A finite element study on the freeze-thaw behaviour of LRT structures in glacial till deposits in Toronto

GeoCalgary 2022 October 2-5
Reflection on Resources

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ABSTRACT
Finite element modelling of freeze-thaw behaviour in engineering practice is typically hampered by the large number of input parameters required for the model, which are generally not available using standard geotechnical testing. The growing climate change necessitates a re-evaluation of the current understanding of freeze-thaw on LRT infrastructure, particularly for the long-term design performance and maintenance of these infrastructures. This paper reviews the practicality of using the Barcelona Frozen Unfrozen (BFUF) constitutive model to simulate frost heave behaviour through a fully coupled thermal-hydro-mechanical (THM) finite element analysis for the design of underground LRT structures. Two sites were considered in this study; Site A which is located in Southern Ontario and Site B which is located in central Toronto. The BFUF constitutive model was calibrated based on a case study of shallow piles responses under frost heave in glacial till deposits in Site A. The basic soil parameters at Site A were compared to Site B. The calibrated model is then applied to understand the preliminary behaviour of tunnel portals exposed to winter conditions at Site B. Result of the backanalysis and limitations of the analysis are discussed herein.

RÉSUMÉ
La modélisation par éléments finis du comportement au gel-dégel est entravée généralement par le grand nombre de paramètres d'entrée requis pour la maquette, qui ne sont pas disponibles à l'aide d'essais géotechniques typiques. Le changement climatique nécessite une réévaluation de la compréhension actuelle du gel-dégel sur les infrastructures du train léger, en particulier sur la performance à long terme et sur l'entretien de ces infrastructures. Le potentiel d'application pratique du modèle constitutif Barcelona Frozen Unfrozen (BFUF) pour simuler le comportement de soulèvement dû au gel grâce par éléments finis de thermique-hydro-mécanique (THM) a été examiné. Deux sites ont été considérés dans cette étude; Site A qui est situé dans le sud de l'Ontario et site B qui est situé au centre-ville de Toronto. Le modèle constitutif de BFUF a été calibré à partir d'une étude de réponses de pieux peu profonds sous le soulèvement par le gel dans les dépôts de till glaciaire au site A. Les paramètres du sol au site A ont été comparés au site B. Le modèle constitutif de BFUF calibré est ensuite appliqué pour meilleur comprendre le comportement préliminaire de la tête de tunnel exposée aux conditions hivernales au site B. Les résultats de ces analyses sont discutés ci-joint.

1 INTRODUCTION

The application of freeze-thaw analysis is typically limited to empirical solutions in standard engineering practice. The predictions of frost induced forces and the magnitude of frost heave on structures typically do not take into consideration the site-specific conditions. The growing climate change necessitates more detailed site-specific evaluation of structural responses under freeze-thaw conditions. This is pertinent to the recent LRT infrastructures in the Greater Toronto Area (GTA), particularly with regard to the long-term design performance and maintenance of these infrastructures.

The use of finite element modelling for freeze-thaw behaviour in engineering practice is typically hampered by the large number of input parameters required for the model, which are generally not available using standard geotechnical testing. The practicality of using the Barcelona Frozen Unfrozen (BFUF) constitutive model to simulate frost heave behaviour through a fully coupled thermal-hydro-mechanical (THM) finite element analysis to observe the response of underground LRT structures is evaluated.

Two sites were considered in this study; Site A which is located in Southern Ontario, southwest of Toronto, and Site B which is located in central Toronto. The appropriateness of the BFUF constitute model to analyze the freeze-thaw behaviour of underground structures was investigated through back-analysis of pile load test performed on a driven pile in glacial till at Site A. The model was subsequently calibrated for frost heave behaviour based on works previously reported by Adams & Ma, 2021. The calibrated BFUF model was subsequently applied at Site B to understand the preliminary behaviour of tunnel portals exposed to winter conditions.

2 SITE A AND SITE B

2.1 Background Information

Site A is located in a region southwest of Toronto as shown in Figure 1. The site is underlain by glacial till deposits, typical of southern Ontario. Groundwater at this site is near ground surface.

