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EVALUATION OF CONSOLIDATION SETTLEMENT IN SOFT SOILS UNDER HIGHWAY EMBANKMENT: A COMPARATIVE STUDY BETWEEN ONE-DIMENSIONAL SETTLEMENT THEORY AND FINITE ELEMENT MODELING USING MODIFIED CAM-CLAY MODEL

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ABSTRACT

Assessment of consolidation settlement under a highway embankment requires consideration in terms of variability in fill heights as well as clayey soil thickness and proprieties. Settlement calculation based on one-dimensional consolidation theory often relies on the evaluation of the critical section and assumes the applied load to be infinite in the x and z directions. Advanced solutions based on the modified Cam-Clay theory that evoke 2D and 3D finite element modeling and account for the stress distribution and volume changes during yielding as well as the geometric configurations of the studied area could result in optimized conceptions when light weight fill is required. This paper examines as a case study the consolidation settlement under an existing embankment on highway 50, in Quebec, Canada using 2D and 3D FEM modified Cam-Clay theory, to first validate the models against historical data. Then, the models are applied to design the new embankment of the adjacent north bound lanes where light weight fill will be required. The results obtained from these models are compared with those provided by the 1D consolidation theory.

RÉSUMÉ

L'évaluation des tassements de consolidation sous une autoroute mérite une attention particulière par rapport aux épaisseurs des sols de remblai en place et les couches d'argile variables. Les théories de tassement (1D) se fient généralement sur la coupe jugée critique et des calculs basés sur le principe d'une charge externe dont la configuration est infinie sur les plans x et z. Des méthodes plus récentes basées sur la théorie de Cam-Clay modifiée pour l'argile, qui impliquent une modélisation des éléments finis en 2D et 3D et qui tiennent compte des changements subis aux pressions hydrostatiques durant la période de consolidation peuvent s'avérer plus efficaces. Cet article examine le tassement de consolidation sur une section d'une nouvelle chaussée de l'autoroute 50. Une modélisation d'éléments finis basée sur la théorie Cam-Clay est développée pour évaluer les tassements de consolidation. Les résultats sont comparés avec la théorie de tassement 1D et une discussion comparative est présentée.

1 INTRODUCTION

Consolidation settlement is a primary concern for geotechnical engineers in predicting settlements of soft soils below future embankments. The consolidation occurs when soft clayey soils are subjected to an external load, causing excess pore water pressure to dissipate and resulting in ground settlement. This process is time-dependent and often lasting over long periods due to the low permeability of clayey soils. The more permeable a soil is, the faster the consolidation process will be completed (Samtani et al. 2006).

Complications arise when foundations witness excessive downward displacement, which could lead to structural damage and deformations along highway roads. Such displacements become more consequential when they occur unevenly below the foundation, a process known as differential settlement and mainly caused by variation in subsoils conditions, asymmetrical applied loads, or a combination of both. It is therefore incumbent on geotechnical engineers to carefully assess the settlement of foundations overlying soft soils prior to construction and prevent potential uneven pavement surface and damage.

To this effect, one-dimensional (1D) consolidation theory, which was first proposed by Terzaghi (1925), is traditionally used in practice to quantify the consolidation settlement of soft clayey soils due to a new highway embankment. 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 programs couple one-dimension consolidation theory with the geometric configurations of applied loads to obtain more reliable results.

However, the Terzaghi model is restricted to the one-dimensional problem of a soft deposit undergoing a constant load. The consolidation theory presented by Biot (1941) introduces a three-dimensional extension to consolidation settlement. Finite element software models further incorporate modified Cam-Clay theory (Roscoe and Burland 1968) and proceed with 2D and 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; 3) 2D and 3D finite element calculations 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 is to 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 under study in this paper, called Ruisseau Pagé, lends its name to the presence of a creek that cuts below the highway. The Ruisseau Pagé segment is roughly 100 m long and is particularly challenging due to the presence of high existing embankment 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 Figures 1 and 2, the new embankment will be constructed mainly along the north slope of existing embankment.

