Managing of tailing's stability against earthquakes impact

prof. ass.dr. Kemajl Zeqiri

Abstract— Managing of mining industry is becoming a worldwide concern and this for two reasons, first (i); society have been and continue to be depending on mineral resources exploitation, in order to meet their needs, which means the tailing creation will continue and second (ii); the challenges on managing of environment protection against mining industry. Impact in tailing stability is just a component of tailing management. Unfortunately, several tailing's failures worldwide have been caused as earthquake impact. This paper will examine several examples of the tailings failure as earthquake impact, the consequences by these cases and shall trying to determine measures to be taken in order to avoid earthquake impact in the tailing stability.

Key words— tailing, stability, management, environment, mining, industry, failure.

1. Introduction

Tailings are basically made of remaining material after processing of ore and created waste materials that have to be deposited or disposed on the so called tailing dumps (Zeqiri, 2016).

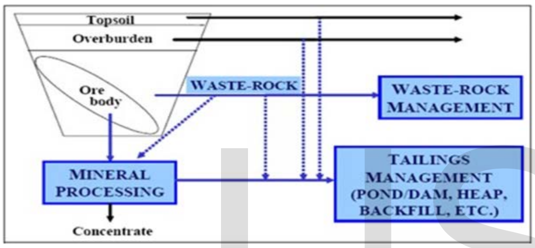


Figure 1. Flow chart of tailing creation

The mining industry is an inseparable part of the development of human society. Today's economic development and improvement of living conditions cannot even be imagined without the participation of the mining industry (Pruchnicka. J., Zeqiri. K, 2017).

Table 1. Mineral utilization and society development

Need	Objective	Period of time
Kitchen utensils	Food, accommodation	prehistoric
Weapons	Hunting, defense , battles	prehistoric
Decorations and ornaments	Jewelry, cosmetics, color	Antique
Currency	Exchange	Early
Structures and equipment	Accommodation and transport	Early
Energy	Heating and travelling	Middle ages
Machinery	Industry	Modern
Electronic	Communication , computers	Modern
Fission nuclear	Energy, wars	Modern

Thus, mineral consumption continually has support development of society, increasing amount of consumption in continuity, consequently resources consumption have been raised five to six fold, between years 1960-2009, for e.g. copper demand was raised for 393% from 1960 up to 2009 (Zeqiri. K, Biserka. D., et al, 2013).

In the other hand due to different reasons, including earthquake, the thousands tailings worldwide, in the beginning of '70s, started to occur not only as permanent "slower polluter" but as a "fast and destroyed polluter".

- *Author is professor at "Isa Boletini" University of Mitrovica, Faculty of Geoscience. Countr;, Kosovo. E-mail: kemajl.zeqiri@umib.net*

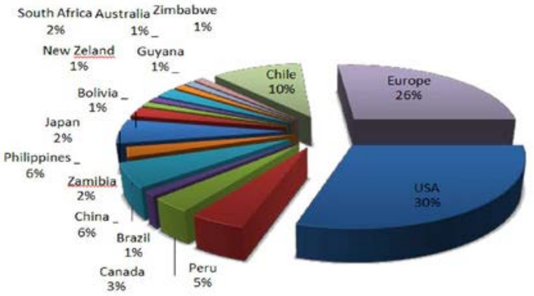


Figure 2. Worldwide tailings failure percentage

There have been recorded more than 100 (hundred) tailing dams failure worldwide from 1961 till 2012. In the USA are recorded 26 tailings failure, in Europe 23, Chile 9, Canada 3 while in Australia one.

It should be highlighted, the Australia and Canada despite of huge mining activities, there have been recorded just a few tailing failure, hence tailing management practice of these countries might be considered as best practice.

2. Earthquake impact in tailing failure, facts and figures

The engineering practice has registered catastrophic failures of tailings dams triggered by the dynamic forces of earthquakes, causing severe losses to the private property, important destruction of agricultural lands and in many cases loss of human lives (Verdugo, 2009).

About 20% of recorded tailings failures, between 1960-2012 were caused directly from earthquake events. Six tailings failure happened from one earthquake events in Chile, in 1965.

