STABILITY OF A MINE TAILINGS DAM CONSIDERING DYNAMIC LIQUEFACTION

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ABSTRACT: The purpose of this work is to determine the effects of dynamic liquefaction on the tailings dams stability in the Andes mines of Perú. Perú is a mining country, many mines in the mountains of Peru store tailings in dams resulting from mineral processing, which are subject to seismic actions produced by the activity of geological faults and mainly by the subduction process of Nazca plate. The aspects investigated include determining the effect of dynamic liquefaction on the deformation of the tailings dam, calculating the effect on the development of water pore pressure of the tailings dam in the mines of the Andes of Peru. The stability of the dam is determined by the material resistance reduction method was applied, and to assess the effect of the liquefaction, the UBCSAND method was used, and the FLAC - Fast Lagrangian Analysis of Continua (ITASCA, 2005) computer program was used. Finally, the evaluations carried out show that the liquefaction of mining tailings due to earthquakes does affect the stability of the tailings dams, which must be taken into consideration in the design of dams to avoid dam failures, of tailings that generate large economic losses of the mines.

KEYWORDS: Dynamic liquefaction, mechanical damping, pressure, dam, mine tailings

I. INTRODUCTION

As [1] "soil liquefaction is one of the most common causes of dam failure in general, and the most common cause of tailings dam failure related to the occurrence of earthquakes".

Tailings dam failures can occur due to many causes, such as flooding, slope instability, seismic action, foundation subsidence, seepage, structural defects, internal and external erosion [1]. Failure of a structure causes loss of life, as well as environmental and economic damages, and even generate social problems and the definitive closure of many mines.

As [2] says "earthquakes, which can transfer normal stress from the sand matrix to the interstitial water if the soil is saturated and cannot drain during movement. The result is a reduction in the effective stress of effective confinement within the soil and an associated loss of strength and stiffness that contributes to deformations of the soil deposit". The earthquake- is a contributors to the tailings dam seismic risk [3].

The objective of this work is to evaluate dynamic liquefaction effects, in the mines of the Sierra del Perú. For this case, the deformations of the dam, the values of excess pressure of water pores generated in the tailings, and the post-seismic safety factor values were evaluated before and after the tailings liquefaction. The material resistance reduction method was applied to determine the stability of the dams, and the UBCSAND method was used to determine the effect of liquefaction and the FLAC - Fast Lagrangian Analysis of Continua computer program [4] was used.

II. LIQUEFACTION PHENOMENON

Liquefaction is one of the significant, remarkable, and complex issues in geotechnical engineering. Liquefaction-induced failure has been and continues to be one of the leading causes of destruction during earthquakes. Its devastating effects caught the attention of geotechnical engineering in 1964 when the Niigata earthquake followed the Alaska earthquake in Japan. Both earthquakes caused severe damage to buildings, foundation foundations, and natural slopes due to liquefaction.

A qualitative explanation of the liquefaction of sand and its effects under cyclical loads was first presented by Casagrande (Casagrande, 1936). The term liquefaction was originally devised [6]. Iin assets the soil mass decreases to values similar to the resistance of liquefied soil (Sladen et al., 1985).

"Loose, cohesionless soils tend to contract during cyclical loading, which can transfer normal stress from the soil skeleton to interstitial water if the soil is saturated and largely unable to drain during the quake. The result is a reduction in the effective stress of confinement within the soil and an associated loss of resistance and stiffness that contributes to the deformations of the soil deposit This loss of resistance and stiffness due to the increase in pore pressure is called liquefaction [3]"

Among the factors that influence the occurrence of liquefaction are:

• Type of soil
• Relative compactness or void ratio
• Initial confinement effort
• Magnitude of the cyclical effort
• Structure

In mining waste dams, under seismic load, pore pressures are increased, resulting in the reduction of effective efforts and the resistance to the cut of tailings, producing liquefaction.

III. POST EARTHQUAKE ANALYSIS

According to [2], in the post-earthquake period, the acting forces make the disturbances in the soil mass, caused by the earthquake, tend to adjust, adapting the soil deposit to a new permanent state condition. A post-earthquake stability analysis determines that if liquefaction occurs, the soil tends to collapse. In this case, the expected consequences are disastrous, as they can include extensive movements or crumble of the soil masses that make up the embankments or dams or any other soil structure.

