A Case Study of Las Palmas Tailings Dam Failure

T. S. Aswathi, Ravi S. Jakka, and David Frost

Abstract The increasing demand for minerals and their subsequent mining causes tailings to be produced in large amounts. Hence, tailings dams have increased in number as well as height to accommodate more storage capacity. Failure of these structures is dangerous with respect to toxic exposure, landslides, liquefaction, etc. In this study, the possible failure mechanisms of the Las Palmas tailings dam, which failed following the 2010 Maule, Chile earthquake, have been examined. Numerical simulation of the dam is carried out using the GeoStudio package to assess the condition of the dam during this seismic event and a pseudo-static analysis is carried out. The strong ground motion of the 2010 Maule, Chile earthquake recorded at three of the stations near the dam site was used as input since there is no record available at the tailings dam site. Slope stability analysis is performed to understand the possible failure mechanism. The Mohr–Coulomb failure criterion is used to define the material properties. Furthermore, the simulation results are compared with the final dam failure scenario.

Keywords Tailings dam · Earthquake · Slope stability · Pseudo-static analysis

1 Introduction

Tailings are the by-product of the mining industry from the mineral extraction process. Normally, the particle size distribution of tailings varies from medium sand to silt and clay size. These by-products in the form of slurry are transported to

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a disposal area through pipelines. There are different disposal techniques such as sub-aerial discharge, subaqueous discharge and thickened discharge which can be used for distributing the slurry. In the process of distribution, the coarser particles settle close to the point of discharge, and the fine particles run down the beach into the pond and settle there. Tailings are generally stored in surface impoundments, which commonly consist of raised embankments. The raised embankment is generally constructed with either of the following raising methods: upstream, downstream or centerline [1]. Of the raised embankment construction, the downstream method is the most stable construction [2, 3, 1].

With an increase in mineral extraction annually, the tailings containing toxic chemicals that are harmful to the environment are produced hugely in large quantities. Therefore, it is necessary to store the tailings in an environmentally safe and economical way. In order to contain the increased amounts of tailings, the height of the tailings has to be increased. With increasing tailings height, there is a risk of tailings dam failure [4–7, 3, 8, 9]. The main concern with a tailings dam is the stability during the mining operation and after its closure. From the studies, it is seen that a total of 198 tailings dam failure has occurred before the year 2000, about 20 failure cases between the years 2000 and 2010 [4] and 11 other cases from 2010 to 2015 [10]. According to these statistical results, the rate of failure of tailings dams is estimated to be 1.2%, which is more than the failure rate of conventional water retention dams which is about 0.01% [4, 11]. The high failure rate of tailings dams has led to increasing awareness of the need for enhanced safety in the design and operation of tailings dams.

In this paper, the stability of the Las Palmas tailings dam under the February 27, 2010, Maule, Chile earthquake is studied. This earthquake is the sixth-largest recorded earthquake since 1900 and occurred at 3:34 am local time with a moment magnitude of 8.8 with its epicenter of the coast of Bio Bio, Chile. The hypocenter is located at an approximate depth of 35 km (21.7 miles) at about 95 km (60 miles) off the coast and 335 km (210 miles) southwest of the capital of Santiago. The Las Palmas tailings dam contains the tailings from a gold mine operated between 1981 and 1997. The tailings dam was constructed in four stages during the operation span of the mine. During the earthquake the tailings dam became unstable and the flow slide happened. The failed tailings traveled approximately 500 m. The collapse of the dam caused the death of 4 people living nearby. The sand boils in the tailings indicated liquefaction failure (Villavicencio 2014).

