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Settlement analysis for a nuclear plant design

Etude de tassement pour le design d'une centrale nucléaire

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ABSTRACT: Nuclear plants are very heavy and sensitive structures, therefore very interesting to study in geotechnics. When the site contains soft soil layers, settlements can be significant, and foundation adaptation may be required. Since standard methods are not fit for such high displacements and low tolerances, sophisticated settlement studies are carried out to ensure feasibility. First, adequate geotechnical soil investigations have to be carried out in order to evaluate soil behavior and particularly to estimate their stiffnesses accurately. Once in-situ and laboratory tests have been cross-analysed, soil moduli are derived for the correct range of strains. For new projects on existing sites, the choice of soil moduli is often guided by a back analysis carried out on the nearby operating plant. The complexity might lead to build a 3D model to assess the settlements, taking into account various elements (dewatering, sequence of construction, different backfill areas, etc.). Both drained and undrained (with consolidation) situations are considered. Non-linear behaviour is also assessed for sensitivity calculations. The results are to be used in the different aspects of the design with regards to the tolerances (raft design, thresholds against flooding levels, joints between buildings, pipe displacements, etc.). The article presents the calibration of the settlement model using in-situ data as well as the back-experience from the monitoring on the current plant nearby and give an overview for the use of the results.

RÉSUMÉ: Les centrales nucléaires sont des infrastructures sensibles apportant une charge importante au sol, ce qui rend leur étude géotechnique très intéressante. Lorsque le sol est compressible, les tassements peuvent être significatifs et les systèmes de fondations doivent être adaptées en conséquence. Ainsi, des études de tassements détaillées sont menées afin d'assurer la faisabilité de construction de tels ouvrages. Tout d'abord, des investigations géotechniques sont réalisées afin d'établir un modèle géotechnique. Pour cela, une analyse croisée est réalisée entre les essais de laboratoire et les reconnaissances in-situ. Les modules de sol sont ensuite adaptés aux gammes de déformations apportées par le projet. Pour les nouveaux projets sur les sites existants, le choix des modules est également conditionné par une analyse en retour des déplacements de la centrale en activité. Dans le cadre de notre étude, un modèle 3D a été réalisé afin d'estimer les tassements sous un projet de centrale nucléaire. Des comportements linéaires et non linéaires ont été considérés avec des calculs drainés et en consolidation. Les résultats peuvent être utilisés pour différents éléments de design (radier, joints entre galeries ou bâtiments, etc.) en prenant en considération les tolérances adéquates pour traduire la variabilité des terrains et du phasage de construction par exemple.

Keywords: Settlement analysis; nuclear plant; finite elements analysis.

1 INTRODUCTION

A nuclear plant as built in the 20th century weights several hundred thousand tons, inducing average stresses under the rafts of 200 to 500 kPa. New models in current projects around the world are more powerful, have more features, therefore get larger and heavier (exceeding half a million tons, and inducing average stresses up to 700 kPa). Before the construction of a new nuclear plant, a settlement study is thus essential to ensure an adequate design.

A geotechnical soil model has to be built based on in-situ investigations and laboratory tests. Depending on the soil and the loads expected to be brought by the project, geotechnical moduli have to be adapted to fit the range of strains the soil will experience. In our study, the fitting is based on the back-experience from the monitoring on the current plant nearby, with a nonlinear elastic model derived from pressuremeter data as developped in the ARSCOP project (Hoang et al. 2020). This model already allowed the reproduction of many sets of settlement data: nuclear power plants, high-rise towers in the district of La Défense (Paris, France) and pre-loading embankments at Calais, France.

In our study, two different geotechnical models have been built: one to validate the soil moduli under the existing power plant, and a second one for the new plant, based on the first model but with a strain adaptation because of the greater loads of the future buildings (therefore inducing more strain).

2 SETTLEMENT STUDY FOR THE EXISTING NUCLEAR PLANT

In our study, the geotechnical model has been built with the analysis of the extensive in-situ and laboraty tests and an adaption to strains ranges.

2.1 Nonlinear elastic model from pressuremeter

In the framework of the French national project ARSCOP devoted to the development of the pressuremeter test, a total review of the settlement calculation has been initiated. The aim of this project is to develop a unified calculation approach of shallow foundations and rafts settlements.