With regard to earthquake impact on tailing failure, it should be taken into consideration that earthquake, has at last two effects of its impact into tailing dam stability: the first (i) direct impact, which instantly causes dam failure and the second (ii) indirectly impact, which has impact on weakening of tailing stability'(broking of cohesive forces), this way over entire length and width of the tailing body, stimulates or creates: fractures, cracks, liquefaction spilling etc. up to causing of local tailing body's slides, damaging of isolation layer and seepage infrastructure (Zeqiri. K, Biserka. D., et al, 2013).

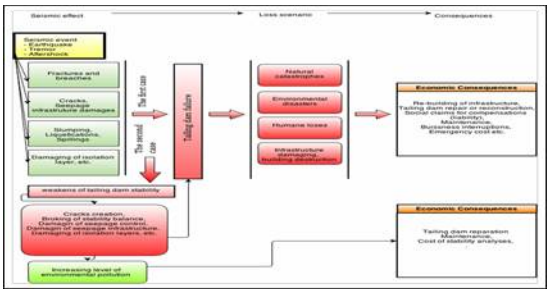


Figure 3. Flow chart of earthquakes impact in tailing stability

From analyses done of earthquake of 27 February 2010 in Chile it was concluded that in those dams showing partial or total liquation, that's basically describes general impacts of the earthquakes in to tailing stability.

- The seismic inertial forces caused liquefaction of the superficial layers of fine materials.
- Liquefied tailings and the decant pond showed an oscillatory movement during and immediately after the earthquake, temporarily leaving the upstream slope of the dam unconfined. Therefore, the upstream slope, in its weakened state, slumped towards the tailings basin, generating cracks or fissures parallel to the dam crest.
- Landslide wedges were created in the downstream slope due to the combined effect of inertia forces, pressure of liquefied tailings, and decrease of basal contact areas.
- Movement of liquefied fine materials through cracks and fissures eroded the retaining dyke and generated sloughs.
- Adjacent sloughs and slumps allowed the escape of unconfined fine material, thus allowing the generation of progressive liquefaction, with large volumes of fines showing a low resistance and flow vulnerability.
- The combination of the large pressures of liquefied fines and the likely decrease of the shear strength of tailings sand may have led to failures due to landslides and flow failures.

- The gradual progress of liquefaction to greater depths within the tailings compromised the entire deposit, generating staggered terraces that remained even after the earthquake (Fig. 4a).

The evidence of liquefaction in the tailings basin was shown by the eruption of volcanoes caused by the increased pore pressures (Fig. 4b). Once the excess pore pressures dissipated, the structures stabilized, with a new geometry that provided less resistance (residual, post-liquefaction) than the original retaining dyke (Villavicencio.G, et al, 2014).

The term liquefaction was coined by Hazen (1920) to describe the failure of the hydraulic fill sand of Calaveras Dam on March 24th, 1918. In this failure, the up-stream toe of the under construction Calaveras dam, located near San Francisco in California, suddenly flowed moving approximately 700,000 m3 of material for around 90 m (Verdugo, 2009).

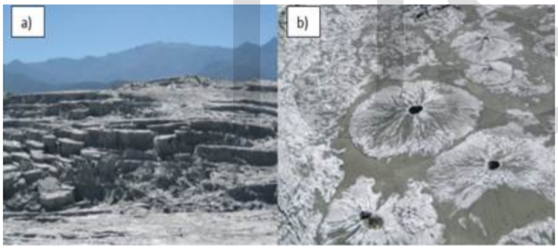


Figure 4. Some of consequences after seismic event in tailing

The failure mechanisms in tailings sand dams constructed using upstream and centreline methods usually develop sliding-wedge type failure surfaces.

Figure 5. Upstream slope deformations of retaining dyke caused by settling of underlying slimes

Since the beginning of the 20th century until now (from 1901 to 2013), a total of 38 cases of mechanical instability of sand tailings dams in Chile were caused by seismic liquefaction (Villavicencio.G, et al, 2014). Hence, liquefying-damage is a typical destruction of mine tailings dams in earthquakes (Cai. S, et al, 2017).

