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Tailings Storage Facilities in the Philippines: Environmental, Geotechnical and Seismic Design Considerations

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ABSTRACT

The Philippines is a country known to have rich deposits of gold, copper, nickel, and is currently listed as the fifth most mineral-rich country in the world. It has the third largest deposits of gold, fourth for copper, and fifth for nickel. In 2021, the government lifted the ban on open pit mining to reinvigorate the industry. The resumption in the operations led to the construction of new tailing storage facilities (TSF), as well as expansion of existing ones to contain the mining by-products. As the design approach and construction methodology for large embankment dams continue to develop through the years, it is imperative that new TSFs be designed in accordance with latest guidelines such as ICOLD, ANCOLD and GISTM. This paper presents the geotechnical and seismic design considerations for TSFs in the Philippines in accordance with the latest international guidelines and in conformance with the strict guidelines of the Philippine Department Environment of Natural Resources Mines and Geosciences Bureau (DENR-MGB). The challenges in designing structures in a region endangered by several geohazards, both seismic and climate related, such as the Philippines are discussed. Discussions focus on seismic tests using seismic velocity logging (SVL) to obtain dynamic properties of the soil, hydrologic and hydraulic study for flood design, probabilistic seismic hazard analysis (PSHA) to quantify the overall seismic hazard of the area and obtain appropriate ground motions, and non-linear time history analysis (NLTHA) to assess the performance of the dams during earthquake events. Case studies for mining projects are discussed.

Keywords: dams, tailings storage facilities, probabilistic seismic hazard analysis, non-linear time history analysis, numerical analysis, finite element method

1 INTRODUCTION

When the Philippine government lifted the 2017 ban on open pit mining in December 2021, it was inevitable that the industry of mining copper, gold, silver and complex ores across different parts of the country would immediately resume to compensate for loss time and opportunity. As a result, several mining companies and mine sites have pursued to increase and expand their mineral production capacities that led to the expansion of their structures, including tailings storage facilities (TSFs) which contain the mining by-products. Two (2) tailings storage facility case study projects are presented in this paper, one inside a gold mine site located at the crossroads of Luzon and Visayas islands, in the province of Bicol, and another gold mine site located in Mindanao.

In the early years of dam design in the country, the design considerations have been based on a number of different codes, guidelines and provisions. However, in recent years, there has been an active push amongst the local and foreign mining owners and designers to adopt the latest internationally accepted guidelines such as the International Commission on Large Dams (ICOLD), Australian National Committee on Large Dams (ANCOLD) and Global Industry Standard on Tailings Management (GISTM)

– while also conforming with the strict guidelines of the Philippine Department of Environment and Natural Resources – Mines and Geosciences Bureau (DENR-MGB). The DENR-MGB regulation strictly requires additional design considerations to account for the engineering consequences presented by the country's geographical location. Being situated along the Pacific Ring of Fire, the Philippines accounts for 3.2% of the world's seismicity, posing threats of ground shaking, landslides, and liquefaction all over the country, and has more than twenty (20) typhoons passing over it every year. This paper focuses on the geotechnical engineering, seismic hazard assessment and hydrologic and hydraulic study of TSFs. A design approach is discussed which is specifically tailor-made to design against the unique hazards present in the country due to its geographical location using state-of-the-art analyses and technologies in geotechnical and earthquake engineering such as seismic velocity logging (SVL) geophysical test, probabilistic seismic hazard analysis (PSHA), nonlinear dynamic time-history analysis (NLTHA) using finite element numerical method (FEM), and hydrologic and hydraulic study. Details are discussed using two case study projects – both of which entail 3rd-party review of the embankment design as part of the environmental audit conducted at the mine sites by the DENR-MGB.

2 DESIGN APPROACH

In consideration of the project requirements and the various factors affecting the engineering design of the TSFs, the following design approach for geotechnical engineering, seismic hazard assessment, and flood study was developed:

2.1 Identify all potential geohazards

The first step is to identify the potential geohazards that may occur at the project area in order to plan and develop the appropriate design schemes and types of analyses that will mitigate and address such engineering disasters. The geohazards identified for the case study project are:

1. settlement of foundation layer due to presence of soft soil covers;
2. slope instabilities of dam embankments;
3. settlement or displacement of dam embankments due to seismic events;
4. liquefaction of both in-situ soil cover and tailings materials; and
5. flooding and overtopping due to extreme rainfall events.

This paper covers discussions on items 2,3 and 5. The settlement and liquefaction of embankment materials are addressed by either pre-consolidation or complete removal of materials and are not of interest in this paper.