The Ministry of Transportation Ontario has previously performed load tests on three HP310 X 110 driven piles. The embedded length of the test piles was 3.05m. The ground conditions were reported to comprise hard to very stiff silty clay with the basic soil characteristics summarized in Table 1. The load settlement curve of the pile load test undertaken at Site A is presented in Figure 2.

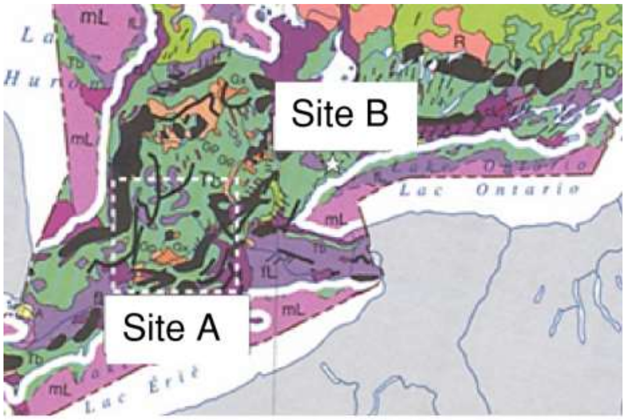

Figure 1. Surficial geology at Site A and Site B (Geological Survey of Canada, 1995).

Site B is located northwestern of Toronto and the site is underlain by glacial till deposits as well, with groundwater table within 2m of the ground surface. Table 1 summarizes the basic soil characteristics of the glacial deposits at Site A and B. The glacial deposits between the two sites are relatively comparable.

Table 1. Characteristics of soils at Site A and Site B

Characteristics (%)	Site A	Site B
Natural moisture content	17 to 25	17 to 31
Liquid limit	37 to 45	26 to 55
Plastic limit	19 to 22	16 to 21
Sand & Gravel	6 to 10	1 to 18
Silt	43 to 44	34 to 51
Clay	46 to 51	24 to 59

2.2 Backanalysis of Pile Load Test

The backanalysis of the test pile at Site A was analysed in PLAXIS 2D using an axis-symmetry model. An equivalent pile diameter of 0.39m with an equivalent weight of 8.9 kN/m^3 was assumed in the model for the HP310 x110 test pile. The soil stratigraphy was modelled as a single stratum of glacial till with a groundwater table of 0.2m below ground surface.

The backanalysis of the pile load test was modelled using the Modified Cam-Clay (MCC) as the unfrozen state of the BFUF model is based on the Modified Cam-Clay model. The pile was modelled as a Linear Elastic non-porous medium.

Results indicate that the MCC model can reasonably mimic the pile response driven in glacial till as shown in Figure 2. The calibrated parameters are summarized in Table *2*. Subsequently, a calibration of the pile load test was undertaken using the BFUF model. As this model only applies the MCC model within the unfrozen elastic stress range, the pile response is limited without having the thermal module activated, as shown in Figure 2. Beyond the elastic range, the BFUF frozen soil behaviour governs. The calibrated elastic parameters are summarized in Table 4. Figure 2 indicates that the BFUF model can be reasonably used to mimic the test pile response.

Table 2. PLAXIS input parameters for Modified Cam Clay

Parameters	Glacial Till	Steel Pile
Material Model	Modified Cam Clay	Linear Elastic
Drained Type	Drained	Non-porous
γ_{unsat} kN/m^3	20	8.9
Stiffness, E (kN/m^2)		200E6
λ (lambda)	0.035	
κ (Kappa)	0.0035	
V'ur/ v	0.2	0.3
Void Ratio, e_{init}	0.35	
M	1.3	
Interfaces		Rigid
C'ref (kN/m2)	30	
Phi (deg)	34	
Initial		
Ko	1.3	Automatic
POP (kN/m^2)	400	

