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Comparative Evaluation of Probabilistic and Deterministic Seismic Hazard Assessment for Tailings Dams in Central Peru: A GISTM Perspective.

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ABSTRACT: The Global Industry Standard on Tailings Management (GISTM) underscores the importance of selecting an appropriate design ground motion based on seismic setting, reliability, and applicability of probabilistic and deterministic methods for seismic hazard assessment. The choice between these methods is crucial for ensuring facility safety and must be decided based on the most appropriate approach (as mentioned in the seismic design criterion table of GISTM) to meet the required safety standards for tailings facilities. However, the term "most appropriate" is open to interpretation, prompting the need for tools to justify the selection of design ground motion. This research aims to provide earthquake engineers with the necessary tools to compare a probabilistic seismic hazard model with various deterministic hazard model scenarios.

Epistemic uncertainties associated with input parameters for Maximum Credible Earthquake (MCE) estimation, such as rupture length, closest distance to the rupture plane, maximum magnitude, and different ground motion models (GMMs) for subduction earthquakes (interface and intra-slab), will be captured by evaluating different deterministic scenarios. The resulting range of spectral accelerations from these deterministic models will be compared with the probabilistic model results for return periods of 200, 1 000, 2 475, 5 000, and 10 000 years, corresponding to consequence classifications in GISTM: low, significant, high, very high, and extreme.

The main objective is to assess the intensity obtained from seismic design criteria stated in GISTM and to recommend the most appropriate approach for seismic hazard evaluation in central Peru, a region with numerous mining facilities. This study seeks to enhance the understanding of seismic hazard assessment in tailings management and contribute to more informed decisions for the safety of mining infrastructure in the region.

KEYWORDS: Global Industry Standard on Tailings Management, Maximum Credible Earthquake, Epistemic uncertainties.

1 INTRODUCTION

The fatal consequences of the catastrophic tailings dam breach at Vale's Corrego do Feijao mine in Brumadinho, Brazil, on January 25, 2019, demonstrated that despite improvements in the operation of the mining and metallurgical industry, much more needs to be done to safeguard lives, improve performance and demonstrate transparency. Thus, based on a collaborative effort and a global review of tailings dams, the Global Standard on Tailings Management for the Mining Industry (GISTM) has been established.

However, being a global standard, the applicability of its recommendations and procedures must be verified in each geographic location in a particular way due to the variation of tectonic environments in different parts of the world. This variation of tectonic environments can generate some problems in the selection of the design earthquake based on the consequence classification (recommended by the GISTM) of a tailings dam according to the human, environmental, socio-cultural and economic losses associated with a possible failure of the dam.

In this study, a deterministic seismic hazard analysis focused on the evaluation of epistemic uncertainties and based on historical data from the region is carried out and then compared with the probabilistic seismic hazard analysis to discuss which method produces the most appropriate ground motion, as this is what is recommended by the GISTM.

2 SEISMIC-HAZARD CHARACTERIZATION

Peru is situated in one of the most seismically active regions on Earth, being part of the Ring of Fire, an area that concentrates 85% of the world´s seismic activity. The broader regional tectonic framework is governed by the interaction between the Nazca and South American plates. Key tectonic features in the western region of South America, such as the Andes Mountain range and the Peru-Chile oceanic trench, are linked to the high seismic activity and other seismic phenomena in the region. This is a consequence of the interaction between two converging plates, with the most noticeable outcome being the contemporary orogenic process that forms the Andes.

The study area in central Peru, situated within the Andes Mountain range at an elevation exceeding 4 000 meters, experiences seismic activity originating from plate subduction at depths between 80 and 140 km to the east of the region. In close proximity lies the Cordillera Blanca Fault System, stretching 220 km in the Ancash region. The northern section of the system features a single fault trace, while the central and southern sections exhibit multiple segments and branches with inclinations both to the west and east. The southern termination has a horse-tail geometry, oriented northwest-southeast, with a dip ranging from 35°W to 45°W.

Table 1 shows the characteristics of the most important historical earthquakes that occurred in Peru, based on the reports of various historians of the time.

Table 1. Hypocentral parameters of the large earthquakes that have occurred on the western edge of Perú since 1500, according to Silgado (1978) and Dorbath et al. (1990).

