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Back-Analysis of the Geotechnical Stability of High Waste Rock Piles

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Abstract

Managing mine waste rock (WR) presents significant challenges due to its environmental impact and stability concerns. Typically, WRs are disposed of in piles using methods tailored to project specifications. The present paper is based on a large waste rock pile (WRP) built during the open-pit backfilling operation at the Canadian Malartic Mine. Backfilling is a cost-effective disposal method that minimizes the environmental impacts of mining operations. However, it often results in the formation of high WRPs that are prone to geotechnical instability during dumping and construction. Stability analyses of these structures often do not follow conventional geotechnical practices, since WR generated through blasting consists of coarse, angular grains, easily exceeding one metre in diameter, leading to considerable heterogeneity and variability in geotechnical properties within the piles. This adds significant uncertainty to conventional testing methods, resulting in potentially unreliable safety assessments. This paper examines the geotechnical stability of a high WRP using a multifaceted approach aimed at reducing these uncertainties. The method incorporates Finite Element modelling using the Hardening Soil constitutive model, with parameters calibrated after various triaxial laboratory tests, and considers the actual geometric configuration and construction sequence of the pile. The results have been validated through deformation monitoring data collected throughout all construction stages, to ensure short-term stability of the pile during truck dumping operations. Numerical modelling using 2D and 3D approaches revealed that, while shear strength was realistically captured, deformations were significantly overestimated due to limitations in laboratory-derived stiffness parameters. Back-analysis using recalibrated stiffness moduli improved alignment with field monitoring, suggesting current design guidelines may be conservative for WRPs in hard rock mines.

Introduction

The stability of waste rock piles (WRPs) can be a critical concern in mining operations, depending on project specifications, site conditions, dumping methods, and the type of mine (Aubertin et al., 2002; Cho

& Song, 2014). Stability analyses typically follow established guidelines and standards, often relying on Safety Factor (SF) assessments using the Limit Equilibrium (LE) method (Aubertin et al., 2013; Hawley & Cunning, 2017; Maknoon & Aubertin, 2021). As global mine production increases and sustainable alternatives gain popularity, practices like open-pit backfilling are becoming more appealing (Ouellet et al., 2021). However, these methods often result in the formation of very high piles at the angle of repose of the WR material, where stability risks become more significant, and safe operation of haul trucks must be carefully ensured during dumping.

A major challenge in evaluating WRP's stability is the heterogeneous nature of the waste rock (WR) material, which comes from a mix of lithologies across the mine. This leads to wide variations in mineral composition and particle size, with coarse, loosely dumped, and segregated material that complicates geotechnical assessments. Over time, physical and chemical weathering, along with particle crushing under stress, might alter the mechanical behaviour of the material (Bard et al., 2011; Osses et al., 2024).

Numerous failures of WRPs have shown the need for careful design, operation, and monitoring (Cho & Song, 2014; Hoy et al., 2024; Kasmer et al., 2006; Richards et al., 1981; Wang & Griffiths, 2019). For example, British Columbia developed specific WRP construction guidelines after repeated failures in coal mines (BCMWRPRC, 1991; Hawley & Cunning, 2017), where conditions often lead to more frequent and severe issues than in hard rock mines. While numerous studies highlight the complex interplay of geotechnical properties, hydrological conditions, and foundation characteristics in WRP stability (Hoy et al., 2024; Kasmer et al., 2006; Steiakakis et al., 2009; Ulusay et al., 1995), the mechanical behaviour of WRPs in hard rock mines is not often monitored to validate model predictions and actual performance.

This study aims to assess the mechanical stability of a high WRP backfilled in the pit of the Canadian Malartic Mine, through the development of multiple real-geometry numerical models using Plaxis 2D and 3D. The Hardening Soil constitutive model is used to capture the mechanical behaviour of the WR material, through calibration with different sets of laboratory data. To refine the geomechanical parameters, such as stiffness, shear strength, and non-linearity, an iterative back-analysis approach is applied, integrating monitored displacement data to enhance predictive accuracy.

Project Description

The Canadian Malartic Mine is the largest open-pit gold mine in Canada, located in Malartic, 25 kilometres west of Val-d'Or, Quebec. The site includes the Malartic pit, which ran from 2011 to May 2023, and the Barnat pit, which has been in operation since 2019. Adjacent to these two pits, there is also the Odyssey underground mine. Barnat and Odyssey are projected to generate around 168 million tons of WR and 108 million tons of tailings over their lifespan. Waste production rates in 2024 were about 133 ktpd and 54 ktpd of waste rock and tailings, respectively. To mitigate the environmental impact associated with expanding the tailings and WR storage facilities from these two mines, a creative approach has been implemented to repurpose the Malartic pit. This strategy involves the deposition of both WR and tailings in the Malartic pit, with a Central Berm (CB) serving as a separation barrier between the two materials. As shown in Figure 1, the CB divides the pit into two sections, separating the WR and tailings deposition areas. In the initial stage of the project, from October 2023 to July 2024, the CB was constructed using WR, reaching a height of over 160 metres at its deepest section (see Fig. 2).