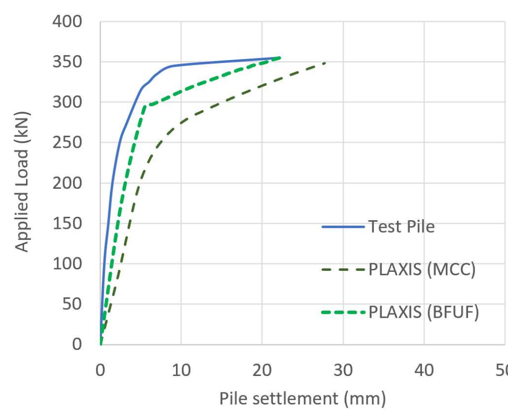

Figure 2. PLAXIS backanalysis of test pile at Site A using MCC and BFUF models

2.3 Frost Heave on Pile

In the region of Site A, frost heave on piles was previously reported by Levasseur et al (2015). Pile heave of 20mm to 36mm was report for 3.4m long steel piles driven in very stiff silty clay to silt where groundwater was at approximately 0.2m below ground surface. Levasseur et al (2015) estimated an adfreeze bond stress between 30kPa and 80kPa within the frost depth, equivalent to between 80kN and 216kN of frost jacking forces.

The mean freezing index, I_m, at the site was reported to be approximately 530 °C-days. A design freezing index, I_d, equal to 784 °C-days was reported by Levasseur et al (2015) and a frost penetration depth of about 1.1 m (with snow cover) to 1.4 m (without snow cover) was reported as derived from the mean freezing index, I_m. The frost penetration depth was within the range provided in the frost penetration contour map from the Ministry of Transportation of Ontario, with an estimated frost penetration depth of 1.2 m for the site.

2.4 Backanalysis of Frost Heave on Pile

The thermal module in PLAXIS was activated using the BFUF soil model calibrated for the MTO pile load test backanalysis at Site A. To mimic the pile presented by Levasseur et al (2015), the pile was modelled with an equivalent diameter of 0.1m and an equivalent unit weight of 5.06 kN/m^3 in PLAXIS.

The thermal input parameters using the BFUF model are summarized in Table 4. It is noted that there are 28 input parameters for the BFUF model of which only 5 input parameters (Go, κo, λo and M) were manually selected based on site specific data in the backanalysis undertaken. The rest of the parameters were based on PLAXIS default or recommended values. In the backanalysis, the grain size segregation parameter, S_{seg}, was varied using trial error between 2375 kPa and 3150 kPa to match the pile heave reported on site by Levasseur et al (2015).

The air temperature in the model was linearly reduced to reach below freezing. The temperature was reduced to between -5°C and -10°C, corresponding to a typical southern Ontario winter. Two temperature functions were considered; Condition 1 and Condition 2. The input parameters for the temperature function are summarized in Table *3*.

The thermal boundaries were defined around the model with the horizontal boundary defined as having a uniform temperature of 238.2K to mimic ground thermal heating. The vertical thermal boundaries were set to "Closed" which correspond to heat source coming only from at depth of the model.

Table 3. Temperature functions

Temperature function	Condition 1	Condition 2
Air temperature (K)	283	283
Surface transfer (KW/m^2/K)	1	1
Signal	Linear	Linear
Time (days)	90	90
ΔTemperature (K)	-14.4	-20
Time interval (days)	120	120

Table 4. PLAXIS input parameters for Barcelona Frozen and Unfrozen Model

Parameters	Glacial Till	Steel Pile
Material Model	BFUF	Linear Elastic
Drained Type	Drained	Non-porous
γ_{unsat} (kN/m^3)	-	0.09
E (kN/m^2)	-	200E6
v (-)		0.3
T_{ref} (K)	273.2	
E_{fRef} (kN/m^2)	450,000	
E_{fincr} (kN/m^2/K)	815,000	
v_f (-)	0.3	
G_o ((kN/m^2)	26,400*	
κ_o (-)	0.015*	
p^*_c (kN/m^2)	-150	
$\lambda_o = C_c/\ln 10$ (-)	0.065*	
γ (-)	1	
K_t (-)	0.08	
M (-)	1.3*	
λ_s (-)	0.5	
κ_s (-)	0.005	
r (-)	0.6	
β (m^2/kN)	8E-8	
λ_r (-)	0.6	
P_r (kN/m^2)	2400	
α (-)	9	
T_{0ref} (K)	273.2	
P_{0ref} (kN/m^2)	-395,000	
M (-)	1	
$P^*\gamma_o$ at γ_{ref} (kN/m^2)	-200	
γ_{ref} (m)	0	
$\Delta P^*\gamma_o$ (kN/m^2/m)	-20	
e_o (-)	0.35*	
S_{seg} (kN/m^2)	2375 to 3150	
P_{at} (kN/m^2)	-100	
K_w (kN/m^2)	1e6	
Groundwater		
Data set	USDA	
Model	Van Genuchten	
Type	Silt loam	
Thermal		
C_s (J/kg/K)	920	470
λ_s (W/m/K)	2	0.05
ρ_s (kg/m^3)	2.6	0.009
α_s (1/K)	5.2E-6	0.045E-3
Interfaces		
C'_{ref} (kN/m^2)	30	
ϕ (deg)	34	
Initial		
$K_{o,x} = K_{o,z}$ (-)	2.5	

