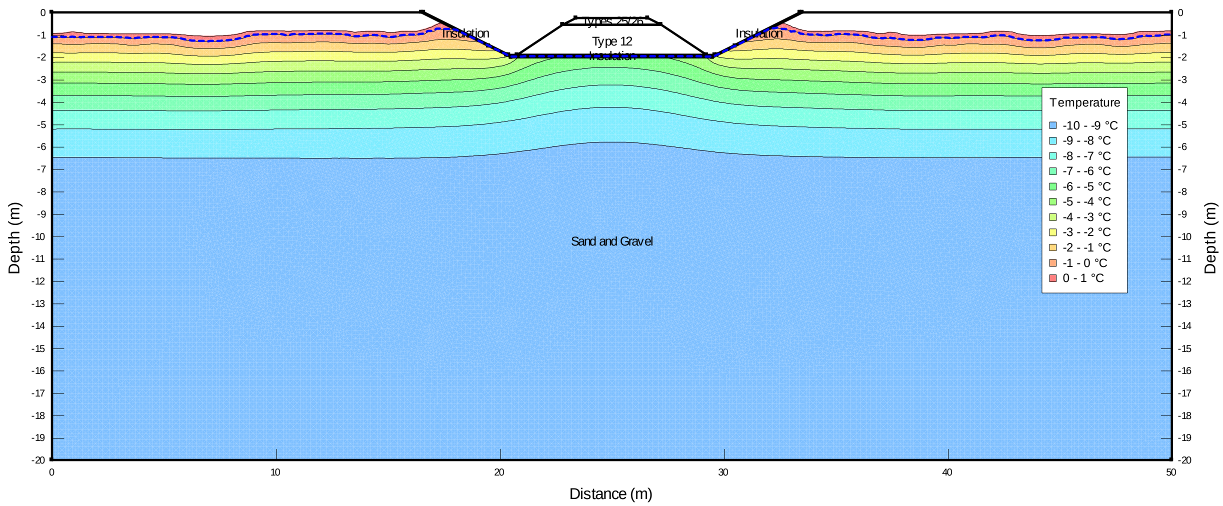


Figure 3: Results of Case A-3

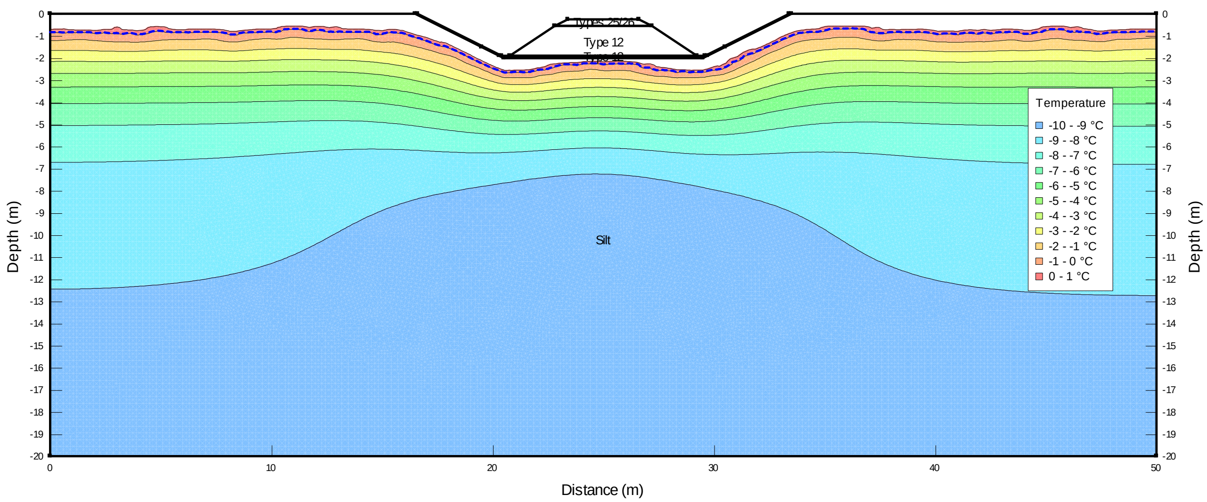


Figure 4: Results of Case A-4