2 Methodology

The analysis was carried out using the GeoStudio package (SLOPE/W) with the model being made with respect to the longitudinal cross-section of Las Palmas tailings dam (Fig. 1). In this paper to distinguish the slopes in the dyke of tailings with ease, three terms were introduced, namely upstream dyke, downstream dyke and middle dyke. The two dykes constructed using the upstream method of construction

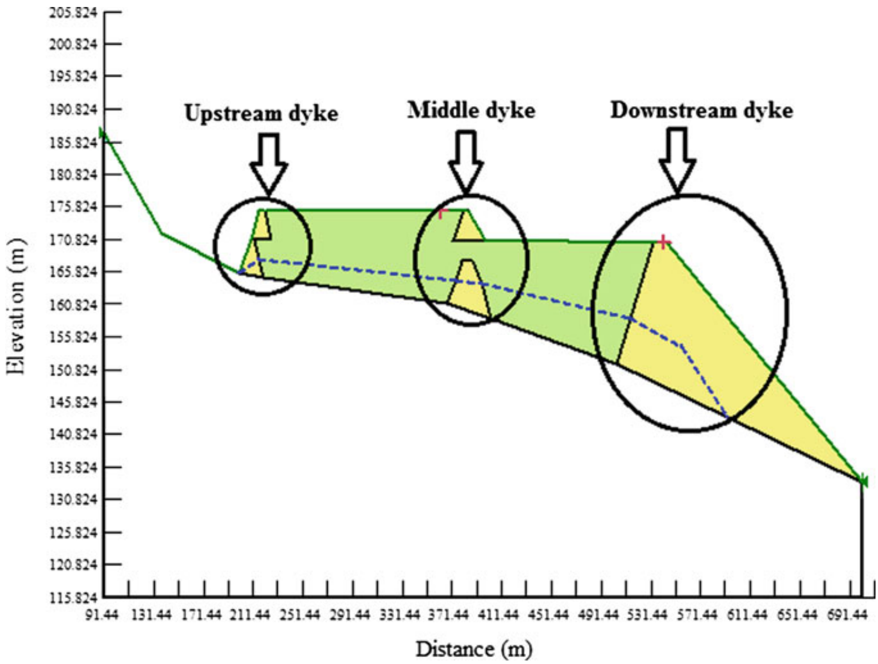

Fig. 1 Cross-sectional view of Las Palmas tailings dam (Note: The horizontal and vertical scales are different)

in the left-hand side of the cross-section are referred to as upstream dykes. Likewise, on the right-hand side, the dykes constructed using the downstream method of construction are referred to as downstream dykes. Similarly, in the middle of the cross-section, the dykes constructed similar to the centerline method of construction (but there were tailings between the two dykes) are referred to as middle dykes (Fig. 1).

In order to study the dynamic response of the tailings dam, a pseudo-static method is used. The pseudo-static method is an extension of the static slope stability method. The inertial forces created during earthquake shaking are represented using seismic coefficients in this process. These inertial forces are disintegrated into vertical (F_v) and horizontal (F_h) components. Hence, the two seismic coefficients are horizontal seismic coefficient (k_h) and vertical seismic coefficient (k_v). The selection of an appropriate seismic coefficient is the most important, and difficult, aspect of a pseudo-static stability analysis.

In theory, the seismic coefficient k_h is taken as PGA recorded at different stations though typically it is taken as 1/3 to 1/2 of crestal acceleration. Due to the unavailability of studies on crestal amplification, this assumption of seismic coefficient equal to recorded PGA is taken in order to take into account the crestal amplification. Here, the seismic coefficients are considered by dividing the peak ground acceleration by gravity. As with any other slope stability analysis, slope/w considers a possible slip surface and divides the failure mass into slices. The seismic coefficients are used to calculate the forces created by the earthquake (Fig. 2). Then the overall equilibrium computation for the individual slices composing the failure surface is done.

For doing this, initially the model is prepared by drawing the cross-section of the dam. Then defining the material properties using the Mohr–Coulomb failure criteria (Table 2),the water table is defined approximately from SPT bore logs given in [12]. The stability analysis is carried out using Morgenstern–Price method and for the pseudo-static analysis additionally seismic coefficients (Table 1) are inputted. As there were no earthquake records for the tailings site, three nearby stations Curico, Talca and Hualane stations (Fig. 3) were taken for the study. Then the analysis is run, the minimum factor of safety obtained from possible slip surfaces are considered as a critical factor of safety and it is stated in the result section (Fig. 4).

