Dynamic calculation for the dry closure of Almagrera tailings dam

Calcul dynamique pour la fermeture à sec du barrage des stériles d'Almagrera

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ABSTRACT: An original model, including dynamic calculation, has been developed for the dry closure of Almagrera tailings dam and is described herein. A dynamic analysis of a structure requires the previous definition of the accelerograms and the structure characteristics. A probabilistic method for selecting calculation accelerograms is presented in this paper. First, the probabilistic hazard equation for site is solved. Based on the hazard curves obtained, the uniform seismic hazard acceleration response spectrum (USHARS) is constructed for the location, according to the type of soil and the required hazard level (exposure time and exceedance probability). Then, calculation accelerograms are selected. Based on this methodology, real accelerograms, for a return period of 975 years, have been obtained.

RÉSUMÉ : Un modèle original, développé pour la fermeture à sec du barrage des stériles d'Almagrera, est décrit ici. L'analyse dynamique d'une structure nécessite la définition préalable des accélérogrammes et les caractéristiques de la structure. Une méthode probabiliste pour la sélection des accélérogrammes de calcul est présentée dans cet article. Tout d'abord, l'équation probabiliste des risques pour l'emplacement est résolue. Basé sur les courbes de risque obtenues, le spectre de réponse d'accélération de risque uniforme est construit pour l'emplacement, selon le type de sol et le niveau de risque souhaité (temps d'exposition et probabilité de dépassement). Puis, les accélérogrammes de calcul sont sélectionnées. Sur la base de cette méthodologie, les accélérogrammes réels, pour une période de retour de 975 ans, ont été obtenus.

KEYWORDS: Tailings dam, dynamic calculation, uniform seismic hazard acceleration spectrum

1 INTRODUCTION

In Europe, there are many abandoned mines. Nowadays, when permission is granted for opening a mine in any country of the EU, a closure plan (including financing) must be presented by the mining company (ITC 2000), but it was not so in the old times. The point is that, up to now, only a small number of the possible closures has been undertaken owing to economic reasons.

2 TAILINGS DAMS INVENTORIES AND FAILURES

The recent (5 October 2010) Ajkai Timfoldgyar dam failure (Fig. 1) poured 700,000 m3 of bauxite ore and formed a flow that struck three villages in Hungary.

Figure 1. Ajkai Timfoldgyar dam failure.

This accident, jointly with the catastrophic failures of Stava, Los Frailes and Baia Mare tailings dams, has emphasized the catastrophic consequences that tailings dams' accidents in EU and the rest of the world might cause, and the need for safer design methods.

Rico et al. (2008) have compiled a corpus of 147 cases of worldwide tailings dam disasters, from which 26 are located in Europe.

Davies & Martin (2000) estimate there are 3500 appreciable tailings dams worldwide. According to Davies (2002) during the last years, there have been from 2 to 5 "major" tailings dam failure incidents. Referred to the worldwide inventory of 3500 tailings dams, equates to an annual probability between 1/1750 and 1/700, compared with 1/10000 for conventional dams. Furthermore, these failure statistics are for physical failures alone. Tailings impoundments can have environmental "failure" (e.g. leaks) while maintaining sufficient structural integrity.

Table 1 shows the inventory of tailings dams and ponds in extractive industry in Spain. Notice the large number of abandoned structures.

Table 1. Inventory of tailings dams and ponds in extractive industry in Spain.

Volume of residues (m^3)		323 million
Number of structures		986
Structures	Dams	610
	Ponds	378
Present state	Active	385
	Abandoned	535
	Restored	54
	Closed	24

3 SAFETY FACTORS REQUIRED FOR SPANISH LEGISLATION

Three kinds of actions are considered according to its risk and permanence. Normal actions are persistent actions; accidental actions are limited duration actions: e.g. rapid drawdown or earthquakes. Extreme are actions that rarely occur. The safety factors are indicated in Table 2.

Table 2. Safety factors required for tailings dams in Spanish legislation.

Class	Category	Actions		
		Normal	Accidental	Extreme
1	A or B	1.4	1.3	1.2
2	C or D	1.3	1.2	1.1
3	C or D	1.2	1.1	1.0

4 ALMAGRERA TAILINGS DAM

Almagrera tailings dam has a height of 35 m above foundation at axis. The height above the lowest foundation level is 37.3 m (Figure 3).

