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# THE INFLUENCE OF WATER CONTENT IN THE SEISMIC BEHAVIOUR OF TAILINGS DRY STACKS

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## ABSTRACT

Tailings dry staking is a relatively new mine waste disposal technology. The system involves reducing the water content of tailings by means of filtration, before placing them in the deposit. The aim is to store tailings in an unsaturated condition. Benefits include stability improvement due to the increase of tailings strength, inhibition of liquefaction and avoidance of contaminating leakages. However, tailing dewatering implies spending energy (in creating vacuum or pressure for filtration) and hence, for economical reasons, the drying process is limited. At the usual placing water contents, tailings are far from being really “dry”. Moreover, excessive drying would lead to dust generation issues. Hence, the saturation degree in such “dry” tailings stacks is usually higher than 50% and may approach 80 or 90% after consolidation. This paper analyses the influence of the placing water content of tailings on the seismic behavior of the deposit. Suction in the water menisci formed at the particle contact points, confers an additional strength to granular materials. For fine grained tailings, the strength arising from suction can be as important, so as to completely determine the stability condition of the deposit. Suction is related to the saturation degree by the retention curve. The higher the saturation degree, the lower are the corresponding suction values, becoming nil upon saturation. By means of finite element modeling of the dynamic behavior of a dry tailings deposit, the influence of the placing water content on its seismic behavior and safety is studied. The models developed are based on laboratory measured properties of the tailings and the influence of suction is introduced following BBM (Barcelona Basic Model) for unsaturated soils. Results show that a slight reduction of water content below saturation condition has a moderate but significant influence in the seismic performance of the deposit.

Keywords: Tailings dry staking, unsaturated soils, seismic behavior.

## INTRODUCTION

Tailings dry staking is a relatively new mine waste disposal technology. The system involves reducing the water content of tailings by means of filtration, before placing them in the deposit. The aim is to store tailings in an unsaturated condition. Benefits include stability improvement due to the increase of tailings strength, inhibition of liquefaction and avoidance of contaminating leakages. However, tailing dewatering

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implies spending energy (in creating vacuum or pressure for filtration) and hence, for economical reasons, the drying process is limited. Moreover, excessive drying would lead to dust generation issues. Therefore, “dry” tailings come out from the filtration process with a water content ranging 15% to 30%. During the transport and placing process, usually done with conveyor belts or simply by truck dumping and spreading with bulldozer, some additional water loss occurs due to evaporation. The amount of evaporated water, during placing and until the layer of tailings is covered by the next one, depends on the climate features at the site and the rate of heightening of the stack. Hence the placing water content varies from case to case and, to some extent, it can be adjusted by changing the extent of the period in which each tailings layer is allowed to dry. In most cases the saturation degree is higher than 50% and may approach 80 or 90% after consolidation due to overburden.

In an unsaturated granular material, suction in the water menisci formed at the particle contact points, confers an additional strength to the material. Tailings are very fine grained materials and therefore the interparticle forces arising from capillary water can be relatively high. In some cases of old abandoned tailings deposits, it seems that such additional strength, completely determines the stability of the deposit. Suction is related to the saturation degree by the retention curve. The higher the saturation degree, the lower are the corresponding suction values, becoming nil upon saturation.

The aim of this paper is to study the influence of the placing water content of tailings on the seismic behavior of the deposit. As a study case, the waste disposal system of the Casposo Mining Project, located in San Juan Province, Argentina, has been selected. The projected waste deposit, foresees the disposal of waste rock and dry tailings into a unique stack. Placing of waste materials are done by dumping from trucks and spreading by bulldozer, alternating layers of dry tailings and waste rock. Tailings are delivered from the extraction plant with 18% water content. During the placing process tailings are expected to reduce their water content by evaporation, to values below 15%. In addition, once the tailings are covered by the next waste rock layer, their water content is expected to reduce again because of the transfer of some amount of moisture to the waste rock. This storage system is a novel concept of waste deposit, with a number of features leading to expect a good seismic performance. Among of them, the most evident is to keep the tailings in an unsaturated state, which hinds the possibility of liquefaction. However the real behaviour under seismic loads of such a deposit, is not known in detail. It is worth exploring how a fundamental variable of waste disposal the process, the tailings water content, influences the seismic behaviour of the deposit.

