Risk Associated with Swelling Rocks in Volcanic Formations in the Design of Hydro-Tunnels

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ABSTRACT: The paper analyses how to detect the swelling potential, quantifying and interpreting the long-term impact on the final lining of underground works, from the design and the construction experience achieved in various hydro-tunnels affected by this phenomena.
In all of the cases analyzed the risk of swelling is associated to volcano-sedimentary rocks as Abanico Formation, Coya-Machalí Formation and in a lesser extent in Farallones Formation, among others, located in the Andes. These swelling phenomena occur due to the presence of swelling (expansive) clay minerals contained in the rocks associated to rock mass degradation and water presence.

1 DEFINITION OF SWELLING

Swelling phenomena can be defined as a time dependent volume increase of the rocks caused by stress changes, increase in water content or by a combination of both.

The open underground excavation produces a variation in the stress state, this fact combined with the adsorption and/or absorption of water can lead to volume increase with time. A similar phenomenon can be observed on a much smaller scale due to particle rebound.

If the rocks to be excavated contain clay minerals, an increase of the volume is expected when they come into contact with water. Figure 1 shows an innercrystalline swelling of montmorillonite (Madsen *et al.*,1989), pressures associated with this type of swelling are normally less than 2 MPa.

Another mechanism of swelling is by developing of diffusive water layer between clay particles (osmotic) causing large deformations reversible by heat or pressure (Fig. 2).

Swelling phenomena produced by the transformation of the anhydrite has not been analyzed in this paper.

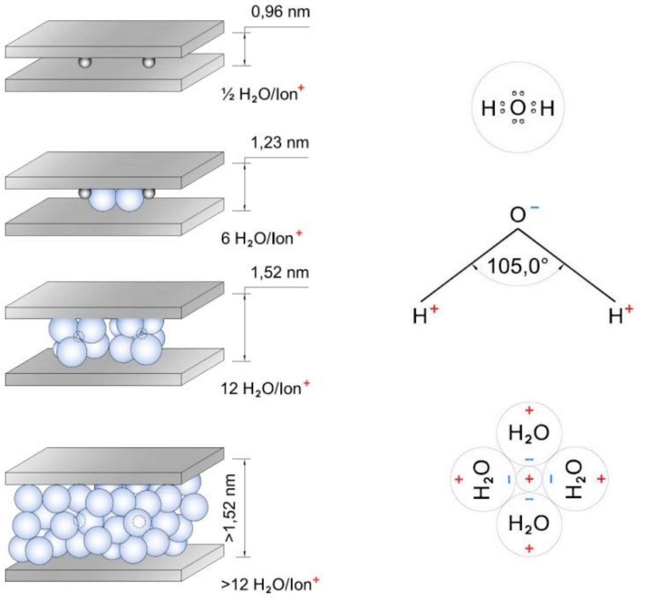

Figure 1. Intercrystalline swelling (Madsen *et al.*, 1989)

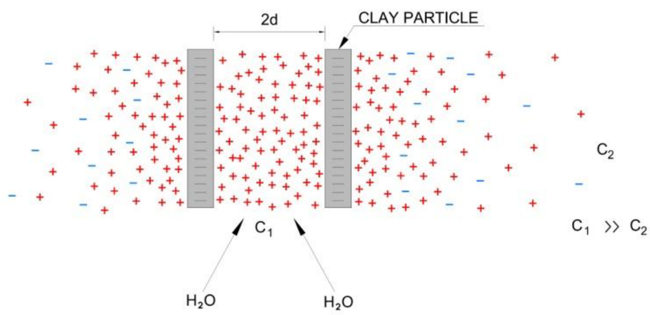

Figure 2. Osmotic swelling (Madsen *et al.*, 1989)

2 FORMATIONS AND LITHOLOGIES

Volcano-sedimentary formations, especially tuffs and breccias, may present swelling minerals in their matrix.

