

Evaluation of consolidation settlement for highway embankment overlying compressible clay: a comparative study between one-dimensional settlement theory and finite element modeling using modified Cam-Clay model

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1. Introduction

Consolidation settlement is an important component during the design phase of highway embankments overlying soft clay deposits. This process occurs when compressible clay is subjected to external loads, causing excess pore water pressure to dissipate and resulting in downward displacement. Consolidation settlement is time-dependent and often lasting over variable periods of time depending on the permeability of the soil deposit; the more permeable a soil is, the faster the consolidation process will be completed (Samtani et al. 2006.)

Complications arise when foundations undergo excessive downward displacement, which could lead to potential structural damage and deformations along the pavement surface. Such displacements become more consequential when they occur unevenly below the foundation, a process coined differential settlement and is typically caused by variations in material properties, asymmetrical applied loads, or a combination of both. The careful examination of consolidation settlement thus becomes paramount during the design stages of foundations overlying soft ground.

To this effect, one-dimension (1D) consolidation theory is generally used in practice to quantify the consolidation settlement of soft clayey soils subjected to embankment loads. The theory is effective for the assessment of consolidation settlement of clayey soils directly subjected to uniform vertical pressure overlying large areas (Gibbs 1953). Some software models couple one-dimension consolidation theory with the geometric configurations of applied loads to obtain more reliable results. Other software models use modified Cam-Clay theory (Roscoe and Burland 1968) that integrate Finite Element Model (FEM) with 2D/3D analysis to provide an accurate geometric representation of external loads and the underlying subsoils stratigraphy. This method factors in the stress and volume changes during the loading process and allows drainage through vertical and horizontal directions, which can be more consistent with the real process on the ground.

This paper examines the primary consolidation settlement of clay subjected to embankment loads using the following methods: 1) 1D consolidation theory; 2) 1D consolidation theory with 2D geometric effects using the numerical computation software SoilWorks from MIDAS; 3) 2D and 3D finite element calculations using the software GTS NX, also from MIDAS, that incorporate modified Cam-Clay theory. A section of highway 50 in Québec, Canada undergoing widening to separate lanes in opposite directions is used as a case study.

1.1 Case Study: Construction of the north bound lanes of highway 50

The segment of highway 50 under study is a section of about 10 km in length between Findlay and Doherty roads in Quebec. The project will separate the south and north bound lanes by the construction of a new two-lane road in the west direction along the existing road.

The embankment examined in this paper, called Ruisseau Pagé, lends its name to the presence of a creek that cuts below the highway. The Ruisseau Pagé section is roughly 100 m long and is particularly challenging due to the presence of a high existing embankment, constructed in 2003, overlying sensitive and normally consolidated to slightly overconsolidated Champlain sea clay deposit (Leroueil et al. 1983). The heights of the existing embankments are variable with a maximum thickness of about 19 m at the centerline of the current highway. As shown in Figure 1, the new embankment will be constructed mainly along the north slope of the existing embankment.



Figure 1 Top view of the Ruisseau Pagé segment under study (Google Earth, 2020)

It is estimated from Lidar survey and as built construction drawings that since the construction of this highway section in 2003, the Ruisseau Pagé embankment has undergone a maximum settlement of 152 mm at the centerline of the highway. Such displacements have mostly occurred following the end of construction, suggesting the main cause to be consolidation settlement.

The purpose of this study, which is part of a broader design project for Quebec Ministry of Transportation, is to evaluate the anticipated settlements beneath the Ruisseau Pagé embankment following the construction of the new fill of the north bound lands. The evaluation of the anticipated settlements is conducted on both the existing and new highways.

2. 1D Primary consolidation settlement

The 1D primary consolidation settlement theory projects that deformation under an applied load is occurring expressly along the vertical axis (Coduto 2001). The computation of 1D primary consolidation settlement depends on the stress state in the clay deposit, which is computed by dividing the maximum past effective stress p_c over the initial vertical effective stress p_o , yielding the overconsolidation ratio (OCR) (Day 2012). Thus, an $OCR > 1$ defines the clay deposit as overconsolidated, meaning that the maximum past effective pressure exceeds the initial effective stress; $OCR = 1$ defines the clay deposit as normally consolidated, meaning that the maximum past effective pressure is equal to the initial effective stress; and $OCR < 1$ defines the clay deposit as underconsolidated, suggesting that the clay deposit, subjected to an external load, is not fully consolidated and excess pore water pressures are not totally dissipated.

It is recognized that the Champlain sea clay deposit, historically subjected to erosion of glacial sediments, is naturally in an overconsolidated state (Leroueil et al. 1983). Laboratory tests performed on soil samples at the Ruisseau Pagé site in 2001 confirmed the clay to be in an overconsolidated state. In this case, 1D consolidation settlement evaluates settlement for overconsolidated clay using the following relationship (Samtani and Nowatzki 2006):

$$S = \sum_i^n \frac{H_o}{1+e_o} (C_r \log_{10} p_o/p_o + C_c \log_{10} p_f/p_c) \quad [1]$$

where:

H_o = thickness of the clay layer

e_o = initial void ratio

C_r = recompression index

C_c = compression index

p_c = maximum past effective stress

p_o = initial effective vertical stress at the center of layer

Δp = external load at the center of the layer

p_f = final effective vertical stress at the center of layer.

The typical consolidation curve for an overconsolidated clay is shown on Figure 2 below. The initial flat portion of the curve represents change in void ratio due to recompression, when the total vertical effective stress ($p_o + \Delta p$) remains smaller than the preconsolidation pressure p_c . The second curve line represents the change in void ratio when the final vertical effective stress surpasses the maximum past effective stress p_c ; the displacement witnessed in the second portion of the curve is considered consolidation settlement.

