THE EFFECTS OF CULVERTS ON EMBANKMENT PERFORMANCE IN COLD REGIONS

By

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Abstract

In Arctic regions where permafrost is present, culverts are installed during winter construction where the fill material is placed and compacted under frozen conditions. Culverts affect the thermal and mechanical stability of road embankments. They act as heat conduits during the summer months but depending on its diameter can trap heat during the winter months when their ends are covered with snow. Thawing of the frozen soil around and below the culvert will lead to differential settlements and longitudinal cracks at the road surface and embankment slopes, respectively.

In order to study the influence of culverts covered with snow during the winter months on the thermal and mechanical behaviour of frozen fill embankments, a 5-noded thermistor string was installed inside an 800 mm diameter culvert along its length on an existing test section along the Inuvik-Tuktoyaktuk Highway (ITH) in the Northwest Territories, Canada. Camera traps were installed around the research site to monitor snow depth. In addition, heat transfer and coupled thermal-mechanical finite element models were developed using the commercially-available finite element software ABAQUS. The temperatures recorded from this thermistor string were used as a boundary condition. The models were run for two years of recorded field data obtained from the field to provide an understanding in the thermal regime around the culvert and its associated deformations.

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CHAPTER 1

1. Introduction

Culverts installed across road embankments maintain natural drainage conditions and minimize hydrological impacts. In northern applications where permafrost is present, culverts are installed during winter, such as the case of the newly-opened Inuvik-Tuktoyaktuk Highway (ITH) in the Northwest Territories. This means the fill material is placed and compacted under frozen conditions. Culverts affect the thermal stability of road embankments. They act as heat conduits during summer, but depending on its diameter can trap heat during winter. Thawing of soil around and below the culvert will lead to differential settlements and longitudinal cracks at the road surface and embankment slopes. In order to study the effects of culverts on the thermal behaviour of surrounding soil, a 5-noded thermistor string was installed inside an 800 mm diameter culvert along its length. Temperature readings along the culvert from the time of instrumentation installation and during the winter months are presented in this study. Based on site conditions, soil parameters, and local weather data, a thermal-mechanical model has been developed to assess the effect of the culvert on embankment thermal regime and mechanical performance with the commercially available finite element software ABAQUS. This study was developed as part of the PhD research project of De Guzman (2020a) in assessing the structural stability of highway embankments in the Arctic corridor.

1.1. Background

The completion of the Inuvik to Tuktoyaktuk Highway (ITH) has been a long-standing goal of the Town of Inuvik, the Hamlet of Tuktoyaktuk, and the residents of the Inuvialuit Settlement Region (EIRB, 2011). The construction of the ITH will help address the goals of Northern economic development, enabling future natural resource exploration, development, and production (such as the natural gas and oil reserves in the Mackenzie Delta and Basin), and reinforcing Canadian sovereignty objectives (EIRB, 2011; Infrastructure Canada 2015).

Detailed road alignment, environmental data gathering, and engineering design were conducted in the 1960's and 70's and has been continuously revised to address the concerns of local communities and other stakeholders during an extensive environmental review process, leading to the development of the route alignment alternatives in 2009. The highway has been identified as a priority development by the Government of Canada and Government of the Northwest Territories (GNWT). The ITH, which extends the Dempster Highway past the community of Inuvik to the Arctic Coast, will be an all-weather transportation link and will complete Canada's road network from the Pacific, to Atlantic, and to Arctic coasts. Fig. 1-1 shows the constructed alignment of the highway.

The warming trend in air temperatures due to climate change in the Northwest Territories (IPCC, 2014) has and will continue to pose challenges for the transportation system (TAC, 2010). Climate change has impacted fall freeze-up and spring thawing, causing delays and reduced operations of highways. Construction is performed only during the winter season for ease in moving fill materials and to minimize environmental impact. Typical ‘cut and fill’ techniques employed in the southern areas of the Northwest Territories are not used in this project to protect the permafrost terrain along the highway alignment (EIRB, 2011). There are uncertainties related to the mechanical behaviour of embankments that were initially compacted with frozen fill and then experienced natural thawing and settlements during the summer following construction. The fill material of the ITH embankment is dominated by fine till that may include high content of ground ice. Fills are very difficult to compact at sub-zero temperatures when ice is present, but are relatively strong while they remain frozen. They become soft and compressible upon thawing.

Embankment performance is affected by the presence of culverts. Culverts are structural elements installed across road embankments to maintain natural drainage conditions and minimize hydrological impacts, but these culverts also pose thermal and mechanical concerns on embankment performance. Because frozen soil is difficult to compact and an optimum density cannot be achieved (De Guzman et al., 2018), thawing around the culvert will translate to settlements and cracking at the ground surface and slopes. Fig. 1-2 shows some of these issues along the highway after the first thawing in the summer following winter construction.

Culverts are conservatively designed to satisfy hydraulic requirements along highway embankments (Lingnau, 1985; TAC, 2010). Water flow and temperature impact embankment temperatures, where heat transfer underneath the culvert is more affected by water temperature compared to water flow (Perier et al., 2015). The thermal capacity and conductivity of water is significantly greater than that of air and contributes to the thermal regime of the embankment, particularly ponding water at the toe and large flows which may accelerate thawing and impact the depth of the permafrost table (Esch, 1988; TAC, 2010; Bouchard and Guimond, 2012). The effect of water on the thermal performance of the underlying foundation embankment has been studied extensively in literature. However, the air inside the culvert is cooler than the ambient air temperature during the summer months but provide passive cooling in the winter months if the culvert is large enough for the culvert ends not to be covered in snow. Most culverts installed along the ITH however are 800 mm in diameter which get covered in snow during the winter months. The snow is either deposited naturally or due to snow road clearing operations. To determine the temperature changes inside a culvert shortly before and during the winter months, a thermistor string was installed along the culvert at the research sections of the University of Manitoba along the ITH (De Guzman, 2020a; De Guzman et al., 2020b). This study presents the results of the temperature monitoring program along the culvert from September 2017 to September 2019. The measured temperatures will be used as boundary conditions for thermal-mechanical modelling that to investigate the effects of culverts on overall embankment performance.

1.2. Objectives

(a) Determine seasonal trend of air temperatures throughout the length of an 800 mm culvert.

(b) Determine the thermal influence culverts have on thick and thin embankments and underlying permafrost foundation.

(b) Develop an understanding of the effects and instabilities caused by culverts on the thermal and mechanical performance of embankments in cold regions environment.

1.3. Hypothesis

The primary function of culverts is to maintain natural drainage conditions, and therefore culverts are placed at the base of the embankment. For ‘small’ sized culverts, it is expected that snowfall will inevitably block both inlet and outlets of the culvert limiting heat loss in winter months.

Typical embankment design in Arctic regions ensures that the permafrost table aggrades into the embankment. The placement of a culvert thus changes the temperature profile and influence of the surrounding soil temperatures affecting the ability of permafrost to aggrade within the culvert region.

For ease of construction and environmental factors, embankments are constructed with frozen fill, and compacted at subzero temperatures. It is expected with the intrusion of culverts, increase in soil temperatures are expected at these locations and embankments will experience additional thaw settlement at culvert locations.

1.4. Research Approach

(a) Collect and assess temperature data along a culvert

(b) Develop thermal numerical models based on recorded temperatures

(c) Develop thermal-mechanical numerical models based on recorded temperature and available soil properties for the embankment fill and foundation soil

1.5. Thesis Organization

The thesis is organized into the following chapters:

Chapter 2: *Literature Review:* Identify, overall embankment degradation factors including existing knowledge of conduits passing through embankment in cold regions and their effects on embankment and foundation performance.

Chapter 3: *Field Instrumentation and Monitoring:* Describes installation and data collection of temperatures along an instrumented culvert, as well as its influence on the existing embankment test sections.

Chapter 4: *Numerical Modelling:* Provides the numerical modelling approach, material properties selected, and presents the results of the pure thermal and coupled thermal-mechanical modelling conducted.

Chapter 5: *Conclusion and Recommendation for Future Works*

Fig. 1-1. Alignment of the Inuvik-Tuktoyaktuk Highway and the University of Manitoba's research section (courtesy of DOI-GNWT).

(a)

(b)

Fig. 1-2. Observed issues around culverts: (a) lateral cracking and (b) differential settlements (photos courtesy of L. Arenson, with permission).

CHAPTER 2

2. Review of Related Literature

The permafrost in northern Canada and other locations such as Alaska have necessitated the consideration of the thermal regime of the ground in their construction (Zarling et al., 1984). The provision of stable road bases particularly in embankments is a critical issue in permafrost areas such as northern Canada. The advancement of global warming and the unpredictable shifts in climate have necessitated critical thinking in engineering that focuses on the effectiveness of culverts in road embankments in permafrost areas. Climatic conditions in Canada lead to surface ground freezing for multiple months during winter in almost every part of the country (CFEM, 2006). Depending on the local climate and other factors such as snow cover and soil conditions, the impact usually leads to the volumetric expansion of soil, leading to the heaving of structures above the soil. When springtime comes, the thaw releases the excess water which may weaken the soil structure or even collapse it. Culverts are installed across road embankments to keep natural drainage and maintain hydrological conditions. However, impacts should be understood regarding culvert construction and placement, particularly in northern applications where permafrost is present. Permafrost is described as rock or soil that had been under temperatures below 0°C for at least two years. Culverts (perpendicular to the embankment) constructed along Inuvik-Tuktoyaktuk Highway (ITH) serve to maintain the natural drainage channel flow with efforts to maintain existing hydrological conditions and are placed in locations where there are no fish habitats (EBA, 2010). Currently, there are limited studies that evaluate the impacts of culverts on the performance of embankments in cold regions- more specifically continuous permafrost regions. However, systems such as air ventilated ducts, tunnels, and culverts in seasonally frozen regions will provide a similarity to construction and behaviour in understanding influences of culverts in embankments constructed in cold regions.

2.1. Embankment Construction and Performance in Cold Regions

It is indicative that permafrost across North America is showing a warming trend (Smith et al., 2010). Jorgensen and Ingeman-Nielsen (2012) have suggested that the increasing annual air temperatures will lead to embankment instabilities. These instabilities include conditions such as longitudinal cracks and lateral spreading of embankment slopes (McGregor et al., 2010). When permafrost thaws, it threatens the integrity of transportation structures due to settlements and destabilization of the terrain through thermal erosion or landslides (Allard et al., 2012; Brooks et al., 2015). Slope instabilities in constructed embankments occur when thaw conditions advance, melting ground ice at active permafrost transition and creates excess pore pressures over a perfect slipping plane (Allard et al., 2012). Thermal erosion occurs when water flows directly along with icy permafrost like in the outlet of culverts. According to Cheng et al. (2008), approximately 85% of damages on highway embankments are caused by settlements due to soil thawing.

Embankments constructed with well-drained soils are more stable compared to cut or natural slopes (Linell & Johnston, 1973). Linell & Johnston (1973) highlight that embankment toes are susceptible to shear strength loss during thaw particularly when a locus of deeper yearly thaw penetration and possible thermal instability, which are made intense by ponding of surface water. As an example, embankment instability is often observed along the Alaska Highway, with some of the instability issues observed near culverts (Périer et al., 2015). There are various uncertainties on the mechanical behavior of embankments where the frozen soil is used as the fill material and therefore undergoes natural thawing and settlements after the initial thawing season following the construction of the embankment (De Guzman et al., 2020b). This is particularly frequent since fill material is typically locally sourced and is mostly made of fine till which has high ground ice content. The use of this material typically leads to the development of side slope sloughing and fill cracking because of the frozen soil thawing, and the growth of localized thaw settlements under the shoulders of embankments and side slopes (De Guzman et al., 2021). In their research, they found that the center and underneath layers of the embankment fill remained frozen for 4 years while the depth of thaw increased at the toe. Périer et al. (2015) have highlighted that the construction of road embankments changes the thermal regime of the soil under and next to the road, which may lead to thaw of permafrost and loss of infrastructure integrity. The slopes of embankments in warm permafrost areas often creates severe problems from long-term thaw-related settlements. This is heavily influenced due to the snow that is plowed from the road, creating a thicker and increased insulation cover on the side slopes (Esch, 1978). Soils underlying the slopes do not completely refreeze each winter like in cleared road portions. The yearly deepening of thaw zones underneath the slopes leads to the continuous settlements of the outer edges of the roadway and mostly leads to longitudinal cracking of the road (Esch, 1978). The thickness is designed to give adequate ground insulation and reduce permafrost degradation under various climatic conditions (Argue et al., 1981). The permafrost degrades if the insulating effect that the embankment fill provides is less than the insulating effect of the original active layer (De Guzman et al., 2020b). The thermal regime in the active layer and underneath the permafrost also largely depends on the thermal properties of the foundation soil and the interactions between the ground and atmosphere (De Guzman et al., 2021). Further, De Guzman (2020a) has indicated thick embankments act as windbreakers, which favour snow accumulation on the shoulders and toes, hence insulating the ground surface, reducing heat loss in winter, and eliminating further ground freezing. In this perspective, culverts can be designed to accommodate the accumulation of snow at the toes, given the potential of inlet and outlet blockage.

2.2. Ventilated Ducts

Air ventilated ducts is a technique to mitigate the affects of thaw through linear infrastructure on permafrost. Niu et al. (2004) determined that ventilation ducts in railway embankments in permafrost regions can effectively remove heat from soils around the ducts of the embankment and subsequently cooling the ground. The temperature of the permafrost below the embankments where ducts were buried in relatively high positions was similar to that of the common embankment (Niu et al., 2004). The temperature of the frozen soils below the embankment where the ducts were placed in relatively lower positions increased minimally in the initial stages after which it gradually cools down. The researchers found that ventilation ducts effectively reduced the thermal disturbance that was caused by filled soils. They have concluded that ventilation embankments with low-posited ducts have efficient temperature-regulating effects and can actively cool subgrade soils and keep roadbeds thermally stable. Further studies reinforce these and agree that ventilation in embankments can effectively decrease ground warming, hence preventing thawing effects (Arenson et al., 2006; Goering & Kumar, 1996; Wu et al., 2002; Lai et al., 2004; Lai et al., 2004; Cheng, 2005; Liu & Lai, 2005; Yu et al., 2005; Ma et al., 2006). Malenfant-Lepage et al. (2012) studied the benefits of installing longitudinal culverts along embankments. Longitudinal plastic waterproof culverts were buried under an embankment slope and parallel to roads with the aim of cooling due to air circulation (Malenfant-Lepage & Dore, 2012; Grozic et al., 2010). The effects are that warm air tends to go up through vertical outlets during winter, hence drawing cold air in the embankment's base through inlets (Malenfant-Lepage & Dore, 2012). Results from this particular study suggest that the longitudinal culvert was one of the three successful techniques in the cooling of natural ground and was the only technique that did not lead to a warming trend. However, the study highlights that the good prospects offered by the longitudinal culverts are only present during the first three years of service.

The installation of air convection ducts combined with the use of insulation layers and embankment toe berms has been recognized as a means of assuring satisfactory yearly refreezing (Esch, 1987; Zarling et al. 1984), which in turn prevents the long-term settlement of thaw in snow-covered embankment slopes. Several studies along the Qinghai-Tibet Highway in China also showed this benefit (Cheng et al., 2008; Chou et al., 2008). Zarling et al. (1984) have illustrated the determination of average air speed in the vent duct based on static pressure caused by the stack effect as a means to determine the heat transfer rate. This accomplished the approximation for the freeze radius surrounding the ventilated duct. Fujun et al. (2008) has determined that wall temperatures around the duct are variable, having placed temperature probes along the walls and center of the ventilating duct. Convection in culverts is important and various studies stress it stating that they are similar to convection ducts (Hua et al., 2014). Tommik (2019) has acknowledged ventilation ducts in permafrost settings are comparable to culverts in terms of behavior, although culverts not only have the possibility of cooling an embankment, but also may accomplish the opposite.

In efforts to address the quality of roadway performance Jumikis (1973) presented the effects of seasonally cold temperatures on roadways, demonstrating the soil-culvert interaction system seen below in Fig. 2-1. The system is in context of assessing frost penetration through soil, which are responsible for the deformation at the road surface over the culvert (Jumikis, 1973). Although, the general arrangement of heat exchange does remain consistent with permafrost regions.

2.3. Culvert Construction and Performance in Cold Regions

Consequentially, the placement of a culvert (or similar structure ie. ventilated duct) creates a discontinuity, leading to the development of differential settlements; the effects are exacerbated when the structures are on soils susceptible to frost (Andersland & Ladanyi, 2003). Typical observed distresses of the embankment at culvert locations are transverse cracks along the culverts, and ‘dips’ at their location (Jumikis, 1973; Lingnau, 1985; Cowherd, 2002; Hsieh, 2019). Zhang & Radoslaw (2012) investigated frost heave around culverts and suggest that temperatures inside and outside culverts are expected to be equal. The porosity rate function simulations in the study using ABAQUS proved that the placement of the culvert created deformations on the road surface above. The study however recommends that the conditions of the boundary need to be changed. The temperature distribution around the culvert walls impacts the frost heave and should therefore be given critical importance (Zhang & Radoslaw, 2012). Culverts could be assumed to depict the same behaviour when it comes to their impacts on embankment performance. Since the general cooling can be transferred to the underlying ground through convection, this suggests culverts cool embankment soil, hence improving the general performance of linear infrastructure.

Périer et al.(2015) found that water circulation in a culvert could raise the heat input which may continue to disrupt the thermal regime. The authors identified that various issues associated with culverts can be observed including the distortion of culverts, joint failure leading to water flowing beneath the culvert, and escalating to a circumstance of culvert collapse. Studies concluded that the construction of culverts during freezing periods had minor effects on permafrost degradation (Périer et al., 2015; Zhang and Wang, 2007). The observation was that the air circulation in the culvert produced more temperature variation close to the side slopes of embankments rather than in the middle hence making the permafrost table higher beneath the center of the culvert than at the end (Périer et al., 2015).

The soil temperatures underneath the culvert were higher than in other points of the embankment at similar depths (Périer et al., 2015). A thermal-hydro-mechanical model developed by Zhang (2014) showed that short freezing periods led to the formation of a small bump before culverts, but long-term freezing periods led to a dip. This is because initially, the frost penetrated greatly above the culvert than on each side, hence the bump. Later, when frost penetration in the embankment passes downward beyond the culvert and temperatures are sustained below 0°C, the heave ceases at the culvert but continues below which leads to the dip (Zhang, 2014). The researcher found that the viable solution was the insulation of the culvert walls, which reduced frost penetration from the culvert up to the soil surface, reducing bumping, but did not stop the formation of the dip (Zhang, 2014).

Another research examining the thermal regime between soil and culvert considered the shapes of the culverts in their study (Hua et al., 2014). The study found that the circular pipe had less impact on the thermal regime during winter compared to the square design, but opposite results were observed in the thawing season due to the geometry of the heat exchange surface (Hua et al., 2014). The researchers additionally assessed the use of different insulation designs on the culvert such as complete insulation along the culvert's length and only at the shoulders of the embankment. Their results highlighted that there was a decline in temperature perturbation at full-length insulation hence concluding that the impact of the culvert on the thermal regime could be ignored if the insulation had good thermal elements and a substantial thickness. Culverts can be considered as the ventilation ducts of embankments. In permafrost locations such as most parts of Norther Canada, culverts or duct-ventilated embankments are used as a temperature lowering device combined with several cooling methods such as heat conduction (Hua et al., 2014; Cheng, 2005). The presence of culverts impact the thermal effects of sunny and shady slopes in embankments since the influence of convection by slopes is stronger than inroad bed surfaces. As consequence, the presence of culverts reduces the difference by serving as a large ventilation duct that with the potential to extract heat and reduce temperature.