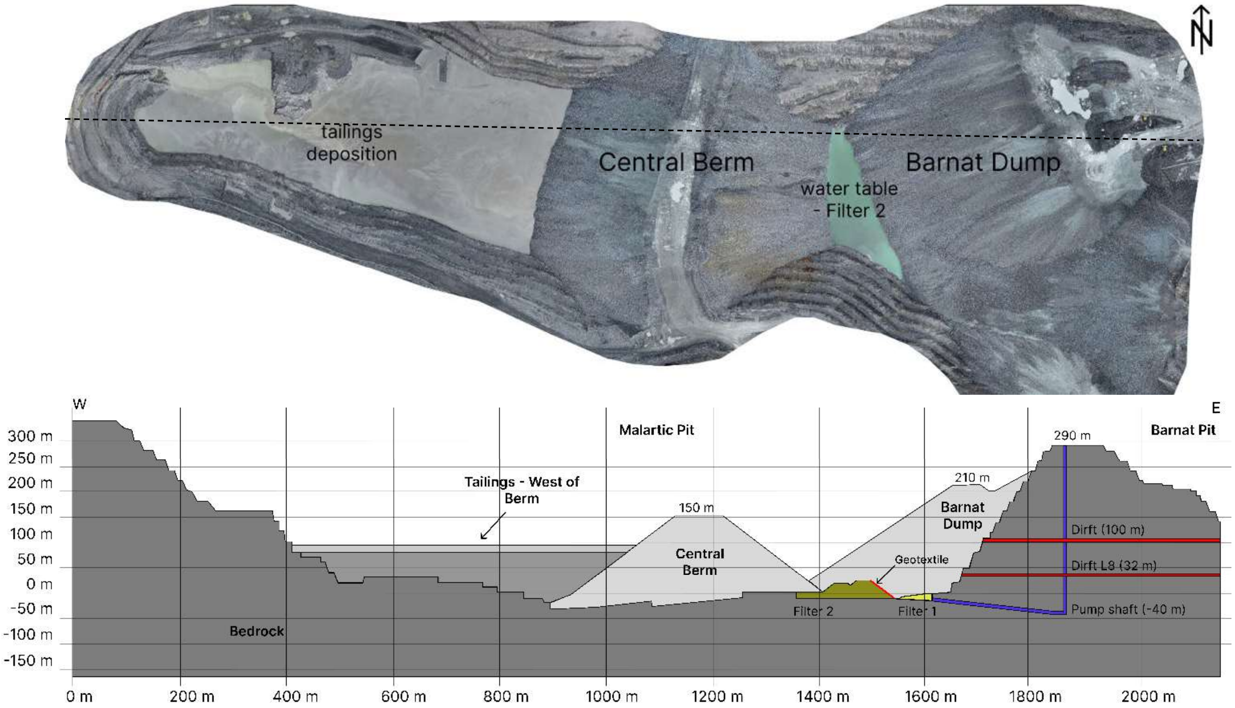

Figure 1: Project advancement up to October 2024; top view and cross-section

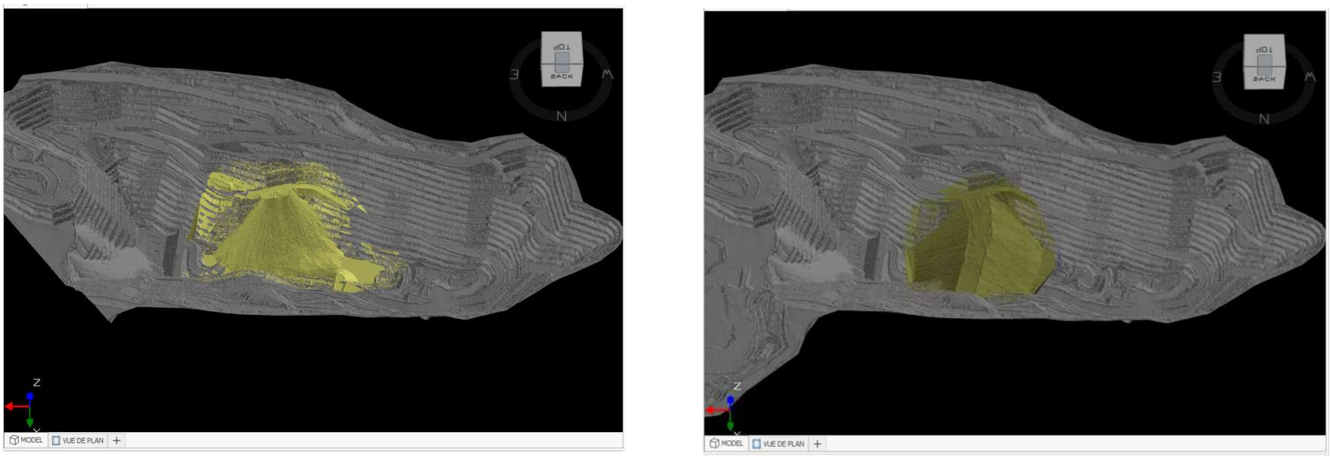

Figure 2: Construction advancement of the CB starting from October 2023 (left) until July 2024 (right)

After completion of the CB, the east side is being filled with WR, forming a 210-metre-high WRP that advances to reach the CB on its west side, while tailings are deposited on the west side of the CB (Behlke et al., 2025). Note that this study focuses only on the stability of the CB during its construction phase, prior to the start of tailings deposition.

Numerical Modelling

Geometry and Construction Stages

The mechanical behaviour of the CB pile has been modelled using the Finite Element (FE) software Plaxis 3D V.22. This modelling has been conducted to assess the SF of the CB at different stages, as well as deformations, to compare the results with in-situ settlement data obtained from monitoring. For this study, the model will incorporate the actual pile geometry obtained through aerial drone scanning. The geometry was then reproduced in AutoCAD to generate the mesh of the FE model for import into Plaxis. The construction of the pile follows the daily mine production schedule, leading to progressive advancement of the pile crest. This was modelled considering the pile as sequential 10 m thickness layers to represent the actual construction nature; the deformation of the pile and its SF are computed layer by layer.

