IMPROVING SLOPE STABILITY ANALYSES BY USE OF 3D FEM FOR HIGHWAY EMBANKMENT WITH COMPLEX GEOMETRY OVER CLAYEY SOIL

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ABSTRACT

In Quebec, highways are mostly constructed on clayey deposits. Embankments constructed on such compressible soft soils are further subjected to slope stability issues and require an in-depth understanding of the failure mechanism in order to choose the right analysis method. These embankments are sometimes constructed on highly fluctuated areas where 3D calculations are necessary in order to take the complexity of geometry and subsurface geology under consideration. The aim of this study is to compare the results of 2D and 3D analyses using Midas GTS NX and Soilworks. The construction of a north direction of highway 50 in Gatineau, Quebec, will be used as a case study. A large segment of the new highway will be simulated on the 3D model and compared to the chosen critical sections that were evaluated for the same segment using a 2D analysis.

RÉSUMÉ

Au Québec, les autoroutes sont principalement construites sur des dépôts argileux. Les remblais construits sur de tels sols compressibles sont en outre soumis à des problèmes de stabilité des pentes et nécessitent une compréhension plus approfondie du mécanisme de rupture afin de choisir la bonne méthode d'analyse. Ces remblais sont parfois construits sur des zones comportent une configuration géométrique complexe et un état tridimensionnel où des calculs 3D sont nécessaires pour prendre en compte la complexité de la géométrie et de la géologie souterraine. Le but de cette étude est de comparer les résultats d'analyses 2D et 3D avec Midas GTS NX et Soilworks. La construction de la chaussée nord de l'autoroute 50 à Gatineau Québec servira d'étude de cas. Un grand segment de la nouvelle autoroute sera simulé sur un modèle 3D et comparé aux sections critiques évaluées pour le même segment à l'aide d'une analyse 2D.

1 INTRODUCTION

Slope stability problems have been investigated for decades by researchers and engineers (Leshchinsky and Baker 1986, Azzouz and Baligh 1978, Morgenstern and Price 1965).

Two-dimensional (2D) limit equilibrium techniques are the most commonly used slope stability analyses in engineering, not only because of their simplicity, but due to time effectiveness and wide applicability. These types of analyses are based on the limit equilibrium method (LEM) where the soil mass is divided into slices. The shear and normal forces acting in between inter-slices are governed by the soil model which gives the shear resistance at failure and should satisfy the static equilibrium conditions. This method comes with its limitations such as the critical cross section has to be defined, slip shape is assumed to be circular, and the slope geometry as well as geo-strata and water level are assumed to be unchanged in the 3rd dimension.

Additional assumptions are made on the inter-slice shear force and the shape of the critical slip surface (Krahn 2003, Duncan 1996). Such assumptions have proven 2D analysis to be conservative and underestimate the safety factor (F) of slopes where 3D conditions predominate (Azzouz and Baligh 1978, Ugai 1985). In various researches, authors have found the difference between 2D and 3D safety factors to be greater than 50% (Chaudhary, et al. 2016, Leshchinsky and Baker 1986, Chen and Chameau 1983)

The vast majority of engineering stability problems, exhibit complex 3D geometric configurations. Therefore, assumptions made for 2D cross-sections where the slip surface is considered continuous in the crosswise direction do not hold anymore.

When performing 2D analysis for complex ground geometry, the selection of the most critical or representative cross-section is always challenging and depends on engineering judgment and experience. On the other hand, 3D analysis avoids this difficulty by including the whole geometry of the site.

As such, many different concepts in 3D slope stability analysis have been developed. However, many of them were methods derived from the extension of 2D LEM to 3D LEM. Although these methods take into consideration the 3D geometry, topology and that constitutive material model can statically vary, but still continue to suppose predetermined failure surfaces. Actual researches essentially accentuate on the third dimension and boundary effects in slope stability analysis; however, 3D slope stability problems with complex geometric ground configurations have rarely been investigated (Nian, et al. 2012).

With the advance of computational techniques, solving algorithms and bigger memory capacities in recent years, increasing attention has been paid to assess slope stability problems using 3D finite element methods (FEM). This numerical modeling is based on deformation calculation and requires its own hypotheses, in particular on the model behavior of soils and on boundary conditions (Lane and Griffiths 1997, Duncan 1996).