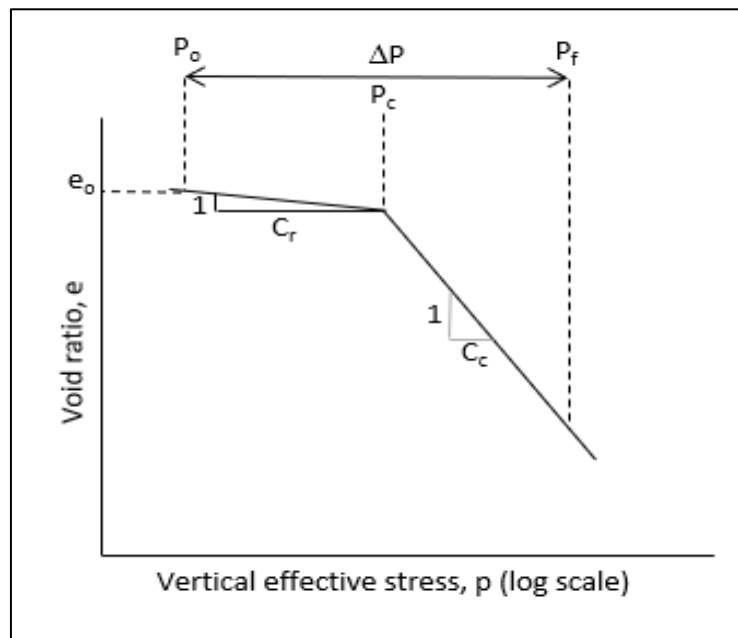


Figure 2 Typical consolidation curve for overconsolidation curve (Samtani and Nowatzki 2006)

2.1 Computation of consolidation settlement since the construction of the existing highway

As mentioned in section 1.1, on-site monitoring revealed that the construction of the existing highway at the Ruisseau Pagé section in 2003 provoked consolidation settlement estimated at 152 mm. However, this estimation was recorded following the construction of the existing embankment, suggesting that settlement caused by recompression, which traditionally occurs during the construction period, was not recorded. Figure 3 shows the configuration of the embankment that was constructed in 2003.

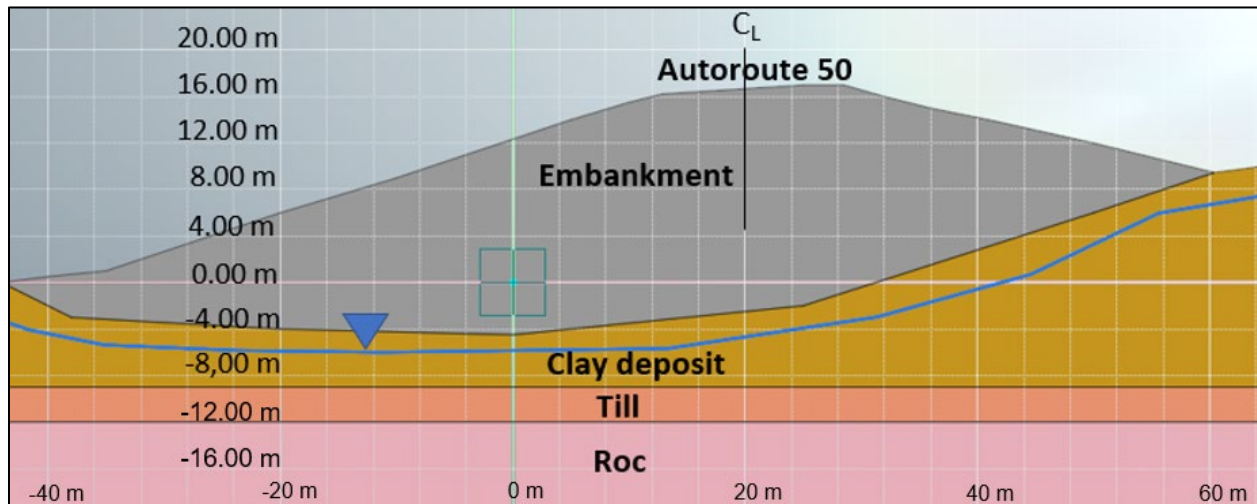


Figure 3 Critical section of the Ruisseau Pagé segment for the construction of the embankment in 2003

The parameters used to calculate the settlement using 1D theory were compiled from clay samples that were tested during the site exploration in 2001. Table 1 presents the thicknesses and parameters for the fill and clay deposit at the centerline of the existing highway.

Table 1 Soil parameters for 1D historical consolidation settlement

Soil	Thickness	Unit weight	e_o	Cc	Cr
	m	kN/m ³			
Fill	18.5	19	-		
Clay	6.4 ¹	17	1.5	1.2	0.02
Till	2.0	21			
Rock	5.0	27			

¹thickness measured at center of the highway

Table 2 indicates the values for the stresses used to compute Eq. 1. These values were taken at midpoint of the clay deposit beneath the centerline of the highway. The water table follows the hydraulic gradient and is estimated at about 4 m to 5 m below ground level at the centerline of the existing highway.

Table 2 Stress values for 1D historical consolidation settlement

Soil	p_o	p_c	OCR	Δp	p_f
	kPa	kPa	-	kPa	kPa
Clay (midpoint)	42	290	6.9	352	394

From Eq. 1, the maximum recompression and consolidation settlements that took place since the construction of the current embankment are 43 and 410 mm, respectively. The results reveal that calculated 1D consolidation settlement is about 260 mm higher than the recorded value of 152 mm.

2.2 Computation of consolidation settlement for the new fill

The computation of consolidation settlement at the centerline of the new fill considers the existing embankment in the computation of the initial vertical effective stress. Figure 4 shows the configuration of the new fill at the critical section.