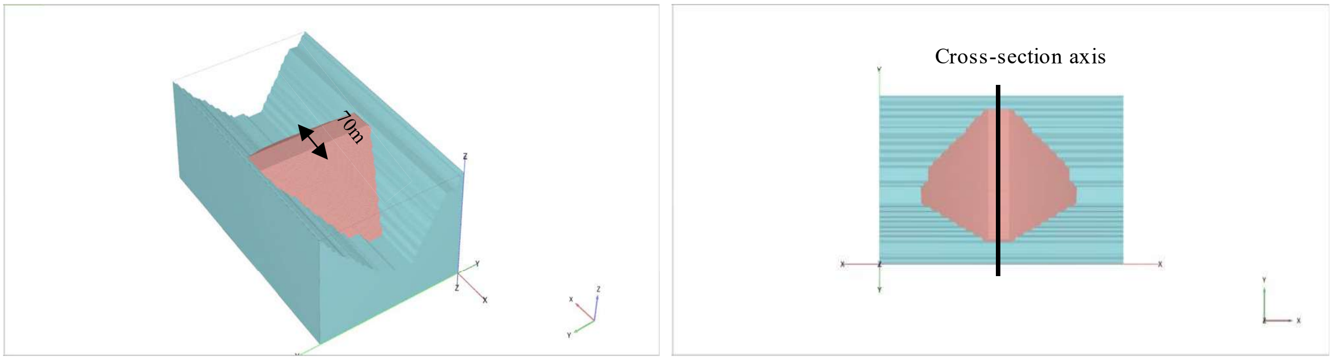

Figure 3: Final model geometry

To compare the results of the 3D model with plane-strain behaviour, a cross-section of the pile (Fig. 4) was modelled in a 2D approach, as commonly adopted in slope stability analyses (García-Torres et al., 2024; Majdanishabestari et al., 2024; Stark & Eid, 1998).

Material Properties

Consolidated drained triaxial compression tests were performed on different WR material sets from the Canadian Malartic Mine: CM and Sed1 (see grading in Fig. 5). Tests were carried out on relatively large cylindrical specimens with a diameter of 300 mm and a height of 600 mm. Loose dry specimens were prepared without compaction by pouring the material in 10 layers of homogeneous composition with a range of confining pressures $\sigma_3' = 0.1 - 0.5$ MPa. Since the specimens were dry, volumetric strains were determined by monitoring water volume changes in the confinement cell. Table 1 summarizes the material and specimens' properties. More specific details about the testing methodology can be found in Girumugisha et al. (2024).

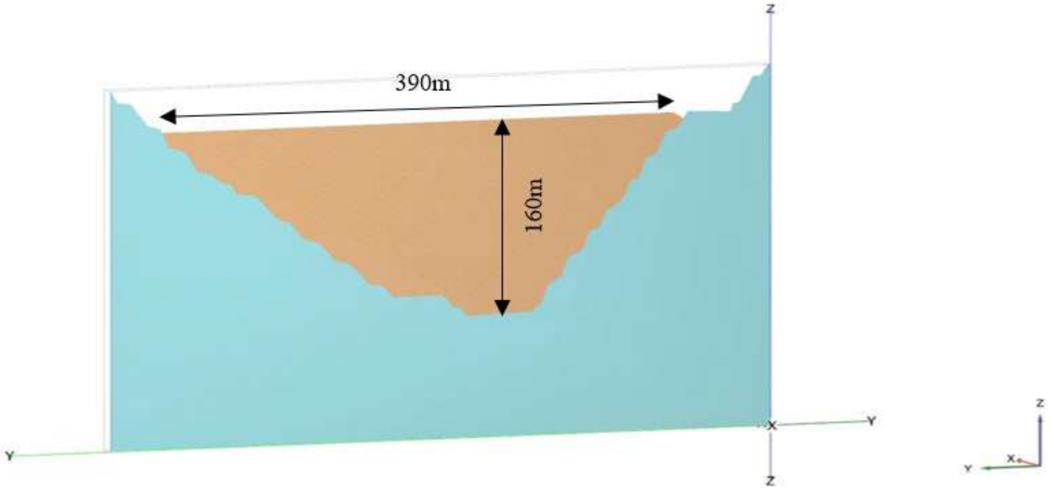

Figure 4: 2D model (1-metre slice from the middle of the 3D model) showing the variation of the pile height during different construction stages

Table 1: Triaxial Tests Configuration and Material Properties Adopted for CM and Sed2 Materials

Material	Initial Void Ratio e_i	UCS (MPa)	Specific Gravity G_s	Maximum Grain Size d_{max} (mm)	Confining Pressure σ_3(MPa)	Reference
CM	0.68	120	2.7	50	0.1-0.5	(Polytechnique Montreal, 2021)
Sed2	0.43	128	2.75	12.5	0.15-0.21	(Girumugisha et al., 2024)

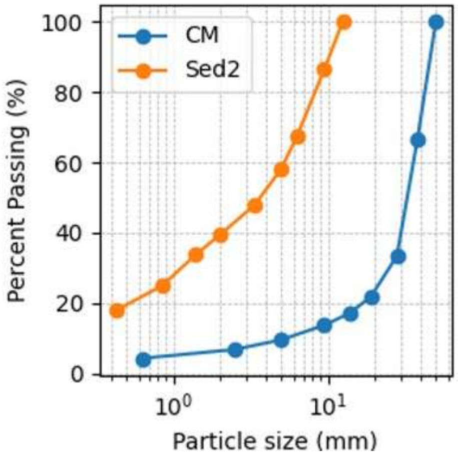

Figure 5: PSD of the material before triaxial testing

The results of the triaxial tests are presented in Figures 6 and 7 (where $q = \sigma_1' - \sigma_3'$ is the deviatoric stress). CM material exhibits fully contractive behaviour, while minor dilation was observed in Sed2. Additional parameters are discussed in the following section.

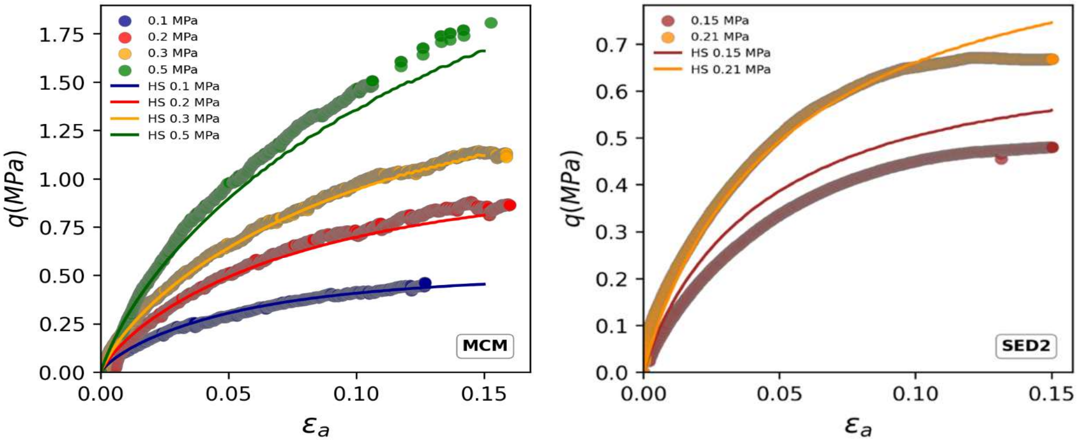

Figure 6: Calibration (solid lines) against triaxial test results (points) for WR materials: deviatoric stress vs. axial strain

