The Use of 3D Models and Analysis In Support of Waste Stockpile Design and Operations

Luciano Piciacchia P.Eng., Ph. D.,
Vahid Marefat P.Eng., Ph. D.
& Jenyfer Mosquera P.Eng.
October 2018

BBA.CA

Disclaimer

This document is provided for informational purposes only. Anyone who uses this document is responsible for determining whether or not it applies to his or her activities. At no time will BBA or the author be held liable for any error or omission that the document may contain or that may result from its use.

The information contained in this document is the proprietary and exclusive property of BBA Inc. except as otherwise indicated. No part of this document may be reproduced, stored, transmitted, or used for design purposes without the prior written consent of BBA Inc.

The information contained in this document is subject to change without notice.

Luciano Piciacchia P.Eng., Ph. D.,
Vahid Marefat P.Eng., Ph. D. & Jenyfer Mosquera P.Eng.

Executive Summary

The complexities of waste rock stockpiles are often underestimated. Slope stability analysis for such earth structures is usually carried out using two-dimensional (2D) slope stability methods. Furthermore the sections used in the analysis are often idealized. Selecting a typical or critical section is left to the designer. Given the number of parameters that can affect stability this approach may not always bring focus to those areas of the waste stock pile which are most critical. As such, three-dimensional (3D) slope stability analysis offers a more complete screening tool which assists the designer in identifying the most critical areas. Mining projects, in which complex co-deposition schemes are employed, using both fine and coarse material, coupled 3D seepage and slope stability analysis can prove useful. This allows modelling the impact of various co-deposition methods on the waste rock pile's hydraulic regime and its effect on stability. Some complex co-deposition configurations modelling cannot be carried out with 2D analysis.

- Note that this white paper was presented at the Tailings and Mine Waste'18 Conference in Colorado State University.

Table of contents

Introduction

Slope stability analyses are typically performed using two dimensional (2D) methods. The 2D analysis assumes an infinitely wide failure surface. As such, the influence of shear resistance and force on the 3rd dimension is negligible compared to the overall driving and resisting forces (Akhtar, 2011). However, most slopes are finite and have 3D geometry. For example, waste rock piles and tailing dams on mine sites generally have definite 3D geometries. Conducting 2D slope stability analysis for such cases is thought to be conservative for engineering applications, because the influence of shear resistance along the 3rd dimension is ignored. For slope design, the conservative result of 2D analysis might be accepted, but for the case of back-calculation analysis of a slope failure, 2D slope analysis can overestimate shear strength by about 30% (Stark and Eid 1998).

Three dimensional slope stability analyses take into account the influence of topography, internal stratigraphy in the 3rd dimension, and groundwater level change within the model. Furthermore, 3D slope stability analysis is an important screening tool to identify the most critical section for further 2D slope stability and seepage analyses.

In common engineering applications, slope stability analysis is mostly conducted by limit equilibrium (LE) method rather than finite element (FE) or finite difference (FD) strength reduction methods. The LE methods are worldwide accepted, easy to handle, require less computational effort and are preferred for routine engineering analyses. On the other hand, LE methods do not take into account constitutive stress-deformation relationships. As such, the stability result provided by LE methods for high risk projects needs to be validated by FE or FD strength reduction procedures (Akhtar, 2011).

This paper puts emphasis on using 3D slope stability and seepage analysis in mine waste applications. The LE method was applied in the 3D slope stability analysis described in this paper. Two general examples were analysed. The first example presents the use of 3D slope stability analysis as a screening tool to identify the critical sections. The second example illustrates the use of 3D seepage analysis to model the groundwater surface for a complex codeposition method where the geometry changes in the 3rd dimension.

Example and applications

3D slope stability analysis of a homogenous stockpile

In 3D slope stability analysis, contrary to 2D analysis, some additional aspects need to be taken into consideration. The most important aspects are slip surface shape, aspect ratio and the slip direction. This example focused on the application of 3D slope stability analysis as a screening tool to identify the critical locations through a stockpile model which is founded partly on competent and partly on clay foundation.

To create a 3D geometry of the stockpile, AutoCAD DXF files of the original topography, various internal strata and stockpile contours were used. Figure 1 shows the geometry of the model. In this example, where the foundation is clay, the failure can occur either in the foundation or within the deposited material itself.

