Practical Nomograms for Waste Rock Piles Design on Competent Foundations

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Executive Summary

Waste Rock Piles can measure hundreds of meters in height and their failure can put life and property at extreme risk as well as significantly impact the surrounding environment. As such, waste rock piles should be considered structures, rather than dumps. Waste rock piles geometry and height is site-specific and govern the level of risk associated to its construction, operation and management. However, the design of these structures does not always garner the rigorous attention that they should be afforded. This paper provides practical nomograms for designing waste rock piles on solid competent foundations. In cohesionless soils, commonly placed using end-dumping methods, the stability of the stockpile slope depends on the angle of internal friction (Ø), slope angle and the height, for a given depth of critical slip failure. The nomograms presented herein are based on the requirement of attaining an overall factor of safety of 1.5 and a local factor of safety of 1.2.

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

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Introduction

Failure in Waste Roc Facilities (WRF) can occur in the foundation soils or within the deposited material itself. As such, an evaluation of both materials is required to properly assess their overall stability and risk. Regardless, of where failure may occur, proper design can be used to mitigate such failure and reduce risk. For purposes of developing the practical nomograms presented in this paper, the regulatory requirements of the Quebec Ministry of the Environment and Natural Resources (MERN) have been used. Table 1, outlines these requirements.

Table 1: Stability analysis - Minimum values for factor of safety (MERN)

Condition	Factor of safety
Bearing capacity of the foundation under WRF	1.5 to 2.0
Local stability of the piles (for each bench)	
Short term static analysis*	1.0 to 1.1
Long term static analysis	1.2
Overall stability, for deep failures or failures pass through foundation	
Short term static analysis *	1.3 to 1.5
Long term static analysis	1.5
Pseudo-static analysis	1.1 to 1.3

* According to risk and uncertainty

The nomograms presented in this paper are intended for WRF where the foundation is deemed to be competent (i.e., rock and/or shallow deposit of till) and the deposited material is selfdraining.

A common method for deposition of waste rock disposal facilities is end-dumping or pushdumping. In both deposition methods, the overall waste rock pile slope angle follows the angle of internal friction of the materials that compose it. In other words, materials repose on their angle of internal friction. For instance, an angle of repose approaching 37° is a result of end dumping for a material with an Ø value of around 37°. The deposited mass in these types of slopes is always in a state of equilibrium. In the other words, a FS of unity is always expected for these types of slope, except in dynamic condition or change pore water pressure conditions.

In this type of material the critical failure mechanism is usually shallow sliding. The depth for critical slip failure not only considers a serious failure but also eliminates the shallow (insignificant) failures, which may occur on the slope surface. The methodologies to define the appropriate depth of failure for the critical slip circle and nomograms to design waste rock piles that will meet MERN regulatory requirements are presented herein.

Methodology

Critical slip surface depth (D_{cf})

The most common failure mechanism of cohessionless soils is shallow sliding. As such, an appropriate depth for the critical slip failure needs to be defined in order to conduct more realistic slope stability analyses. A question may arise: what depth should be considered for the critical slip failure when conducting slope stability analysis? The depth of the critical slip failure is related to the angle of internal friction of the material in the waste rock pile. Consider two slopes similar in height but containing two different materials. The first slope is comprised of fine sandy material and the second contains oversized coarse rock and boulders. It is certain that the depths of critical slip failure will not be similar for these materials. What is known is that a slope angle which corresponds to Ø will have a FS of 1, for a stockpile with infinite height. As such, a depth of failure (Dcf) which would yield a FS=1 is considered appropriate.

To define the depth for critical slip surface, a number of 2D slope stability analyses were conducted using the limit equilibrium (LE) method. An idealized cross section of a waste rock pile with a fixed height of 150 m was considered. The waste rock pile was considered to be resting on a competent foundation. As a result, all of the slip failures pass through the waste rock pile and not the foundation. The waste rock pile is made of various cohessionless materials with an angle of internal friction ranging between 32 and 42 degrees. The slope angle (a) in the model was maintained at an angle equal to Ø. Figure 1 presents a general sketch of the 2D slope stability model used in this study.

