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# Mine tailings properties and its hypoplastic predictions

## Propriétés des résidus miniers et leurs prédictions hypoplasiques

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**ABSTRACT**: Copper mine tailings (CMT) are the waste material that remains after the economic fraction is extracted from the mineral ore and consist of a slurry of ground rock, water, and chemical reagents that remain after metallurgical processing. These tailings are considered toxic to the environment, so controlling their environmental toxicity and improving their mechanical properties are crucial. However, only a few studies have focused on assessing such performance by establishing the constitutive behaviour of the CMT. In this paper, we describe mine tailings properties and perform laboratory tests to calibrate clay hypoplasticity. Hypoplasticity is a constitutive model that includes concepts from Critical State Soil Mechanics, as a stress-dependent critical void ratio and a critical stress cone, according to Matsuoka-Nakai. The results show that hypoplasticity can well predict the mine tailings triaxial test behaviour.

**RÉSUMÉ**: Les résidus miniers de cuivre (CMT) sont les déchets qui restent après l'extraction de la fraction économique du minerai minéral et consistent en une boue de roche broyée, d'eau et de réactifs chimiques qui restent après le traitement métallurgique. Ces résidus sont considérés comme toxiques pour l'environnement, il est donc crucial de contrôler leur toxicité environnementale et d'améliorer leurs propriétés mécaniques. Cependant, seules quelques études se sont concentrées sur l'évaluation de ces performances en établissant le comportement constitutif du CMT. Dans cet article, nous décrivons les propriétés des résidus miniers et effectuons des tests en laboratoire pour calibrer l'hypoplasticité de l'argile. L'hypoplasticité est un modèle constitutif qui inclut des concepts de la mécanique des sols à l'état critique, comme un indice de vide critique dépendant de la contrainte et un cône de contrainte critique, selon Matsuoka-Nakai. Les résultats montrent que l'hypoplasticité peut bien prédire le comportement des essais triaxiaux des résidus miniers.

**Keywords:** Mine tailings; waste material; constitutive model; hypoplasticity.

## 1 INTRODUCTION

Mine tailings are the materials left over after the process of separating the valuable fraction of mined ores from the uneconomic fraction of the ore. Tailings can contain a variety of materials depending on the ore being mined. They often include finely ground rock particles, chemicals used in the extraction process, and water (Sarker et al., 2022).

Mine tailings pose significant environmental concerns. Proper storage in dams is crucial to mitigate their impact on surrounding ecosystems and water sources. The necessity of determining the behaviour of mine tailings is essential to design how it is deposited, which will influence their potential environmental impact and their management strategy (Cacciuttolo and Atencio, 2023). This assessment helps safeguard ecosystems, water sources, and communities from potential hazards such as acid mine drainage and other health risks, not to mention their mechanical stability (Rezaie and Anderson, 2020).

Constitutive models are indispensable for understanding and predicting the mechanical behavior of materials. Their importance extends beyond academic study to practical engineering solutions that drive innovation. Determining the behavior of mine tailings with constitutive models involves using mathematical representations to describe how these materials respond to various mechanical conditions (Qiu et al., 2018). These models are based on fundamental principles of material behavior, which are also determined through triaxial tests and can help predict stress-strain relationships, peak and critical shear strength, among other important aspects that control the overall response of tailing deposits. By applying constitutive models, users can simulate and analyse the performance of mine tailings in different scenarios, aiding in the design of safe storage and containment systems (Bursa et al., 2023).

## 2 EXPERIMENTAL WORK

To assess the behaviour of copper tailings from the Neves Corvo mine located in Portugal, triaxial compression undrained tests (CU) were conducted to determine the shear strength characteristics of mine tailings. According to the ASTM unified classification (2006), the copper mine tailing was designated as CL—lean clay with liquid and plastic limits of 23% and 11%, respectively (Manaviparast et al., 2022).

For the purpose of simulating the deposition of mining waste in landfills and simulating deposition in layers, each test sample was molded in 6 layers, with a pre-established amount of mixture introduced into each layer and compacted. The compaction process of each layer was important since each layer was compacted with a different degree of compaction; as the layers progressed, the greater degree of compaction applied. However, in theoretical terms, all layers will have the same density due to the adjustments that the material makes with the different degrees of compaction applied to each of the layers.