The stockpile has a variable height ranging between 90 m and 70 m on the left and right sides, respectively. The waste rock pile's slope angle is variable. The waste rock pile contains 4 benches on the left and 3 benches on the right sides (Figure 1). The two first benches are steeper than the others. In general, there is a slope angle of about 29 degrees. The waste rock is deposited on a clay foundation on the right side. However, its foundation on the left side is competent bedrock.

The pile contains waste rock material with an angle of internal friction of 38 degrees. The material is considered self-draining. Therefore, the slope stability analysis was conducted under dry condition. The groundwater is within the foundation with no water within the waste rock pile. The material strength type was characterized as Mohr-Coulomb for the waste rock and depth depended undrained shear strength for the clay layer. The bedrock was assumed to comprise a competent foundation. Table 1 summarises the material properties and strength type used in this simulation.

The stockpiles are commonly constructed by end or push dumping method. The failure can occur in the foundation soil or within the deposited material itself. For a stockpile comprising a material with an angle of internal friction of 38 and benches with a height of less than 55 meters (m) a minimum local factor of safety of 1.2 is expected (Piciacchia et al., 2018). This example focuses only on the global slope stability based on the requirement of attaining a factor of safety (FS) = 1.5. Global stability here is defined as a failure surface that extended into more than one bench.

As shown in Figure 1, the left side of the stockpile has a higher exposed slope than the right side. On the other hand, the right side has a weaker foundation condition with a varying thickness of clay. In the absence of a 3D analysis it is left to the user to choose the most critical cross section for the 2D slope stability analysis. At first glance, the user might focus on that portion of stockpile with the weaker clay foundation. If so, where within the waste rock pile is the critical section? Where the clay is thickest or where the pile is highest? Conducting a 3D slope stability analysis screens the critical sections and helps users to analyse a problem with a comprehensive understanding of a location and mechanism of the failure. For the geometry illustrated in Figure 1, the 3D slope stability analysis focused only on the front exposed face.

Table 1: Material properties used for 3D slope stability analysis in this paper.

Material	Strength characterization	γ (kN/m^3)	Ø (degree)	Min shear strength (kPa)	Undrained strength ratio
Waste Rock	Mohr Coulomb	19	38	NA	NA
Clay	Undrained strength ratio	17.5	0	40	0.23
Bedrock	NA	NA	NA	NA	NA

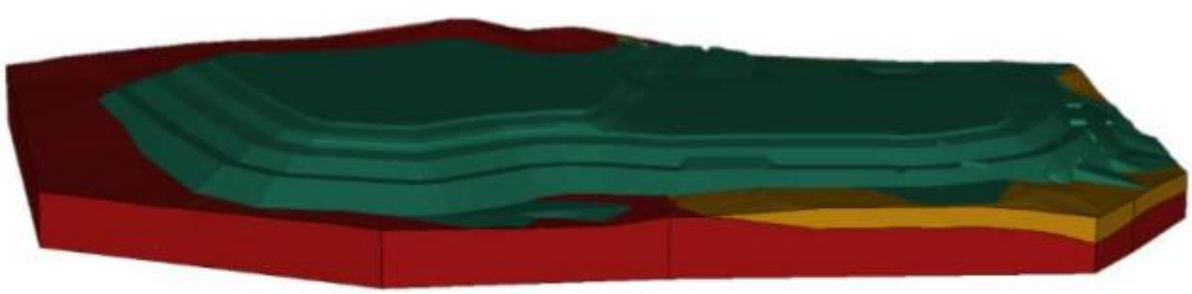

Figure 1: geometry for the 3D slope stability model.

The 3D slope stability model was performed based on the following criteria:

- Slip surface shape: ellipsoid;
- Ellipsoid aspect ratio: between 0.7 and 3.0;

- Slip Surface search method: Slope search;
- Number of surfaces: 20000;
- Direction of the slip: perpendicular to the principal axis.

Figure 2 presents the result of the 3D slope stability analysis.