* Site specific parameters

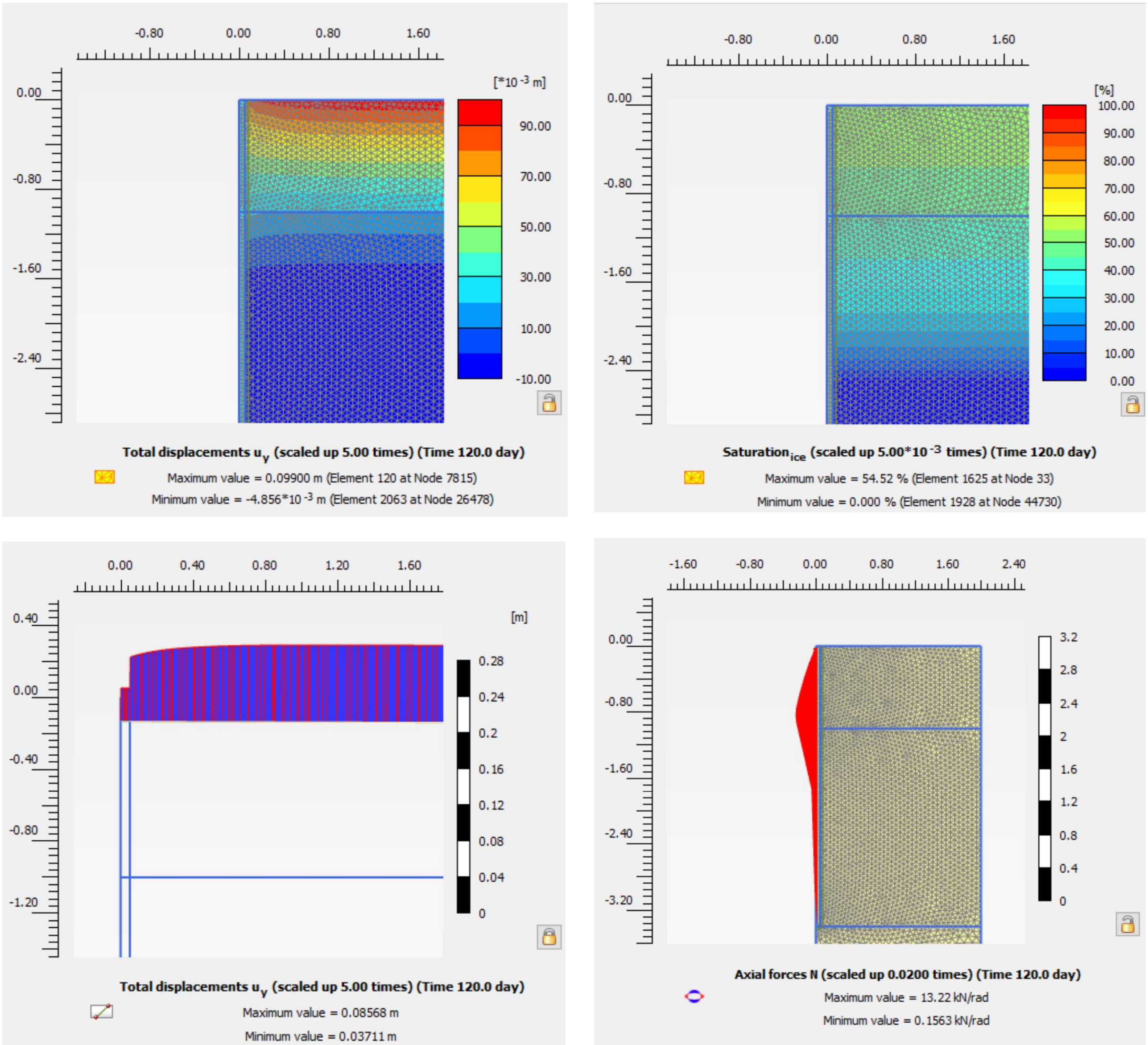

Figure 3. PLAXIS pile displacement, ice saturation & axial forces (Condition 1 with S_{seg}=3150 kPa)