2.2 Obtain and develop engineering parameters

From the geotechnical and geophysical investigation programs and related literature, obtain and derive the necessary material parameters to be used for the analyses. This includes both geotechnical and seismic engineering parameters.

2.3 Perform seismic hazard analysis (SHA) and spectral matching

Being situated in a seismically active zone, conducting advance analysis to quantify the seismic hazard of the project area is almost always necessary. A probabilistic seismic hazard assessment (PSHA) is performed for the projects to provide structural and geotechnical designers with the response spectra at different levels of ground motions where seismic design parameters and inputs can be extracted from. This provides site-specific parameters that are not provided by local and/or international guidelines and manuals on earthquake engineering. Spectral matching and ground motion selection is then carried out for a pre-selected ground motion suite to come up with input ground motions for the nonlinear time-history analysis (NLTHA).

2.4 Perform geotechnical analyses

With the identified geohazards and derived engineering parameters, geotechnical analyses shall be performed to come up with a design that ensures the safety and stability of the reclamation structures. The following analyses performed for the case study projects are discussed in this paper:

1. slope stability analysis by limit equilibrium method (LEM) of dam embankments; and
2. nonlinear time-history analysis (NLTHA) by finite element method (FEM) of dam embankments to check deformations during seismic loadings.

2.5 Perform hydrologic and hydraulic study

As the Philippines is visited by almost twenty (20) typhoons a year, it is important to design the TSFs to withstand such strong typhoon events. The hydrologic and hydraulic study of the TSFs is conducted in order to determine the maximum flood level of the storage and design the spillway discharge structure during typhoon events.

3 SEISMIC VELOCITY LOGGING

Seismic velocity logging (SVL) is one of the many geophysical testing methods that utilize well-established physical laws of wave mechanics to gain insight about the subsurface in terms of both Compressional Wave (P-wave) and Shear Wave (S-wave) velocities (V_p and V_s, respectively). It is an intrusive non-destructive method used to determine the physical properties of the underlying soil or rock surrounding a borehole and the speed with which seismic waves propagate through the strata. The test is conducted by lowering a PS suspension logger probe that has an acoustic wave source and geophone receivers into the borehole. The source, which is located bottom of probe, will apply waves that will then travel through the soil/rock material and the geophones, located top of probe, will receive and record the signal. The resulting outputs are the mechanical and dynamic properties of the soil such as shear wave velocity, Vs, modulus of elasticity, E, shear modulus of elasticity, G_0, and Poisson's ratio, ν, which are important parameters for the seismic hazard analysis (SHA), simplified deformation analysis (SDA) and nonlinear time-history analysis (NLTHA). Alternatively, other geophysical tests for measuring shear wave velocities may be conducted such as Downhole Seismic Test (DST), Multichannel Analysis of Surface Waves (MASW), Microtremor Array Survey (MAS), etc.

4 SEISMIC HAZARD ANALYSIS

Seismic hazard analysis (SHA) is the process of quantifying the overall seismic hazard of an area in terms of acceleration. The probabilistic approach (PSHA) in performing SHA quantifies seismic hazard at different levels of risk depending on the recurrence interval or return period of the design ground motion. PSHA also considers multiple seismic sources simultaneously and accounts for uncertainties related to distance, time, recurrence, and size (magnitude).In performing SHA, empirically-formulated attenuation models are utilized to determine the expected surface acceleration by estimating how seismic waves propagate and travel from source to site. Attenuation models are commonly referred to as Ground Motion Prediction Equations (GMPE), and these equations were formulated using globally-acquired earthquake information (e.g. epicenter location, depth, and magnitude). The New Generation Attenuation West2 (NGA-West2) GMPE's developed by the Pacific Earthquake Engineering Research (PEER) Center were used for fault systems, and the BC Hydro GMPE (Abrahamson et al., 2016, 2018) was used for subduction zone sources.

5 SPECTRAL MATCHING AND GROUND MOTION SELECTION

To carry out a nonlinear time-history analysis (NLTHA) for the TSF embankments, a ground motion suite of records of at least three (3) ground motion records should be developed as per requirements of the Philippines' seismic design code, which is referred to in the DENR-MGB guidelines. The ground motion records selected must have similar characteristics to the seismic source with the most contribution to the overall seismic hazard at the project area and shall be spectrally matched with the target response spectra discussed in the previous section. Spectral matching is the process of modifying the amplitude and/or frequency content of a certain ground motion record such that the original record's response spectrum matches the response spectrum obtained from the SHA. By doing so, the modified record can be surmised to be an event that may happen on-site given the nature of the potential earthquake generators, their respective recurrence parameters, and their rupture/focal mechanisms. Spectral matching was done using SeismoMatch 2018 by Seismosoft. SeismoMatch performs spectral matching using the wavelet algorithm of Al Atik and Abrahamson (2010), which is an update of the original algorithm proposed by Abrahamson (1992). This wavelet algorithm utilizes an improved tapered cosine adjustment function that prevents drift in the modified velocity and displacement time series without baseline correction. The quality of the matching is assessed by looking at how well-matched ground motions compare with the original records' time-histories (velocity and displacement). The primary criterion would be to check if the non-stationary parameters of the original ground motion is well-maintained even after matching.