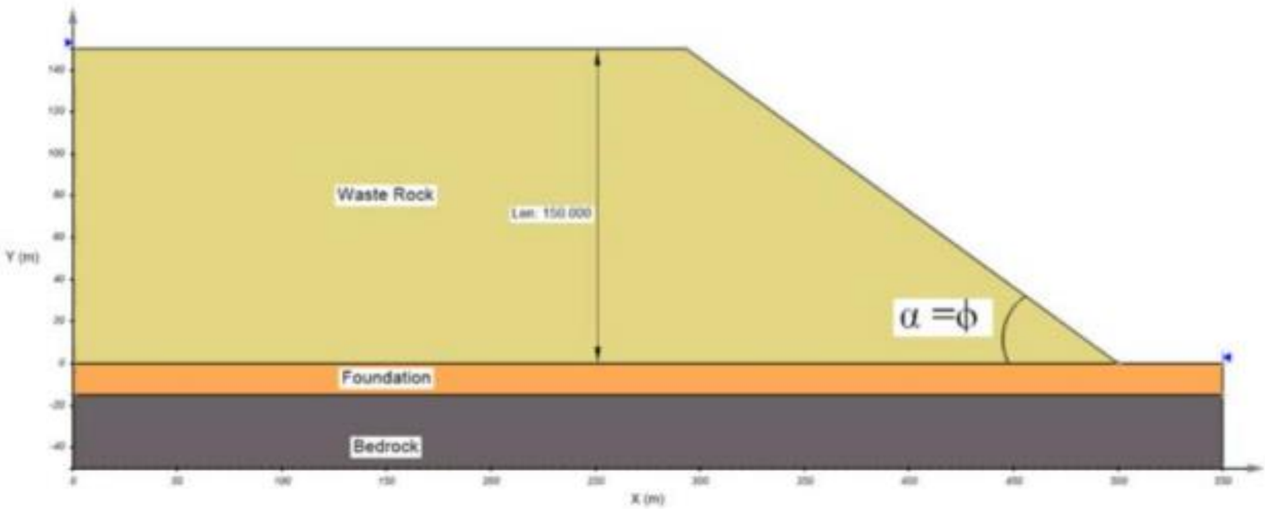

Figure 1: sketch of 2D slope stability model.

The depth of critical slip failure was determined based on the premise of attaining a FS=1. To do so, a number of depths were assigned in the LE slope stability analysis. The maximum depth D_{cf} was defined when the obtained FS was equal to 1. This depth not only represents a serious slip failure with a FS = 1, but also eliminates the shallow slip failures along the slope.

The exercise was repeated for a range of materials with angle of internal friction between 32 and 42 degrees. The resulting D_{cf} are represented in Figure 2.

