GEOTECHNICAL DESIGN CHALLENGES LINKED WITH DYNAMIC STABILITY ANALYSIS TO ENSURE THE SAFETY OF MINE TAILINGS STORAGE FACILITIES WITH LARGE DAMS LOCATED IN PERU.

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ABSTRACT: The global failures of mine tailings storage facilities (TSFs) in recent years have affected the mine industry's reputation, prompting the establishment of standards integrating best practices and advanced technologies in the design, construction, and management of TSFs. Dynamic stability analyses, encompassing both pseudo-static and dynamic assessments, are pivotal in ensuring the physical stability of TSF dams. This article focuses on geotechnical design challenges in dynamic stability analysis for large TSF dams in Peru, particularly addressing extreme topographic and seismic conditions in the Andean region. Two cases are studied a 265 m high rockfill dam (Case Study 1) and a 300 m high cycloned tailings dam (Case Study 2) considering the performance results of dynamic stability analysis evaluated based on two extreme seismic events recorded in Peru: Chimbote Earthquake 7.9 Mw for case study 1, and Arequipa Earthquake 8.4 Mw for case study 2. The result of the study indicates that considering the best available engineering practices (BAEPs) related to the design of: (i) dam material properties, (ii) dam geometry, (iii) dam foundation characteristics, (iv) dam constructive sequence and schedule, and (v) mine tailings management activities, among others, the performance of these TSF dams is safe. Finally, the study concludes that according to applying conservative engineering and construction design criteria focusing on the reduction of risks, the performance of these TSFs with high dams will meet the admissibility criteria for safety factors, displacements, and deformations indicated by local and international regulations in an extremely seismic region. However, to promote the sustainability of mining, to reduce the risks/uncertainties related to climate change hazards, and ensure the most high-quality standards of safety, and periodic control, actualization, and evaluation of the dynamic stability analysis of the lifetime of mine tailings infrastructure will be strictly necessary.

KEYWORDS: Dynamic stability analysis, extreme seismic conditions, mine tailings storage facility, high dams, cycloned tailings dams, rockfill dam, safety, local and international regulations.

1. Introduction

The management of mine waste is widely recognized as one of the major socio-environmental concerns in major mine operations worldwide. In numerous mines, especially those dedicated to the extraction of gold and copper, over 99% of the processed material is transformed into waste, including mine tailings (Cacciuttolo and Atencio, 2022). Given that mine tailings often contain a significant proportion of water mixed with heavy metals, their safe and sustainable disposal is critical to prevent groundwater and surrounding environment contamination (Cacciuttolo, Cano and Custodio, 2023). Furthermore, compiled research shows a relatively high frequency of failures in tailings dams, especially under dynamic loads, which can lead to serious consequences such as loss of human life and property, as well as significant and irreversible environmental impact (Cacciuttolo and Cano, 2023).

1.1 Context of Recent Tailings Storage Facility Failures

An extensive database compiling failures of mine tailings dams from 1915 to the present, categorized by dam and failure characteristics, is publicly available and updated periodically at (CSP2, n.d.). It is important to note that the statistics included in these data comprise only reported failures of mine tailings dams; many failures and associated lessons learned are not published due to sensitivities or legal implications. Below, we present Table 1 with the list of TSF failures from different countries since 1915.

Table 1. Tailings dam failures registered worldwide (CSP2, s.f.).

Country	N° of Failures
Japan	5 failures
Australia	7 failures
Brazil	14 failures
Canada	18 failures
China	18 failures
Peru	19 failures
Chile	47 failures
United States	104 failures

1.2 Importance of TSF Physical Stability Analyses

Conducting pseudo-static and dynamic physical stability analyses fort TSFs is of vital importance in addressing the issue of prevent failures in tailings dams, especially those located in complex geographical sites considering highly seismic and high-altitude characteristic. The consequences of failures like a dam break in these mine tailings infrastructures can be devastating for both the environment and society (Sernageomin, 2018).

The physical stability analysis process in this study, involves assessing the safety of mine tailings dams located in the Andean region of Peru constructed using the centerline and downstream methods. Additionally, the TSF stability analysis considering factors such as dam geometry, dam and mine tailings material properties, groundwater conditions, static conditions, pseudo-static conditions, and residual conditions resulting from cyclic loads under extreme seismic conditions. The aim is to understand the phenomena that occur in the stress state of mine tailings when subjected to seismic loads. By gaining a deeper understanding of these extreme seismic events and phenomenology, the aspiration is to comprehend the principles governing the physical stability of these infrastructures. These analyses are essential to ensure the safety and sustainability of mine tailings dams in seismic environments, also considering the uncertainty of the effects of climate change, thereby minimizing the risk of potential catastrophic failures and their associated impacts. In summary, conducting pseudo-static and dynamic stability analyses on large mine tailings dams is crucial to reduce risks as low as reasonably practicable (ALARP), ensure safety, comply with regulations, optimize designs, and prevent devastating consequences in the event of seismic events or other extreme loads. These analyses are an integral part of responsible and sustainable mine tailings governance linked with the main principles of the Global Industry Standard on Tailings Management (GISTM).

1.3 Characterization of Study Area for Case Study 1 and Case Study 2

The study area for Case Study 1 is located within the Peruvian Andes Mountain range, with facilities situated at elevations ranging from 2,300 to 4,000 meters above sea level. In this context, the milling operation is projected to recover approximately 575 million tons of ore and transport 1.4 billion tons of extracted rock over a project duration of 24 years. This operation is expected to generate an estimated 546 million tons of mine tailings, which will be storage in a TSF with a rockfill dam reaching a final height of 265 meters.

According to regarding the severe Peruvian seismic context, the region occupies a relatively low-seismicity zone within the active convergent arc region, between the subducting Nazca oceanic plate to the west and the overlying South American continental plate to the east. Positioned within the high Andes of the South American plate, the mine site experiences seismic activity predominantly associated with normal slip faults and widely distributed earthquakes. Additionally, it is situated on a hydrographic basin with a wet climate with low annual precipitation of 2000 mm. For a visual representation, please refer to Figure 1, which illustrating the geometry of the mine tailings dam constructed using the downstream method, showing a typical cross-section and its primary components in its final dam stage.

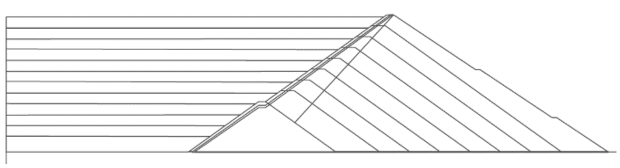


Figure 1. Typical cross-section of mine TSF dam case study 1. Source: (Eldridge, Moffitt, Botts, and Dechert, 2014).

In Case Study 2, the TSF comprises an initial 85-meter-high zoned rockfill dam, succeeded by a 300-meter-high embankment constructed with cycloned mine tailings, compacted using the centerline method. It is located on an eroded Peruvian plateau with valleys of dry streams that create steep topography. Elevations range from 2,300 to almost 3,000 meters above sea level.

The local geology encompasses volcanic ash, alluvial deposits, and colluvial deposits atop metamorphic, volcanic, sedimentary, and igneous rocks. The soil predominantly consists of robust rock with low permeability. Alluvial and colluvial soils are prevalent at the valley floor and slopes. Downstream of the mine tailings dam, the alluvial soil appears thicker, while colluvial soil comprises thin layers on steep slopes. Additionally, it is situated on a hydrographic basin with a dry climate with low annual precipitation of 200 mm.