The Transportation Association of Canada (TAC) recognizes the impacts of culverts on embankments, particularly in permafrost environments and provides guidelines on how to build them (TAC, 2010). In areas with more ice, TAC advises construction of a 1.5 m thick granular protection tier beneath the culvert to reduce permafrost disturbances. Incorporation of camber at the center of the culvert and a culvert gradient between 1% and 2% is also recommended to make up for uncertainties due to permafrost conditions and protection of the soil against compression and differential settlements (Lingnau, 1985 & TAC, 2010). Lingnau (1985) has emphasized that a culvert on a camber allows the reduction of ponding of water caused by the potential culver sag. If installed above permafrost, the culvert should also have large openings, thick walls, and rivets to prevent stresses from soil movement. A common practice is the placement of insulation beneath and on the sides of the culvert to keep the soil frozen, while also protecting the culvert from soil movement. The insulation is placed immediately after winter to keep the soil frozen since the insulation decreases heat transfer from the surface to the permafrost while also lowering heat extraction from the permafrost under the insulation (Périer et al., 2015). Adding insulation might be feasible for critical culvert crossings but may be uneconomical for larger infrastructure projects. Another design practice of culverts and embankments in permafrost regions is the reinforcement of various sections of the embankment with woven geotextiles on the side slopes to reinforce the embankment against lateral movements during thawing season (De Guzman et al., 2020b). Embankments thickness differ along the length of linear infrastructure due to terrain conditions. Lingnau (1985) has suggested minimum culvert size of 760 mm diameter to mitigate icing potentials with the culverts. Meanwhile Cowherd (2002) has suggested the structural design and evaluation methods for culverts constructed in both arctic and non-arctic regions, emphasizing the benefits of a bedding material to minimize differential settlements, additional insulating for permafrost, and increase the bearing capacity of soil.

Water flow and its temperature impact embankment temperatures, where heat transfer underneath the culvert is more affected by water temperature compared to water flow (Périer et. al, 2015). The thermal capacity and conductivity of water is significantly greater than that of air and contributes to the change in thermal regime of the embankment, particularly ponding water at the toe and large flows, which may accelerate thawing and impact the depth of the permafrost table (Esch, 1988; TAC, 2010; Bouchard & Guimond, 2012). The effect of water on the thermal performance of the underlying foundation embankment has been investigated extensively in these studies. This research focuses on the air temperatures inside the culvert during the summer and winter months, and how it impacts the thermal regime of the surrounding embankment fill and foundation soil. No measurements were made on the water temperature flowing through the culvert.

Brown et al. (1984) conducted a study to assess the performance of culverts in the Arctic, where they identify various ways that culverts interact with embankments. The study identified that if culverts are placed too high, then the subsequent ponding may have thermal effects of raised toe-of-slope thawing and thaw-degradation of the adjacent permafrost. Ponding may also result from the increased thaw settlements underneath the middle of the roadway from an uplifting of the culvert ends. Additionally, the accumulation of snow and ice in the culverts leads to retardation of seasonal thawing and hence leads to ponding and even washouts. Their study had one primary result that the culvert placement and the techniques used to maintain the Prudhoe Bay area were inadequate in the prevention of water ponding and occasional washouts. In this case, the insulation was placed beneath the culverts and did not demonstrate any thermal benefits of the insulation. The researchers however recommend that the culverts that are not in active streams should be covered at the beginning of winter to eliminate snow and ice from plugging, and opened during the beginning of snowmelt to provide unimpeded drainage.

The thermal regime is considered a critical element of consideration due to the negative impacts of frozen soil that is used in the construction of embankments and grounds surrounding culverts (Périer et al., 2014). From his assessment of the effect of water flow and water temperature on thermal regimes around culverts built on permafrost, Van Everdingen (2005) identified that the variation of more or less than 10% of water flow had no impact on the thermal regime under the culvert, while a similar variation at the entrance of the culvert yields a slight influence on the thermal regime. The results also suggest that an increase in temperature leads to a slight warming of the permafrost, while the reduction in temperature leads to slight cooling (Van Everdingen, 2005). Additionally, the study also conducted simulations without insulation and the importance of insulation was clear; thaw depth was significantly higher at120 cm without insulation, compared to 30 cm with insulation. The study also highlights several important issues related to areas near culverts including several problems concerning stabilization. The free circulation of air and water in the conduit was observed to have a high impact on the thermal regime. It is assumed that the depth of thawing permafrost is typically higher under culverts due to the air and water flowing inside the pipe, hence the pipe transferring heat to the ground.

Culverts were added in a study by the Department of Transportation of the Government of the Northwest Territories (GNWT-DOT, 2011) to prevent ponding against the road embankments This particular study found that there were numerous smaller creeks where there were larger culverts, whereas smaller culverts were found to prevent ponding against road embankments. The study identified that adverse weather may also impact the reliability of culverts since situations such as adverse rain led to exceeded flow capacities for the culverts. In these cases, the road surface above culverts was observed to have traverse cracks and settlements. The study also highlighted that culverts can be structurally impacted by the shifting number of frost cycles in a location that causes deformations.

Kuznetsova et al. (2014) found that thermal erosion also happens at culvert crossings. Their study concluded that particles of thawed soils are detached by moving water inside culverts, which is transported and deposited downstream of culverts. This particular process of thermal erosion includes both thermal and hydraulic components, and the finer the soil and the high the ice content is, the faster and more destructive the thermal erosion is. The study also identified that culverts typically act as heat sources such that they cause deeper thawing of permafrost. The excessive settlements of culverts lead to possible pipe breakage and blockage, as well as internal water ponding and consequent freeze-up which may lead to blockage of the drains.

2.4. Summary

Construction in permafrost regions will inevitably affect the thermal regime of the surrounding ground-surface, in doing so embankment designs should understand the impact of permafrost and its potential for degradation. Moreover, thaw conditions contribute to several embankment instabilities, which negatively influence the performance of the embankment. With the addition of a 'discontinuity' such as a culvert in an embankment, conditions are further influenced, especially with the presence of water.

The use of air ventilated ducts has been well documented and are used as a basis of understanding the principles and characteristics of air convection which is a driving force for heat exchange. Despite the similarity of air flow through ventilated duct as a culvert, it is not guaranteed that the heat exchange of a culvert will be equivalent to that of a ventilated duct, a primary factor would be the heat exchanged caused by the flow of water through the culvert, typically not experienced with ventilated ducts. It is evident that culverts have significant impacts on the effectiveness and performance of embankments. The importance of these culverts in embankments makes it critical to ensure that the culverts promote the efficient performance of embankments.

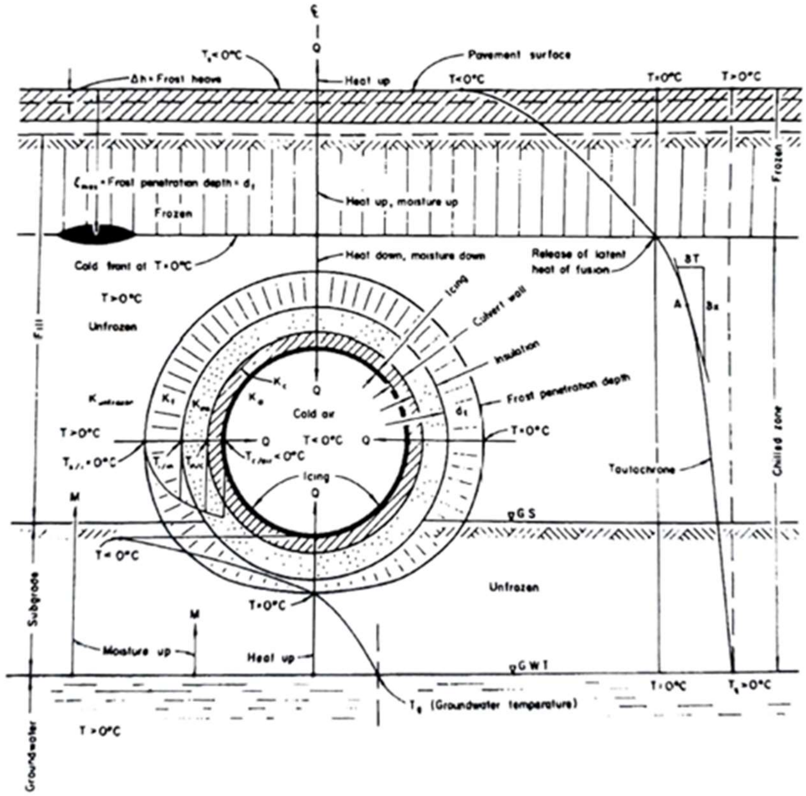


Fig. 2-1. Soil-culvert thermal interaction (Jumikis, 1973)

CHAPTER 3

3. Field Instrumentation and Monitoring

This chapter discusses in detail the observations during embankment construction, culvert placement, thermistor installation, and monitored results. The temperature results obtained are used in the coupled thermal-mechanical modelling presented in Chapter 4.

3.1. Culvert Installation and Field Observations

The University of Manitoba's research site along the Inuvik-Tuktoyaktuk Highway (ITH) is shown in Fig. 3- 1. Zone A and Zone B are 5.3 m in height, 20 m in length, and have side slopes of 3H:1V. Zone A has its side slopes reinforced with wicking geotextiles. Zone B is unreinforced and serves as the control section. These embankments were constructed in April 2015. The full account of the embankment construction, instrumentation, and monitored results are presented in De Guzman (2020a) and are briefly summarized here in reference to Zone B.

Both of these test sections (Zone A and Zone B) are instrumented with sensors to measure temperatures and displacements. Zone C is instrumented with temperature sensors (thermistors) to compare the thermal regime of high-fill sections (such as Zone A and Zone B) with low-fill sections. Zone C has an embankment height of 1.83 m. All sensors are connected in Zone D and accessed remotely via a satellite system. The culvert being investigated is located at KM 82+375 of ITH from Inuvik (Fig. 3- 1). The culvert was installed prior to the construction of the University of Manitoba test sections in April 2015. An initial lift was placed above the culvert (Fig. 3-2) to facilitate continuous construction operations until the desired height was reached. The culvert is 10 m away from the centreline of Zone B. Fig. 3-2 shows frozen chunks of soil were dumped above the culvert for compaction once the embankment was being constructed in stages. Unlike the other culverts along the highway, which have diameters larger than 800 mm, no riprap material (i.e. gravels larger than 300 mm) was added around the perimeter of this culvert. The culverts for ITH were constructed at positive camber to account for differential settlements. Success of this technique was observed along the Dempster Highway to reduce sagging and ponding of water (Lingnau, 1985).

The physical properties of the frozen chunks were determined by De Guzman et al. (2018). The soil has fines content ranging from 11% to 13%, an average plastic limit of 16.4%, an average liquid limit of 24.6%, and a plasticity index of 6.6%. About 72% passing the 0.075 mm (No. 200) sieve was of silt fraction based on the results of the hydrometer test. The soil is classified as well-graded sand with silt and gravel to silty sand with gravel based on the Unified Soil Classification System (USCS). The foundation soil is predominantly organic (peat) based on frozen soil cores obtained from the centreline and at an offset from the embankment toe in March 2017. The organic mat is approximately 7 m thick. This is underlain by highly plastic clay with some presence of cobbles based on visual inspection of the grab samples. De Guzman et al. (2018) also determined the shear strength properties of the frozen using a large-scale direct shear box at different environmental conditions.

The culvert was found clogged on May 18, 2016 (Fig. 3-3) and was remediated six (6) days after. One of the key issues with the clogged culvert was that the water ponded at the toe of the embankment, which may lead to two concerns: (1) accelerated thawing of the frozen foundation soil and (2) water seeping into the embankment towards the frozen core of the embankment. The actual number of days when the culvert was clogged and depth of standing water are unknown. This event is recurring every spring thaw season and remediated once access to the highway is permissible. Fig. 3-4 shows the forced thawing done by the field crew of the Department of Infrastructure (DOI) of the Government of the Northwest Territories (GNWT). During the thawing period when the air temperatures are warmer (April, May), the camera trap has recorded that the compacted snow can block the downstream end of the culvert. The snow around the culvert has already thawed but the unexposed region inside shows dense snow/ice. Field crew manually applies heating lines to accelerate the thawing and facilitate water flow. The two time steps shows when the culvert is still clogged (Fig. 3-4a) and when water started flowing after applying heat on top of the compacted snow (Fig. 3-4b). Heat was applied for 30 minutes before water started flowing.

Embankment slopes above culverts were also observed to develop cracks, which are significantly larger and wider compared to embankment sections along the highway where there are no culverts installed. Culverts act as heat conduits, which thaws the embankment and foundation soils. This was prominent during site visits before the final surfacing was added as passing through sections with culverts felt like road ‘humps’ and undulations. In Fig. 3-5, a silt fence was installed in one of the culverts around KM 118+000 to prevent the embankment soil from flowing through the crown as this can lead to clogging of the culvert. Compaction density of frozen chunks during winter is significantly lower in comparison to unfrozen soil (De Guzman et. al, 2018). Compaction is even lower around culverts to prevent damaging the structural conduit before it is put to service.

3.2. Thermistor Installation

A 5-noded thermistor string was installed on August 12, 2017 along the culvert. The thermistor nodes have a spacing of 13.5 m as shown in Fig. 3-6. An issue encountered on site was tensioning of the cable where the thermistor string was attached. The self-weight of the thermistor string led to a significant sag, which had the middle thermistor barely above the water level within the culvert. The tension cable was replaced on September 28, 2017 with a higher strength cable and was attached to a winch system to adjust the tension and minimize sagging of the thermistor string. The cable was tensioned to have the thermistor string approximately 75 mm below the crown of the culvert. This ensured that the thermistor node was not in contact with the cable and the culvert. The thermistor node in the upstream side (TS-X-A) was left outside the culvert to measure the ambient air temperature. This also measures the temperature just outside the crown when it is buried in snow.

The thermistor node in the downstream side (TS-X-E) is 100 mm from the edge of the crown and left to hang 250 mm at the connection point. This was done to provide comparison of air temperature just at the exit of the culvert. Fig. 3-7 shows the upstream (Fig. 3-7a) and downstream (Fig. 3-7b) thermistor nodes. The thermistor string is connected to the data acquisition system in Zone D (Fig. 3- 1).

A camera trap was installed on the West side of the culvert to monitor how snow is accumulating at the toe. A survey rod was installed in front of the culvert on the downstream side to measure the snow depth during the winter season (Fig. 3-8a). Fig. 3-8b shows the same survey rod on December 11, 2017 which clearly displays that the culvert ends are buried in snow. Approximately 900 mm of snow was recorded on the downstream side of the culvert in Fig. 3-8b. As mentioned earlier, culverts are structural conduits which can passively cool or exacerbate heating in the embankment and foundation soils. With the ends of the culvert buried in snow during the winter months, the temperature inside the culvert is warmer compared to the ambient temperature as will be discussed in the following section.

3.3. Monitored Results

Plots of temperature with time for the thermistor string along the culvert are illustrated in Fig. 3-9. The mean air temperature from the site was obtained from Environment Canada at a weather station in Tuktoyaktuk as shown in Fig. 3-9b plotted with thermistor nodes TS-X-A and TS-X-E. In Fig. 3-9b, it can be seen that the readings recorded by TS-X-A (upstream thermistor node) corresponds to the trend of the mean air temperature for this period, a similar observation can be made with TS-X-E (downstream thermistor node). Temperature readings of the thermistor nodes before mid-October showed the same pattern, although the thermistor nodes inside the culvert are slightly cooler than the ones at the end. After this time, the mean air temperature significantly dropped; however, TS-X-B, TS-X-C, and TS-X-D were recording temperature readings between 0°C and -5°C. The batteries powering up the thermistor string and satellite connection were depleted during the period of November, December, and January at the height of the winter season. Batteries were typically replaced in February or March when DOI personnel are available. The mean air temperature was significantly cooler than the temperature inside the culvert during the winter months. The readings recorded by TS-X-A and TS-X-E further support the discussion regarding Fig. 3-9b where the ends of the culvert are covered in snow. Snow is a good insulator as it prevents considerable heat transfer between the outside air temperature and the air temperature within the culvert. Temperature data presented are only until September 2019 due to frost-jacking of the upstream culvert (Fig. 3-10). The thermistor cable needed to be removed from the culvert to replace this section; however, the thermistor cable was not re-installed by field personnel.

In Fig. 3-9a, the nodes closest to the end of the culvert (TS-X-A, TS-X-B, TS-X-E) have similar behaviour until April, when TS-X-A and TS-X-E started to experience a warming trend. TS-X-B similarly showed the same pattern of warming by April. Temperatures recorded by TS-X-C have been linearly decreasing since February 23, 2018. As both upstream and downstream ends of the culvert were becoming exposed to ambient air temperatures, the culvert temperatures have generally increased. Of all the thermistor nodes, TS-X-D has remained at the threshold of 0.2°C below freezing point since February 16, 2018, with a slight cooling trend beginning March 30, 2018. Similar behaviour was observed from beginning of December 6, 2018 to December 19, 2018; due to site conditions batteries required replacement where the observed trend continued from January 24, 2019 to May 12, 2019 where it experienced temperatures as cool as -0.5°C, immediately warming up afterwards.

Fig. 3-11 shows the temperature along the culvert at specific time steps since its installation. October 1 shows that while the ambient temperature already dropped below 0°C, the temperature inside the culvert has remained above the 0°C. From the period of November 2017 to March 2018, TS-X-C and TS-X-D are within the range of 1°C from each time steps; however, TS-X-C significantly dropped after March 2018 while TS-X-D has remained relatively the same. Fig. 3-11 confirms that although the ends of the culvert are covered in snow, there is change in temperature month to month inside the conduit.

Temperature changes along the culvert every three (3) hours for the dates of April 22, August 1, and October 14 are shown in Fig. 3-12 to Fig. 3-14. All dates include the years 2018 and 2019 with the exception of October 14, which includes the year 2017. During the transition phase from summer to winter season, temperature fluctuations are observed in Fig. 3-13a and Fig. 3-13b, confirming the temperature inside the culvert fluctuates with ambient temperature. As temperatures trend cooler, the temperature fluctuations within as seen in Fig. 3-

14a, Fig. 3-14b, and Fig. 3-14c are not as pronounced, which indicate the upstream and downstream ends are beginning to accumulate snow. When the culvert ends were covered in snow, there is almost no change in temperature for the 3-hour reading cycle. In Fig. 3-12a and Fig. 3-12b, TS-X-D is significantly warmer than the other thermistor nodes.

This warm temperature inside the culvert is of interest in this research since this can affect the thermal regime of the soil around the culvert. The embankment was constructed using frozen soil and this could have thawed already due to warm temperatures inside the culvert in the summer months, thus resulting to settlements and cracks at the road embankment surface. Unfortunately, no thermistor strings were attached around the culvert that is contact with soil. The closest thermistor in the embankment soil is 10 m away at the base of the unreinforced embankment section (Zone B in Fig. 3- 1). Fig. 3-15 shows a comparison of the soil temperature recorded at the aforementioned location, with the thermistor node inside the culvert at TS-X-C. The temperature recorded inside the culvert was warmer than the one recorded for the embankment soil. Once the culvert ends have been cleared off from the snow cover, air was able to flow though again and hence the fluctuation in temperature at TS-X-C while the temperature of the soil is adjusting to the new thermal boundary in the spring season. Larger culverts based on field observations along ITH are not covered in snow and thus allow the cold air temperatures 'cool' the soil around the culvert through convection. The major implication found in these recorded temperature data is that there should be consideration to clear snow at the ends of culvert crossings to allow the cooling effect during the winter months to preserve the permafrost in the foundation soil. De Guzman (2020a) found that for embankments thicker than 5 m without a culvert, the permafrost aggrades to the embankment core. With the presence of the culvert as presented in this study, the culvert acts as a 'break' from the permafrost foundation and lead to positive temperatures between the interface of the embankment soil and culvert crown. These positive temperatures will lead to thawing of the frozen soil around the culvert and should be accounted for during embankment design. These recorded temperatures inside the culvert are used as thermal boundary conditions for the thermal-mechanical models developed in the following chapter.