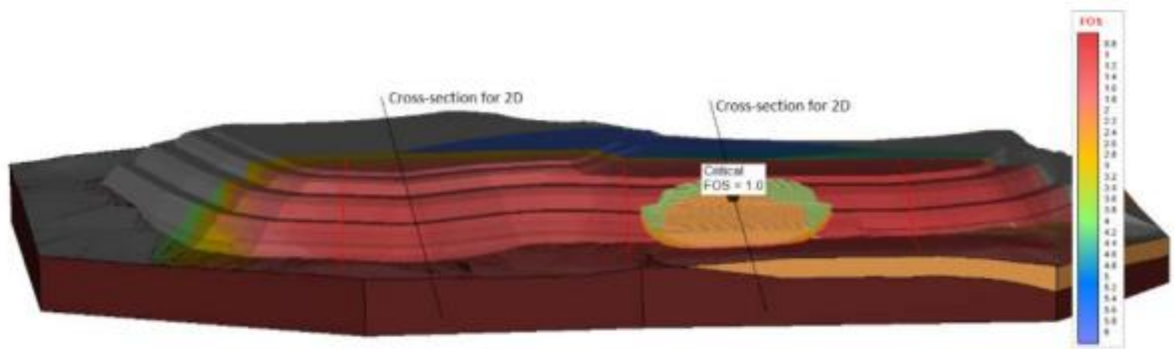

Figure 2: 3D slope stability result.

As expected the critical section passes through the clay foundation on the right side of the stockpile. However, this does not occur where the clay is thickest, rather where the pile is the highest and the clay is closer to the surface. However, on the left side of the stockpile, there are some locations that are critical as well (having a factor of safety less than 1.5), as shown by the isocontours for factor of safety (Figure 2). Based on the 3D analysis, two critical sections were selected for detailed evaluation. Figure 3 presents the results of 2D analysis.

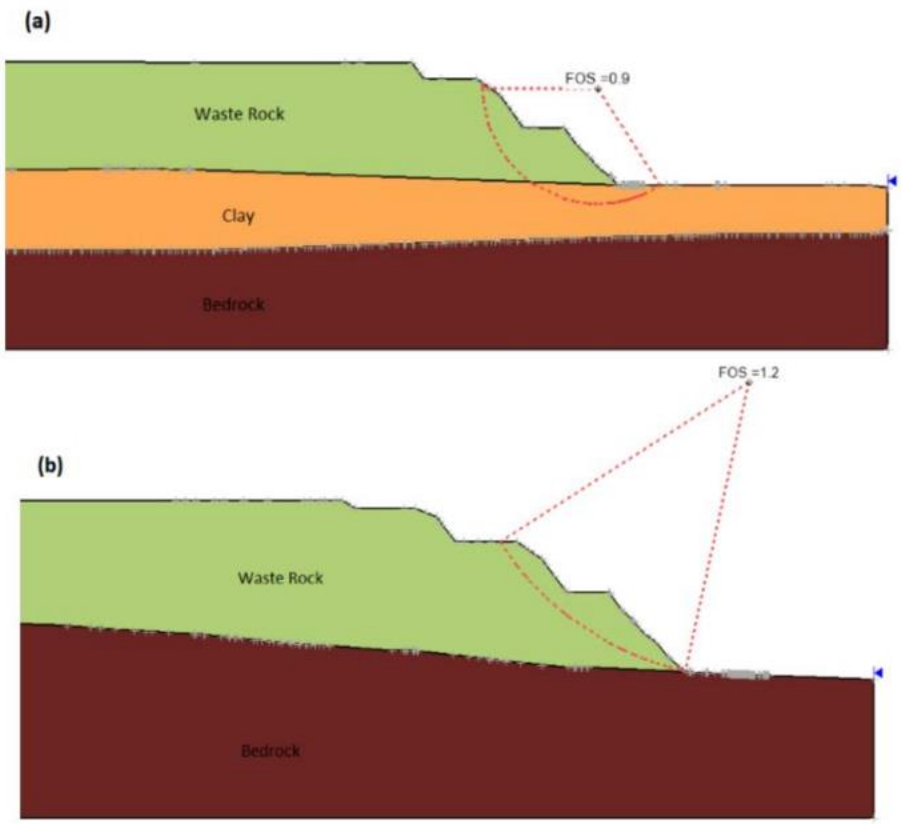

Figure 3: 2D slope stability analysis: a) right side with clay foundation and b) left side with rock foundation.