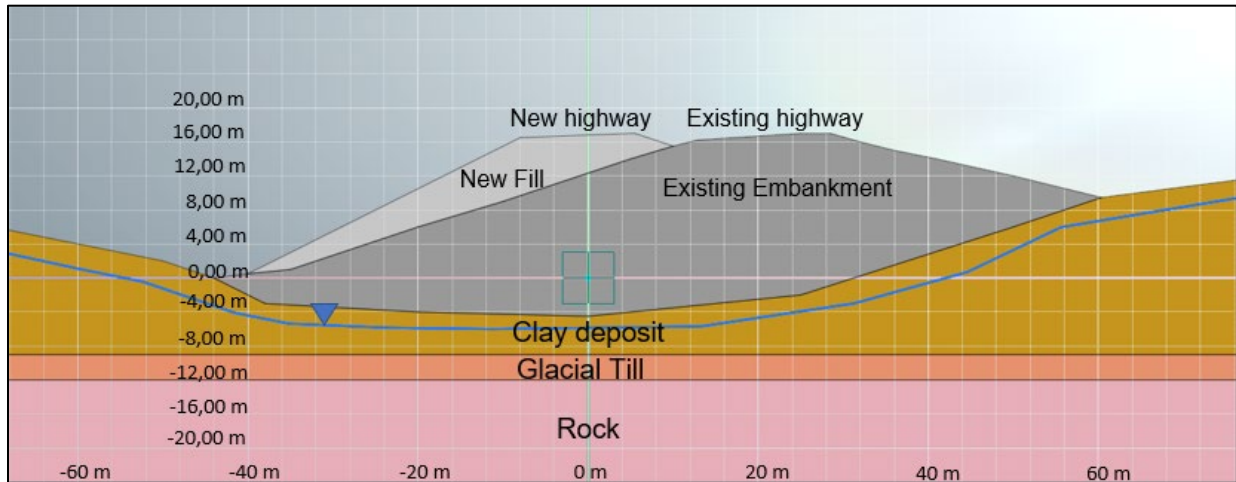


Figure 4 Critical section of the Ruisseau Pagé embankment for the construction of the new fill

Clay samples taken during site exploration in 2019 were tested at site and in the laboratory to evaluate the maximum past effective stress. Table 3 presents the thicknesses and properties for both fills and clay deposit at the centerline of the projected new highway fill.

Table 3 Soil parameters for new highway consolidation settlement calculations

Soil	Thickness	Unit weight	e _o	C _c
	(m)	(kN/m ³)		
Existing Fill	16	19	-	-
New Fill	5	22	-	-
Clay	5	17	1.0-1.2	1.0-1.2

It is estimated from oedometer consolidation tests that the clay deposit below the peak of the embankment is in a normally consolidated state (OCR = 1). This suggests that future settlements will thus fall into consolidation. Equation 2 evaluates consolidation settlement for normally consolidated clay:

$$S = \sum_i^n \frac{H_o}{1+e_o} (C_c \log_{10} p_f/p_o) \quad [2]$$

Where $p_o = p_c$. Table 4 presents the stress values used to compute Eq. 2. These values were taken at midpoint of the clay deposit beneath the centerline of the new fill.

Table 4 Stress values for the computation of future settlements

Soil	p_0	p_c	OCR	Δp	p_r
	kPa	kPa	-	kPa	kPa
Clay (midpoint)	305	305	1	110	430

Thus, the consolidation settlement at the centerline for the critical cross-section of the new highway is estimated to 360 mm.

2.3 1D consolidation settlement using SoilWorks

The 1D consolidation settlement was conducted on the highway using the software program SoilWorks, commercialized by the company MIDAS Engineering Software. The program incorporates the 1D consolidation settlement theory with the geometric configuration of the embankment. The Ruisseau Pagé embankment model was developed using the construction phase modulus implemented in SoilWorks. In total, 5 construction stages were considered:

- 1- Initial in-situ condition, (prior to the construction of the first embankment in 2003)
- 2- Construction of the first embankment
- 3- Settlement period of about 15 years including consolidation
- 4- Construction of the new fill
- 5- Final settlement including consolidation

The soil properties introduced in the soil models are shown in Tables 1 and 2. The elevation of the ground water table was estimated based on piezometers installed in the clay deposit at one to two different depths and in the underlying till deposit.

Figure 5 shows the same critical section on figure 4 but developed in SoilWorks. The software was able to compute the settlement at any given axis, which means that it considered the geometric configurations of external loads while computing 1D settlement. For this study, two axes were selected; axis 0 was set at the centerline of the new highway while axis 20 was set at the centerline of the existing highway.

