A tale of two explanations (for heaving claystone)

[A summary for the paper "The positive history of an error. Modelling the heave of a nuclear power station" accompanying the 3rd Blight Honor Lecture delivered by Eduardo Alonso at UNSAT2023]

BACKGROUND

1. The construction of a nuclear power plant started in early 1970s in the Ebro basin in northeast Spain. The importance of the constructed facility was a factor in the detailed monitoring and studies that followed.

2. The large excavation at a valley slope of horizontally layered claystone created a much steeper slope and horizontal parts at varied elevations. Figure 1 shows the soil profile before and after excavation. The slope was difficult to drain, but eventually a phreatic level was established. Later studies made clear that the excavation (performed by blasting) damaged the claystone layers close to the excavation surfaces and created fissures, which will play an important but different role in the two explanations.
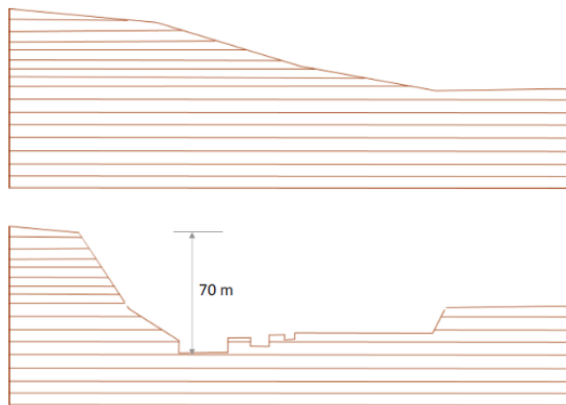

Figure 1. Original profile of valley and geometry of excavation [Fig. 2 in Alonso (2023)].

3. Heaving displacements of buildings were observed around mid 70's. Extensometers identified an active swelling layer under the power plant and piezometers within this active layer recorded all possible states: negative pressures (i.e. suction) and positive pressures, some of which at equilibrium with the post-excavation phreatic level.

4. Long-term 1-D swelling tests showed swelling to occur in two phases, or in two time scales, i.e. an initial swelling followed by a second phase of delayed swelling, as shown in Figure 2.
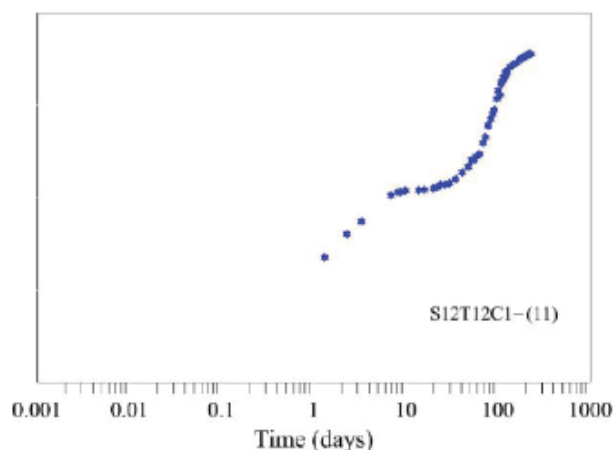

Figure 2. Long term oedometer swelling test at vertical confining stress σ = 0.01 MPa, with swelling in the Y axis reaching a maximum value of about 140 microns. [Fig. 5a in Alonso (2023)].

EXPLANATION NO 1

5A. The first explanation attributed the two-phase swelling to the dual structure of the unsaturated clay, as shown in Figure 3, which was hypothesized to consist of clay particles at the micro scale, under micro-suction (s_m), and clay aggregates (of clay particles) and other inert grains at the macro scale, under macro-suction (s_w). Water permeating the fissures formed due to the excavation infiltrated first between aggregates, resulting in the first phase of swelling, at the macro scale. Water moving within the aggregates contributed to the delayed swelling of the clay particles, at the micro scale.
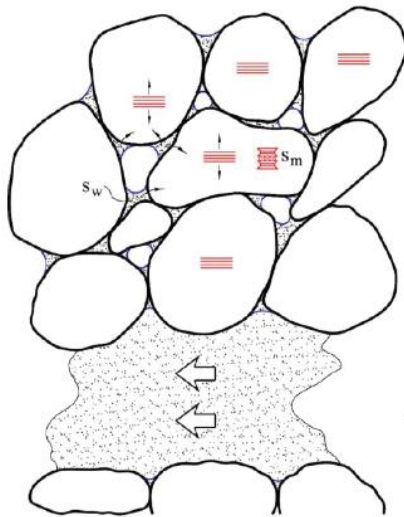

Figure 3. Representation of clay aggregates in an unsaturated expansive clay and a water conducting fissure [Fig. 7 in Alonso (2023)].