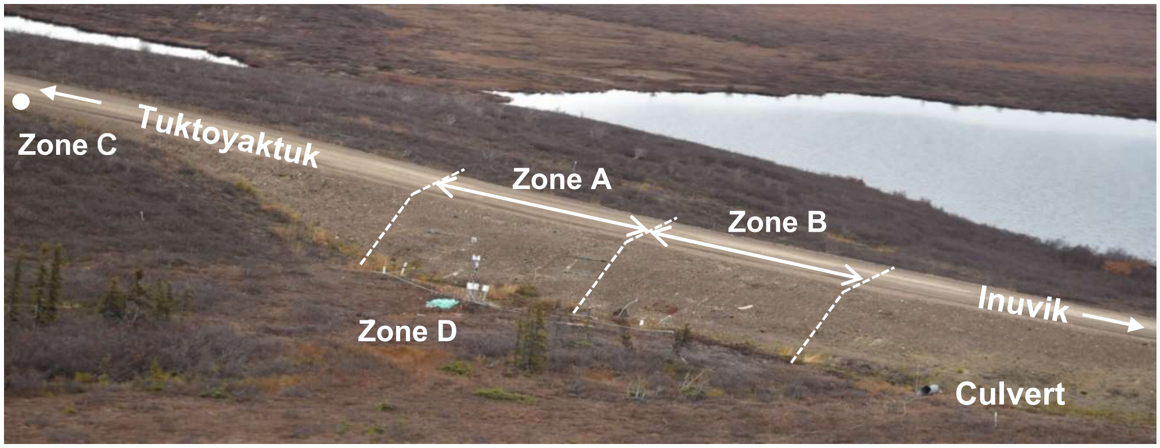


Fig. 3- 1. Aerial view of the University of Manitoba research site along ITH.

Fig. 3-2. Construction of highway fill embankment above the culvert at the research section of the University of Manitoba.

Fig. 3-3. Clogged upstream side of the culvert in May 2016.

(a)

(b)

Fig. 3-4. Thawing of downstream end of the culvert: (a) clogged with compacted snow, and (b) after application of heat.

Fig. 3-5. Aerial shot of slope cracking above culverts.

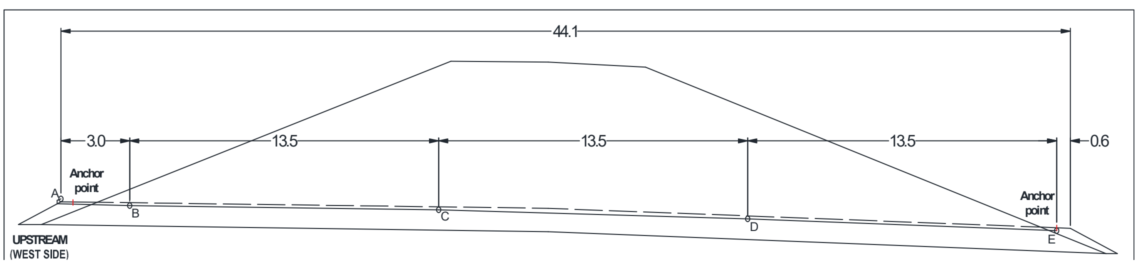
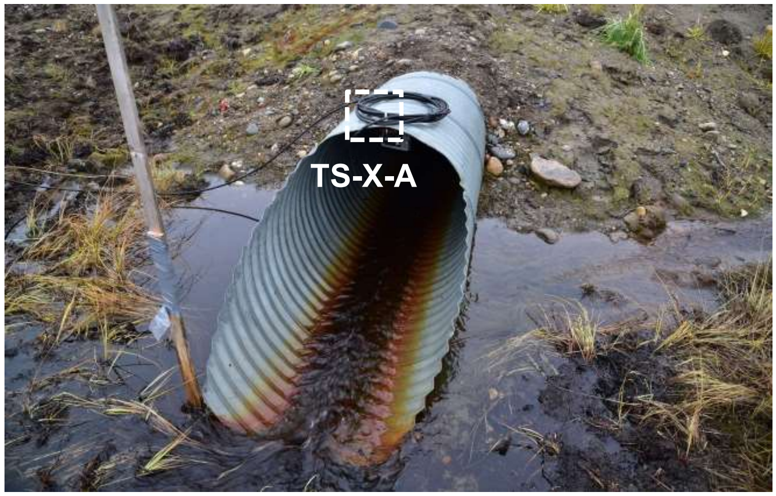


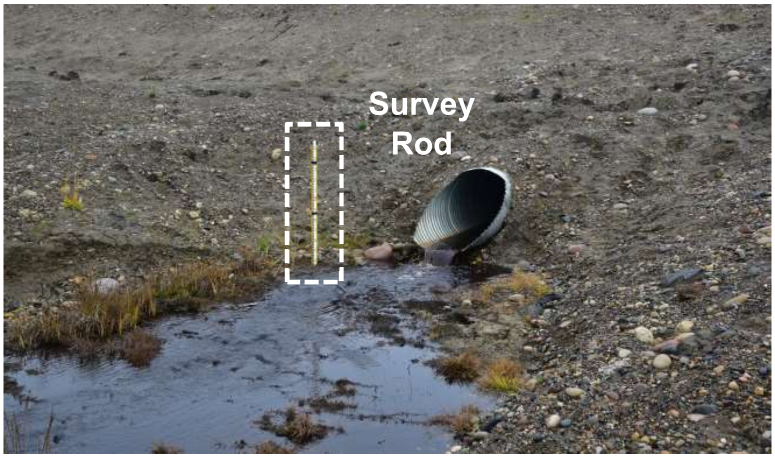
Fig. 3-6. Thermistor installation detail.



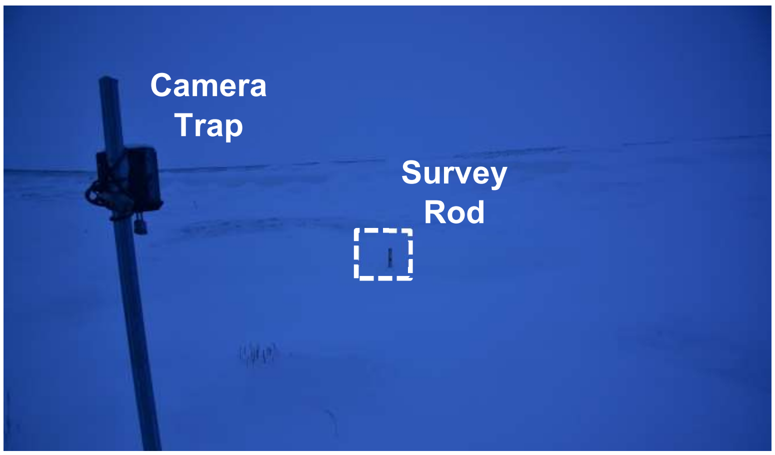
(a)

(b)

Fig. 3-7. Culvert at KM 82+375 (a) upstream and (b) downstream sides.

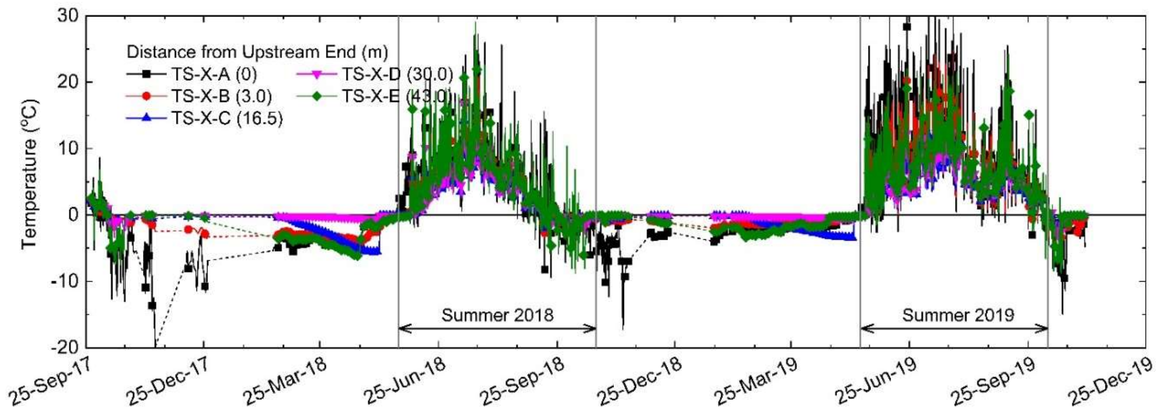


(a)

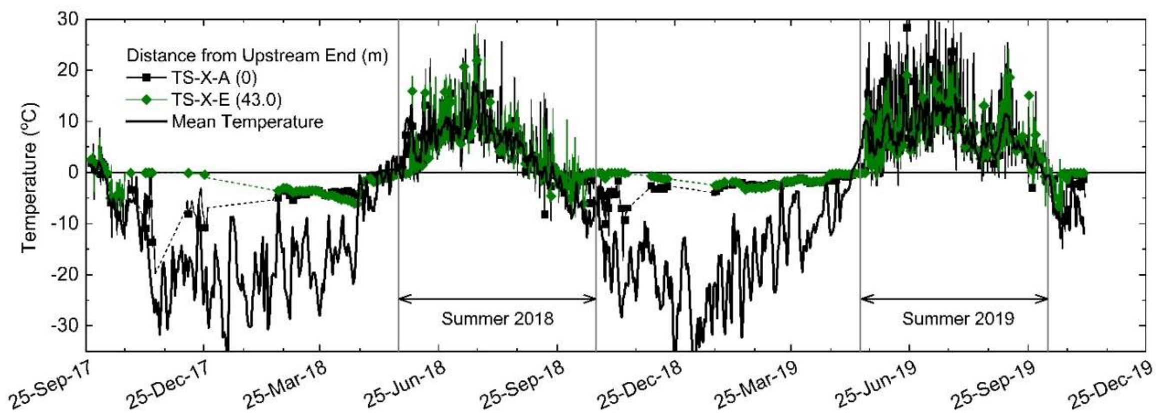


(b)

Fig. 3-8. Culvert section on the east side of the embankment (a) September 2017 after installation of thermistor string and (b) December 2017 during winter conditions.



(a)



(b)

Fig. 3-9. Temperature readings along the culvert with time: (a) All nodes from September 2017 to November 2019. (b) Nodes A, E and Mean Temperature from September 2017 to November 2019.

Fig. 3-10. Broken culvert at the upstream side of the embankment.

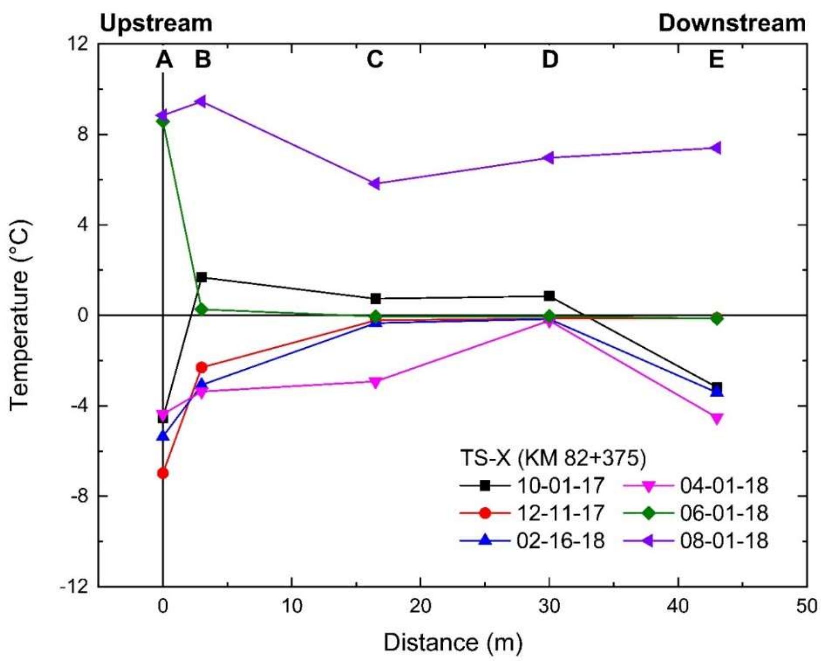
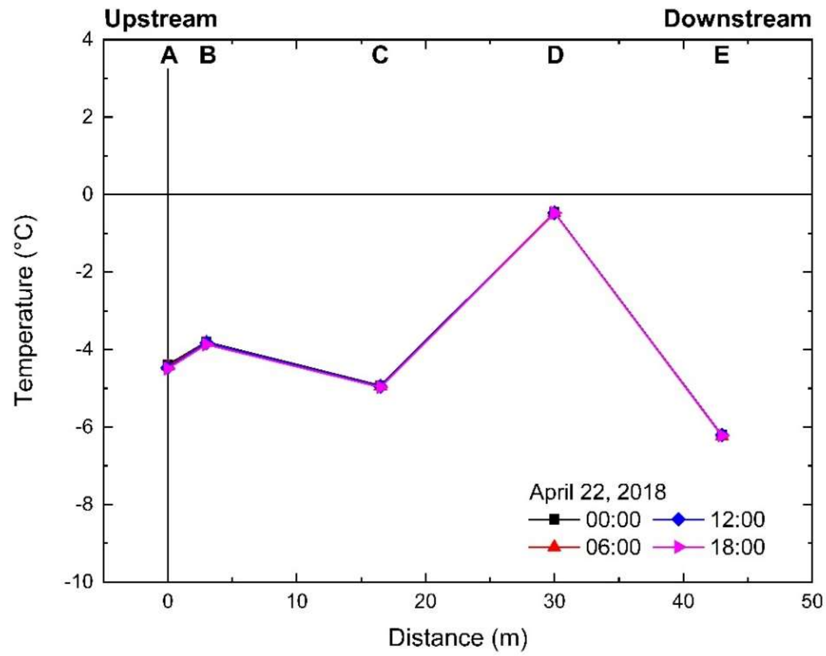
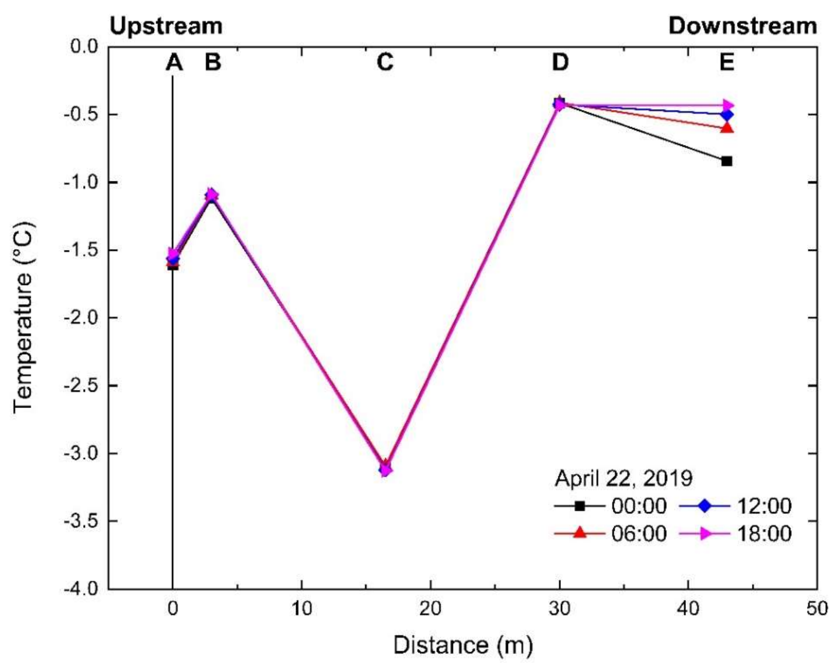


Fig. 3-11. Temperature along the culvert at different time steps.

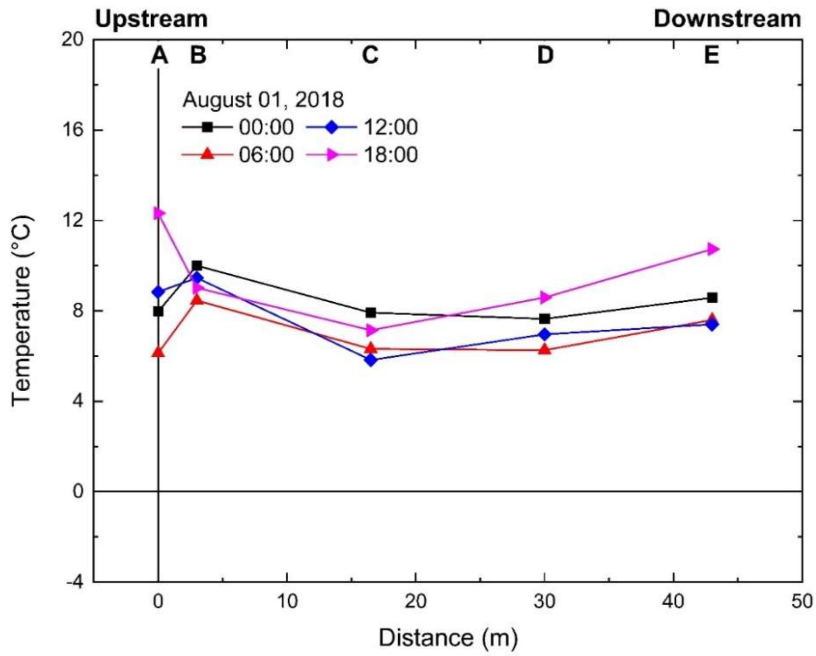


(a)

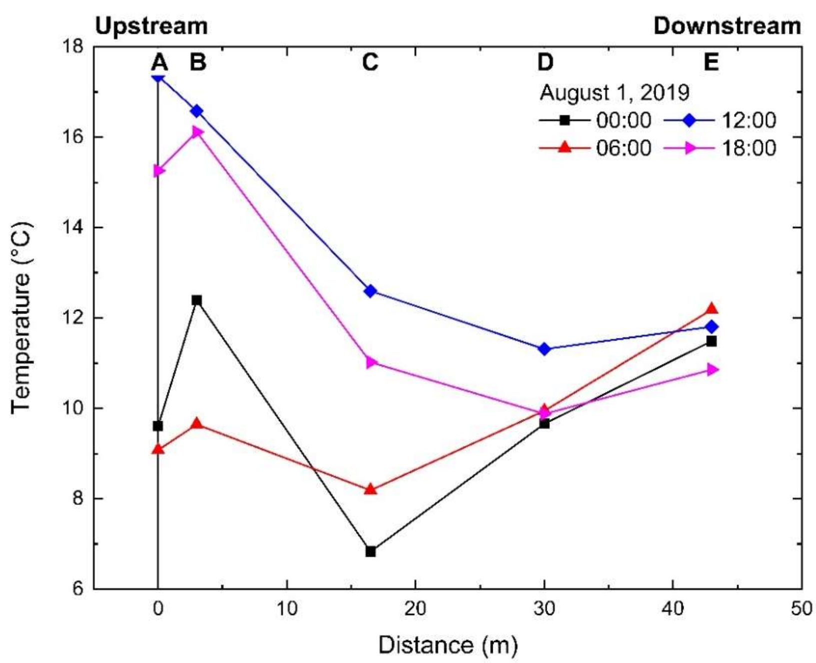


(b)

Fig. 3-12. Temperature along the culvert April 22 from 2018 to 2019 at different time intervals throughout the day.