Date	*Depth (km)*	*Magnitude (Mw)*	*Rupture Length (km)*
01/22/1582	-	7.5	80
07/10/1586	-	8.1	175
11/24/1604	-	8.4-8.7	450
02/14/1619	-	7.8-8.0	100-150
05/12/1664	-	7.5	75
06/16/1678	-	8	100-150
10/20/1687	-	8.2-8.4	300
10/21/1687	-	8	150
08/23/1715	-	7.5	75
01/07/1725	-	7.5	75
10/29/1746	-	8.5-8.6	350
05/13/1784	-	8	300
09/18/1833	-	7.7	50-100
08/13/1868	25	9	500
05/24/1940	50	8.1-8.2	180
08/24/1942	33	8.2	200
10/17/1966	37	7.7-8.1	100
05/31/1970	42	7.9	130
10/03/1974	21	7.9-8.1	140
11/12/1996	18	7.7	150
06/23/2001	29	8.2	350

3 METHODOLOGY

The seismic design criteria outlined in the GISTM presents varying levels of seismic intensity corresponding to different consequence classifications, each associated with a return period determined through probabilistic seismic hazard analysis. Additionally, a note emphasizes the importance of selecting the design ground motion method—either probabilistic or deterministic—best suited for the facility. This paper conducts both probabilistic and deterministic seismic hazard analyses for a specific site in Central Peru and compares their results to determine the most appropriate design ground motion approach. Furthermore, the analysis was performed for a BC soil type according to ASCE 7-22, i.e. for average shear wave velocities in the first 30 metres in the range of 640 to 914 m/s, specifically the value of Vs30 equal to 760 m/s was used.

3.1 *Probabilistic Seismic Hazard Analysis (PSHA)*

For the probabilistic seismic hazard analysis, all possible and relevant seismic scenarios in the study area were considered. For this purpose, crustal and subduction seismogenic sources were determined, the latter being divided into two groups, interface sources with a depth of 50 km and intraplate sources with depths greater than 50 km, taking as a reference the subduction surface proposed by Hayes et al. (2012) and Hayes et al. (2018). For the case of crustal sources, these have been adopted from the study of Roncal (2017) that defines 9 crustal seismogenic sources for Peru, being the F22 and F28 sources the ones that influence the seismicity of our study area, also these have a depth range between 0 and 30 km. Figure 1, Figure 2 and Figure 3 shows these seismogenic sources from a plan view.

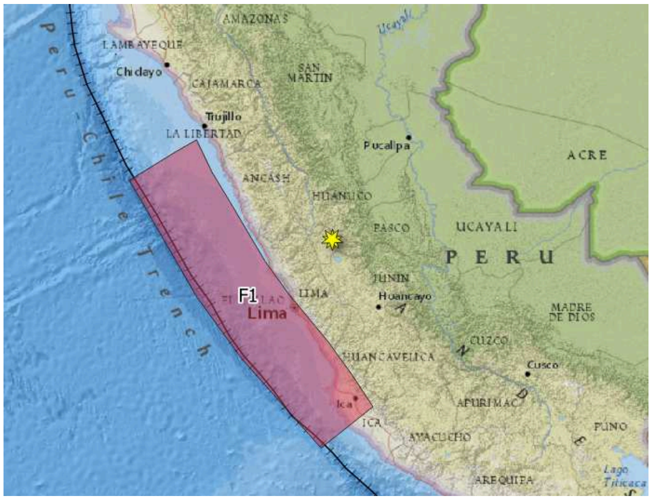
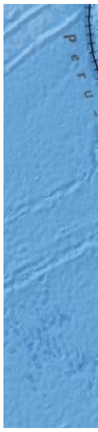


Figure 1. Intraplate seismogenic source.



historical information (1471-1960) and instrumental information (1960-2023). With the compilation of this seismic catalogue, the seismological parameters of each seismic source were determined using the exponential recurrence model of Gutenberg & Richter (1944), modified by Cornell & Vanmarcke (1969) for interface and intraplate sources and the Youngs & Coppersmith (1985) characteristic model for crustal sources.