Often the instant impact of the earthquakes cause tailing failure, which then causes natural catastrophes and disasters up to humane losses, in the second one (ii) earthquake, weakens tailing dam stability, being this way as a relevant factor for eventually future dam failure. On the other hand, damaging of seepage infrastructure, isolation layer etc., indirectly increase contamination of underground water, i.e. environmental negative impact.

Obviously, there is no doubt that earthquake has impact on the tailing dam stability i.e. environmental pollution and disasters, even this impact could be instantly or background (which almost increases environmental pollution and stimulate tailing failure) (Zeqiri. K, Biserka. D., et al, 2013).

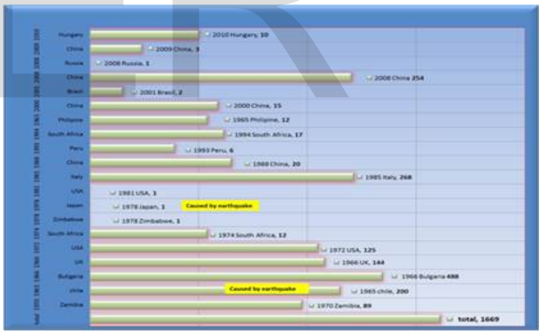


Figure 6. Humane life's losses caused from tailing failure, 1970-2010

The current example of the earthquake's impact in tailing failure held in Brazil, exactly; on 5 November 2015, around 4 P.M. local time (UTC_02:00), a tailings dam in the Samarco Mine, state of Minas Gerais, Brazil, collapsed releasing more than 30 million cubic meters of water and mine waste. The failure of this structure, called Fundão dam, caused the flooding of the small town of Bento Rodrigues situated less than 5 km from the dam. As a result, 17 fatalities have been confirmed while 2 persons remain missing. The mudflow reached

the Atlantic coast through the Doce River, along more than 500 km of river course, and the spill of the mine tailings and mud is already considered one of the worst mining accidents in the history of Brazil (Agurto-Detzel.H., 2016).
This example bears in mind, that tailing failure after earthquakes impact, overcomes local and even regional disasters, thus causes the global environmental pollutions as well as global problems.

The economic impact of tailings failure is huge and shall be based on three measures, reflected after tailings failure:

1. Emergency impact, including business interruption,
2. Infrastructure rebuilding or repairing,
3. Long term of environmental and social impact, including claims and liabilities

Considering these three components (measures) of economic impacts, it can be concluded that determination of cost-impact from tailing failure is complex and difficult to determine (Zeqiri. K, Biserka. D., et al, 2013).

Approximately estimated tailing failure cost

Table 2. Approximately estimated tailing failure cost

Cost Emergency impact including business interruption	**Cost of: Infrastructure rebuilding or repairing**	**Cost of: Long term of environmental and social impact including claims and liabilities**	**Approximately total cost**
75,182,785.19 €	252,564,116.50 €	6,848,517.52 €	334,595,419.21 €
Notes: there is not included impact-cost of business interruption and impact-cost of claims and liabilities, and animal loses.			

The calculation is based in literature research, for tailing failure worldwide; there has not been any "in situ" estimation. As calculation parameters have been take into consideration number of victims (life loses and injured victims), reported infrastructure damaged or destroyed, number of evacuated people, contaminated of drinking water i.e. cost for treating of contaminated water and soil from high metals content.

2.1. Tailing stability and seismic events

The factor of safety for slope stability analysis is usually defined as the ratio of the ultimate shear strength divided by the mobilized shear stress at incipient failure, **Fm=Mr/Md,** where; "Mr" is the sum of the resisting moments and "Md" is the sum of the driving moment.
Geotechnical stability of tailings is one of the key factors for managing tailing safety and ultimately the safety of ITMF systems. In fact, geotechnical stability includes the geological formations on which the tailing lies and the stability of the tailing slope against falling of materials. Based on statistic data, 99% of tailing failures have taken place by sliding of the slope as a consequence of earthquakes, floods or due to breaking of stability forces. The mechanical stability of the tailing mass is very poor as well due to the small grain size and high water content (Zeqiri, 2016).
Tailing are initially not established to their completion, but are raised subsequently based on three methods as are upstream (I), downstream (II) and centreline (III).