Some volcano-sedimentary formations located in the Central and Southern Andes, which had been affected by swelling phenomena, are the following:

- Abanico formation: is composed of stratified sequences of volcanic materials basically andesites and tuffs, and sedimentary layers of shale, sandstones and conglomerates of lacustrine origin, interbedded.
- Coya-Machalí formation (local equivalent from Abanico formation; Klohn, 1960): is composed of pyroclastic breccias of wide range particle size, arranged in layers of variable thickness, with porphyritic andesites, as well as detritus sedimentary levels of shale, sandstones and conglomerates of lacustrine origin, interbedded.
- Lo Prado formation, formed by andesites and ocoites (porphyritic andesites) with sedimentary materials interbedded.
- Farellones formation: is a sequence of volcanic rocks, including lavas, rhyolitic tuffs, andesitic and rhyolitic breccias with continental sediments intercalations.
- Llama formation: is composed of volcanic ash deposits, and andesitic tuff layers. In depth there is a very hard and stable basal conglomerate.

There are several documented cases about problems with swelling in tunnels of The Andes, associated with this type of volcano-sedimentary formations, with shale and limonite, as well as lithic tuffs with a matrix compound of hematite and expansive clays, such as the nontronite and montmorillonite.

Here is a brief description of the recent tunnel instabilities due to swelling phenomena occurred during the excavation and/or the exploitation of hydraulic tunnels:

- According with *Axel et. al*. (2012), high values of convergences were registered, as well as opened fissures, invert heaves and rockfalling phenomena were observed, due to swelling pressure in hydraulic tunnels on these formations, located in the Andes.
- In El Teniente mine, an important geotechnical rock quality degradation occurred due mainly to the effect of the volume increase produced by the hydration of illite, esmectite and zeolite present in the rockmass.
- Other underground excavations located in The Andes show evidences of problems with swelling phenomena in shale and reddish tuffs of the Abanico formation.

Note that the swelling phenomena are produced mainly due to the clay minerals, and also, clay aggregates, present in the matrix of the volcanic-sedimentary formations, composed of minerals such as shown in Table 1:

Table 1. Main swelling clay minerals

Clay mineral
Esmectite (Montmorillonite): $(Na,Ca)_{0,3}(Al,Mg)_2Si_4O_{10}(OH)_2$
Esmectite (Nontronite): $Na_{0.3}(Fe^{3+})_2(Si,Al)_4O_{10}(OH)_2 \cdot nH_2O$
Illite: $(K,H_3O)(Al, Mg, Fe)_2(Si, Al)_4O_{10}[(OH)_2,(H_2O)]$
Zeolite (Laumontite): Ca $Al_2Si_4O_{12}.4H_2O$
Chorite (Clinochlore): $(Mg,Fe^{2+})_5Al((OH)_8/AlSi_3O_{10}$

Therefore the lithologies more susceptible to present swelling phenomena are those with a significant amount of these minerals, being mainly the lithic tuffs with fine, shale, more possible if they are of continental origin, and to a lesser extent, breccias with fine matrix.

The execution of X-ray diffraction analyses are necessary in order to analyze the mineralogy of the expansive formation, while Ethylene Glicol Test are very helpful to detect expansive minerals.

3 DETECTION AND QUANTIFICATION OF THE PHENOMENA

In the design phase of an underground project it is hard to carry out preliminary estimation of the overpressure to be exercised in the contour. The swelling potential will depend on the expansive clay minerals/aggregates content, the rock mass degradation, fracturation and the presence of water.

However, tests such as ethylene-glycol in conjunction with Atterberg limits, among others, can allow early detection of overpressure magnitude in order to design and optimize lining in accordance to the problems associated with these phenomena.

Therefore, the main hypothesis states that swelling clay minerals present in the rocks will determine the rockmass behavior under weathering processes.

The fact is that detecting swelling potential by the site investigations prior to the drafting of the detailed engineering is extremely difficult. However a good analysis of geological-geotechnical features, not only of the project but from experience acquired in nearby projects, may be the key to assess in a preliminary way the possibility of occurrence of this phenomenon.