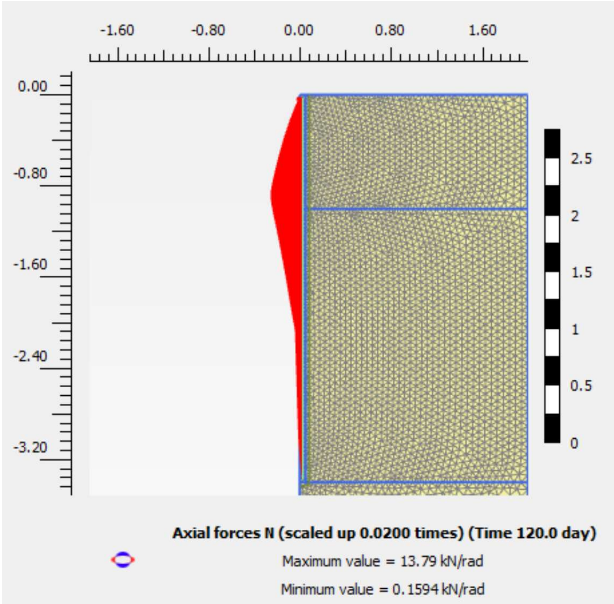

Figure 4. PLAXIS pile adfeeze forces for Condition 1 with S_{seg} = 2375kPa

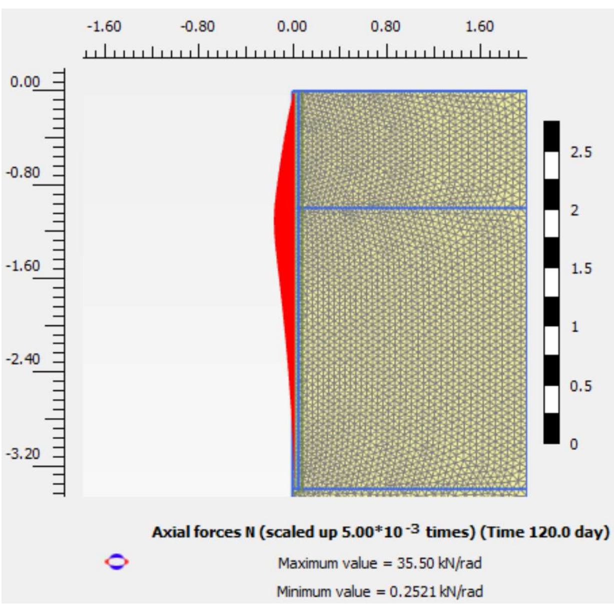

Figure 5. PLAXIS pile adfeeze forces for Condition 2 with S_{seg} = 2375kPa

2.5 Frost Heave Prediction for Pile

Preliminary results of pile response due to frost heave for varying grain size segregation parameter S_{seg} are summarized in Table 5. A S_{seg} value of 3150 kPa provided a pile heave settlement close to that observed at Site A of 20 to 35mm compared to a S_{seg} value of 2375 kPa. The adfreeze forces are noted to be concentrated in the top 1.6m, as shown in Figure 3, slightly deeper than the typical 1.2m frost depth in Toronto. The pile was observed to be fully in tension over the length of 3.4m with a total axial force of 115kN. The PLAXIS prediction is within the estimated adfreeze force range suggested by Levasseur et al (2015) of between 80kN and 215kN.

Table 5. Result of pile response to frost heave with varying *S_{seg}* parameter

S_{seg} (kPa)	2375	3150
Pile heave (mm)	70	35
Max ground heave (mm)	165	100
Max ice saturation in ground (%)	54.5	54.5
Max axial heave force on pile (kN)	125	115

Temperature function = Condition 1

A sensitivity analysis of the heave and heave forces due to more extreme winter conditions on the pile was undertaken. Based on a S_{seg} of 2375 kPa, the winter temperature in the model was decreased from -5ºC to - 10ºc. The pile heave and heave forces increase significantly as summarized in Table 6. The adfreeze force distribution along the pile for both Condition 1 and Condition 2 are shown in Figure 4 and Figure 5, respectively.