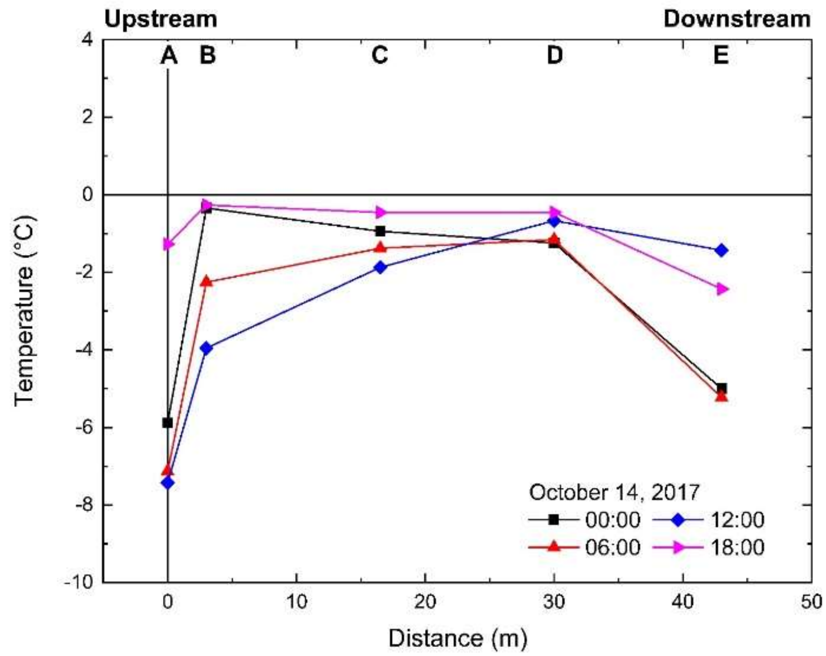


(a)

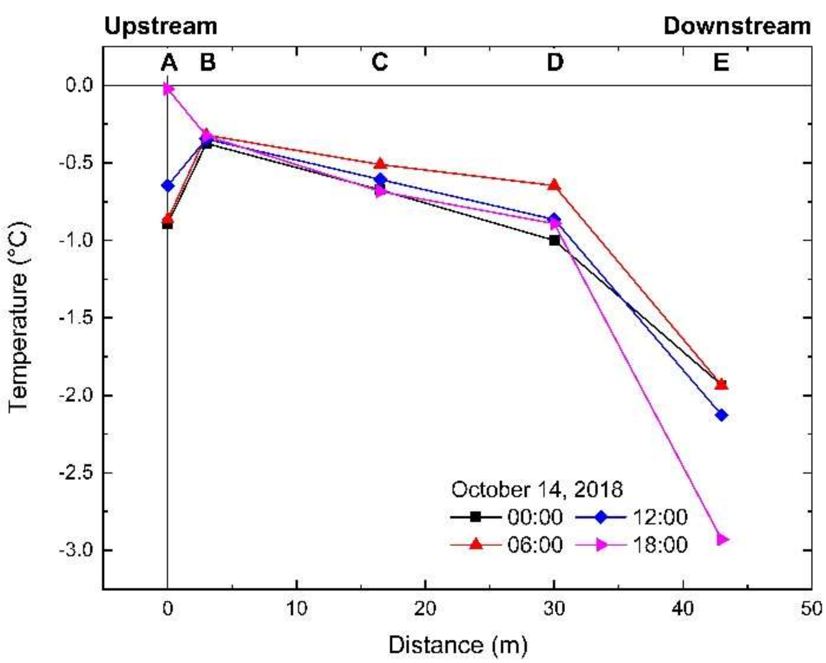


(b)

Fig. 3-13. Temperature along the culvert August 1 from 2018 to 2019 at different time intervals throughout the day.

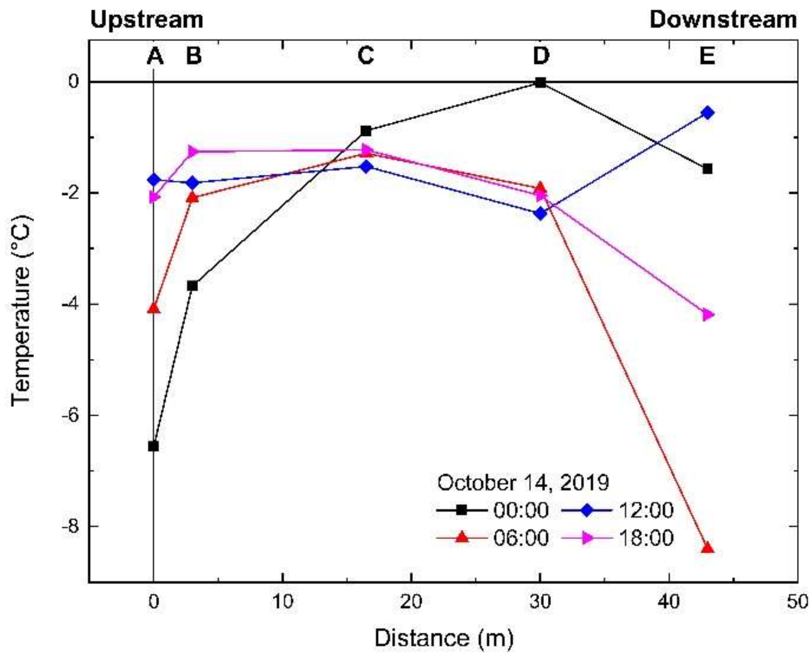


(a)



(b)

Fig. 3-14. Temperature along the culvert October 14 from 2017 to 2019 at different time intervals throughout the day.



(c)

Fig. 3-14. Temperature along the culvert October 14 from 2017 to 2019 at different time intervals throughout the day. (continued)

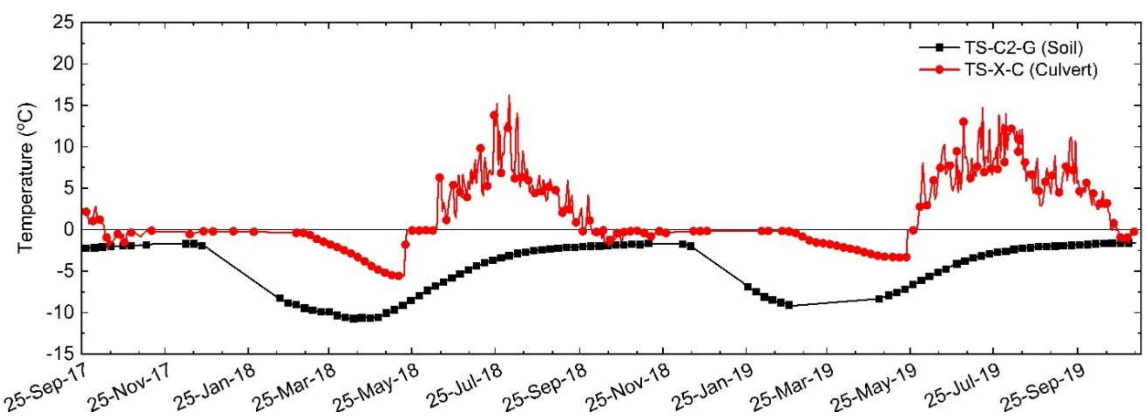


Fig. 3-15. Comparison of middle thermistor inside the culvert (TS-X-C) with nearest thermistor at the base of the embankment (TS-C2-G).

CHAPTER 4[1]

4. Numerical Modelling

The following sections within this chapter describe the details involved in the development of a 3-dimensional numerical model to analyze the behaviour of embankments with culverts. The commercially available software ABAQUS, developed by Dassault Systèmes®, was utilized in constructing the numerical models.

4.1. Introduction

Heat transfer is a driving contributor to the performance of the embankment-culvert system, due to the sensitivity and strength variation of ice within the soil as it begins to thaw and reach the 0°C temperature. The following heat transfer modes are discussed as they are the driving forces for temperature change, and some of the parameters are key inputs into the model to analyze temperature changes throughout the system.

Convection:

Convection describes the mechanism of diffusion and advection between the ambient air temperature (T_{∞}) and surface temperature T_s, which is directly proportional to the convective heat transfer coefficient h_{conv}, as shown in

[1] Parts of this chapter will be published as a conference paper as follows:
Kaluzny, S.W., De Guzman, E.M.B., Alfaro, M.C., Doré, G., and Arenson, L.U. 2022. Influence of an Instrumented Culvert Crossing on the Thermal-Mechanical Performance of a Highway Embankment in the Arctic. Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering. Sydney, Australia.

Equation 4.1. Typically, convection is observed from a surface to a fluid, and falls into two categories: (1) natural convection and (2) forced convection. Natural convection is the condition of which the bulk of the fluid is motionless; the motion is caused by the temperature gradient and buoyancy. Whereas in forced convection, the bulk of the fluid is in motion caused by external means.

Eq. 4-1 $$q''_{conv} = h_{conv}(T_s - T_\infty)$$

Conduction:

The mode of conduction describes heat transfer between solid bodies in contact flowing from an element of high temperature to low temperature, as demonstrated in Equation 4-2.

Eq. 4-2 $$q''_{cond} = -k\frac{\Delta T}{L}$$

The parameter k is the thermal conductivity of the material.

Radiation:

Radiation requires no medium to travel through; everything emits thermal radiation. The transfer is through electromagnetic waves and is described in Equation 4-3,where σ is the Stefan-Boltzman constant, ε is the emissivity which a property of the materials surface, A is the emitting surface area, and T is the emitting temperature and T_{surr} is the temperature of the surrounding area.

Eq. 4-3 $$q''_{rad} = \sigma\varepsilon A(T^4_{surface} - T^4_{surr})$$

Surfaces will reflect radiation as well as absorb radiation and these properties are highly dependent on the surface properties. A blackbody will emit max radiation possible as well as absorb all incident radiation, meanwhile typical materials will only absorb a fraction of black bodies.

Surface Energy Balance:

To assess the heat transfer system that occurs at the soil/pavement surface we should consider the Energy conservation at the land surface as shown in Equation 4-4.

Eq. 4-4 $$(q_{ns} - q_{nl}) = q_h + q_l + q_g$$

Where:

q_{ns} – net solar radiation (shortwave)

q_{nl} – net terrestrial radiation (longwave)

q_h – Sensible heat flux

q_l – Latent heat flux

q_g – Ground heat flux

The net solar radiation (q_{ns}) is incoming solar radiation shown in equation 4-5, and α is the surface albedo, which is a measurement of reflected solar radiation. Albedo will differ substantially depending on the ground surface such as vegetation, pavement and snow

Eq. 4-5 $$q_{ns} = q_s(1-\propto)$$

Meanwhile the longwave radiation can be determined by Equation 4-6 below, reminiscent of Equation 4-3. Where ε_a is the emissivity of the air which is directly related to air temperature and relative humidity. Meanwhile, ε_s is the emissivity of the soil/pavement surface.

Eq. 4-6 $$q_{nl} = \varepsilon_s \sigma T_g^4 - \varepsilon_a \varepsilon_s \sigma T_a^4$$

Sensible heat flux is the energy to change the material's temperature when no phase change occurs. The coefficient h is a function of the surface temperature and the wind speed as sensible heat is a loss of energy from the surface to the atmosphere.

Eq. 4-7 $$q_h = h(T_g - T_a)$$

The presence of snow throughout the winter will have significant effects to the energy losses, where heat conducted through snow is represented in Equation 4-8 shown below. Where k_{snow} is the conductivity of the snow and h_{snow} will change in reference to the depth of the snow present.

Eq. 4-8 $$q_{snow} = -k_{snow}\left(\frac{T_g - T_{snow}}{h_{snow}}\right)$$

Latent heat flux q_l is generated by the evaporation and condensation of water from the surface as is energy loss from the surface when temperature does not change although a phase change occurs. Latent heat flux can be determined by Equation 4-9 below. Where L_v is the latent heat of vaporization, ρ_v is the density of vapor at the ground surface meanwhile ρ_a is the density of vapor at the dew point temperature. The resistance to vapor exchange r_v is generally assumed as caused by turbulent eddy mechanisms (Walter et al., 2004).

Eq. 4-9 $$q_l = L_v\left(\frac{\rho_v - \rho_a}{r_v}\right)$$

The application of SEB is accomplished by applying the ground heat flux (q_g) as a boundary condition and equation 4-4 above can be re-arranged as shown in Equation 4-10.

Eq. 4-10 $$q_g = (q_{ns} - q_{nl}) - q_h - q_l$$

The ground temperature can then be solved for and applied as boundary condition. The required inputs for these equations require sophisticated and expensive instrumentation installed at a local site to get an accurate calibration.

Surface N-Factor:

The surface N-factor accounts for the differences in surface ground temperature of 100 mm depth from air temperature, due to factors such as snow cover, vegetation, surface properties, and solar radiation (Andersland and Landanyi, 2004). This is accomplished by the use of air thawing (I_{at}) and freezing (I_{af}) indices. The empirically determined surface N-factors can be determined shown in Eq. 4-11 and Eq. 4-12 for thawing and freezing conditions, respectively.

Eq. 4-11 $$n_t = \frac{I_{st}}{I_{at}}$$

Eq. 4-12 $$n_f = \frac{I_{sf}}{I_{sf}}$$

Immediately upon inspection of Eq. 4-11 and Eq. 4-12 it is observed that the value of a surface-N factor equals to 1 indicates that ground surface temperatures are equal to air temperatures. Meanwhile values greater than 1 indicate the ground surface is warmer than air temperatures and less than 1 indicate the ground surface is cooler than the air temperatures. Shown in Table 4-1 are the applied surface N-factors throughout various surfaces of the model. The differentiation between the thawing and freezing seasons are determined when ground surface temperatures rise above 0°C (thawing) and the first day when ground surface temperatures fall below 0°C (Karunaratne and Burn, 2004). Due to several factors such as snow cover, changes in vegetation, topography, and elevation, seasonal n-factors may change over short distances (Klene et al. 2001). However, the N-factor approach requires fewer inputs compared to the SEB equations. The use of N-factors is accepted in general engineering practice and is therefore used in converting air temperatures to ground surface temperatures.

4.2. Model Geometry

Two 3-dimensional model embankments modeled were categorized as ‘Thick’ and ‘Thin’ embankment which were assessed in (1) heat transfer and (2) fully coupled thermal-mechanical (TM) analyses. The embankment and foundation parts were initially constructed in the commercially available software AutoCAD and imported into ABAQUS where it was sectioned and assembled; a similar procedure was adopted for the culvert. It was assumed in the model that the culvert terminated at the embankment slopes for simplicity and did not extend beyond the embankment extents.

4.2.1. Thick Embankment Geometry

The thick geometry is composed of three parts listed below and assembled within the ABAQUS user interface; the distinct parts can be seen in Fig. 4-2.

1) Emb (referring to embankment) and Fdn (referring to foundation);

2) Emb-Sec above culvert;

3) Emb-Sec with culvert;

Part 3 was combined with a 1 m section of embankment soil in the model construction which allowed for improved meshing, as the mesh was developed separately for each part. The purpose of creating distinct sections and partitions simplified the meshing procedure and minimized element distortion, as mesh sizes would be dependent on the parts established. Tie constraints were used on soil-to-soil surfaces. The tie constraints ‘tie’ two surfaces together as if they were part of a whole even with different meshing configurations, as consequence this may complicate the in-solution convergence. In the model construction, the culvert was combined with a 1 m width embankment section as a single part, differed only by the material which defined them. However, tie constraints were applied to the contacting surfaces of Parts 1 to 3, 1 to 2, and 2 to 3. The mesh size of Part 1 was 0.5 m for the embankment which increased with depth from 0.5 m to 0.85 m to the base of the model. The mesh size for Part 2 was set to 0.5 m, and for Part 3 varied from 0.15 m to 0.25 m to accommodate the challenging hollow cylindrical segment of the of culvert geometry. The embankment dimensions were modelled to match the research embankment discussed in Chapter 3 constructed as part of the ITH. The embankment height is 5.3 m, with 1V:3H slopes and a total length of 40.3 m. The culvert diameter was 0.8 m with a thickness of 4 mm modeled as a smooth pipe. The embankment length into the page (X-direction) is 10 m, and the determination of the length will be discussed in the sections below. To accommodate the various applications of surficial temperature boundary conditions, which are dependent on surface conditions, the model was sectioned as shown in Fig. 4-3 for the embankment and Fig. 4-4 for the culvert. The sections such as Slope-Top, Slope-Middle, Slope-Bottom allowed for different boundary conditions to be applied to each respective section using N-factors, similarly for Sections A through E throughout the culvert.

4.2.2. Thin Embankment Geometry

The same procedure as discussed in the previous section was applied to the construction of Thin Embankment geometry. The main distinctive difference is the embankment size, which was constructed to meet the minimum embankment height of 1.8 m throughout the ITH wherever feasible. The total embankment width is 19.3 m, with a 0.8 m diameter culvert traversing through the embankment. The Thin Embankment was similarly constructed of three distinct parts in ABAQUS, connected with tie-constraints in the same fashion the 'Thick' model. However, the surface sectioning of the embankment slope differed, as there was only one surface for the slope defined as 'Slope-Top' in Fig. 4-5 (a). Given the reduced culvert length, the temperature distribution inside the culvert will not be the same as the one for the instrumented section. The culvert was assumed to have three sections: Sections A, C, and E shown in Figure 4-5 (b).

4.3. Numerical Modelling with ABAQUS

The initial thermal model developed was a spin-up analysis given that there were no recorded initial temperature conditions for the models. This was required so that constructed models reach equilibrium for the embankment fill and foundation soil; applying a constant temperature boundary condition as a sinusoidal function that is equivalent to the temperatures observed according to the geographic locations of the civil infrastructure. The boundary conditions are applied until a steady-state is achieved, the temperature profile produced is then set as a predefined field for subsequent analyses. Heat transfer models were run after an initial spin-up model, prior to running actual temperature boundary conditions. The elements forming the mesh are DC3D8, a hexahedral 8-node linear heat transfer brick.

4.3.1. Thermal Material Properties

The thermal properties for the embankment fill and foundation soil are summarized in Table 4-2. The surfaces of the embankment fill and foundation soil interacting with the ambient air temperature were subdivided accordingly as shown in Fig. 4-3. The road surface is labelled as Top, while the slope is divided into three regions. The surface on the foundation soil immediately at the base of the embankment is labelled as Toe, and outside this the foundation surface is labelled as Prairie. The rightmost and leftmost boundaries are no flow boundaries, while a constant temperature of -4.3°C was applied at the base of the foundation soil in both thin and thick heat transfer models based on the recorded ground temperatures at the research site. The corresponding freezing ($n_{freezing}$) and thawing ($n_{thawing}$) n-factors were applied to these boundary conditions at the ground surface. The n-factor values summarized in Table 4-1 are typical of literature values and are based on calibrations conducted by De Guzman (2020), which were adjusted accordingly to best match the recorded temperature results from field measurements approximately 25m away from the culvert research site. Given the proximity, it was assumed that the values were applicable to this research site. In addition, temperature results obtained from the model agreed with recorded temperatures obtained by De Guzman (2020) as observed in Fig. 4-14. A thawing and freezing index inside the culvert of 1 was used due to absence of information pertaining to air flow, water flow, and water temperatures through the culvert which will impact the interior boundaries. The CSP has a high thermal conductivity however the thickness is negligible at 8.5mm, given the fact that n-factor determines surface temperatures 100mm in depth.