6 NON-LINEAR TIME HISTORY ANALYSIS

Nonlinear time-history analysis (NLTHA) measures the response of a soil-mass over the period of during and after the application of a full ground motion time-history record. With NLTHA, the stress state of materials is allowed to exceed the linear-elastic region and behave with nonlinear material properties (plastic or elastoplastic behavior). As such, moving past the limitation of being within the linear-elastic region may approximate or realize a more realistic behavior of the soil-mass (e.g. plastic hinge manifestation, stiffness degradation, hysteretic damping). NLTHA utilizes earthquake records that must capture the expected hazard on-site as described in the previous section. In geotechnical analyses, NLTHA is performed via numerical modeling, where the process is often referred to as "Site Response Analysis" (SRA). SRA is a process that measures accelerations and deformations by means of deconvolution-convolution cycles. Deconvolution and Convolution refer to the attenuation and amplification of ground accelerations, respectively, as seismic waves propagate across the subsurface. The deconvolution-convolution cycle is generally performed in a multi-step manner. SRA was carried out using a finite element method (FEM) numerical analysis tool, PLAXIS 2D. FEM is a numerical technique used for finding approximate solutions by continuum-based methods wherein the governing equations describing the state of stress of the soil/rock mass are derived on the principles of conservation of mass, momentum, and energy. These equations, together with the prescribed boundary conditions, result in a nonlinear boundary value problem.

7 HYDROLOGIC AND HYDRAULIC STUDY

According to the design guidelines of ANCOLD, the design rainfall and flood level depends on the potential health and environmental impacts of the release of the tailings. Considering that majority of the TSFs in the country are near local communities and are exposed to very high frequency of typhoons, the dams are typically categorized under High A or Extreme Risk Category. This corresponds to an extreme storm storage allowance of 1:10^4 Annual Exceedance Probability (AEP), 72-hr flood. Moreover, the recommended minimum design flood for spillway design and wave-freeboard allowance is for a Probable Maximum Flood or PMF. Design approach for the hydrologic and hydraulic study is as follows:

- Hydrologic Analysis
    - Generate frequency storms from statistical estimates
    - Delineate watersheds
    - Generate rainfall for difference design periods
    - Perform hydrologic simulations using hyetographs and storage curves
- Hydraulic Analysis
    - Generate storage routing
    - Perform hydraulic simulations and derive spillway capacity and storage capacity

HEC-HMS and HEC-RAS are typically used in the simulation and analysis. Furthermore, refinements and adjustments in the recommended approaches in the ANCOLD guidelines were made to reasonably and correctly use the local rainfall data in the Philippines.

8 CASE STUDY NO. 1: GOLD MINE TAILING STORAGE FACILITY IN BICOL REGION

The gold mine project in Bicol region has six (6) active tailing storage facilities (TSFs) with total heights ranging from 20m to 50m, cross sectional width greater than 100m, and slope gradients approximately 1V:2.5H with multiple berms. The current stage requires raising the embankments up to 4m high and the construction is a downstream type. The entire TSF system is founded on competent rock foundation layer. The TSF generally consists of a clay core, filter materials and massive structural fills which comprise majority of the embankment section. The tailings materials are generally characterized as medium stiff silty and clayey soils with shear strength varying with depth. The project entails a 3rd-party review of the design of the TSFs.

8.1 Embankment Stability Analysis

Slope stability analysis by limit equilibrium method (LEM) is performed for the various construction and operation conditions of the TSFs. The definition of LEM was intentionally left out of this paper as it is already a well-known and established approach in geotechnical engineering. From the dam break analysis conducted by the designer, the most critical slope configurations are determined and modeled in the limit equilibrium analysis. Bishop Simplified, Janbu Simplified, and Morgenstern-Price methods for both circular and non-circular failure planes are adopted. Material properties were derived from the exhaustive geotechnical investigation conducted at the project site, including SPT, CPT, UCS and Triaxial tests. Key material properties are shown in Table 1. All parameters are derived from field tests results and laboratory tests and are checked and validated with widely known references and correlations (i.e., *Bowles J. E. 1996. Foundation Analysis and Design 5th Edition; Das B. M. 2010. Principles of Geotechnical Engineering 7th Edition; Lambe W.T. and Whitman R. V. 1969. Soil Mechanics*).