The analysis is performed by means of a finite element model, computing the non-linear dynamic response of the deposit, including the effect of suction in the tailings shear strength. It is expected from this mathematical model, to show to what extend the placing water content exerts an influence in the development of permanent deformations of the deposit during an earthquake.

## MATERIALS CHARACTERIZATION

Tailings and waste rock samples taken from Casposo Project, were tested in order to characterize their hydraulic and mechanical properties. The testing program for the tailings material included the determination of the grain size distribution curve, the water retention curve and the edometric compression curve. For the waste rock, the grain size distribution curve and the edometric compression curve were obtained.

Figure 1 shows the grain size distribution for the two materials contained in the deposit. The waste rock is a gravel containing some blocks with sizes up to 0.5 m (not included in the shown grain size distribution), a fraction of sand sized particles which varies with the alteration degree of the of the parent rock and almost no fines. The samples analyzed were classified as GP (poorly graduated gravels).

The tailings grain size distribution was obtained by sieve analysis for the fraction greater than 0.074 mm and sedimentation, for smaller particles. The samples analyzed contained 52% of fine grains (silt size) and 48% of fine sands. This material was classified as ML.

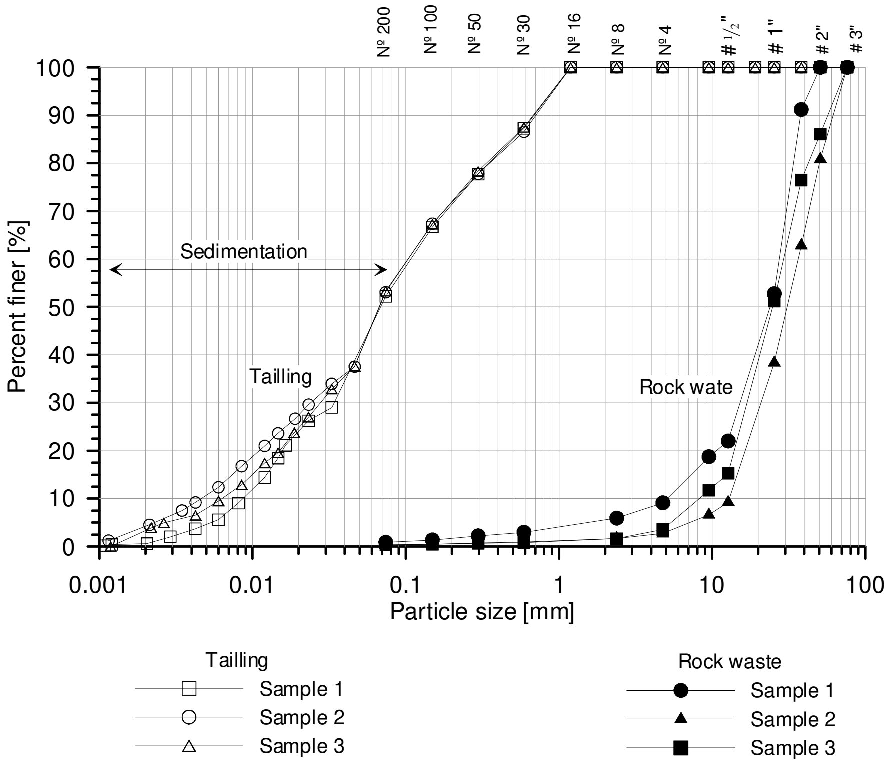


**Figure 1. Tailing's granulometric curve**

**Water Retention Curve (WRC)**
Water retention curve represents the tailings ability for storing water by means of the capillary phenomenon. It is defined as the relationship between water content or saturation degree and suction. Suction is the difference between pore's gas pressure and water pressure at the capillary meniscus. Tailings WRC was obtained using two complementary techniques. Vapor equilibrium technique was used for applying suction greater than 2MPA. (Delage et al (1998); Romero (1999)). For smaller suction values filter paper technique was used (Leong et al (2002); Marinho and Oliveira (2006)). WRC depends on the dry unit weight of the material. Three values of unit weight where tested $\gamma_d$ = 14.71, 16.5 and 18.0 kN/m3. Figure 2 shows WRC data obtained for tailings with dry density $\gamma_d$ = 16.5kN/m3. Experimental data are fitted with the van Genuchten model (van Genuchten (1980)) and their parameters are indicated in Figure 2.