The meshing applied around the culvert is finer and increases to a coarser size away from it to minimize the computational effort and reduce convergence issues.

4.3.2. Mechanical Properties

The shear strength of the fill material was obtained from De Guzman et al. (2018a) from large-scale direct shear tests subjected to different environmental conditions (frozen, thawed, cyclic freeze-thaw). In the absence of laboratory data, the shear strength properties obtained by De Guzman and Alfaro (2018b) for amorphous peat above 0°C were used for the foundation soil. A summary of mechanical and hydraulic properties is shown in Table 4-3. The hydraulic conductivity for both foundation and fill material was considered as temperature dependent. The model assumes that during staged construction of the embankment the embankment fill would thaw and settle over the seasonal transitions prior to final completion of the embankment construction. If a modelling approach intends to model staged construction where the embankment is constructed with frozen fill material, it would be ideal to associate frozen and unfrozen densities to consider the effects of thaw settlement over time based on the construction methodology.

The Drucker-Prager/Cap (MDPC) was selected to model the elasto-plastic behavior of the embankment and foundation soils identified at the site. The use of MDPC in geotechnical engineering is ideal as the soils model exhibit pressure-dependent yield, in addition it also accounts for stress history, stress path, dilatancy, and the effect of intermediate principal stress (Helwany 2007). Detailed data of hydraulic conductivity and void ratio was not available to conduct an accurate thaw consolidation analysis, however Dayarathne et al. (2021) have demonstrated with the detailed hydraulic conductivity and void ratio of thawed soil MDPC in ABAQUS/CAE is capable of modelling shear stresses along with settlements due to thaw.

The MDPC failure surface is defined by equation:

Eq. 4-13 $$Fs = t - p \tan \beta - d = 0$$

where t is the deviatoric stress and p is the equivalent pressure stress. In addition, β is the soils friction angle and d is its cohesion in the p-t plane. The equations below were utilized to convert θ friction angle of soil in degrees and c the soil cohesion in kPa.

Eq. 4-14 $$\tan \beta = \frac{\sqrt{3} \sin \theta}{\sqrt{1+(\sin^2 \theta/3)}}$$

Eq. 4-15 $$d = \sqrt{3}\mathrm{c} \frac{\sqrt{3}\mathrm{c} \cos \theta}{\sqrt{1+(\sin^2 \theta/3)}}$$

The volumetric plastic strain (ε_{vol}^{pl}) develops as the material yields in the cap region. Where e_0 is the initial, void ratio, $p_b^{'}$ is the hydrostatic compression yield stress, and p' is the mean effective stress. Values of λ and κ can be determined from testing methods based on lines of compression and unloading/reloading.

Eq. 4-16 $$\varepsilon_{vol}^{pl} = \left[\frac{(\lambda - \kappa)}{(\lambda - \kappa)}\right] \times \ln \frac{p'}{p_b'}$$

The parameter $p_b^{'}$ is the defining position of the cap in the plasticity model where the initial ε_{vol}^{pl} is zero, while p' is any mean effective stress to define the hardening curve. The cap yield surface is defined by equation 4-17, where the parameter α defines the transition surface between the Drucker-Prager failure surface and the cap.

Eq. 4-17 $$F_c = \sqrt{(p - p_a)^2 + (\frac{Rt}{1+\alpha-\frac{\alpha}{\cos\beta}})^2} - R(d + p_a \tan\beta) = 0$$

The shape of the yield surface is managed by R, the cap eccentricity and p_a is the evolution parameter. With the inputs of soil friction (β), cohesion (d), initial volumetric strain (ε_{vol}^{pl}), transition surface (α), and the yield surface dependence parameter (K) the MDPC can be modeled. The MDPC constitutive model may predict shear stresses and their displacements but will not directly capture displacements directly related to thaw consolidation which may over predict shear stresses and underestimate settlement.

4.3.3. Modelling Procedure and Boundary Conditions

As part of the development of the 3D thermal-mechanical model to further understand the influence of the culvert on the embankment, thermal and in-situ stress initial conditions were established by a spin-up model and a geostatic model. The output data sets of the spin-up and in-situ geostatic models were exported into an initialization step of the coupled model, thus establishing initial temperature and soil stress conditions.

Site-specific n-factors were determined by De Guzman et al. (2022) which were applied to the mean daily air temperatures (MDAT) of the respective planar surfaces of the model. As previously discussed, actual recorded temperatures were assumed to be applied directly to the exposed interior surface of the culvert, a thermal modifier equal to one was assumed and applied accordingly. The culvert was divided into five (5) sections for the Thick model and three (3) sections for the Thin models as nodal tributary areas as represented by the thermistor nodes within the field. The applied culvert temperature boundary conditions are shown in Fig. 4-1.

The spin-up model was run for 1095 days with applied constant sinusoidal function temperature boundaries. The models were then run using actual recorded culvert temperatures measured by the thermistor nodes as presented in Chapter 3, and as shown in Fig. 4-1. Meanwhile, the geostatic model was run with associated material body force (unit weight) establishing the initial stress conditions.

The model cross-section in ABAQUS is shown in Fig. 4-1, where the global datum is established at the interface of the embankment fill and foundation soil at the embankment centreline. Only half of the culvert was modelled due to assumed symmetry. The model extends to Zone B in Fig. 3-1, which is 10 m from the centerline of the culvert.

For the stress-deformation part of analysis, the left-vertical and right-vertical sections of the model were restrained in the X- and Y- directions. The base of the model was restrained in all directions, while the Y-Z plane was restrained in the X-direction. A zero pore pressure boundary condition was also assigned at the natural ground surface, slope faces, and top of the embankment to allow seepage across these surfaces. The model datum is located at the embankment centerline at the base of the culvert or model grade surface (Z=0). Left and right vertical surfaces of the model were restrained in the Z- and X- direction, meanwhile the front and rear of the model were restrained in the Z- and Y- plane.

The base of the model was constrained in the X-, Y-, and Z- directions. Across the entire exposed soil surfaces a zero pore pressure boundary was assigned to allow for seepage.

Since there is no direct coupling between shell and 3D solid surfaces in ABAQUS that would satisfy the degrees of freedom for both types of elements (e.g. pore pressure), the culvert was assumed to be modeled as a solid pipe with a thickness of 4 mm. This allowed the model to be run in a fully-coupled approach. The hydraulic conductivity of the corrugated steel pipe (CSP) was assumed to be close to zero. The hydraulic conductivities in unfrozen condition were estimated from typical values available in the literature supported by several modelling iterations to obtain a best fit with the field results and were made dependent on void ratios once the temperatures reach 0°C (De Guzman, 2020a). A high thermal conductance property was also added on the interface between the culvert and the soil to ensure thermal flow.

4.4. Results and Discussion

Results of the temperature and mechanical performance for the Thick and Thin embankment models are discussed below. The impacts of the culvert presence are discussed along with distinct differences between the Thick and Thin models.

4.4.1. Thick Embankment

Within the illustrations of Fig. 4-6 and 4-7 there is a frozen region in between the ground surface of the embankment and above the culvert crown. The thickness of the region is approximately 2 m in July 2019 which reduced to

1.4 m in September 2019. The maximum thickness of the frozen core outside the culvert at Zone A and Zone B (Fig. 4-6) is 2.7 m from the base of the embankment, similar to observations made by De Guzman et al. (2021). The results show that temperatures around the culvert extend outwards radially by at least 1 m during the summer months, to a maximum influence of 2.1 m from the culvert centreline. Unlike Zone A and Zone B where embankment surface settlements will be uniform, additional settlements are expected around culvert areas due to the additional thickness of thawed material around it. The model results also support the results shown in Fig. 1-2. Temperatures were plotted at the embankment centerline with depth, at the culvert location (Fig. 4-15) and outside of the culvert influence (Fig. 4-16). Within Fig. 4-15 the frozen core region above the culvert is reducing with time, and the region around the culvert is warming, as the 0°C temperatures influence expand with depth. The warming trend is also observed in Fig. 4-16 as temperatures of 0°C or greater pass the 3 m elevation mark with time.

To confirm the temperature impacts as additional confirmation, a heat transfer only model was conducted and based on results provided in Fig. 4-19 for mid-July 2018 and Fig. 4-20 for mid-September differences within the frozen core from a fully-coupled model (Fig. 4-6 and Fig. 4-7) are marginal.

Global displacement contours are plotted in figure 4-8 along the cross-section of the culvert on mid-July 2018 (Figure 4-8a) and on mid-September 2019 (Figure 4-8b). These are global magnitudes and are approximately symmetric along the embankment centerline. These figures demonstrate that the displacements are accumulating over time due to the change in ambient air temperatures interacting with the embankment and the culvert. The global displacements are approximately 0.25 m in Figure 4-8a and increased to 0.6 m in Figure 4-8b. The displacements are primarily accumulating at the mid-slope of the embankment, similar to the field observations by De Guzman et al. (2020b) and thermal-mechanical model results by De Guzman et al. (2022) for Zone B (unreinforced embankment).

Figure 4-9 shows the global displacement contour on mid-September 2019 that is 5 m away from culvert centerline. The contour shown has global displacements in the range of 0.28 - 0.32 m, which is in the same range as the results of De Guzman et al. (2022). These results indicate that the presence of the culvert contribute to displacements in Chapter 1 Figure 1-2 and should be accounted for during the design stages to reduce the potential impacts caused by settlements on embankment performance, specifically on how ‘humps’ and undulations can be mitigated during the thawing season. It is expected that with climate warming the compacted frozen soil bounded by the embankment and above the culvert will thaw and contribute to additional settlements. As consequence, the frozen core will be subject to continual warming and will deteriorate over time. Based on the recorded data Section A (culvert inlet) recorded the highest temperatures, leading to uneven thaw along the embankment causing differential settlements. Despite that this study did not focus on the structural capacity of the culvert, the reduction in shear strength caused by thawing in the fill embankment and foundation may amount to additional stresses the culvert may not have necessarily been designed to withstand, especially in differential thaw events. The application of the summer air temperatures around the entire interior area of the CSP may be considered conservative as the water temperature moving throughout the base of the culvert would be cooler than peak air temperatures. As previously discussed, due to limitations no data was recorded for water flow or temperatures flowing through the culvert throughout the seasons and no boundary was modeled to account for water or ice conditions. Périer et al. (2014,2015) have presented the impacts water flow has on soils beneath the culverts and concluded the sensitivity of infrastructure to water temperature. The impact of water would contribute to extended warm temperatures into the foundation

4.4.2. Thin Embankment

The thin embankments temperature profile for mid-July 2018 demonstrates that permafrost will not aggrade into the embankment as observed in the profiles from Fig. 4-10 to Fig. 4-12. However, during mid-September 2018 the culvert presence allows for a quick response for heat extraction during cooler periods and shown by the temperature differences surrounding the culvert in Fig. 4-11 (b). The culverts temperature radial extents do not differ to the observations previously noted and are dependent on both the culvert geometry and size. Due to the significantly reduced height of the embankment of 1.8m in comparison to the 5.3 m height embankment, there is no presence of a permanently frozen core between the embankment top and the top of the culvert as illustrated in Fig. 4-17. Further, there the presence of the frozen core is not present without the culvert present as seen in Fig. 4-18. However, the depth of thaw extents is similarly consistent to the thick embankment and penetrates approximately 1.1 m below the base of the embankment. The heat transfer model temperature differences in Fig. 4-21 and Fig. 4-22 demonstrated no significant differences when compared to Fig. 4-11 and Fig. 4-12, although a slight extension of temperature influence was observed from the culvert in Fig. 4-11.

The global displacements modeled with the thin embankment at the culvert face vary from 0.024 to 0.048 m, meanwhile displacements along the cross-section 5 m away from culvert centerline, vary in magnitude from 0.08 to 0.17 m as shown in Fig. 4-13 (a), (b), and (c). The difference in magnitude of displacements indicates the mechanical contribution of the material stiffness provided by the culvert. In comparison to the thick embankment, there is substantially less soil and fewer lifts constructed under frozen conditions which would result in less settlement.

Table 4-1: Applied thermal modifiers

Location	$n_{freezing}$	$n_{thawing}$
Top	0.95	1.00
Slope Top	0.92	1.00
Slope Middle	0.83	1.00
Slope Bottom	0.55	1.00
Toe	0.20	0.55
Prairie	0.20	0.45
Slope (Thin embankment)	0.65	1.00

Table 4-2: Material thermal properties

Property	Units	T (°C)	Foundation	T (°C)	Fill	CSP
Thermal conductivity	J/days·m·°C	-0.5	120000	-1	163948	4650000
		0	45000	0	122500	4650000
Specific heat	J/kg·°C	-0.5	2756	-0.5	890	510
		0	5086	0	1160	510
Latent heat	J/kg	Solidus: -0.5 Liquidus: 1	334000	Solidus: -2 Liquidus: 0	21850	-
Density	kg/m^3	---	1039.8	---	1625.9	7850

Table 4-3: Material mechanical and hydraulic properties

Property	Units	T (°C)	Foundation	T (°C)	Fill	CSP
Material cohesion (d)	Pa	-1	25000	-1	21764.4	-
		0	7294.1	0	7115.4	-
Angle of friction (β)	°	-1	51.2	-1	49.4	-
		0	39.5	0	37.3	-
Elastic modulus (E)	Pa	-1	100000000	-1	214000000	200×10^9
		0	130000	0	150000	200×10^9
Poisson's ratio (ν)	---	-1	0.25	-1	0.25	0.3
		0	0.3	0	0.3	0.3
Lambda (λ)	---	-1	0.006	-1	0.006	-
		0	1.6	0	0.9	-
Kappa (κ)	---	-1	0.0008	-1	0.0008	-
		0	0.2	0	0.02	-
Hydraulic conductivity (k)	m/day	-1	1E-8	-1	1E-8	-
		0	0.00226 (e_o = 5.0) 0.00076 (e_o = 0.1)	0	0.001 (e_o = 0.64) 0.005 (e_o = 0.72)	1×10^{-15}
Density	kg/m^3	---	1039.8	---	1625.9	7850

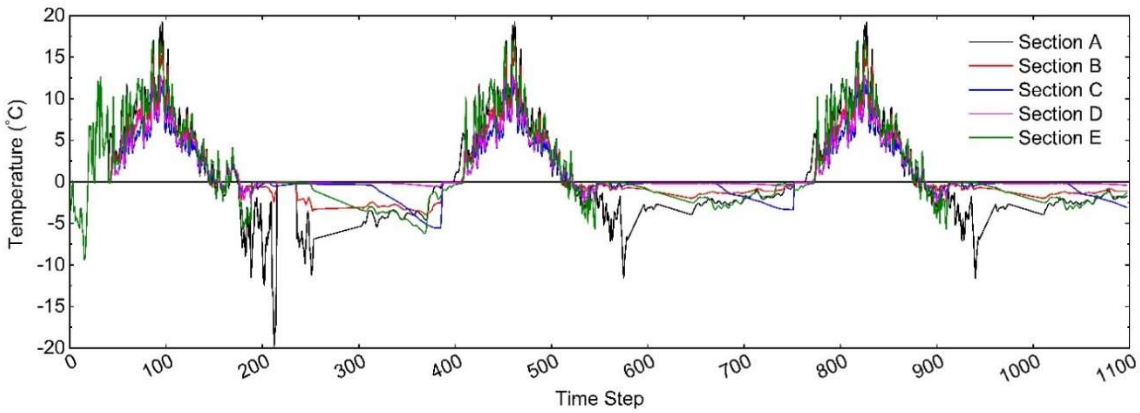
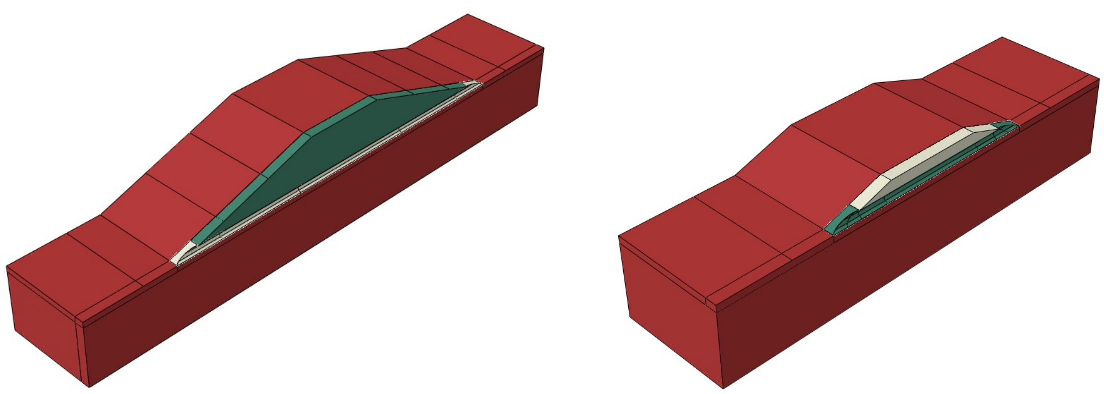
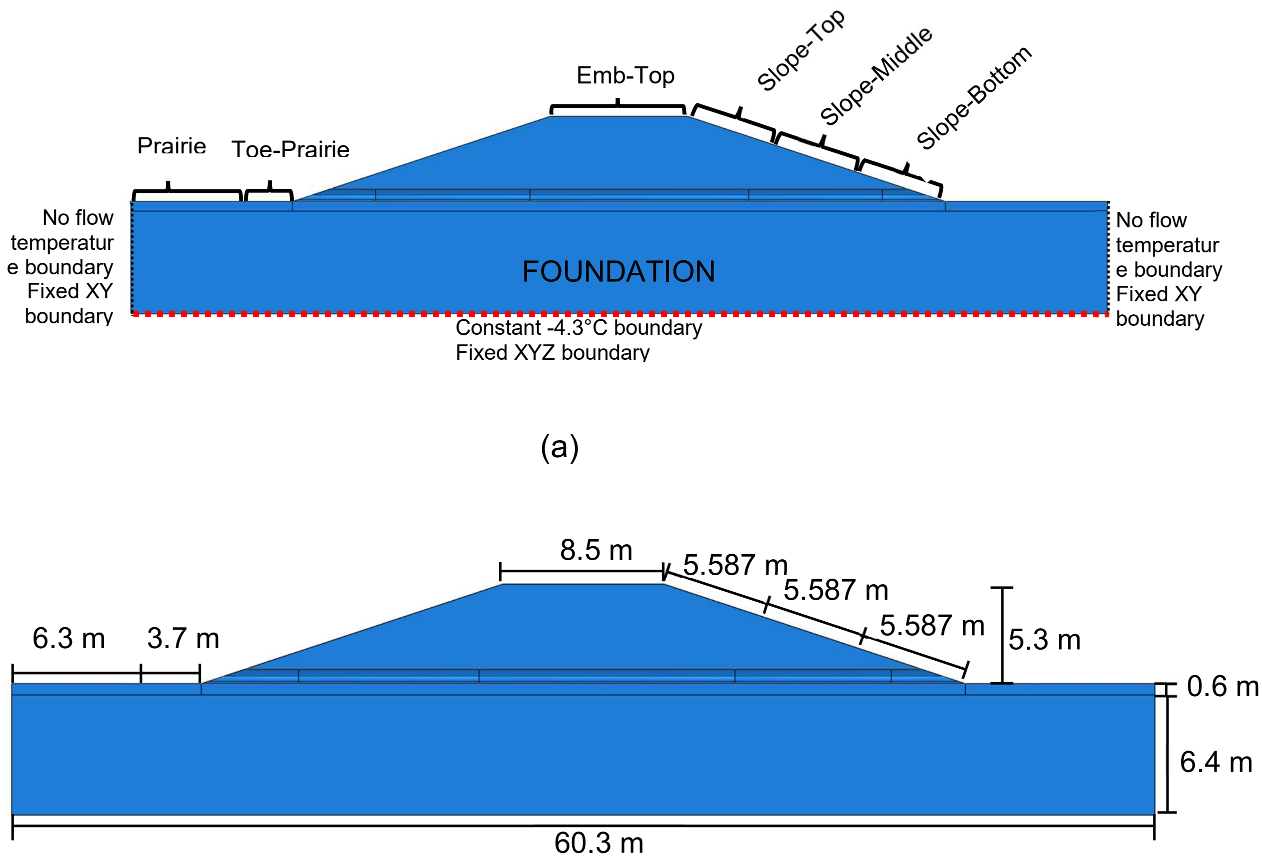


Fig. 4-1. Applied culvert section temperature boundaries



(a) (b)

Fig. 4- 2. Orthogonal view of the Thick embankment (a) and Thin embankment (b) with distinguished model sections.