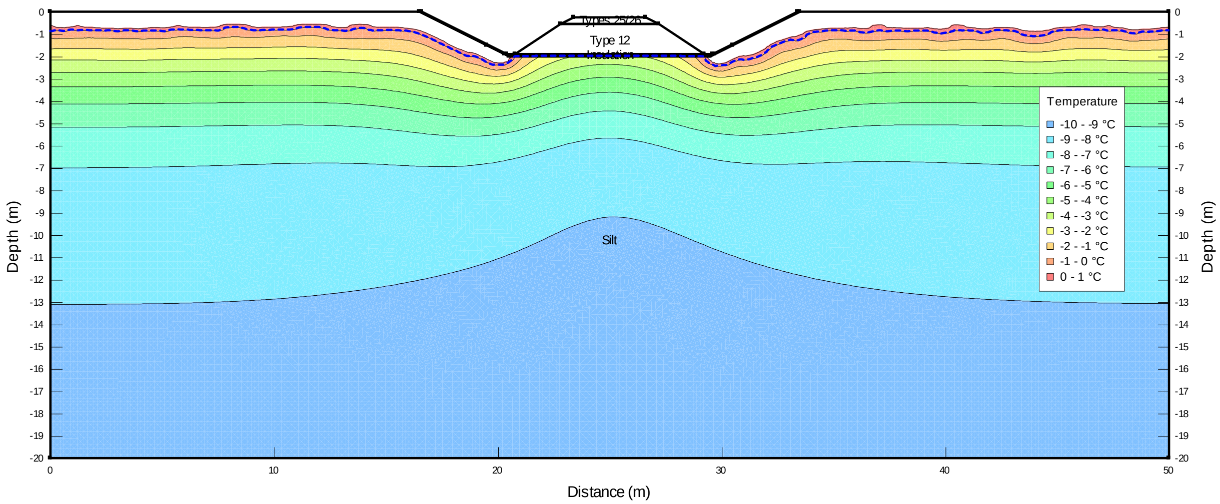


Figure 5: Results of Case A-5

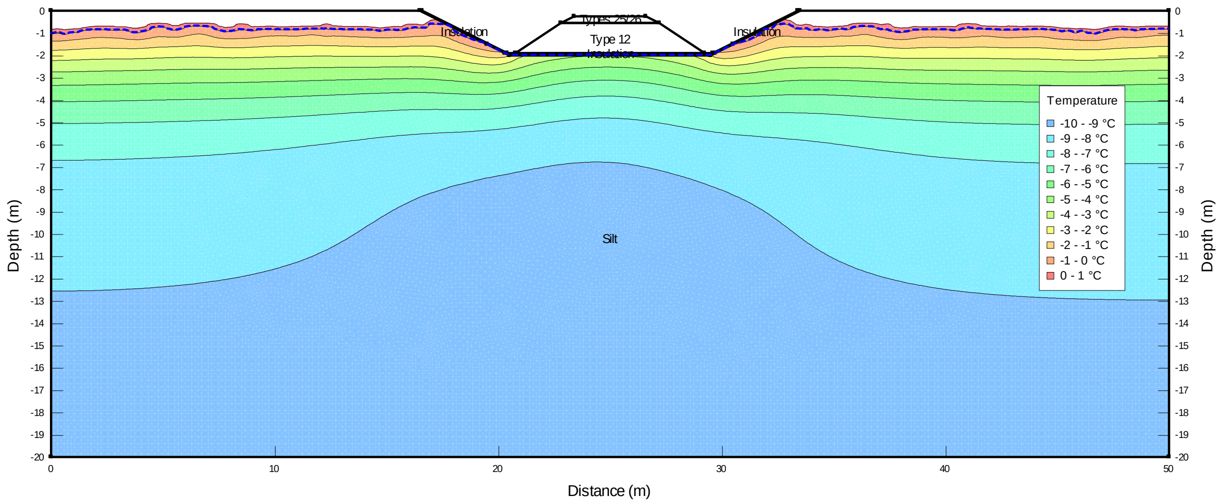


Figure 6: Results of Case A-6