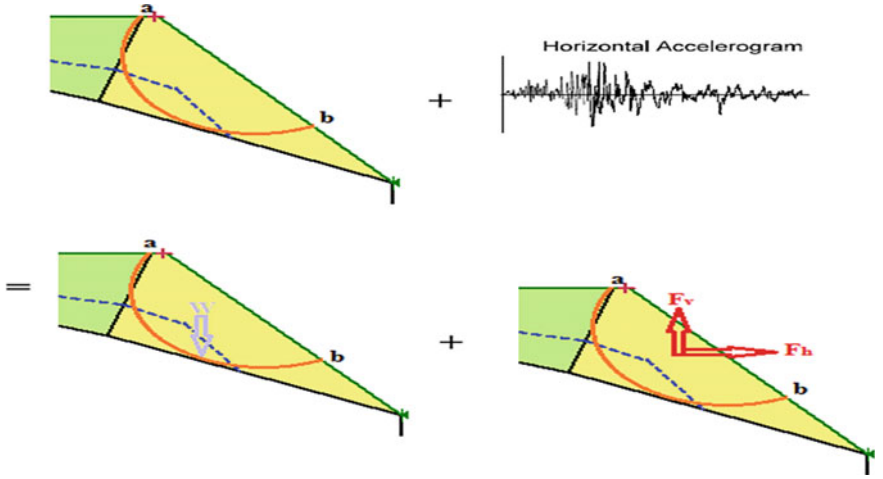

Fig. 2 Pseudo-static procedure illustration considering downstream dyke

Table 1 Stations and their corresponding PGA and k_h values

Station	PGA (cm/s^2)	k_h
Curico	461.07	0.47
Hualane	382.59	0.39
Talca	470.88	0.48

Table 2 Material properties considered in the study

Material type	Phi, ∅°	Cohesion (in kN/m^2)	Unit weight (in kN/m^3)
Containment wall	26	23.9	15.7
Tailings	10.5	11.97	14.9

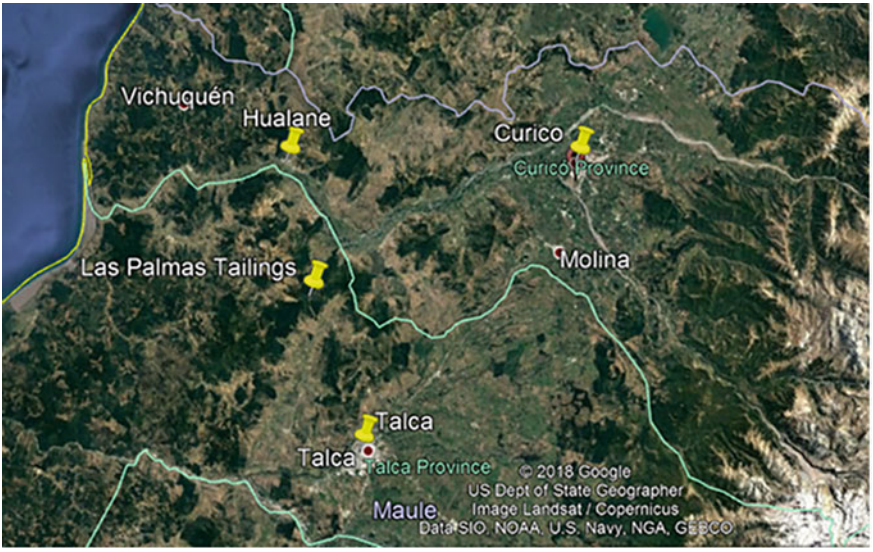

Fig. 3 Location of Las Palmas tailings dam along with Curico, Talca and Hualane stations