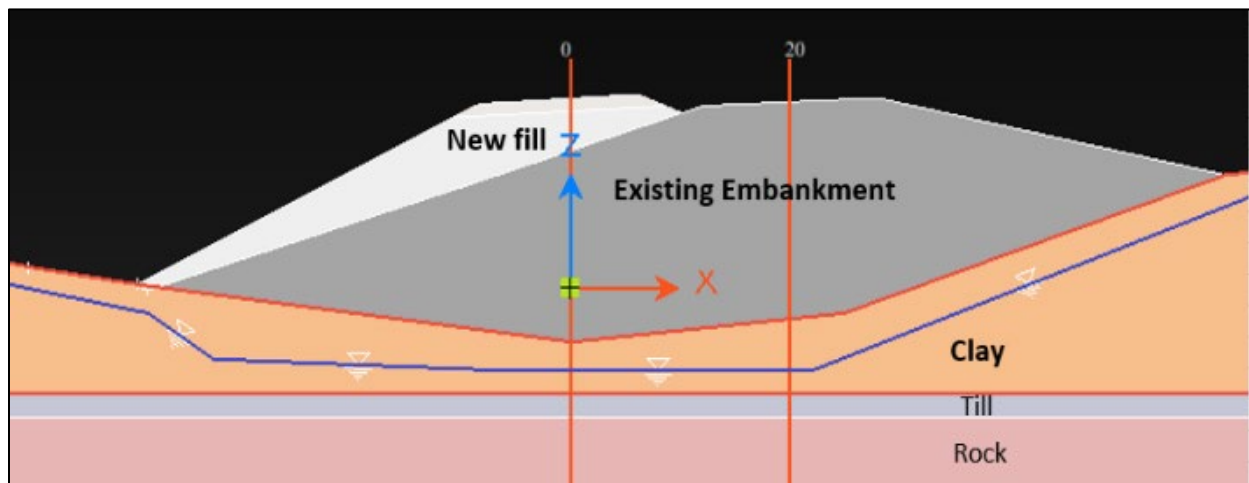


Figure 5 Critical section of the Ruisseau Pagé embankment developed in SoilWorks

The results obtained at axis 20 show that since 2003, the construction of the existing embankment caused recompression and consolidation settlement estimated at 52 and 430 mm, respectively.

At the centerline of the new fill, the settlements will be in the normally consolidated domain and are estimated to 172 mm.

A summary of the results for both 1D consolidation theory and SoilWorks (1D consolidation with 2D geometry) are shown in Table 5.

Table 5 Summary of the results obtained for 1D theory and SoilWorks at the centerline of fills

	Existing Highway (since 2003-2020)		New fill for north bound lane (beginning 2021)	
	1D	SoilWorks	1D	SoilWorks
Recompression	43 mm	29 mm	-	-
Consolidation	459 mm	452 mm	261 mm	212 mm
Historical consolidation settlement	152 mm		-	-

The results show strong parallels regarding the estimation of consolidation settlement following the construction of the highway in 2003; 1D theory displays an estimated consolidation settlement of 459 mm, while 1D with geometric considerations provided by SoilWorks estimated the consolidation settlement at 452 mm, both calculated at the centerline of the existing highway. The conformability in results could be significantly attributed to the relatively wide and thick existing embankment, which reaches a maximum width of 68 m at its base, compared to the overlying clay deposit, which as a thickness of about 6.4 m at the centerline of the highway. In this case, the ratio of the width of the embankment over the thickness of the clay deposit surpasses 10, and thus the geometry plays a negligible effect at the centerline of the embankment. It is important to note that both estimations significantly exaggerate the consolidation settlement reading in the area, which was recorded to 152 mm.

The calculation of future settlements for the new fill reveals disagreements between the two computations. 1D theory estimates consolidation settlement of 261 mm while Soilworks gives consolidation settlement of 212 mm, despite both computations relying on the same theory. Here, the geometry of the new fill and its location above the clay deposit play considerable impact on the results. This is mainly due to the size of the new fill, which is relatively smaller than the existing embankment with a maximum width of 12.5 m at the top of the highway. In this case, 1D theory exaggerates the final effective stress at the centerline of the new highway because it assumes the fill to be infinite in the horizontal x-direction, whereas SoilWorks considers the horizontal geometric effects of the new fill and stress distribution with depth. Thus, it provides a more accurate representation of the final effective stress at midpoint of the clay deposit. In fact, the additional vertical stress ΔP of the new fill at midpoint of the clay deposit was estimated at about 110 kPa¹, while SoilWorks estimates ΔP equal to 83 kPa, which explains the discrepancy in settlement results.

2.4 2D and 3D settlement analysis using modified cam-clay

Modified Cam-Clay theory has been widely used in the field of numerical analysis to assess the consolidation settlement of soft soils. Based strictly on the critical state concept, modified Cam-

¹ This estimate was calculated using $\Delta P = \gamma H$, which in this case is equal to $22 \text{ kN/m}^3 \times 5 \text{ m} = 110 \text{ kN/m}^2$.

clay is well known for its relative simplicity and for capturing the essential features of the anisotropic soil behavior (Ling et al., 2002). The model is very relevant for simulating the behavior of overconsolidated cohesive soils (Ling et al., 2002).

The software program GTS NX, developed and commercialized by MIDAS Engineering Software, provides 2D and 3D finite element modeling (FEM) to compute consolidation settlement using modified Cam-Clay for soft soils.

2.5 2D FEM using modified Cam-Clay

The 2D FEM model was developed for the same critical section that was considered for 1D analysis in SoilWorks. The model parameters are provided in Tables 1 and 2 with slight modifications. The consolidation curve shown in Figure 3 is introduced in the model using the \log function and thus the values for C_c and C_r are converted as follows (GTS NX User Manual):

$$\lambda = \frac{C_c}{2.303} \quad \kappa = \frac{C_r}{2.303} \quad [5]$$

where λ and κ are the representative values for C_c and C_r , respectively. The FEM mesh was then generated for each soil layer. The model was developed using the construction stage method. The same construction stages presented in section 2.3 were used. Figure 6, 7 and 8 illustrate the construction phases developed in the 2D model.