Table 1. *Geotechnical properties of embankment materials*

Material Type	Unit weight, kN/m^3	Short term			Long term	
		Friction angle, ϕ', [^{0}]	Cohesion, c' [kPa]	Undrained shear strength, Su [kPa]	Friction angle, ϕ', [^{0}]	Cohesion, c' [kPa]
Structural fill	19	34	0	-	34	0
Filter material	18	34	0	-	34	0
Clay core	20	0	0	80	30	0
Deposited tailings	19	-	-	40	$S_u/\sigma_v' = 0.15$	
Residual soil	19	-	-	130	32	0
Foundation layer	22	25	250	-	25	250

Figure 1 shows a typical result of the slope stability analysis for the 50m high TSF embankment. Overall, the results show that all TSF sections under any static loading conditions yield adequate factors of safety (FoS). However, as expected for such large earth embankments, all sections resulted to failing FoS considering pseudo-static or earthquake conditions. Thus, non-linear time history analysis is necessary to be performed to further establish the TSFs' performance under seismic events.

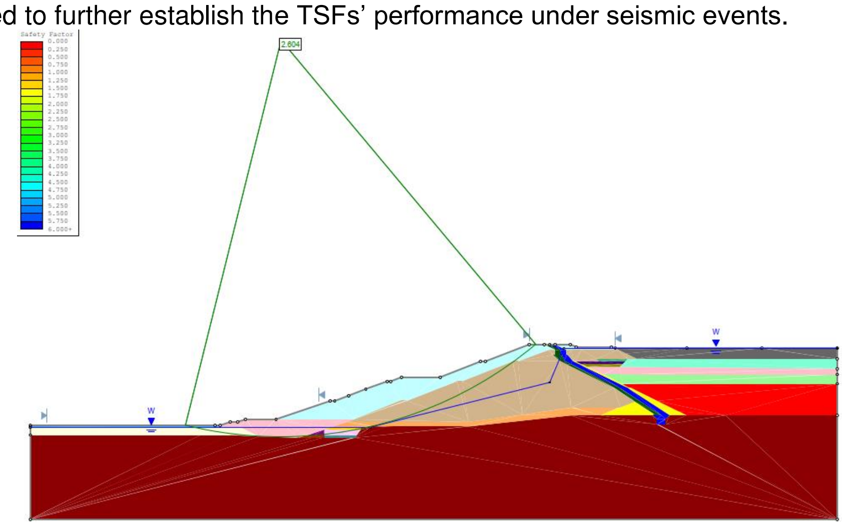

Figure 1. *Slope stability analysis result for the 50m high TSF (Source: Rocscience Slide)*

8.2 Seismic Design Considerations

As discussed in the previous sections, seismic hazard analysis was carried out to quantify the overall seismic hazard at the project site and derive the target response spectra for design. Using this target response spectra, a suite of multiple ground motions can be developed by way of spectral matching, which will then be utilized as input design ground motions in the non-linear time history analysis. Following the guidelines and provisions of ICOLD and ANCOLD 2019, the gold mine site has a consequence category of Extreme as the population-at-risk (PAR) may possibly exceed 1,000 in the case of dam failure or overtopping. For dams classified under this category, ANCOLD 2019 prescribes the following two earthquake levels:

1. Operational Basis Earthquake (OBE) with an annual exceedance probability of 1:10,000
2. Safety Evaluation Earthquake (SEE) with an annual exceedance probability of 1:1,000

Figure 2 shows the resulting target response spectra considering OBE and SEE hazard levels:

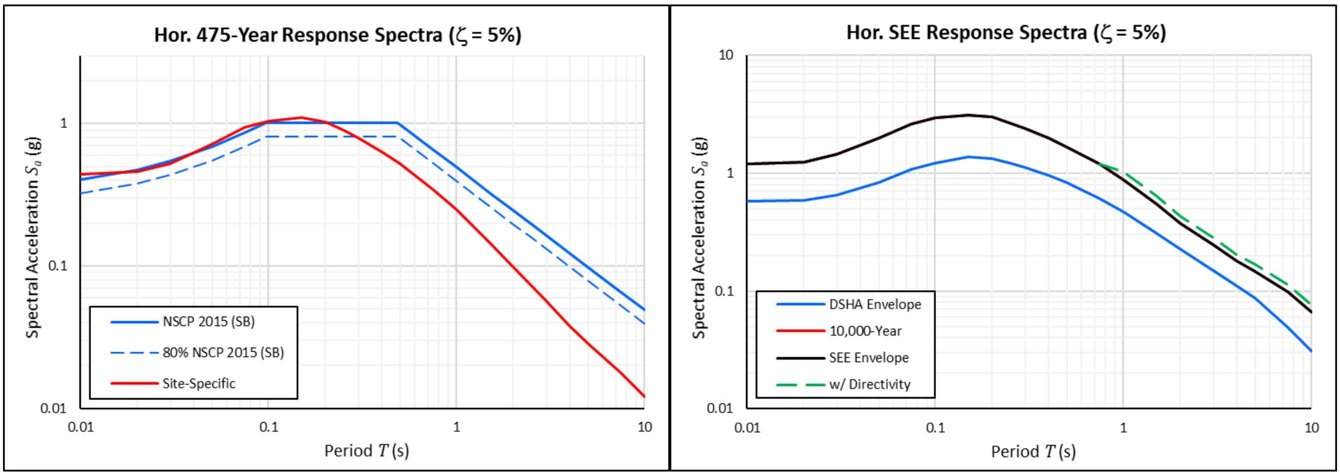

Figure 2. *5%-damped horizontal OBE response spectra (Left), 5%-damped horizontal SEE response spectra (Right) (Note: red plot coincides with black plot)*

Figure 3 shows the acceleration time histories for a sample ground motions that was used in the analysis. A total of five (5) ground motions, with two (2) horizontal components each (H1 and H2), were matched and utilized as input design ground motions for the project.

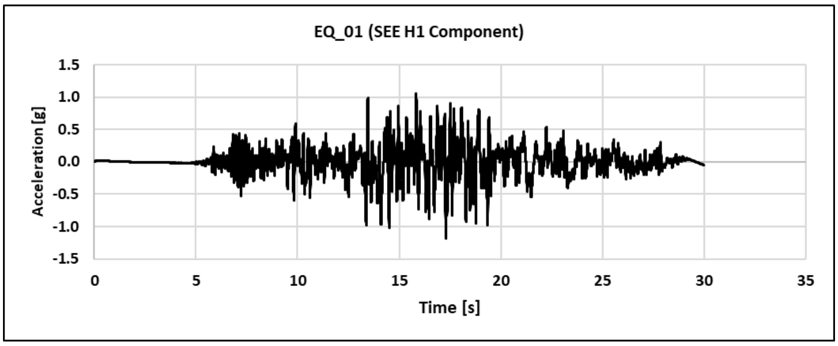

Figure 3. *Acceleration time history for 3 sample ground motions*

8.3 Non-linear Time History Analysis

NLTHA was performed for the TSF embankments using the 5 spectrally matched ground motions discussed in the previous section. In PLAXIS 2D, the Hardening Soil Small-strain (HSS) constitutive model (Benz 2007) was used to model the soil materials which involves dynamic parameters such as the shear wave velocity, Vs, shear modulus of elasticity, G_0, and modulus of elasticity, E_{50}, E_{oed}, and E_{ur}. The HSS model has the ability to capture hysteretic behaviour of soils at large and small strain levels. A compliant base boundary condition was set to account for the outcrop ground motions and a factor of

0.5 was applied to the time-histories to consider only the upward travelling seismic waves. The finite element model was extended such that there will be no 'confining effects' that will impact the results. To capture a more realistic seismic behaviour of the soil layers, the bedrock layer thickness at the base of model was assumed to be minimal to allow the reflection and refraction of the seismic waves as they propagate from the bedrock. The horizontal ground motions developed from the SHA at rock outcrop was applied at the base of the model using an appropriate factor then the seismic waves will be transmitted up to the topsoil by nonlinear convolution (i.e., amplification and/or dissipation), whilst considering soil non-linearity, damping, and hysteresis in the dynamic runs. The hardening soil with small strain (HSS) parameters for key embankment materials are presented in Table 2. In addition to the results of the field and laboratory tests, some dynamic properties such as E_{50ref} are derived from references provided by PLAXIS and are also checked with established literatures (i.e., Bowles) and previous project experiences.

Table 2. *Hardening Soil with Small strain (HSS) parameters of embankment materials*

Material Type	E_{50}, kPa	E_{oed}, kPa	E_{ur}, kPa	ν_{ur}	G_0, kPa	$\gamma_{0.7}$
Structural fill	50000	50000	150000	0.2	210000	0.000048
Filter material	50000	50000	150000	0.2	188000	0.000055
Clay core	42000	26000	83000	0.2	250000	0.00014
Deposited tailings	6600	4200	33000	0.2	77000	0.00015
Residual soil	23000	14000	58000	0.2	141000	0.00015

A general summary of the results of the NLTHA are presented in the following figures considering SEE level. Figure 4 and Figure 5 show the typical deformed mesh and deformation contour outputs of the NLTHA in PLAXIS 2D. Figure 6 presents the calculated residual vertical settlements at the crest for every ground motion.