It has an upstream sloping core. The foundation is formed by alternation of volcanic and inter-stratified sedimentary rocks.

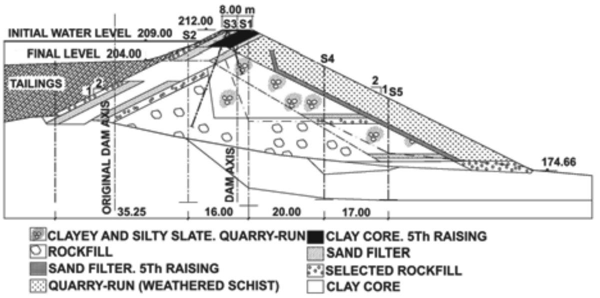


Figure 3. Central cross-section of Almagrera dam before closure.

The dam corresponds to the downstream borrow material type, and was raised 5 times adding material into the downstream side. The slide shows the original dam axis and the states of the dam at the end of 3rd, 4th and 5th heightenings. The downstream slope was 1.7 (H): 1 (V) up to the third phase, and 2 (H): 1 (V) for the last two phases. According to a report delivered before the 5th phase construction, the filter criteria were not fulfilled. This way, after the 4th phase, the dam rather behaved as a homogeneous dam. During the 5th phase, an inclined sand and gravel filter was placed between the 4th and 5th phase shells using normalised filter criteria. A downstream foot drain was placed below the inclined filter and the downstream shell, protected by a non-woven geotextile. Leaks ranging from 1 up to 16 m^3/h appeared in the downstream slope.

4.1 *Simulation of closure operations*

A mechanical model for all the operations involved during closure was entrusted to the main author. A finite element model was set up to reproduce all the steps that are being taken during closure:

1. Finding the initial safety factor.
2. Upstream water drawdown produced by pumping the contaminated reservoir water.
3. Upstream filling with coarse waste material.
4. Long term stability. Calculation of tailings settlements.
5. Seismic calculation, including consideration for tailings liquefaction.
6. If necessary, finding the new safety factors with the reinforcement from step 3.

Plaxis 2D-9.02 program has been used and the calculations have been carried out with 15-node elements. A Mohr-Coulomb materials model has been used; this is a model of perfect, non-associated plasticity

Table 3 shows the calculation parameters.

4.2 *Tailings*

Figure 4 shows the tailings thickness inside the reservoir and the thickness of Las Viñas material that will be placed above. The hatched area is the area that should be treated with band-shaped drains. Band-shaped drains should be always placed when the tailings thickness is ≥15 m.

Table 3. Calculation parameters

Soil type	USCS	c' kPa	Φ'	γ kN/m^3	k m/s	E MPa
Core	SC	18	30º	19.8	10^{-8}	50
Filter	SP-SM	1	35º	20	10^{-5}	50
Quarry run	GC	6	33º	20.2	$6.5*10^{-5}$	30
Rockfill		15	31º	21.9	$9.5*10^{-7}$	60
Selected rockfill		1	35º	20	$5.1*10^{-3}$	60
Weathered rock		50	20º	20.5	$1.4*10^{-6}$	300
Rock		250	20º	21.4	$1.3*10^{-6}$	10^4
Soft tailings	ML	1	29º	13.2	$5.1*10^{-9}$	0.52
Medium tailings	ML	1	32º	19.7	$5.1*10^{-9}$	1.0
Las Viñas Material		1	30º	20	$1.2*10^{-4}$	10

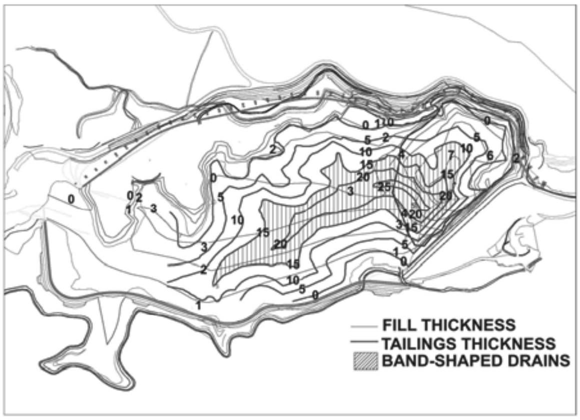


Figure 4. Tailings thickness inside the reservoir and the thickness of Las Viñas material that will be placed above.