**Oedometer tests**
Oedometer tests were carried out on tailings specimens in order to study their consolidation behaviour under different water contents. Figure 3 shows the measured stress-void ratio curve and the evolution of the saturation degree, during loading and unloading paths on a specimen with 15% water content.

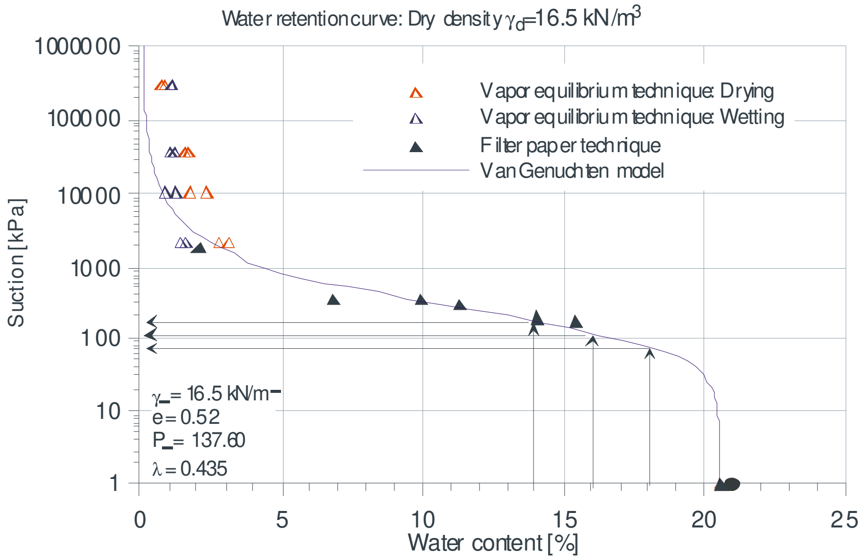


**Figure 2. Tailing's water-soil characteristic curve in terms of suction and water content**

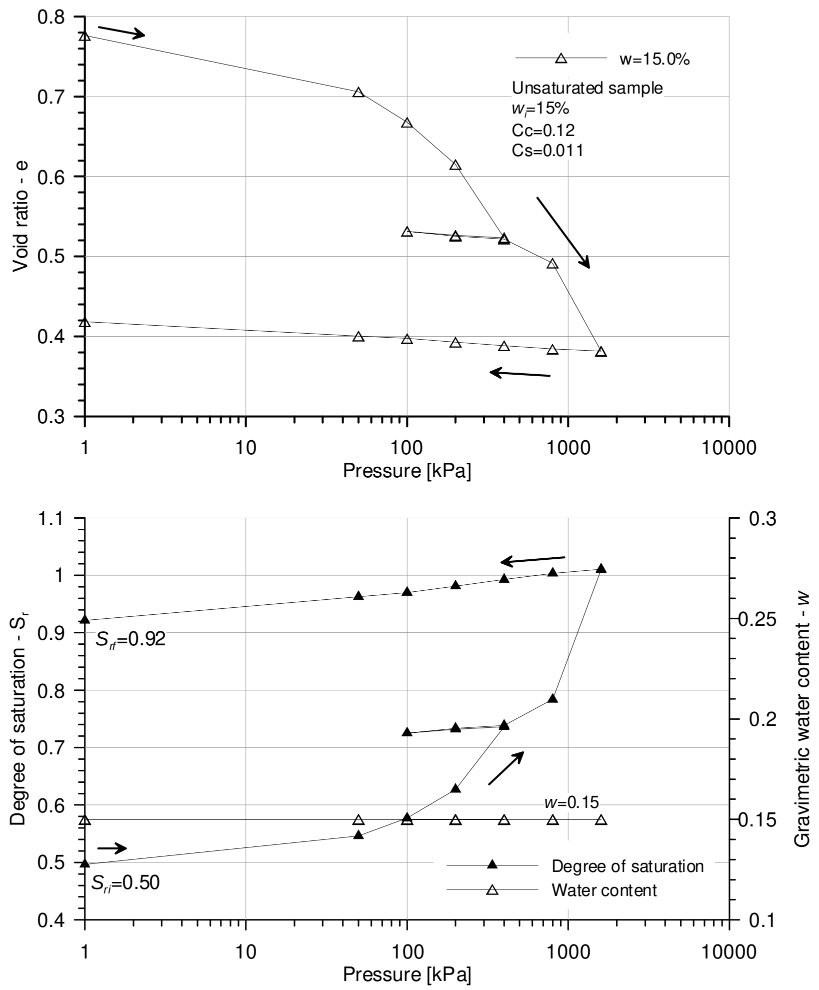


**Figure 3. Results of oedometer test on a tailings specimen with 15% water content.**

## FINITE ELEMENT MODEL

Dynamic finite elements simulations were performed to investigate the behavior of the deposit under seismic excitation, considering different placement water contents of the tailings layers. The transversal section of the deposit shown in Figure 5, was modeled with the finite element mesh shown of Figure 6. The analyses were performed using the open source software OpenSees ((Mazzoni et al (2006)). Materials were modeled using an elasto-plastic constitutive law.