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

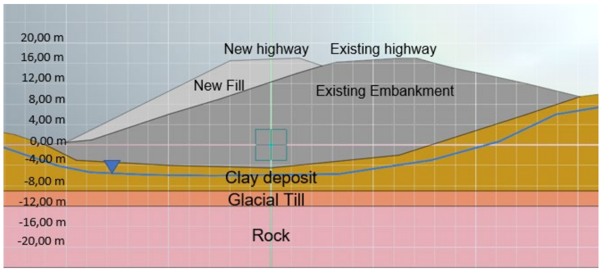

Figure 2. Critical section of the Ruisseau Pagé segment

Figure 2 illustrates the critical section that will be examined for 1D and 2D analyses. This section is selected based on the maximum heights of the existing and new embankments above the top of the natural deposit.

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 downward displacement 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 primary 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 existing highway and new highway.

2 1D PRIMARY CONSOLIDATION SETTLEMENT

The 1D primary consolidation settlement prediction means that deformation under 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 pressure exceeds the initial effective stress; OCR = 1 defines the clay deposit as normally consolidated, meaning that the maximum past 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 conducted on soil samples from boreholes at the Ruisseau Pagé site confirm the clay to be in an overconsolidated state. In this case, Eq. 1 evaluates 1D consolidation settlement for overconsolidated clay (Samtani and Nowatzki 2006):

n

$$S = \sum_{i} \frac{H_o}{1+e_o} \left(C_r \log_{10} p'_c/p'_o + C_c \log_{10} p'_f/p'_c\right) \qquad [1]$$

where:
H_o = thickness of the clay layer at the center of 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 overconsolidated clay is shown on Figure 3.

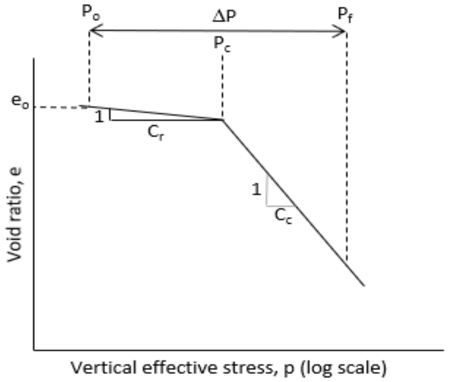

Figure 3. Typical curve for overconsolidated clay (Samtani and Nowatzki 2006).

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 less than the preconsolidation pressure p'_c. Once the total vertical effective stress surpasses p'_c, the displacement falls into the second portion of the curve and becomes subjected to consolidation.

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 embankment 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 4 shows the configuration of the existing embankment that was constructed in 2003. The parameters used to calculate the settlement using 1D theory are compiled from clay samples that were tested during the site exploration and characterization conducted in 2001.Table 1 presents the thicknesses and parameters for the fill and clay deposit at the centerline of the existing 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 below ground level at the centerline of the existing highway.

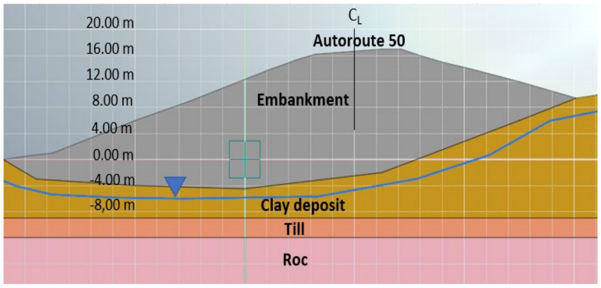

Figure 4. Critical section of the Ruisseau Pagé segment for the construction of the embankment in 2003

Table 1. Soil parameters for 1D historical consolidation settlement

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

[1] thickness measured at center of the highway

Table 2. Stress values for 1D historical consolidation settlement

Soil	p'_0 (kPa)	p'_c (kPa)	OCR	Δp (kPa)	p'_f (kPa)
Clay (midpoint)	42	290	6.9	333	375

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 5 shows the configuration of the new fill at the critical section.

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 new highway fill.