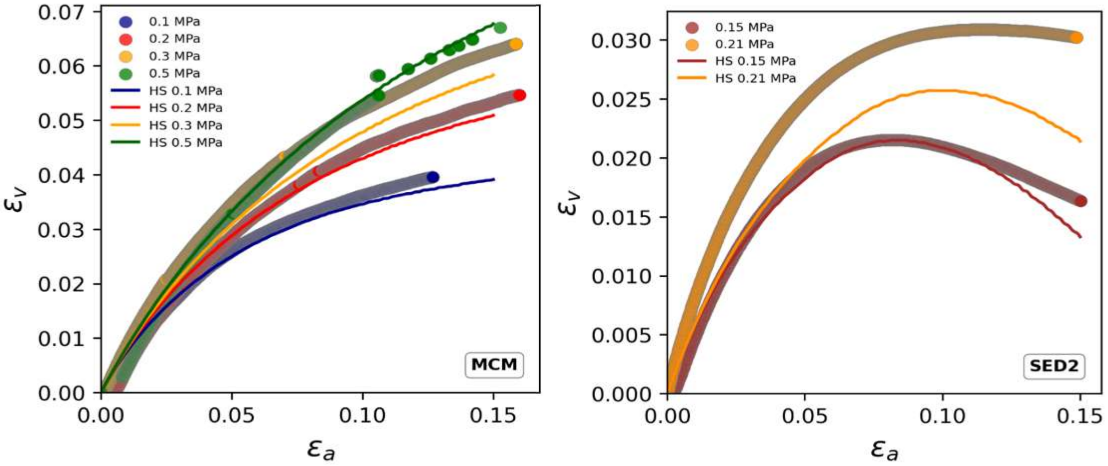

Figure 7: Calibration (solid lines) against triaxial test results (points) for WR materials: volumetric strain vs. axial strain

Hardening Soil (HS) Constitutive Model Calibration

According to previous studies (Majdanishabestari, 2023; Pramthawee et al., 2011; Schanz et al., 1999b; Soroush & Aghaei Araei, 2006), the HS model is efficient capturing the behaviour of rockfill materials. The HS model is based on a hyperbolic stress–strain relationship originally proposed by Duncan and Chang (1970) to describe soil behaviour under primary loading at drained triaxial conditions. This formulation was later adopted and extended in the HS model by Schanz et al. (1999) to capture more complex, stress-dependent stiffness characteristics. The hyperbolic stress-strain relation is given by:

$$\varepsilon_1 = \frac{1}{2E_{50}} \cdot \frac{q}{1 - \frac{q}{q_a}} \quad (1)$$

where ε_1 is the strain in the major principal direction, q_a is the asymptotic value of the deviatoric strength and E_{50} is defined as the secant modulus corresponding to 50% of the peak deviatoric stress, given by $E_{50} = 0.5 q_{\text{peak}} / \varepsilon_{50}$, where ε_{50} is the axial strain mobilized at $0.5 q_{\text{peak}}$. The stiffness parameters are stress-dependent and controlled by different moduli as:

$$E = E^{ref} \left(\frac{c \cos\varphi - \sigma_3 \sin\varphi}{c \cos\varphi + p^{ref} \sin\varphi} \right)^m \quad (2)$$

where m is a material constant, E is categorized into three moduli E_{50}, E_{oed} and E_{ur} (each defined for a different loading path), E^{ref} is a reference modulus at a reference stress level p^{ref} (100 kPa in this study), c is cohesion and φ is the internal effective friction angle. m has been set to 0.45, representing a typical value for rockfill materials as suggested by previous research studies (Cho & Song, 2014; Pramthawee et al., 2011; Soroush & Aghaei Araei, 2006; Sukkarak et al., 2021). Oedometric compression modulus E_{oed}, which governs the volumetric stress–strain response, and E_{ur}, the unloading modulus, are often assumed due to limited data available. The approach proposed by Sukkarak et al. (2021) has been adopted for E_{oed}^{ref}, by approximating its value within the range $(0.8 - 1.2)\ E_{50}^{ref}$, calibrated based on the volumetric strain response observed in triaxial test results. E_{ur}^{ref} was set to the default assumption commonly adopted in the literature: $E_{ur}^{ref} = 3E_{50}^{ref}$ (Honkanadavar & Sharma, 2016; Pramthawee et al., 2011; Schanz et al., 1999a; Sukkarak et al., 2021; Xu & Song, 2009).

The strength parameters φ and c were derived from the triaxial test results at peak deviatoric stress, according to the Mohr-Coulomb criterion for cohesionless material. For granular materials such as sand, gravel, and rockfill, c is typically assumed to be negligible. However, $c = 3$ kPa was adopted in this study to prevent numerical instabilities in the FE model. The dilatancy angle ψ defines the volumetric response, with positive values for dilatancy and negative ones for contractancy. Table 2 presents the calibrated parameters for the different materials utilized. Figures 6 and 7 illustrate the comparison between the HS calibrated results and the laboratory triaxial test data.