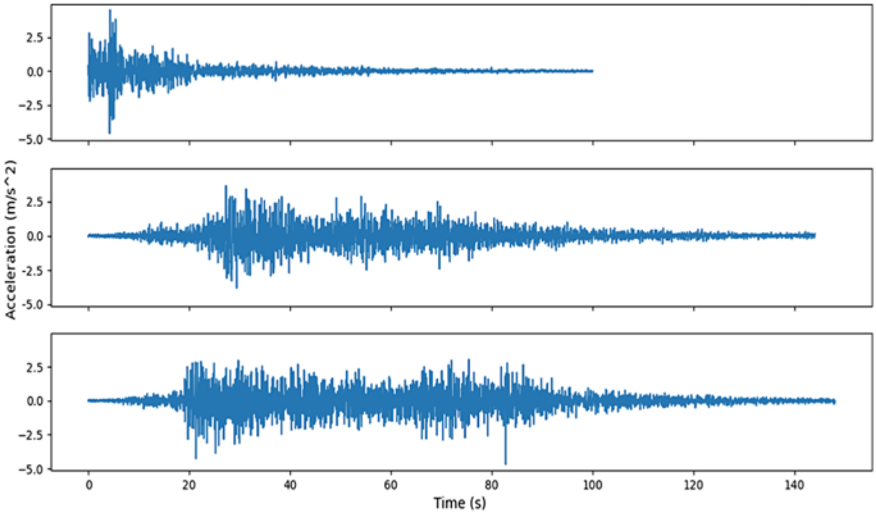

Fig. 4 Time history records at Curico, Hualane and Talca stations

3 Results and Discussion

The analysis was carried out in the following way: first, the static slope stability and then the seismic slope stability using the pseudo-static method. The pseudo-static analysis has been carried out for the motions which are recorded at three nearby stations to the tailings dam. This was done as there was no strong motion record recorded on the site. As the effect of the vertical seismic coefficient is negligible, only horizontal seismic coefficients are considered for this study. Table 1 gives the PGA and horizontal seismic coefficients of the three stations. Figure 5 shows that the factor of safety in the middle and downstream dyke are 2.325 and 1.472, respectively, indicating the tailings dam is stable under static conditions. Figure 6 shows that the factor of safety corresponding to the seismic coefficients 0.47, 0.39 and 0.48 in the downstream dyke are 0.806, 0.846 and 0.796, respectively. And Fig. 7 shows that the factor of safety corresponding to the seismic coefficients 0.47, 0.39 and 0.48 in the middle dyke are 0.935, 1.061 and 0.922, respectively.

From Table 3, it is seen that there is a decrease in stability under earthquake loading. Further, the pseudo-static factor of safety is less than one in all the cases for the downstream dyke, i.e., it is unstable during earthquakes, whereas the middle

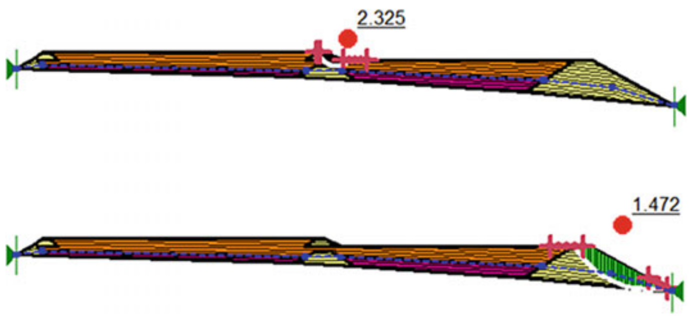

Fig. 5 The static slope analysis of Las Palmas tailings dam before an earthquake

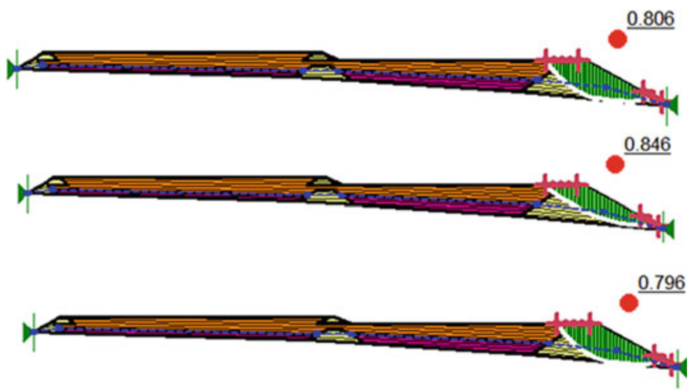

Fig. 6 The Pseudo-static factor of safety of downstream dyke corresponding to horizontal seismic coefficients of 0.47, 0.39 and 0.48