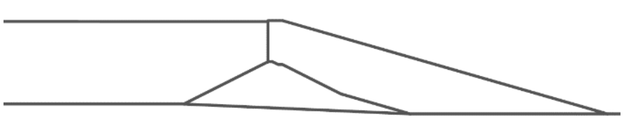


Figure 2. Typical cross-section of the mine TSF dam case study 2. Source: (Obermeyer and Alexieva, 2011)

1.3.1 Seismic Context for Case Study 1

Near the Case Study 1 area, the renowned Ancash earthquake of 1970 struck off the coast of Chimbote. Its epicenter was situated 20 km southwest of Chimbote city in the Pacific Ocean, at a depth of 1 km. According to the Peruvian Geophysical Institute (IGP) and the United States Geological Survey (USGS), it registered a magnitude of 7.9 Mw on the moment magnitude scale. This seismic event reached a maximum intensity of grade IX on the Modified Mercalli Scale in the city of Casma. Furthermore, it triggered a severe landslide in the towns of Yungay and Ranrahirca. The Ancash earthquake inflicted significant damage on the population, deemed the most destructive and devastating in Peru's history. The Ancash earthquake recorded its maximum acceleration of 0.12g from the accelerogram of the Parque de la Reserva station in Lima city.

1.3.2 Seismic Context for Case Study 2

According to the Peruvian Geophysical Institute (IGP), an earthquake measuring magnitude 8.4 (Mw) impacted the entire southern region of Peru, extending to the cities of Arica and Iquique in Chile, and La Paz in Bolivia. The earthquake's epicenter was in the southern region near the coastline, 82 km northwest of the town of Ocoña, Department of Arequipa. This earthquake exhibited notable characteristics, including evidence of a heterogeneous and shallow rupture process, leading to surface undulation. The Arequipa earthquake on June 23, 2001, registered a magnitude of 8.4 (Mw), with its maximum acceleration of 0.3g recorded from the accelerogram of the MOQ001 station in Monquegua city.

2. Materials and Methodology

To conduct the physical stability analysis of the proposed case studies, the Geostudio software was implemented, focusing specifically on: (i) the use of SLOPE/W modules for deterministic slope stability considering pseudo-static analyses, using the conventional limit equilibrium methods, (ii) the use of SEEP/W module for steady-state seepage analyses, which enables the modeling of groundwater conditions and pore pressures, and (iii) the use of QUAKE/W module, which was considered to perform dynamic analyses to determine the acceleration history at the crest of the mine tailings dams, identify liquefaction-prone areas in the zone of the TSF reservoir, and to calculate displacements generated at the mine tailings dam crest during seismic events.

2.1 Materials and Research Resources

A comprehensive review of scientific literature related to the objectives of this study has been conducted. This review encompasses various sources such as scientific articles, geotechnical books, and seminars/conferences focusing on the research topic. All the considered resources are detailed in the bibliographic references.

Is important to note that, this study primarily relied on the research conducted by authors Naeini and Akhtarpor, titled "Numerical analysis of seismic stability of a high centerline tailings dam" (Naeini, M., & Akhtarpour, A., 2018). This work focuses on the dynamic analysis of a tailings dam subjected to seismic loads, exploring the potential for liquefaction and its implications on mine tailings dam stability. The research delves into stress analysis as a function of depth within the mine tailings dam, as well as the assessment of seismic characteristics. It is noteworthy that the Geostudio software, specifically the QUAKE/W module, was employed for this detailed analysis.

2.1.1 TSF Physical Stability Analysis Regulations Applied in Peru

As defined by the Canadian Dam Association (CDA) in the proposed mine tailings dam safety guidelines, the established practice in assessing dam safety is primarily based on a standards-based deterministic approach. This regulation is valid and commonly applied in mine tailings dam designs in Peru. The safety factors proposed by the CDA for different stages of a dam's lifetime, according to static and pseudo-static analyses, are provided below in Tables 2 and 3, respectively.

Table 2. Admissibility Criteria - Minimum Factors of Safety for Mine Tailings Dam Slope Stability considering Construction, Operation and Transition Phases - Static Analysis (CDA, 2013).

Loading Conditions	Factor of Safety	Slope
Construction	>1.3 to the evaluation of risks during construction	Mainly Downstream
Long Term (steady-state seepage)	1.5	Downstream
Rapid, partial, or total drawdown	1.2 – 1.3	Upstream Slope, if applicable

Table 3 Admissibility Criteria - Minimum Factors of Safety for Mine Tailings Dam Slope Stability considering Construction, Operation and Transition Phases – Pseudo Static Analysis (CDA, 2013).

Loading Conditions	Factor of Safety
Pseudo-static	1.0
Post-earthquake	1.2

Furthermore, in Peru for some cases, the safety criteria for mine tailings dams defined by the Australian standard ANCOLD are also considered valid. The factors of safety recommended by ANCOLD for mine tailings dams under various loading conditions emphasize that there are no "rules" for acceptable safety factors, as they must consider the consequences of failure, the risk associated, and the uncertainty of material properties and subsurface conditions.

The Admissibility criteria based on the factor of safety proposed by ANCOLD are summarized in Table 4.

Table 4. Admissibility Criteria - Minimum Factor of Safety for Mine Tailings Dam Slope Stability considering different load cases (ANCOLD, 2012)

Loading Conditions	Factor of Safety	Shear strength to be used for slope stability analysis
Drained, long-term	1.5	Effective Strength
Undrained, short-term (potential loss of containment)	1.5	Consolidated undrained Strength
Undrained short-term (no potential loss of containment)	1.3	Consolidated undrained Strength
Post-seismic	1.0 – 1.2	Post seismic shear strength

2.2. Methodology

This study assesses two mine tailings dams, both exceeding over 200 meters in height, being considered large human-constructed infrastructures.

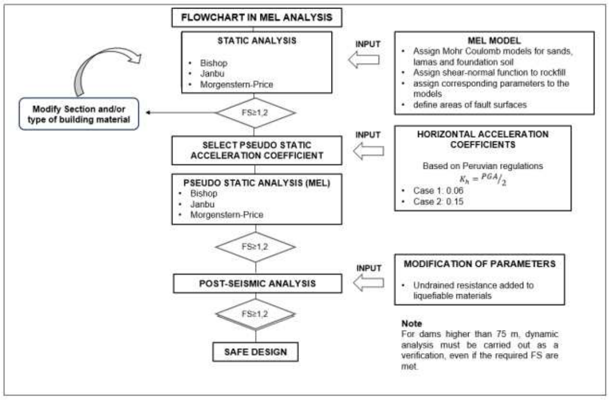
The variables being analyzed are those that impact shear strength, utilizing both pseudo-static stability analysis and dynamic stability analysis methods. The primary goal is to assess the physical structural strength by applying a factor of safety, which indicates the balance between stabilizing (strength of the materials) and destabilizing forces (acceleration and displacements produced by the earthquake). Furthermore, conditions governing the modeling of mine tailings dam deformation during dynamic analyses are integrated. This approach encompasses considerations such as seismic loads, shear modulus, cyclic stress ratio (CSR), and the liquefaction susceptibility.

To analyze the physical stability of the mentioned cases, the procedure is divided into 3 stages, as outlined in Table 5.

Table 5. Methodological Procedure considered in this Study.