Table 4 shows the maxima settlements in tailings obtained using several hypotheses.

Table 4. Maxima settlements in tailings.

Test	Tailings thickness (m)	Fill thickness (m)	Maximum settlement (m)	Remainder settlement after construction (m)	
				No drains	Drains
Oedometer	25	5.5	3.3	2.5	0.42
	20	7	3.4	2.4	0.19
Piezocones	25	5.5	2.5	1.9	0.32
Soft tailings	20	7	2.6	2.6	0.15
Piezocones	25	5.5	1.3	1.0	0.16
Medium tailings	20	7	1.3	0.9	0.07

4.3 *Dam calculations*

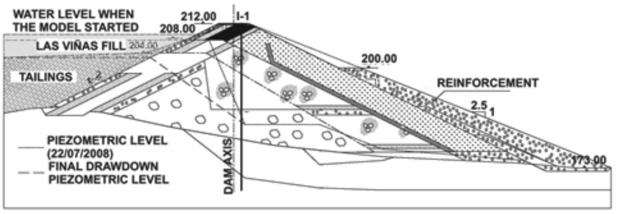
According to the inventory of tailings dams and ponds in extractive industry in Spain (ITC 2000) it is clear that Almagrera dam is class 1 (height greater than 15 m) but only category C (moderate damage only incidentally affecting lives). So, the first row of the safety factors in Table 2 must be accomplished.

Compacted rockfill reinforcement was projected to fulfil with the safety factors specified by the Spanish Regulations (Figure 5).

Figure 5. Reinforcement needed to fulfil the safety factors of Table 2.

Table 5 shows the results of the calculations with the FE method.

Table 5. Final displacements and safety factors with the FE method.



Phase	δ_{max} (mm)	Safety factor
Initial		1.44
Reservoir at 207.5 level		1.43
Drawdown	193	1.47
Fill	1300	1.36
Long term	2060	1.79
Earthquake & liquefaction	278	1.19 (inside tailings)

5 DYNAMIC CALCULATION

The NCSR 2002 considers that large dams (height greater than 15 m) are constructions of special importance, which should be calculated for a return period of 1,000 years. The seismic acceleration for pseudo-static calculation was 0.08g. The reinforcement has been calculated using this acceleration. The ITC (2000) required a safety factor of 1.3.

A dynamic calculation has being carried out. A method to select accelerograms (Morales-Esteban et al., 2012), for the closure calculation, has been developed based on uniform seismic hazard response spectra and is detailed in the paper.

The arrival of earthquakes to the site that exceed a reference value $\log S_0$ is modelled as a Poisson stationary process, defined according to the Gutenberg-Richter law. The seismogenic areas defined by Martin (1984) were used.

Next, the uniform seismic hazard response spectra are calculated. The arrival of earthquakes to the site that exceed a reference value $\log S_0$ is modelled as a Poisson stationary process, defined according to the Gutenberg-Richter law.

For source *i,* the average number of events per year is:

$$\lambda_i = v_i \int_{M_{\min}}^{M_{\max}} P(\log S \geq \log S_0 / M, D) f(M) dm \quad (1)$$

where:

v_i is the seismic rate of earthquakes of the individual source.

P is the probability for $\log S$ to exceed the reference value, $\log S_0$, for an earthquake of magnitude M that occurs at a distance D from the site.

f(M) is the magnitude probability density function between the minimum and maximum magnitudes considered.

If N individual seismic sources act simultaneously, the rate λ of arrivals at the site of earthquakes that exceed the reference value, $\log S_0$, is:

$$\lambda = \Sigma \lambda i \quad (2)$$

The return period, T, is the average time interval between events and its value is:

$$T = 1/\lambda \quad (3)$$

The probability of exceeding the reference value $\log S_0$ during the period of time, t, owing to the simultaneous action of N individual seismic sources is:

$$P(\log s \geq \log S_0; t) = 1\text{-}e^{-\lambda t} \quad (4)$$

Equation (1) cannot be applied to the hazard calculation as the seismogenic areas have been modeled as areas and not as punctual seismic sources. To solve this problem, the seismogenic areas are divided into elements small enough to be assimilated to punctual seismic sources.