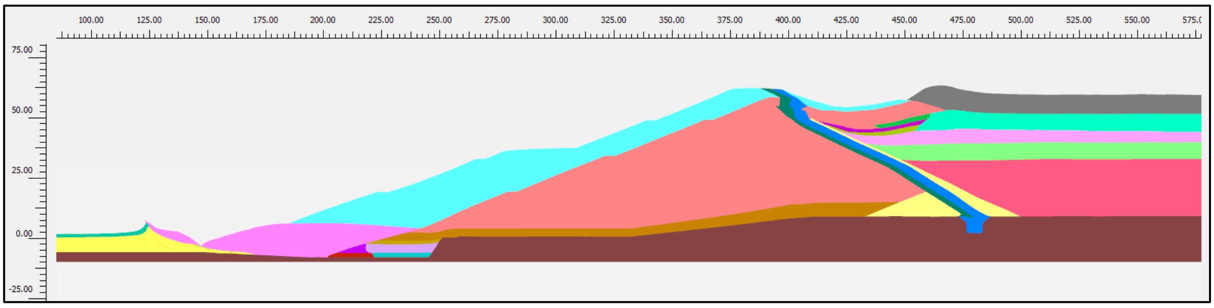

Figure 4. *Exaggerated deformed mesh of the 50m high TSF at the end of EQ_01 (Source: PLAXIS)*

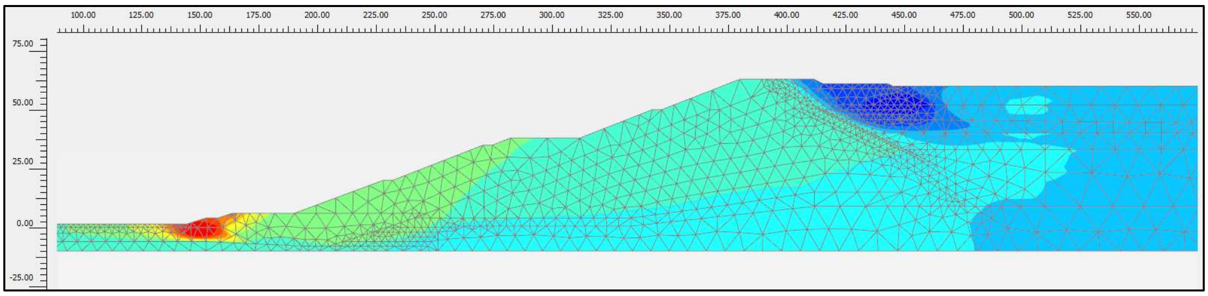

Figure 5. *Horizontal deformation contour of the 50m high TSF at the end of EQ_01 (Source: PLAXIS)*

To investigate the vertical deformations, the time history of the settlements of the 50m high TSF under all five ground motions are presented in Figure 6. Each curve already shows the mean settlements of the crest in response to the H1 and H2 components of every ground motion. The average residual settlement is about 0.69 m which is much less than the allowable freeboard, hence, the TSFs shall perform well during earthquake events.

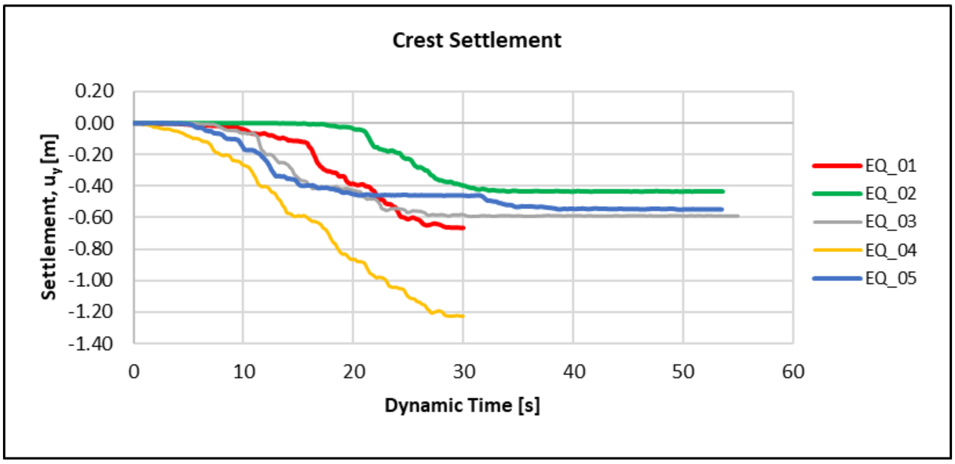

Figure 6. *Upstream crest settlement of the 50m high TSF considering the 5 ground motions*

9 CASE STUDY NO. 2: GOLD MINE TAILING STORAGE FACILITY IN MINDANAO

The gold mine in Mindanao consists of six (6) tailings storage facilities, 3 of which are active, with heights ranging from 5m to 20m, sloped at approximately 1V:2H gradients. Unlike the typical composition of an earth dam, the TSFs in this project predominantly consists of clay fill materials with layers of gravel or boulder fill at the face and base of the slopes. The project also entails 3rd-party review of the embankment design as part of the environmental audit.