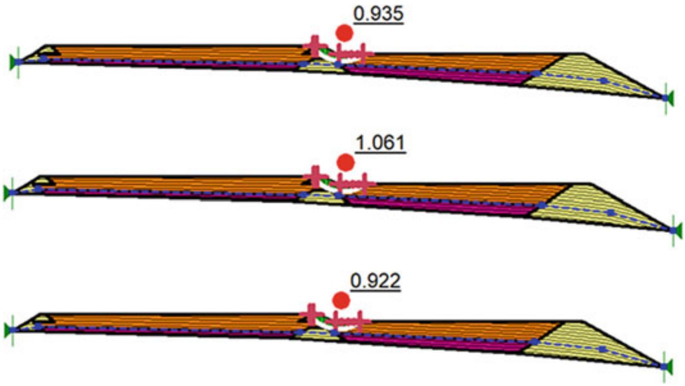

Fig. 7 The Pseudo-static factor of safety of middle dyke corresponding to horizontal seismic coefficients of 0.47, 0.39 and 0.48

Table 3 Factor of safety of dykes at different conditions

Condition	Middle dyke	Downstream dyke
Static	2.325	1.472
Pseudo-static for k_h 0.47	0.935	0.806
Pseudo-static for k_h 0.39	1.061	0.846
Pseudo-static for k_h 0.48	0.922	0.796

dyke is more stable in the static as well as pseudo-static cases when compared to that of downstream dyke. However, the factor of safety is around one (slightly more or less than one) indicating that a slight increase in seismic force is enough to make the middle dyke unstable.

4 Summary and Conclusions

Las Palmas tailings dam was built from a gold mine operated between 1981 and 1997. It was constructed in four stages. All three types of raised construction have been used in the construction of this tailings dam. In the middle dyke, there is a layer of tailings because of stage 3 and stage 4. This layer happens to be the weak layer. Many literature points this to cause the failure of the middle dyke. In this paper, the Las Palmas tailings dam stability during the Maule, Chile earthquake is studied using pseudo-static analysis.

The following conclusions are drawn from the study. The tailings dam is stable under static conditions. However, the pseudo-static analysis representative of stability under earthquake indicates that the dam is unstable under the Chile earthquake. The slope stability of the middle dyke is more in the case of both the static as well as pseudo-static cases when compared to the downstream slope. This proposes the mechanism that the downstream dyke failed first and then the middle dyke during the earthquake. Upon the failure of the downstream dyke, the contained tailings flowed down which further triggered the failure of the middle dyke, that is, the flow failure occurred.

References

1. Vick SG (1983) Planning, design, and analysis of tailings dams. Wiley, New York
2. Jakka RS, Ramana GV, Datta M (2011) Seismic slope stability of embankments constructed with pond ash. Geotech Geol Eng 29(5):821–835
3. Psarropoulos PN, Tsompanakis Y (2008) Stability of tailings dams under static and seismic loading. Can Geotech J 45(5):663–675
4. Azam S, Li QR (2010) Tailings dam failures: a review of the last one hundred years. Geotech News 28(4):50–53
5. Davis MP (2002) Tailings impoundment failures: are geotechnical engineers listening? Geotechnical News, BiTech Publishers, Richmond, BC, Canada, pp 31–36
6. Ferdosi B, James M, Aubertin M (2015) Investigation of the effect of waste rock inclusions configuration on the seismic performance of a tailings impoundment. Geotech Geol Eng 33(6):1519–1537
7. Ferdosi B, James M, Aubertin M (2015) Numerical simulations of seismic and post-seismic behavior of tailings. Can Geotech J 53(1):85–92
8. Klohn EJ (1997) Tailings dams in Canada. Geotechnical news. BiTech Publishers, Richmond, BC, Canada, pp 117–123
9. Rico M, Benito G, Salgueiro AR, Díez-Herrero A, Pereira HG (2008) Reported tailings dam failures: a review of the European incidents in the worldwide context. J Hazard Mater 152(2):846–852
10. WISE (World Information Service on Energy) (2015) Chronology of major tailings dam failures. www.wise-uranium.org/mdaf.html
11. ICOLD (International Commission on Large Dams) (2001) Tailings dams—risk of dangerous occurrences—lessons learnt from past experiences. Commission Internationale des Grands Barrages, Paris
12. Moss RES, Gebhart TR, Frost DJ, Ledezma C (2019) Flow-failure case history of the Las Palmas, Chile, Tailings Dam. PEER Report No. 2019/01