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SOME OBSERVATIONS ON THE RAFT FOUNDATION SETTLEMENT AND BENDING BASED ON LONG TERM CONCRETE STRAIN MONITORING OF REACTOR BUILDINGS

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ABSTRACT

In France, the foundation rafts of several reactor buildings are equipped with monitoring devices such as extensometers in upper part and lower part of the raft, leveling pots and settlement gauges. These devices have been operated since the beginning of the construction and are still used nowadays. The monitoring measurements provide curvature, deflection and settlements in different situations regarding Nuclear Power Plant (NPP) design: during the periodic structural integrity tests and during normal operation. The consistency between different monitoring systems has been verified. The raft behaviour during the periodic tests (every 10 years) is linear, reversible and repetitive. Possibly, deflections or curvatures during the 1st test may be more important. The maximal deflection occurs in the central part of the raft and the curvature shows an elongation in the lower fibre and a shortening in the upper fibre. Despite the concrete cracking, the observed repetitiveness shows a limited cracks opening under the pressure effect. Under the effect of the dead loads, the first 5 or 10 years of NPP life show a linear settlement and from then one an accumulation of settlement. The curvature under permanent loads is smaller than in pressure test situation. Both curvatures are acting so that the lower face of the rafts is in extension and the upper face in compression. This observation has been made despite a distribution of the dead loads mainly in the periphery of the raft. The analysis of the available measurements should make it possible to better understand the behaviour of the rafts in service and in pressure test.

INTRODUCTION

The reactor building of a French 900 MWe nuclear power plant (NPP) is composed of the prestressed concrete containment with metallic liner, the reinforced concrete internal structures and the circular raft. The containment and the raft constitute a safety system with the requirements to be submitted to an initial structural integrity test (ISIT) and to periodic tests and to have monitoring devices in order to follow the behavior evolution during the life of the power plant and during the periodic integrity tests under internal pressure. See references Galan (2022).

24 units were built between 1975 and 1986 and the measurements of 6 units was analyzed in this study. Thanks to the standardization of EDF NPP 900 MWe series named CP1-CP2, the geometry, the dead loads and the pressure level are the same for the reactor building rafts of this series. The only difference concerns the soil characteristics, see reference Costaz (1987). The foundation rafts are equipped with monitoring devices placed at several radius such as extensometers in upper part and lower part of the raft, leveling pots and settlement gauges. These devices have been operated since the beginning of the construction and are still operational nowadays. This article presents the description of the reactor building (geometry, soils condition, loads and constructions sequences, …) and the raft monitoring devices.

After presenting, typical measurements and comparisons with several types of monitoring, the results for several sites are analyzed and an estimation of the bending moments and the normal forces inside the raft is proposed in order to compare with the design calculations.

REACTOR BUILDING DESCRIPTION AND RAFT MONITORING DEVICES DESCRIPTION

The containment of the NPP-900 MWe consists mainly of a cylindrical prestressed concrete building 37 m in diameter and 59 m high. The wall thickness of the cylindrical wall is 0.90 m, that of the dome - 0.80 m. The raft is 3.50 m thick in central part and 5,00 m thick in the periphery including the prestressing gallery and is made of reinforced concrete.

This reactor building contains the reinforced concrete internal structures supporting the main equipment such as the reactor, steam generators, primary pumps, fuel loading and unloading pool… (Figure 1). The dead load is approximately 540 MN and the average soil reaction under the raft is 0,45 MPa. The dead loads of the inner structures are generally distributed between the reactor pit in central part (1,80 m thick cylinder) and the shield cylindrical wall in periphery (1,00 m thick). A particularity of the 900 MWe inner structures design is that the reactor pit was untied from the raft during construction. This operation occurs about 2 years after the beginning of the construction. The consequence is that the dead loads distribution is exactly the same for each site.