Stage	Objective	Details
N°1	Bibliographic Review and Compilation of Parameters	During this stage, essential information is gathered to model the designated mine tailings dams, including details on construction materials, geological site conditions, soil and dam material geotechnical parameters, and dam geometry. Additionally, documents with similar objectives are sought for result comparison.
N° 2	Dam Stability Analysis	During this stage of the study, the modeling of the physical stability of each mine tailings dam is addressed using various modules of the Geostudio software, employing a comprehensive approach. The process begins with obtaining pore pressures and flow lines through finite element analysis using SEEP/W module. These pore pressures, of vital importance, significantly influence the physical stability of the mine tailings dams. Subsequently, the SIGMA/W module utilizes these pressures to calculate both total and effective stresses. Slope stability considering Pseudo-static analyses are conducted using SLOPE/W module, and equivalent linear dynamic analyses are performed using QUAKE/W module.
N°3	Evaluation and Discussion of Results	During this stage, factors of safety and deformations are analyzed based on the construction method of each mine tailings dam. These results are compared with relevant international guidelines and acceptance criteria.

Regarding obtaining results from pseudo-static and dynamic models, the following methodology is employed as a guide, based on the work conducted by Barrera and Campaña in their study called : "Analysis of mine tailings dam physical stability, a Chilean practice" (Barrera and Campana, 2011). Figure 3 presents a flowchart that summarize this methodological procedure for analyzing the physical stability of TSF dams considering static analysis and pseudo-static analysis.



Flowchart of Methodology for carried out Slope Stability of Mine Tailings Dam considering Static Analysis, and Pseudo-Static Analysis (Campaña & Barrera s.f.).

2.2.1 Constitutive Laws for Material Properties for Static Analysis and Pseudo-Static Analysis

In slope stability of mine tailings dams considering static and pseudo-static analysis, inherent to the deterministic limit equilibrium method, it is assumed at this study that all materials behave according to the elastic-perfectly plastic constitutive model with the Mohr-Coulomb yield criterion as the yield function.

2.2.2 Constitutive Model for Dynamic Analysis

Dynamic analysis of mine tailings dams is a study that evaluates the response of the dam-foundation system to dynamic loads, such as the motion produced by earthquakes near the dam. This type of analysis is conducted using advanced numerical methods considering finite elements that simulate the dynamic behavior of the mine tailings dam and its surroundings. The main objective is to verify the physical stability and associated safety of the dam and determine if additional measures are required to protect it from potential damage against the hazards of earthquakes. Various issues are considered in a dynamic analysis, including (I) dam geometry design, (II) mechanical properties of construction materials, (III) characteristics of the surrounding terrain considering soil foundation, and the dynamic loads produced by earthquakes it faces. The outcome of the analysis provides a range of displacement and deformation values indicating the mine tailings dam's response to different levels of magnitude and intensity of dynamic loading.

Dynamic analysis in this study is performed using the linear equivalent constitutive model, which is suitable for simulating dynamic loading, development of pore water pressure, and liquefaction in mine tailings dams. The method assumes that the seismic behavior of the mine infrastructure can be represented by a mass-spring-damper model, and that the dynamic response of the mine infrastructure can be approximated using a stiffness reduction function.

In particular, the finite element method is a useful approach in infrastructure dynamic simulations (Geo-Slope, 2014), where the equation of motion can be expressed as follows:

$$[K]\{d\} + [D]\{v\} + [M]\{a\} = \{F\} \quad (1)$$

Where:
In the equations provided, {d} corresponds to displacement, {v} to velocity, and {a} to acceleration. [K] is the characteristic stiffness matrix of the element, [D] is the damping matrix, and [M] is the mass matrix. The vector {F} represents the external nodal force applied to the infrastructure. To solve the dynamic equation presented, the value of the displacement vector needs to be established first. This is achieved by initially solving the equation [K]{d} = {F}.

To address this subproblem, the initial displacement is determined by considering the anticipated boundary conditions within the model under scrutiny. In linear equivalent dynamic analysis, soil and structural properties are defined, and the infrastructure's reaction to seismic forces is simulated using linear differential equations. Following this, an iterative approach is employed to refine the soil stiffness according to the calculated deformations at each iteration. This process iterates until convergence is attained, as outlined by Anil K. Chopra (2014).

Utilizing the Linear Equivalent Model (LEM) in QUAKE/W module initiates a dynamic analysis by defining the shear modulus. QUAKE/W module progresses through the entire seismic acceleration record, calculating peak shear stresses at each numerical Gauss integration point for every finite element. Subsequently, the shear modulus (G) undergoes adjustment based on a predetermined reduction function, iteratively repeated until the modifications to G meet a specified tolerance level. It's crucial to note that G remains constant throughout an iterative time step of the seismic record, though it is altered at each step change. Figure 4 visually depicts the constancy of G in each iterative pass, with changes in slope indicating reductions in G between iterations (GeoStudio, 2022).

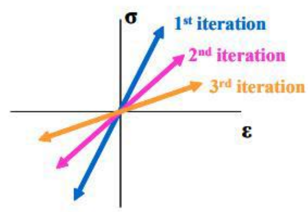


Figure 3. Equivalent Linear Method (ELM) iterations. Source: (Geostudio, 2022)

2.2.3 Maximum Shear Modulus (G_{max})

There are various methods to obtain the value of G_{max}, which can be estimated from geotechnical tests both in the laboratory and in situ, using various parameters such as shear wave velocity, void ratio function, stress ratio, among others. It is important to consider the scope and limitations of each test to obtain representative results for each type of soil in the site-specific mine tailings dam condition (Kramer, 1996).

As an approximation, in case laboratory tests are not available, it is possible to estimate the value of G_{max} for granular soils using the following formula (2) (GEO-SLOPE International Ltd. October 2012 edition)

$$G_{max} = 22K\sqrt{P_a \sigma'_m} \quad (2)$$

Where P_a is the atmospheric pressure, and σ'_m is the mean effective principal stress. The latter must be estimated with the coefficient of lateral earth pressure at rest K0, such that (3(GEO-SLOPE International Ltd. October 2012 edition):

$$\sigma'_m = \frac{\sigma_v + K_0\sigma_v + K_0\sigma_v}{3} \quad (3)$$

Where σ_v It is the depth of the point of interest multiplied by the unit weight of the soil. The values of K can be estimated according to Table 6.

Table 6. Values of K Parameter (GEO-SLOPE International Ltd. October 2012 edition)

Soil Material	Values of K Parameter
Loose sand	30
Medium dense sand	50
Dense sand	70
Loose gravel	80
Medium dense gravel	130
Dense gravel	180

The literature based on the research of Hardin and Drnevich (1972), Hardin (1978), and Mayne & Rix (1993) suggests that G_{max} of cohesive soils can be estimated from:

$$G_{max} = 625\left(\frac{1}{(0.3 + 0.7e^2)}\right)(OCR)^k\sqrt{P_a\sigma'_m} \qquad (4)$$

where e is the void ratio, OCR the over-consolidation ratio and k an exponent related to the soil plasticity index PI. (GEO-SLOPE International Ltd. October 2012 edition)
The k exponent is computed from,

$$k = \frac{PI^{0.72}}{50} \qquad (5)$$

2.2.4 Shear Modulus (G) Reduction Function

When soil is exposed to dynamic loads, it typically experiences a reduction in stiffness due to cyclic deformation. In the linear equivalent model, this "softening" process is described in terms of shear strain, normalizing G_{sec} with respect to G_{max} By plotting this relationship, the modulus reduction curve is obtained, as shown in Figure 5, which presents the modulus reduction curves of the different soil materials used in the analyses, including cycloned tailings, slimes, and rockfill, among others.