Liquefaction does not necessarily need to occur for the consequences of an earthquake to be dire. Significant development of excess pore pressure is natural, even if liquefaction is not enough. An effective stress reduction associated with excess pore pressure can reduce soil stiffness, and consequently, significant cracks can occur as a result of the dissipation of pore pressures. However, if the post-earthquake stability analysis indicates that the failure can be avoided, the consequent damage will remain below the considerable level, despite the need for some degree of improvement.

On the slopes or embankments or dams made up of saturated sand deposits, after determining if the sand is susceptible to liquefaction, it is necessary to evaluate the possibility of flow-type deformation or slippage when cyclical softening or liquefaction conditions have occurred. material. This type of evaluation is called post-earthquake stability analysis, and the resistance used in this analysis is residual resistance or resistance in this permanent.

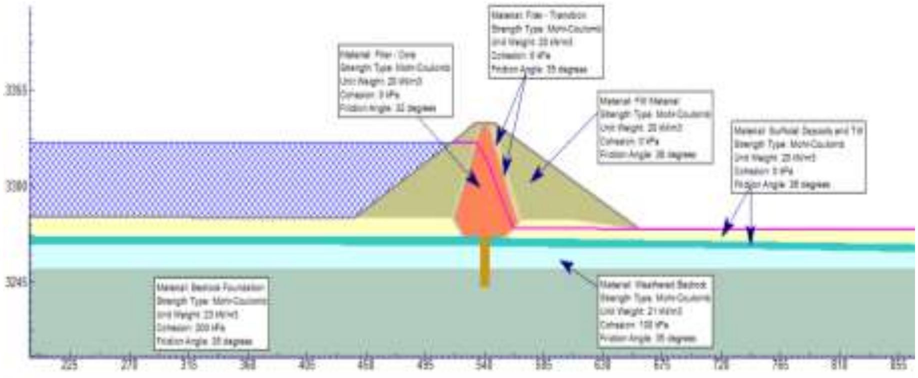
IV. GEOTECHNICAL CHARACTERIZATION OF THE DAM

Three critical sections have been defined for each dam for slope stability analysis, including configuration after foundation preparation. Table 1 shows the properties of the dam fill and tailings materials that were obtained through field investigations and laboratory tests.

Table 1. Properties of the dam and tailings fill materials

Material	Unit Weight (kN/m3)	The angle of Friction (°)	Cohesión C (kPa)	Shear resistance not drained Su (kPa)
Granular fill	20	38	0	-
Core drain	18	32	0	-
Core not drained	18	-	-	90
Filter	19	36	0	-
Transition	19	36	0	N/A
Tailings drained	16	25	0	N/A

The water table was defined with a depth of 2 m above the tailings using the SLIDE program version 5. The seismic stability analysis was conducted with a horizontal coefficient of kh = 0.19 according to the criterion of the consequence of the failure of the dam and criterion of design. Figures 1 and 2 present the stability analysis model and the tailings dam drainage system model, which will be considered for the numerical analysis of the structure.



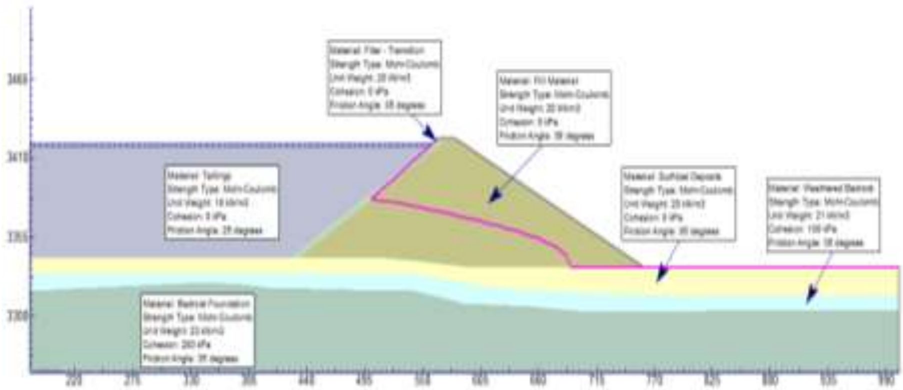


Figure 1. Tailings dam model for stability analysis.