According to the BS 1377-7 (1990) standard, tests were performed through three distinct phases of saturation, consolidation, and shear under confining stresses of 97 kPa, 188 kPa, and 277 kPa in normally to slightly overconsolidated conditions to be utilized as a pivotal foundation for the calibration of model parameters. The experimental results, including the trajectory of stress paths, deformation characteristics, the stress-strain relationship, and the evolution of pore pressure with axial strain, are shown in Figures 1 to 4, respectively.

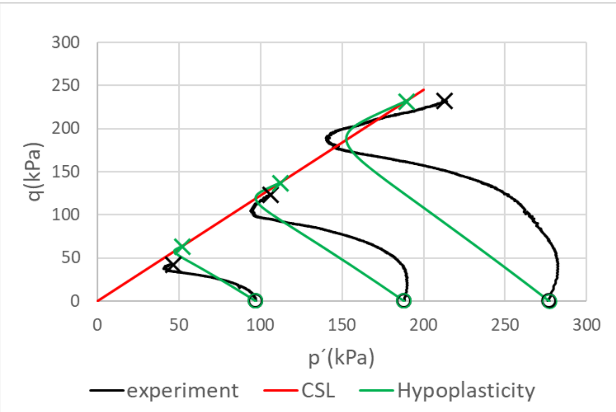


*Figure 1. Experimental and hypoplastic stress paths observed in the q-p' plane for triaxial tests (CU) on mine tailing samples under slightly overconsolidated conditions.*

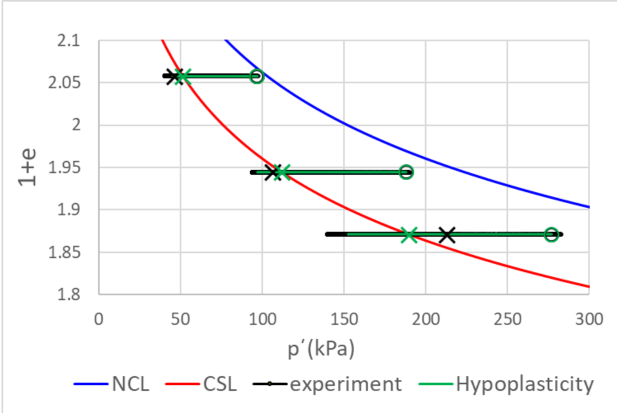


*Figure 2. Experimental and predicted hypoplastic paths observed in the (1+e)-p' plane for triaxial tests (CU) on mine tailing samples under slightly overconsolidated conditions.*

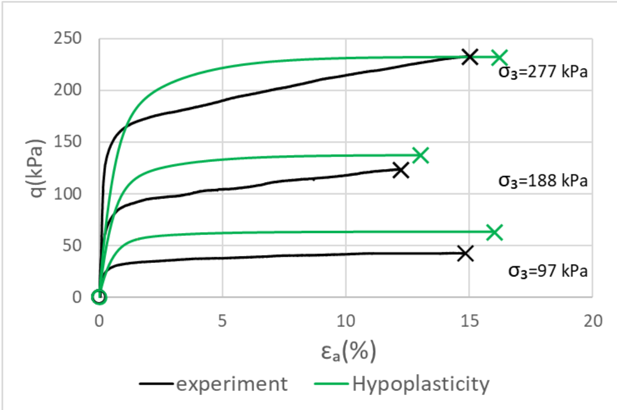


*Figure 3. Experimental and predicted hypoplastic relation between deviatoric stress and axial strain.*

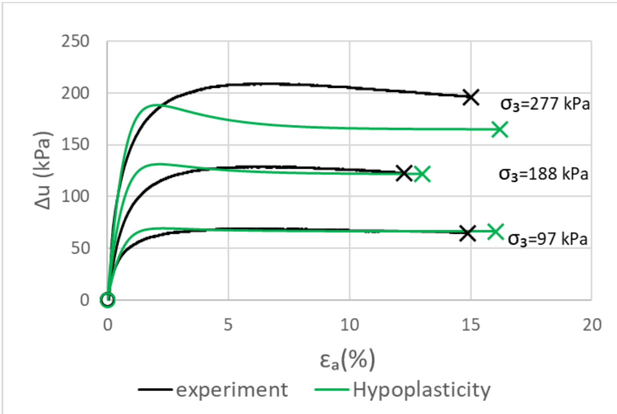


*Figure 4. Evolution of pore pressure with axial strain in the experiments and the hypoplastic predictions.*

## 3 PREDICTIONS WITH CLAY HYPOPLASTICITY

Clay hypoplasticity (Mašín, 2013) is a constitutive model in which the stress rate is formulated as a tensorial function of the current stress $\boldsymbol{\sigma}$, void ratio $e$, and strain rate.