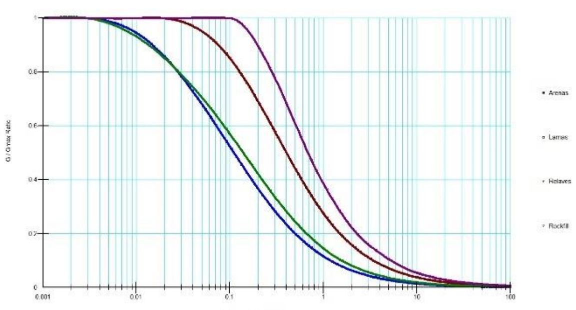


Figure 4. Shear modulus (G) reduction function. Source: Own elaboration

It's worth noting that the damping curves are obtained from the shear modulus (G) reduction functions. Figure 6 presents the damping curves of the materials.

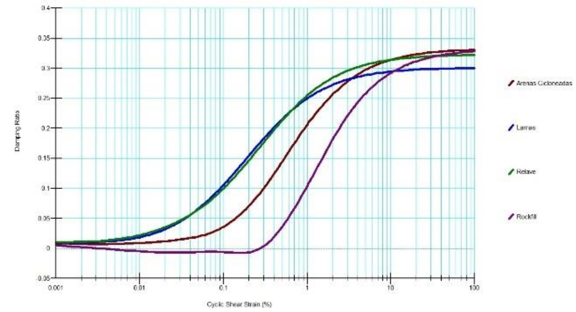


Figure 5. Damping of soil material function. Source: Own elaboration

2.2.5 Cyclic Stress Ratio

The excess pore pressure required to initiate liquefaction is related to the amplitude and duration of cyclic loading induced by an earthquake. Laboratory tests demonstrate that the number of loading cycles required to produce liquefaction failure, NL, increases as the shear stress amplitude decreases and soil density increases.

The relationship between density, cyclic stress amplitude, and the number of cycles to mine tailings liquefaction failure can be graphically represented by laboratory cyclic strength curves (Kramer, 1996). These curves are commonly normalized using the initial overburden pressure to obtain a Cyclic Stress Ratio (CSR).

After several cyclic triaxial tests on mine tailings with fine aggregates, (Geremew and Yanful, 2012) proposed:

$$0.037{e_c}^{-1.87} \leq \frac{CRR_{20}}{G_s} = 0.047{e_c}^{-1.95} \leq 0.059{e_c}^{-1.92} \qquad (6)$$

Where, Gs is the specific gravity, of the soil, and e_c It is the void ratio after consolidation. Using values recorded in the literature, it is possible to estimate the CRR (Cyclic Resistance Ratio) of mine tailings using for all layers, given that the CRR of mine tailings normally consolidated with fine aggregates is independent of the confining stress (Naeini and Akhtarpour, 2018).
If e_c = 0.85 and Gs = 2.78, then CRR20 takes an average value of 0.179.

3. Results

3.1 Geometry and Meshing of the Models

The corresponding domains for the previously discussed case studies 1 and 2 are presented, as depicted in Figures 6 and 7. Additionally, their geometrical descriptions are provided in Tables 7 and 8, respectively.

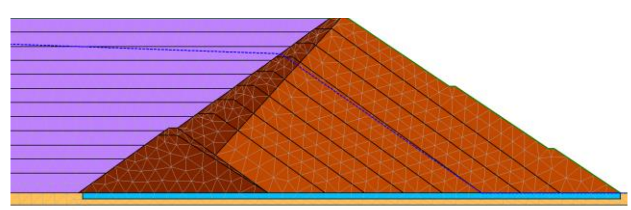


Figure 6. Case Study 1 Mine Tailings Storage Facility with Rockfill Dam.

Table 7. Dam Geometry Case Study 1, Mine tailings storage facility with rockfill dam, considering downstream construction method.

Dam	Height (m)	Crest width (m)	Upstream Slope	Downstream Slope
Starter Dam	110	15	1.4:1.0 (H:V)	-
Rockfill Dam	265	15	1.4:1.0 (H:V)	1.5:1.0 (H:V)

The geomechanical parameters for the materials utilized in the TSF with rockfill dam are outlined in Table 8 below.

Table 8. Material Strength Properties. Case Study 1 Tailings Storage Facility with Rockfill Dam.

Material	Unit Weight (kN/m^3)	Cohesion (kPa)	Internal Friction Angle (°)	Permeability (m/s)
Jumasha Formation Limestone	-	-	-	1.00E-07
Mine Tailings	16	0	20	3.00E-05
Rockfill	22	-	-	1.00E-02
Drainage System	21	0	30	0.35

It's crucial to emphasize that the foundation soil of the TSF rockfill dam comprises limestone rock. Consequently, it's imperative to ensure that no failure surface passes through this material.
The Rockfill material has been modeled with the constitutive model Shear normal function, in order to represent the resistance changes due to the pressure exerted by the tailings.

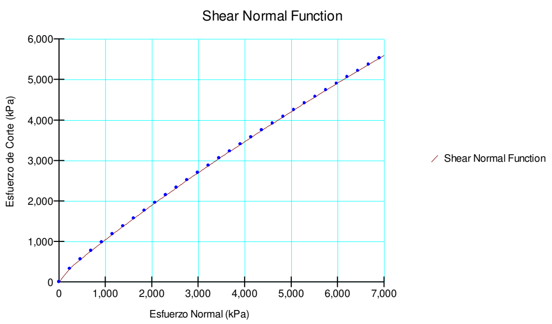


Figure 7. Case Study 2 Rockfill Shear Normal Function constitutive model

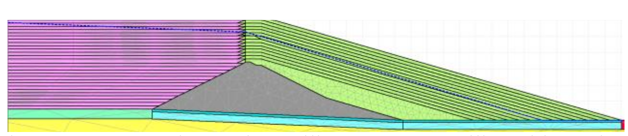


Figure 8. Case Study 2 Mine Tailings Storage Facility with Cyclone Tailings Dam

Table 9. Dam Geometry of Case Study 2, Mine Tailings Storage Facility with Cyclone Tailings Dam.

Dam	Height (m)	Crest width (m)	Upstream Slope	Downstream Slope
Starter Dam	60	15	2:1 (H:V)	-
Cycloned Tailings	300	50	-	3.5:1 (H:V)

The geomechanical parameters of the materials used in the cycloned tailings dam is outlined in Table 10 below.

Table 10. Material strength properties. Case Study 2, Mine Tailings Storage Facility with Cycloned Dam.

Material	Unit Weight (kN/m^3)	Cohesion (kPa)	Internal Friction Angle (°)	Ky (m/s)
Foundation Soil	22.3	65	30	1.0E-5
Slimes	16.7	12	30	
Cycloned Tailings	18	0	35	4.90E-06
Drainage System	21	0	30	0.35

3.2 Pseudo-Static Stability Analysis

The pseudo-static analysis involves applying a horizontal force to the sliding mass as determined by the deterministic limit equilibrium analyses. This force varies depending on local seismicity and is defined by regulations and mine tailings dam scales. These results offer a practical and straightforward means of assessing case study stability without the necessity of analyzing accelerations at specific points in the mine infrastructure. However, it's crucial to select appropriate acceleration coefficients with engineering criteria and experience/knowledge of seismic site-specific conditions, to obtain coherent and representative results.

Below, we present the results of the pseudo-static analyses conducted in this study. In these models, mine tailings liquefaction was considered, simulating the complete loss of both cohesion and internal friction angle of both mine tailings and slimes. Additionally, undrained parameters were assigned to cycloned sand regions that were below the phreatic surface according to the SEEP analysis results. The residual strength employed in the former case is set to 20% of the overburden stress (su=0.2). Figure 9 illustrates the critical failure surface of the slope stability of the rockfill dam considering the pseudo-static analysis, using the Morgenstern-Price limit equilibrium method. To define the critical slip surface under pseudo-static conditions, according to the general principles of geotechnical engineering and design of tailings containment structures, it is established that a significant portion of the crest must remain intact to ensure the stability and functionality of the dam under critical conditions. In this context, the critical sliding surface presented limits the width of the crest of the wall to 50% of its total width.