In this framework, in order to have a good estimate of settlement under spread foundations, a calculation method has been developed to combine the variation of the deformation modulus according to the strain range and take advantage of short calculation time of analytical methods. This method is based on decay curves, allowing moduli to vary according to the strain range. The aim is to provide the load-settlement curve of any spread foundation up to a load close to 50% of its bearing capacity. For higher loads, the time effects should be considered, and the elasticity theory is not appropriate. The deformation modulus is assessed by considering Menard pressuremeter modulus (Ménard and Rousseau, 1962) for high strain level (10^{-2} to 10^{-1}).

The ground under the spread foundation is divided into various sublayers where E can vary according to the strain level:

$$\frac{E}{E_M} = k(\varepsilon) = \frac{k_0}{1 + \varepsilon/\varepsilon_0}$$

where E_M is the Menard pressuremeter modulus and k_0 and ε_0 depending on the soil type from the Ménard α parameter, as described in (Hoang et al. 2020):

- Type 1: sands and gravels (α=1/3) k_0=6,67 and ε_0=0,005
- Type 2: dense sands and gravels (α=1/2), k_0=4,5 and ε_0=0,008
- Type 3: overconsolidated clays (α=2/3), k_0=3,20 and ε_0=0,014

2.2 Geotechnical model

The existing nuclear plant has been monitored with displacement sensors, during both construction and operation of the buildings. It is a very good way to evaluate repartition of settlements in different soil layers to calibrate the geotechnical model and check its consistency.

Predictive calculations at the time gave greater settlements than the observations show. The available documents suggest that strain corrections were not properly applied and might have led to this overestimation. ARSCOP curves have been used to calibrate soil moduli for the current plant with regards to the calculated strain range. Pressuremeter modulus can be used directly with a non-linear elastic model to match the measurements. Corrected moduli were 3 or 4 higher than E_M, depending on the soil type.

The modulus obtained for each layer shows a relative homogeneity, therefore a linear elastic soil model with one single equivalent modulus per layer is deemed sufficient in our study (Figure 1).

2.3 Modelization

An axisymetrical Plaxis 2D model has been implemented with the calibrated soil moduli. A realistic construction sequence has been set, including excavations, dewatering, backfilling, and loading of the buildings. Drained and undrained behaviors have been computed for 2 soil laws: an elastic and Hardening Soil Model (HSM).

Drained behavior has been firstly implemented to assess the maximum settlement. Undrained

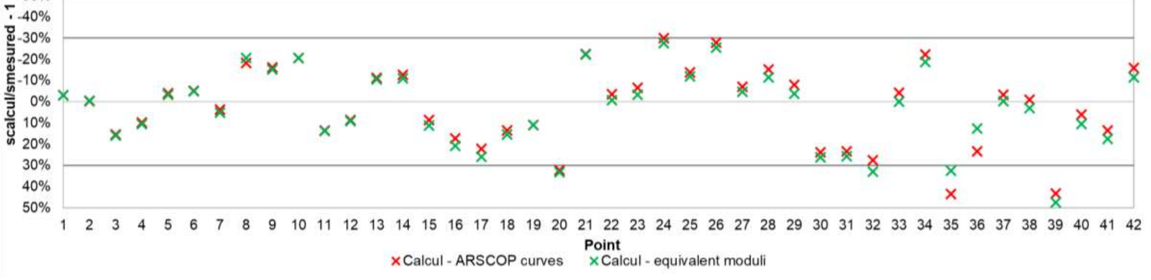

Figure 1. Comparison of measured and back-calculated settlement for the current plant (the ordinate is the discrepancy between calculation and observation, the x-axis represents the various monitoring points all over the existing plant).

calculation was considered to evaluate the impact of the excess pore pressure in deep layers, due to the additional building loads. During the loading, an insignificant increase of excess pore is observed under the plant and dissipated at the end of construction (Figure 2). Therefore, drained and undrained simulations get similar settlement during the loading, and then equal settlements at the end (no more excess pore pressure). After the construction, settlement observations showed no evolution, which correlates with the absence of consolidation or creep of any kind. Excess pore pressure calculations were therefore consistent with settlement observations.