(b)

Fig. 4-3. Thick Embankment sections and boundary conditions (a) and outlined dimensions (b) of model..

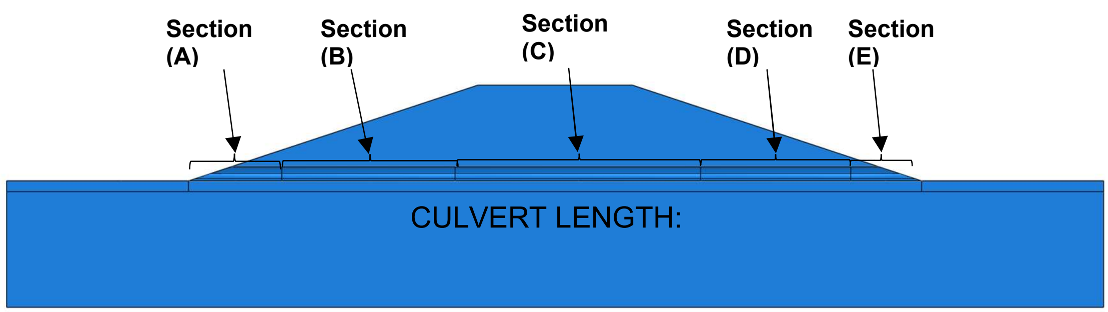
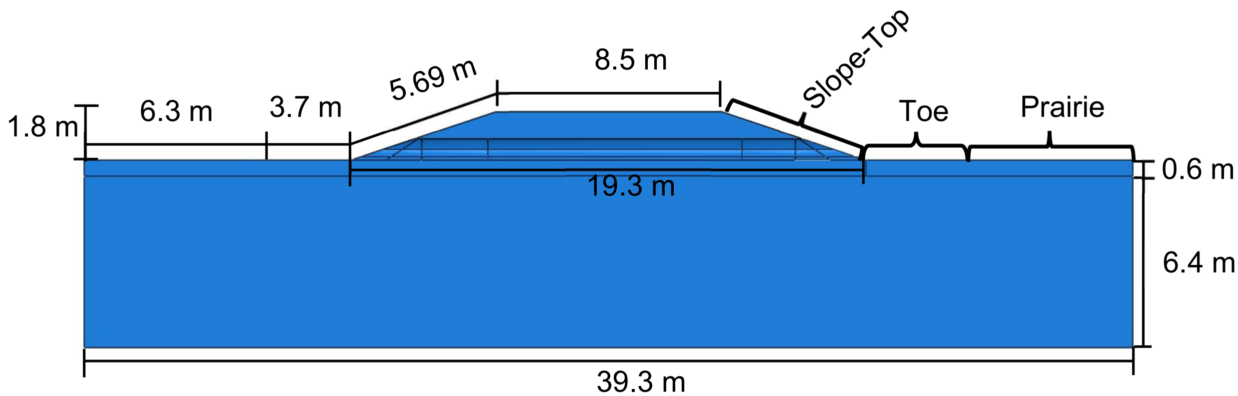
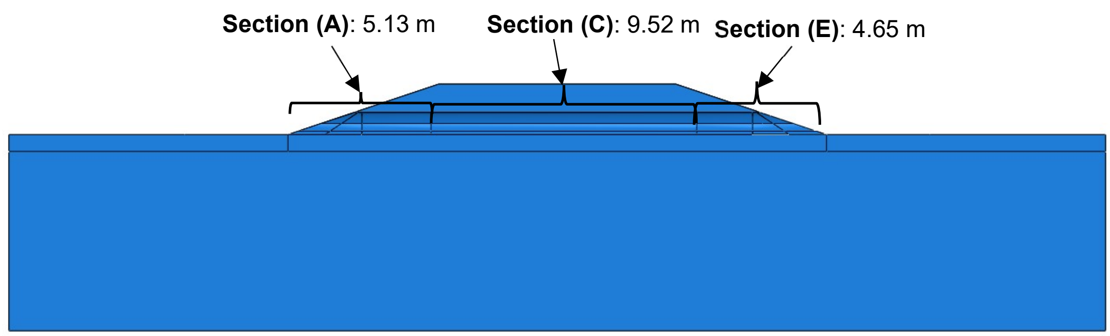


Fig. 4-4. Thick embankment culvert sections and dimensions.

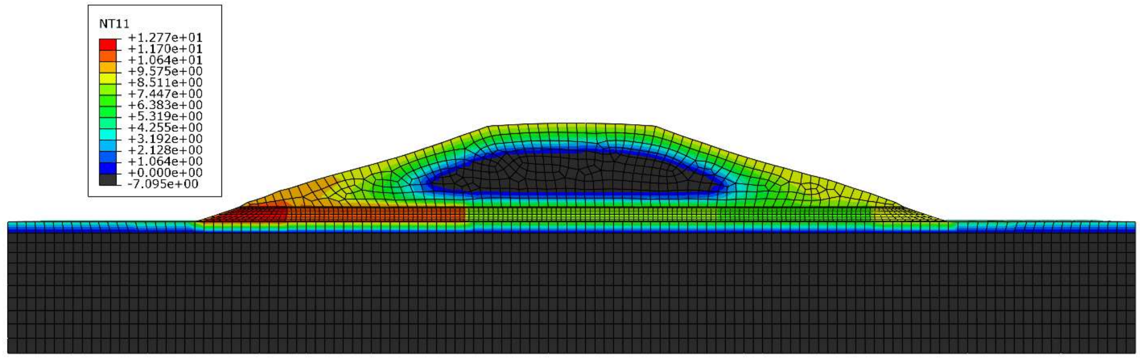


(a)

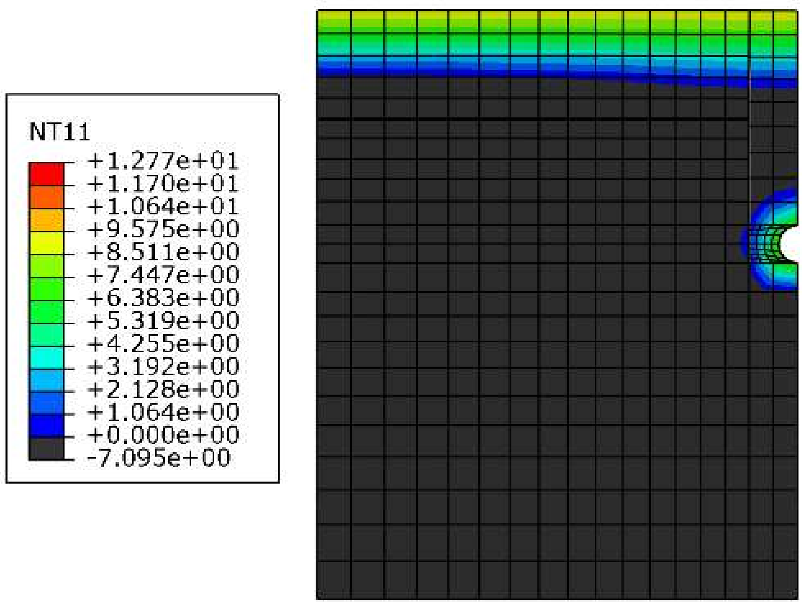


(b)

Fig. 4-5. Thin embankment (a) dimensions and sections with (b) culvert section dimensions.

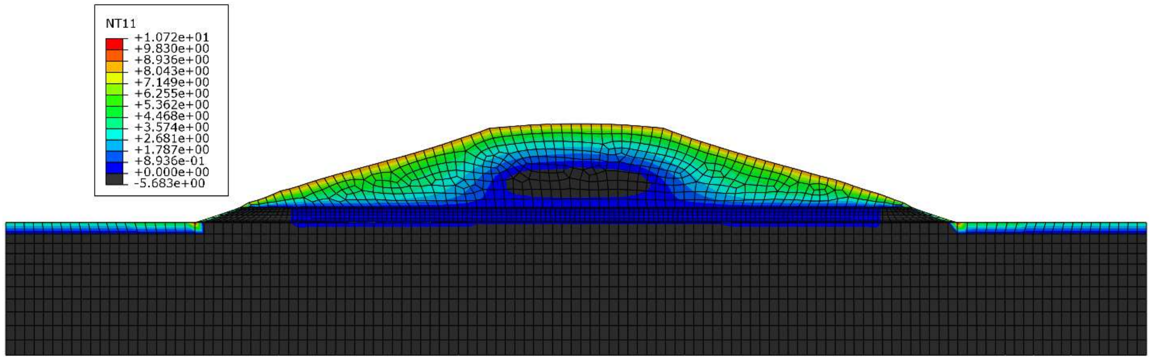


(a)

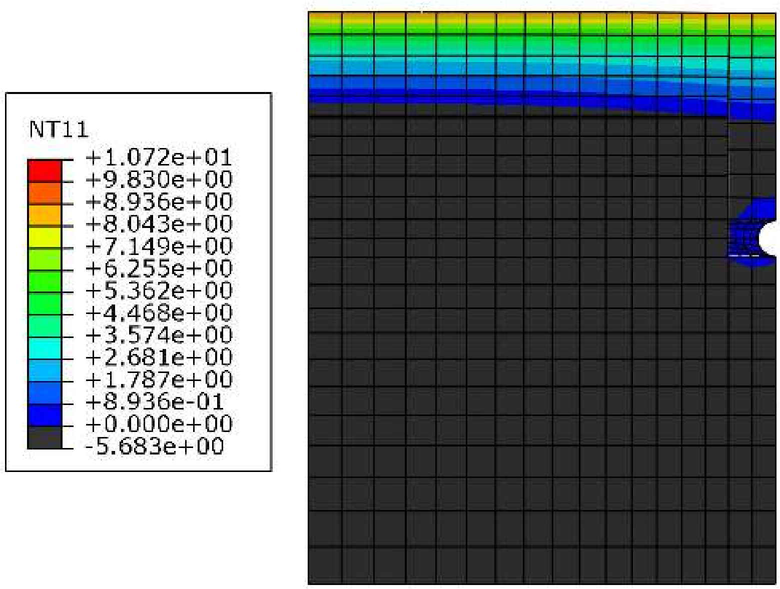


(b)

Fig. 4-6. Modelled temperature contours (a) along the cross-section of the culvert and (b) at the embankment centerline on mid-July 2018.

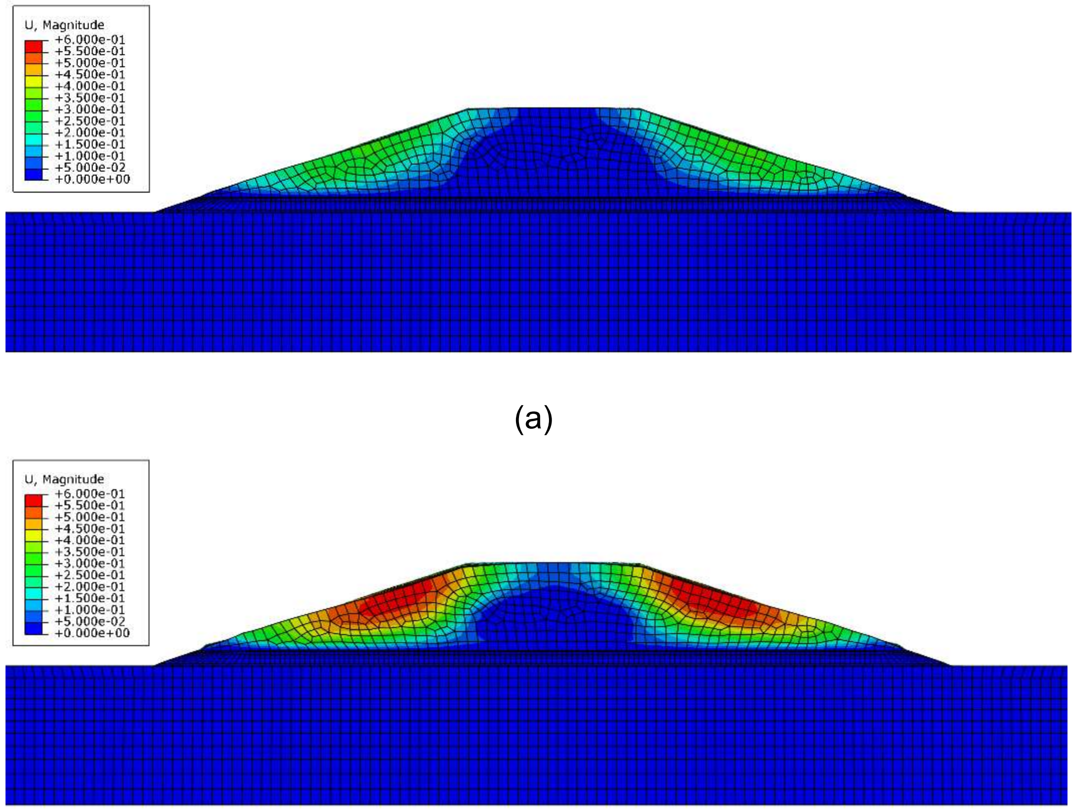


(a)



(b)

Fig. 4-7. Modelled temperature contours (a) along the cross-section of the culvert and (b) at the embankment centerline on mid-September 2018.



(a)

(b)

Fig. 4-8. Modelled displacement (global) contours (a) on mid-July 2018 and (b) mid-September 2018 along the cross-section of the culvert.

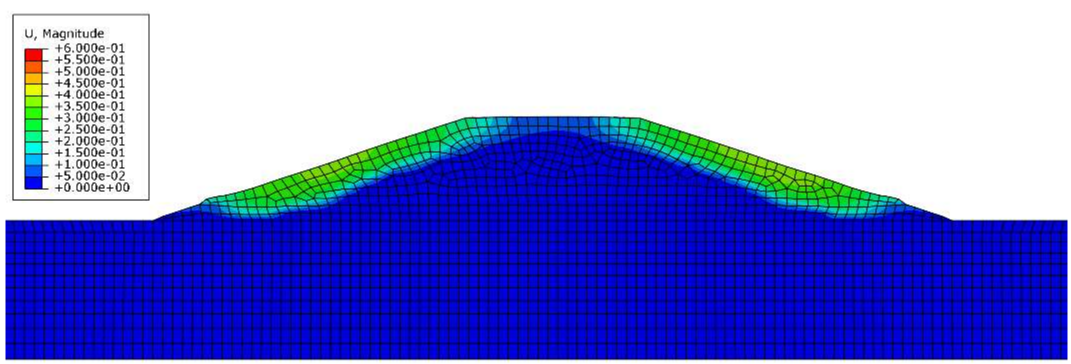
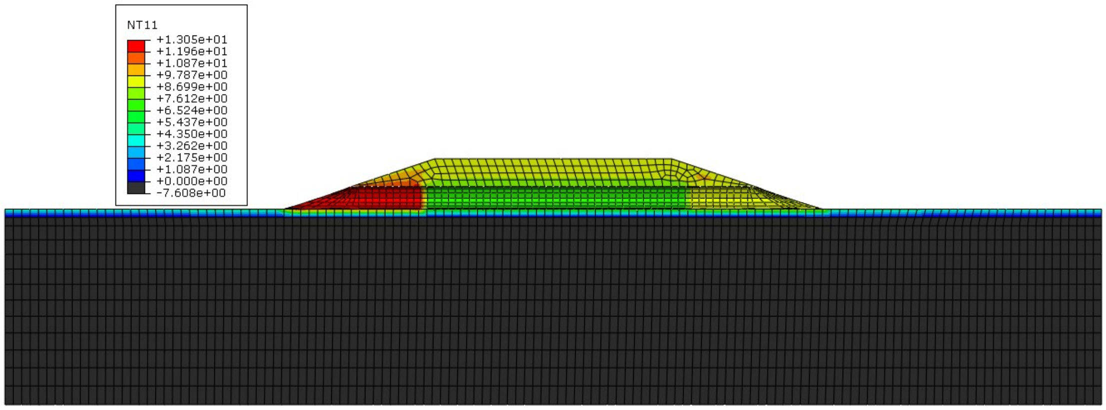
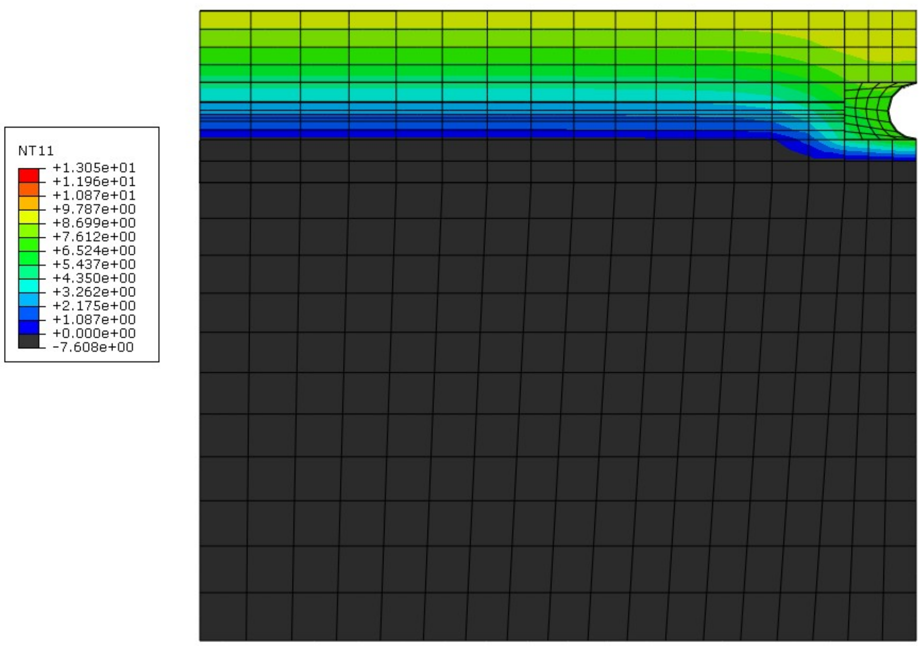


Fig. 4-9. Modelled displacement (global) contours on mid-September 2018 along the cross-section of the culvert 5 m away from culvert centreline.

