Cyclic Response of Mine Tailings at Field and Laboratory Scales – Example Using a Novel Database

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Abstract

Cyclic liquefaction induced by seismic loading from earthquakes is a major concern for countries with active mining industries and moderate seismicity such as Peru, Chile, and the USA. Cyclic liquefaction is more likely to induce flow failure as compared to other failure modes, and has been associated with a large portion of failures in seismic countries like Chile. Chile is a leading provider of copper and lithium to the global market, and the country's ability to sustain such a large mining sector could be hindered by its ability to safely store its tailings. Mine tailings have been shown to have unique mechanistic responses dissimilar to that of traditional soils (i.e., sands and clays). Much of engineering practice relies on techniques and procedures developed from data derived from sands and clays. As such, our understanding of the cyclic behavior of mine tailings needs continued research interest to extract new insights into their unique behavior. This paper utilizes a recently developed database focused on the cyclic response of mine tailings to highlight some insights into their peculiar behavior. Specifically, their unique range of material properties and resulting liquefaction curves, the applicability of existing factors in the liquefaction assessment of these materials as compared to sands, and a comparison of in-situ and laboratory-derived cyclic resistances are showcased.

Introduction

The design of sustainable tailings storage facilities (TSFs) is of major concern to both the countries they lie within and the countries that benefit from the extracted resources. The Paris Climate Agreement was adopted by 196 member countries of the United Nations in 2015. The agreement aims to keep global warming below 2 degrees Celsius through the transition from fossil fuels to more sustainable energy solutions (e.g., wind, solar, hydroelectric, electric cars, etc.). Many countries have implemented legislation to match. As an example, the U.S.A. aims to reduce its greenhouse gas emissions by 50% below 2005 levels by 2030. However, with this transition to renewables comes increased demand for the raw materials required to implement such technologies. As an example, the demand for copper, which is utilized in a wide array of renewables, is expected to double from 25 million metric tons in 2022 to over 51 million metric tons by 2050 (S&P Global, 2022). Similarly, the demand for other metals is projected to increase as well (Eyzaguirre and Araya, 2021). This creates a major hurdle, because with the increasing demand and the degradation of ore grade (Bowker and Chambers, 2017), the amount of in-situ material that needs to be extracted for processing grows drastically. This leads to an enormous amount of waste material (tailings), which poses a direct threat to the environment and human life. Consequently, this has led to more dams being constructed in the past decade than any decades prior (Warburton et al., 2019), as well as dams being designed to hold larger volumes of waste. While the average number of yearly TSF failures has remained constant (Piciullo et al., 2022) the severity of failures (i.e., the amount of released waste) has been increasing (Piciullo et al., 2022; Bowker and Chambers, 2017).

After several high-profile TSF failures (e.g., Brumadinho, 2019; Fundao, 2015; Cadia, 2018) a consortium of agencies, one of which was the United Nations Environmental Program, released the global industry standards on tailings management (GISTM) (ICMM et al., 2020) with the goal of reducing TSF failures. Several notable tailings engineers also conducted their own studies seeking to highlight the contributing factors to these failures. One such individual was Norbert Morgenstern, who evaluated fifteen TSF incidents and classified their contributing factors into three categories: engineering, operations, and regulatory. Morgenstern (2018) determined that engineering was the primary factor in the failures. Other independent studies (Been, 2016; Jefferies, 2021) have reached similar conclusions.

In a detailed look at failure causes by Piciullo et al. (2022), the three known major causes of failure are overtopping (23%), static (16%), and dynamic liquefaction (14%). However, despite dynamic liquefaction only being the third most common cause, it sees a disproportionally higher association with flow failures as compared to overtopping and static liquefaction (Halabi et al., 2022). This makes the seismic design of TSF in countries with active mining industries and moderate to high seismicity (e.g., Peru, Chile, USA) a major concern.

For instance, Chile is the leading producer of copper ore and the second largest producer of lithium in the world at 28% and 30%, respectively (USGS, 2023a; USGS, 2023b). Chile also has the largest reserves of copper and lithium (USGS, 2023a; USGS, 2023b), and therefore its ability to safely mine and store tailings in perpetuity is crucial to the global supply. However, between 1901 and 2013 the primary cause of TSF failures in Chile was earthquake-induced (cyclic) loading (Villavicencio et al., 2013) with nearly 50% of those involving flow failure. These studies highlight the lack of knowledge surrounding the cyclic response of mine tailings and the need for further research into their unique cyclic behavior.