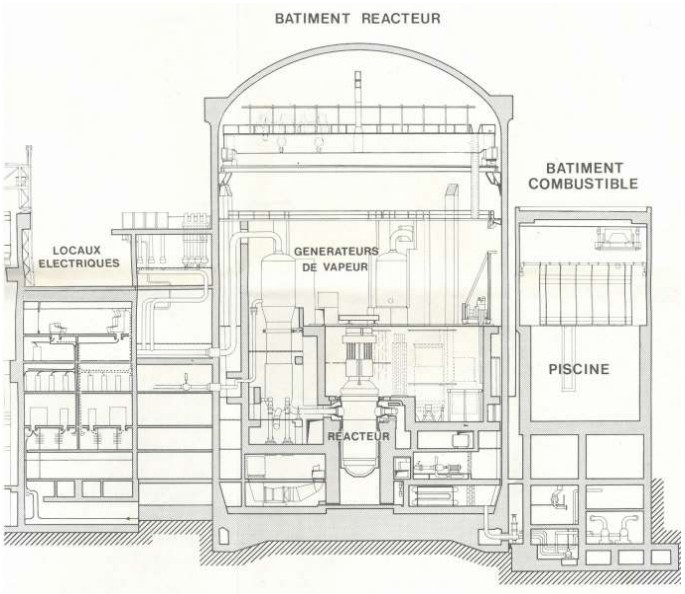

Figure 1: Vertical section of the NPP with the reactor building in central part

The geometry presented on figure 1 including the raft geometry and the loads are the same for the all sites with soft soils, but for hard soils, the raft is flat and 3.00 m thick and the gallery is under the raft. The foundation rafts are equipped with extensometers (acoustic strain gauges) and thermometers in upper part and lower part of the raft in several radii (see figure 2). The leveling pot monitoring is of the same type for all sites with 13 leveling pots on 2 perpendicular diameters (see figure 3). Settlement is achieved by measurements on settlement gauges under each raft and by optical leveling in the gallery and the possible inclination of the reactor building is measured by topography.

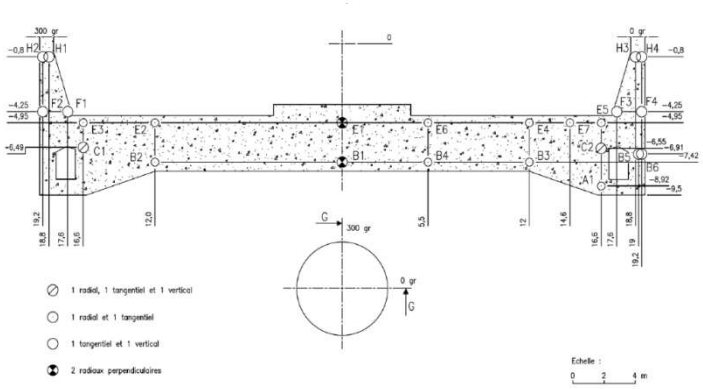

Figure 2: Example of location of extensometers in the reactor raft

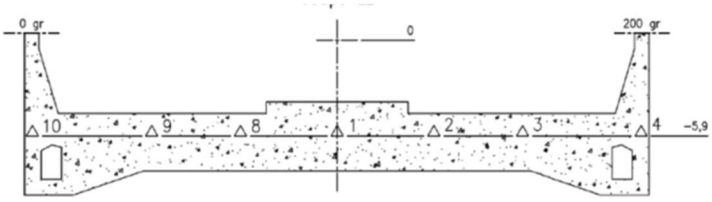

Figure 3: Example of location of levelling pots in the reactor raft

The containment is submitted to regular pressure tests in order to measure the air tightness of the containment. At the end of the construction, the initial structural integrity test (ISIT) is performed at 0,46 MPa and periodic (each 10 years) structural integrity tests (SIT) are performed at 0,4 MPa. During these tests, the monitoring devices (extensometers and leveling pots) are measured according to the pressure. These devices have been operated since the beginning of the construction and are still used nowadays, except for leveling pots which are grouted after 10 or 15 years in order to avoid leakage in case of severe accident with core melting. The measurements give indications for the raft behavior during the life of the NPP and during each periodic test.

The duration of the construction is about 5 years, with 1 year for the raft concreting, 2 years for the inner structures and the containment concreting and 2 years for equipment installation and testing. The initial structural integrity test (ISIT) occurs about 4 years after the first concrete and the commissioning occurs 5 years after the first concrete. The measurements are analyzed for the 6 sites, with 5 soft soils sites (A, B, C, D and E sites) and 1 hard soil site (F site). The table 1 gives the construction date for each NPP unit.