Figure 2. Drainage system model for stability analysis.

Considering the maximum acceleration as a project criterion, it was necessary to apply a reduction factor of 2/3 to study the effects of the average acceleration of the time history record instead of the maximum acceleration. The Moquegua accelerogram values were then modified; the record is being normalized for the maximum acceleration of 0.19 g, see Figure 3.

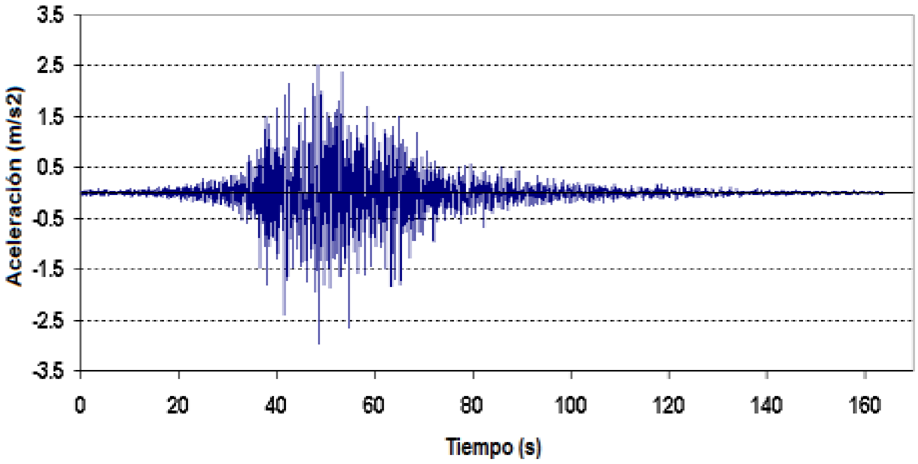


Figure 3. Moquegua earthquake acceleration record on 06/23/2003.

V. RESULTS

Tailings Dam Deformations

Several deformations analyze with FLAC were obtained by applying the corrected seismic acceleration for baseline in the model and at the different control points on the crest of the dam reported the results shown in Figure 4. According to the results, it is confirmed that the horizontal displacements if they increase with the dynamic liquefaction phenomenon. In this case, these horizontal displacements, and the signs of tensile cracks are not significant towards the crest of the dams.

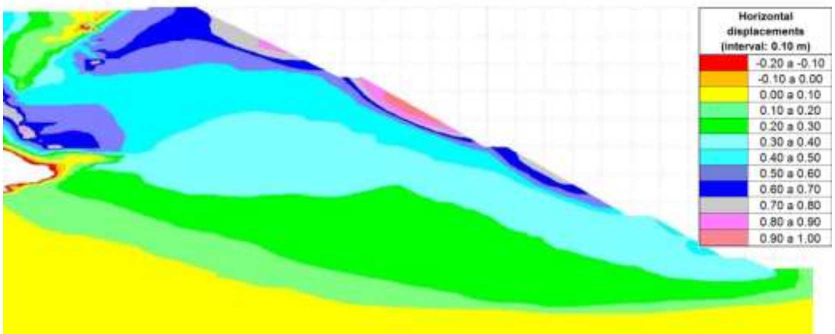


Figure 4. Horizontal displacement before the liquefaction phenomenon –Presa Antamina

Excess Pore Pressure

According to the numerical analysis, liquefaction does increase the water pore pressure of the tailings dam. Figure 5 shows the water pore pressure ratio in Lima earthquake (1974). In general, all the tailings were liquefied in 15 seconds of seismic movement, except for compacted tailings that have not reached liquefaction.