The 2D slope stability analysis confirms the results of 3D analysis. The right side where the stockpile is constructed on the clay foundation is the most critical. The 2D slope stability analysis resulted in a lower FS value than 3D analysis showing that the 2D analysis is more conservative. This is consistent with previous findings (Akhtar, 2011; Chaudhary et al., 2016). The lower calculated factor of safety for the 2D analysis is due to the geometry aspect of the slope in the 3rd dimension. Therefore, the 3D factor of safety is slightly higher. The 2D section presented in Figure 3b exhibits that the setback distance for the second bench is not properly designed. The stockpile's global slope for the 2 first benches is about 7 degrees steeper than the pile's global slope. This resulted in a global FS of less than 1.5.

3D seepage analysis for a co-deposition method

The waste materials produced from mining activities can have a vast grainsize distribution and angle of internal friction. These materials should be separated and deposited with a proper strategy. There are several methods that are commonly followed by mining companies: a) fine and coarse materials are mixed and deposited together; b) fine materials are deposited in successive layers in front of previously deposited coarse materials; and c) fine and coarse material are separated and the fine materials are deposited as a single stockpile. In the case of mixing fine and coarse materials, the waste rock pile stability can be affected by a possible rise in the phreatic surface. Mixing of fine and coarse materials decrease the local and global hydraulic conductivity of the pile and can potentially increase pore water pressure within the waste rock pile. If fine material is deposited in successive layers in front of previously deposited coarse material, a failure of this new layer of fine material could occur. The fine material blocks the drainage of the waste rock pile, which results in a pure water pressure build up and failure of the pile. For these reasons, it is strongly recommended that fine and coarse materials be managed separately where possible.

The management of fine materials can be conducted by various means: as a single pile or codeposition of fine and coarse materials. Managing the fine material as a single pile may create drainage problems, safety issues and depending on haulage distances may be cost intensive. A proper co-deposition method help resolve some of these issues. The evaluation of particular codeposition scheme must first consider the effect that the deposition plan will have on the phreatic surface within the combined waste rock stockpile. In this example, a co-deposition method in which the fine materials are deposited in separate layers within the body of a coarse stockpile is presented. In this example the focus is on the 3D seepage analysis for the proposed codeposition method, which could not be modelled in 2D due to the fact that fine material is not continuous parallel to the pile crest, as shown in the cross-sections of Figure 4. If 2D modelling of this configuration was attempted, it would lightly result in perched water conditions above and within the fine grained material. Figure 4 presents a plan view and cross sections for the proposed co-deposition method.