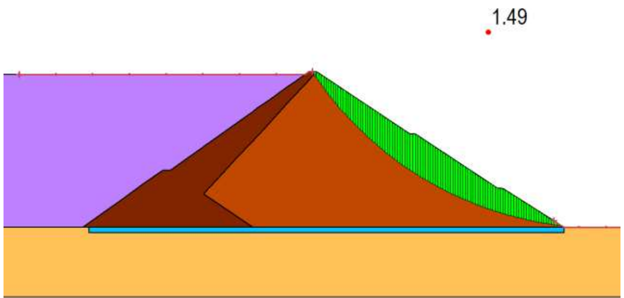


Figure 9 Potential Critical Failure Surface, Case Study 1 Mine Tailings Storage Facility with Rockfill Dam.

Figure 10 presents the slip surface of the pseudo-static analysis of the cycloned tailings dam according to the Morgensten-Price limit equilibrium method.

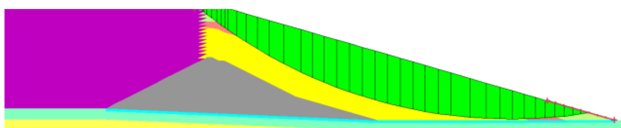


Figure 10 Potential Critical Failure Surface, Case Study 2, Mine Tailings Storage Facility with Cycloned Tailings Dam.

The following table summarizes the results of the pseudo-static analysis conducted on the two mentioned case studies. The results of the pseudo-static analysis were performed using the Janbu, Bishop, and Morgenstern-Price limit equilibrium methods. Additionally, we provide details on the maximum ground accelerations (PGA) and horizontal acceleration coefficients used for these analyses. According to Peruvian regulations, the horizontal seismic acceleration coefficient utilized in these analyses should be half the PGA.

Table 11 Pseudo-static analysis parameters (Ministry of Housing, Construction and Sanitation, 2014), (Obermeyer and Alexieva, 2011).

	Case Study 1 TSF with Rockfill dam	Case Study 2 TSF with cycloned tailings dam
PGA	0.12	0.22
Horizontal seismic coeficient	0.06	0.11

Table 12 Pseudo-static analysis results considering factors of safety.

Limit Equilibrium Method	Case Study 1 FS	Case Study 2 FS	Admissibility Criteria (CDA)
Janbu	1.49	0.77	
Bishop	1.50	0.88	>1
Morgenstern-Price	1.49	0.89	

3.3 Stress State Analysis

To perform a dynamic analysis of mine tailings dams using numerical methods considering finite elements, it's essential to first estimate the stress state of the infrastructure, which requires a thorough understanding of effective stresses. In this regard, approximating pore pressures becomes crucial and is achieved through seepage analyses of the TSF.

Seepage analyses were conducted using the SEEP/W module of GeoStudio, a numerical method considering a finite element tool designed to simulate seepage, pore pressures, and groundwater levels by utilizing specific soil parameters. Two-dimensional steady-state seepage analyses were undertaken using the saturated constitutive model. This choice was made due to the complexity associated with simulating partially saturated materials under seismic loads. It was considered that the mine tailings prone to liquefaction could only be accurately modeled in a fully saturated state, thus guiding this decision.

Two boundary conditions were defined: one representing hydrostatic loading and the other a surface of zero hydrostatic pressures. Following the seepage analysis, the groundwater level was manually adjusted, considering the obtained results. The maximum suction was limited to 5 kPa to counteract excessive negative pressures.

Subsequently, effective stresses throughout the model under static conditions were estimated using the SIGMA/W module. This involved specifying unit weights and utilizing the seepage analysis results as input data. Deformations were constrained at the lateral boundaries and at the base of the model.

With information on stress and pore pressure conditions, the dynamic behavior of the mine tailings dams was modeled by applying seismic loads at the base of the model.

The vertical effective stresses obtained using the SIGMA/W module are presented in Figure 11 and 12 for case study 1 and case study 2 respectively.

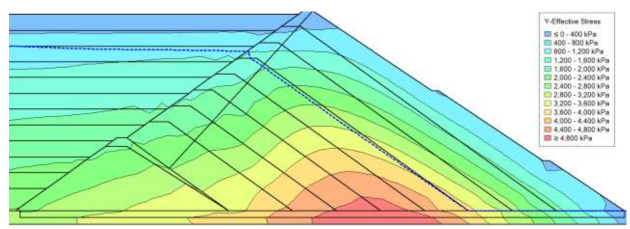


Figure 11. Vertical effective stresses for Case Study 1 Mine Tailings Storage Facility with Rockfill Dam.

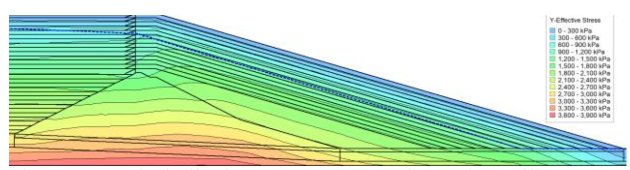


Figure 12. Vertical effective stresses Case Study 2, Mine Tailings Storage Facility with Cycloned Tailings Dam.

3.4 Dynamic Loading

Given the significant seismic activity in the study area and challenges in obtaining realistic and representative in-situ data, two notable earthquakes in Peru's history were selected for this study. The first, the 1970 Ancash earthquake, measured 7.9 on the Richter scale with a peak ground acceleration (PGA) of 0.12g, recorded by the Parque de la Reserva station in Chimbote. This data was utilized to model dynamic loads for case study 1. The second event, occurring on June 23, 2001, registered a magnitude of 8.4 and a PGA of 0.22g, impacting southern Peru and extending to cities like Arica and Iquique in Chile, as well as La Paz in Bolivia. Data from the MOQ001 station in Moquegua was used for case study 2.

In all dynamic analyses, the duration of the earthquake was limited to the segment with the highest recorded accelerations, a standard practice in the equivalent linear dynamic model. Additionally, the maximum seismic acceleration amplitude of the record was adjusted according to PGA citing of the maximum credible earthquake based on seismic zoning. Although the selected earthquakes were of significant magnitude, they do not guarantee that they induced the highest accelerations in the studied area. To address this uncertainty in modeling, to a degree, adjustments were made to the records as mentioned earlier. This adaptation in amplitudes affects the entire seismic record and facilitates the analysis of dam seismic response under extreme conditions.

3.4 Dynamic Analysis

This analysis is conducted using the GeoStudio software considering QUAKE/W module, which is a numerical method using finite elements, that has the capability to predict damping and stiffness as a function of deformation through a linear equivalent analysis. This is achieved after defining parameters such as Gmax, damping ratio, behavior curves, and modulus reduction curves, along with values obtained from the previously defined stress state analysis. This method modifies the static stress condition by incorporating a cyclic load based on a seismic record, and increases pore pressures to levels equivalent to those induced by an earthquake with an equivalent number of cycles. Therefore, the results of the dynamic analysis not only facilitates the identification of liquefaction zones but also provide insight into the acceleration history at each nodal point and the induced shear stresses at each element during the earthquake. This information is instrumental in the subsequent analysis aimed at determining permanent deformations.