Mine tailings are typically classified as silts or silty sands and have characteristics that separate them from naturally occurring silts (e.g., angularity, mineralogy, etc.). This poses a challenge to tailings engineers, as most engineering approaches for seismic design have been developed from databases and case histories of sites mainly containing sands and a few natural silts (Seed and Idriss, 1982). Additionally, several studies have highlighted that the scaling of mechanical properties in mine tailings varies from that of naturally occurring soils (Macedo and Vergaray, 2021; Jefferies and Been, 2016) even at similar gradations (Ishihara et al. 1980; Geremew and Yanful, 2012). This paper utilizes a recently developed database (Arnold and Macedo, 2024) focused on the cyclic response of mine tailings to look at unique trends in their behavior, as well as to assess existing procedures for seismic design. Specifically, the scaling factor for overburden stress (K_σ) is assessed for a selected tailing from the database in conjunction with past trends for sands. Additionally, the Boulanger and Idriss (2014) method for estimating the cyclic resistance (CRR) from cone penetration testing (CPT) is compared against laboratory-based estimates from cyclic simple shear (CSS) tests, for a selected tailing.

Database

A recently developed database (Arnold and Macedo, 2024) focused on the cyclic response of mine tailings grants a novel opportunity to study the unique response of tailings materials. As shown in Figure 1a, there is a wide range of particle size distributions (PSD) present within the database. The database contains about 130 CSS tests on 20 different mine tailings gradations. As previously mentioned, mine tailings are typically identified as non-plastic silty sands to sandy silts with fine contents (FC) typically ≥ 35%, which is indeed the case for many of the tailings in the database, as highlighted by the histograms in Figures 1b and 1c. This does however highlight an existing gap with regard to tailings that do contain plasticity, as they are not as well represented.

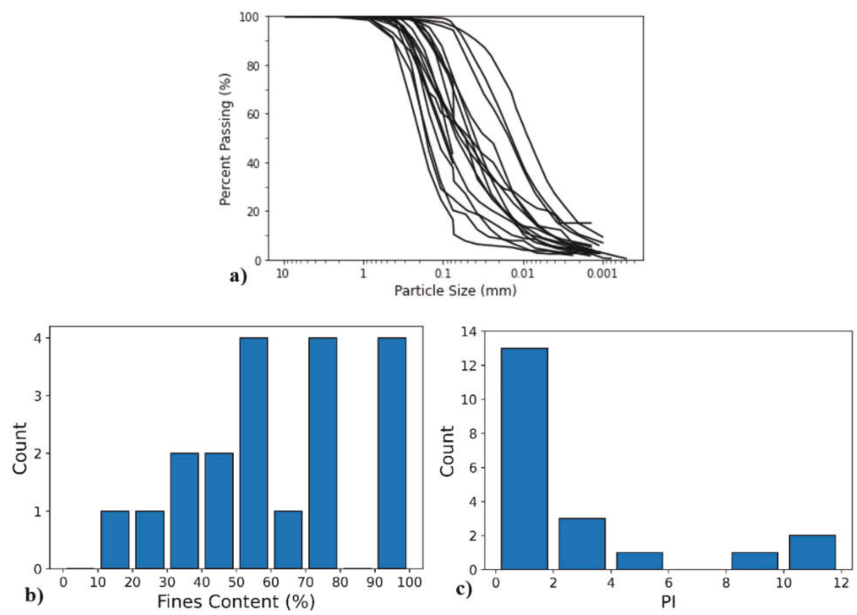

Figure 1: Range of a) PSD, b) FC, and c) PI for available mine tailings within the database (Arnold and Macedo, 2024)

The database is also unique in that it offers a robust amount of secondary information on its materials in the form of critical state line (CSL) via triaxial testing and in-situ information via CPT. To discern the materials by how much data is available on each they are placed into one of three classes: A, B, and C. Class A is the most numerous and indicates those materials containing all three data types (CSS, CSL, and CPT). Class B denotes those with CSS and one other data type (CSL or CPT), and class C denotes those with only CSS data available. Furthermore, supplemental data (e.g., FC, plasticity index (PI), ore type, etc.) regarding the materials is also made available, when possible.