3D FEM analysis can be very useful in hilly area where the geometry is complex and cannot be represented by a 2D cross section; the slope inclination, material properties, water pore pressure, shear strength as well as the slip surface varies significantly in all directions. Therefore using 3D FEM, it becomes possible to combine all of these effects to find the course of development that leads to a least figure of security (Albataineh 2006).

In the FEM for slope analysis an elastic plastic constitutive law is first considered for the material. The first appearance of plastic zones marks the border of the elastic domain and the initiation of a failure mechanism. The plastic zones then extend and a stage is reached in which plastic deformations are no longer contained. The failure is considered to happen when plastic deformations reach a point where convergence can no longer happen or when deformations reach values deemed inadmissible. The safety factor is calculated by the strength reduction technique described by (Griffiths and Lane 1999), by reducing shear strength of soil in stages until the slope fails.

This paper presents a case study that takes into account the complex geometry of a large embankment on clayey soils, in order to compare 2D LEM, 2D FEM and 3D FEM for slope stability analyses to provide a comparison between the results obtained from each analysis highlights the limitation of each method in engineering practice. For this purpose the software Soilworks and GTS NX developed by Midas Information Technology Co. are used for 2D LEM, 2D FEM and 3D FEM slope analyses, respectively.

2 CASE STUDY

In 2019, the Quebec Ministry of Transport had the will to separate lanes of a 10 km segment of highway 15 in each direction by the construction of the north carriageway in Gatineau, Quebec (Canada). This case study presents an example of the construction of the north-bound lanes planned on an existing embankment which lies over clayey soils. These works will require the extension of the embankment by adding fill material on its north (left) side that could reach a maximum height of 5 to 7 m depending on the location.

As illustrated on Figure 1, the existing land is characterized by the south lanes of highway 15 which is set up on a hilly area. The three-dimensional distribution of groundwater level is highly variable due to site conditions and inflow from the existence of the Pagé Stream. The stream flows through a culvert at the bottom of a depression that had required the installation of a huge embankment with a maximum height of about 18 m.

Figure 1. Existing site conditions (Image from Google Earth, 2020-05-20) (North on the left side).

2.1 Soil Profile and Site Conditions

The soil stratigraphy can be summarized by the presence of clayey fill material with a maximum thickness of around 18 m in the center of the embankment. The observations made in the field, and the results of the geotechnical study carried out on the site highlight the presence of a thick deposit of silty clay under the embankment. The silty clay deposit is present over a thickness of up to 15 to 20 m depending on the location and is generally of medium plasticity (CL) to high (CH), of stiff consistency to very stiff and normally consolidated to slightly overconsolidated. The clay is underplayed by a till layer resting on the rock. The new fill for the north-bound lanes will be built entirely on the existing embankment and could reach a maximum height of 7 m. The physical and mechanical characteristics of each soil layer are summarized in Table 1.

Table 1. Summary of soil properties

Soil Parameters	Granular Fill	Clay Embankment	Road Structure	Silty clay	Till	Rock
Unit Weight (kN/m3)	22.0	18.5	22.0	17.5	23.0	28.0
Angle of Friction (°)	35.0	-	35.0	-	38.0	-
Cohesion (kPa)	0.0	-	0.0	-	0.0	-
Undrained Shea Strength (kPa)	0	100	0	75	0	-
Young Modulus (MPa)	200	50	200	30	500	10000
Poisson Coefficient	0.35	0.40	0.35	0.45	0.35	0.25

For clayey soils only short-term analysis was performed since the undrained conditions are usually more critical for the stability analysis with cohesive soils as the clay gains strength during the dissipation over time of the excess pore pressure after the construction of the new fill over the existing embankment.

2.2 Stability analysis by limit equilibrium method

The first slope stability analysis was performed using limit equilibrium method by the use of Soilworks software which makes it possible to carry out calculations for circular failures. The soil behavior is considered to control by Mohr-Coulomb law, which gives the shear strength failure. In undrained conditions, this resistance is the undrained shear strength.