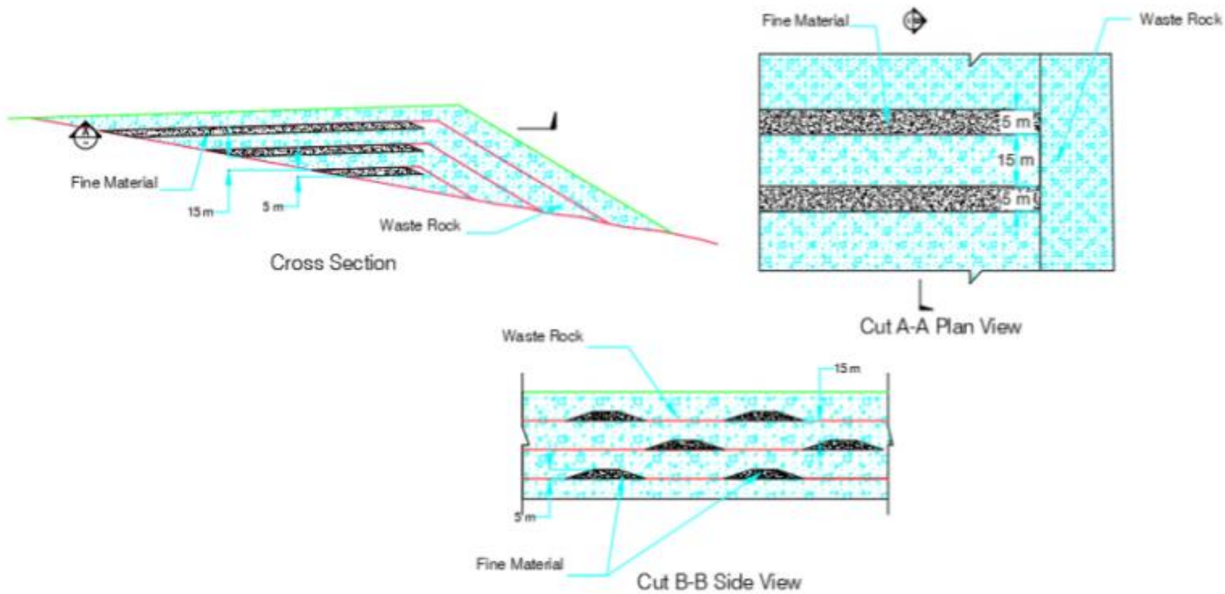

Figure 4: Cross-section, plan and side view for the proposed co-deposition method.

To investigate the impact of fine material on the pore water pressure condition in the proposed co-deposition method, an idealized 3D seepage model was performed. The model was constructed based on the geometries presented in Figure 4. The dimensions presented in Figure 4 are not the optimised dimensions and are used only for the purpose of seepage analysis in this example. The model length and width were 600 m and 200 m respectively. The pile was constructed on a ground with a natural slope of about 8 degrees. The foundation material is saturated silt material with a hydraulic conductivity on the order of 1×10-7 m/s. The construction comprised 4 lifts with heights of 20 m. The fine material was placed with a setback of 30 m from the slope crest. The fine material had a width of 5 m and placed at 15 m intervals from the crest setback. The length of the fine material was variable from each lift, depending on the original ground slope. The percentage of fine to coarse material for this model was about 5%.

The fine and coarse material are initially considered as unsaturated materials in the seepage analysis. Hydro-geotechnical characterization of waste material plays a crucial role in the longand short-term stability of the waste rock piles. One of the most important hydrogeotechnical parameters of waste material is the water retention capacity, which is associated with the material grain size distribution and in-situ condition. Coarse waste materials are usually considered as a self-draining. However, fine waste material has a high capacity to retain water. As such, this type of material is able to quickly build up pore pressure (e.g. during a high intense precipitation event), which may endanger the stockpile's stability.

The unsaturated properties of material are presented in water retention curve (volumetric water content versus matric suction). There are theoretical methods to estimate the unsaturated hydraulic conductivity of materials based on the water retention capacity of the material. This example used modified Campbell method to estimate the unsaturated hydraulic conductivity of the fine and coarse material. Figure 5 presents the water retention curve for the fine and coarse material used in this analysis. These properties were taken from the literature (e.g., SoilVision data base).