Insights

The cyclic resistance of soils can be assessed in several ways but the use of CSS testing is quite commonly used. Estimating the cyclic resistance requires a minimum of 3 CSS tests to derive a liquefaction resistance curve. However, it is not uncommon for 4 or 5 tests to be used for greater accuracy. The liquefaction resistance curve relates the cyclic stress ratio (CSR) to a predefined failure criterion (N_{liq}), typically associated with a strain criterion (i.e., 3.75% single amplitude). The failure point of each test is then plotted CSR against N_{liq} in log scale and is fitted by a power law. Equation 1 represents a resistance curve with fitting parameters *a* and *b*.

$$(1)\ \boldsymbol{CSR = aN^{-b}}$$

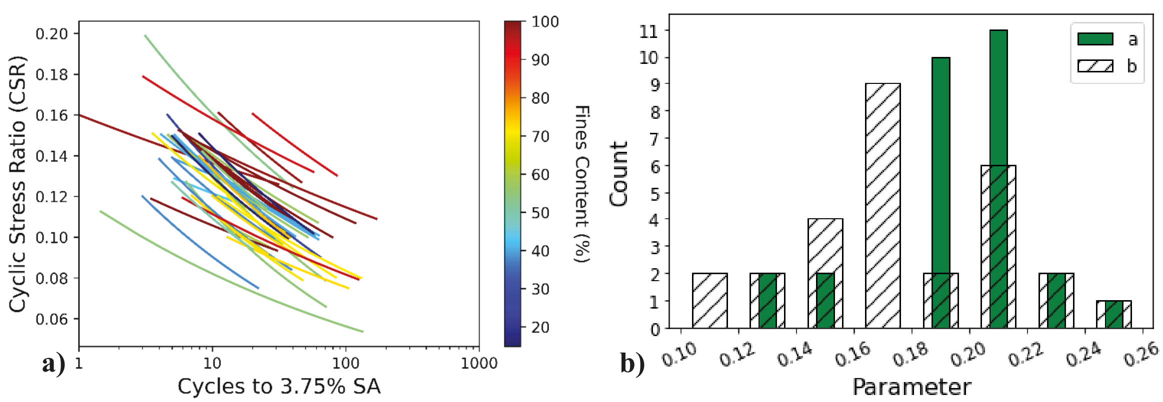

Figure 2: a) Liquefaction resistance curves for database materials labeled by FC and b) range of fitting parameters (*a* and *b*) (Arnold and Macedo, 2024)

The resistance curve is then used to further interpret a cyclic resistance of an equivalent earthquake loading. For instance, it is quite common to consider 15 cycles (CRR_{15}) in liquefaction-triggering procedures such as the Seed and Idriss (1982) procedure. Thus, deriving CRR_{15} at a given confinement and density requires the previously mentioned 3 to 5 CSS tests. Figure 2a shows the liquefaction resistance curves from the database labeled by FC, and the resulting fitting parameters are shown in Figure 2b. In general, *a* is lower than what is typically seen in sands (~ 0.27). This is further highlighted by Figure 3a which shows that the database tailings need only relatively low CSR values to liquefy, even under high-stress states (a significant number of tests ≥ 300 kPa).

Another aspect to highlight is the slope of the resistance curves which is captured by the *b* parameter, which is on average around 0.19 (Figure 2b). This is notable as sands have typical b values on the order of 0.34 (Idriss and Boulanger, 2008). In fact, it is more similar to the *b* value seen in clays (~ 0.14 - Idriss and Boulanger, 2008) which is interesting as mine tailings would typically be expected to show a more "sand-like" response based on their material properties. For instance, considering the fact that most of these are non-plastic tailings (Figure 1c) the method from Idriss and Boulanger (2006) would classify them as sand-like (PI ≤ 7). This discrepancy highlights the challenges in designing for these materials as they exhibit "sand-like" responses but have significant compressibility more akin to clays.

The compressibility of these non-plastic tailings is further exemplified by the magnitude of their CSL slopes (λ_e). Figure 3b shows the range of λ_e for the tailings within the database, on average they are around 0.07. This is twice as large as λ_e typically reported for common testing sands (~ 0.033) and for natural sands (~ 0.037) as reported by Jefferies and Been (2016).