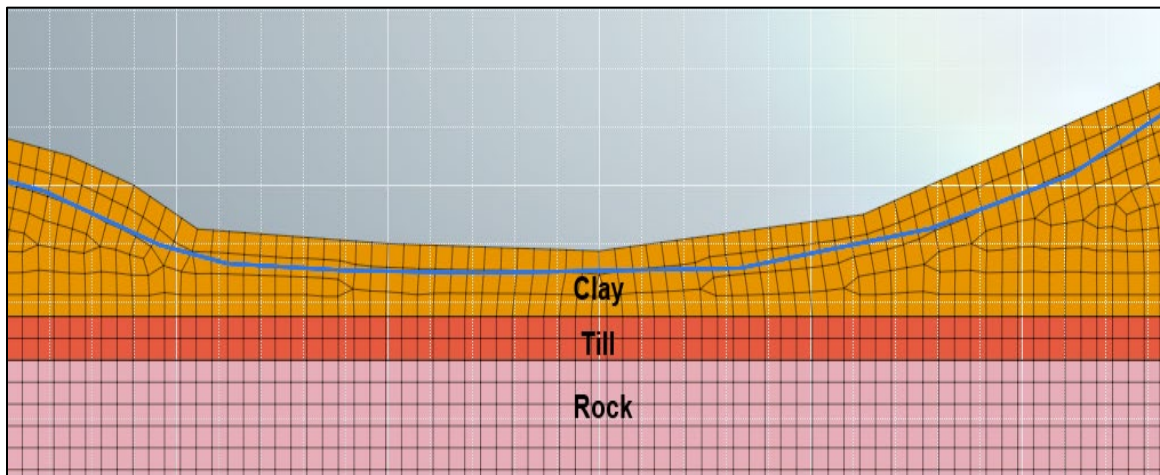


Figure 6 Construction stage 1 of the 2D FEM

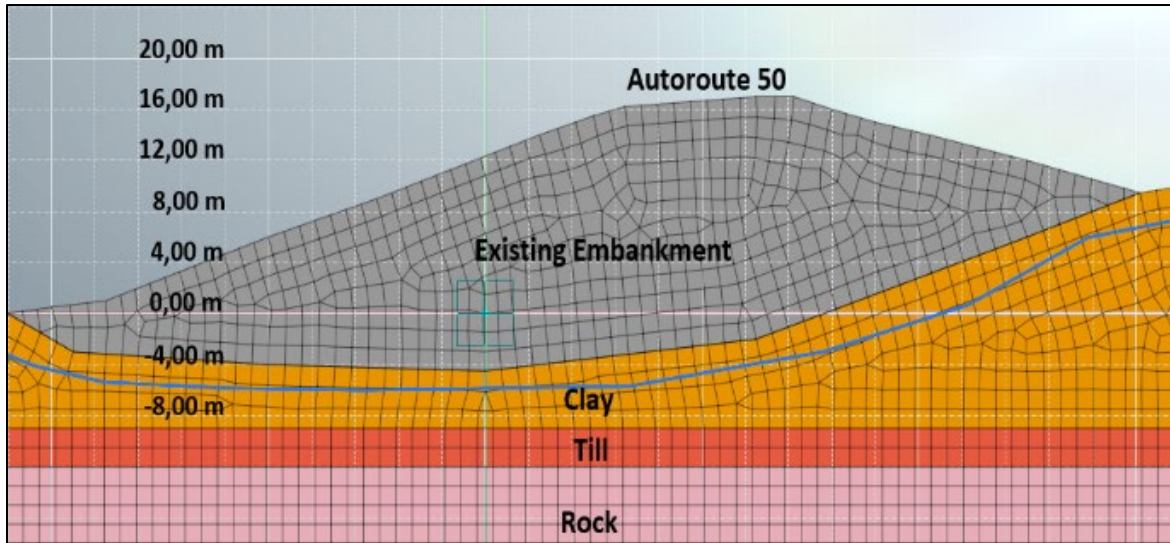


Figure 7 Stages 2 and 3 of the 2D FEM

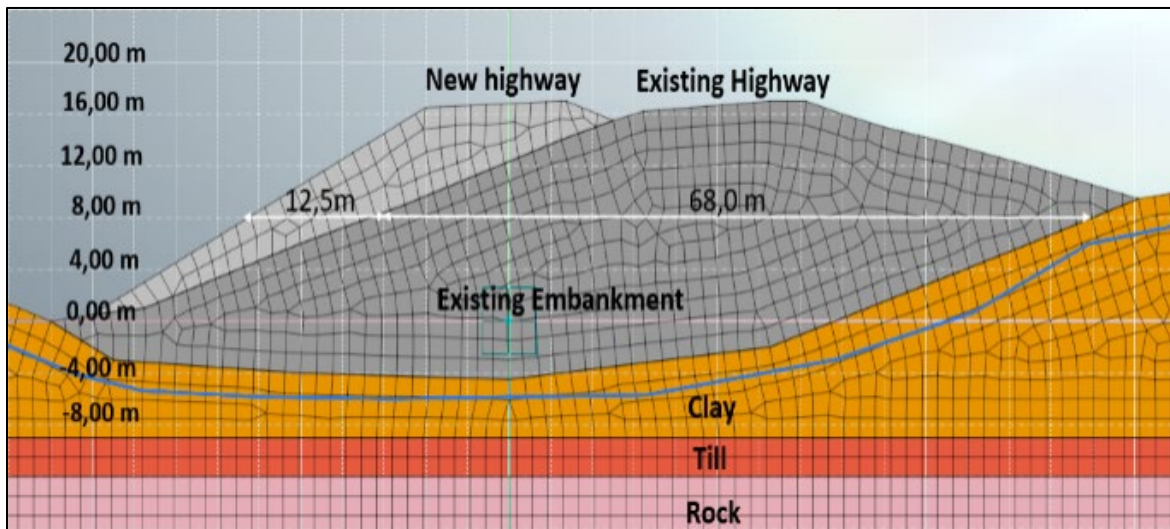


Figure 8 Stages 4 and 5 of the 2D FEM

2.6 2D FEM results

The results from the 2D FEM analysis are presented in Figures 9 and 10. Figure 9 shows the distribution of consolidation settlement starting after the construction of the existing embankment in 2003 until 2020, while Figure 10 shows the anticipated consolidation settlement on both highways after the construction of the new fill. Primary consolidation settlement was completed after less than 10 years.