Table 2: Calibrated Mechanical Parameters Used in the Model

Material	E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur}^{ref} (MPa)	φ (°)	ψ (°)	c (kPa)
CM	7.3	6.7	23	45	0	3
Sed2	8.3	8.7	25	41	8	3

Monitoring

Due to the numerous uncertainties in the stability analysis of WRPs, SF alone may not provide a reliable measure of stability. In addition, site conditions can sometimes prevent achieving the recommended SFs outlined in existing guidelines. Alternatively, regular field monitoring enhances stability assessments by identifying potential instability triggers before failure occurs. Additionally, monitoring is used to validate numerical modelling results during and after construction, ensuring greater accuracy. These data also play a crucial role in recalibrating the mechanical parameters of WR materials based on their in-situ behaviour, addressing challenges such as heterogeneity and segregation within the pile, which are difficult to model precisely.

The monitoring system for the CB employed two Trimble S9/S9 HP total stations, paired with two Trimble 360 prisms. The system provided real-time coordinate measurements, enabling precise deformation tracking at installed locations. Additionally, aerial drone imaging was conducted regularly to analyze large-scale operational behaviour. Surveyors recorded prism coordinates every half hour, with each monitoring period defined by fixed prism positions. Only the height (z) changed significantly during each period, reflecting pile settlements. Total z-displacements were calculated as the difference between maximum and minimum heights of the measured period of 24 hours, then converted to daily settlement rates to align with guideline comparisons.

Results and Discussion

Deformations and SF of the pile with varying dumping heights were calculated using both 2D and 3D models, considering the two different material sets (CM and Sed2). In practice, the SF for global slope stability of a WRP should be at least 1.3 in the short term (i.e., during mining operations), while an SF greater than 1.5 is recommended for ensuring long-term stability (Aubertin et al., 2002; Maknoon & Aubertin, 2021; MERN, 2016).

As shown in Figure 8, the SFs with CM material are 1.24 and 1.35 for 2D and 3D models, respectively, and 1.20 and 1.23 for Sed1. Thanks to the mobilization of dragged lateral strength on 3D convex failures, 2D models yield slightly lower SF values than the 3D models, which is consistent with established slope stability studies (Griffiths & Marquez, 2007; Wu et al., 2024). Higher SFs with CM are due to its greater shear strength, while the SF of Sed2 material remains below the minimum of 1.3. This illustrates that numerous factors can affect the SF, while they do not necessarily elucidate the stability condition. Thus, relying on a given SF value seems to be insufficient to ensure stability.

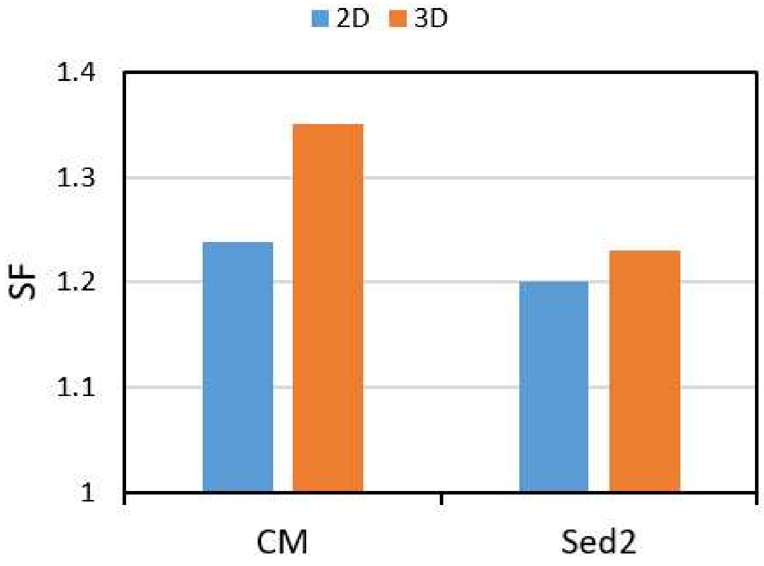

Figure 8: SF values for CM and Sed2 materials obtained by 2D and 3D methods

Figure 9 presents the settlements monitored between October 2023 and July 2024, where the orange line shows the average values, and the bars stand for maximum and minimum settlements. It is worth noting that most of the settlements occurred within the first 24 hours after WR deposition, followed by only minor creep strains. Thus, it is assumed that the FE model is comparable with the settlements during the first 24 hours, neglecting time-dependent deformation afterwards. Creep deformations were indeed observed in the following weeks, but the magnitudes of the delayed settlements were always more than one order of magnitude smaller than the 24-hour settlements.

According to the Waste Hazard Classification system (WHC) proposed by Hawley and Cunning (2017), the current case study is classified as WHC II (Low Hazard), and settlements should be less than 0.72 m/day to ensure stability during operation. As shown in Figure 9, in-situ deformations generally remained below this limit, with some readings exceeding the operational threshold, although visible signs of instability did not accompany these exceedances. This underscores that existing guidelines may be conservative, particularly in the context of hard rock mines.

Comparing modelling approaches, 3D models predicted higher deformations than 2D models (around 10% on average). This difference is due to a key limitation of 2D modelling that assumes infinite model extension in one direction, which is not realistic for the actual pile's width of less than 70 m. Since the geometry of the pile is one of the most sensitive factors on its stability (Maknoon & Aubertin, 2021), real 3D geometry can better capture the deformation behaviour, as supported by previous studies (Griffiths & Marquez, 2007; Wu et al., 2024). The predicted deformations using the CM material are approximately 50% larger than those calculated with Sed2, primarily due to differences in stiffness moduli and the more contractive behaviour exhibited by CM (Fig. 9).