The site of the deposit is located in a seismically active region. A number of active faults are known to exist nearby the mining project. Among of them, the most conspicuous is the *El Trigre Fault*, a 200Km length rectilinear strike-slip feature, which affects modern alluvial fans and passes some 20 km east from the project site. No strong motion records are available neither from earthquakes originated in El Tigre fault nor from other active faults in the region. Hence the considered seismic action for the analysis was selected among available records from similar seismotectonic environments. The 1992 Landers Earthquake (M = 7.3) strong motion record, obtained at Joshua Tree (E-W component), is considered as a representative motion of the earthquake shaking which is likely to occur at the project site. The horizontal acceleration time histories used as the model input and the corresponding 5% damping response spectra are shown in Figure 4

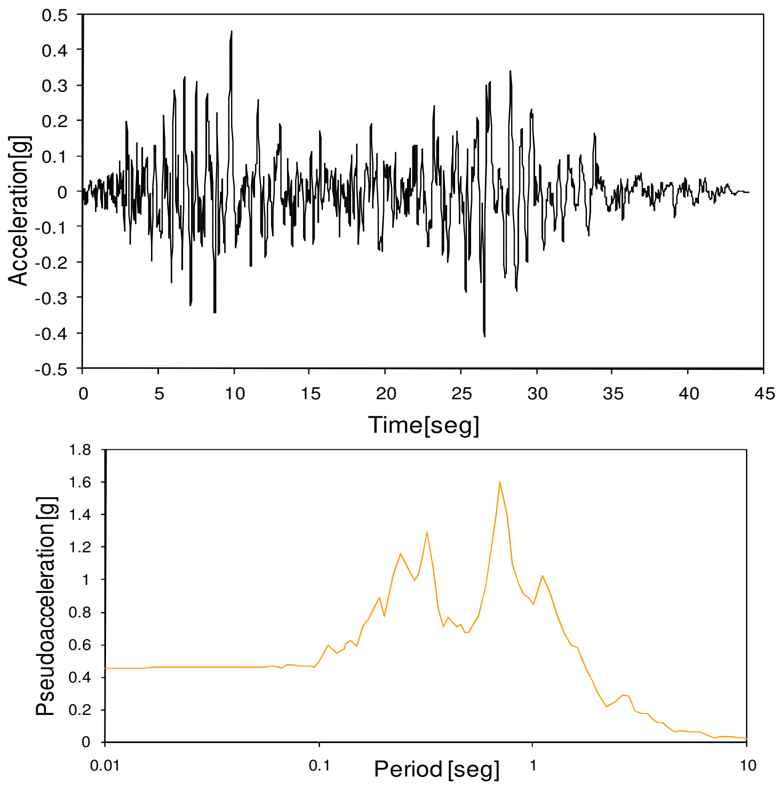


**Figure 4. 1992 Landers Earthquake. Joshua Tree Station, E-W horizontal component (PEER Strong Motion Database). A) Acceleration time history. B) PSA response spectra for 5% damping.**