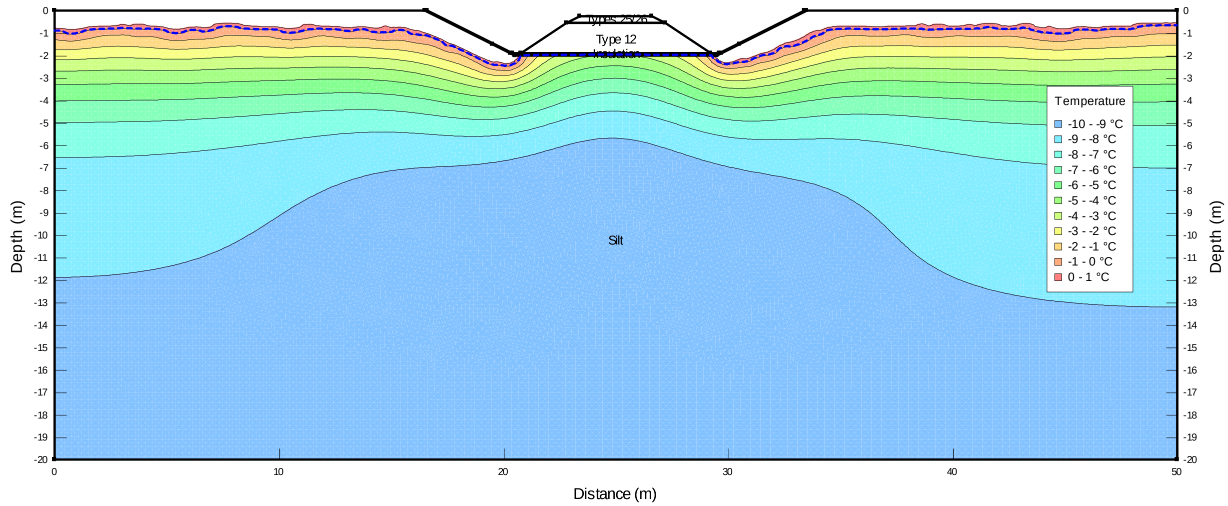


Figure 7: Results of Case A-7

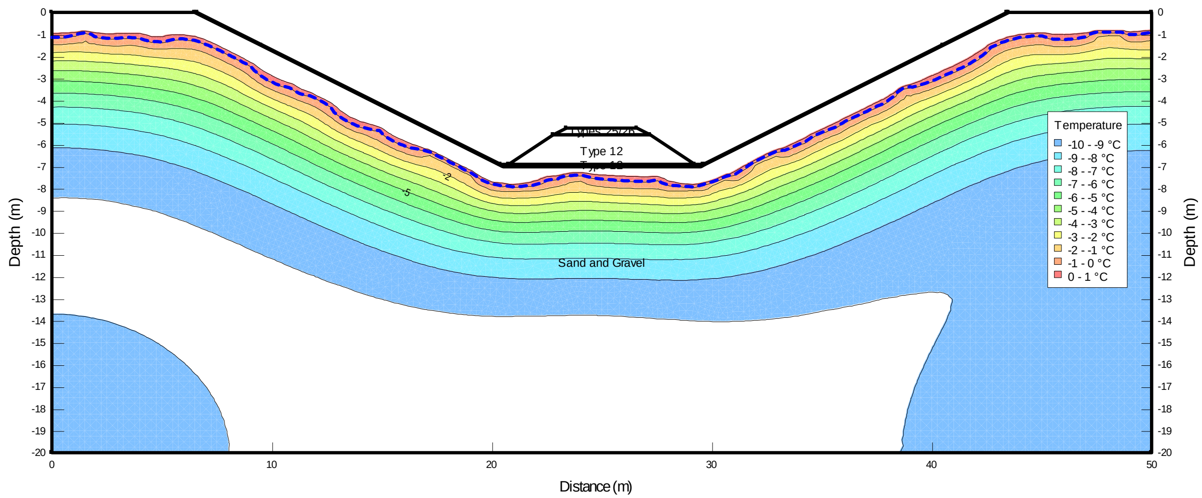


Figure 8: Results of Case B-1

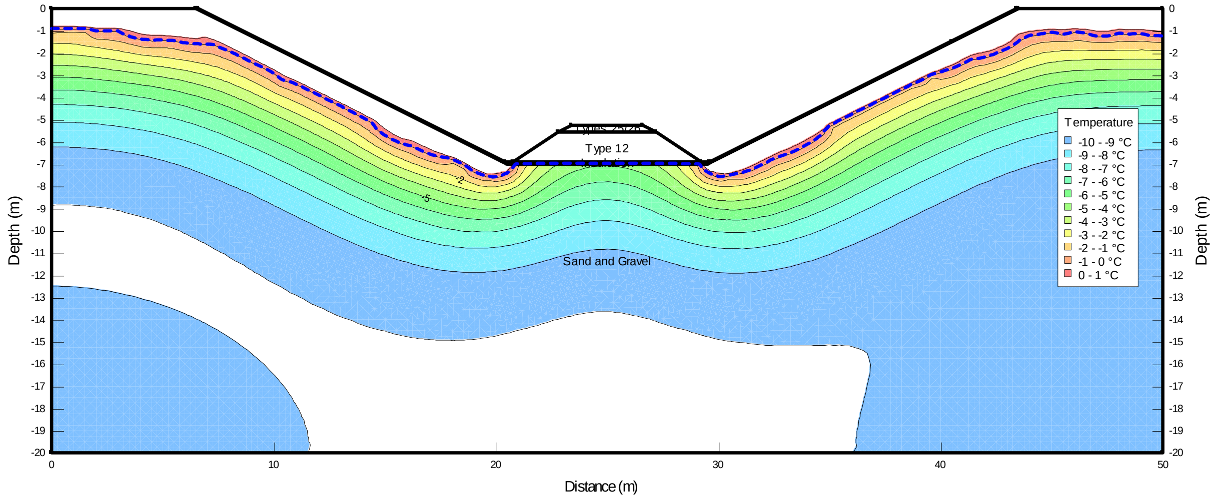