It's important to note that, at this stage, the lateral boundaries of the model are fixed only in the vertical direction to prevent the reflection of vibrations in the mine tailings dam. This approach is adopted because the horizontal movement beyond the ends of the model mirrors that at the ends of the mesh, and there is no resistance to lateral movement beyond these ends. Additionally, it's crucial to highlight that the two boundaries at the end of the mesh are modeled at a sufficiently distant distance from the body of the mine tailings dam to ensure that the zero vertical displacement constraints do not significantly impact the dynamic shear stresses at the mine tailings dam crest.

Figure 13 illustrates the horizontal accelerations induced by the earthquake, captured at the mine tailings dam crest over time.

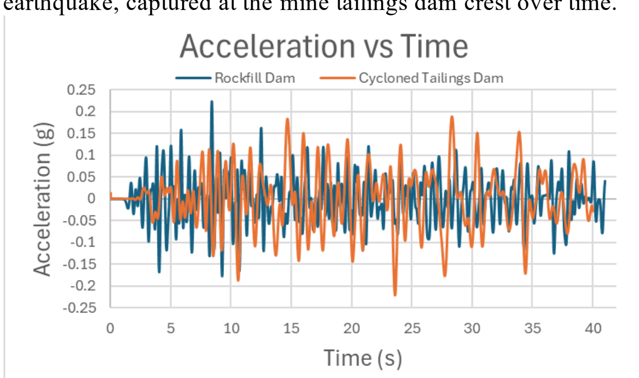


Figure 13. Horizontal earthquake accelerations (g) vs time (s), where orange case applies to rockfill dam, and blue case applies to cycloned tailings dam.

3.5 Assessment of Liquefaction

The methodology used to identify any potential liquefaction zone in the TSFs analyzed in this study through the linear equivalent method using finite elements, follows the specifications outlined in the QUAKE/W module user´s manual:

- Calculate a q/p' ratio for each Gauss integration region within each element using initial static stresses.
- Any data point q/p' above the collapse surface or to the left of the Steady-State Line is marked as 'liquefied' before the dynamic analysis begins.
- Points above q_{ss} but below the collapse surface may move toward or beyond the collapse surface due to the buildup of excess pore pressures, and when this occurs, the element is marked as 'liquefied'.
- Stress points below q_{ss} are never marked as 'liquefied', even though excess pore pressures may develop. The implication is that the steady-state strength is not used for this region; instead, effective stress parameters c' and φ' are used.
- The generation of excess pore pressures is limited in such a way that the effective mean stress p' is never less than p'_{ss}

Once the variables are defined, the procedure involves reducing the minor principal stress in each finite element of the model by the magnitude of the pore pressure increase generated after each equivalent cycle. This magnitude is given by:

$$\Delta u = ru \cdot \sigma_3' \quad (7)$$

Where σ_3' is the initial static minor principal stress and ru is a function of the number of cycles (N) and the number of cycles to liquefaction (NL), as given by the following equation:

$$ru = \frac{1}{2} + \frac{1}{\boldsymbol{\pi}} sin^{-1}\left[2\left(\frac{N}{NL}\right)^{\frac{1}{\alpha}} - 1\right] \quad (8)$$

If the stress path of the element under seismic loading intersects the collapse surface, then the element has liquefied, and is assigned residual strengths.

This method allows to model the strength loss due to soil liquefaction to any element throughout the model that has met the liquefaction criteria at any point and time during the seismic record.

Figures 14 and 15 represent the results obtained by the software marking liquefaction zones in yellow.

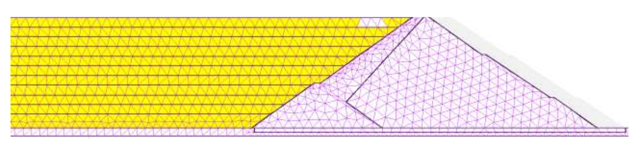


Figure 14. Liquefaction zones, Case Study 1, TSF with Rockfill Dam.

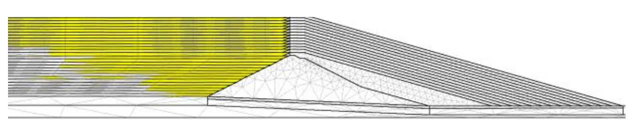


Figure 15. Liquefaction zones, Case Study 2, TSF with Cycloned Tailings Dam.

In the above results, the yellow color assigned to each Gauss region indicates the occurrence of mine tailings liquefaction in that area, indicating that the material is operating at its residual strengths.

3.6 Stress Redistribution Analysis

To determine post-seismic dam deformations, an elastic-plastic static analysis is conducted in which the dynamic stresses from each time step stored in QUAKE/W module are redistributed throughout the model using SIGMA/W module. The incremental load vector is determined, which expresses the algebraic difference between stress states in two consecutive time intervals, according to the following formula:

$$\Delta F = \int [B]^t \{\Delta\sigma\}\, dv \tag{9}$$

Where:

$$\{\Delta\sigma\} = \{\sigma_n\} - \{\sigma_{n-1}\} \tag{10}$$

Where [B] is the strain-displacement matrix, $\{\Delta\sigma\}$ is the incremental nodal stress, $\{\sigma_n\}$ is the stress vector, and dv is the incremental displacement. By applying $\{\Delta F\}$ at each time step, each point undergoes a specific amount of elastic and plastic deformation. Permanent displacement is calculated by summing up the plastic deformations. In this analysis, initial stress conditions and interstitial water pressure before seismic activity are imported into SIGMA/W module. Subsequently, dynamic stresses and interstitial water pressures developed over the time steps stored in QUAKE/W module are applied to the model. In cases where liquefaction zones emerge in the reservoir area of the mine tailings storage facility due to seismic loads, it is presumed that materials in these zones experience reduced strength; therefore, residual strengths are employed in such areas.

Vertical dam deformations obtained from case study 1 and case study 2 are depicted in Figure 16a and Figure 16b respectively.

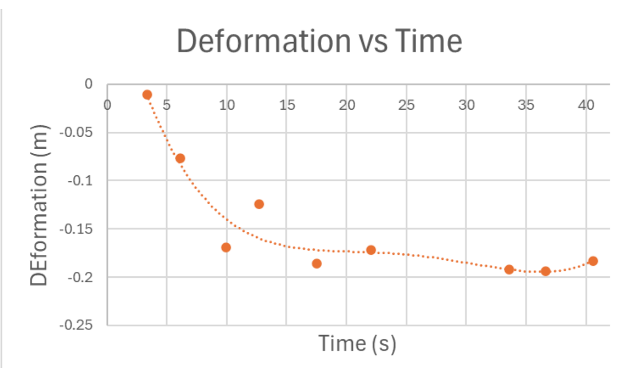


Figure 16a Vertical dam deformations, Case Study 1

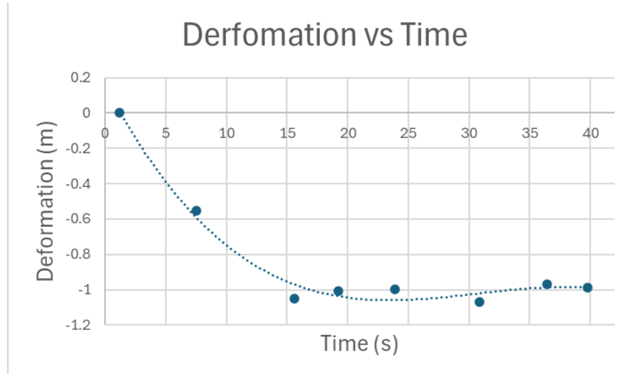


Figure 16b Vertical dam deformations, Case Study 2

4 Discussion of Results

4.1 Pseudo-Static Stability Analysis

The results show that Case Study 1 TSF dam meets the pseudo-static admissibility criteria considering the valid regulations in Peru. In the other hand, Case Study 2 does not meet the Pseudo-Static admissibility criteria. This outcome is attributed to the high phreatic surface, which was modeled through a steady state seepage analysis, by defining unfavorable border conditions. Nevertheless, it's essential to recognize the limitations of pseudo-static analysis, particularly when dealing with large mine infrastructures such as the ones presented in this study. The failure surface spans a large distance with varying accelerations throughout surface. According to Garga (2014), "a pseudo-static factor of safety of less than 1.0 does not mean that the dam is unsafe. A deformation analysis should then be carried out."

