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Field monitoring of the water pressure and displacement of a partially saturated expansive marl under an unloading stress path due to deep excavation

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Abstract. This paper presents, an in situ monitoring of the behaviour of a partially saturated soil, subjected to an unloading stress path resulting from excavations. The study case is a 30m deep excavation for the construction of a metro station, The aim of the study is to monitor the evolution of displacements and pore pressure during and after the different stages of excavation. The monitored soil is an expansive marl. The first results have been collected and analysed. Nevertheless the monitoring system should remain in place for a few years.

1 Introduction

The unsaturated character of soils is most of the time neglected in the design of geotechnical structures (with assumptions leading to overestimation of the loads applied to the structure or underestimation of the resistance of these soils), in particular for the "short term" situation. Furthermore, in some cases, due to the applied stress path, a saturated soil can become unsaturated and therefore exhibit larger resistances and strengths. A typical example can be the response of a fine soil submitted to a high vertical stress reduction due to a deep excavation. This question can be partly tackled by means of laboratory tests such as oedometer tests but there is a few number of data collected on real structures in the literature.

The aim of this paper is to present the methodology implemented during the excavation of a subway station supported by deep diaphragm walls to monitor the response of an expansive soil (in particular in terms of suction and soil swelling/heaving). Only the results obtained during the excavation phase are analysed here. Monitoring will continue after the construction of the raft and the inner structure and will allow to analyse the effect of swelling in the long term.

Before any discussion, let us precise the adopted definition of an unsaturated soil . For many people, a soil is unsaturated when the pores contain at least a small amount of air. In other words, a soil is unsaturated when the degree of saturation is less than one. For Fredlund ([1]), the unsaturated character of a soil should be associated with the presence of a positive suction rather than the value of the saturation degree. This definition of unsaturated soils is most general because it includes soils that are totally saturated with water under tension. We will thus consider as unsaturated, a soil with a positive value of the suction.

2 Presentation of the project

The excavation is realized for the construction of a metro station located in the east of Paris. It is a 30m deep excavation retained by a 1.2m thick diaphragm wall. The station is a peanut shaped building bounded by the diaphragm wall.

The soil profile is presented on Fig. 1. As one can notice, the layers are not horizontal. The bottom layer (substratum) consists of gypsum. The following layer is the monitored expansive marl. Initially, this layer is about 10m thick. At the end of the excavation, the remaining thickness of the marl layer is approximately 3 meters on the north side of the structure. On the south side, the marl layer remains 10m thick. The layers above the marl are excavated. They are mainly made of clays and silts. The construction took place according the following planning:

- Stage 1: Construction of the diaphragm wall.
- Stage 2 : Excavation, retained by the diaphragm wall. The 30m excavation have been decomposed into 6 sub-steps (8m - 6m - 3m - 4m - 3m and 6m). Between two sub-steps of excavation, a strut was constructed. Thus, there were at least two weeks of no active excavation between every sub-step of excavation.
- Stage 3: Construction of the station building (raft at the bottom of excavation and then different slabs from the bottom to the top) .

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The sensors have been placed in the marl just after the first step of excavation during the construction of the first strut. Vertical displacements and pore pressure evolution have thus been monitored since the second sub-step of excavation. Consequently, 22m of excavation have been monitored. Some of the collected results are presented in section 4.

At the end of the excavation, earth pressure cells have been placed directly at the bottom of the excavation in order to measure the vertical stress right under the raft of the future structure.

3 Material and methods

3.1 Material

Fig. 1 shows a plane view and vertical cross-section of the system. This system consists in:

- Two (2) chains of elongameters
- Two (2) piezometers
- Three (3) tensiometers
- Four (4) earth pressure cell