Hypoplasticity incorporates concepts from critical state soil mechanics, such as the critical stress cone, according to Matsuoka-Nakai, and a stress-dependent critical void ratio $e_c$, i.e., the critical state line (CSL) in the void ratio vs the mean effective stress plane. The strength and stiffness response is, therefore, dependent on the stress level and the overconsolidation ratio. Figure 5 shows the so-called asymptotic state boundary surface (ASBS) of clay hypoplasticity in the *p'-q-e* space (left) and in the *p'-q* and *e-p'* projections. All feasible states lie within the ASBS. In the *(1+e)-p'* projection, the Normal Compression Line (NCL), as well as the CSL are defined as follows:

$$\text{NCL: } ln(1+e) = N - \lambda^* \, ln\, p' \qquad (1)$$

$$\text{CSL: } ln(1+e) = N - \lambda^* \, ln(2p') \qquad (2)$$

The slope of the CSL in the *p'-q* projection is

$$M = \frac{6 sin\, \varphi_c}{3 - sin\, \varphi_c} \qquad (3)$$

for axisymmetric triaxial compression.

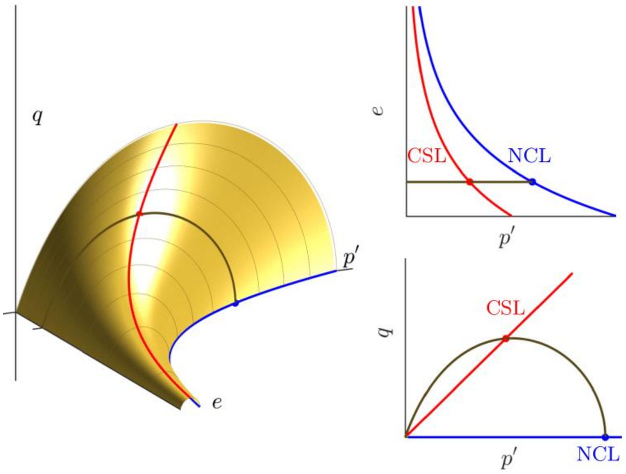


*Figure 5. Clay hypoplasticity: Concepts from Critical State Soil Mechanics are included in the model. Left: Asymptotic state boundary surface (ASBS) of clay hypoplasticity in p'-q-e space, above right: e-p' projection, below right: p'-q projection [Link].*

## 3.1 Calibration

For the calibration of some of the model's parameters, the automatic calibration software Excalibre, soilmodels.com/excalibre-en, developed by Kadlíček et al. (2022a, 2022b), available on the platform SoilModels (Gudehus et al., 2008) was used.

Due to the lack of compression data, the parameters to define the NCL have been estimated based on the initial states of the normally to slightly overconsolidated initial states of the CU tests, see Figures 1 and 2. The slope of the CSL in the $p'$-$q$ plane is governed by the critical friction angle $\varphi_c$ according to equation (3). The parameter $\nu$ was calibrated by parametric study to capture the shape of the undrained stress paths, see Figure 1. In the absence of isotropic unloading data, $\kappa^*$ was set to the typical value of 0.1 (Mašín, 2013). All parameters of clay hypoplasticity are provided in Table 1.

*Table 1. Calibrated model parameters.*

| Parameters | Value |
|---|---|
| Ordinate intercept of the NCL (N) | 1.06 |
| Slope of the NCL ($\lambda^*$) | 0.073 |
| Slope of unloading line under isotropic compression ($\kappa^*$) | 0.01 |
| Critical friction angle ($\varphi_c$) | 30.6° |
| Poisson's ratio ($\nu$): controls the shear modulus and affects the shape of undrained stress paths | 0.25 |

## 3.2 Predictions with hypoplasticity

The samples are initially normally to slightly overconsolidated, with the initial states marked with o in Figures 1-4.