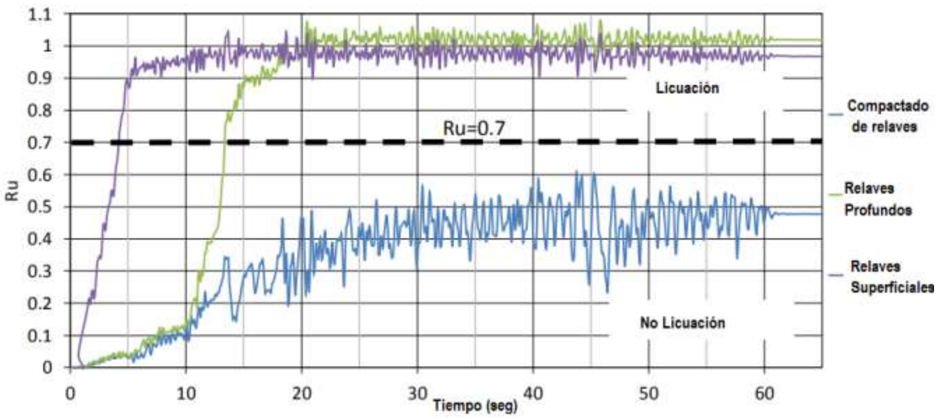


Figure 5. Water pore Pressure Radius developed in tailings of the dam.

Stability Analysis Results

For the stability analysis, circular failure surfaces were considered, the calculations were made with the FLAC 2D computer program considering the finite difference numerical method and the Resistance Reduction criterion was used.

The stability analysis of the tailings dam before liquefaction results in a safety factor (FS) of 1.56, with FS> 1.5 above the minimum criteria established by the International commission on [5]. However, when the stability of the tailings dam is analyzed after the liquefaction phenomenon, a safety factor of 0.76 results, as illustrated in Table 2, which means that the structure will be unstable and that there is a dynamic liquefaction effect on the structure and consequently requires greater control of field monitoring and to anticipate some contingencies to avoid the failure of the structure.

Table 2. Results of Static and Post-earthquake Safety Factor of tailings dams in the Peruvian highlands.

Presa	Critic section	Security factor	
		FS Estática	FS Post Sismo
Antamina	A-A'	1,56	,96
	B-B'	1,57	,89
	C-C'	1,52	,89
Toromocho	A-A'	1,59	,86
	B-B'	1,60	,89
	C-C'	1,53	,96
Hudbay	A-A'	1,65	,94
	B-B'	1,55	,93
	C-C'	1,64	,97
Pachon	A-A'	1,65	,98
	B-B'	1,86	,95
	C-C'	1,75	,92
Cerro Verde	A-A'	1,58	,91
	B-B'	1,68	,88
	C-C'	1,70	,99

VI. DISCUSSION

According to the results of the deformation analysis with the FLAC program, the horizontal displacements reached up to 98 cm in the crest of the dam, it is attributed to the readjustment and relaxation of the stresses produced by its own weight and external mechanical loads during the construction stage, In this state they did not present significant presence of tensile cracks, which is typical for the deformation of the dam's ridge. Then, applying a seismic event producing tailings liquefaction, it can be observed that the displacement values increase up to 104.50 cm, that is to say in 6.6%, in general, the displacements of these quantities in dam are considered within the permissible limits [6].

The development of water pore pressures due to seismic events caused liquefaction of tailings over 15 seconds as shown in Figure 2. Values above the pore pressure ratio (Ru) over 0.7 indicate tailings liquefaction [7]. The results of excess pressures reach up to Ru = 0.86, which in terms of deformation would not affect the dam stability.

For static conditions before liquefaction and for seismic load and post-earthquake conditions were analyzed based on a safety factor, using the FLAC program using the criterion for reducing soil resistance. Consequently, the Morh coulomb model was used to calculate post-earthquake safety factors after dynamic analysis developed with the UBCSAND model.

The values of safety factors (FS) for static conditions reported values over 1.52, with FS> 1.5 being the minimum allowable according to [5] and the dam is considered stable for this static condition, however, when a seismic excitation being a zone of seismic activity, the values are reduced to FS = 0.86, caused by the reduction of the resistance of the material.

VII. CONCLUSION

Through the determination of deformations before and after the dynamic liquefaction event at the crest of the dam, it is concluded that there is an increase in horizontal and vertical deformations of the crest.

Water pore pressure results indicate excess water pore pressure in tailings materials, values of ru≥0.7 (minimum referential value according to [5] that predicts sectors upstream of the dam if they are prone to dynamic liquefaction. To analyze the results of the static safety factor that corresponds before the seismic event and the post-earthquake safety factor of the slopes of the tailings dam, located in seismic activity zones should be designed to evaluate the effect of dynamic liquefaction that will affect structures.[8]

VII. REFERENCES

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