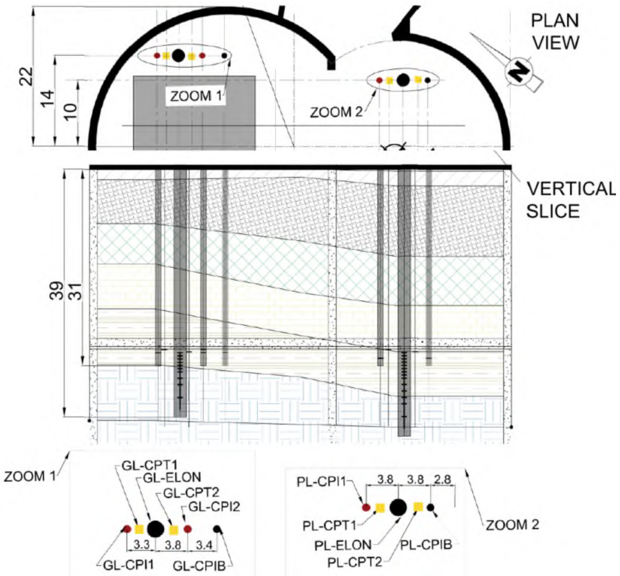

Fig. 1. Monitoring system

3.1.1 Elongameters

Chains of elongameters are used to measure vertical displacement. Correctly grouted in the soil, an elongameter can lengthen or shorten in coherence with the displacement of the soil. To measure the global displacement of the layer, several elongameters have been attached together to create chains of elongameters. The size of each chain and the number of elongameters by chain, depend on the thickness of the Marl layer at the chosen position. Two chains have been placed at two different positions.

The first chain is made of 10 elongameters, covering 9m of soil. The elongameters are numbered from the top to the bottom. This chain will be referred to as GL-ELON in the rest of the text. Thus GL-ELONi is the i-th elongameter of the chain GL-ELON. The second chain, referred to as PL-ELON, is a chain of 14 elongameters, covering 12m of soil.

3.1.2 Piezometers and tensiometers

To measure pore water pressure, two types of equipment have been used: piezometers and high range tensiometers. Piezometers are able to accurately measure positive pore pressures. But for suction and/or water tension, tensiometers are more adapted. The combination of the two types of equipment helps to insure accuracy on the pressure measurement for both positive or negative values.

Most piezometers and tensiometers consists in a water reservoir, a porous stone, and a measuring part that depends on the sensor.

As tensiometer, we used the “Full Range Tensiometers” commercialized by UGT. They are able to measure suction/tension values up to 1500 kPa with an accuracy of $\pm 0.5\%$. The technical description mentions the use of a really fine ceramic perfectly saturated and a small reservoir containing some water and a polymer. These processes are consistent with the suggested actions to decrease the risk of cavitation, usually limiting the tensiometers capacity to a maximum of about 100 kPa (see [2], [3]).

Three (3) high range tensiometers have been placed. They are referred to as GL-CPI1; GL-CPI2 and PL-CPI in Fig. 1.

In addition to these tensiometers, two (2) piezometers have been placed. The chosen model is the GEOKON standard piezometer 4500. This kind of sensor can measure positive pressures up to 350 kPa and negative pressures up to 100 kPa with an accuracy of $\pm 0.1\%$.

The results presented in this paper only concern GL-CPI1.

3.1.3 Earth pressure cells

An earth pressure cell is a sensor that measures total stress. The model used is the GEOKON circular cell pressure 4800. They can measure pressures up to 350 kPa with an accuracy of $\pm 0.1\%$.

3.2 Method

Fig. 2 sums up the method used to install the sensors. Step 1 to 3 represents the installation of the sensor. Step 4 and 5 show the evolution during excavation.

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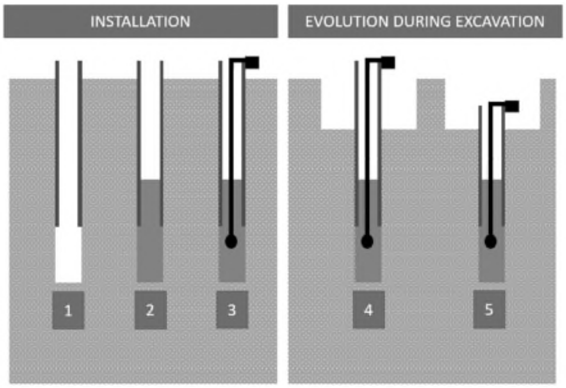

Fig. 2. Installation from the surface

3.2.1 Installation

The elongameters, the piezometers and the tensiometers have been placed at different positions from the surface through boreholes. The installation have been decomposed into 3 steps.

Step 1 – Boreholes installation : To monitor the soil's response during excavation, the sensors had to be placed before the excavation. For that reason they were installed at the correct depth through boreholes from the surface. Each equipment has been placed in one borehole. 7 boreholes have been thus required. As the sensors had to work while the excavation was going on, metallic pipes have been place in every borehole. These pipes remained during the excavation to protect the equipment and the cables.