Figure 9: Results of Case B-2

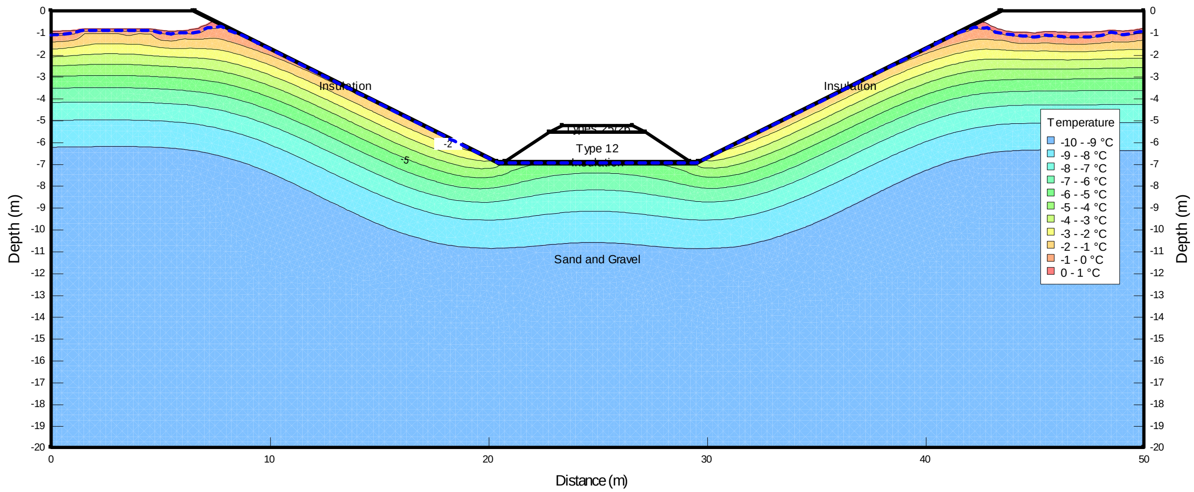


Figure 10: Results of Case B-3

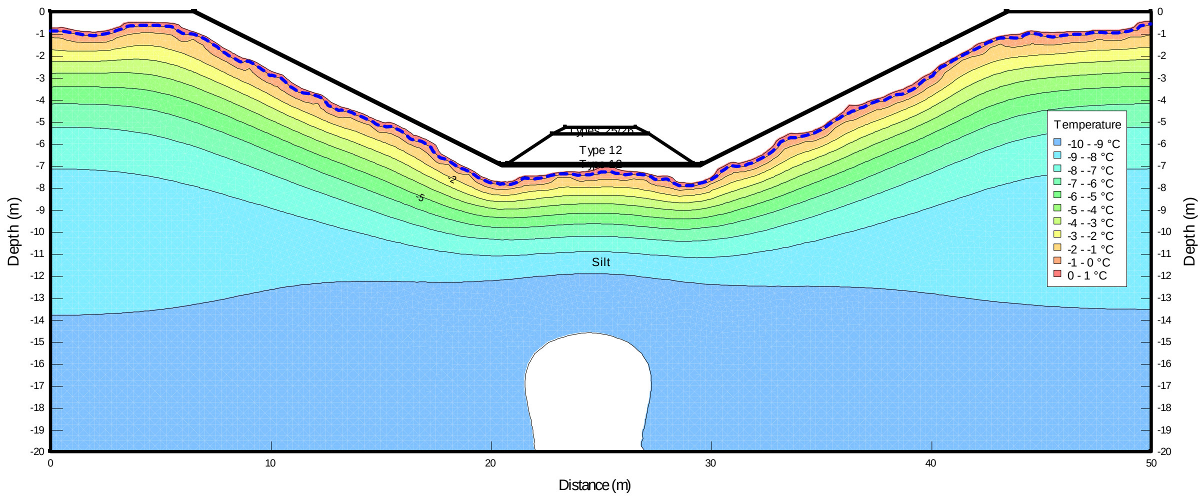


