

Three-Dimensional Analysis of the Lodalen Landslide

Gilson Gitirana Jr.¹, Marcos A. Santos², and Murray D. Fredlund³

¹Professor, School of Civil Engineering, Federal University of Goias, Goiania, GO, Brazil;
gilsongj@eec.ufg.br

²Ph.D. student, Dep. of Civil and Environmental Engn., University of Brasilia, Brasilia, DF, Brazil;
marcosaress@gmail.com

³President, SoilVision Systems Ltd., 202-640 Broadway Ave., Saskatoon, SK, Canada S7N 1A9;
murray@soilvision.com

ABSTRACT: A convenient three-dimensional slope stability approach, presented in the accompanying paper, is applied to the analysis of the Lodalen landslide. Simple finite element stress and seepage analyses are employed to compute the three-dimensional factor of safety. The analysis shows that the three-dimensional factor of safety computed for the Lodalen landslide was 1.29 in average. The value obtained is 23% higher than that obtained using two-dimensional solutions. The hypotheses and procedures adopted in the analyses are discussed and the validity of rigorous three-dimensional computations is evaluated.

INTRODUCTION

The Lodalen landslide has been studied and analyzed by numerous authors. The early work by Sevaldson (1956) presents a thorough documentation of the slide. Sevaldson (1956) presented compelling results, indicating the power of the relatively new method of two-dimensional analysis proposed by Bishop (1954). Bishop's method provided factors of safety near 1, which are expected for a failed slope. However, the most significant result was the accurate prediction of the position of the actual slip surface along three chosen cross sections.

More recently, Pham and Fredlund (2004) and El-Ramly et al. (2006) present new analyses, using more elaborate methods of two-dimensional analysis. Pham and Fredlund (2004) have demonstrated that the dynamic programming method of analysis was able to reasonably predict the position of the actual slip surface. El-Ramly et al. (2006) presented a probabilistic analysis which demonstrated the high likelihood of a slide, which ended up occurring.

This paper presents a three-dimensional analysis of the Lodalen slide. The survey information and soil property data provided by Sevaldson (1956) are adopted herein.

The re-analysis is directed towards a better understanding of the advantages and of the method of analysis using three-dimensional procedures. The results of the three dimensional analysis are compared against those obtained using conventional two-dimensional analysis.

DESCRIPTION OF THE LODALEN LANDSLIDE AND THE PREVIOUS ANALYSES FOUND IN THE LITERATURE

According to Sevaldson (1956), the Lodalen slide occurred in the area of a marshalling yard, less than 2 miles east of the Oslo East railway station. The river Lo used to flow through the area of the slide and was conducted through a different path about 30 years prior to the slide.

Figure 1 presents the geometry and water table at cross-section 2, prior to the slide. This section was located approximately at the middle of the slide mass. The geometry of the slopes has been modified and trimmed a number of times prior the final geometry presented in Fig. 1. The final inclination was 1V : 2H. Sevaldson (1956) indicated that the slide was a long-term stability problem, characterized by the reduction in shear strength due to the reduced overburden pressure.

The soil was determined to be sedimentary clay. The slopes were remarkably homogeneous. Numerous borings were done for sampling. Unconfined and triaxial tests were performed for determining the shear strength characteristics of the profile. The position of the water table was also determined.

Using the data collected, Sevaldson (1956) presented a detailed stability analysis of the landslide. Bishop's simplified method of limit equilibrium analysis was used in the original work. The slip surface shape and position was determined by surface inspection and the numerous test borings.

Three cross sections were analyzed by Sevaldson (1956) and the actual and theoretical critical slips surfaces were compared. The pore-water pressures used in the analyses were determined using a phreatic line. The phreatic line was obtained with piezometers. Artesian conditions were also observed. The unsaturated shear strength above the water table was not considered.

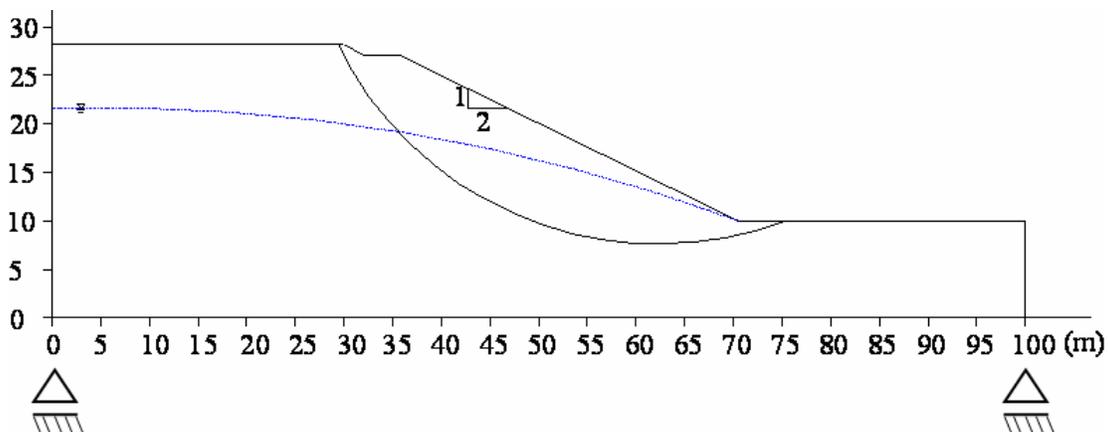


FIG. 1. Lodalen landslide: cross section 2.