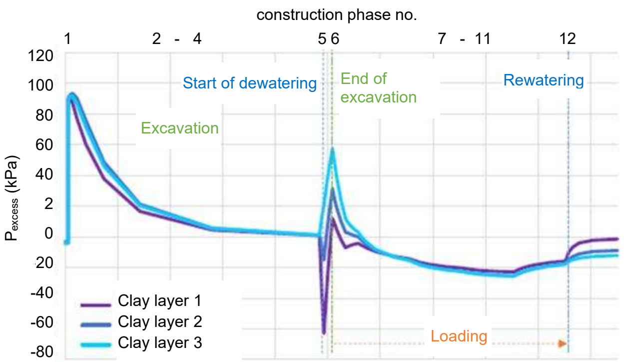

Figure 2. Estimation of the generation of excess pore pressure in deeper layers under the existing nuclear plant.

Linear and HSM calculations were done, both for the drained and undrained cases, to evaluate if there were discrepancies that would invalidate the previous estimation that a linear model with a single modulus for each layer was sufficient to accurately reproduce the expected settlements (as long as it is carefully calibrated). Settlement results are similar and consistent with observations (Figure 3). It does not however mean that the additional loads only solicited the soil in the elastic domain (small deformations) since the choice of the moduli has been made with (secant moduli). The computed strains are also within the estimated range, ensuring consistency of the calculation.

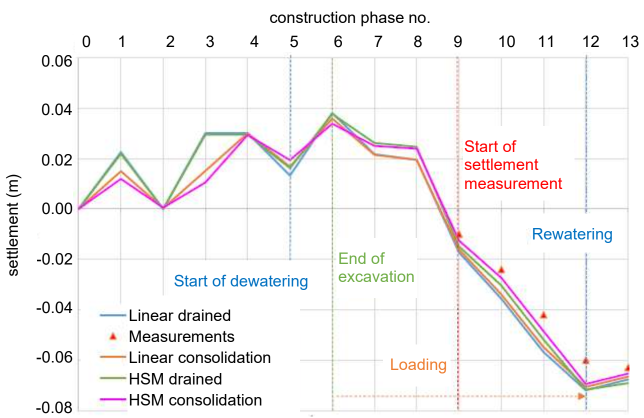

Figure 3. Comparison between settlement calculations and observations for the existing nuclear plant.

The geotechnical model for the existing plant is therefore validated since calculations and observations give similar results. Moduli can be used with a reassessment for the adequate strain ranges for the future nuclear plant.

3 SETTLEMENT STUDY FOR THE NEW NUCLEAR PLANT

3.1 Geotechnical model

The same process is considered for the new plant to be built nearby (with a stratigraphy not significantly different) using the same pressuremeter modulus, and approximately 50% higher loads induced on the soil. Therefore, degradation is applied on soil moduli with the adequate range of strain.

Moduli for the new nuclear plant are approximately 20% smaller than the corrected moduli used for the existing nuclear plant, resulting in stronger degradations (

Figure 4).

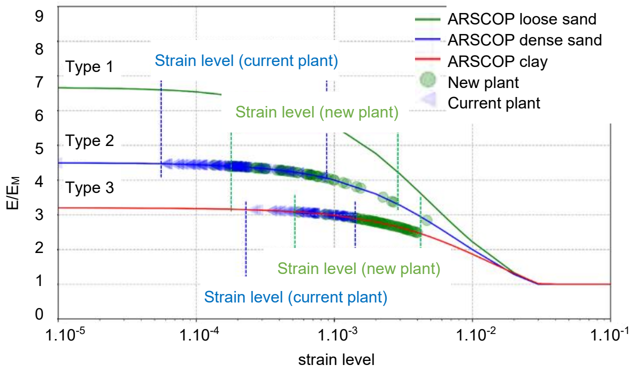

Figure 4. Variation of modulus with strain levels on the current and new plants – ARSCOP curves.

3.2 Modelization

Once soil moduli have been calibrated, a Plaxis 3D model has been built to evaluate the plant settlements (Figure 5). Most of the buildings were implemented as rigid elements except for the bigger and heavier ones - to assess raft deformations.

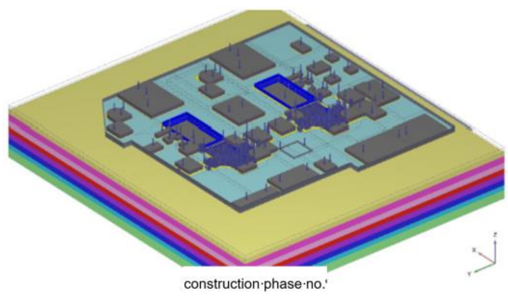

Figure 5. Plaxis 3D model for the future nuclear plant.