Figure 11: Results of Case B-4

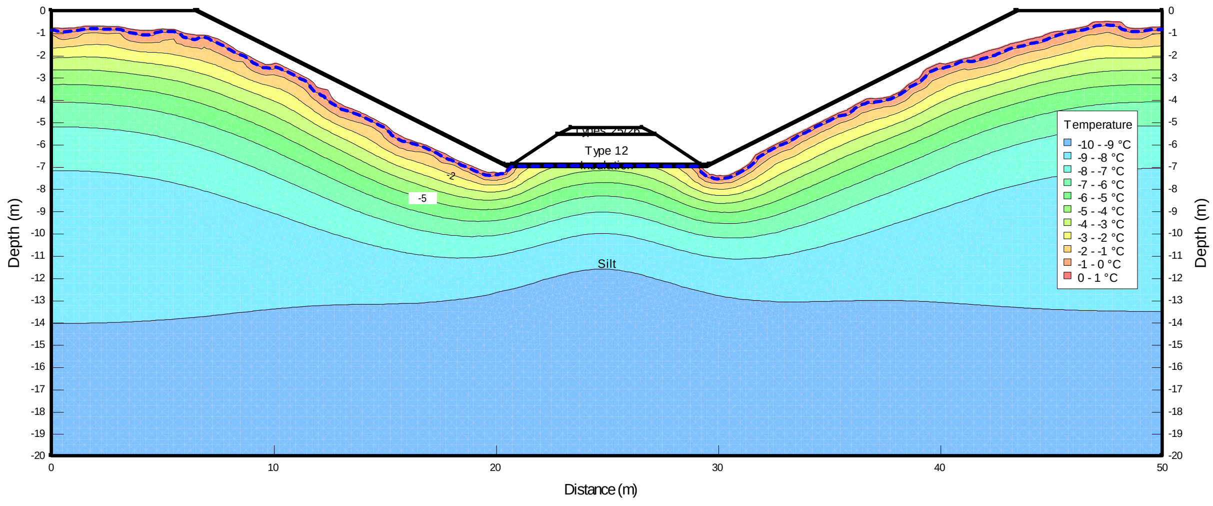


Figure 12: Results of Case B-5

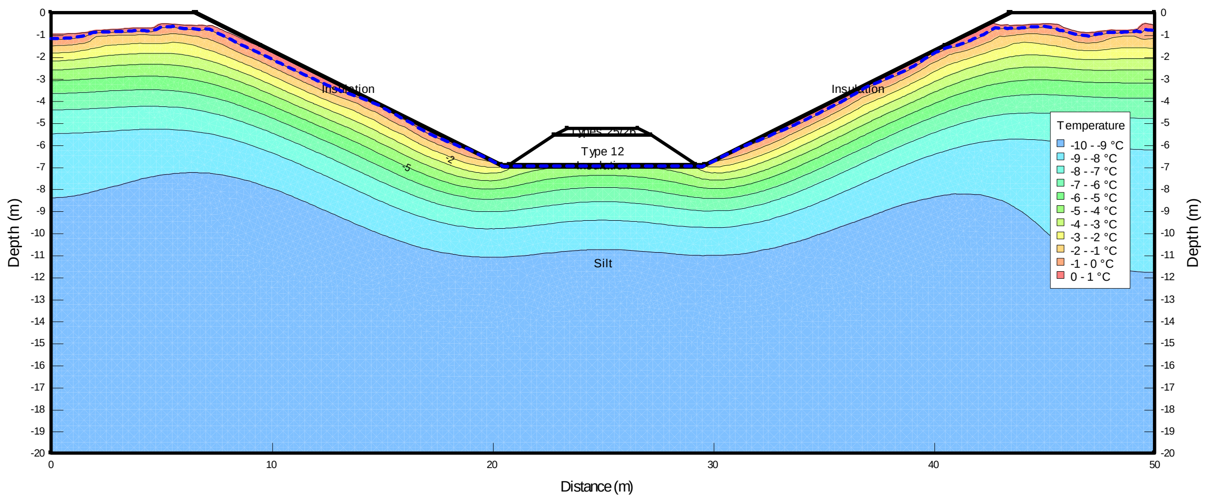