The Morgenstern-Price method was used to assess the stability of the extended embankment. The presumed geotechnical section of the critical slope is presented in Figure 2.

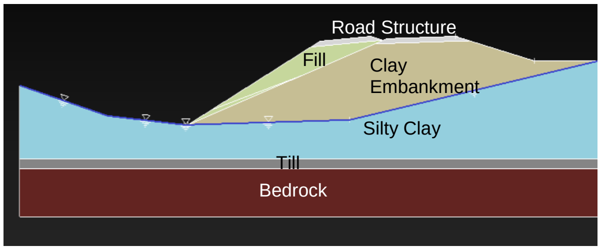

Figure 2. Two-dimensional critical section.

2.3 2D and 3D Slope Stability Analysis by the Finite Element Method

The finite element calculations were performed in 2D and 3D geometries to highlight the difference between the finite element and the limit analysis as well as the effect of the third dimension. For the 2D FEM stability analysis, the assumption of plane strain conditions is adopted.

The surface of the 3D model was replicated from the existing Lidar data of the south bound lanes of highway 50 and the projected profile as well as the expected 2H:1V slopes for the construction of the new north-bound lanes. The stratigraphic layers were linearly interpolated from the boreholes carried out during the site investigations.

The mechanical behavior of materials used for the Finite Element Analyses (FEA) in this study follows a Mohr-Coulomb elastic perfectly plastic (without hardening) constitutive law. It is known that the majority of these clayey soils present a plastic dilatancy significantly lower than the one corresponding to an associated behavior. However, Durville et al. (2003) have found that the dilation angle, which governs plastic deformation, had little influence on the results.

Therefore, for the sake of simplicity, an associated plastic flow rule is considered ($\phi = \psi$). In case of associated plastic flow rule, the stiffness matrix is symmetrical, hence, fast convergence is obtained. The Mohr-Coulomb model requires the determination of two additional empirical parameter values E (Young Modulus) and v (Poisson Coefficient) associated with the strength and type of soils which are estimated in Table 1.

The boundary conditions are the same for 2D and 3D FEA. Displacements are fixed at the base, horizontal displacements fixed on the lateral edges.

For calculation procedures, the first stage consists of applying the weight of each soil layer. To establish the lateral earth pressure, the soil is considered homogeneous and normally consolidated in each layer. Therefore, the lateral earth coefficient K_0 could be reasonably estimated using Jaky's K_0 equation (Jaky 1944).

As illustrated in Figures 3 and 4, triangular and quadrilateral elements were used for 2D mesh, and tetrahedral elements for 3D mesh.

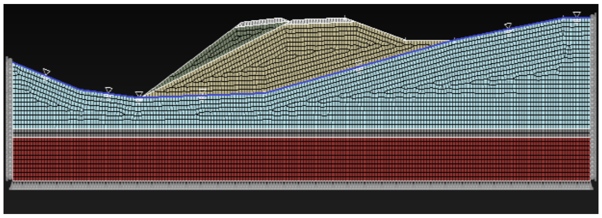

Figure 3. Mesh and Boundary Conditions for 2D FEM using Soilworks.

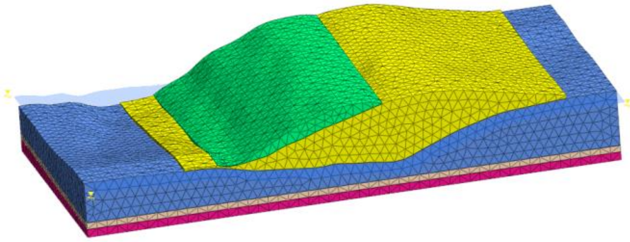

Figure 4. Mesh and Boundary Conditions for 3D FEM using GTS NX.

The stability analysis with the finite elements method allows to calculate a safety coefficient from the reduction of soil shear strength parameters. This is also called the strength reduction method. In this approach, the resistance characteristics ϕ and c of the soil are reduced progressively until failure is obtained (slope instability). The formula for the safety factor is obtained from the strength reduction factor (SRF):

$$F = \frac{\tau}{\tau_f}$$

$$\tau = c + \sigma_n \tan\varphi$$

$$\tau_f = c_f + \sigma_n \tan\varphi_f$$

$$c_f = \frac{c}{SRF}, \varphi_f = \tan^{-1}\left(\frac{\tan\varphi}{SRF}\right)$$

The 2D mesh includes 6220 elements and 7036 nodes (Figure 3). The 3D mesh presents and 69131 elements and 13833 nodes (Figure 4).