Table 6. Result of pile response to frost heave

Temperature function	Condition 1	Condition 2
Pile heave (mm)	70	290
Max ground heave (mm)	165	440
Max ice saturation in ground (%)	54.5	66.8
Max axial heave force on pile (kN/m)	125	375

S_{seg} = 2375 kPa

The sensitivity of the interface was assessed, where c=34kPa was decreased to c=1kPa. The results did not indicate any change to the axial forces on the pile or the heave of the pile. Similarly, a sensitivity of the model to Ko value was assessed. Ko=2.5 was increased to Ko=6. No changes to the pile axial forces or heave was noted. The results appear to indicate that the initial conditions or elastic conditions have minimal effect on the heave response of the pile.

As such the selection of c and Ko should not affect the results for the subsequent U-portal analysis. This is of note as no compaction at the interface between the U-portal and the soil is likely to have occurred, as would have around a driven pile where Ko and c values are elevated.

3 SITE B

Site B is located in Toronto as shown in Figure 1 and the soil characteristic in this area was reported in detail by Ma et al (2020). The basic soil characteristics at Site B are summarized in Table 1. It is noted that the till at Site A has similar basic characteristics (i.e. grain size distribution, plasticity limit) to the till layer at Site B.

3.1 U-portal

The calibrated BFUF model presented in Section 2 was subsequently tested to estimate the preliminary response of an LRT underground U-portal structure at Site B. The U-portal modelled has a 4m height cantilever with a 1m thick upstand and base slab. The U-portal was analysed using a plane-strain model and was "wished in place".

The soil stratigraphy is modelled as a single stratum of Glacial Till with a groundwater table of 0.2m below ground surface. Condition 1 temperature function (i.e. -5°C) was applied in the analysis.

3.2 U-portal frost response

The preliminary results indicate that temperature below the base of the portal was maintained above freezing. Most heat loss occur behind the upstand of the portal as shown in Figure 6. Figure 7 suggests ice formation along a horizontal extent within the top 2m of soil behind the U-portal upstand. The development of ice does not appear along the entire back of the U-portal upstand or at the base of the U-portal base slab.

The results indicate that provision of insulation in the horizontal plane behind the U-portal upstand to potentially govern insulation design. The current standard approach to provide insulation along the full depth of the U-portal upstand will need to be further reviewed.

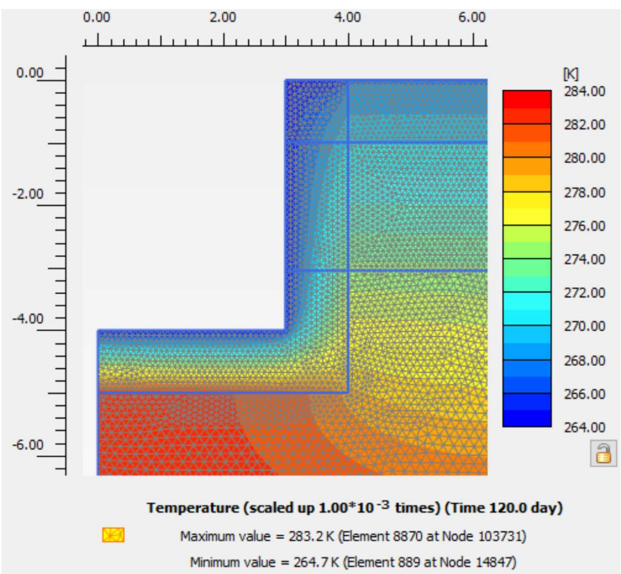

Figure 6. PLAXIS temperature distribution behind the U-portal

The maximum surface heave of the model is 55mm to 60mm. The frost pressure distribution acting on the upstand of the U-portal is shown in Figure 8. The total force acting on the upstand is approximated at 430kN/m.