Step 2 – Injection of grouting cement: To fill the boreholes and ensure the continuity between the sensors and the soil, a grouting cement has been used. The cement has been chosen, based on a permeability and a deformation modulus criteria (see section 3.2.3).

Step 3 – Installation of the sensor before the grout hardens and connection with dataloggers.

The earth pressure cells have been directly installed at the end of the excavation. Thus the pressure cells are right under the raft and allow to measure the stress directly applied to the structure.

3.2.2 Evolution during excavation and data collection

During the excavation phases, dataloggers have been used to automatically collect data on some of the sensors. Four (4) measurements were realised every day (one every 6 hours) and stocked in the loggers. At the end of each excavation phase, the metallic pipe was sectioned to avoid risk of falling. To do so, the dataloggers were disconnected, the pipes were sectioned and then the dataloggers were reconnected. The measurements stocked in the datalogger were collected during this time to be processed.

3.2.3 Formulation of the grouting cement

For an accurate measurement of the displacement, the cement must have a deformation modulus as close as possible to the deformation modulus of the soil. If the cement is too rigid compared to the soil, the soil displacement will not be correctly transmitted to the sensor. The deformation modulus (based on pressuremeter tests) in the monitored soil is 350 MPa. The selected cement had to be as close as possible to this value.

On the other hand, for an accurate measurement of pore pressure, the cement must have a permeability as close as possible to the permeability of the soil. The monitored soil have a permeability of 10^{-7} m/s based on Lefranc permeability tests. Piezometers and tensiometers have been placed according to the fully grouted method [4]. If we call k_s the permeability of the soil and k_g the permeability of the grout, the relation (1) should be verified while using the fully grouted method:

$$10^{-3} \leq \frac{k_s}{k_g} \leq 10^{3} \qquad (1)$$

Based on this relation and on the value of the measured permeability, the grout's permeability should be in the range of [$10^{-4}, 10^{-10}$] (m/s).

A commercial cement and a specifically designed cement have been compared. The deformation moduli have been measured through uniaxial compression tests and the permeabilities have been measured through oedometer consolidation tests. In terms of permeability, the relation (1) was verified for every cement. The commercial cement has been eventually chosen because it had the closest deformation modulus. In addition, the use of a commercial grout has been advantageous given the amount of cement required for the installation of all the sensors.

4 Results

Fig. 3 and Fig. 4 represent respectively the vertical displacements for GL-ELON and pore water pressure for GL-CPI1. On both figures, the horizontal axis represents the time, the origin has been considered as the first day of excavation.

As mentioned in section 2 the sensors have been placed after the first step of excavation. Therefore, the curves start around day 60 and there are 22m of monitored excavation, which is sufficient for the analysis (but does not ensure that the initial values of displacements and pressure correspond to steady state regime nor to the initial values before excavation). The absence of measurements concerning the initial state and the displacements induced by the excavation of the first 8m introduces a new difficulty in the analysis. This lacking information will be simulated as parameters during the numerical modelling. The vertical axis on the left of the figures represents the level (altitude) of the excavation. The maximum value is 113.5m NGF (French national reference) and corresponds to the initial ground level. The minimum value of this axis is 85.4m NGF and represents the ground level in the sensors' zone at the end of excavation and right before installation of the concrete raft of the future structure. The excavation curve represents the evolution of the bottom of excavation with time. The decreasing phases correspond to active excavations and the constant phases correspond to construction of struts.

The level of the ground has been precisely measured during the phases of struts construction. The presented excavation curve has been determined based on these measured levels. The same curve is used for every sensor. The excavation ended on day 160.