Once the recurrence parameters of each seismogenic source had been obtained, the ground motion models (GMMs) were applied to calculate the intensity measurements in terms of spectral pseudo-accelerations, previously a logic tree was made for each source type and the result was obtained by means of a weighted average. For interface and intraplate sources, the models developed by Montalva et al. (2017), Parker et al. (2020), Abrahamson & Gülerce (2020) and Kuehn et al. (2020) were evaluated and for crustal sources, the models developed by Abrahamson, Silva & Kamai (2014), Campbell & Bozorgnia (2014), Chiou & Youngs (2014) and Boore et al. (2014) were used. The choice of these ground motion models was based on the location of the study area, the central highlands of Peru.

Finally, this analysis allows the association of a pseudo-spectral acceleration curve (PSA) for each return period or annual exceedance rate, also known as the uniform hazard spectrum (UHS). The return periods analyzed were those described by the GISTM for each level of classification by consequence: 200, 1 000, 2 475, 5 000 and 10 000 years.

3.2 *Deterministic Seismic Hazard Analysis (DSHA)*

As part of the study, a deterministic seismic hazard analysis was performed evaluating seismic scenarios for each type of mechanism, these scenarios are plotted in Figure 4, which shows the location of our study area in front of the subduction surface proposed by Hayes et al. (2018), the section corresponds to the line perpendicular to the contour lines of the subduction surface.

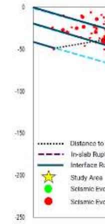


Figure 4. Transversal Section.

For the deterministic analysis it was not necessary to use the seismic catalog or the recurrence parameters of each seismogenic source, but it was necessary to identify and characterize the main seismic sources that can affect the study site. The earthquakes generated by these sources are evaluated to identify the largest events and the most severe seismic movements produced by them in a given location. These maximum earthquakes are characterized by magnitude and source-site distance and for computational purposes it is assumed that these maximum events could occur in the portion of the seismic source most unfavorable to the design objectives.

3.2.1 *DSHA – New Approach to estimate the Maximum Credible Earthquake (MCE)*

Martinez et al. (2023) proposed a logic-tree-based approach to estimate the maximum credible earthquake, where some characteristics other than the ground motion models were also weighted, in order to capture epistemic uncertainties related to the analysis such as the size, shape and location of the rupture, as well as the magnitude Mw. This methodology was taken as a basis in the present study in order to capture the epistemic uncertainties of the deterministic analysis in order to have a more rigorous support of the comparison of the result of the deterministic seismic hazard analysis with the probabilistic seismic hazard analysis and thus evaluate the most appropriate ground motion in accordance with that described by the GISTM.

To obtain the MCE corresponding to the interface source (depth less than 50km), the historical earthquakes presented in Table 1 were evaluated in order to identify values of maximum rupture area, taking as a basis the earthquake that occurred in Arica on August 13, 1868 with a rupture length of 500 km (corresponding to an approximate area of 100 000 km^2) and a Mw magnitude of 9. Likewise, three (3) Mw magnitude values associated to each of these rupture areas were analyzed, in addition, three (3) different rupture locations (as shown in Figure 4) were evaluated for each case according to the subduction surface proposed by Hayes (2018) and surfaces parallel to this at 20 and 40 km depth respectively. For the case of ground motion models, those developed by Montalva et al. (2017), Parker et al. (2020) and Abrahamson & Gulerce (2020) were used. The logic tree corresponding to the cases explained and the weights associated to each one are presented in Figure 5, in addition, it is worth highlighting that the estimation of these weights was analyzed during the development of the study but the details will not be delved into since it is not the main purpose of this research.

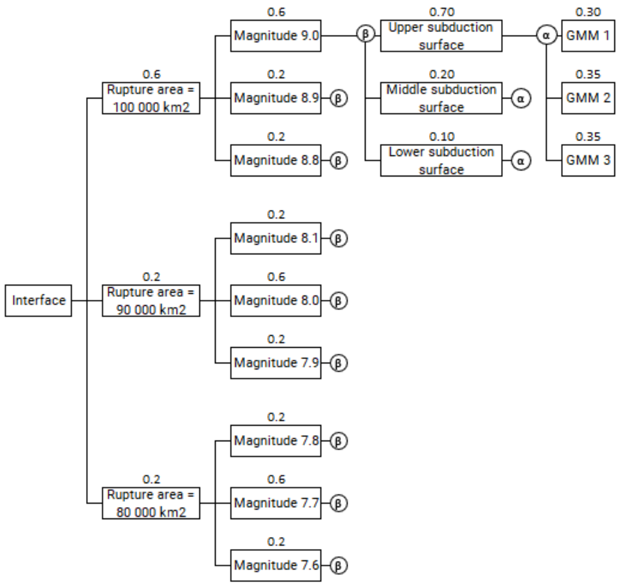


Figure 5. Logic tree - Interface.