A comparison of the frost pressure obtained from PLAXIS with empirical method was undertaken and results presented in Table 7. As highlighted by Andersland and Ladanyi (2004), Sui et al. (1993) proposed a simple empirical method for predicting lateral frost forces acting on retaining wall, based on field experience in China and Japan. The frost pressure is predicted using the following relation:

$$p_h = C.M.F.P_{max}$$

Where C = 0.7, F = 1-√S, S = 0 for total restrained wall and 1 for unrestrained wall, p_{max} =100kPa to 150kPa for frost type III where frost heave is between 50mm and 120mm. The empirical method estimated between 235kN/m to 350 kN/m of frost forces, for a frost heave of 50mm to 120mm. Note that these estimates are over a wide range and typically result in uncertainty of the design.

Table 7. Comparison of U-Portal response to frost heave estimated using PLAXIS versus empirical method

Conditions	PLAXIS	Empirical Method
Ground surface heave (mm)	55 to 60	50 to 120
Frost pressure on upstand (kN/m)	430	235 to 350

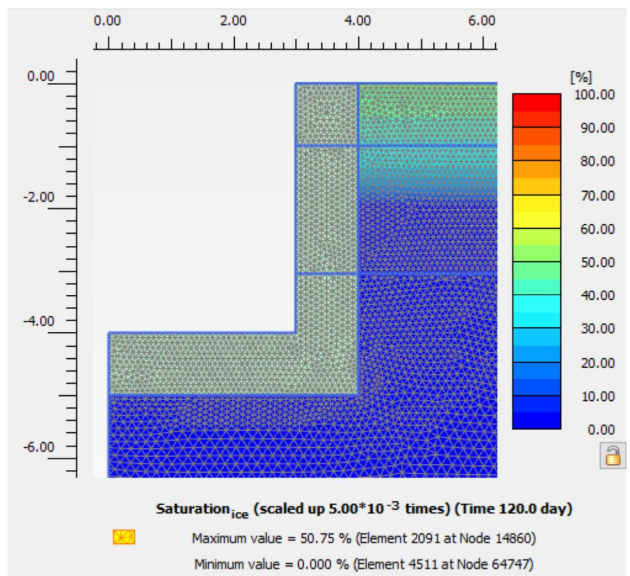

Figure 7. PLAXIS ice development behind the U-portal

Structurally, results indicate that the U-portal upstand could experience an additional 10mm to 15mm of lateral deflection as shown in Figure 9 due to frost. The base slab heave was observed to be negligible at ~5mm as shown in Figure 10.

The estimated shear forces and bending moments on the U-portal due to frost heave is summarized in Table 8. The effect of frost is estimated to result in an increase of 0.45% of steel to concrete section ratio to the U-portal section. Structural design under static condition is typically targeted at approximately 1% steel for U-portal. Note that the U-portal is currently modelled as a linear elastic material with no allowance for cracking. The observed load attraction by the structure is therefore pessimistic.

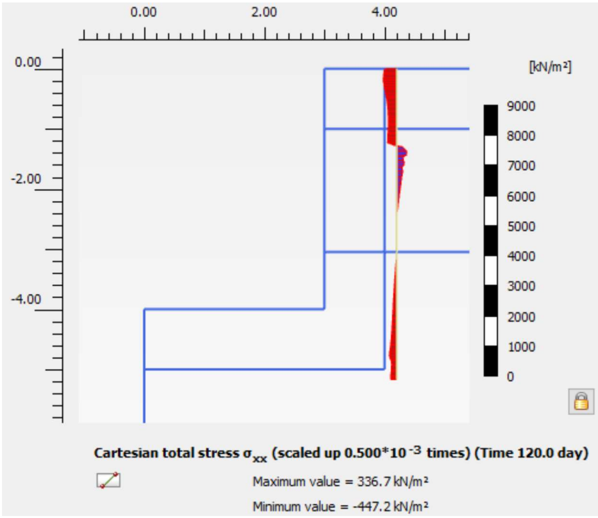

Figure 8. PLAXIS pressure behind U-portal upstand

Table 8. U-Portal structural response to frost heave based on PLAXIS

Conditions	Frost	% Steel
U-Portal upstand lateral deflection (mm)	10 to 15	
Shear force on upstand (kN/m)	395	0.45
Bending moment on upstand (kNm/m)	1095	