Table 1: Typical construction sequences

	First concrete	First monitoring measurement	ISIT	Grid connexion
Site A	November 1974	09/06/1976	January 1979	May 1980
Site B	February 1975	30/06/1977	January 1979	March 1980
Site C	February 1975	23/09/1977	May 1979	March 1980
Site D	March 1976	28/08/1978	March 1980	January 1981
Site E	January 1977	17/05/1979	September 1980	June 1981
Site F	March 1977	05/07/1979	August 1981	November 1982

The soils conditions are the following:

- Site A soil:
  - A layer of alluvium, modulus E of 120 MPa;
  - A marl layer cut into several sub-layers, with a modulus evolving from 25.6MPa to 70.5MPa to the right of the BR,
- Site B soil:
  - Continuous slab of gravel cement,
  - Quaternary deposits – fine sands – modulus of 35 MPa
  - Clay of Flanders modulus of 17 MPa
- Site C soil:
  - Alluvions - modulus E of 230 MPa
  - Clay material and flint – modulus of 90 MPa
  - Altered chalk – modulus of 300 MPa
  - Sound or cracked chalk – modulus of 1000 MPa
- Site D soil:
  - Coarse sands - modulus E of 240 MPa
  - Phitiviers and Morancez limestone - modulus from 70 to 104 MPa
  - Lower Eocene limestone – modulus from 68 to 270 MPa
  - Clay material and flint and chalk – modulus of 1000 MPa

MEASUREMENTS DURING STRUCTURAL INTEGRITY TESTS AND DURING THE LIFE OF THE NPP

With extensometers in upper part and in lower part of the raft, it is possible to estimate the curvature of the raft and the average elongation of the raft in several radii during the periodic tests and during the life of the NPP. With leveling pots, it is possible to obtain the raft deflection during the tests. With the settlement gauges, the reactor building settlement is obtained according to the time and completed by the topography to obtain the inclination of the reactor building. Figure 4 shows the curvature and the average deformation during the life. The curvature increases during about 15 years and then remains constant at 20 µm/m/m. The average deformation is a contraction due to the prestress pressure applied to the containment. The evolution occurs during 10 years and then remains constant at - 40 µm/m.

Figure 4: Example of curvature and average strains in the center of the raft plotted with respect to time

Figure 5 shows the curvature potted with respect to pressure during the integrity test. Generally, the curves are linear and reversible, i.e., the raft behavior under the pressure load is elastic and the curve

slope is constant for the periodic tests. For several sites, during the first ISIT, the slope is higher, but for other sites, the slope is the same. The elongation under the pressure load is small.

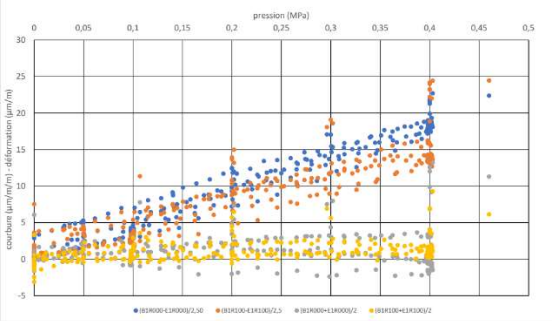

Figure 5: Example of curvature and average strains in the raft during the periodic tests

Figure 6 shows the raft deflection under normal operating during the life of the NPP. Initially the deflection is close to zero, and as the time increases a deflection with the higher settlement in the center part is observed. This is consistent with a positive curvature in normal operating situations. An inclination is observed with a higher settlement at 100 gr which corresponds to the direction of the Nuclear Auxiliary Building with higher loads applied to the soil. Figure 7 shows the deflection plotted with respect to pressure. The deflection for the fist ISIT is higher than the deflection for the periodic test, in coherence with the results for the curvature.

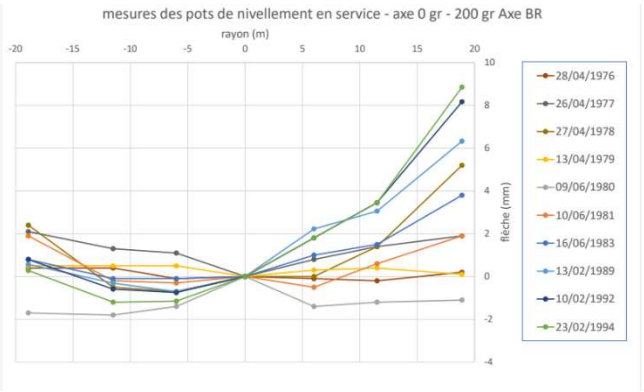

Figure 6: Example of raft deflection during the life of the NPP given by the leveling pots