9.1 Seismic Design Considerations

In order to supplement the soil investigation conducted at the project, SVL was conducted to obtain in-situ seismic wave velocities. Tests were conducted at two (2) locations, one at the crest and the other at the toe of the TSF. From the results of the testing and data interpretation, the upper 10m of the embankment is found to be composed of loose to dense and stiff materials with Vs readings generally within 500 m/s. It is then followed by stiffer or harder materials, with Vs generally ranging from 500 m/s to 650 m/s. Figure 7 (Left) presents the results of the SVL tests. Based on these results, the representative V_{s30} or harmonic mean of the measured velocities as per the National Structural Code of the Philippines (NSCP) 2015 is 535 m/s. This corresponds to site class S_c or very dense soil and/or soft rock. Furthermore, after conducting seismic hazard analysis at the project site, the 475-year earthquake response spectra was derived as per design requirements of the owner and ANCOLD.

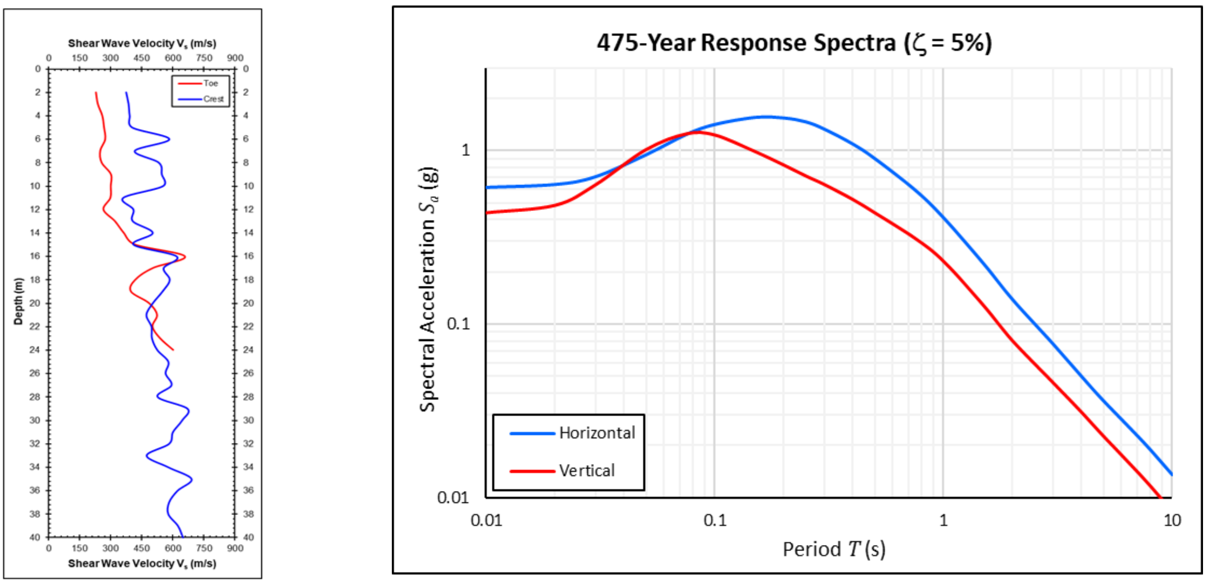

Figure 7. *(Left) In-situ Vs profiles of the 2 SVL test locations (Note: Depths are measured relative to the top of each borehole, actual location of toe borehole is at a lower depth), (Right) 5% damped 475-year response spectra*

9.2 Simplified Deformation Analysis (SDA)

Since the requirements of the project does not necessitate the more advanced and complex numerical deformation analyses, a simplified deformation analysis approach was implemented to establish the TSFs' performance during seismic events. In simplified deformation analysis (SDA), the seismic demand is represented by the average yield acceleration of the slip surface, a_y. The yield acceleration is defined as the horizontal seismic coefficient that leads to impending failure, where FS = 1.0, as determined from limit-equilibrium slope stability analysis in iterative fashion. The empirical equations by Ambraseys & Menu in 1998 and Saygili & Rathje in 2008, which are based on Newmark's methods, were then used to calculate the estimated deformations based on the design peak ground acceleration, PGA, earthquake magnitude, M_w, and the yield acceleration, a_y. The design PGA based on the SHA is 0.624g.