Figure 13: Results of Case B-6

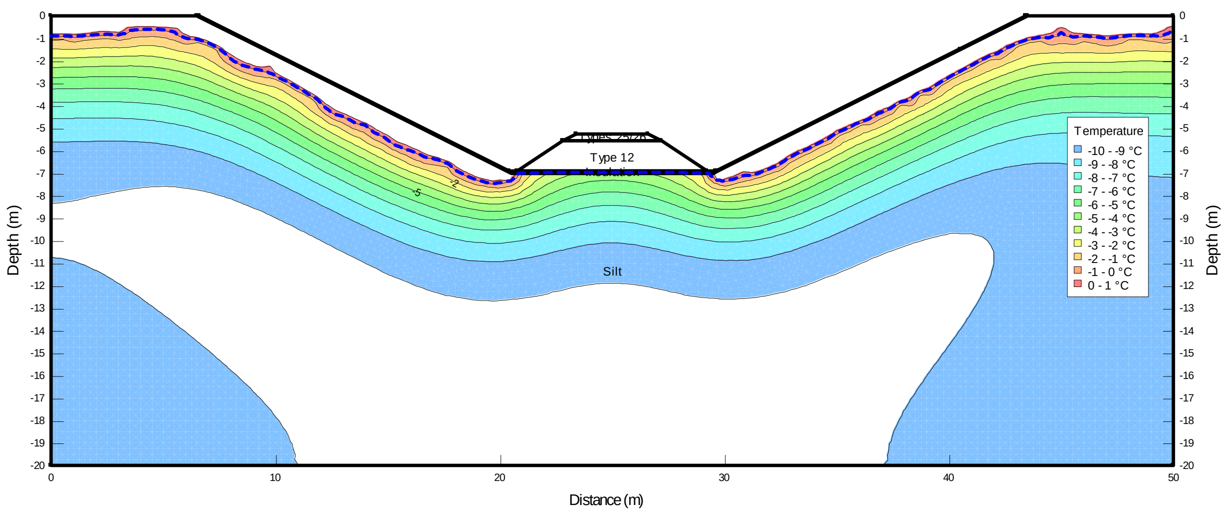


Figure 14: Results of Case B-7

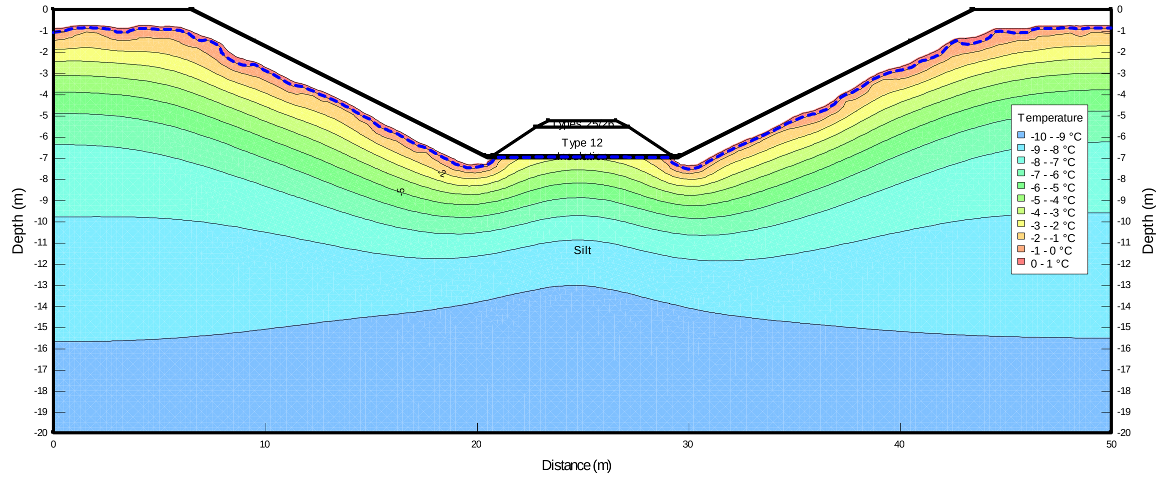