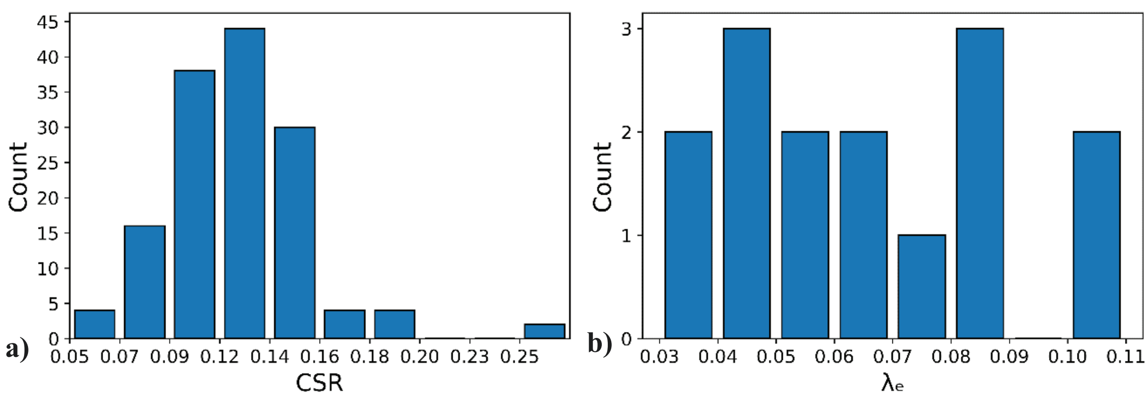

Figure 3: Range of a) CSR and b) λ_e for available mine tailings within the database (Arnold and Macedo, 2024)

Overburden stress effect

As previously discussed, the K_σ scaling factor plays an important role in the liquefaction assessment of soils. This is especially true in large TSF as the large height to which these structures are built is accompanied by large overburden stresses. The original scaling factors were derived from case histories on predominantly sandy soils. These factors denoted that increasing vertical stress would negatively affect the cyclic resistance (i.e., increasing confinement results in lower K_σ). Several authors since have proposed their own trends for K_σ in sands. For instance, shown in Figure 4 is the consensus curve proposed by Hynes et al. (1998) for sands as well as the semi-empirical trends proposed by Idriss and Boulanger (2006) based on case histories for non-cohesive soils (PI ≤ 7).

Conversely, data for mine tailings has been shown to indicate little or even a positive effect from increasing confinement. The data from Ingabire (2019) shows a base metal tailing at two varying relative densities (D_r); which are close to K_σ values of 1. A material from the database is also plotted, indicating an agreement with the Ingabire tailings. The chosen material (5_3) is non-plastic with about 40% fines. For both sands and tailings, researchers have noted that the looser the material the less impactful K_σ will be. However, for the tailings shown here even denser states have significantly less effect from K_σ than has been seen in sands. This has been noted by other authors as well (Sanin, 2005; Sanin, 2010; Verma, 2019; Al Taarhouni et al., 2011). Some authors have also noted a positive effect from K_σ (Wijewickreme et al., 2005; Sadrekarimi and Jones, 2019).

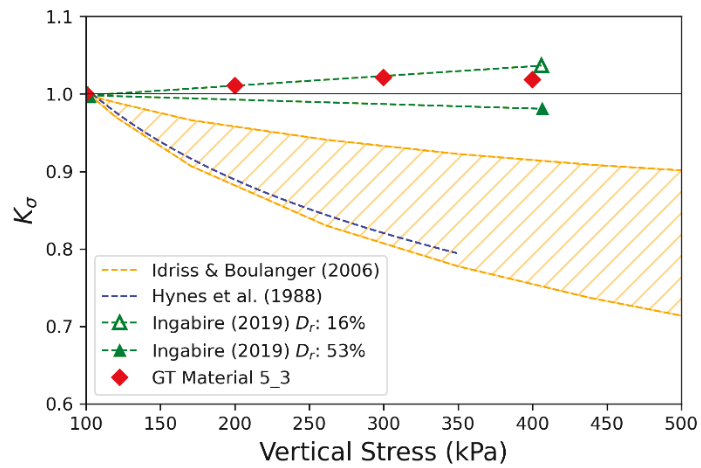

Figure 4: Kσ for GT material 5_3 compared against published trends

In summary, the effect of overburden stress and how it will ultimately affect the scaling factor (K_σ) in mine tailings is largely unknown. Despite the numerous studies that exist to date there does not yet seem to be a consensus on how to approach this for mine tailings materials. In the development of K_σ trends for sands large databases of either laboratory testing or case histories were required. This is where mine tailings suffer from a large knowledge gap as there are very few databases available to utilize. We expect that the database referred to in this study would be instrumental in allowing for further insights into the K_σ factor applicability to mine tailings by conducting more comprehensive assessments similar to those shown in Figure 4.