The same type of calculations as for the existing nuclear plant have been implemented: linear and HSM soil laws for drained and undrained behaviors.

The consolidation calculation shows greater excess pore pressure during construction (Figure 6 phases 14 to 21 - 200 kPa, compared to Figure 2 phases 6 to 11 - 20 kPa on the existing plant). It is due to the greater loads. It explains that the undrained model (orange line in Figure 7) induces less settlement than the drained model (blue line in Figure 7): excess pore pressure is significant during loading and does not allow immediate settlement.

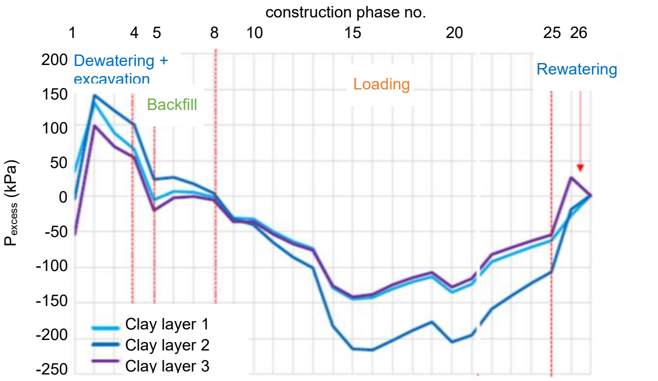

Figure 6. Estimation of the generation of excess pore pressure in deeper layers under the future nuclear plant.

However, excess pore pressures are dissipated at the end of the loading because the construction time is longer than it was for the existing nuclear plant. Therefore, drained and undrained calculation give similar final settlement (Figure 7).

Linear and HSM (drained and undrained) calculations were also done to evaluate if there were any nonlinear behavior in soil layers. Both soil laws give similar final settlement results (Figure 7), demonstrating that the soil still globally works in the estimated strain ranges.

Figure 7. Comparison between linear and HSM calculation – settlement of HR centre.

The difference between phases 25 and 26 (corresponding to the rewatering at the end of the earthworks) lies in the way the reloading modulus is estimated in both behavior laws (all the calibration is done on first loading moduli).

The 3D-settlement model allows to extract the settlement at any point and any phase. It is then possible to evaluate differential settlements along structures like the various embedded galleries (example in Figure 8). Those are essential for calibrating adequate rebars and joints.

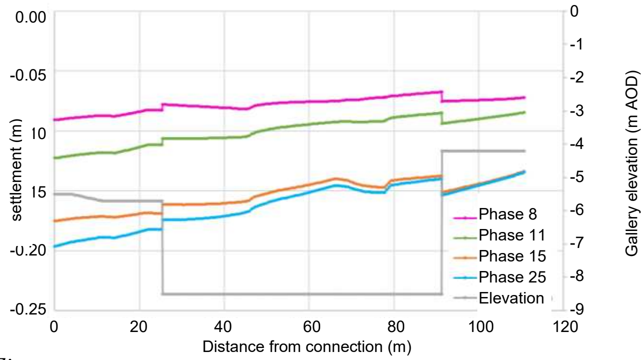

Figure 8. Settlement estimated along a gallery for different phases against its elevation profile (in grey).

4 CONCLUSION

An adapted geotechnical model is essential to predict and understand settlement under buildings. In order to evaluate the settlement of a future nuclear plant and give adequate settlement values for the design, detailled settlement studies are done. They are based on a geotechnical model calibrated on extensive in-situ and laboratory tests data. Depending on the range of strains, the moduli can be corrected with ARCSCOP cuves. It has been tested and compared with existing plant monitoring data on the same site. Settlement observations and calculations are consistant thanks to the calibration done on the moduli. For the future project, since the loads are greater, the moduli should however be adapted with the strains. It can lead to realistic settlement values for the future design.

REFERENCES

Menard, L., Rousseau, J. (1962). L'évaluation des tassements. Tendances nouvelles. Sols Soils No. 1, pp. 13-20, Paris.

Hoang M.T. & al. 2020. Vers une approche de calcul unifiée du tassement des semelles et des radiers, JNGG2020.