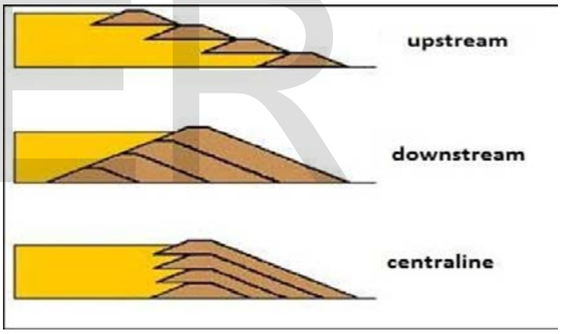


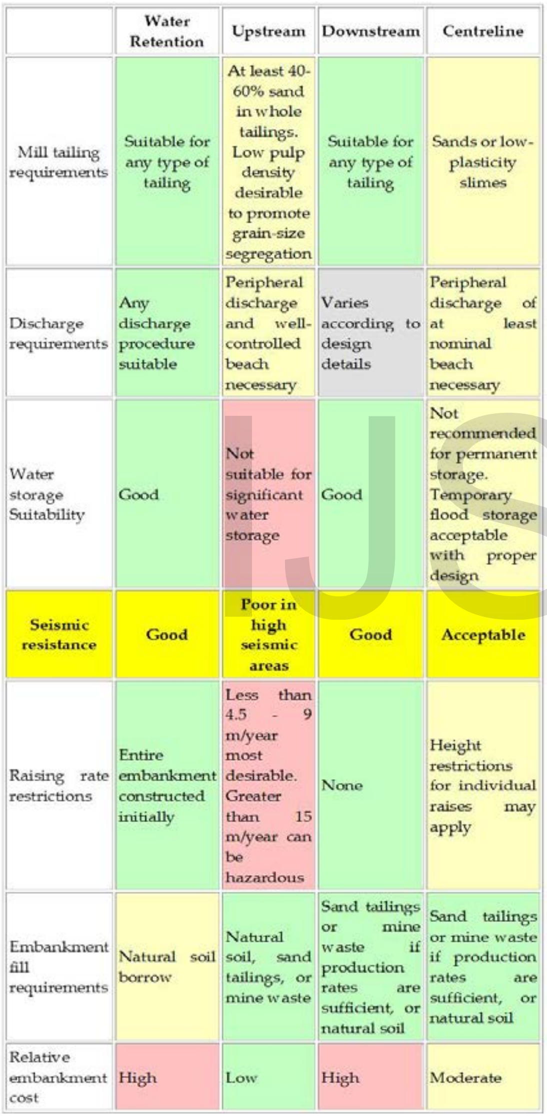
Figure 7. Three base methods of tailing constructions

Phreatic surface is critical for the dump stability. Tailing failure occurs if the beach width between the dump crest and the decant pound becomes too short from flood inflow (Indeed, there is no data about exact distance which will ensure tailing stability, this can be explained due to the fact each tailing has own characteristics, and using any correlation between them may not generate satisfactory results).
Upstream dams – embankments are particularly sensitive to liquefaction, which mainly are created during severe seismic ground motion that can originate from an earthquake, a nearby mine blasting or even nearby heavy equipment.
The upstream dam stability is endangered if the raising rate of a dam is too high. Raising rates greater than 15 m/year may be hazardous. They

produce excess pore pressure within the deposit thus decreasing the stability (Zeqiri, 2016).

Despite of poor resistance in high seismic areas (tab.3), but due to the low cost most of the tailings are constructed based on upstream method. The world experience has shown that these tailings are not properly maintained wherefore there have been hundreds of tailing dam failures worldwide, some of which with catastrophic consequences (Zeqiri, 2016).