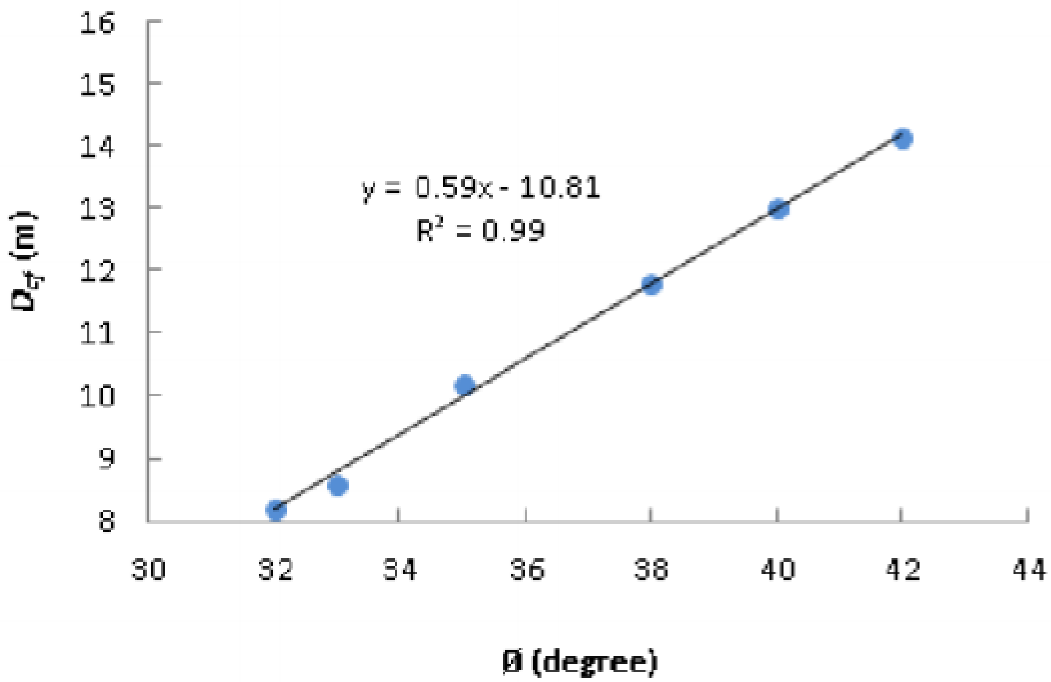

Figure 2: Angle of internal friction versus depth of critical slip failure.

Maximum bench height (h_{max})

For an infinite slope and a defined D_{cf} yielding FS=1, the FS can be increased by reducing the slope height. In this way, a maximum exposed slope height can be determined, which will yield a FS=1.2. This height, called the maximum bench height (hmax) in this paper, was also found by means of LE slope stability analysis for a bench comprising various waste rock materials with an Ø ranging from 32 to 42 degrees.

To determine the maximum bench height of a bench comprising a material with a given Ø and a given D_{cf}, various heights were assigned for the bench in the slope stability analysis. The height at which a local FS of 1.2 was obtained is considered as the maximum bench height, for a given material.

Minimum bench width (*W*)

For a waste rock pile with a general configuration, shown in Figure 3, the minimum bench width (W) was calculated based on the requirement of attaining an overall FS of 1.5. As shown in Figure 3, W can be obtained as follows:

$$W = X2 - X1 = \frac{h}{tan\,\beta} - \frac{h}{tan\,\emptyset_1} \tag{2.1}$$

In which, h is the bench height and β is the angle of the waste rock pile's overall slope. The angle (β) represents the overall slope angle corresponding to a global FS=1.5. The global FS is defined as the ratio of available shear strength to strength required to maintain stability:

$$FS = \tan\emptyset \,/\, \tan\beta \tag{2.2}$$

For an overall FS=1.5, the overall slope angle can be calculated as follows:

$$\beta = tan^{-1}(\tan\emptyset\,/1.5) \tag{2.3}$$

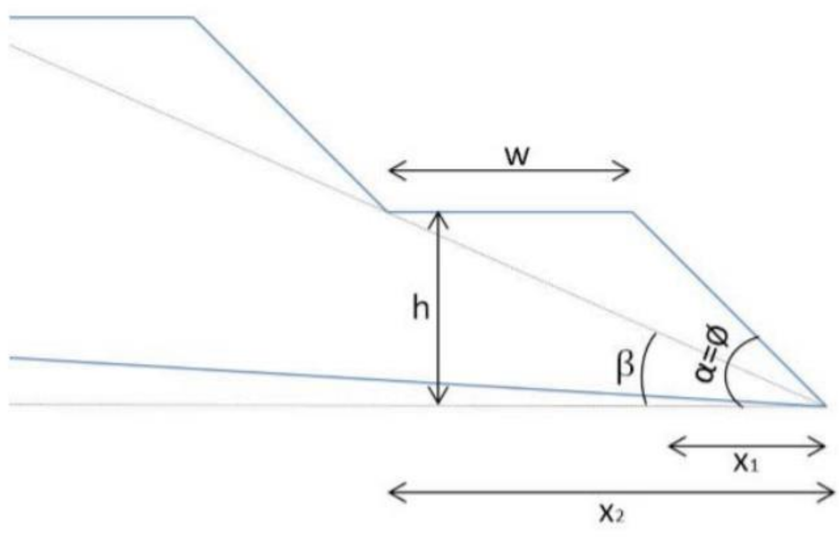

Figure 3: sketch for general configuration of a waste rock pile.