With this procedure, uniform seismic hazard response spectra can be created for the site according with the period of exposure, the probability of exceeding the design spectrum and the type of soil. Then real design accelerograms can be selected following these steps:

-The period of exposure of structure is established according to its estimated lifetime.

-The probability of exceeding this level is established according to the seismic hazard required. In this case, as the return period is established (1,000 years), the probability is calculated using equations (3) and (4).

For the type of soil at the site, the uniform seismic hazard response spectrum is calculated according to the required seismic hazard level.

From the database of accelerograms, those recorded at the same type of soil are selected.

The standard deviation is defined as:

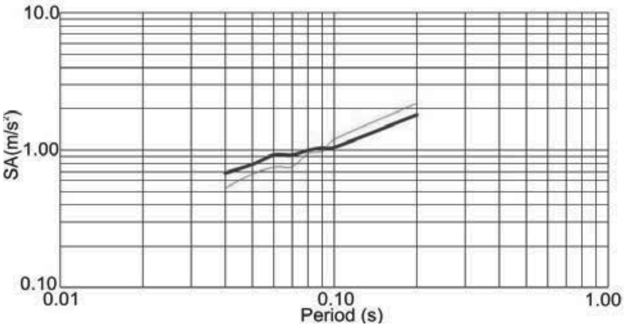
$$S = \left(\sum \left[\log(f.S_R - \log S_C)\right]^2 / n\ \right)^{1/2} \quad (5)$$

where:

$$f = \left(\sum \log S_C - \sum \log S_R\right) / n \quad (6)$$

Here S_R are the values of the response spectrum corresponding to the real register, S_C are the values of the calculated response spectrum, n is the number of intervals considered in the calculation and f is the scale factor that minimizes the standard deviation.

This methodology has been applied to the site of Almagrera Dam, founded on rock, for a damping ratio of 5%, considering a return period close to 1000 years. The accelerograms have been selected from the European Strong Motion Database that can be obtained from Internet at *http://www.isesd.cv.ic.ac.uk/.* Figure 5 shows the comparison between the response spectrum calculated for Almagrera dam, in rock, for 1000 years return period, and the response spectrum from one of the selected accelerogram.



Uniform seismic hazard response spectrum (clear line).
Spectrum for accelerogram 7488 (dark line).

Figure 5. Comparison between the response spectrum calculated for Almagrera dam, in rock, for 1000 years return period, and the response spectrum from the selected accelerogram.

From the database, the accelerograms that have a scale factor near to 1, and a smaller standard deviation are finally selected (Table 6)

Table 6. Selected accelerograms, scale factor and standard deviation.

Accelerogram	f	s
128	0.991	0.016
361	1.016	0.028
365	0.931	0.130
608	1.099	0.172
990	1.006	0.011
5826	0.931	0.129
6269	1.095	0.165
6270	1.014	0.026
6331	0.969	0.057
7480	1.033	0.058

Once the accelerograms have been selected, they are not scaled to be introduced in the dynamic calculation. One of these accelerograms selected is shown in Figure 6.

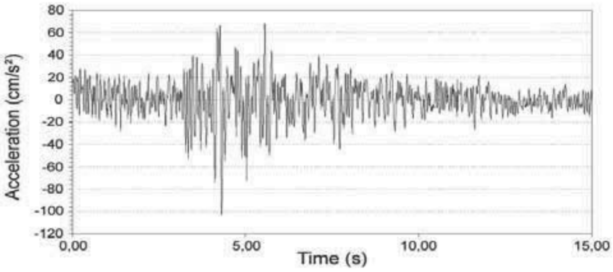


Figure 6. Accelerogram No. 128. Scale factor for all periods 0.99.