Once the proper analysis of the geological record is performed and when the rocky formations are expected to be capable of generating swelling, it must be designed:

- A systematic sampling during the tunnel construction and the accomplishment of laboratory tests to measure the pressure in each section
- Perform a monitoring data during construction
- A pre-liner design depending on different pressures, such a way that the hydraulic section of the tunnel will not be reduced

3.1 *Laboratory tests*

3.1.1 *Ethylene Glycol test*

The ethylene Glycol test consist of 40 pieces of equidimensional aggregate (25 mm in diameter) placed in a tray and covered by ethylene glycol, according with ASTM D2693-02 standard. The aggregate pieces are placed in a fixed pattern (five rows of eight pieces) so that, each particle can be individually assessed with time recorded. The material is inspected after 1, 5, 10 and 20 days and the number (and location in the tray) of spalled pieces (shed small fragments from their edges), fractured pieces (split into two or three fragments) and disintegrated pieces (spilt into more than 3 fragments) is recorded at each assessment. A value of the EG Durability Index (EGDI, ranging from 1 to 3) is calculated by comparing the weight obtained after 5 days and by the degree of disintegration.

An example of performance testing is presented in the following photographs for three different samples.

Photography 1. Non reaction

Photography 2. Fractured-desintegrated

Photography 3. Desintegrated

3.1.2 *X-Ray Diffraction*

The X-Ray diffraction method is commonly used to detect clay minerals presence, according with ASTM E2627-13 standard.

The main disadvantages of this technique are the following:

- Laborious sample preparation
- Difficult interpretation due to multiplicity of lines when many components are present
- Several samples are needed in order to carry out a precise assessment.

3.1.3 *Clay content*

The andesitic breccias of these formations have a matrix composed of clay minerals such as illite, esmectite, or zeolite. In this type of minerals have been documented numerous cases of swelling produced by the presence of water between the layers of their structure. The expansiveness will be higher when the more abundant clay minerals/aggregates content in the matrix is.

There are different possible criteria to estimate the swelling potential. Some of these criteria are shown below in Tables 2, 3 and 4.

Table 2. Risk assessment (Jiménez Salas, 1980)

Parameter	Non-existent	Marginal	Critical	Very critical
Liquid Limit LL	<30	30-40	40-60	>60
Plasticity Index IP	0-15	10-35	20-55	>45
% <1 µm	<15	13-23	23-30	>28
% < 0.074 µm	<30	30-60	60-95	>90
PVC Lambe Index	<2	2-4	4-6	>6
Drying Index ID	>1	0.8-1	0.6-0.8	<0.6

Table 3. Estimation of volume change for expansive soils (Holtz and Gibbs, 1956)

Contain Colloidal % <0.001 mm	Plasticity Index IP	Retracction Limit	Volumetric Change %	Swelling level
>28	>35	>11	>30	Very high
23-28	25-41	7-12	20-30	High
13-23	15-28	10-16	10-30	Moderate
<15	<18	<15	<10	Low

Table 4. Swelling criteria according Chen (1988)

% pass through #200	Liquid Limit	S.P.T.	Swelling %	Swelling pressure	Swelling level
>95	>60	>10	>10	>10	Very high
60-95	40-60	3-10	3-10	2.5-10	High
30-60	30-40	1-5	1-5	1.5-2.5	Moderate
<30	<30	<1	<1	<0.5	Low

3.1.4 *Slake durability test*

The test method is used to estimate qualitatively the durability of weak rocks, according with ASTM D4644-04 standard.

The experiences show that the swelling capacity is inversely proportional to the value of SDI (Slake Durability Index), so that the lower this index materials are potentially more expansive.

Test carried out show a good correlation between the values of plasticity index and SDI versus free swelling index and swelling pressure index, so that the values are irrelevant to expansiveness when SDI is higher than 80, moderate for values between 60 and 80, severe for cases in which the SDI is less than 60.

In Figure 3 the obtained results of the comparison between the SDI and the swelling pressure is shown. In this Figure, SDI lower values can be correlated with higher swelling pressures.

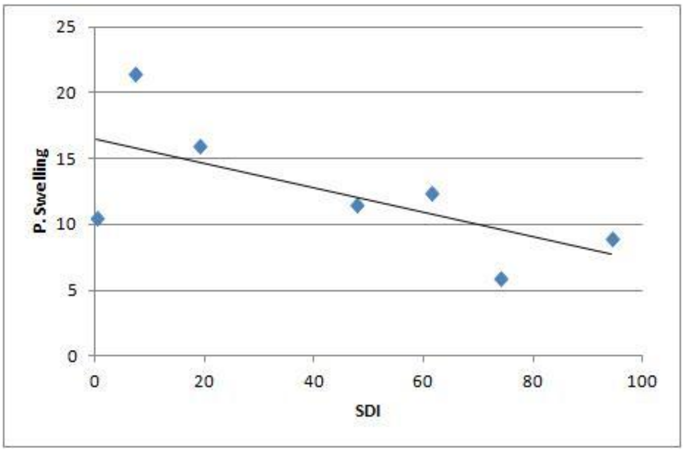

Figure 3. SDI vs Swelling pressure.