Table 3. Comparison of surface impoundment embankment types



	Water Retention	Upstream	Downstream	Centreline
Mill tailing requirements	Suitable for any type of tailing	At least 40-60% sand in whole tailings. Low pulp density desirable to promote grain-size segregation	Suitable for any type of tailing	Sands or low-plasticity slimes
Discharge requirements	Any discharge procedure suitable	Peripheral discharge and well-controlled beach necessary	Varies according to design details	Peripheral discharge of at least nominal beach necessary
Water storage Suitability	Good	Not suitable for significant water storage	Good	Not recommended for permanent storage. Temporary flood storage acceptable with proper design
Seismic resistance	**Good**	**Poor in high seismic areas**	**Good**	**Acceptable**
Raising rate restrictions	Entire embankment constructed initially	Less than 4.5 - 9 m/year most desirable. Greater than 15 m/year can be hazardous	None	Height restrictions for individual raises may apply
Embankment fill requirements	Natural soil borrow	Natural soil, sand tailings, or mine waste	Sand tailings or mine waste if production rates are sufficient, or natural soil	Sand tailings or mine waste if production rates are sufficient, or natural soil
Relative embankment cost	High	Low	High	Moderate

Tailing failure takes place mainly due to two causes:

1. The low geotechnical stability of the geological formations upon which the tailing lies (weak foundation) and
2. Breaking of the tailing material (inner stability).

Even though the earthquake has impact in both cases, the significant impact of earthquake is in second case.

For example, in the case of office buildings, hotels and hospital structures, the investment in structural framing is only around 18, 13 and 8%, respectively; of the total cost (Verdugo, 2009).

Seismic events also have a negative effect upon the dam stability particularly when talking about upstream dams. As a result of such events, most of the impounded tailings may be released in slurry wave and cause devastation in the downstream area in a very short time.

For instance, in Italy, there have been a number of failures of tailings situated in steep mountain valleys in areas of high seismic activity (Zeqiri, 2016).

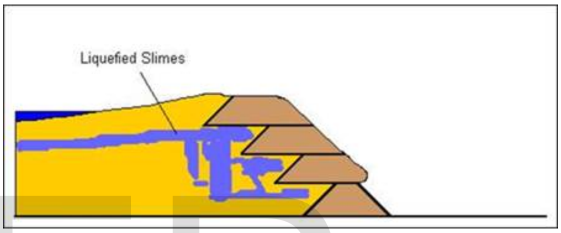


Figure 8. Schematic view of tailing failure as results of seismic event

General analyses of earthquakes often consider only the vulnerabilities of industries and not the surface installations of mines and so special attention must be given especially to tailings ponds and tailings dams, for example. This is because in a loss-scenario the damage caused by a collapse of a tailings dam can be very serious and include wide ecological and economic losses (Rudolph T., et al, 2012).

For instance, the exposure of German tailings facilities to earthquakes is low, especially because of the effective standards and regulations which are used to operate them (Rudolph T., et al, 2012). This statement is very important, because highlights importance of the standards and regulation, with regards to minimizing of earthquake impacts in the tailing's stability.

The seismic failure of Barahona Tailings Dam has been analyzed. Causes of failure were decrease of the shear strength of the slimes and large displacements and breaching of the sand dikes. The dikes were partially founded on the unconsolidated slimes because the dam was built by the upstream method. Liquefied tailings flowed violently down the courses of Barahona creek and Cachapoal river causing heavy destruction over a 50 km long path. It is concluded that the upstream method of construction of tailings dams should not be encouraged in seismic zones; however, it could be considered as an alternative solution, provided that the residual strengths of sands and slimes are properly evaluated (Troncoso. J.H, et al, 1993) .

In the other hand, four causes have been established as the main factors contributing to instability of Chilean sand tailings dams: construction method, poor compaction, high fines content in the cyclone tailings sands, and an elevated degree of saturation. These causes may be attributed to inadequate design, construction, and operation, or combinations of these factors. Associated dominant failure mechanisms that have been observed are: seismic liquefaction with flow failure (true liquefaction), slope instabilities with seismically induced deformations, and overtopping (Villavicencio.G, et al, 2014).