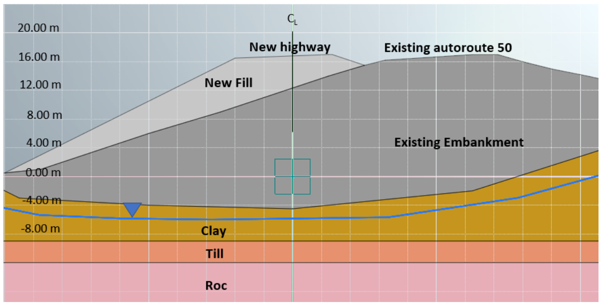

Figure 5. Critical section of the Ruisseau Pagé embankment for the construction of the new fill

Table 3. Soil parameters for new highway consolidation settlement

Soil (Model)	Thickness (m)	Unit weight (kN/m^3)	e_o	Cc	Cr
Old Fill (Elastic)	15	19	0.4	-	-
New Fill (Elastic)	5	22	0.3	-	-
Clay (MCC)	5.3[1]	17	1.2	1.2	0.02
Till (Elastic)	3	22	0.3	-	-
Roc (Elastic)	>12	27	0.2	-	-

[1] thickness measured at center of the highway

It is recorded that the average undrained shear strength s_u that was measured using shear vane tests is equal to 92 kPa.

The preconsolidation pressure can be estimated using the empirical formula that was developed for Champlain sea clay (Leroueil et al. 1983):

$$s_u/p'_c = 0.20 + 0.004\ PI \qquad [2]$$

where PI is the plasticity index, measured at 26. Using Eq. 2, the preconsolidation pressure is 304 kPa. The vertical effective stress was computed using the following relation (West 1995):

$$p'_o = \sum \gamma h - u \qquad [3]$$

where

γ = unit weight of soil

H = thickness of the layer

u = pore water pressure

Using the parameters given in Table 3, the initial vertical stress is approximately about 304 kPa, which is equal to the past effective stress measured from Leroueil's relation. This shows that the margin of consolidation was exhausted following the construction of the existing embankment and the consolidation process that ensued. The stress state of the clay deposit below centerline becomes in a normally consolidated state (OCR = 1) and all future settlements will thus fall into consolidation.

Eq. 4 evaluates consolidation settlement for normally consolidated clay:

$$S = \sum_i \frac{H_o}{1+e_o} (C_c \log_{10} p'_f/p'_0) \qquad [4]$$

Where $p'_0 = p'_c$ in this case. Table 4 presents the stress values used to compute Eq. 3. These values were taken at midpoint of the clay deposit beneath the centerline of the new fill.

Table 4. Stress values for new highway consolidation settlement

Soil	p'_0 (kPa)	p'_c (kPa)	OCR	Δp (kPa)	p'_f (kPa)
Clay (midpoint)	304	304	1	110	414

The consolidation settlement at the centerline for the critical cross-section of the new highway is estimated to 470 mm.

2.3 1D consolidation settlement using SoilWorks

The 1D consolidation settlement was conducted on the highway using the software program SoilWorks, developed by MIDAS Engineering Software. The program incorporates the 1D consolidation settlement theory with the geometric configuration of the embankment. The construction of the embankment was done by stages in undrained conditions. Adding the next stage is applied without allowing the consolidation of the clay deposit due to the previous stage (MIDAS, 2019). Consolidation is then performed after the construction of the whole fill.

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

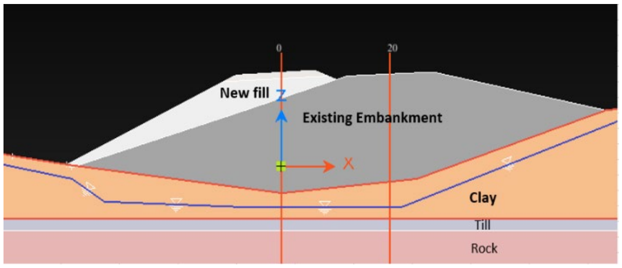

Figure 6. Critical section of the Ruisseau Pagé embankment developed in SoilWorks