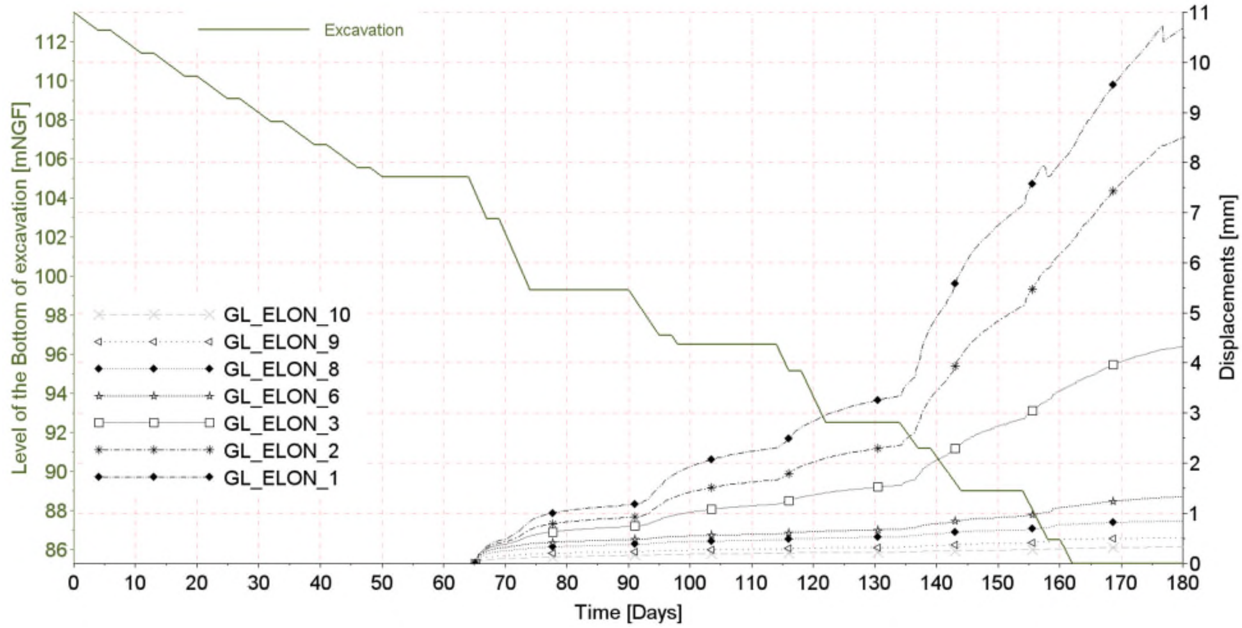

Fig. 3. Vertical displacements from GL-ELON

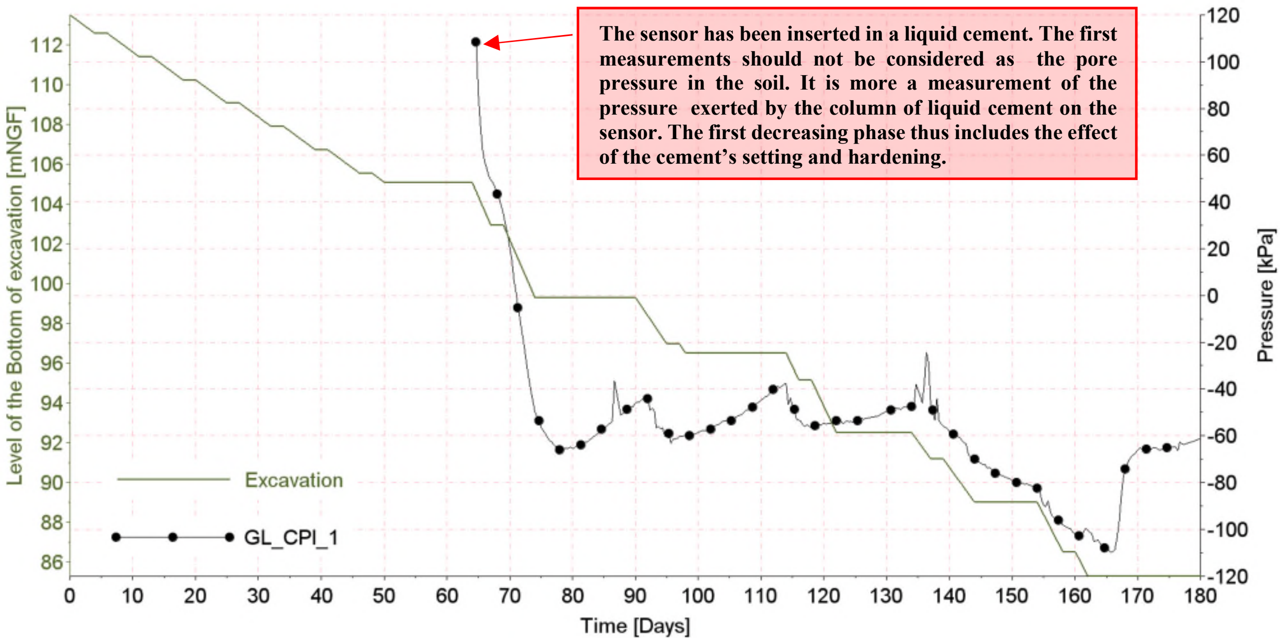

Fig. 4. Pore water pressure for GL-CPI1

4.1 Vertical displacements

Fig. 3 represents vertical cumulated displacements measured by GL-ELON (right vertical axis). The bottom curve (GL-ELON10) represents the displacement of the deepest elongameter of the chain. The following curve (GL-ELON9) represents the cumulation of the two last elongameters (GL-ELON10+GL-ELON9). To say it in a general way, the 'i-th' curve represents the cumulation of the sensors numbered from 10 to i. The top curve (GL-ELON1) consequently corresponds to the sum of all the 10 elongameters. To make the figure clear and legible, some of the elongameters are not represented. The space between two curves 'GL_ELON_i' and 'GL_ELON_j' gives the cumulated contribution of the elongameters with numbers between 'i' and 'j' .

The zero point for the displacement is taken equal to the point of equilibrium between the shrinkage of the cement and the heaving of the soil as the elongameters are inserted in a liquid cement. When the grouting cement sets, shrinkage occurs. This shrinkage leads to the measurement of an initial settlement in the elongameters. When the cement has correctly hardened, it starts heaving in coherence with the soil movements.

The origin of the curve corresponds to the point where heaving compensates the initial settlement due to the shrinkage of the cement.

On each single curve, two main tendencies can be described depending on the construction stage. During excavation stages, we can observe a heaving with a certain average slope. Between two stages of excavation, we observe another heaving but with a smaller rate.

We can also notice that the curves are organized in three (3) groups depending on the position of the sensor.

The first group consists of the two top points (GL-ELON1 & GL-ELON2). These curves present the highest slopes for the evolution of displacements. Their contribution to the cumulated displacement is then preponderant. As an example, if we consider the displacements at the end of the presented curves, we have a total displacement of 11 mm. The contributions of GL-ELON1 and GL-ELON2 to this total heave is about 2.5mm and 4mm respectively. Thus, the first two displacements accounts for 60% of the global displacement of the layer. The second