Figure 15: Results of Case B-5b – Climate Change Consideration

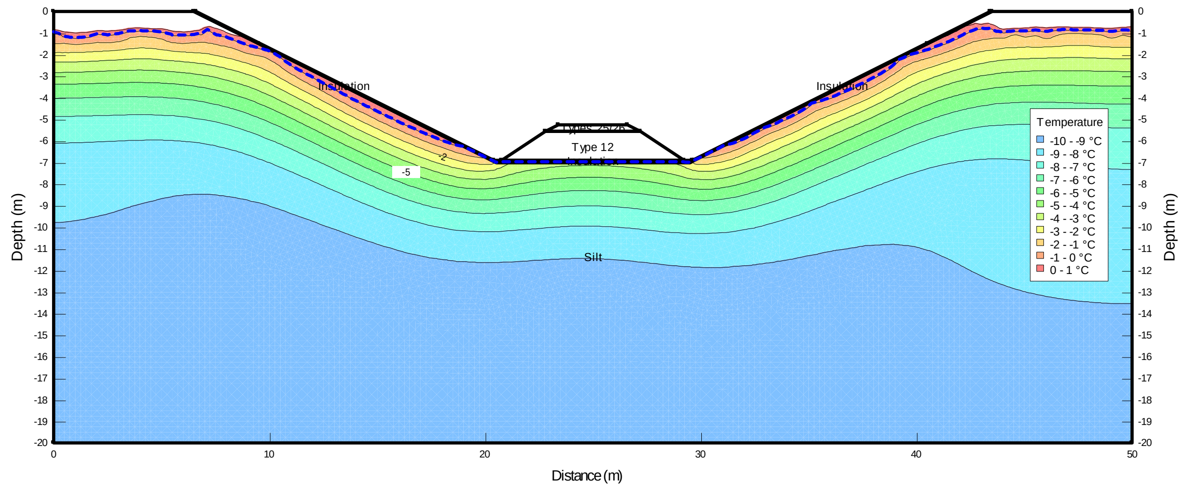


Figure 16: Results of Case B-6b – Climate Change Consideration