Replacing Eq. (2.3) into Eq. (2.1) yields:

$$W = h/\tan\left(tan^{-1}(\tan\emptyset/1.5)\right) - h/\tan\,\emptyset \tag{2.4}$$

Result and discussion

The relationship between the angle of internal friction and the depth of critical slip failure (Dcf) for waste rock materials with an Ø ranging between 32° and 42° has previously been defined in section 2.1. The resulting relationship between Ø and Dcf was found to be linear and is represented by Equation 3.1.

$$D_{cf} = 0.59\emptyset - 10.81 \tag{3.1}$$

For example, for a material with an angle of internal friction of 36 degrees, the critical slip failure depth is about 10 m. The obtained Dcf, for various materials in this study (Ø = 32 – 42 degrees), was then used in the slope stability analysis to determine the maximum height for the bench (hmax) considering a FS=1.2. The relationship between the maximum bench height and Ø was also found to be linear and is represented in Figure 4 and Equation 3.2.

$$h_{max} = 3.22\emptyset - 65.46 \tag{3.2}$$

The obtained h_{max} can then be used to determine the minimum bench width using Eq. (2.4) attaining an overall FS of 1.5. Figure 4 also provides a nomogram showing the relationship between h_{max} and W.

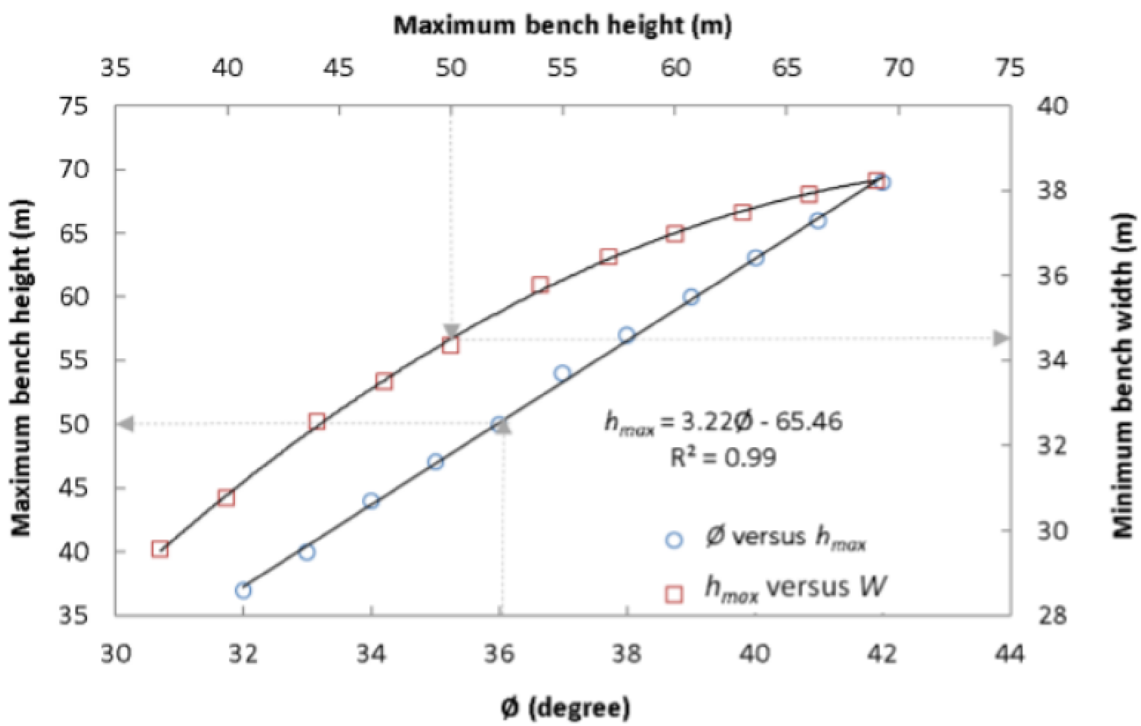

Figure 4: Relationship between Ø, h_{max} and W attaining a local FS of 1.2 and an overall FS of 1.5.

An example is given herein to guide the users when using the nomogram presented in Figure 4. For a material with an angle of internal friction (Ø) of 36 degrees, the maximum height for each bench is 50 m. which can be found from the linear graph representing the relationship between Ø and h_{max}. After having determined the maximum bench height, the minimum bench width (of 34.5 m) can be found by the non-linear graph in Figure 4 representing the relationship between h_{max} and W. The minimum bench width can also be calculated by means of Eq. (2.4).