The critical strength $q_c$ equals $M \cdot p'_c$, where $p'_c$ follows from the location of the CSL in *(1+e) - p'* plane, see Figure 2. In hypoplasticity the position of the CSL in relation to the NCL is fixed by $p'_e/p_c'=2$, where $p'_e$ is the so-called Hvorslev's equivalent pressure on the NCL and $p'_c$ is the mean effective stress at critical state on the CSL. The final states of the simulations, as well as the experiments, are marked with x. The pore water pressure and the deviatoric stress of the experiments are not yet constant. This means that the samples are still approaching the critical state and have not yet reached it. The final points of the simulations already lie on the CSLs in Figures 1 and 2. Deviatoric stress *q* as well as the pore pressure at a given axial strain are well predicted by the model, see Figures 3 and 4. In order to predict the undrained strength of samples with different initial densities, it is necessary to use a constitutive model that incorporates the framework of critical state soil mechanics.

# 4 CONCLUSION

Understanding the behavior of mine tailings is of paramount importance for the safe and responsible management of these waste materials. Triaxial tests provide invaluable insights into the mechanical properties and stability of mine tailings under varying stress conditions, offering essential data for the design of secure containment systems. Furthermore, employing constitutive models enhances our ability to predict and analyse the response of mine tailings, enabling informed decision-making in engineering practices. By leveraging both experimental testing and mathematical representations, we can effectively address environmental concerns and minimize potential risks associated with the disposal of mine tailings. This comprehensive approach underscores the significance of adopting responsible mining practices that prioritise the protection of ecosystems, water sources, and surrounding communities.

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## REFERENCES

Bursa, B., Stefaniak, P., & Kakogiannos, I. (2023). Applying Model-Based Systems Engineering to Tailings Storage Facility Structures. *Materials Proceedings*, 15(1), 12. https://doi.org/10.3390/materproc2023015012.

Cacciuttolo, C., & Atencio, E. (2023). In-Pit Disposal of Mine Tailings for a Sustainable Mine Closure: A Responsible Alternative to Develop Long-Term Green Mining Solutions. *Sustainability*, 15(8), 6481. https://doi.org/10.3390/su15086481.

Gudehus, D., D., Amorosi A., Gens, A., Herle, I., Kolymbas, D. Mašín, D., Muir Wood, D., Nova, R., Niemunis, A., Pastor, M., Tamagnini, C., Viggiani, G. 2008. The soilmodels.info project. *International Journal for Numerical and Analytical Methods in Geomechanics*, 32:1571–1572. https://doi.org/10.1002/nag.675.

Kadlíček, T., Janda, T., Šejnoha, M., Mašín, D., Najser, J. & Beneš, Š. 2022a. Automated calibration of advanced soil constitutive models. Part II: hypoplastic clay and modified Cam-Clay. *Acta Geotechnica,* 17:3439-3462. https://doi.org/10.1007/s11440-021-01435-y.

Kadlíček, T., Janda, T., Šejnoha, M., Mašín, D., Najser, J. & Beneš, Š. 2022b, Automated calibration of advanced soil constitutive models. Part I: hypoplastic sand. *Acta Geotechnica,* 17:3421-3438. https://doi.org/10.1007/s11440-021-01441-0.

Manaviparast, H. R., Pinheiro, J., Najafi, E. K., Abreu, C., Araújo, N., Cristelo, N., & Miranda, T. (2022). Mechanical Behavior of a Mine Tailing Stabilized with a Sustainable Binder. *Applied Sciences*, 13(7), 4103. https://doi.org/10.3390/app13074103.

Mašín, D. 2013. Clay hypoplasticity with explicitly defined asymptotic states, *Acta Geotechnica*, 8, 481-496. https://doi.org/10.1007/s11440-012-0199-y.

Mašín, D. 2013. Clay hypoplasticity with explicitly defined asymptotic states. *Acta Geotechnica*, 07(5):481–496. https://doi.org/10.1007/s11440-012-0199-y.

Qiu, J. P., Yang, L., Xing, J., & Sun, X. G. (2018). Analytical solution for determining the required strength of mine backfill based on its damage constitutive model. *Soil Mechanics and Foundation Engineering*, 54, 371-376. https://doi.org/10.1007/s11204-018-9483-7.

Rezaie, B., & Anderson, A. (2020). Sustainable resolutions for environmental threat of the acid mine drainage. *Science of The Total Environment*, 717, 137211. https://doi.org/10.1016/j.scitotenv.2020.137211.

Sarker, S. K., Haque, N., Bhuiyan, M., Bruckard, W., & Pramanik, B. K. (2022). Recovery of strategically important critical minerals from mine tailings. *Journal of Environmental Chemical Engineering*, 10(3), 107622. https://doi.org/10.1016/j.jece.2022.107622.