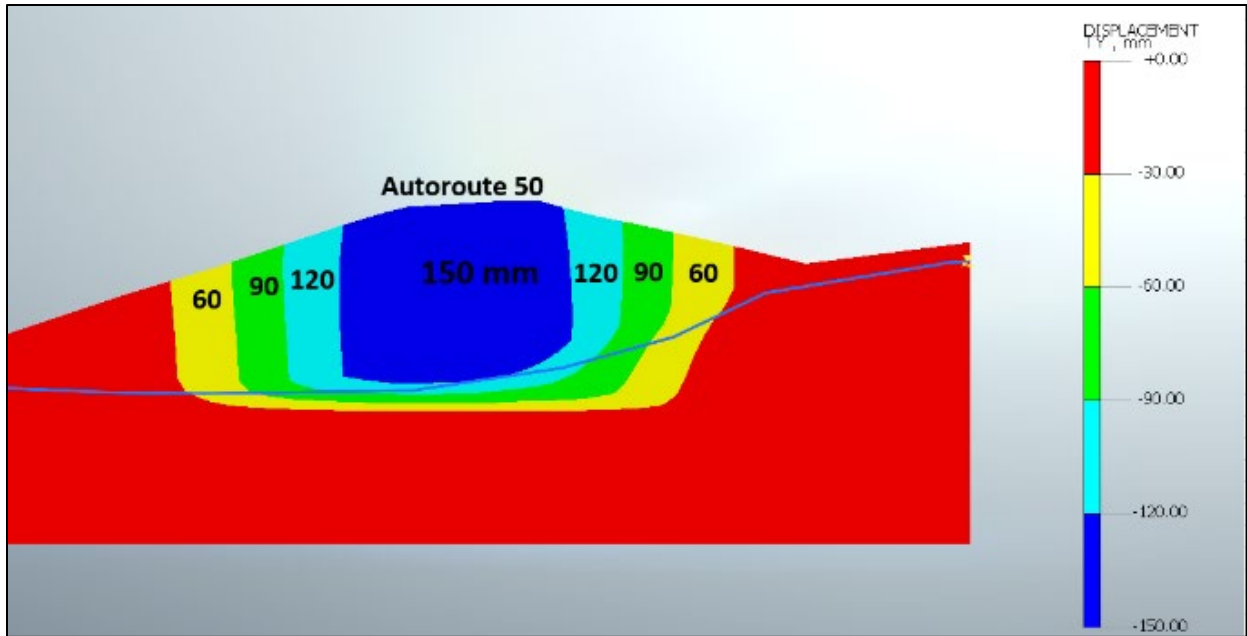


Figure 9 Final consolidation settlement following the construction of existing embankment in 2003

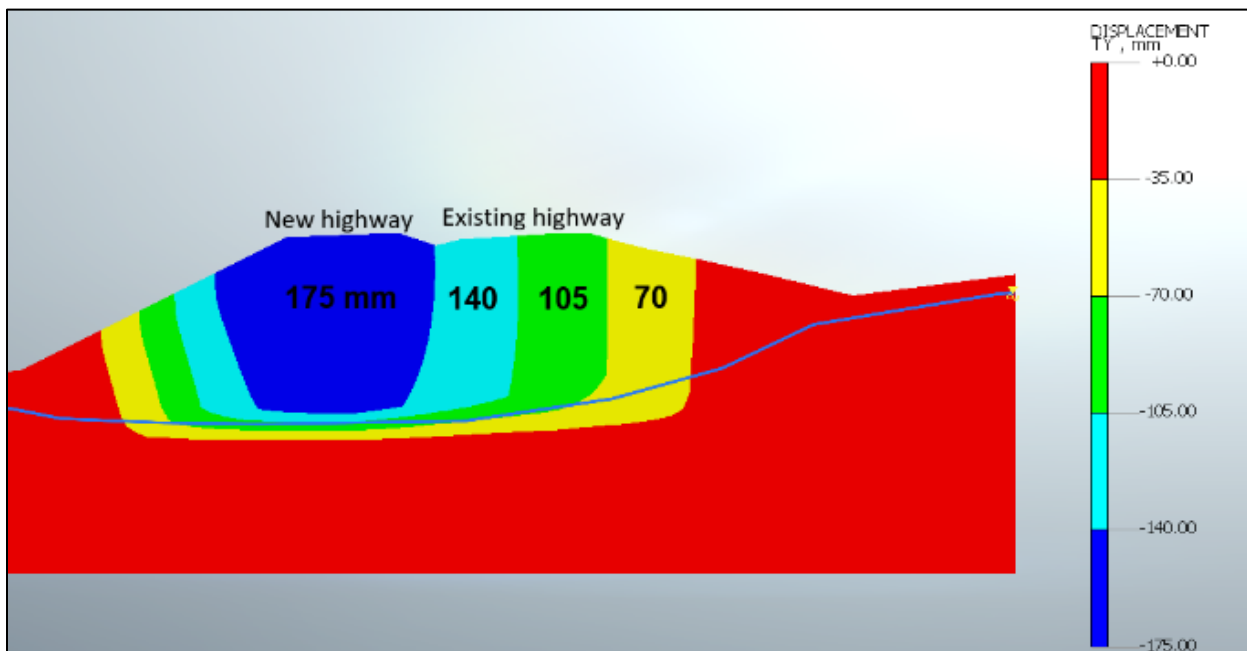


Figure 10 Final anticipated consolidation settlement following the construction of the new fill

The 2D FEM analysis provides settlement at any given axis of the highway, which can be very effective in the assessment of potential differential settlement and impact on adjacent structures. In Figure 10, consolidation settlement for the existing highway will vary between 100 to 140 mm following the construction of the new fill. On the new highway, the consolidation settlements are estimated to vary between 150 and 175 mm

2.7 3D FEM using modified Cam-Clay

The 3D model was built along the entire Ruisseau Pagé embankment. This model provides accurate measurements of the anticipated settlements at different cross-sections of the embankment. Figure 11 shows an overall section view of the 3D FEM model developed for the site.