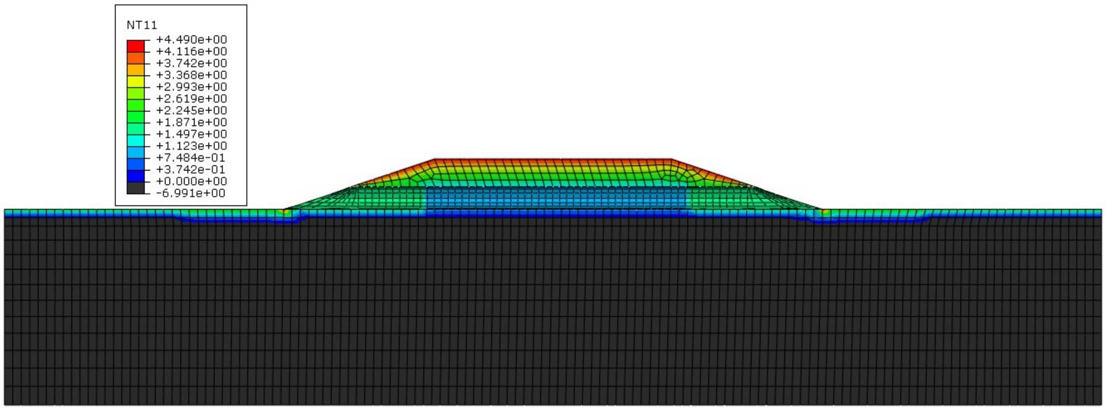


(a)

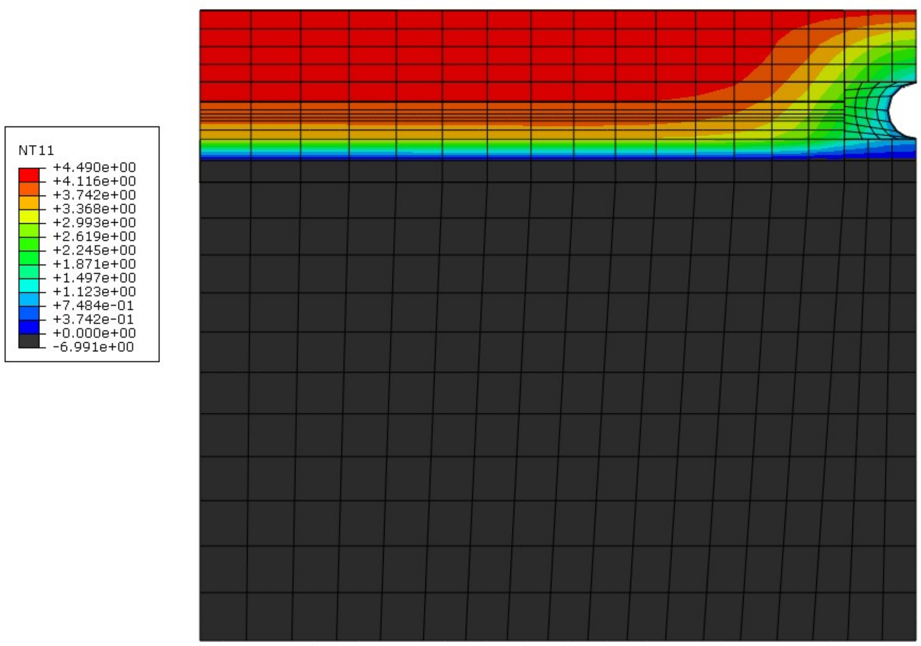


(b)

Fig. 4-10. Modelled temperature contours (a) along the cross-section of the culvert and (b) at the embankment centerline on mid-July 2018.

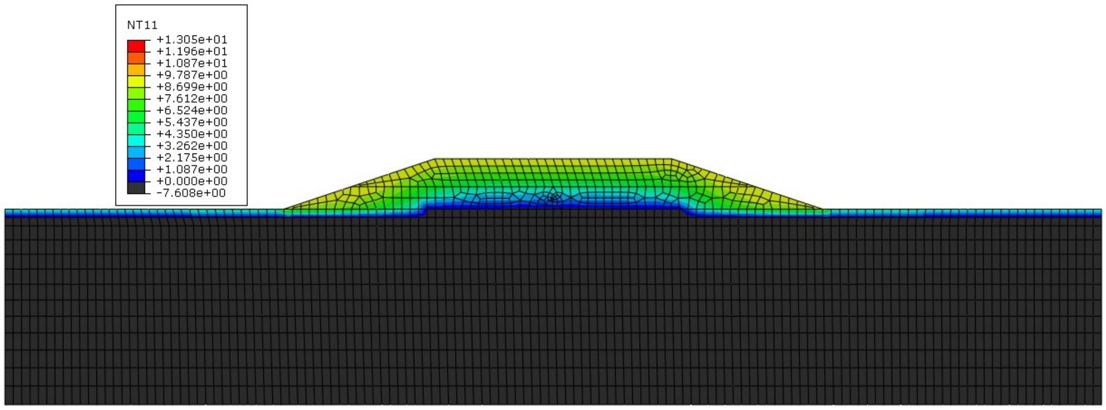


(a)

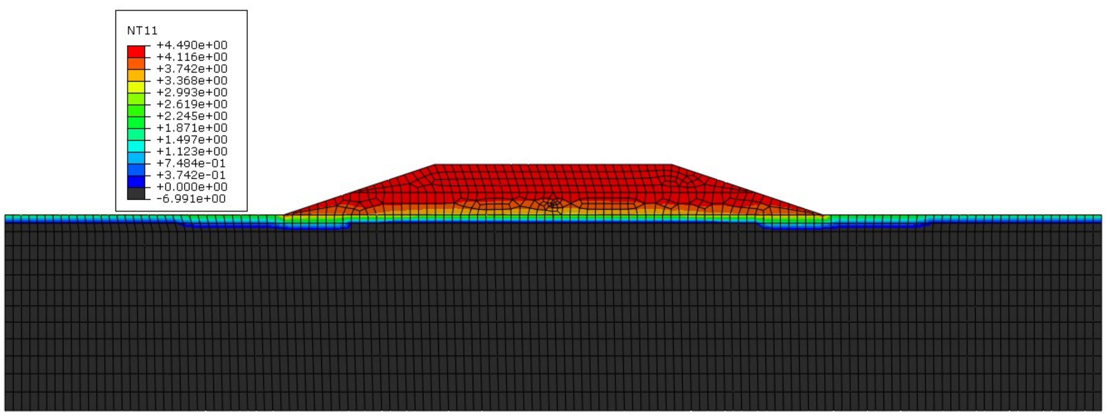


(b)

Fig. 4-11. Modelled temperature contours (a) along the cross-section of the culvert and (b) at the embankment centerline on mid-September 2018.

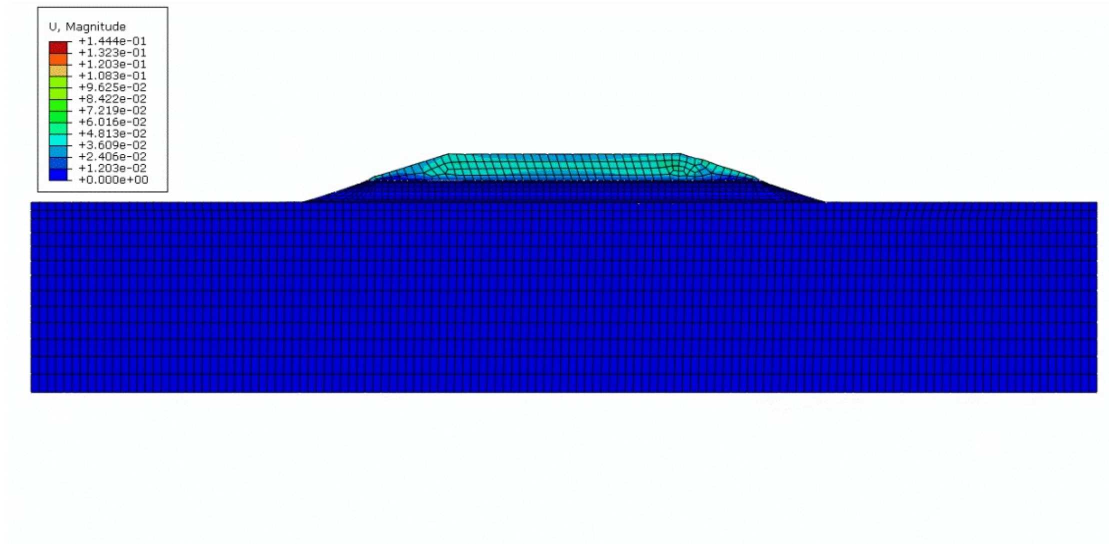


(a)

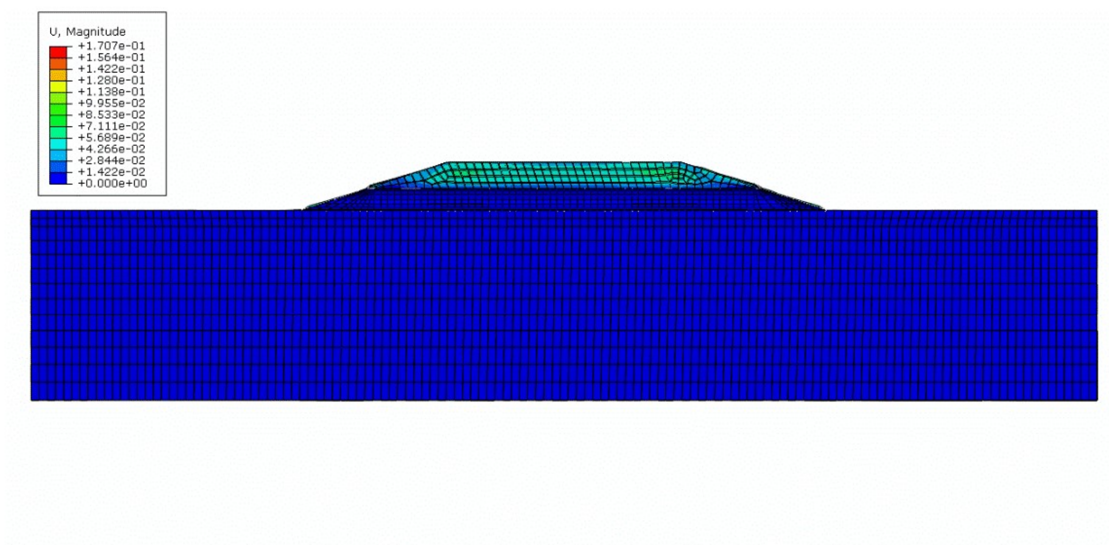


(b)

Fig. 4-12. Modelled temperature contours with no culvert influence at the embankment centerline at (a) mid-July 2018 and (b) mid-September 2018.



(a)



(b)

Fig. 4-13. Modelled displacement (global) contours (a) on mid-July 2018 and (b) mid-September 2018 along the cross-section of the culvert. Compared with displacements in mid-September 2018 (c) along the cross-section of the culvert 5 m away from culvert centerline.

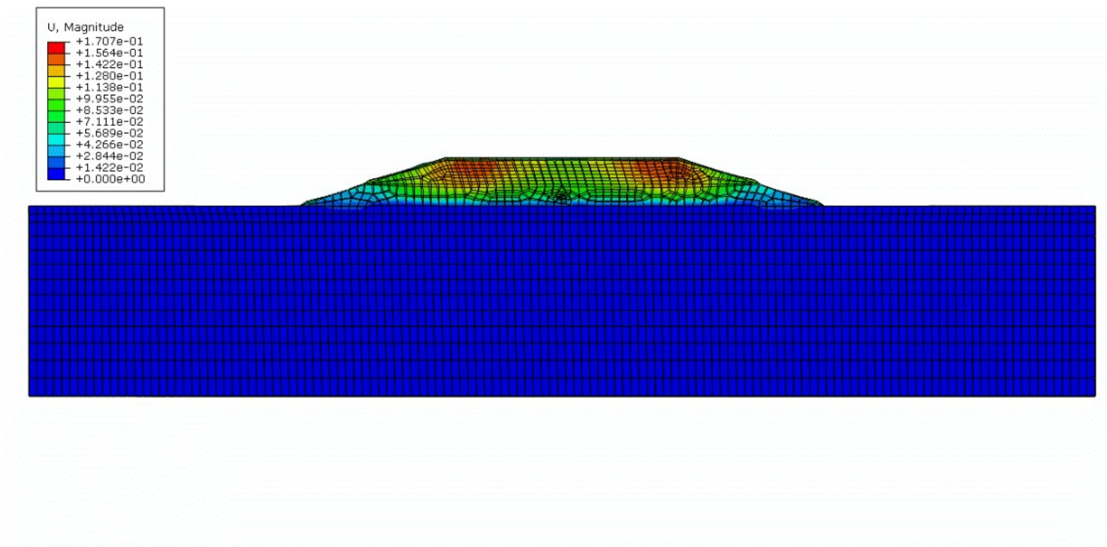


Fig. 4-13. Modelled displacement (global) contours (a) on mid-July 2018 and (b) mid-September 2018 along the cross-section of the culvert. Compared with displacements in mid-September 2018 (c) along the cross-section of the culvert 5 m away from culvert centerline. (Continued)

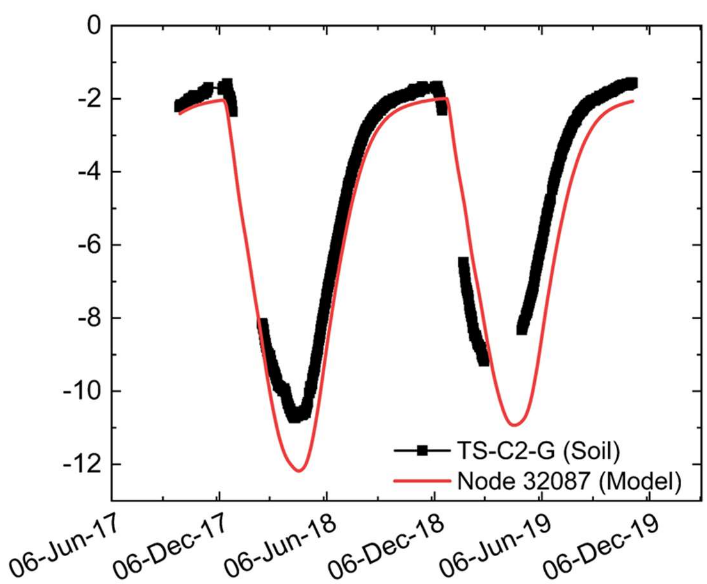


Fig. 4-14. Measured soil temperature and modeled temperature comparison.

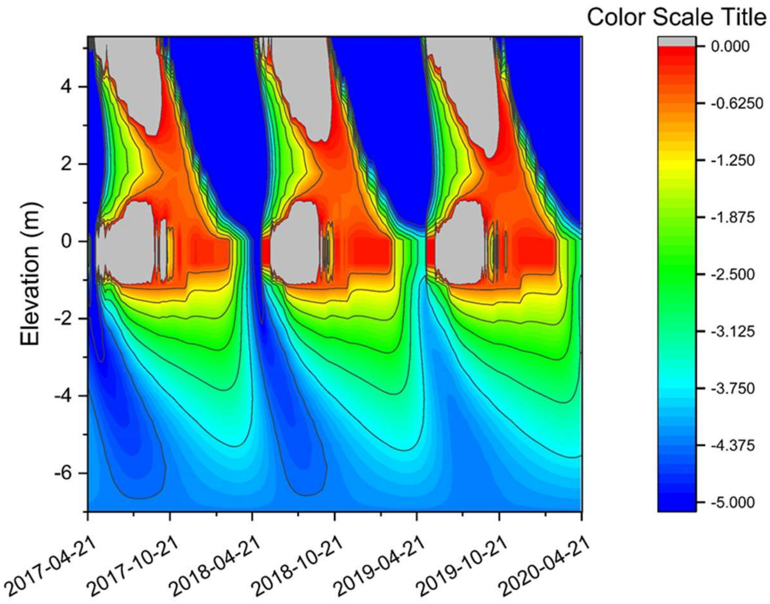


Fig. 4-15. Thick model centerline temperatures at culvert face.

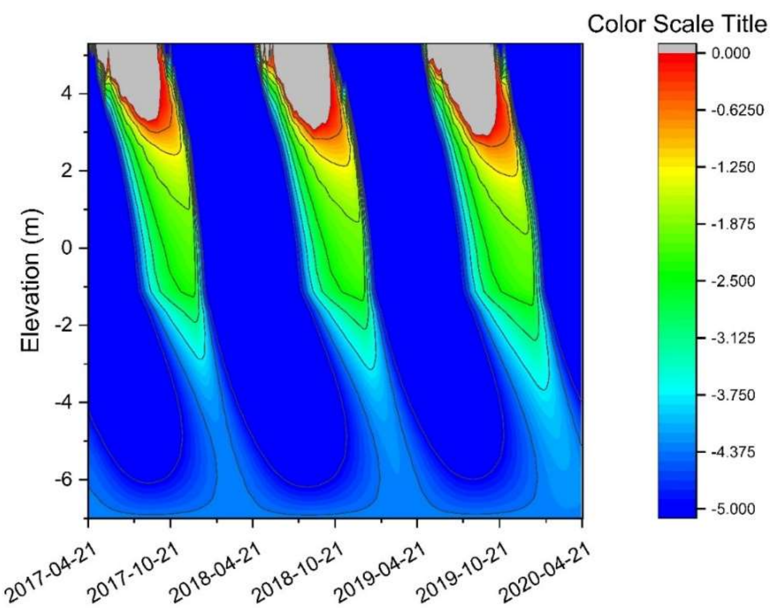


Fig. 4-16. Thick model centerline located out of culvert zone of influence.

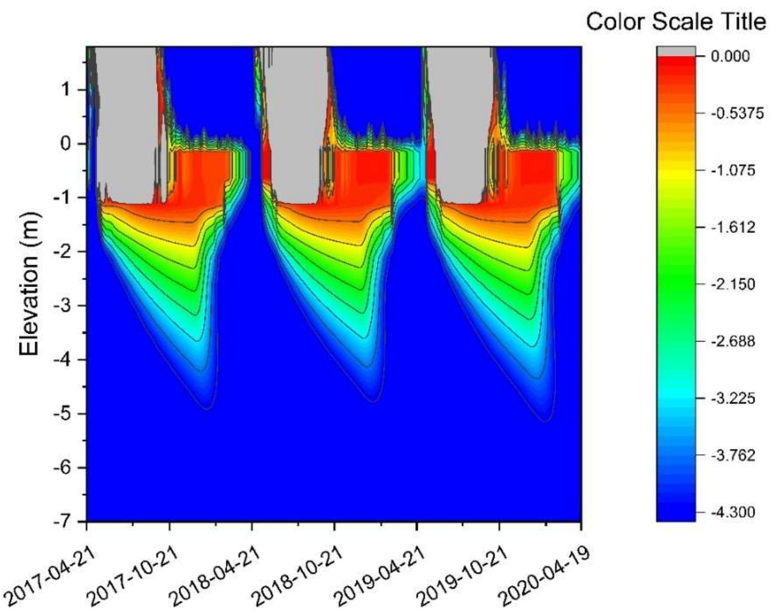


Fig. 4-17. Thin model centerline temperatures at culvert face.