3 RESULTS AND DISCUSSIONS

Numerical modeling of the slope stability was carried out using 3 different methods (LEM, 2D FEM and 3D FEM) by Soilworks and GTS NX. The LEM method was applied on a surface judged critical by its geometry and water ground level conditions. A circular failure surface was considered for this analysis using the Morgenstern-Price method, as the new road embankment will be built on clayey soils. The safety factor obtained for this analysis is shown in Table 2 and the failure surface of the analysis is shown in Figure 5.

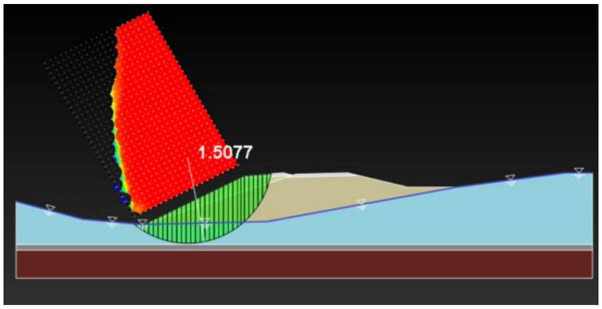

Figure 5. Failure surface obtained from 2D LEM

The second modeling of this numerical study was carried out using a 2D plane deformation FEM. The perfect elastoplastic Mohr-Coulomb model has been used with an associated plastic potential. The factor of safety results as well as the graphic results are respectively shown in Table 2 and Figure 6

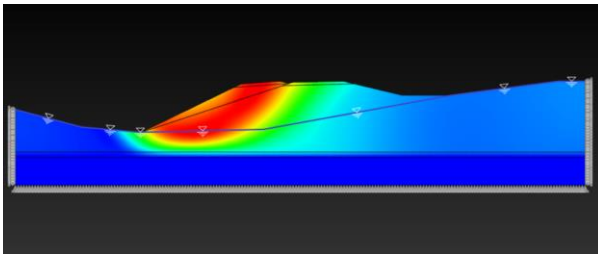

Figure 6. Failure surface obtained from 2D FEM

Table 2. Comparison between the factors of safety

Stability Method	Analysis Method	Factor of Safety
Limit Equilibrium Method (LEM)	2D plane strain	1.51
Finite Element Method (FEM)	2D plane strain	1.49
Finite Element Method (FEM)	Full 3D	2.06

The results of the complementary 3D analysis are respectively shown in Table 2 and Figure 7.

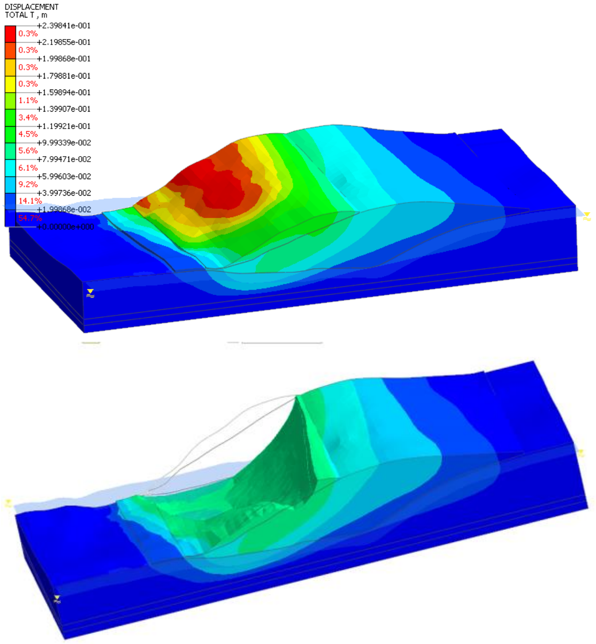

Figure 7. Total displacement obtained from 3D FEM using strength reduction method.