The main disadvantage of this test, besides the relatively high technical effort, is that the test works with oven-dried material, so it does not simulate natural conditions. Especially the immediate response from rock materials with low durability under natural conditions is not recognized.

3.1.5 *Interpretation*

Based on the laboratory test described above, will be crucial to perform an exhaustive analysis to determine preliminary the swelling potential of the rocks.

It is interesting to compare the values of the SDI with the percentage of clay in the rock. From studies it is obtained that the rocks which SDI is above 70 and have less than 10% of clays would be less critical respect to expansiveness.

In Figures 4, 5 and 6 shows the relationship between density and the swelling pressure and the free swelling index in test performed in swelling rocks.

Can be appreciated that a linear correlation exists due to the samples with higher density have a higher swelling pressure and a higher free swelling index.

All of the tests showed in this paper have been performed in compacted crushed samples (non undisturbed samples).

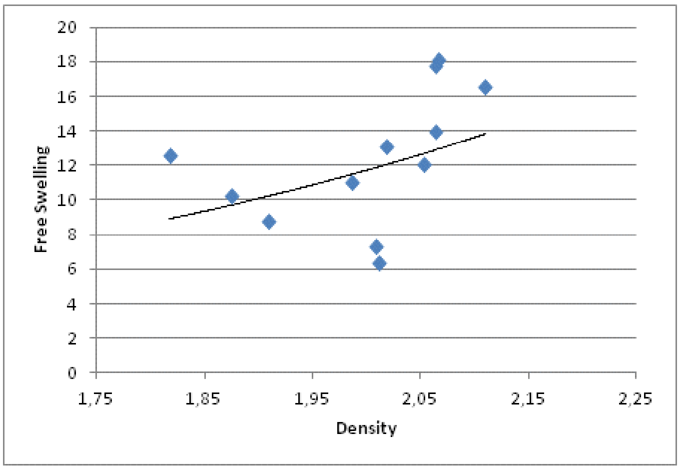

Figure 4. Compaction density vs free Swelling index.

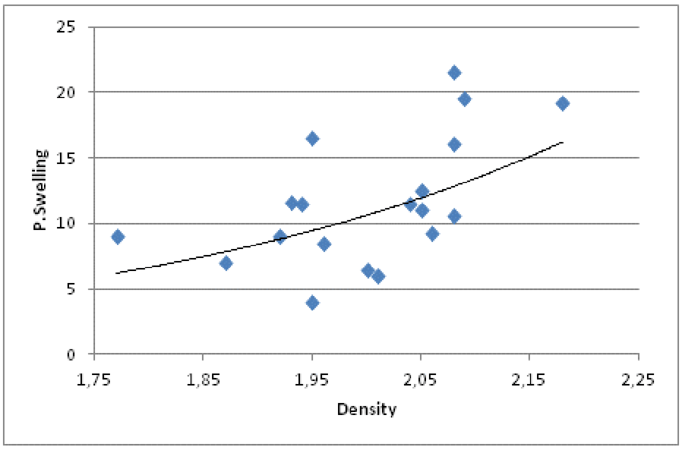

Figure 5. Compaction density vs Swelling pressure.

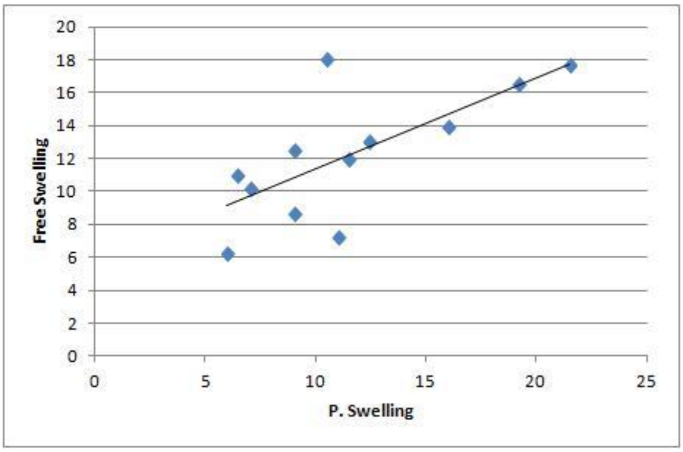

Figure 6. Free swelling index vs Swelling pressure

Figure 7 shows the correlation between clays content (in this case montmorillonite) and swelling pressure.