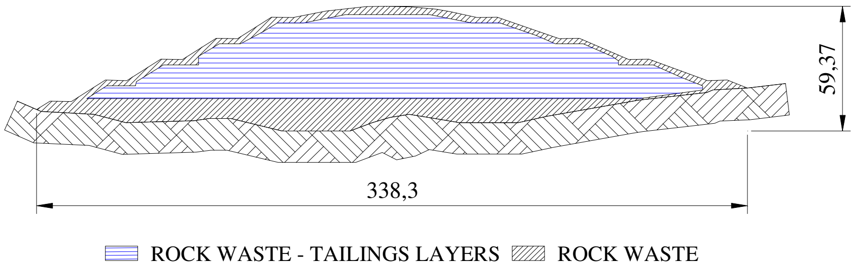


**Figure 5. Transversal section of the deposit.**

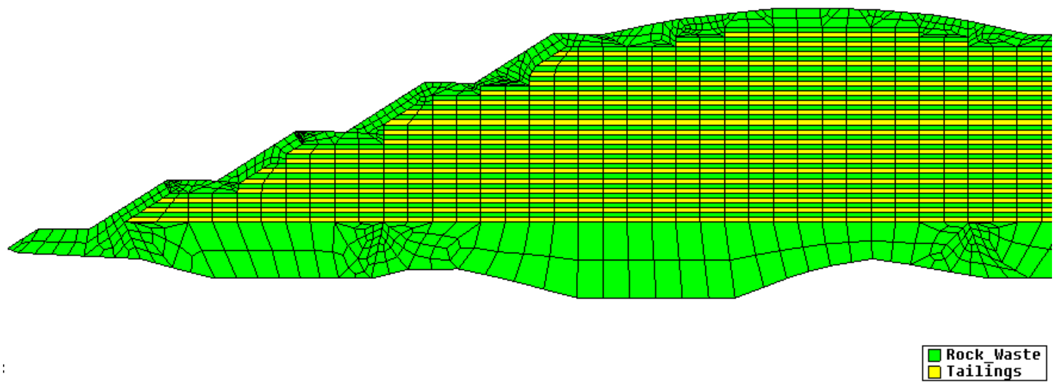


**Figure 6. Finite element mesh (detail).**

*Shear strength of tailings in unsaturated conditions*

Tensile strength arising from capillary water in a tailing material was observed in laboratory Brasilian tests performed by Rodriguez (2002) under different saturation degrees (Figure 7). The observed behaviour was reproduced with de Barcelona Basic Model (Alonso, Gens and Josa (1990) by Zandarin et al (2008) for the high saturation range (S > 0.65) (bold curve shown in Figure 7). The Barcelona Basic Model is a constitutive law for partially saturated soils formulated in the neat mean stress–deviatoric stress-suction space. The shape of the BBM yield surface is shown in Figure 8.

In model developed in this work, the effect of capillary water is introduced as a suction-dependent cohesion in the Mohr Coulomb's failure criterion. Cohesion is computed with the following equation, derived by relating the Mohr Coulomb's failure criterion in triaxial compression, with the BBM:

$$c = p_s.tg\phi = k.s.tg\phi \quad (1)$$

where $\phi$ is the friction angle, $s$ is the suction derived from the WRC, $k$ is a BBM parameter which controls the variation of cohesion with suction. The meaning of $p_s$ can be deduced from Figure 8, and:

$$p_s(s) = p_{s0} + k_s.s \quad (2)$$

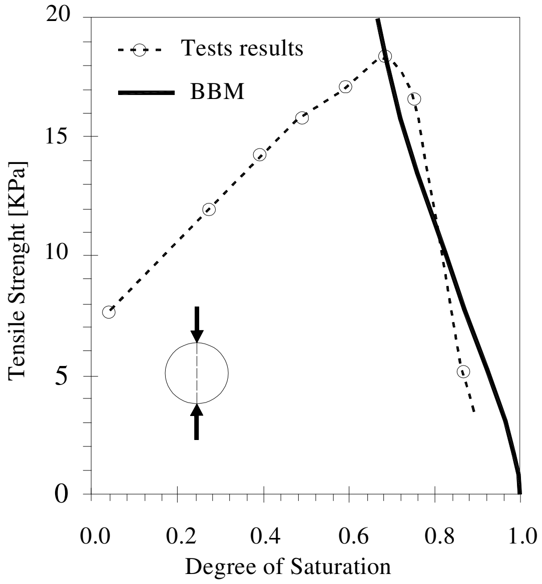


**Figure 7. Tensile strength variation with saturation degree of tailing specimens from Moa Tailings (Rodriguez, 2002)**

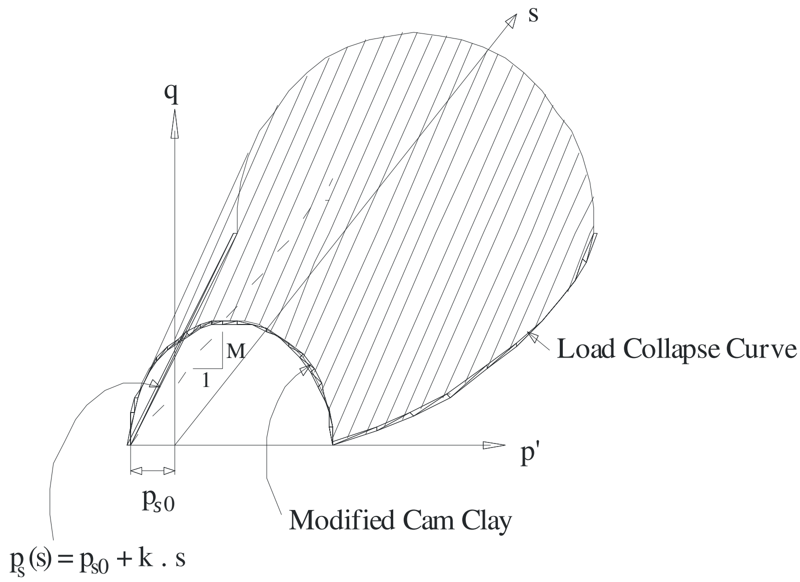


**Figure 8. Yield surface of Barcelona Basic Model**

The determination of the BBM parameters require, in general, performing suction controlled mechanical tests (triaxial or direct shear). No such tests are available at the moment for the Casposo tailings. Parameter $p_{s0}$ is assumed nil, since tailings do not show any cohesion in the saturated state. Fitting of the experimental data in Figure 7 yielded $k_s = 0.26$ (Zandarin et al, 2008). However such value is viewed as a lower bound, which can be related to the fact that Moa tailings contained significant amounts of organic matter. Literature reported $k_s$ values in the range of 0.5 to 2.0 (Alonso, Gens and Josa (1990). A value $k_s = 1.1$ was adopted for the analysis in this work.

*Analyses cases*

Four analysis cases, considering different values of the placing water content of tailings were defined. A near-saturation condition of tailings is assumed in Case 1, only for reference purposes, since such condition is far from the design assumptions. Unit weights of both materials were obtained from oedometer test data. Suction for each case was determined using the WRC in Figure 2. Next, the cohesion was determined using equations 1 and 2. The applied strength parameters for each analysis case are summarized in Table 1.

**Table 1. Variables for analyses cases**

| Case | Material | γd kN/M3 | ρ T/M3 | ϕ ° | Ks | w % | S % | s kPa | c kPa |
|---|---|---|---|---|---|---|---|---|---|
| 1,2,3,4 | WASTE ROCK | 15.70 | 1.60 | 35 | - | - | - | - | - |
| 1 | TAILINGS | 16.87 | 1.72 | 28 | 1.10 | 20.80 | 99.00 | 1.00 | 0.50 |
| 2 | | | | | | 18.00 | 87.35 | 77.81 | 45.51 |
| 3 | | | | | | 16.00 | 77.65 | 120.00 | 70.19 |
| 4 | | | | | | 14.00 | 68.00 | 168.34 | 98.46 |

## MODEL RESULTS

Figures 9 to 12 show the distribution of horizontal displacement in the section analyzed, upon the end of the applied earthquake, for cases 1 to 4 respectively. In each of these figures a pair of nodes located within the maximum displacement zone is pointed. For these particular nodes, the horizontal displacement time history is shown in Figure 13.