Within the main aspects considered, geometric recommendations (slopes, crest width, and freeboard height), basal drainage construction, management of the decant pond, characteristics of the tailing sands to be used in the construction of the retaining dyke (grading, compaction rate, permeability, etc.), and control and monitoring during the operational and closure phase are considered critical. In particular, compaction control (in situ density and percentage of fines <80 µm) and degree of saturation represent two of the processes still requiring improved implementation, being the greatest causes of the most significant failures. There remains inadequate application of specific regulations controlling the deposition, compaction, and testing processes through standardized methodologies allowing improved quality control, and a lack of adequate control tools to assess the fundamental aspects of mechanical stability of these particular structures (Villavicencio.G, et al, 2014).

Other consideration in a broad sense performance-based seismic design (PBSD) can be understood as a design criteria which goal is the achievement of specified performance targets when the structure is subjected to a defined seismic hazard. The specified performance target could be a level of displacements, level of stresses, maximum acceleration, mobilized strength, or a limit state, among others. In this respect, the limit state design can be seen as a particular case of the PBSD, where the performance target is the accomplishment of a resisting force. The PBSD is being strongly promoted by structural engineers, probably encouraged by the heavy financial losses resulting after recent earthquakes (Verdugo, 2009).

3.0. Conclusion

Society shall continue being depended on mineral resource utilization, thus, tailings creation is unavoidable, as is unavoidable tailing disposal in seismic areas.

It is evident of earthquakes impact on tailing failure; there are many worldwide examples of tailings failure worldwide, caused from seismic event. Therefore, there have been caused the environmental disasters, huge economic losses and many human losses.

At first, lack of legislative framework and regulations, is a big gap, which allows design of tailings without certain criteria on seismic zones (see Chiles and Germany cases).

Lack of the engineering and technical methodology application, during tailings construction, i.e. non proper construction with performance-based seismic design (PBSD). As are upstream method (which has weakly performance in seismic events), in situ density and percentage of fines <80 µm, lack of retaining dyke, basal drainage construction, management of the decant pond etc.

Lack of monitoring system, i.e. application permanent displacement methodology, this provides a quantitative measure, an – index - of co-seismic slope performance.

4.0. **References**

[1] Agurto-Detzel.H., e. a., 2016. The tailings dam failure of 5 November 2015 in SE. *Geophysical Research Letters*, pp. 4929-4936.

[2] Cai. S, et al, 2017. Liquefing-damage of mine tailings dams in earthquake. pp. 200-212.

[3] Commission, C. f. t., 2007. *EU rules for safe management of mining waste The new directive and related initiatives,* s.l.: European Commission, DG Environment.

[4] European Association of Mining Industries, M. O. &. I. M., n.d. *http://www.euromines.org/.* [Online].

[5] Pruchnicka. J., Zeqiri. K, 2017. *Mining Impact in Social well-Being - Poland and Kosovo Case.* Krakow, AGH Univeristy.

[6] Rudolph T., et al, 2012. Implications of Earthquakes on the Stability of Tailings Dams. *Institute for Geology-Palaeontology,Institute for Geology-Palaeontology, University of Münster, Corrensstr. 24, 48149 Münster, Germany,.*

[7] Takasuga, K., 2012. *Legislative System for Prevention of Mining Pollution and its examples in Japan,* Tokyo: Ministry of Economy, Trade and Industry - Japan.

[8] Troncoso. J.H, et al, 1993. *Seismic failure of Barahoma tailings dam.* s.l., s.n.

[9] Verdugo, R., 2009. *Seismic performance based-design of large earth and tailing dam.* London, Taylor & Francis Group.

[10] Villavicencio.G, et al, 2014. Failures of sand tailings dams in a highly seismic country. *NRC - Research Press,* pp. 449-464.

[11] Zeqiri. K, Biserka. D., et al, 2013. *Earthquake Impact on Tailing Dam Stability i.e. Environmental Pollution.* Skopje, s.n.

[12] Zeqiri, K., 2016. *Tailing Management.* s.l.:LAP LAMBERT Academic Publishing.