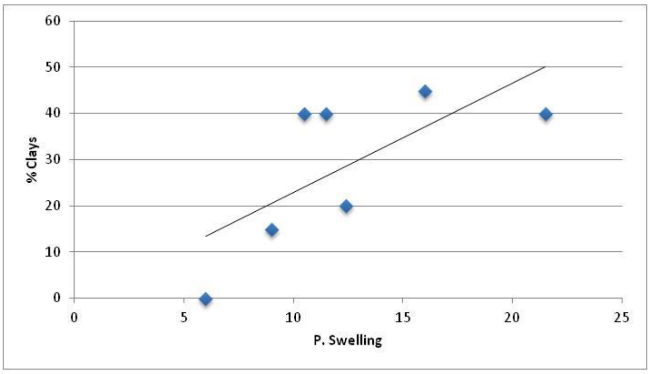

Figure 7. Clays content vs Swelling pressure

4 MONITORING DATA DURING CONSTRUCTION

During the tunnel construction it is recommendable to perform a monitoring by convergence stations complemented by multi point borehole extensometer on the most sensitive sectors.

Also, it may be opportune to compile and analyze the following data:

- Geological and geotechnical characteristics (lithology description and RMR) provided by the face mapping during the excavation, as well as the geomechanical behavior.
- Support class and a detailed description of the reinforcement in those cases in which it was applied
- Overburden

5 LINING DESIGN

The swelling does not occur immediately but subsequently during the tunnel excavation, the lining of the tunnels must be designed regardless of primary tunnel support.

The characteristics of the lining should be sized according to the swelling pressure estimated in the first stage of the project by analyzing the available information and by laboratory tests and the excavation data in the construction phase.

In order to design the lining reinforcement capable to resist the swelling pressure expected, numerical models can be used applying the following methodology:

1. Set the geological and geotechnical characteristics of the ground.
2. Analysis of the behavior of the section to be reinforced
3. Installation the support type.
4. Calibration with construction convergences
5. Construction of the lining.
6. Application of the swelling pressure.

As a result of the previous phases the existing principal stresses at the lining is obtained, in Figure 8 is shown an example of application.

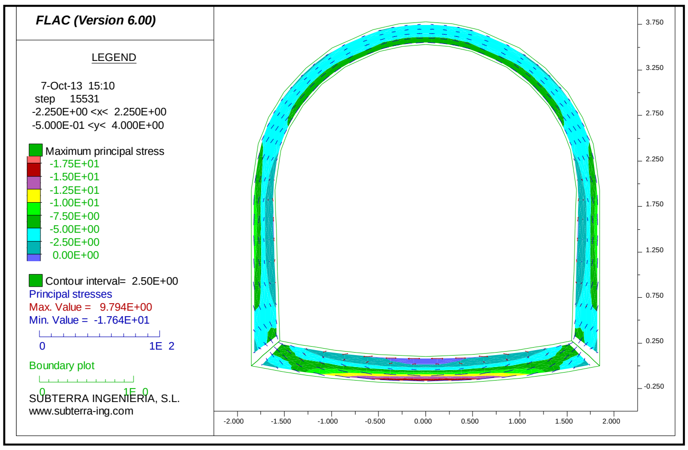

Figure 8. Example of aplication

Experience in modeling performed by finite element programs in hydro-tunnels in the Andes, and with different swelling pressures, it has been seized the following liners:

- In severe grades of swelling with pressures over 0.8 MPa is required a closed lining that consists in a curved structural invert and circular or inclined walls with reinforced concrete and a vault constructed with reinforced concrete or shotcrete. In Figure 9 the design of the lining with curved walls and invert is shown.

- For swelling pressures between 0.4 and 0.8 MPa the lining in a curved structural invert and inclined walls with reinforced concrete and a vault constructed with reinforced shotcrete. Figure 10 shows a lining design for moderate swelling.