According to the observation of FEM results, plastic deformations are very high at the base of the silty clay layer. This localization of the deformations is quite well superimposed on the critical surface of the calculations made by the LEM. However, in contrast to the results of the LEM, the critical slip surface obtained from FEM analyses is not the form of a perfect circle, as there is no predetermined failure pathways. This not predetermined approach leads the FEM to be more realistic and less conservative, hence providing a factor of safety that is generally higher than those obtained from LEM.

The factor of safety obtained in 3D conditions is higher than the one obtained in 2D. This is generally due to the assumption of a plane strain for 2D analysis which considers the critical surface to remain the same along the third dimension. However in reality as shown in Figure 7, the critical surface takes only a portion of the third dimension. Another reason is that in 2D slope stability analysis, the critical slip surface is chosen from the judgments made on the 3D area. A plane strain slip surface is hence obtained perpendicular to a certain axis. However in reality, due to the presence of a hilly terrain, rugged soil layers and uneven water level conditions are such that the critical slip surface is not perpendicular to a certain axis and obliquely flows in between two axes as shown in Figure 7.

The values of the factor of safety calculated from 2D LEM and 2D FEM are quite similar and higher in 3D FEM which is consistent with the result observed in the literature (Wei, Koutnik and Woodward 2010, Habibnezhad 2014, Cala and Flisiak 2001).
The following equation (Azzouz, Baligh and Ladd 1983) is used here, in order to validate the safety factor of 3D results from 2D FEM:

FS(3D) = FS(2D) x (1 + 0.7 (D / L))

Where, D is the depth of the shear surface and L is the longitudinal length of the failure zone. For this analysis D = 20 m and L = 45 m, Therefore the expected 3D factor of safety is 1.94, which is very close to the value of 2.06 presented in Table 2 for the 3D FEM.

It should be noted that the purpose of this study was not to take into account the influence of the mesh size as long as the latter is reasonable enough to predict realistic results.

For this case study, the 3D FEM approach permitted to validate the conservative approach made in 2D analyses through a practical example and suggests the implementation of 3D analyses to be put more into practice to ensure an appropriate failure surface and FS targeted for complicated ground geometries encountered in real construction conditions.

4 CONCLUSION

The analysis of the stability of the embankment of clayey soils is a complex task since a multitude of interfering aspect, including the uncertainty of geotechnical parameters and finding a critical slip surface to analyze. The sliding mechanism is itself very complex and is only described by the slope stability calculation methods in a simplistic manner.

The case study presented in this paper analyzes the sliding stability of sloping ground of the embankment put on soft clays for the construction of the north-bound lanes of highway 50 at the Pagé Stream located in Gatineau, Quebec, as well as the calculations of the factor of safety by different methods (2D LEM, 2D FEM and 3D FEM) and compares results between these approaches.

Limit equilibrium is the most classical method in soil mechanics which envisages the rupture on a predefined failure zone in a plane strain condition and cannot reproduce the real phenomena. In contrast, in the finite element methods the most probable sliding surface can be deduced naturally from the analysis of the state of stress and deformation, this requires a knowledge on the characteristics of the soil layers in addition to those of their resistance. As for every limit analysis methods, the LEM is very fast in calculations and is commonly used by engineers. On the other hand, FEM takes a longer time in modeling but it avoids analyzing many cross-sections in critical area.

The results were compared, on several slope configurations, with the two different methods. The 2D LEM such as the Morgenstern-Price method which is commonly used in practice gives satisfactory results but fairly conservative and it can be considered very well validated with the 2D FEM. The results presented in the paper confirm that the two approaches - rupture and factors of safety - are perfectly consistent. However, the 3D FEM method gives a more realistic results with a higher factor of safety, meaning that the 2D analyses are too conservative in case of slope stability of highly uneven geometries.

It was shown that the slope stability analyses implemented by Midas Soilworks for LEM and 2D FEM with the so-called strength reduction method give quite similar results and underestimates the factors of safety compared to those calculated by F3D EM incorporated in Midas GTS NX 3D.

This study highlights that the slip surfaces by all three approaches were very similar and comparable, although their principles and their factors of safety are different, and it points out the necessity of using 3D FEM analysis for complex ground geometries.

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