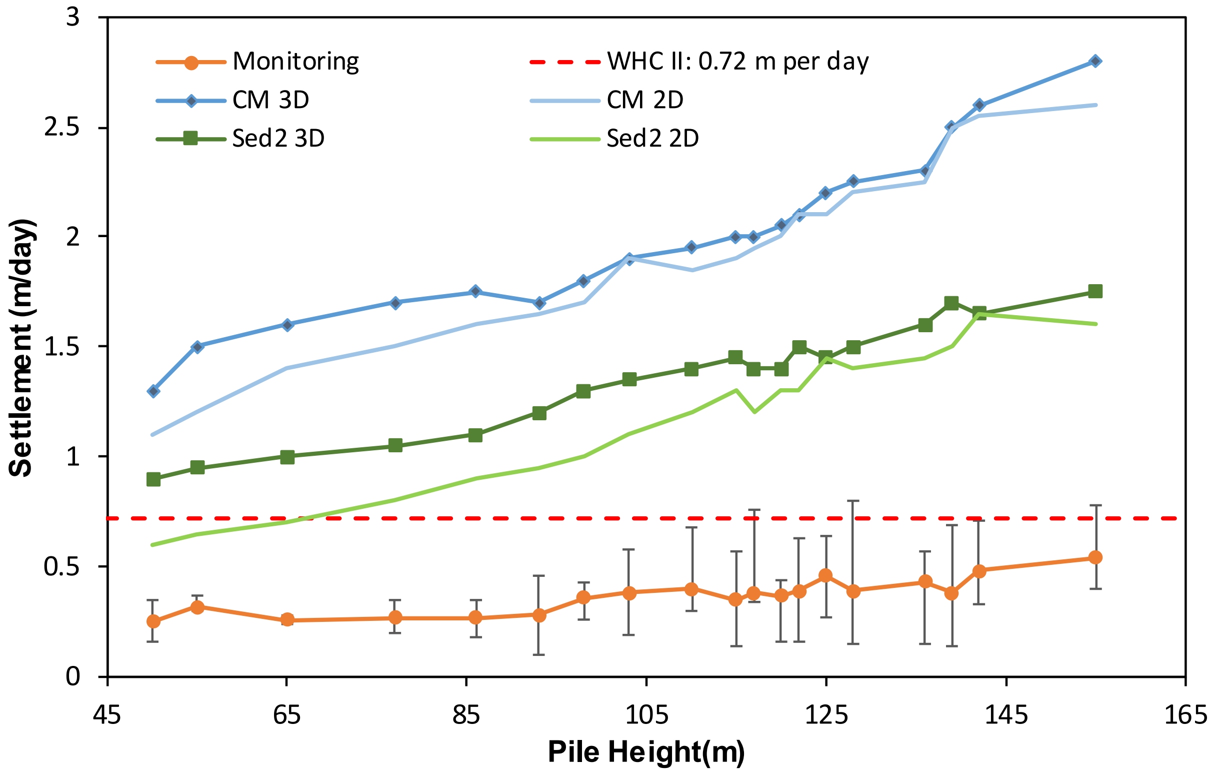

Figure 9: Deformation data calculated by FE models and monitored values at CM mine

Despite differences in materials and modelling approaches, deformations are significantly overestimated by the FE numerical simulations, by around 3.5 and 1.5 times more with the materials CM and Sed2, respectively. This highlights a notable gap between laboratory-derived and in-situ deformation moduli. Even with varied testing techniques and particle sizes, the stiffness values from laboratory tests often fall short compared with field conditions. This discrepancy may stem from scale effects (Ovalle et al., 2014; Ovalle et al., 2020; Girumugisha et al., 2025), as well as unaccounted factors like particle crushing, material heterogeneity, and segregation within the pile. However, given that no sliding surfaces or instabilities were observed during construction, the calculated SFs appear to be reasonable. This supports the idea that shear strength values derived from triaxial testing are realistic (Girumugisha et al., 2024).

Back-Analysis

The gap between monitoring data and modelling results can be revisited using back-analysis techniques. This includes estimating values for material properties that represent the in-situ behaviour of the pile as the most reliable hands-on data. To do so, a series of CM material properties with incrementally increasing stiffness moduli was used in the calculations and compared with the monitoring results. The methodology involved incrementally increasing values of E_{50}^{ref} (assuming $E_{oed}^{ref} = E_{50}^{ref}$), while the rest of the parameters remain realistic (Girumugisha et al., 2024). model results of the recalibrated material with incrementally increasing E_{50}^{ref} values. The results illustrate that E_{50}^{ref} of 24 MPa is needed to capture the envelope of maximum settlements observed in the field. While the clear correlation between material stiffness and predicted defomations can be captured from the results, the SF values changed negligibly during the recalibration process (Fig. 11). The resulting recalibrated values are summarized in Table 3.

Table 3: Recalibrated Mechanical Parameters of CM Material Used in Back-Analyses

Material	E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur}^{ref} (MPa)	φ (°)	ψ (°)	c (kPa)
CM	7.3	6.7	23	45	0	3
Recalib1	12	12	36	45	0	3
Recalib2	16	16	48	45	0	3
Recalib3	20	20	60	45	0	3
Recalib4	24	24	72	45	0	3