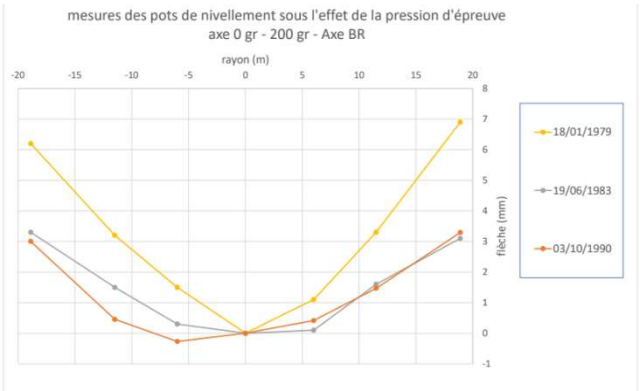

Figure 7: Example of raft deflection during the periodic tests given by the leveling pots

Figure 8 shows the settlement plotted with respect to time. The settlement gauges measurements show two phases with an elastic phase during the loading and some years after loading and a phase of settlement accumulation (consolidation, creep) after about 5 or 10 years. Similar results are observed for the other sites.

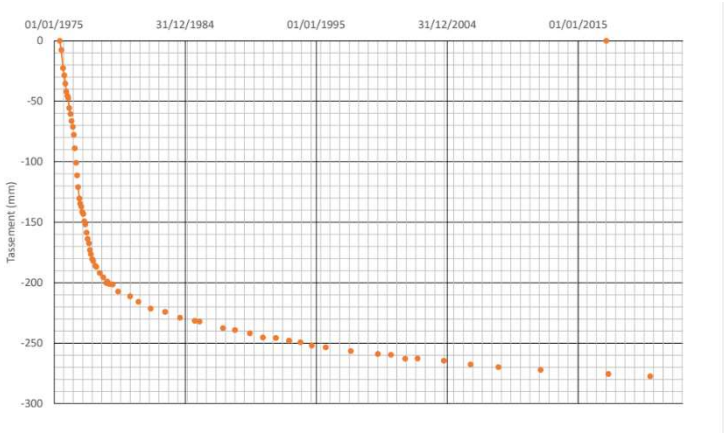

Figure 8: Example of settlement plotted with respect to time given by settlement gauges

COMPARISON BETWEEN SEVERAL MONITORING DEVICES

The consistency between levelling pots measurements and curvatures measurements with extensometers was verified. From the extensometers measurements on radii 0m, 5.50m, 12.00m and 16.80m the radial deformations make it possible to determine the curvatures while the tangential deformations make it possible to determine the rotations.

Assuming a constant radius of curvature over a certain length on either side of the extensometers, we obtain 3 arcs of circles which are connected vertically to obtain the raft deflection under pressure.

Figure 9 compares the post-processing of the extensometers (continuous curve) with the measurements of the levelling pots on the radius 0m, 6.00m, 11.50m and 18.90m (cross point) during the ISIT.

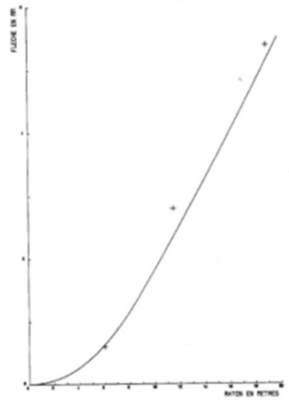

Figure 9: Comparison between measurements with extensometers and with leveling pot during ISIT

COMPARISON OF MEASUREMENTS FOR SEVERAL UNITS

The maximal central curvatures during the ISIT at 0,46 MPa, during the periodic test at 0,4 MPa and the maximal settlements under dead loads after 40 years are given in table 2.

Table 2: Maximal central curvature and settlement after 40 years

Sites	Curvature ISIT (µm/m/m)	Curvature Periodic test (µm/m/m)	Settlement at 40 years (mm)
site A	44	28	130
Site B	25	18	280
Site C	35	20	65
Site D	30	15	260
Site E	28	18	150
Site F	16	7	30

No direct relationship is observed between the settlement under dead loads and the maximum deflection under test. The deflections are about the same for soft soil, but the settlements are more different. The only exception is hard soil, where the deflection and settlement are significantly lower than for soft soils.