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 407 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		New fill for north bound lane	
	1D	SoilWorks	1D	SoilWorks
Recompression	43 mm	52 mm	-	-
Consolidation	410 mm	407 mm	470 mm	172 mm
Total	453 mm	459 mm	470 mm	172 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 410 mm, while 1D with geometric considerations provided by SoilWorks estimated the consolidation settlement at 407 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 underlying 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 470 mm while Soilworks gives consolidation settlement of 172 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 is 110 kPa using Eq. 3, while SoilWorks estimates Δp equal to 83 kPa, which explains the discrepancy in settlement results.

3 2D AND 3D SETTLEMENT ANALYSES 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-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 by MIDAS Engineering Software, provides 2D and 3D finite element modeling (FEM) to compute consolidation settlement using modified Cam-Clay for soft soils.

3.1 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):

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

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 mesh discretization was refined to optimize results and the same construction stages presented in section 2.3 were used. Figure 7, 8 and 9 illustrate the construction phases developed in the 2D model.

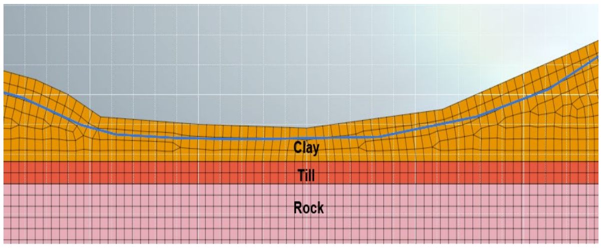

Figure 7. Construction stage 1 of the 2D FEM

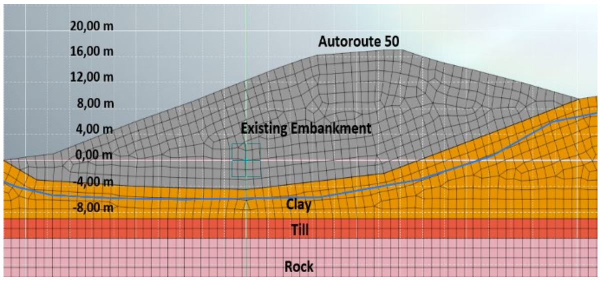

Figure 8. Stages 2 and 3 of the 2D FEM

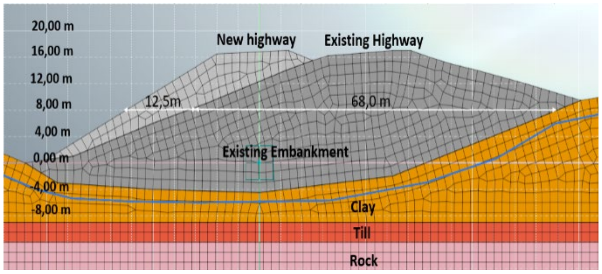

Figure 9. Stages 4 and 5 of the 2D FEM

3.2 2D FEM results

The results from the 2D FEM analysis are presented in Figures 10 and 11. Figure 10 shows the distribution of consolidation settlement starting after the construction of the existing embankment in 2003 until 2018, while Figure 11 shows the anticipated consolidation settlement on both highways after the construction of the new fill. Consolidation settlement where find to be completed after less than 10 years.

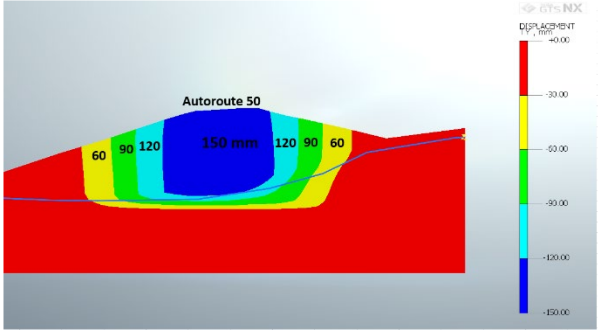

Figure 10. Final consolidation settlement following the construction of existing embankment in 2003