Ambraseys & Menu (1998),

$$log\,u = 0.90 + log\left[\left(1-\frac{a_y}{a_{max}}\right)^{2.53}\left(\frac{a_y}{a_{max}}\right)^{-1.09}\right] \pm 0.30 \quad (1)$$

Saygili & Rathje (2008),

$$Ln\,u = a_1 + a_2\left(\frac{a_y}{a_{max}}\right) + a_3\left(\frac{a_y}{a_{max}}\right)^2 + a_4\left(\frac{a_y}{a_{max}}\right)^3 + a_5\left(\frac{a_y}{a_{max}}\right)^4 + a_6\ln(a_{max}) + \varepsilon\sigma_{lnu} \quad (2)$$

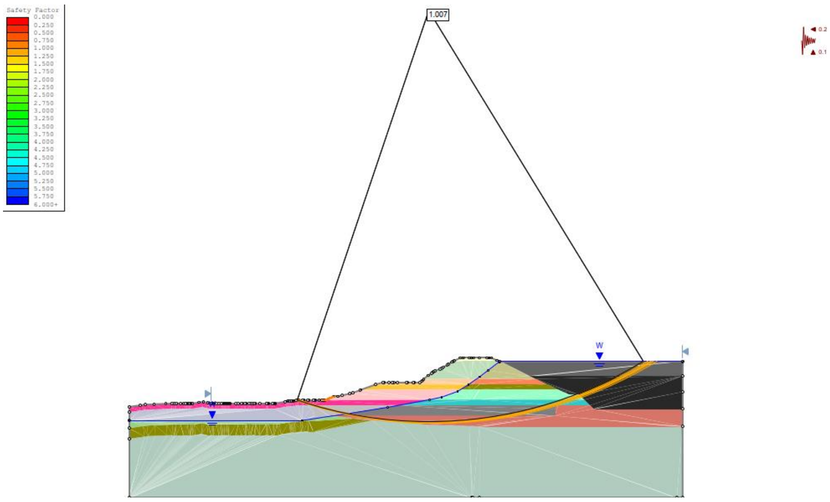

Figure 8. *Results of slope stability analysis to get yield acceleration a_y for the 15m high TSF (Source: Roscience Slide)*

Results of the SDA show that the calculated seismic deformations for the TSFs' range from 192mm to 362mm which are found to be well within the allowable freeboard of the dam.

10 CONCLUSIONS

This paper presented the design approach and considerations for the engineering of two (2) gold mine tailings storage facilities (TSFs) and were specifically developed to address the geohazards present at each project area. The design criteria were developed based on the recent provisions of ICOLD and ANCOLD, which highlights the importance of considering the environmental impacts of the projects. Site-specific seismic hazard assessment was performed to derive target response spectra that are unique to the project area. Slope instabilities under static conditions were handled through classical soil mechanics theories and were still found to provide reliable results. On the other hand, seismic analysis was carried out using advanced numerical methods. By performing simplified deformation analysis (SDA) and nonlinear time-history analysis (NLTHA), the design of the TSF embankments have been assessed in such a way that it will be allowed to displace at certain limiting values. This provided an alternate engineering solution that is much more cost-effective whereas if the traditional limit equilibrium method (LEM) was to be employed, there is a potential for overdesigning. Furthermore, with the site-specific response spectra calculated from the NLTHA, as well as the large set of outputs that it provides including accelerations, stresses, and deformations at any point in the finite element model, optimizations, realistic simulations, and performance-based designs are even more attainable.

The design of large embankment dams in the Philippines has been undergoing continuous improvement and development throughout the years as more projects are being envisioned and realized in the country. Together with the Philippine Department of Environment and Natural Resources (DENR), the mining industry is continuously updating the local standards and guidelines in order to bring emphasis on the environmental and social impact of the industry. The constant rise of state-of-the-art geophysical and geotechnical engineering tests and analyses has led to the advancement in data gathering and design analysis of such structures. A combination of classical soil mechanics theories and advanced nonlinear numerical analyses has helped in providing engineering solutions that are more accurate, elaborate, realistic, and at the same time cost-effective. However, it is extremely important to remember that all of these analyses only provide the best estimates and simulations of the behaviour of the structures and its surrounding. It is still best practice to conduct validation or proof tests, monitoring measurements, and recalibration analysis to verify all theoretical results with the actual observations. Lastly, importance in developing a proper approach in deriving local storm rainfall data and aligning it with international standards such as ANCOLD is also highlighted.

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