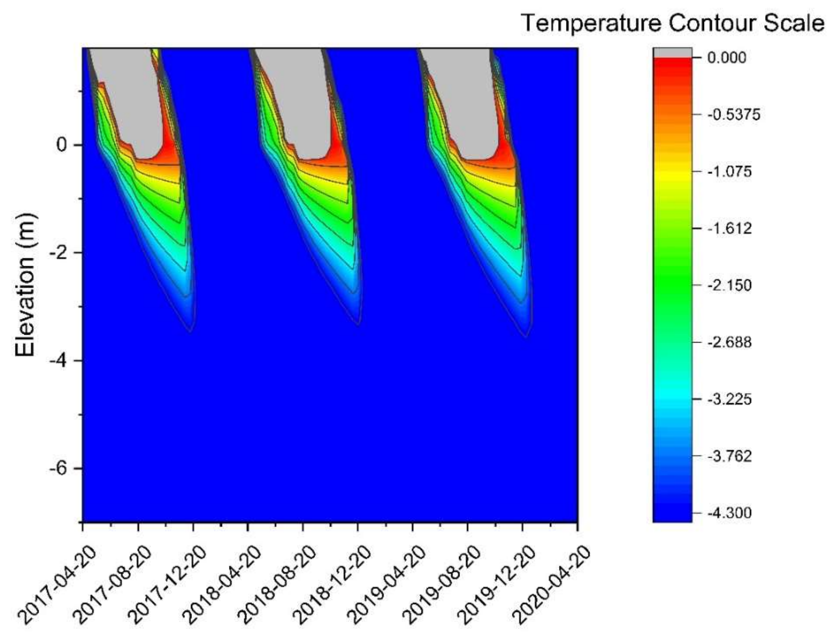
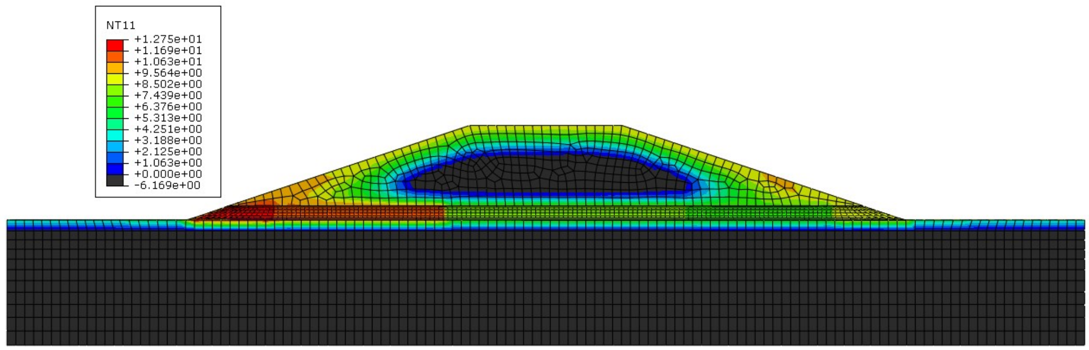


Fig. 4-18. Thin model centerline located out of culvert zone of influence



(a)

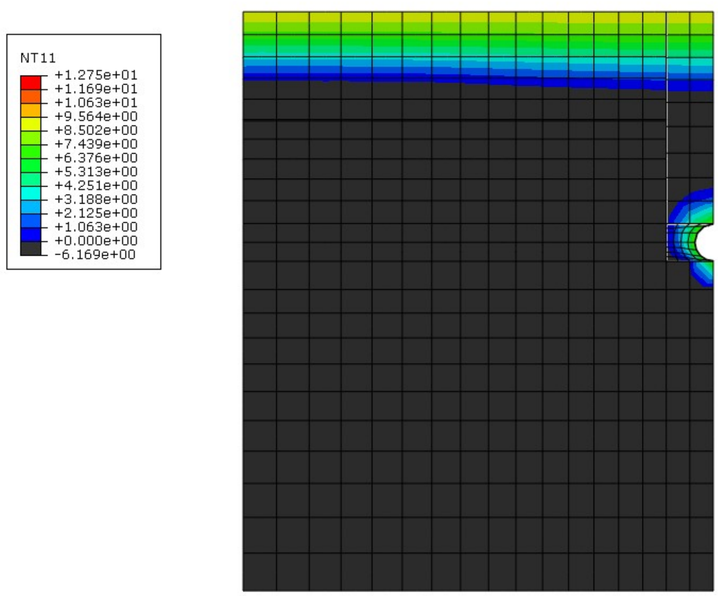
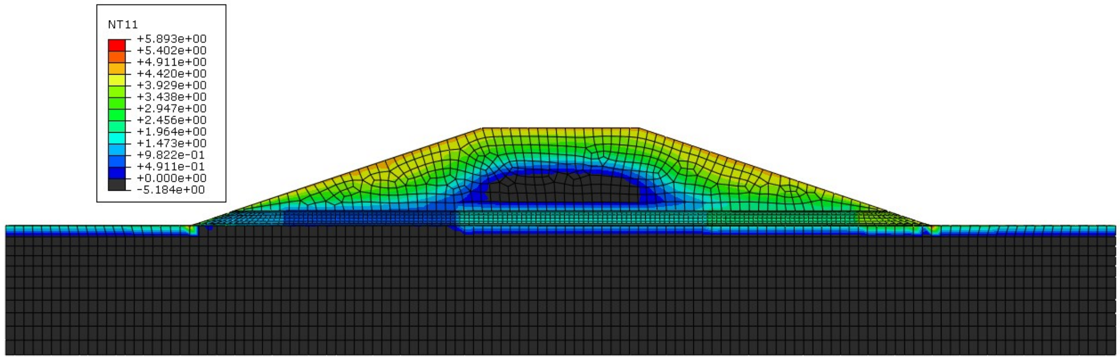
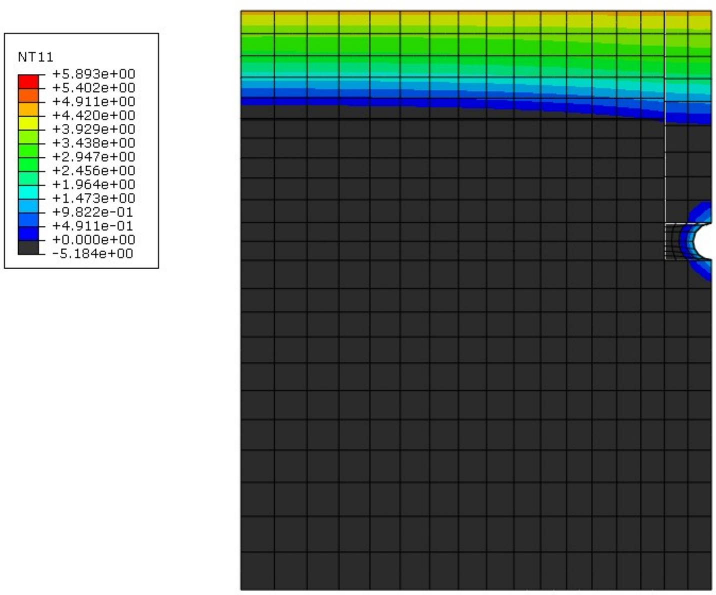


Fig. 4-19. Thick embankment heat transfer modelled temperature contours (a) at the embankment centerline and (b) along the cross-section of the culvert on mid-July 2018.

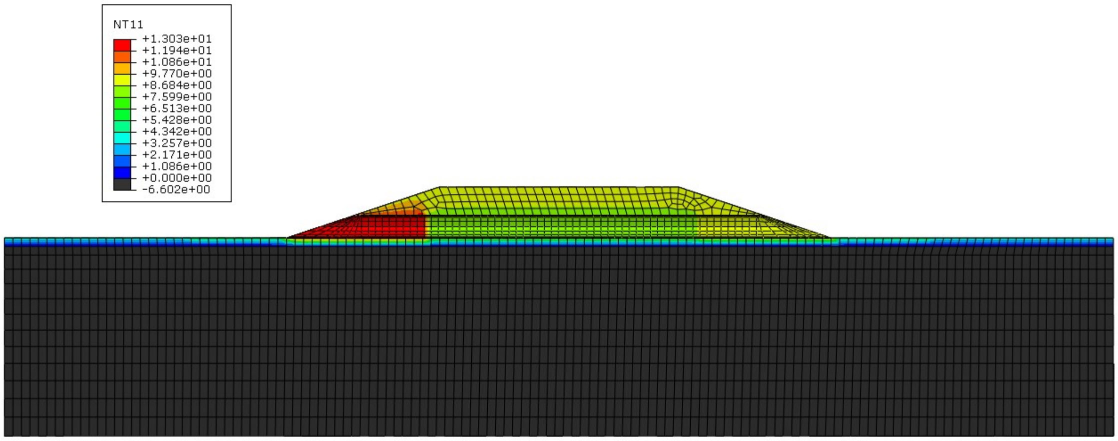


(a)

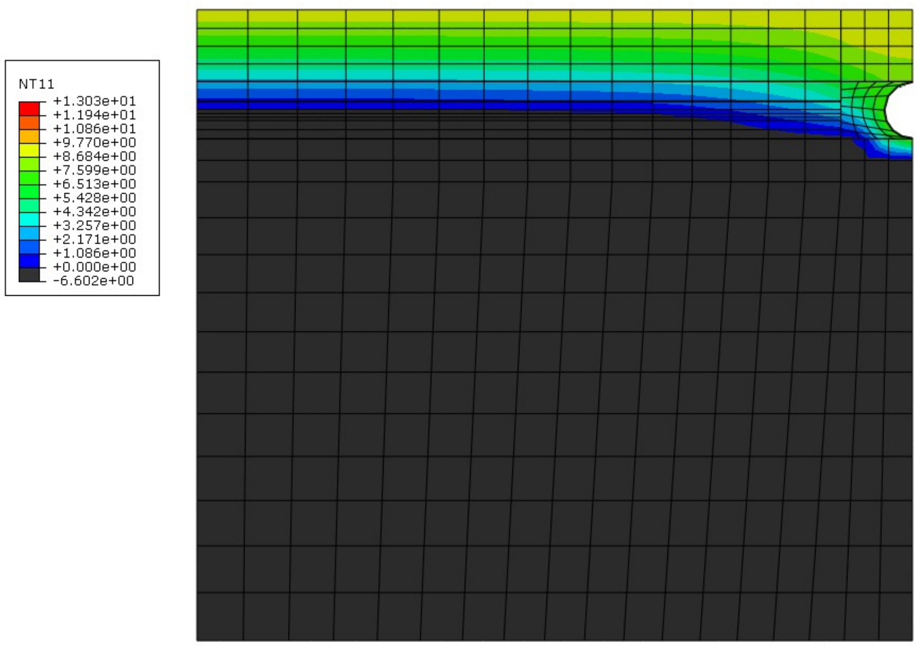


(b)

Fig. 4-20. Thick embankment heat transfer modelled temperature contours (a) at the embankment centerline and (b) along the cross-section of the culvert on mid-September 2018.

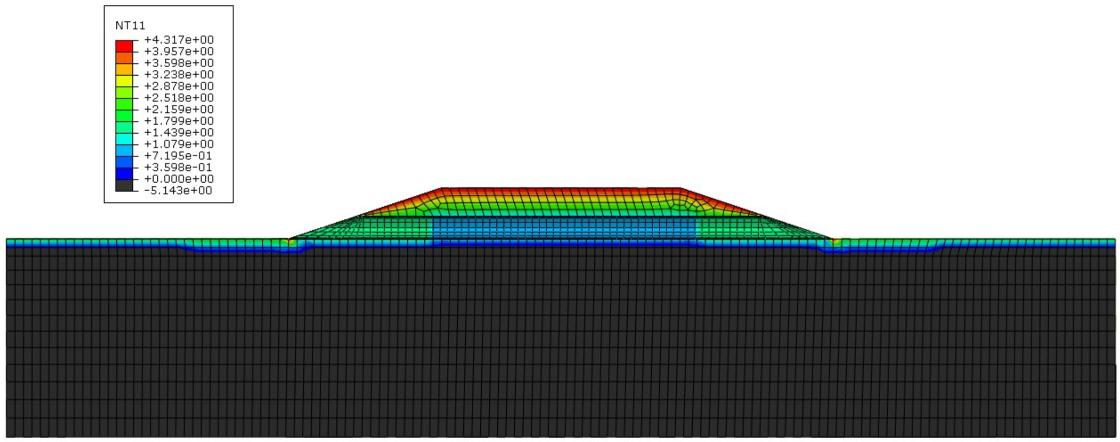


(a)

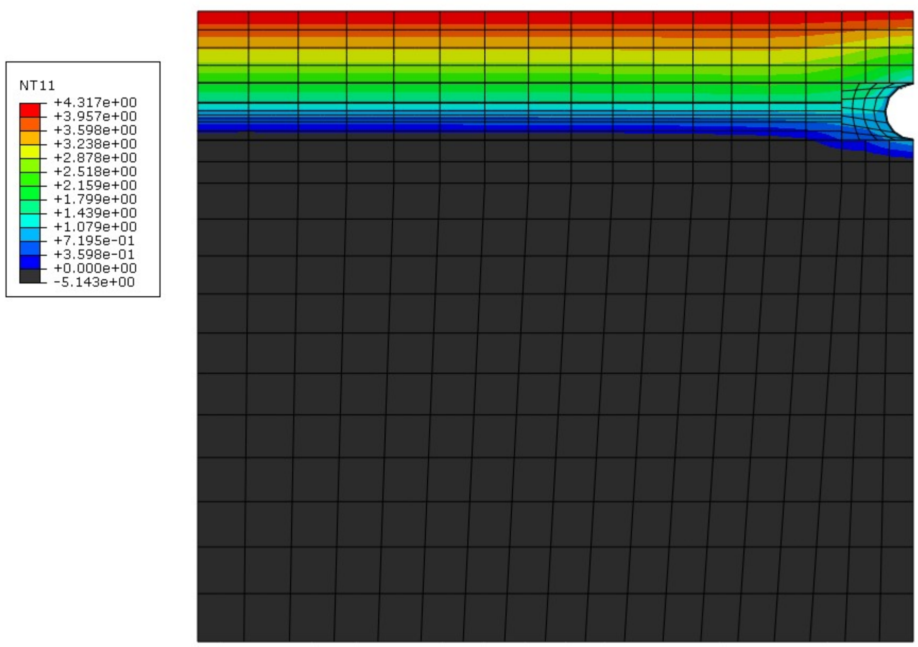


(b)

Fig. 4-21. Thin embankment heat transfer modelled temperature contours (a) at the embankment centerline and (b) along the cross-section of the culvert on mid-July 2018.



(a)



(b)

Fig. 4-22. Thin embankment heat transfer modelled temperature contours (a) at the embankment centerline and (b) along the cross-section of the culvert on mid-September 2018.

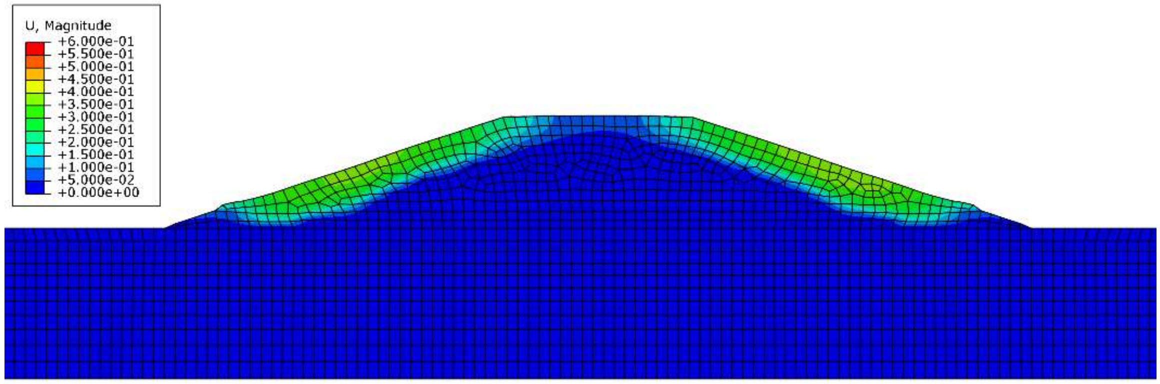


Fig. 4- 23. Modelled displacement (global) contours on mid-September 2018 along the cross-section of the culvert 5 m away from culvert centreline.

CHAPTER 5

5. Summary and Conclusions

This study investigated the influence of culverts on the thermal and mechanical behaviour of embankments constructed under winter conditions. A culvert was instrumented with a 5-noded thermistor to observe the seasonal air temperature changes throughout its length at the University of Manitoba research site along the Inuvik-Tuktoyaktuk Highway (ITH) in the Northwest Territories. The culvert was installed prior to the construction of the University of Manitoba test sections in April 2015, which is approximately 10 m away from unreinforced embankment (Zone B). An initial frozen fill layer was placed above the culvert for compaction purposes, after which frozen fill was placed until the desired height was reached. The thermistor along the culvert was installed in September 2017. A survey rod was installed on the downstream end of the culvert and snow depths were monitored with a camera trap. Similar to field observations made during winter field trips along the ITH for other drainage culverts, the upstream and downstream ends of the culvert are covered in snow. Temperature data during the winter months indicate that the temperature inside the culvert is hovering in the range between -0.5°C and -5°C, which is significantly warmer than the ambient air temperature in the same observation time. With two years of temperature data obtained from the thermistor nodes along the length of the culvert, as well as temperature and displacements recorded by De Guzman et al. (2021, 2022) for the test sections beside the culvert section in this study for calibration, a three dimensional Thermal-Hydro-Mechanical (THM) model was developed to support the assessment of the thermal and mechanical impact of culverts on the performance of thick and thin embankments

The following conclusions are made:

1. From the monitored temperature results presented in this study, it was found that at the transition phase from summer to winter season the temperature inside the culvert during the summer is cooler compared to the air temperature but in the winter months the temperature inside the culvert is warmer.

2. Due to snow cover at the culvert inlet and outlet it is observed that the culvert does not facilitate significant heat extraction throughout the winter months.

3. Based on the three-dimensional TM The radial extents of temperature disturbance around a culvert is approximately 1m, and in the case of the thick embankment – has reduced the area of a frozen core.

4. Modeled displacements indicate the impacts culverts have on the embankment structure causing ‘humps’ and undulations that influences embankment performance. The settlements that will develop due to thawing of the compacted frozen soil around the culvert should be accounted for in the design stages to reduce to potential impact of surface settlements.

5.1. Recommendations for Future Works

The following recommendations for future works are to be considered in conjunction with the findings of this study:

1. Study the convective heat flow from air flow and water flow through the culvert.
    a. Measure air velocity and its flow pattern through the culvert length;
    b. Determine water velocities and water temperatures along the length of the culvert.

    As previously indicated in Chapter 4, the water temperatures are cooler than peak air temperatures in the summer and may facilitate delayed heating effects of the embankment.

2. Impact of the thermal boundary conditions due to ice formation at the culvert base;
3. Study of culvert temperatures maintaining an open inlet and outlet and its potential heat extraction benefit; This study would assist organizations if consideration should be given to programs that prevent inlet and outlet by maintaining open passages throughout the winter months.
4. Comparison of the thermal modifier modeling approach as a boundary condition to a culvert with a conjugate heat transfer model inclusive of convective and conductive heat transfer modes. Arenson et al. (2006) had addressed the complexity of air convection in embankment design as it is dependent on factors such as air permeability, air boundary conditions, and water content.
5. Parametric study based on alternative design methodologies such as
    a. The use of Styrofoam as an insulator around the culvert;

b. Different fill material around the culvert; In some sections along the ITH an air convective material was used to promote air circulation throughout the embankment providing passive cooling. Additionally, not all culverts like the one in this study were constructed with the same fill material as a stiffer base material was placed at the culvert base.

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