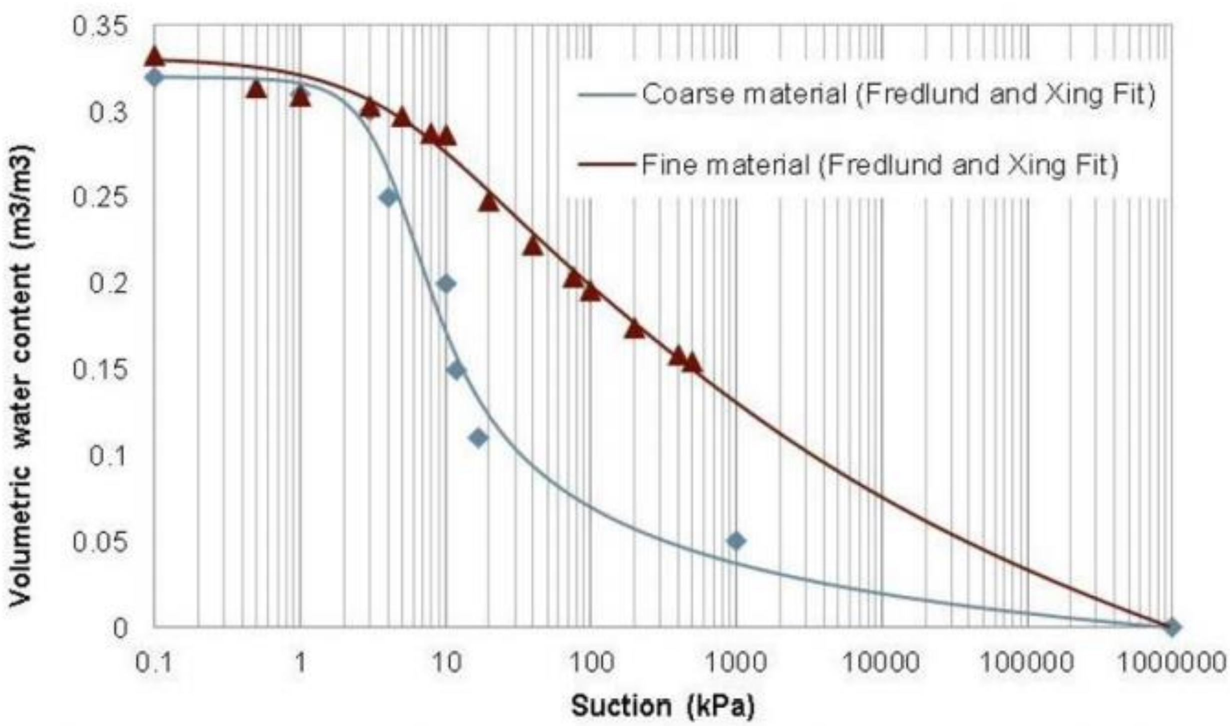

Figure 5: Water retention curves for coarse and fine materials.

The seepage analysis was conducted in 2 phases. First, a steady state model was performed as an initial condition for the subsequent transient seepage analysis. The steady state seepage was performed by setting hydraulic head boundary conditions to the natural ground elevation. For the transient analysis, a climate boundary condition considering an intense precipitation of 100 millimeters per day for 5 days was modelled. Figure 6 presents the isocontour for pore water pressure within the stockpile.

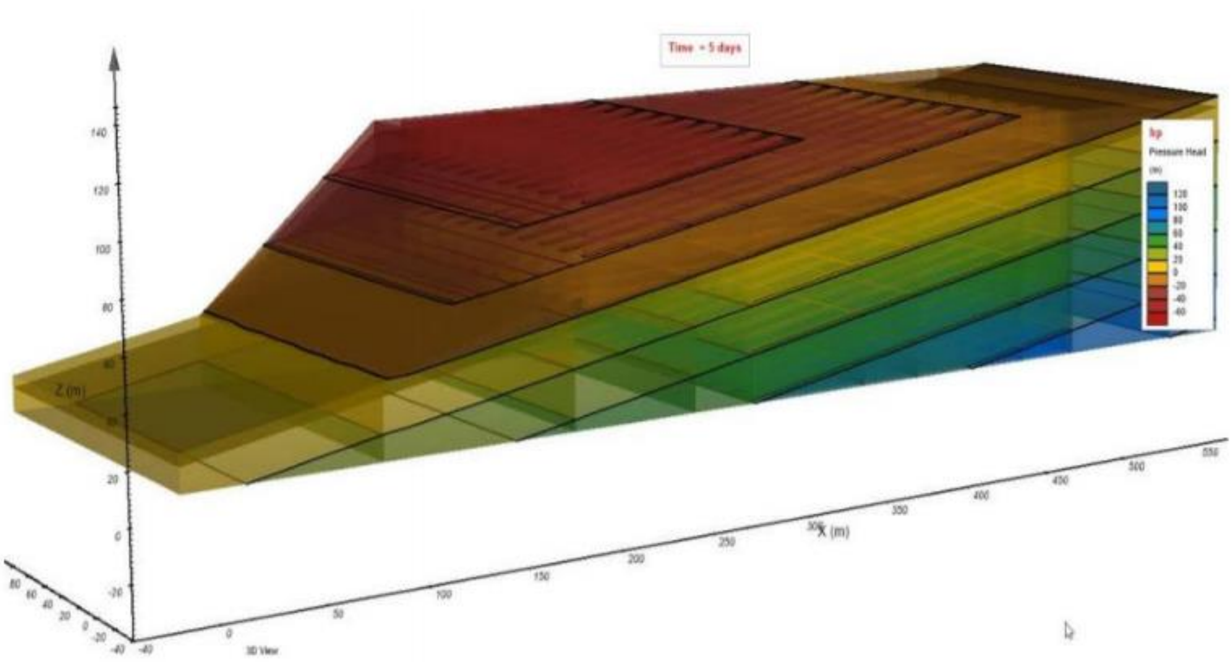

Figure 6: 3D seepage analysis result (pore water pressure isocontour).