ESTIMATION OF THE BENDING MOMENT INSIDE THE RAFT

For the site A, the curvature at the center under the pressure (ISIT) at 0.46 MPa is $d\theta/dr$ = 44 µm/m/m and the rotation at the center is $\theta = 0$. The bending moment under pressure is calculated by equation 1 with a raft thickness h = 4,20 m in center part:

$$M_r = \frac{E_{cm}h^3}{12\cdot(1-\nu^2)}\cdot\left(\frac{d\theta}{dr}+\nu\frac{\theta}{r}\right) = \frac{38500\cdot 4{,}2^3}{12\cdot(1-0{,}1^2)}\cdot 44\cdot 10^{-6} = 10{,}6 MN.m/m \quad (1)$$

The curvature at the center in long-term service is 30 µm/m/m. With the same formula, it is possible to determine the bending moment in normal operation (equation 2). At long term, the bending moment is:

$$M_r = \frac{16\,000\cdot 4{,}2^3}{12\cdot(1-0{,}1^2)}\cdot 30\cdot 10^{-6} = 3{,}0\ MN.m/m \quad (2)$$

In this formula, E_{cm} is the concrete Young's modulus with an instantaneous value during the ISIT (38,5 GPa) and with a long-term value for normal operation (16 GPa). These values are issued from the monitoring analysis of the containment wall.

The formula used for the bending moment calculation assumes no cracking of the concrete in particular during the pressure tests. This is consistent with the observed curvatures which are repetitive and

reversible and with a linear variation according to the pressure. In case of cracking of concrete, damage should be observed.

Figure 10 shows the calculated bending moments issued from the initial calculation, with an elastic assumption for the soil, during the test or during the normal operating conditions. Under pressure load, the calculated bending moment is M = 15 MN.m/m instead of 10,6 MN.m/m for the measured value. In normal operating, the calculated bending moment is 1 MN.m/m instead of 3 MN.m/m for the measured value and the curvature correspond to tensile stresses in the lower part. The calculated deflection under pressure is 13 mm instead of 6 mm for the measured value.

The elastic soil calculation overestimates the moment under pressure and underestimates the moment in service. Figure 11 shows the elastic soil reaction during the ISIT with a ground reaction equal to 27 MPa in the center part. The evolution of the theoretical ground reaction is small under the effect of the pressure load. As the measured bending moment is smaller than the calculated bending moment under the effect of the pressure load, the evolution of the ground reaction under the pressure load is underrated.

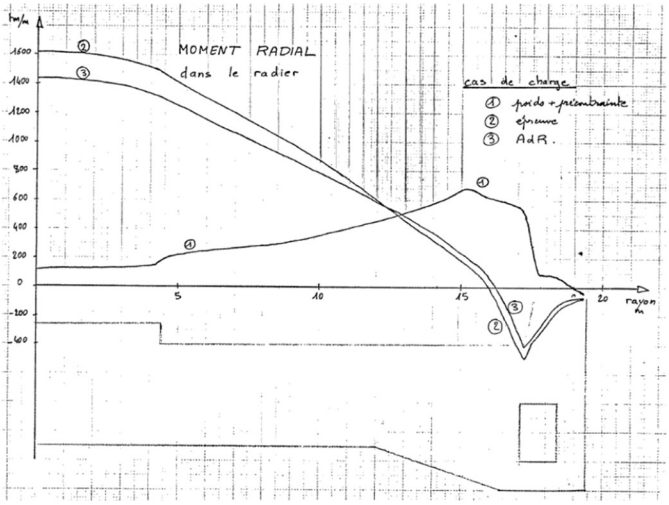

Figure 10: Extract of the initial calculation report – radial bending moment in a raft

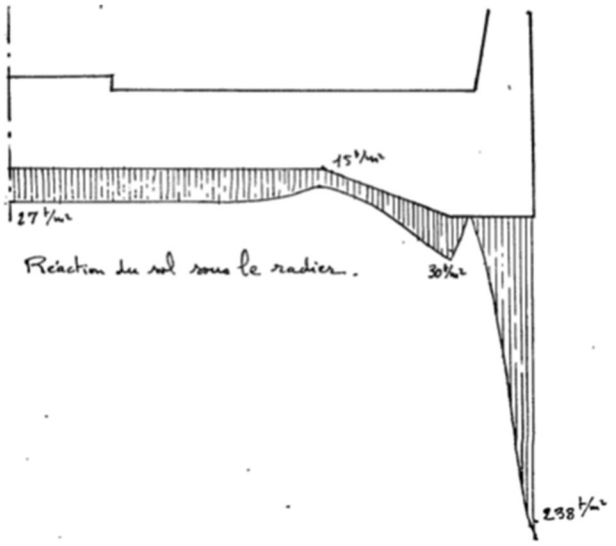

Figure 11: Extract of the initial calculation report – Elastic soil reaction under the raft