4.2 Stress State Analysis

As observed in Figures 11 and 12, the vertical effective stresses reach a range of 4-5 MPa. These values are consistent with expectations due to the scales of the infrastructures in question. Such ranges support the use of nonlinear shear strength models for both the TSF with rockfill material and the TSF with cycloned tailings material. This is because linear models, such as Mohr-Coulomb, tend to overestimate strength in higher stress intervals.

4.3 Dynamic Analysis

According to the results obtained, it is observed that the TSF with rockfill dam corresponding to Case Study 1 experiences slightly higher accelerations at the crest in the first 10 seconds compared to the TSF with cycloned tailings dam corresponding to Case Study 2. After 10 seconds, the accelerations in Case Study 2 exceed those of Case Study 1. Part of this disparity is attributed to the differences in slope geometry and height between the two mine tailings dams, with the slope of the TSF rockfill dam being approximately 2.3 times steeper than that of the TSF tailings dam and 35 meters smaller. Additionally, another factor that could contribute to these differences in behavior is the natural frequency and mode of vibration of these infrastructures, although these details are out of the scope of this study.

Additionally, applying fundamental dynamic principles, Case Study 1, characterized by a notably steeper dam slope compared to Case Study 2, is anticipated to demonstrate greater horizontal accelerations. This expectation aligns with the observed early dynamics depicted in Figure 13. Nevertheless, it is crucial to exercise caution when directly comparing the performance of these two tailings dams.. Their distinct geographical location demands distinct design considerations, tailored to local earthquakes of varying frequencies. Furthermore, it's imperative to acknowledge that these tailings dams were subjected to different seismic scenarios during modeling.

4.3.1 Liquefaction Zones

Based on the results, liquefaction has been observed throughout the entire reservoir area of the mine tailings storage facilities. Several factors contribute to these findings. Firstly, earthquakes with great order of magnitudes were simulated, involving the assignment of large equivalent cycle values (ranging from 20 to 30 cycles) in the linear equivalent dynamic analysis. This methodology was based on the work developed by Seed et al. to induce pore pressures representative of earthquakes of such magnitudes. High boundary conditions in the seepage analysis (due to mine tailings reservoir) contributed to this outcome by decreasing effective stresses. Additionally, the application of Equation (5) from Boulanger et al. for all tailings layers implies the use of a single value of CRR_{20} for the entire material, rendering the entire basin susceptible to liquefaction. These implications simplify the analysis to a degree.

A more accurate modeling of physical behavior requires a comprehensive approach, including shear tests on both compact and loose material, and consolidation tests under high loads, in conjunction with cyclic triaxial tests, all aimed to determine the critical void ratio of the mine tailings. Subsequently, the consolidation of the mine tailings must be modeled considering the stress path as the height of the reservoir increases. This approach allows for the assignment of dynamic parameters based on the contractive or dilative nature of the strata, depending on the material's state parameter. Moreover, a transient seepage analysis is required to accurately model phreatic surfaces to estimate material stress states.

However, this rigorous methodology demands precise and well-documented data, which are often challenging to find in common databases. Therefore, the more simplistic method mentioned above is preferred. Despite its limitations, this approach lends a more conservative character to the analysis by considering, to some extent, the inherent uncertainties in the model.

4.3.2 Permanent Dam Deformations and Admissibility Criteria Verification

Following the dynamic stability analysis admissibility criteria proposed by Barrera and Campaña, a dam is deemed stable if its deformation does not surpass 1-2% of its total height and remains below 50% of the TSF freeboard.

In the linear equivalent dynamic analysis conducted for this study, a maximum vertical deformation of 1 m was observed for Case Study 2, involving the TSF with cycloned tailings dam, and 20 cm for Case Study 1, pertaining to the TSF with rockfill dam. These values align with the recommended limits outlined by regulations to ensure tailings dam physical stability, as set forth by Barrera and Campaña. The detailed results of this analysis are provided in Table 13 below.

Table 13 Dam deformation results from dynamic analysis considering the dam crest and free board of the TSF.

Dam	Total Vertical Crest Deformation (%)	Vertical Freeboard Deformation (%)
TSF with Rockfill (Case Study 1)	<1%	<1%
TSF with Cycloned Tailings (Case Study 2)	<1%	43

Regarding the freeboard, the percentages are calculated considering both the deformation at the upstream slope of the crest and the deformation of the mine tailings reservoir area that limits the upstream slope. It is relevant to mention that the freeboard for Case 1 is 5 meters, while for Case 2 it is 3 meters.

5. Conclusions

Based on the observed results, both TSF dams experienced relatively small deformations in the dynamic analysis. Following the specified admissibility criteria for pseudo-static analysis, the TSF rockfill dam investigated in Case Study 1 meets the thresholds established by Barrera and Campaña in dynamic analysis and satisfies the international regulations from the CDA and the ANCOLD, both valid in Peru. In the other hand, the TSF cycloned tailings dam examined in Case Study 2 did not meet the pseudo-static admissibility criteria; however it does meet the dynamic thresholds, even under demanding circumstances such as adverse boundary conditions, significant seismic forces, and susceptibility to liquefaction materials. It is highly likely that applying transient seepage analysis, which lowers the phreatic surface, will result in factors of safety greater than 1. Nonetheless, it's essential to recognize that in this study, the loading and boundary conditions, along with the material models and strength parameters, are derived from documented databases and may not precisely reflect the characteristics of each TSF dam site specific conditions. To address these uncertainties, conservative approaches have been employed, as outlined in this study.

The result of the study indicates that, with conservative design criteria, the performance of these TSF dams is safe, considering the best available engineering practices (BAEPs) related to the design of: (i) dam material properties, (ii) dam geometry, and (iii) dam dynamic response. Finally, the study concludes that according to applying conservative engineering and construction design criteria focusing on the reduction of risks according to the principle of as low as reasonably practicable (ALARP), the performance of these TSFs with high dams will accomplish the admissibility criteria for factors of safety, displacements, and deformations indicated by local and international regulations in an extremely seismic region. However, to promote the sustainability of mining, reduce the risks/uncertainties related to climate change hazards, and ensure the most high-quality standards of safety, a strict and periodic control, actualization, and evaluation of the dynamic stability analysis over the lifetime of mine tailings infrastructure will be strictly necessary.

6. Recommendations

To enhance the safety of high tailings dams, it is recommended to conduct transient seepage analyses to accurately determine the phreatic level, assess pore pressure, and obtain void ratios through consolidation models.

For construction materials, it is essential to perform laboratory tests to estimate variables such as Poisson's ratio, cohesion, friction angles, permeability, granulometry, compressibility coefficients, elasticity modules, and cyclic strength and deformation parameters.

Additionally, in situ seismic zoning studies should be conducted. It is important to determine the horizontal seismic coefficient by considering the distance and magnitude of the earthquake. Performing spectral acceleration analyses is also advised to identify periods of highest accelerations and design the dams accordingly.