From the dynamic calculation the acceleration versus time of any point of the dam subjected to the accelerograms selected can be obtained as plot in figure 7. Similar is figure 8 where the displacement is shown versus time. Absolute displacement can be obtained by subtracting the displacement of the point to the displacement of point A (placed on the basement). Finally, in the figures corresponding to the relative shear stresses, obtained from Plaxis output, plastic zones appear in the downstream slope, in the tailings and elsewhere. It can be observed that no continuous surface of rupture appears.

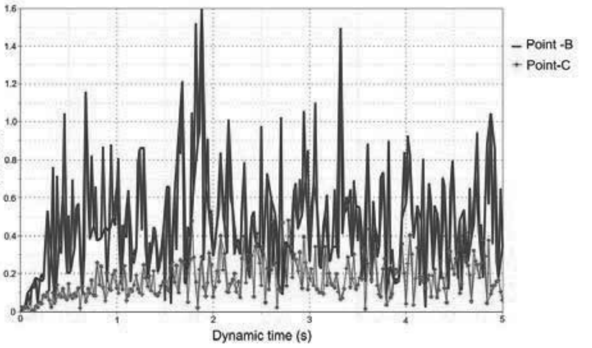


Figure 7. Total acceleration versus time during 5 seconds of calculation with accelerogram 608. Selected points: B over the dam and C at the left side.

6 CONCLUSIONS

A model, reproducing all the closure operations, has been prepared, and results presented herein. Monitoring has been provided that will verify and improve the model presented. Several closure aspects have been examined:

1. The placement, above the tailings, of coarse mineral residues, thereby reducing the volume of mine dumps.
2. Methods to speed up settlements before placing the cover and, this way prevent damage to it; for example the placement of band-shaped drains, inside the tailings, after the fill has been placed on them.
3. A method to select accelerograms for the closure calculation has been developed based on uniform seismic hazard response spectra and is detailed in the paper.
4. Dynamic calculation has shown that relative displacements are small and that no surface of rupture appears.

The model has indicated the necessity to place rockfill reinforcement downstream.

As it may be observed, the calculated dynamic displacements are quite small. Further calculations are being carried out with larger return periods, as indicated by standards specifically related to tailings dams.

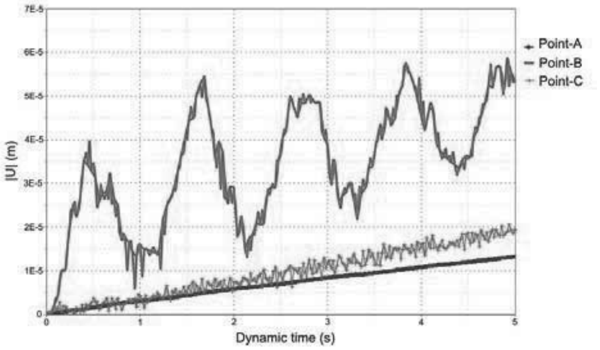


Figure 8. Total displacement versus time for the selected points during 5 seconds of calculation with accelerogram 608. Selected points: A on the base, B over the dam and C at the left side.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Davies M.P. 2002. Tailings impoundments failures: Are geotechnical engineers listening? *Geotechnical News*, September: 31-36.

Davies M.P. and Martin T.E. 2000. Mine tailings dams: when things go wrong. Tailings dams 2000, Proceedings ASDSO Conference, Las Vegas.

ITC 2000. Instrucción Técnica Complementaria 08.02.01 del capítulo XII del *Reglamento General de Normas Básicas de Seguridad Minera Depósitos de lodos en procesos de tratamiento de industrias extractivas*. BOE de 9/6/2000, 17235-17244. Ministery of Industry & Energy (Spain).

Martín A.J. 1984. Riesgo sísmico en la Península Ibérica. Tesis doctoral. *Ph. D. Thesis*, Politechnical University of Madrid.

Morales-Esteban A. de Justo J.L. Martínez-Álvarez F. and Azañón J.M. 2012. Probabilistic method to select calculation accelerograms based on uniform seismic hazard acceleration response spectra. *Soil Dynamics and Earthquake Engineering*, 43, 174-185.

NCSR 2002. *Norma de Construcción Sismorresistente NCSR-02. Parte General y Edificación*. BOE, 244: 35898-35967.