The analysis performed by Sevaldson (1956) using Bishop's method provided factors of safety near 1 for the three cross sections analyzed. Sections 1, 2, and 3 resulted in factor of safety of 1.10, 1.00, and 1.19 respectively. The weighted average factor of safety was 1.05. The theoretical critical slip surfaces obtained matched the field data.

The good results obtained by Sevaldson (1956) using two-dimensional analyses could be considered surprising from the point of view of three-dimensional stress states and considering that the actual slip surface shape was not elongated across the slope face. Three-dimensional factors of safety are often 20 to 30% higher than the two-dimensional factors of safety. Moreover, the consideration of the unsaturated shear strength would further increase the theoretical, supposedly more rigorous, factor of safety. In summary, the factor of safety obtained by Sevaldson (1956) should, from that point of view, be considerably lower than 1.

THREE-DIMENSIONAL ANALYSIS OF THE LODALEN LANDSLIDE

The analyses presented herein were performed based on the theory presented in the accompanying paper and using the software SVOOffice 2006 (SoilVision Systems Ltd., 2007). The formulation was programmed using FlexPDE (PDE Solution Inc., 2007), a general purpose partial differential equation solver. Problem setup time was approximately 20 minutes. The computation work usually took less than 7 minutes on a Core 2 Duo processor running at 2 GHz, with 1 Gb of RAM.

The parameters adopted herein for the stress analysis were as follows: a Young Modulus of 1500 kPa; Poisson's ratio varying from 0.1 to 0.49. An arbitrary value of Young modulus was adopted because it does not affect the factor of safety of homogeneous slopes. The shear strength and body load parameters of the problem are the same as those adopted by Sevaldson (1956): total cohesion of 10 kPa; friction angle of 27.1° ; and unit weight of 19.1 kN/m^3 .

Figure 2 presents the problem geometry and mesh. The problem geometry was obtained using the survey data presented by Sevaldson (1956). A grid of elevation points was generated to describe the surface shape.

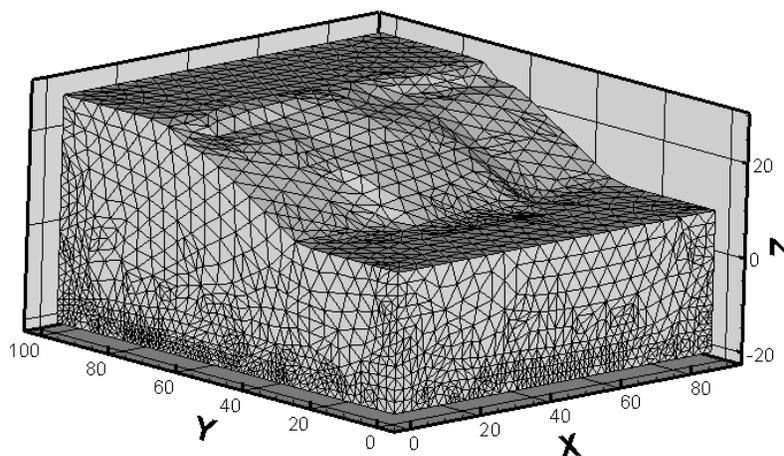


FIG. 1. Lodalen landslide: geometry and mesh.

Figure 3 presents the slip surface adopted herein. The shape of the actual slip surface observed in the field was matched using an ellipsoid. Figure 4 presents the pore-water pressure distribution. The data was generated by means of a steady state seepage analysis. The actual values used in the analysis were multiplied by a factor of 1.339 (El-Ramly et al., 2006), in order to account for artesian conditions observed right after the slide. The effect of negative pore-water pressure to the shear strength was neglected in the analyses presented in this paper.

Table 1 presents the results obtained herein and the original weighted factors of safety obtained by Sevaldson (1956) considering the average value of three cross sections and using three different methods of analysis. Comparing against Bishop’s method, the three-dimensional factors of safety presented herein are 18 to 29% higher than the two-dimensional factors of safety obtained by Sevaldson (1956). Poisson’s ratio had an effect on the factor of safety. Higher values of Poisson ratio result in higher factors of safety.

As discussed above, higher values of factor of safety were expected for the three-dimensional analysis. It is not possible to give a definite explanation, at this point, about why the three-dimensional analysis did not result in a factor of safety near 1. Similarly, the original two-dimensional analysis should provide values lower than 1. Additional studies are being carried out as an attempt to answer these questions.