5B. This dual-structure model accounts for two sources of volumetric deformation. The volumetric deformation of the aggregates themselves, which depends of the prevailing stress and the micro-suction. And the volumetric deformation of the arrangement of aggregates, which depends on the prevailing stress and the macro-suction. A key parameter of the model accounts for the movement of water between the macro and micro domains that will take place when the micro-suction and macro-suction are different. Depending on the magnitude of this parameter, the two deformation mechanisms proceed sequentially or concurrently.

5C. The model was implemented in a finite element code that was very successful in replicating the 1-D heave observed in the laboratory (see Fig. 12 in the paper). The code also matched a 12-year long field record (~mid 70's to ~mid 80's) and predicted heave at a continuously decreasing rate, equal to 1mm/y 60 years after the beginning of swelling (see Fig. 15 in the paper).

REASONS TO THINK AGAIN

6. Mineralogical analysis of the composition of the clay at the site of the nuclear power plant indicated a 5 to 10% content of phyllosilicates and only 0.8% of montmorillonite, which made unlikely the double structure of Explanation No 1. In addition, it was found that the clay contained 0-30% anhydrite (calcium sulfate, $CaSO_4$) and 20-30% gypsum (dihydrate calcium sulfate, $CaSO_4 \cdot 2H_2O$).

7. What is more, during the first two decades of this century, infrastructure projects built in the sulfated claystones of the Ebro basin experienced damages due to rock expansivity. Hence, a new model was sought to explain the heave at the power plant site, which takes into account the clay composition.

EXPLANATION NO 2

8A. The fissures mentioned in points (2) and (5A), again facilitate infiltration of water, causing an initial short-term swelling upon wetting. According to Explanation No 2, the long-term expansion is due to the dissolution of anhydrite and the precipitation of gypsum crystals that apply stresses on fissure walls (see Fig. 21 in the paper). The movement of water in the fissures is not even necessary for this explanation, since diffusion of ions alone would also lead to the formation of gypsum crystals. However, the presence of fissures is a required element of this model too, since crystal growth initially needs some empty space to get started. Tellingly, as Alonso (2023) notes, "Crystals growing in a dense claystone matrix have not been observed".

8B. The crystal-growth model that was developed to describe this alterative mechanism for the observed heave is a complex chemo-thermo-hydro-mechanical model. Emphasis was given to the long-term heave, which is of main interest, which depends to a large extent on the initial content of anhydrite (mainly) and gypsum.

8C. Results obtained with this model were in good agreement with both laboratory (see Fig. 28 in the paper) and field measurements (see Fig. 32 in the paper). When records of heave measured at several locations over a 24-year period were used in the comparison, the observed heave at 24 years was at places either over-predicted or under-predicted by the model (see Fig. 33 in the paper), since the observed spatial heterogeneity of sulfate mineral content in the claystone is expected to affect the accuracy of the prediction. According to this model, heave will stop when the anhydrite will be exhausted by dissolution.

EPILOGUE

9. In Alonso's own words from the 2nd of the three concluding bullets of the 3rd Blight Lecture: *It is somewhat disturbing that widely different interpretations and conceptual models may be justified and "adapted" to reproduce the actual laboratory and field behaviour.* As a visual reminder, Figure 4 gives an example of the good fit of each model.
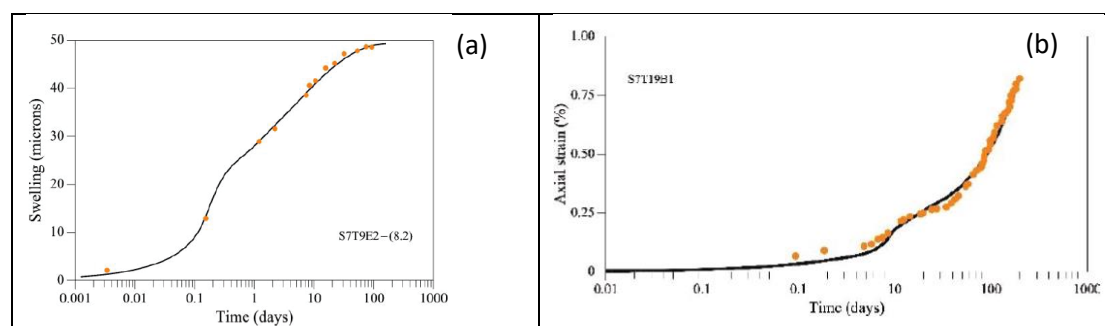

Figure 4. Comparison of laboratory data with predictions of (a) model based on Explanation No 1 and (b) model based on Explanation No 2 [Fig. 12b and Fig. 28 in Alonso (2023)].

REFERENCE

Alonso, E. (2023). The positive history of an error. Modelling the heave of a nuclear power station, 8th International Conference on Unsaturated Soils (UNSAT 2023), https://doi.org/10.1051/e3sconf/202338200002

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