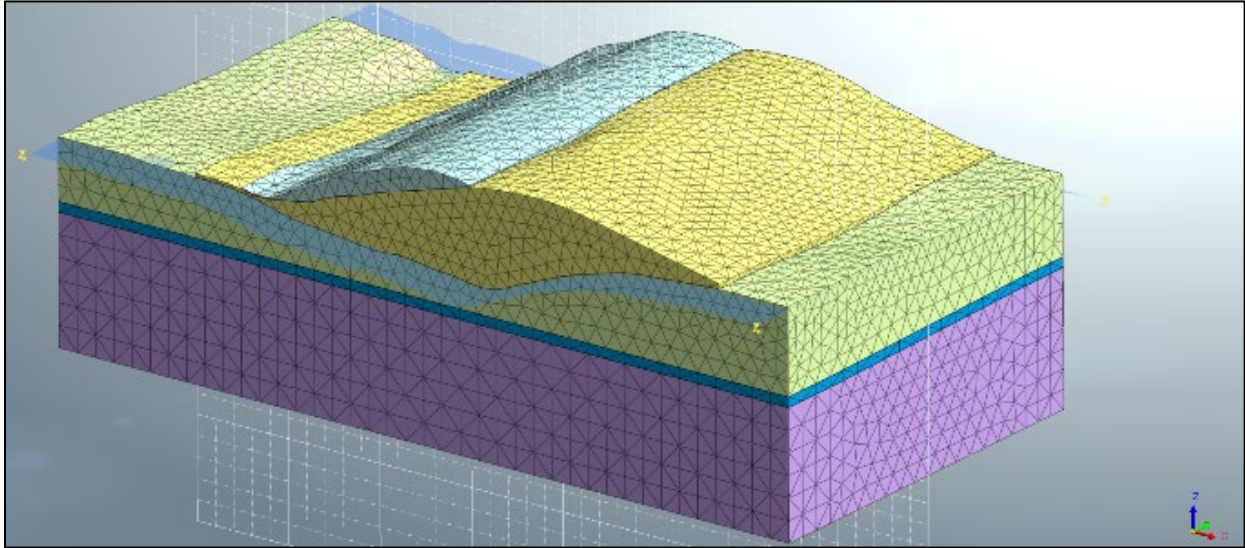


Figure 11 3D section view of the Ruisseau Pagé embankment

The Cam-Clay model parameters are derived from values provided in Tables 1 and 2. Figure 12 shows the final consolidation settlement for the entire Ruisseau Pagé embankment after the construction of the existing embankment in 2003.

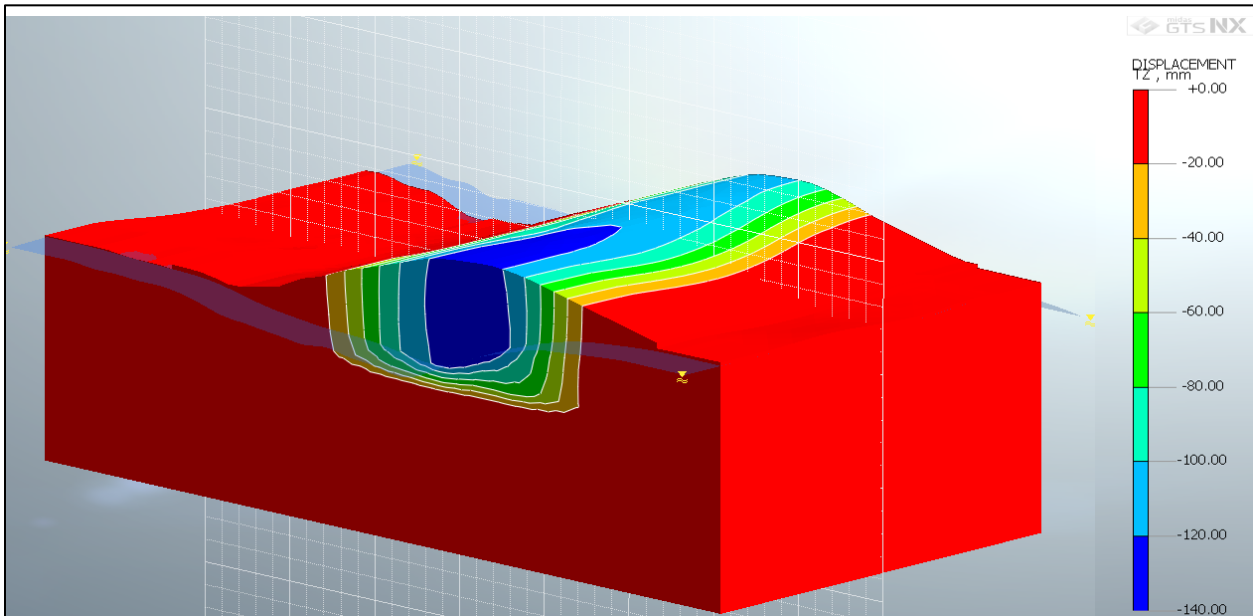


Figure 12 Long term settlement following the construction of the existing embankment in 2003

Consolidation settlement varies between 120 to 140 mm along the centerline of highway 50. Figure 13 reveals the anticipated settlement for both highways following the construction of the new fill. The maximum consolidation settlement of the new highway is about 160 mm. The summary of results is provided in Table 6. The results from 2D and 3D models are similar with respect to historical settlements. For the new fill, the 2D model shows $\pm 10\%$ higher consolidation settlement than the 3D model, that could be attributed to the 2D effect where the critical section is assumed to be infinite along the z-axis, whereas the 3D model accounts for the variation of the embankment and deposit thicknesses along the highway alignment (z-axis in the 3D model).