group consists in the six following curves (GL-ELON3 to GL-ELON8). The rates of evolution of the displacement are smaller than those of the previous group. For instance, at the end of the presented curves, the total contribution of the second group is 3.5mm, i.e. about 32% of the total displacement of the layer. The third group consists in the last curves. Their evolution is very slow. This group's contribution to the global displacement of the soil layer is less than 10%.

The three mentioned groups appear to be compatible with the soil profile in the zone. Indeed, the top of the chain is in the marl and the bottom is sealed in the substratum layer. The deformation modulus of the substratum layer has been estimated (through pressuremeter tests) at 1500 MPa (to be compared with the 350 MPa of the marl). The different groups of curves therefore indicate the transition between the two different layers of soil.

4.2 Pore pressure

Fig. 4 presents the evolution of pore water pressure measured with GL-CPI1 (right axis). A positive value corresponds to water under compression and a negative value shows water tension (or soil suction).

The zero value for the pressures is an absolute value representing the pressure of water only submitted to atmospheric pressure (on the top of a water table for instance).

The measured pressure starts from a positive value around 110 kPa and quickly decreases to -70kPa. As the sensors are inserted in the liquid grouting cement, the initial value actually corresponds to the pressure exerted on the sensor by this liquid cement and should not be considered as the measurement of pore water. The first decreasing phase is the consequence of the excavation and the cement setting and hardening.

Then during the other excavation phases, pressure stays negative. It reaches a minimum value of about -110 kPa at the end of the excavation and starts rising very quickly afterwards.

On this curve, we can see two phases depending on the construction stages. During excavation stages, a decrease of pressure with a relatively high slope (or increase of suction) is measured. Between two stages of excavation, an increase of pressure is measured. The slope for this increase is smaller than the slope of the increase during excavations.

5 Discussion

To understand the response of the soil, the displacements and the pore pressure must be analysed together.