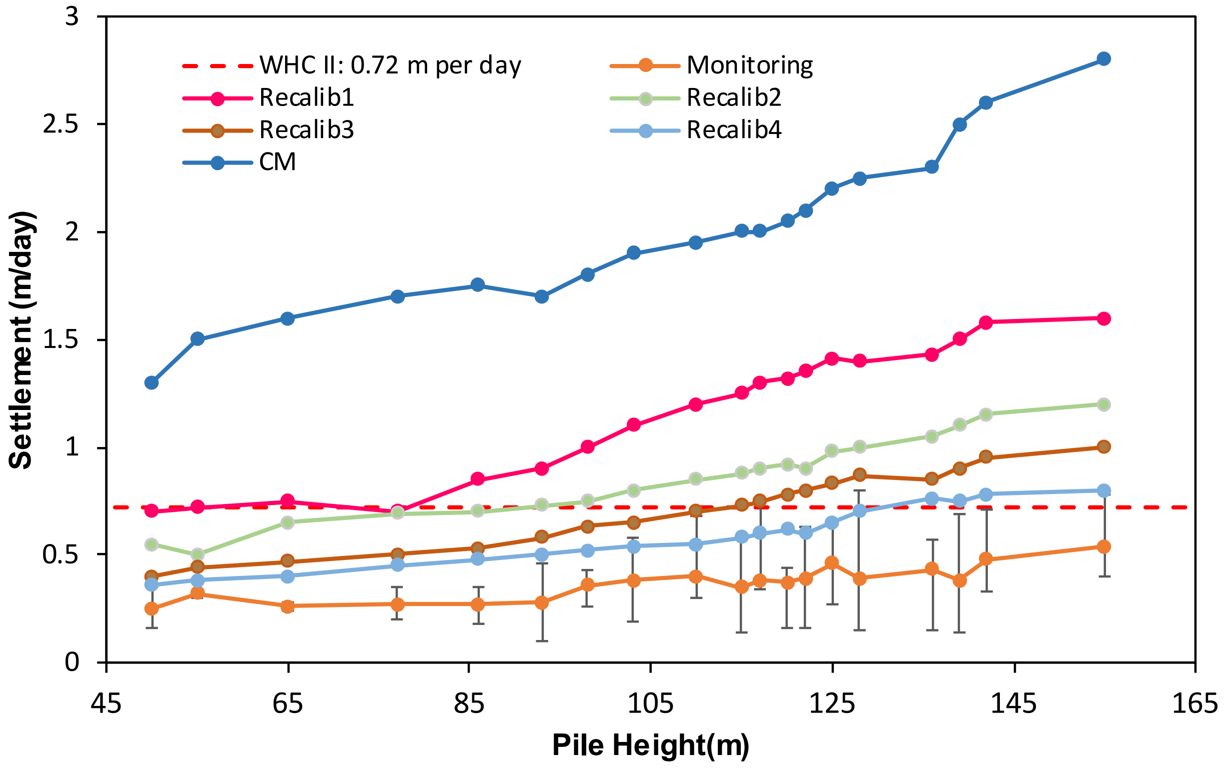

Figure 10: Field monitoring values compared with deformation calculated considering recalibrated material properties

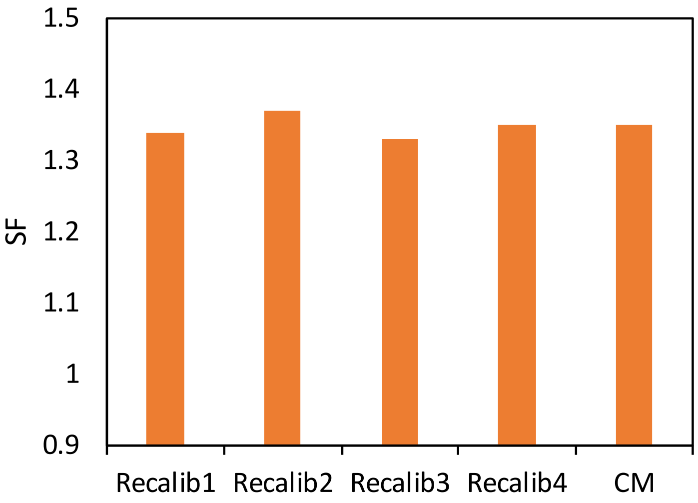

Figure 11: SF values calculated during the recalibration process

Conclusion

This study examined the geotechnical stability of a high WRP backfilled in an open-pit mine, using both 2D and 3D numerical modelling with different WR materials datasets. The predicted deformations were significantly overestimated, highlighting a persistent gap between laboratory-derived stiffness moduli and actual field behaviour, likely due to scale effects given by grading and material heterogeneity. A back-analysis approach was adopted by adjusting stiffness parameters to better match monitoring data. The recalibrated models successfully captured the observed maximum deformations, reinforcing the importance of in-situ monitoring to ensure stability and assess the limitations of numerical modelling. Given the absence of any instability signs during construction, even when monitored displacements exceeded standard thresholds, existing stability guidelines may be conservative for WRPs in hard rock mines, pointing to the need for revised design frameworks tailored to such conditions.

Acknowledgements

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References

Aubertin, M., Bussière, B., & Bernier, L. (2002). *Environnement et gestion des rejets miniers*. Presses Internationales Polytechnique.

Aubertin, M., Bussière, B., James, M., Mbonimpa, M., & Chapuis, R. (2013). Revue de divers aspects liés à la stabilité géotechnique des ouvrages de retenue de résidus miniers: Partie I—mise en contexte et caractéristiques générales. *Environnement, Ingénierie Développement, 64*, 1–XX.

Bard, E., Anabalón, M. E., & Campaña, J. (2011). Waste rock behavior at high pressures: Dimensioning high waste rock dumps. In P.-Y. Hicher (Ed.), *Multiscale geomechanics* (pp. 83–112).

Behlke, F., Ovalle, C., Ouellet, S., & Li, L. (2025, June 8–11). Évaluation de la migration des résidus et du comportement hydrogéologique du remblayage par co-déposition dans la fosse de la mine Canadian Malartic. *Symposium Mines et Environnement 2025*, Rouyn-Noranda, Québec, Canada.

British Columbia Mine Waste Rock Pile Research Committee [BCMWRPRC]. (1991). *Operation and monitoring of mine dumps: Interim guidelines*. British Columbia Mine Waste Rock Pile Research Committee; Klohn Leonoff Consultants for the British Columbia Ministry of Energy, Mining & Petroleum Resources.

Cho, Y.-C., & Song, Y.-S. (2014). Deformation measurements and a stability analysis of the slope at a coal mine waste dump. *Ecological Engineering, 68*, 189–199.

García-Torres, S., Ovalle, C., & Ouellet, S. (2024, September 15–18). Stability assessment of an open-pit waste rock backfilling: Field monitoring and numerical back analysis. *Annual Conference of the Canadian Geotechnical Society, GeoMontréal 2024*, Montreal, Canada.

Girumugisha, G., Ovalle, C., & Ouellet, S. (2024). Grading scalping and sample size effects on critical shear strength of mine waste rock through laboratory and in-situ testing. *International Journal of Rock Mechanics and Mining Sciences, 183*, 105915. https://doi.org/10.1016/j.ijrmms.2024.105915

Girumugisha, G., Ovalle, C., Reith, H., & Stutz, H. H. (2025). Effects of triaxial sample scaling on the mechanical behavior of alluvial gravels. *Journal of Geotechnical and Geoenvironmental Engineering*. Advance online publication.