The nomogram presented in Figure 4 provides only the design parameters based on the maximum bench height (h_{max}). For the cases in which the bench height is not as high as h_{max}, an optimised nomogram is needed to assist the designers. Figure 5 presents another nomogram, which is developed based on the requirements of attaining an overall FS of 1.5. For various waste materials with an Ø between 32 degrees and 42 degrees, the nomogram was developed based on Eq. (2.4). For a given material, the nomogram provides a bench width associated with a proposed bench height achieving an overall FS of 1.5.

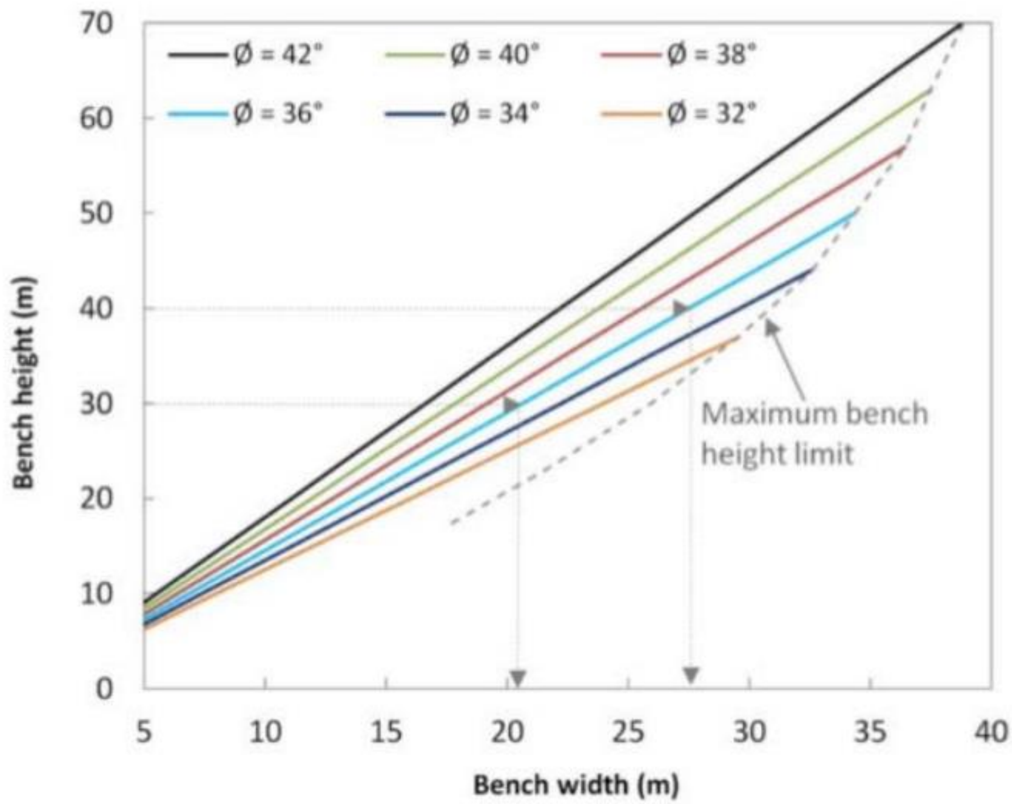

Figure 5: Waste rock pile design nomogram, achieving an overall FS of 1.5.

As mentioned, the maximum height for a bench comprising a waste rock with an Ø of 36 degrees is 50 m, which needs a minimum bench width of 34.5 m attaining an overall FS=1.5. For bench heights of less than h_{max} corresponding bench widths should be designed in order to optimize volume and maintain overall slope. This will ensure that an FS=1.5 is achieved. For example, 40 m and 30 m of bench heights for a pile comprising a waste rock with an Ø=36 degrees would have the minimum bench widths of 27.5 m and 20.5 m respectively.

The results and analysis provided herein can be used to design the waste rock piles comprising dry/unsaturated waste material constructed on unyielding competent foundation. The effect of pore water pressure on the pile stability is not considered in this study as the material to be considered self-draining. In piles comprising fine waste material, the phreatic level may rise during wet seasons, which may greatly affect the stability of the pile. These nomograms are not intended to be used in such cases.