The 3D seepage analysis showed that for the idealised model the coarse material was free drainage and did not become saturated. It is noteworthy that the 3D seepage analysis performed here only represents the result for the geometry and dimensions presented in Figure 4. Any other layout than that of modelled herein needs a further numerical analysis.

Conclusion

This paper presented the importance of 3D analysis in mining application through two practical examples. The 3D slope stability analysis was successfully used as a screening tool to identify the critical sections through the model. The 3D slope stability analysis provided slightly higher FS that 2D analysis. For the case in which the actual shear strength is applied for the slope stability, the 2D slope stability analysis would be conservative. Quebec regulations require a minimum FS values based on 2D slope stability analysis for man-made slope design. However, the results of this paper, which is aligned with the pervious findings on 3D slope stability analysis, shows that the 2D slope stability analysis is conservative.

The need for 3D seepage analysis was illustrated using a complex co-deposition layout, which could not be modelled otherwise. The analysis performed in this study indicated that for the proposed co-deposition method the coarse materials was free drainage and did not become saturated. This co-deposition method needs further investigation in order to evaluate various combinations of the fine and coarse material and geometry of the model. These combinations can only be modelled using 3D analysis.

References

1. Akhtar, K.2011. Three Dimensional Slope Stability Analysis for Natural and Manmade Slopes. PhD Thesis, Civil Engineering Department, University of Illinois at Urbana-Champaign.
2. Chaudhary, K., Honorato D. V., Gitirana, G., Fredlund, M., & Lu, H. 2016. Three-Dimensional Slope Stability: Geometry Effects. 16th Tailing and Mine Waste Conference, at Keystone Colorado.
3. Piciacchia, L., Marefat, V., & Vides, A. 2018. Practical Nomograms for Waste Rock Piles Design on Competent Foundations. 18th Tailing and Mine Waste Conference, The Department of Civil and Environmental Engineering at Colorado State University.
4. SoilVision Systems Ltd. 2017. SVSLOPE Theory Manual (SVOFFICE 2017). Saskatoon, Saskatchewan, Canada.
5. Stark, T. D., and Eid, H. T. 1998. Performance of three-dimensional slope stability methods in practice. Journal of Geotechnical Engineering Division, ASCE, 124(11), 1049-1060.

About the Authors

Luciano Piciacchia, P. Eng., Ph.D.
Manager, Waste Management and Environment
luciano.piciacchia@bba.ca

Dr. Luciano Piciacchia, P.Eng., Ph.D., is an experienced mining engineer with 30 years of solid geotechnical and environmental experience. He has worked on numerous site characterisation and decontamination projects as well as mine tailings impoundment design and waste management. He has been responsible for the planning, execution or supervision of laboratory and field investigations. Dr. Piciacchia has further been involved in numerous complex decontamination projects requiring specialised methods such as the requirement for sheet piling, bacteriological remediation and on-site encapsulation. His involvement has extended to tailings impoundment planning from the standpoint of scoping, pre-feasibility and feasibility perspectives. He has been involved in the design, site supervision and project management for earthworks, roads and dams for a number of mining sites including Bloom Lake, Mont Wright, Kearl, Mine Aurizon to mention some of the more recent assignments.

Vahid Marefat, P. Eng., Ph.D.
Geotechnical Engineering and Hydrogeology
luciano.piciacchia@bba.ca

Dr. Vahid Marefat is a skilled professional with more than 12 years' of experience in the domain of geotechnical and geoenvironmental engineering and hydrogeology. He has worked on numerous geotechnical projects including 3D and 2D slope stability analysis, tailings and earth dam design, seepage analysis, foundation and earth structure design, excavation stability analysis and sheet piling, instrumentation, site investigation, as well as construction projects. Dr. Marefat's research and expertise centered on the slope stability and seepage analysis of waste rock piles and tailings/rockfill dams. His expertise has also extended to geotechnical engineering and hydrogeology of the Champlain Clay. Dr. Marefat has also led and supervised several complex research projects on geotechnical instrumentation, regional hydrogeology, geotechnical field and laboratory tests, grouting and climate impact on the foundation engineering in the laboratory of Geotechnical and Geoenvironmental Engineering and in the laboratory for Hydrogeology and Mining Engineering in Montreal, Quebec, Canada.

BBA.CA