To obtain the MCE corresponding to the intraplate source (depth greater than 50km), the data presented by Bozorgnia et al. (2020) developed for the Next Generation Attenuation Subduction (NGA-Sub) project of the Pacific Earthquake Engineering Research Center (PEER) was evaluated. Based on what was identified in this database of instrumental records, the earthquake that occurred in the department of Madre de Dios near the Peru - Brazil border on November 24, 2015, was taken as the basis since the approximate rupture area determined from the rupture length and width (85.7 and 50.8 km respectively) was the largest. Likewise, the maximum expected Mw magnitude value of 8.2 was taken into account for being close to the maximum magnitude values of intraplate earthquakes recorded in Japan such as the one that occurred on May 24, 2013, in the Sea of Okhotsk or the one that occurred on October 4, 1994 near the coast of Hokkaido. Then, three (3) Mw magnitude values associated with each rupture area were analyzed, in addition, seven (7) different rupture locations (as shown in Figure 4) were evaluated for each case according to the subduction surface proposed by Hayes (2018) and surfaces parallel and oblique to it. For the case of ground motion models, those developed by Montalva et al. (2017), Kuehn et al. (2020), Parker et al. (2020) and Abrahamson & Gulerce (2020) were used. The logic tree corresponding to the cases explained and the weights associated with each one are presented in Figure 6, in addition, it should be noted that the estimation of these weights was analyzed during the development of the study, but we will not delve into the details since it is not the main purpose of this research.

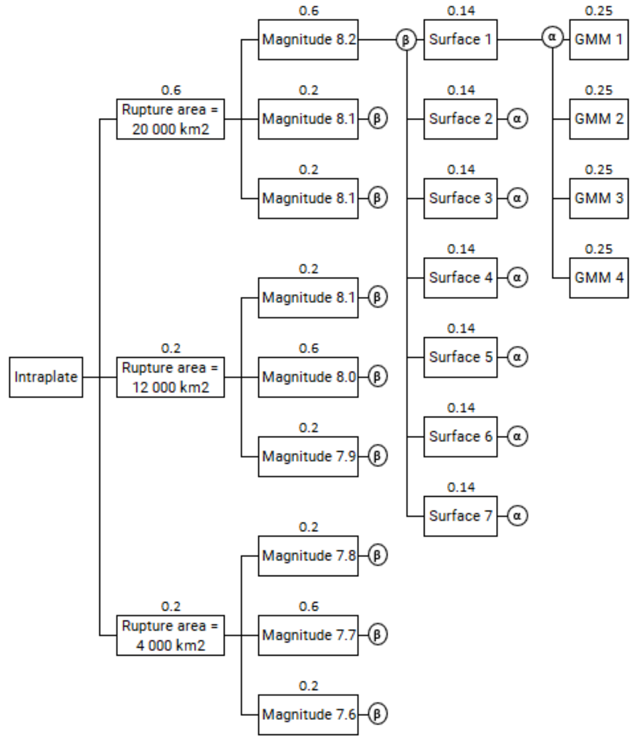


Figure 6. Logic tree - Intraslab.