7. Acknowledgments

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7. References

ANCOLD. (2012). Guidelines on Tailings Dams, Planning, Design, Construction, Operation and Closure. Disponible en: https://www.resolutionmineeis.us/sites/default/files/references/ancold-2012.pdf

Barrera, S. V., y Campaña, J. Z. (2011). Análisis de estabilidad de presas de relave-practica chilena.

Bhanbhro, R. (2014). Mechanical properties of tailings: Basic description of a tailings material from sweden (Tesis Doctoral, Lule˚a University of Technology, SE-97187 Lule˚a, Sweden). Descargado de http://www.ltu.se

Bray, J. D., y Travasarou, T. (2011, January). Pseudostatic slope stability procedure. En Proceedings of the 5th international conference on earthquake geotechnical engineering. Santiago, Chile.

Cacciuttolo, Carlos, and Edison Atencio. 2022. "Past, Present, and Future of Copper Mine Tailings Governance in Chile (1905–2022): A Review in One of the Leading Mine Countries in the World" International Journal of Environmental Research and Public Health 19, no. 20: 13060. https://doi.org/10.3390/ijerph192013060

Cacciuttolo, Carlos, Deyvis Cano, and María Custodio. 2023. "Socio-Environmental Risks Linked with Mine Tailings Chemical Composition: Promoting Responsible and Safe Mine Tailings Management Considering Copper and Gold Mine Experiences from Chile and Peru" Toxics 11, no. 5: 462. https://doi.org/10.3390/toxics11050462

Cacciuttolo, Carlos, and Deyvis Cano. 2023. "Spatial and Temporal Study of Supernatant Process Water Pond in Tailings Storage Facilities: Use of Remote Sensing Techniques for Preventing Mine Tailings Dam Failures" Sustainability 15, no. 6: 4984. https://doi.org/10.3390/su15064984

Canadian Dam Association (CDA). (2013). DAM SAFETY GUIDELINES, Application of Dam Safety Guidelines to Mine Dams. Disponible en: https://cda.ca/publications/cda-guidance-documents

Campaña, J., Valenzuela, L., Figueroa, A., y Alarcon, J. C. (2015, October). The quillayes sand tailings dam in chile: Design and operation. En Proceedings of tailings and mine waste 2015 (p. Page Range). Vancouver, BC, Canada: Publisher Name.

Clarkson, L., y Williams, D. (2019). Critical review of tailings dam monitoring best practice. International Journal of Mine, Reclamation and Environment. Descargado de https://doi.org/10.1080/17480930.2019.1625172 doi: 10.1080/17480930.2019.1625172

Chopra, A. (2014). Dynamic of Structures, Theory and Applications to Earthquake Engineering.

CSP2. (s.f.). Tailings storage facility failures: An overview. Descargado Accessed: 25/09/2023, de http://www.csp2.org/tsf-failures-from-1915

Das, B. M. (2015). Fundamentos de ingeniería geotécnica (Cuarta edición ed.). Corporativo Santa Fe, Av. Santa Fe n´um. 505, piso 12, Col. Cruz Manca, Santa Fe: Cengage Learning Editores, S.A. de C.V. (© D.R. 2015 por Cengage Learning Editores, S.A. de C.V., una Compañía de Cengage Learning, Inc.)

Fell, R., MacGregor, P., Stapledon, D., Bell, G., y Foster, M. (2015). Geotechnical engineering of dams. CRC Press/Balkema is an imprint of the Taylor and Francis Group, an informa business.

Fredlund, D. (2012). Unsaturated soil mechanics in engineering practice. JOHN WILEY & SONS, INC.

Garga, V. (2014). Tailings Dams - Today for Tomorrow. Presentation at the Perumin Conference, 2014.

GEO-SLOPE International Ltd. (July 2012 Edition). Seepage modeling with seep/w: An engineering methodology. 1400, 633 – 6th Ave SW, Calgary, Alberta, Canada T2P 2Y5: GEO-SLOPE International Ltd. (Copyright © 2004-2012 by GEO-SLOPE International, Ltd. All rights reserved. Trademarks: GEO-SLOPE, GeoStudio, SLOPE/W, SEEP/W, SIGMA/W, QUAKE/W, CTRAN/W, TEMP/W, AIR/W and VADOSE/W are trademarks or registered trademarks of GEO-SLOPE International Ltd. in Canada and other countries. Other trademarks are the property of their respective owners. Web: http://www.geo-slope.com)

Geremew AM, Yanful EK. Laboratory investigation of the resistance of tailings and natural sediments to cyclic loading. Geotech Geol Eng 2012; 30:431–47.

Kramer, S. L. (1996). Geotechnical earthquake engineering. Upper Saddle River, New Jersey 07458: Prentice Hall.

LEVENICK, J., ZAWADZKI, W., HAYNES, A., y MANRIQUE, R. (2009). Hydrogeological assessment of seepage through the antamina tailings dam – antamina copper/zinc mine, peru, south america. Journal Name or Conference Proceedings.

Malvern, L. E. (1969). Introduction to the mechanics of a continuous medium. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Mosquera, J. (2013). Static and pseudo-static stability analysis of tailings storage facilities using deterministic and probabilistic methods (Tesis de Master no publicada). McGill University, Montreal. (A Thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Engineering in Mine Engineering)

Naeini, M., y Akhtarpour, A. (2018). Numerical analysis of seismic stability of a high centerline tailings dam. Soil Dynamics and Earthquake Engineering. doi: https://doi.org/10.1016/j.soildyn.2018.01.019

Pauca, P. E. P. (2016). Criterios para el diseñó de la cortina de inyecciones de la presa de arranque del depósito de relaves linga del proyecto de expansión de la unidad minera cerro verde - arequipa (Tesis de Master no publicada). UNIVERSIDAD NACIONAL DE SAN AGUSTI´N DE AREQUIPA, AREQUIPA, PERÚ.

Quispe Tunque, D. G., y Zúñiga Espinoza, A. (2019). Tesis.

Riemer, M., Moriwaki, Y., y Obermeyer, J. (2008). Effect of high confining stresses on static and cyclic strengths of mine tailing materials. Journal Name or Conference Proceedings.

Rosidi, D., McCullough, N., Shin, S., Lawrence, C., y Dorang, C. (2016). Dynamic response and deformation analysis of a marginal wharf. Journal Name. doi: https://doi.org/DOI-Here

Sernageomin. (2018). Guía Metodológica para Evaluación de la Estabilidad Física de Instalaciones Mineras Remanentes. Disponible en: https://www.sernageomin.cl/wp-content/uploads/2019/06/GUIA-METODOLOGICA.pdf

Schnaid, F., de Mello, L. G. F., y Dzialoszynski, B. S. (2020). Guidelines and recommendations on minimum factors of safety for slope stability of tailings dams. Soils and Rocks: An International Journal of Geotechnical and Geoenvironmental Engineering. doi: https://doi.org/10.28927/SR.433369

Smesnik, M., Krstic, S., y Verdianz, M. (2019). Determination of rockfill shear parameters for dam stability analysis of an embankment dam. En Proceedings of the xvii ecsmge-2019: Geotechnical engineering foundation of the future. doi: https://doi.org/10.32075/17ECSMGE-2019-0975

Torres, P., Macedo, J., y Paihua, S. (2020). Dynamic effective stress analysis of a centerline tailings dam – case study. Journal Name or Conference Proceedings.

Valenzuela, L. (2016). Design, construction, operation and the effect of fines content and permeability on the seismic performance of tailings sand dams in chile. Obras y Proyectos, 19, 6-22.