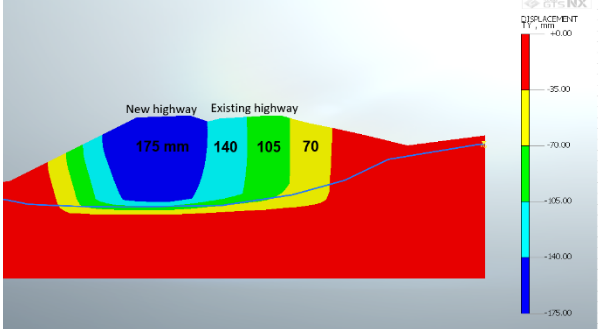

Figure 11. Final anticipated consolidation settlement following the construction of the new fill

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 11, the existing highway is expected to be subjected to settlement that 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.

3.3 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 12 shows an overall view of the 3D FEM model developed for the site.

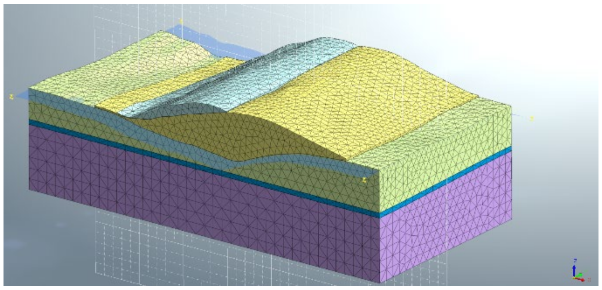

Figure 12. 3D view of the Ruisseau Pagé embankment

The Cam-Clay model parameters are derived for values provided in Tables 1 and 2. The mesh discretization for each soil layer was refined to optimize results. Figure 13 shows the final consolidation settlement for the entire Ruisseau Pagé embankment after the construction of the existing embankment in 2003 until 2018. Consolidation settlement varies between 120 to 140 mm along the centerline of highway 50. Figure 14 reveals the anticipated settlement for both highways following the construction of the new fill.

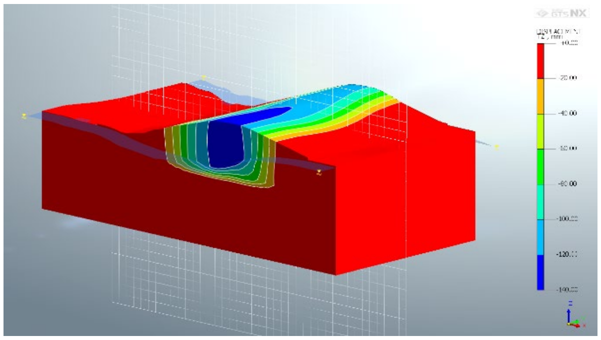

Figure 13. Final consolidation settlement after the construction of the existing embankment in 2003.

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. For the existing highway, the total settlement for 2D and 3D models are 227 and 225 mm, respectively. For the new fill, the 2D model shows 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).

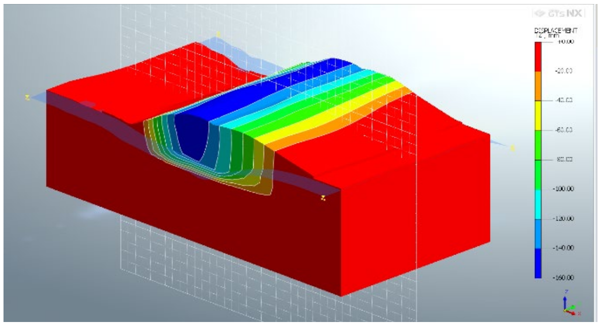

Figure 14. Final primary consolidation settlement following construction of the new fill after 15 years

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	152 mm	140 mm	175 mm	160 mm
Total	227 mm	225 mm	175 mm	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 will be longer than calculated values.

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

An alternative solution is to use within the embankment light weight fill. 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.

4 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 used 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 lead to 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 becomes more consequential in the calculation of the vertical stress and thus the results will come closer to the ones computed for 2D and 3D FEM models.

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