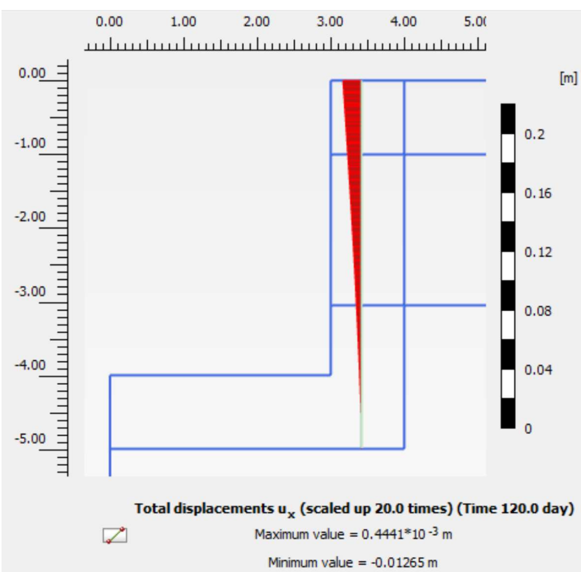

Figure 9. U-Portal upstand lateral deflection

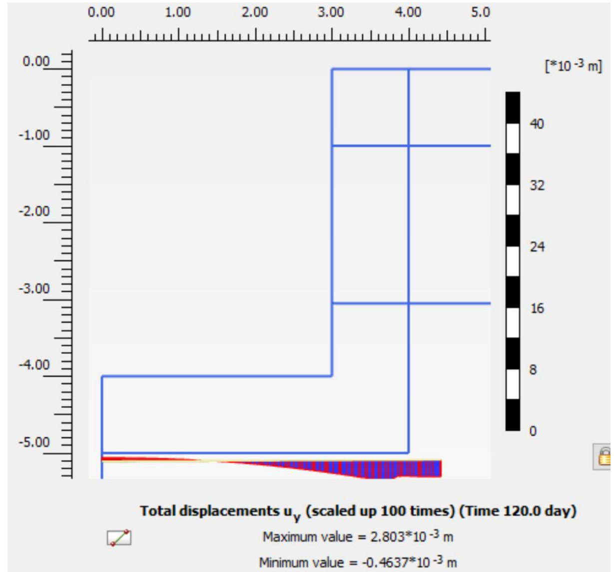

Figure 10. U-Portal base slab heave

4 CONCLUSION AND FURTHER WORKS

The following are a few observations on the implementation of the BFUF model:

- The BFUF model could be implemented by considering only 5 site specific parameters out of the 28 input parameter, where the other 23 input parameters were based on PLAXIS default or recommended values.
- The selection of S_{seg} is important to predict frost heave with confidence.
- Empirical methods for estimating frost forces as demonstrated by Levasseur et al. (2015) and Sui et al. (2003) can provide a wide range of results resulting in uncertainty to the design.
- The BFUF model can provide a narrower estimate of frost forces and heave allowing for more certainty in the design. In addition, estimation of structural deflection due to frost is possible which helps inform the long-term performance of the structure.
- The Temperature Function in the BFUF model is highly sensitive to the selection of Time, ∆Temperature and Time Interval as inputs the analysis. Several iterations by trial and error are often required to allow completion of the PLAXIS run.
- However, computational time is long for the model lasting between one to two days for a simple model.

The following further works are required

- Comparison of the BFUF model predictions with actual site observation to better calibrated the parameters in the model, particularly S_{seg}.
- The effectiveness of concrete U-portal to provide insulation by itself to reduce frost heave.

- Further review of the current approach to providing insulation over the full depth of the U-portal upstand is required.
- More realistic modelling of concrete structure to consider cracked section stiffness to provide a more realistic estimation of frost pressure behind the U-portal upstand.

Preliminary assessments indicate that the use of more complex BFUF constitutive model in standard engineering practice for frost design is possible, even though an extensive calibration of soil model to accurately mimic site-specific heave response is required, it is not impossible. However, the potential cost savings on insulation design and the development of a more robust structure which may be more cost-effective for long-term maintenance may offset the verification process and computation time spent at design stage.

5 REFERENCE

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