To obtain the MCE corresponding to the crustal source, the Cordillera Blanca fault system was considered because it is the longest regional fault (216 km) and the closest to the study area according to the Geological System and Mining Cadastre (GEOCATMIN, 2023), two dip values were taken into account (45° and 60°) because they are the ones reported in GEOCATMIN (2023), in addition, three (3) different cases of rupture length equivalent to 100, 70 and 50% of the total length of the fault were analyzed, likewise 3 different Mw magnitude values were evaluated for each case being one of them the one calculated from the geometry of the fault according to the equations proposed by Leonard (2014). Likewise, three (3) different cases were analyzed for the rupture surface at 5, 10 and 20 km depth and finally, for the case of ground motion models were used those developed by Abrahamson, Silva & Kamai (2014), Campbell & Bozorgnia (2014), Chiou & Youngs (2014) and Boore et al. (2014) being these models those developed for faults with normal kinematics concordant with the Cordillera Blanca fault. The logic tree corresponding to the explained cases and the weights associated to each one are presented in Figure 7, in addition, it is worth highlighting that the estimation of these weights was analyzed during the development of the study, but we will not delve into the details since it is not the main purpose of this research.

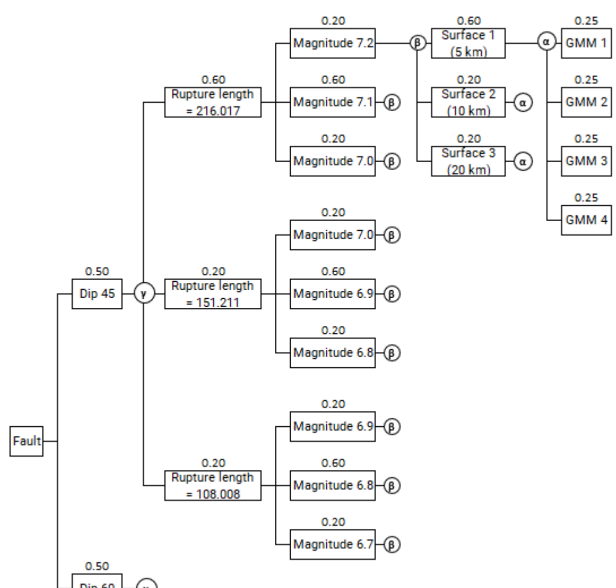


Figure 7. Logic tree – Cordillera Blanca fault system

4 RESULTS

4.1 *Results of Probabilistic Seismic Hazard Analysis (PSHA)*

Figure 8 presents the results of seismic disaggregation by magnitude and distance, calculated for soil type BC.

According to the results of the probabilistic seismic hazard analysis, the seismic disaggregation by magnitude and distance was performed, showing that the events with the greatest participation in the total hazard correspond to earthquakes of Mw = 7.0 to 8.0, at a focal distance R that varies from 90-120 km with reference to the project site, considering return periods of 200, 2 475 and 10 000 years; and spectral accelerations PGA, Sa (0.2 s) and Sa (1.0 s). These values of magnitude and distance are associated with the corresponding values for Intraplate seismogenic sources since the approximate distance to the seven (7) intraplate seismogenic sources shown in Figure 4 varies between 80 and 130 km, and the magnitudes evaluated vary between 7.6 and 8.2.

Figure 8. Seismic disaggregation by magnitude and distance.

4.2 *Results of Determinístic Seismic Hazard Analysis (DSHA)*

As Martinez's method (2023) includes epistemic uncertainties through the logical tree approach, it is suitable to calculate fractiles associated with the distribution of the results of the MCE 84th percentile. In this study, 216 crustal scenarios, 108 interface scenarios, and 252 intraplate scenarios were analyzed. Figure 9 shows the distribution of the MCE 84th percentile ground acceleration calculated for the PGA.

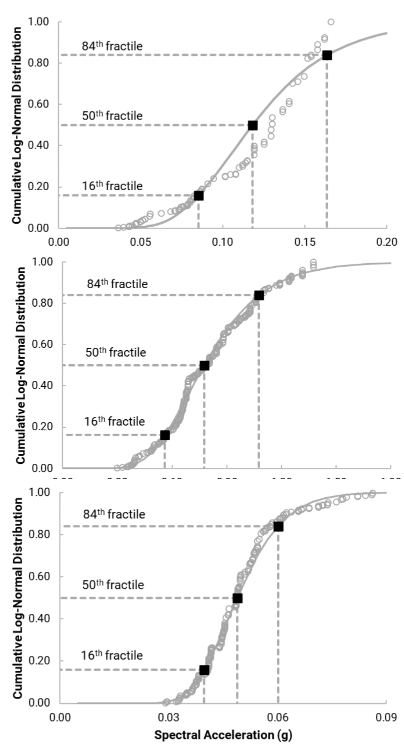
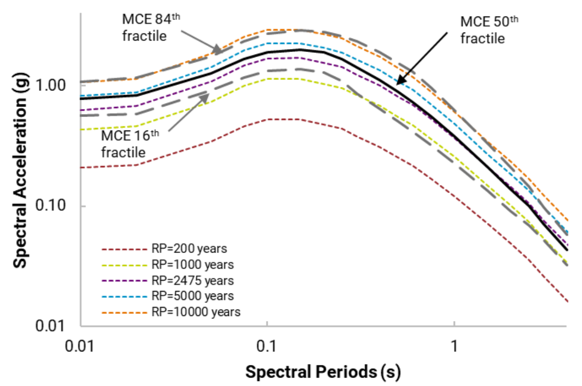