In the initial calculation reports, the upper reinforcement is calculated with a more uniform soil reaction with a stronger value in the centre, for example 0,37 MPa or even 0,45 MPa (see figure 12), assuming a reduction of the high value in periphery. The consequence is that the calculated bending moment is negative in normal operating condition, with tensile stresses in the upper fibre. These initial assumptions are too conservative and lead to a misestimation of the raft behaviour ("reversed plate") subjecting the upper fibre to tension. The measurements show that the upper fibre of the raft is not in tension during the life of the NPP.

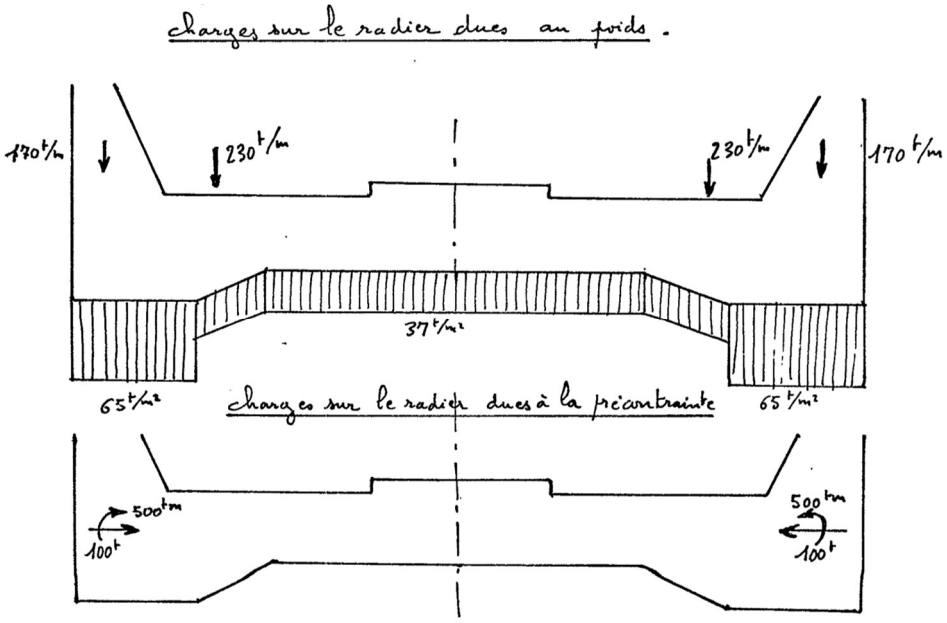

Figure 12: Extract of the initial calculation report – example of more uniform soil reaction under the raft

CONCLUSIONS

The analysis of the available measurements of local strains by the extensometers brings into light very interesting results, which show that the reinforced concrete rafts are not cracked under the pressure test, because the curvature are repetitive and reversible under pressure. They provide also the evolution with the time and show the creep effect of the concrete structure and of the soil. The reference Galan (2022) confirms the absence of drift of extensometer over time and the robustness of the deformation measurement with a small dispersion.

It can be recommended to perpetuate intrados and extrados deformation measurements in the rafts, with sufficient discretization on the radius and exploit the measurements for the new NPP as soon as possible in the construction phase.

The settlement gauges measurements show two phases with an elastic phase during the loading and some years after loading and a phase of settlement accumulation (consolidation, creep) after about 10 or 15 years. The relative settlement value is depending of the soil characteristics, the phenomena are similar from several sites.

The leveling pots give the raft deflections and they are coherent with the curvature issued from the extensometer measurements.

All these measurements provide a basis of results to interpret the behavior of the rafts through more refined geotechnical analyses: such analyses have been performed to improve design assumptions to better follow the monitoring and presented in reference Pineau (2024).

ACKNOWLEDGMENT

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