Griffiths, D., & Marquez, R. (2007). Three-dimensional slope stability analysis by elasto-plastic finite elements. *Geotechnique, 57*(6), 537–546. https://doi.org/10.1680/geot.2007.57.6.537

Hawley, M., & Cunning, J. (2017). *Guidelines for mine waste dump and stockpile design*. CSIRO Publishing.

Honkanadavar, N. P., & Sharma, K. G. (2016). Modeling the triaxial behavior of riverbed and blasted quarried rockfill materials using hardening soil model. *Journal of Rock Mechanics and Geotechnical Engineering, 8*(3), 350–365.

Hoy, M., Doan, C. B., Horpibulsuk, S., Suddeepong, A., Udomchai, A., Buritatum, A., Chaiwan, A., Doncommul, P., & Arulrajah, A. (2024). Investigation of a large-scale waste dump failure at the Mae Moh mine in Thailand. *Engineering Geology, 329*, 107400. https://doi.org/10.1016/j.enggeo.2023.107400

Kasmer, O., Ulusay, R., & Gokceoglu, C. (2006). Spoil pile instabilities with reference to a strip coal mine in Turkey: Mechanisms and assessment of deformations. *Environmental Geology, 49*, 570–585.

Majdanishabestari, K. (2023). *Slope stability analysis of high waste rock piles constructed by push/end dumping using 2D and 3D FEM simulations* [Doctoral dissertation, Polytechnique Montréal].

Majdanishabestari, K., Ovalle, C., & Aubertin, M. (2024, September 15–18). Stability of high waste rock piles using 2D and 3D FEM simulations. *Annual Conference of the Canadian Geotechnical Society, GeoMontréal 2024*, Montreal, Canada.

Maknoon, M., & Aubertin, M. (2021). On the use of bench construction to improve the stability of unsaturated waste rock piles. *Geotechnical and Geological Engineering, 39*(2), 1425–1449.

Ministère de l'Énergie et des Ressources Naturelles [MERN]. (2016). *Guidelines for preparing mine closure plans* (M08-03a-1711).

Osses, R., Pineda, J., Ovalle, C., Linero, S., & Sáez, E. (2024). Scale and suction effects on compressibility and time-dependent deformation of mine waste rock material. *Engineering Geology, 340*, 107668.

Ouellet, S., Chapuis, S., & Ovalle, C. (2021, June 14–16). Le projet de co-déposition dans la fosse Canadian Malartic. *Symposium Rouyn-Noranda 2021 sur l'environnement et les mines*, Québec, Canada.

Ovalle, C., Frossard, E., Dano, C., Hu, W., Maiolino, S., & Hicher, P.-Y. (2014). The effect of size on the strength of coarse rock aggregates and large rockfill samples through experimental data. *Acta Mechanica, 225*, 2199–2216.

Ovalle, C., Linero, S., Dano, C., Bard, E., Hicher, P.-Y., & Osses, R. (2020). Data compilation from large drained compression triaxial tests on coarse crushable rockfill materials. *Journal of Geotechnical and Geoenvironmental Engineering, 146*(9), 06020013.

Polytechnique Montréal. (2021). *Rapport des tests de cisaillement direct de grande taille sur des roches stériles de la mine Canadian Malartic*.

Pramthawee, P., Jongpradist, P., & Kongkitkul, W. (2011). Evaluation of hardening soil model on numerical simulation of behaviors of high rockfill dams. *Songklanakarin Journal of Science & Technology, 33*(3), 281–292.

Richards, B. G., Coulthard, M. A., & Toh, C. T. (1981). Analysis of slope stability at Goonyella mine. *Canadian Geotechnical Journal, 18*(2), 179–194. https://doi.org/10.1139/t81-022

Schanz, T., Vermeer, P., & Bonnier, P. G. (1999a). The hardening soil model: Formulation and verification. In *Beyond 2000 in computational geotechnics—10 years of Plaxis* (pp. 281–296). Balkema.

Soroush, A., & Aghaei Araei, A. (2006). Analysis of behaviour of a high rockfill dam. *Proceedings of the Institution of Civil Engineers—Geotechnical Engineering, 159*(1), 49–59. https://doi.org/10.1680/geng.2006.159.1.49

Stark, T. D., & Eid, H. T. (1998). Performance of three-dimensional slope stability methods in practice. *Journal of Geotechnical and Geoenvironmental Engineering, 124*(11), 1049–1060. https://doi.org/10.1061/(ASCE)1090-0241(1998)124:11(1049)

Steiakakis, E., Kavouridis, K., & Monopolis, D. (2009). Large scale failure of the external waste dump at the "South Field" lignite mine, Northern Greece. *Engineering Geology, 104*(3–4), 269–279.

Sukkarak, R., Likitlersuang, S., Jongpradist, P., & Jamsawang, P. (2021). Strength and stiffness parameters for hardening soil model of rockfill materials. *Soils and Foundations, 61*(6), 1597–1614.

Ulusay, R., Arikan, F., Yoleri, M. F., & Ağlan, D. (1995). Engineering geological characterization of coal mine waste material and an evaluation in the context of back-analysis of spoil pile instabilities in a strip mine, SW Turkey. *Engineering Geology, 40*(1–2), 77–101.

Wang, W., & Griffiths, D. V. (2019). Case study of slope failure during construction of an open pit mine in Indonesia. *Canadian Geotechnical Journal, 56*(5), 636–648.

Wu, C., Wang, Z. Z., Goh, S. H., & Zhang, W. (2024). Comparing 2D and 3D slope stability in spatially variable soils using random finite-element method. *Computers and Geotechnics, 170*, 106324.

Xu, M., & Song, E. (2009). Numerical simulation of the shear behavior of rockfills. *Computers and Geotechnics, 36*(8), 1259–1264.