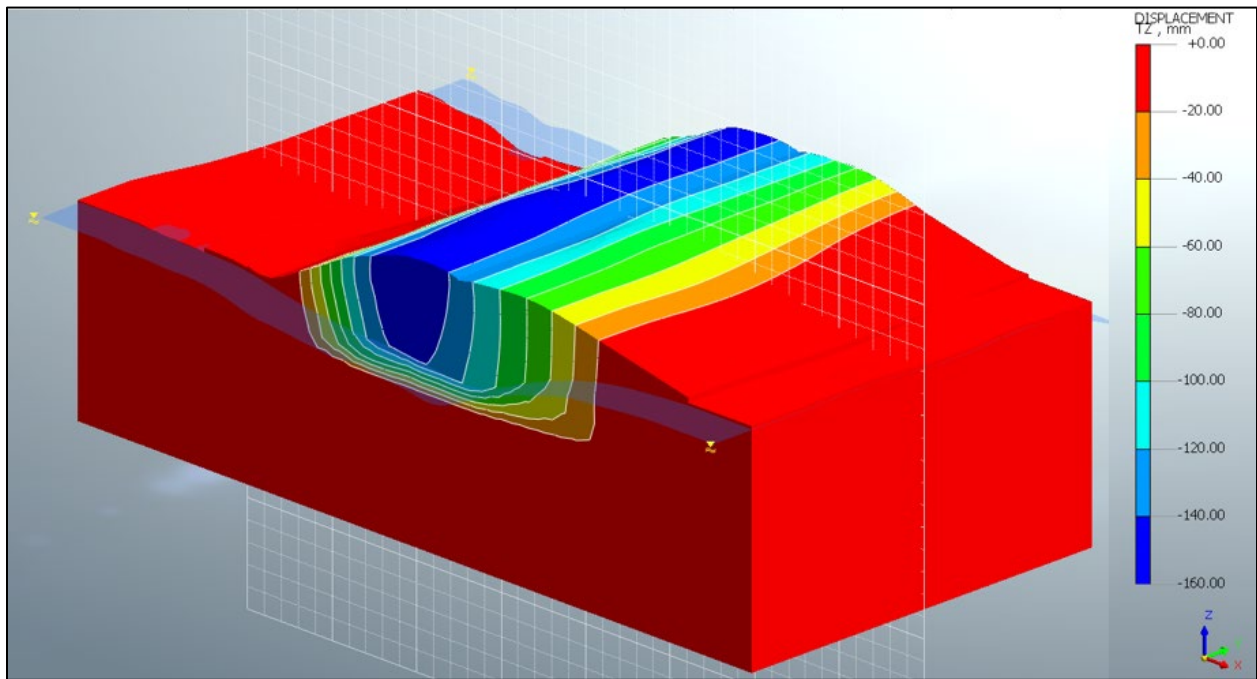


Figure 13 Final primary consolidation settlement following construction of the new fill

Table 6 Summary of the maximum settlements for 2D and 3D FEM using modify Cam-Clay model

	Existing Highway		New fill for north bound lane	
	2D	3D	2D	3D
Recompression	75 mm	85 mm	-	-
Consolidation	130-150 mm	120-140 mm	150-175 mm	120-160 mm
Historical consolidation settlement	152 mm		-	-

¹ Recompression values were taken during construction stage of 30 days

² Consolidation values were taken following construction stage for a period of 15 years.

The disagreement is mostly shown in the period of consolidation; 2D model estimates settlement to be fully mobilized at about 3000 days after construction, whereas 3D model shows that consolidation settlement was halted following a period of 1000 days. This suggests that pore water dissipation patterns could play a significant role in the rate of consolidation. Unfortunately, the variation of water conductivity was kept constant during consolidation, which will mean that the consolidation time could be longer than calculated values.

2.8 Discussion

It is expected that the construction of the new embankment on the side of the existing embankment over normally consolidated clay will cause detrimental long-term settlement to the new and existing highways, based on the results presented in the previous section.

The final vertical stresses due to the new embankment are found to be above the preconsolidation pressure, which results in primary consolidation settlement as calculated, and thereafter in secondary settlement, thus increasing the need for regular pavement maintenance. Such situation should be avoided when feasible.

In some cases, the use of wicker drains with preloading to accelerate the process of consolidation before the construction period can be a viable solution. In this case, such solutions cannot be implemented because of the plausible consequences on the existing highway in service.

An alternative solution is to use within light weight fill for the construction of the new embankment. The geometry of the lightweight fill can be optimized using 2D and 3D modeling to limit the increase of the final vertical stresses below the preconsolidation pressure. In case where the clay deposit is normally consolidated, some part of the existing embankment in this case study will need to be replaced by lightweight fill in order to allow the construction of the pavement structure.

3. Conclusion

This paper discussed primary consolidation settlement for soft clayey soils subjected to highway embankments. A section of the highway under expansion, named the Ruisseau Pagé embankment, was studied. Several methods were developed to compute the primary consolidation settlement, including 1D consolidation theory, 1D consolidation with horizontal geometric considerations, 2D FEM and 3D FEM using modified Cam Clay.

With regards to historical settlements, 2D and 3D FEM models provided comparable results with the established consolidation settlement of 152 mm that was recorded since the construction of the existing highway in 2003. The incremental update of stress and volume reduction of the soil during computation in the numerical modeling using modified Cam-Clay, coupled with accurate representation of the geometry for the applied stress, play an important role in the more precise estimation of primary consolidation settlement than 1D consolidation theory for this case with a complex geometry.

1D theory results suggest that estimations of added vertical pressures ΔP , without consideration to the horizontal and longitudinal stress distribution components, could overestimate the settlements. However, such discrepancies could be settled when the second dimension along the horizontal x-axis is considered. In this case, it seems that with smaller embankments, the horizontal configuration plays a higher factor in the calculation of the vertical stress and thus the results will come closer to the ones computed for 2D and 3D FED models.

4. References

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