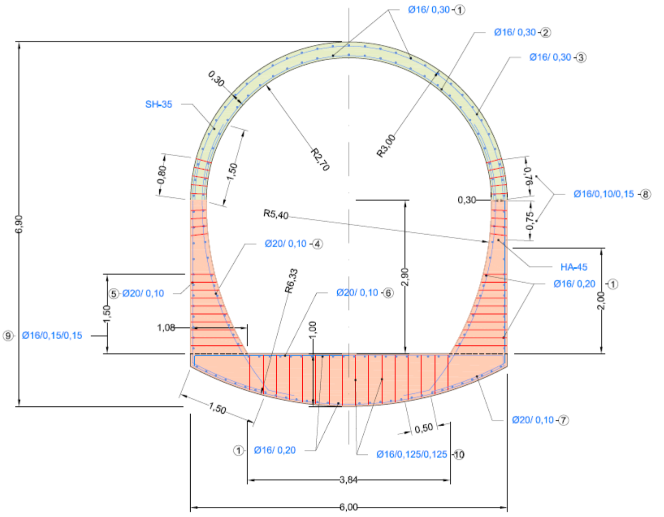

Figure 9. Designed reinforcement for lining 1.5 MPa

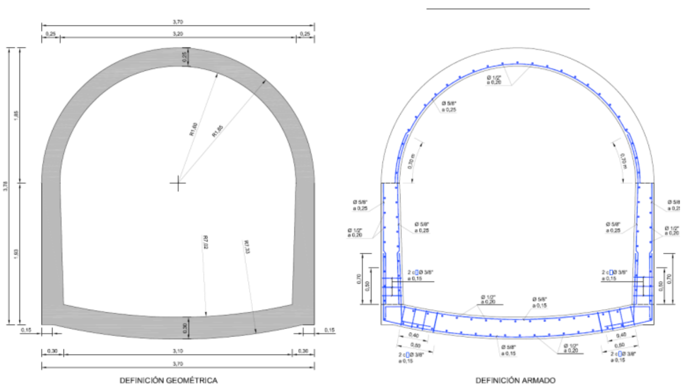

Figure 10. Designed reinforcement for lining 0.6 MPa

– For swelling pressures less than 0.4 MPa may be necessary a structural slab and inclined walls with reinforced concrete and a vault constructed with reinforced shotcrete. Figure 11 shows a lining design for a swelling of 0.2 MPa.

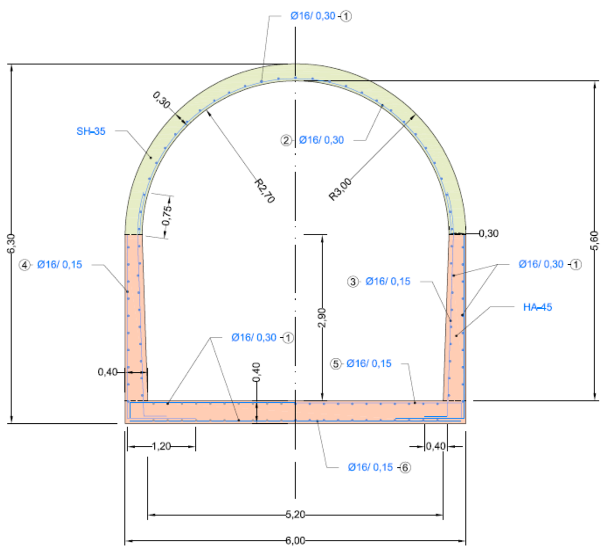

Figure 11. Designed reinforcement for lining 0.2 MPa

6 CONCLUSIONS

Swelling is a long-term phenomena that depend on the expansive clay minerals/aggregates content, the rock mass degradation, fracturation and the presence of water.

Ethylene Glycol, Atterberg Limits, X-Ray Diffraction and Slake Durability Test are used to determinate of swelling potential

It is essential to perform an intensive monitoring during the construction of the tunnels in sections where swelling phenomena is expected.

The experience in the design of the lining of several hydro-tunnels indicate that for swelling pressure over 0,8 MPa is required a closed lining with reinforced concrete, and pressure over 0,4 MPa is necessary a curved structural invert.

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