Application

As such, if we apply this approach to a material having an Ø=40 degrees and an overall height of 200 m. The maximum bench height of 63 m with a corresponding width of 37 m should be considered for the design. Alternately, should the operator decide to limit bench height to 50 m, the bench width could be reduced to 30 m based on the nomogram presented in Figure 5. Both configurations would yield an overall FS of 1.5 and a local FS=1.2. The slope stability analysis presented in Figures 6 and 7 validates this application.

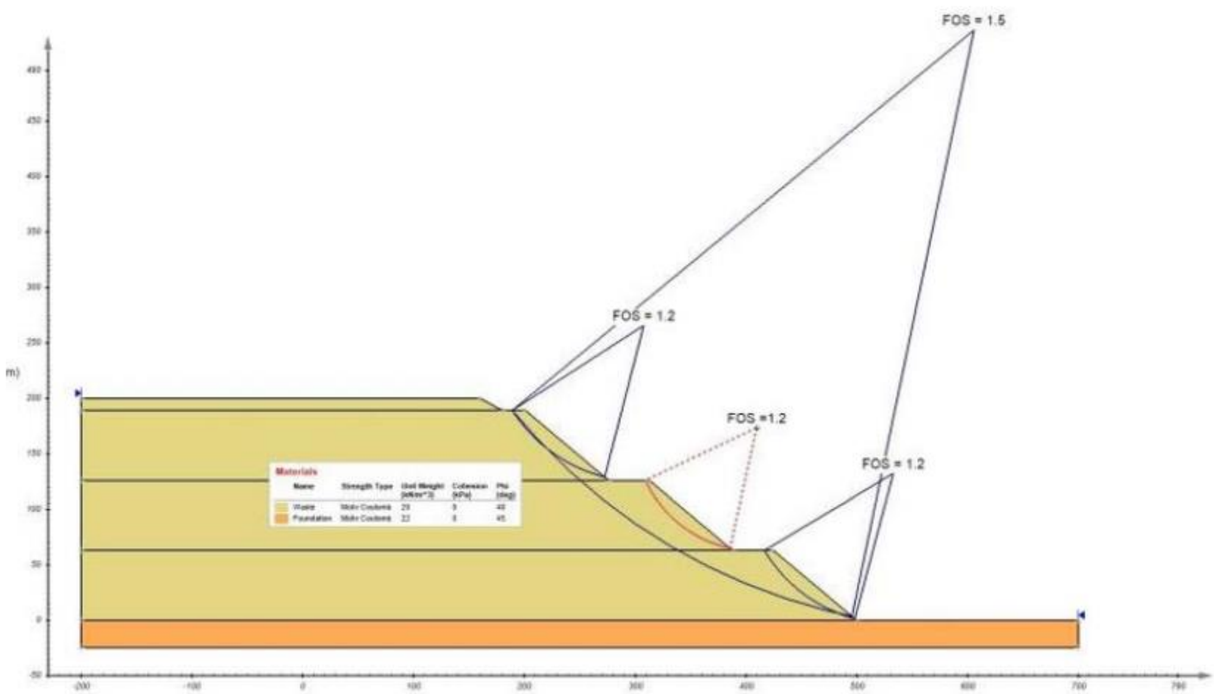

Figure 6: Slope stability simulation for maximum bench height.