Figure 9 Fractile Distribution of PGA from Deterministic Scenarios for Interface (Top), In-Slab Subduction Zones (middle), and Crustal Zone (bottom).

Figure 9 displays the fitting of MCE 84th percentile ground motions. The log-normal distribution provided a good fit for in-slab subduction and crustal zones, while the interface subduction zone did not exhibit a strong fit. Nevertheless, based on probabilistic disaggregation analysis and the intensity of deterministic analysis, in-slab subduction emerges as the primary contributor to seismic hazard in the studied zone. Therefore, its results will be used as the MCE of the study area.

4.3 *Comparison of Spectras Required by GISTM*

Figure 10 shows the results of the probabilistic seismic hazard analysis for the return periods specified in the seismic design table of the GISTM. Additionally, the weighted MCE-84th percentile is overlaid on the in-slab subduction scenario at the 16th, 50th, and 84th fractiles.



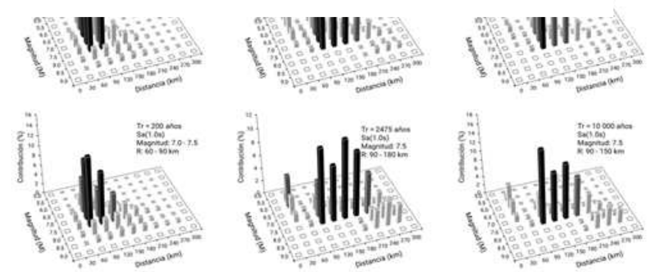


Figure 10 Comparison of Weighted MCE Acceleration Response Spectra with Probabilistic Seismic Hazard Analysis

In Figure 10, it shows that the MCE 16th fractile exhibits lower spectral accelerations across the entire spectral period range compared to the probabilistic spectrum for a return period of 2 475 years. Conversely, the MCE 50th fractile shows lower spectral accelerations than the probabilistic spectrum for a 5 000-year return period, whereas the MCE 84th fractile closely resembles the probabilistic spectrum for a 10000-year return period.

5 DISCUSSION AND CONCLUSIONS

The goal of the seismic design criteria in the GISTM, as per consequence classification, is to provide an appropriate seismic design level for tailings dams, considering the potential effects of a catastrophic failure. However, this seismic design level must be suitable for the study area, as there are regions with a predominant and well-defined rupture mechanism (subduction zones), where deterministic MCE would prevail over probabilistic spectra, which are appropriate for defining seismic design levels in areas known as stable continental regions. These regions are challenging to characterize due to the limited seismic records available.

According to the findings and observing the results of this study, the seismic disaggregation magnitude-distance emerges as a reliable indicator to realize that the contribution of in-slab subduction earthquakes is the highest in this analysis, surpassing the rest of the mechanisms analyzed. Additionally, according to the results of the deterministic analysis, in-slab subduction scenarios present the highest spectral acceleration values. It can be concluded that the most appropriate design ground motion for the study area located in central Peru is the MCE of in-slab subduction.

Considering this and the definition of Safety Evaluation Earthquake (SEE) by ICOLD (2016), the following table has been prepared with the proposed seismic design spectra for the central zone of Peru.

Consequence Classification	Seismic Criteria – Operation and Closure (Active Care)
Low	1/200
Significant	1/1000
High -	1/2475
Very High	MCE
Extreme	MCE

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