During the active excavation stages, the decrease of pore pressure coincides with a relatively fast vertical displacement. Between two excavation phases, the increase of the pore pressure is associated with a slower vertical displacement. During these phases, because there is no active excavation, the total stress can be assumed to be constant. The increase of the pore pressure with a constant total stress thus implies a decrease of effective stress (assuming that the effective stress can be defined with the Terzaghi's formula) leading to a heaving/swelling of the soil (essentially the marl layer). This process is similar to the consolidation process observed during compressions stress path (Fig. 5).

5.1 Expected behaviour

In a compression stress path in saturated soils, the expected response consists in a first undrained step characterized by the increase of pore pressure without volumetric strain. Then the pore pressure is supposed to slowly decrease towards its initial value. This pressure decrease generates consolidation's deformation. (Fig. 5) illustrates this response.

The absence of deformation during the undrained step is theoretically explained by the assumption of pure water's incompressibility. Assuming this incompressibility, one can deduce that:

- The compression loading force is totally transmitted to water, increasing pore pressure. In other word the value of the Skempton ratio B (see (2)) is 1.
- The increase of pore pressure doesn't lead to any deformation.

The deformation during the consolidation step can be theoretically explained by the transfer of the loading force from water to the soil.

The Skempton ratio B can be defined by equation (2) with u_w and p respectively the pore water pressure and the mean total stress. As one can notice, B=1 implies that all the mean stress increment goes to the water, meaning that there is no evolution of the mean effective stress (assuming that the effective stress can be defined with the Terzaghi's formula)

$$B = \frac{du_w}{dp} \quad (2)$$

When the soil is not saturated, the pore fluid cannot be considered as incompressible. Without this assumption, two facts can be deduced about the undrained response:

- When the soil is submitted to a compression loading force, a portion of the loading force is transmitted to the fluid, and the other portion is transmitted to the soil (meaning that we have $0 < B < 1$),
- The portions of loading force transmitted to the water and soil both lead to an instantaneous volumetric deformation. Then the consolidation process leads to an additional deformation.

The Skempton ratio during the excavation phases can be estimated. Pore water pressure increment can be directly read on Fig. 4. Mean total stress increment can be estimated based on the weight of the excavated soil.

It appears that this value is about 0.3. According to the previous paragraph, this value indicates an unsaturated behaviour for the marl. The degree of saturation can be estimated based on the value of the Skempton ratio. A lot of theoretical models propose a relationship between the two values ([5],[6],[7],[8]).

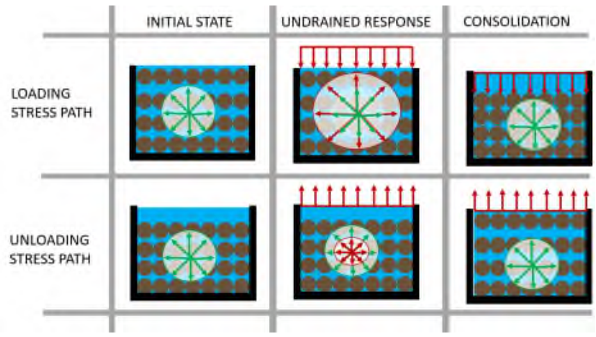

Fig. 5 Theoretical expected soil response

5.2 Next steps of the project

In summary, the monitored pressure and displacements indicates an undrained unsaturated response (pore pressure decrease and soil heaving) followed by a consolidation phase (pressure increase and heaving) in an unloading stress path. Negative pore pressures may indicate the presence of air in the pores. In this case, as the pore fluid (mixture of air and water) can no more be considered as incompressible, the compressibility of the mixture must be correctly assessed and considered in the estimation of short term displacement. Therefore, in the future, the following tasks will be realised:

- The evolution of pore pressure will be associated with an evolution of fluid compressibility ;
- The fluid compressibility will be associated with the soil compressibility to estimate the short term global displacement and pore pressure evolutions on a soil,
- The computed displacement and pressures will then be fitted with the measures.

6 Conclusion

In situ monitoring of soil behaviour can be complex and there is only a few number of case studies in the literature for the case of unsaturated soil submitted to unloading . However, this type of study is very useful to better understand the behaviour of soils. This paper presented an example of methodology that allowed us to monitor the displacement and the pore pressure of an expansive and partially saturated marl during and after excavation. Some of the first results have been presented. They will be useful to perform numerical simulations (back-analysis) of the response of partially saturated soils.

The data collected during this project belongs to SGP . The authors thus kindly thank SGP for allowing them to use these information.

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