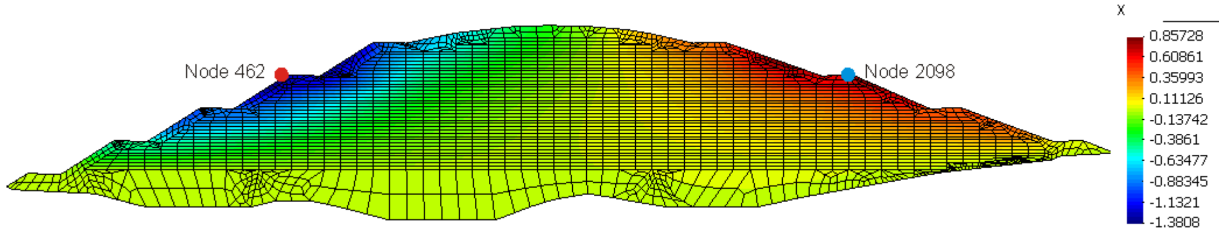


**Figure 9. Horizontal displacements – Case 1**

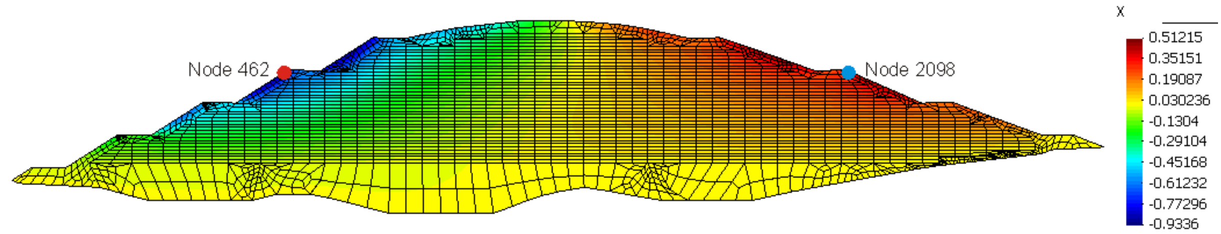


**Figure 10. Horizontal displacements – Case 2**

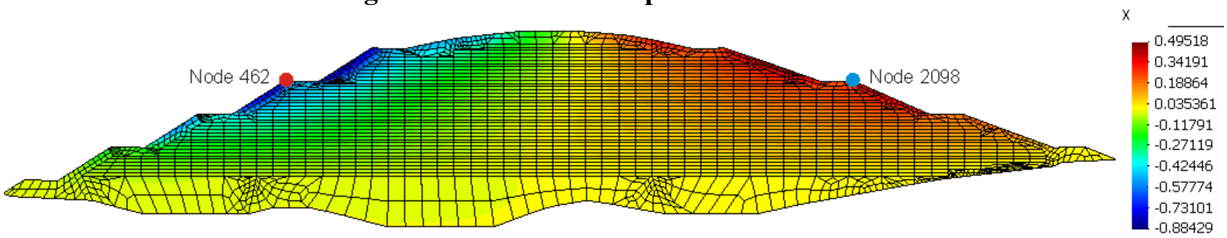


**Figure 11. Horizontal displacements – Case 3**

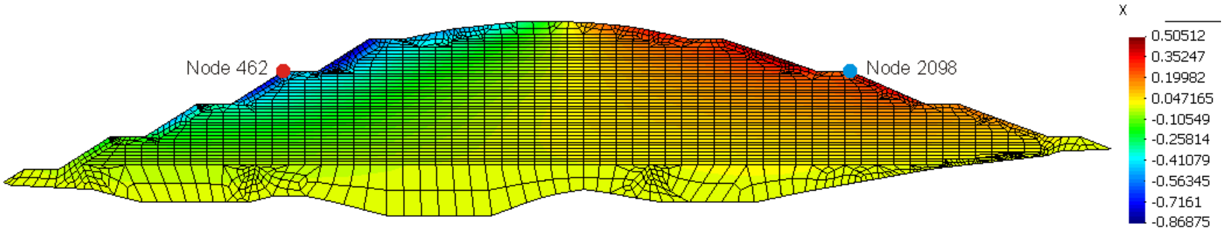


**Figure 12. Horizontal displacements – Case 4**

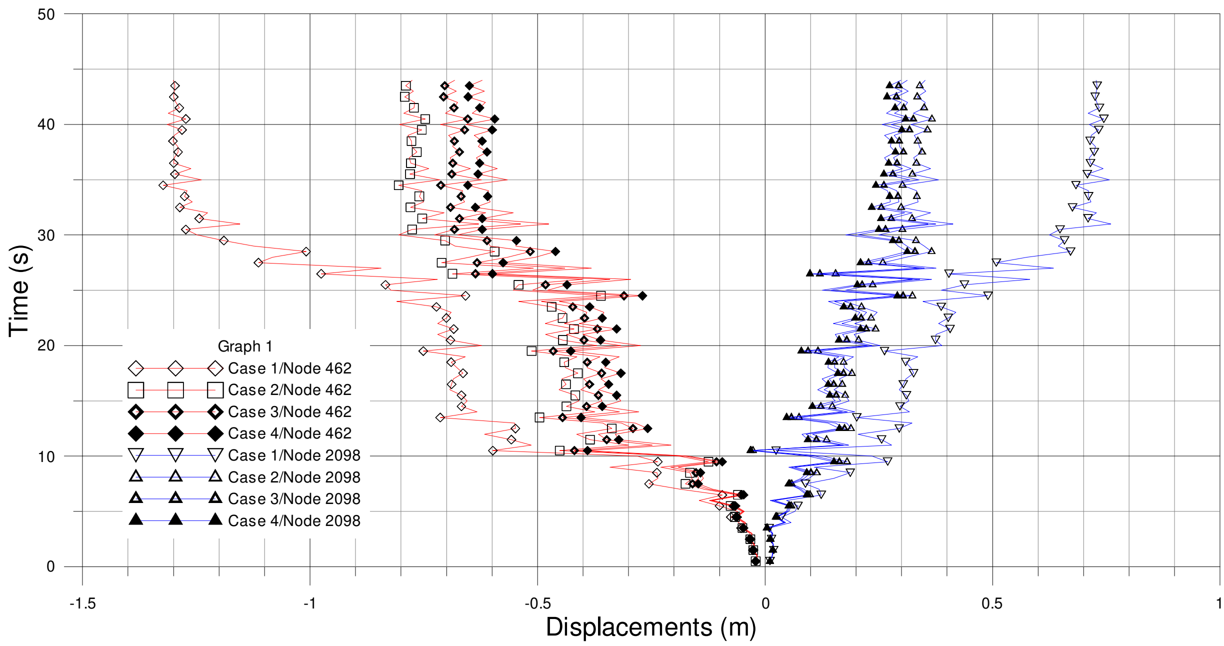


**Figure 13. Horizontal displacements of nodes 462 and 2098**

## CONCLUSIONS

The results obtained with the mathematical model show that, as it was expected, the decrease in the placing water content of tailings, leads to lower permanent deformations arising from earthquake action. Further improvement in the accuracy of the model would require the execution of suction controlled mechanical tests, characterizing the variation of the material strength with suction changes. So far, the effect of water content in the development of earthquake permanent displacements seems moderate. This can be attributed to the singular layered structure of the studied deposit.

It is interesting to note that the major change in magnitude of the resulting displacements occurs among case 1, in which the tailings are assumed almost saturated, and case 2, with S $\cong$ 0.9. Hence, most of the improvement in seismic behaviour is obtained with a slight reduction of water content below saturation condition. Figures 9 to 12 also suggest that dryer tailings lead, not only to a reduction in the maximum permanent displacements, but also reduce the extent in which displacements affect the deposit body. A lower tailings water content determines that deformation occur in a more superficial pattern along the slopes.

It is worth noting that this study does not take into account pore pressure generation or liquefaction effects, which could arise for the case of the saturated o nearly saturated tailings subjected to earthquake action. Deformations much larger than those computed in this work, or even failure, could occur in such case. That is why avoidance of tailings saturation was one of the basic design goals.

## ACKNOWLEDGEMENTS

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