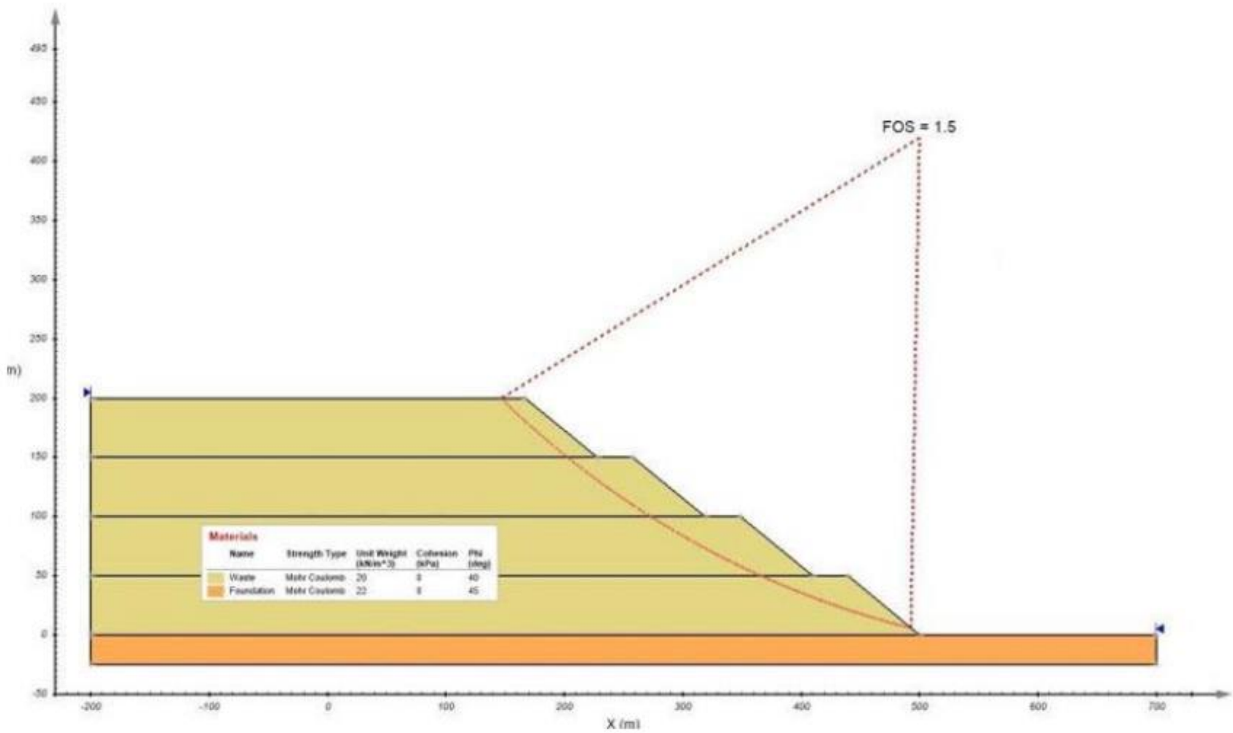

Figure 7: Slope stability simulation for the reduced bench height.

Conclusion

Waste rock piles geometry is site-specific and governs the level of risk associated to its construction, operation and management. As such, waste rock piles should be considered structures, rather than dumps. Therefore, rigorous attention should be afforded for the design of these structures. Several slope stability analyses were conducted to define the parameters for designing local and overall geometry of the waste rock piles. The stability results showed that maximum bench height should be limited in order to attain a local FS=1.2. The results showed that maximum bench height is linearly related to the bench material angle of internal friction.

The overall stability of a waste rock pile is controlled by its global slope angle (β). To achieve an overall FS=1.5 the method of construction becomes critical variable. It is not possible to simply end dump and anticipate satisfactory configuration. An analytic solution for a range of bench heights and material types was developed to calculate minimum bench width. The analytic solution provided a non-linear relationship between bench maximum height and bench width. For a case in which the bench height is less than the maximum bench height, this paper presented another nomogram to design optimum geometry for waste rock piles.

The results obtained in this paper can be used to design waste rock piles comprising selfdraining waste material on unyielding competent foundations.

References

1. SoilVision Systems Ltd. 2017. SVSLOPE Theory Manual (SVOFFICE 2017). Saskatoon, Saskatchewan, Canada.

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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.

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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.

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Mr. Vides is a Civil Engineer with more than 13 years of experience in civil and environmental engineering. As Project Manager and Engineer, he has participated in several prefeasibility, feasibility and detailed engineering studies as well as construction projects in Canada and around the world in the mining, oil and agriculture sectors. He has worked on the design and construction of numerous systems, such as water management, tailings management and land use systems (water management infrastructure, drainage systems, irrigation systems, access roads, landscaping, and buildings). He has led multidisciplinary and multicultural engineering teams, in both the office and on site and has carried out and managed several field studies.

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