Table 1. Lodalen landslide: factors of safety obtained by Selvadson (1956) and obtained in this study.

Sevaldson (1956)	Fs 2-D	This study, Fs 3-D				
		$\mu = 0.1$	$\mu = 0.2$	$\mu = 0.3$	$\mu = 0.4$	$\mu = 0.49$
Swedish method	1.010					
Ordinary method	0.850	1.237	1.260	1.289	1.323	1.359
Bishop’s simplified	1.050					

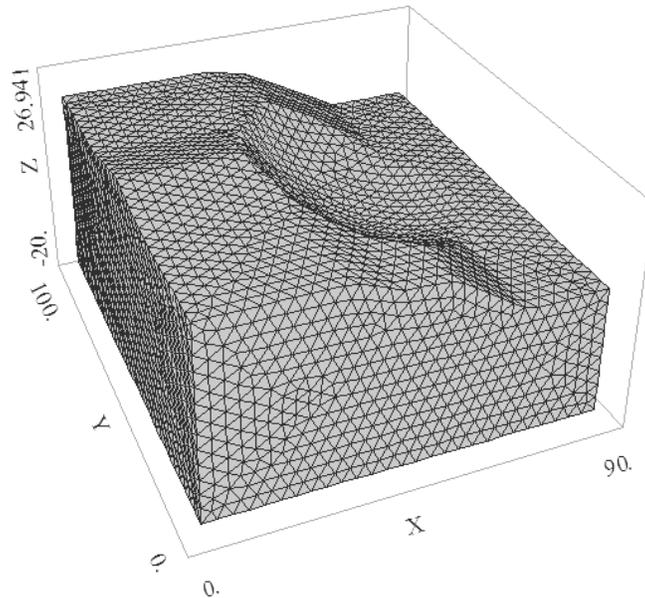


FIG. 3. Lodalen landslide: geometry and slip surface.

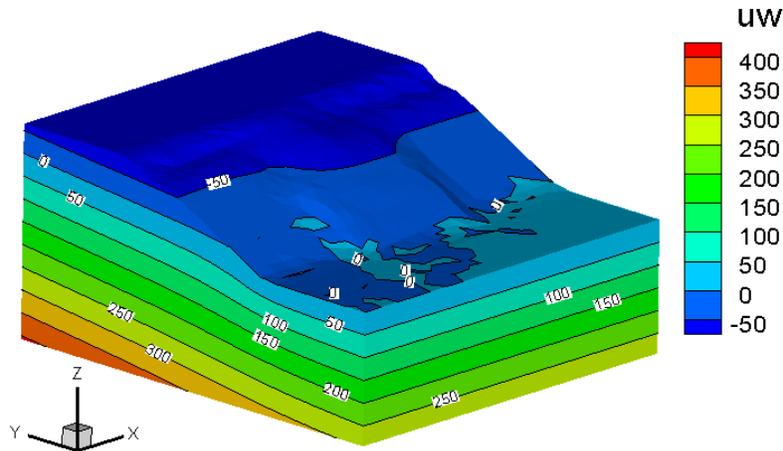


FIG. 4. Lodalen landslide: pore-water pressure distribution.

CONCLUSIONS

The Lodalen landslide was analyzed using the three-dimensional solution. The results were compared to those present but Sevaldson (1956). The three-dimensional factor of safety for the Lodalen landslide was 18-29% higher than that obtained with the two-dimensional solution. The differences observed between the three- and two-dimensional factors of safety are within expected ranges. However, further studies are needed in order to determine why the original two-dimensional analyses did not result in factors of safety lower than one.

ACKNOWLEDGMENTS

The authors would like to thank “Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq, Brasil”, for financial support and Jason Stianson for the discussions and for providing unpublished data from his PhD research.

REFERENCES

- Bishop, A.W. (1954). The use of the slip circle in the stability analysis of slopes. Proc. European Conf. Stab. Earth Slopes, Stockholm, 1:1-13, and *Géotechnique*, V :1 :7.
- El-Ramly, H., Morgenstern, N.R. and Cruden, D.M. (2006). Lodalen slide: a probabilistic assessment. *Can. Geotech. J.* 43:956-968.
- PDE Solutions Inc. (2007). *FlexPDE 5.0 - Reference Manual*, Antioch, CA, USA.
- Pham, H.T.V. and Fredlund, D.G. (2003). The application of dynamic programming to slope stability analysis. *Can. Geotech. J.* 40:830-847.
- Sevaldson, R.A. (1956). The Slide in Lodalen, October 6th, 1954. *Geotechnique*, 6: 167–182.
- SoilVision Systems Ltd. (2007). “SVOOffice 2006 User’s and Theory Guide.” Saskatoon, SK, Canada.