Comparison of field-corrected laboratory derived cyclic resistance with CPT estimates

As discussed in the previous section, the estimation of cyclic resistance for a given soil under a given demand can be estimated via laboratory testing (i.e., CSS) however, several methods (e.g., Boulanger and Idriss, 2014) exist for estimating from in-situ testing (i.e., CPT). These types of methods are very desirable, especially in the early stages of design, as it can take time to acquire samples and perform the necessary tests. The validity of these in-situ estimations is of great interest and given the availability of CPT and CSS information within the database it is worthwhile to compare the two. Other authors have made similar comparisons, however for natural soils (Mijic et al., 2021).

Figure 5 showcases material 4_1 from the database with both the Boulanger and Idriss (2014) interpretation as well as the laboratory-derived CRR_{15}, with a correction factor of .9 (Seed, 1979). The laboratory samples were recovered from 7.5 m and 10.5 m; however, the tested specimens were reconstituted in the laboratory. Given this, it is surprising to see that the laboratory and field-derived CRR values are quite similar. Even for fully intact specimens, many factors could result in differences between the two interpretations (i.e., in-situ fabric). More comparison between in-situ and laboratory estimates, as those presented in Figure 5 are encouraged as it is quite difficult to recover undisturbed tailings samples (Wijewickreme et al., 2005), and most procedures for assessing the cyclic resistance have been developed for soils with low fines content and cannot be assumed to apply directly to tailings. The recent database developed by Arnold and Macedo (2024) could contribute to that direction, hopefully with more contributions from the tailings community.

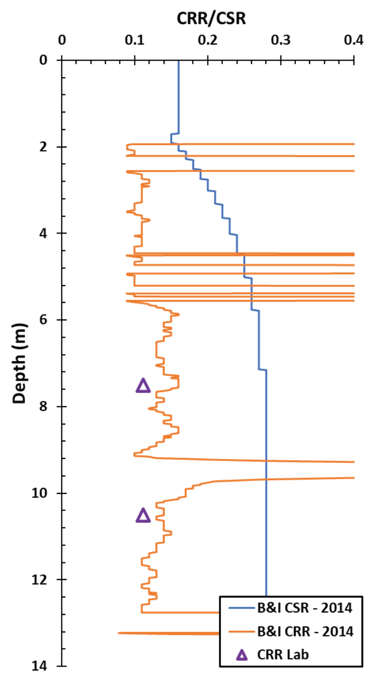

Figure 5: Comparison of field-adjusted laboratory derived CRR and field estimated CRR for material 4_1

Conclusion

This paper highlights the usefulness of a recently developed database on the cyclic response of mine tailings (Arnold and Macedo, 2024). The database provides a wide range of different mine tailings gradations with many having field (CPT), cyclic (CSS), and critical state (CSL) information available. This presents a novel opportunity for investigating the unique behavior of these materials and assessing the applicability of procedures developed for sands and clays. Initial insights from the database are shown herein.

The database tailings are comprised of mostly non-plastic sandy silts to silty sands with FC ≥ 35%, on average. Their liquefaction resistance curves highlight a unique response that is influenced by their compressibility, which is shown to be more significant than in natural silts and sands. The overburden stress correction factor (K_σ) has been studied heavily in sands by many authors and the expected behavior is a negative effect of cyclic resistance with increasing confinement. However, a mine tailing from the database is plotted against these trends showing an inverse behavior, increasing resistance with increasing confinement. This raises questions regarding the applicability of existing K_σ relationships to mine tailings materials.

Lastly, the estimation of cyclic resistance via in-situ testing (i.e., CPT) (Boulanger and Idriss, 2014) is compared against the laboratory-derived values. The results show good agreement between the field and laboratory values, which is surprising considering that the laboratory specimens were reconstituted. This could be because mine tailings are relatively young materials geologically and there is not much difference between in-situ fabric and laboratory reconstructed specimens (e.g., lack of field bonding). Estimating the cyclic resistance from reconstituted specimens is quite common considering the challenges associated with recovering intact tailings samples. More comparisons such as this are encouraged to gain confidence in the laboratory and field-based estimates of cyclic resistance; particularly, because field-based methods have not been formulated for mine tailings specifically.

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