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DESIGN OF REACTOR BUILDING RAFTS ON SOFT SOILS – COMPARATIVE ANALYSES BETWEEN MEASURES OF OLD GENERATION NPP AND DESIGN ASSUMPTIONS

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ABSTRACT

For some Nuclear Power Plants (NPP), the geotechnical properties are likely to be responsible for large total and large differential settlements and therefore for significant deformations of the foundation raft. For the design of the reactor building (RB) rafts, these properties are conventionally considered by defining conservative soil reaction profiles in order to approximate the actual reaction profile and its consequences on the behavior of the raft.

Several rafts of reactor buildings have been instrumented with monitoring devices such as extensometers, leveling pots and settlements gauges. The analysis of these measurements for a selection of RB located on soft soils highlights the real behavior of these rafts and allows a comparison between instrumented response and design assumptions.

In this regard, this paper aims to compare the design practice with the measurements in different situations regarding Nuclear Power Plant (NPP) design, namely: for periodic structural integrity tests and for normal operation conditions. This leads to a better understanding of the real behavior of the rafts on soft soils and helps to identify the potential design conservatisms. This comparison is carried out on several axes, such as soil properties and soil behavior, stiffness of the structural elements and influence of the modelling choices, influence of the loads distribution etc.. Proposals are provided to adapt soil structure interaction approaches in current engineering practices according to the geotechnical context.

KEYWORDS: Soil Structure Interaction, monitoring, raft design, settlements, deflections

INTRODUCTION

In the presence of compressible soil, generally classified as soft soil, absolute and differential settlements can occur, accompanied by deformations of the foundation raft. For the design of the reactor building (RB) rafts, the geotechnical properties are conventionally considered by defining conservative soil reaction profiles to approximate the actual reaction soil profile and its consequences on the behavior of the raft. Given the significant impact the geotechnical conditions can have on the quantity of steel reinforcement and therefore on the constructability of the raft for reactor buildings, it is of great importance to improve our understanding of the behavior of raft foundation on soft soil conditions.

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, which have been operated since the beginning of the construction and are still operational nowadays.

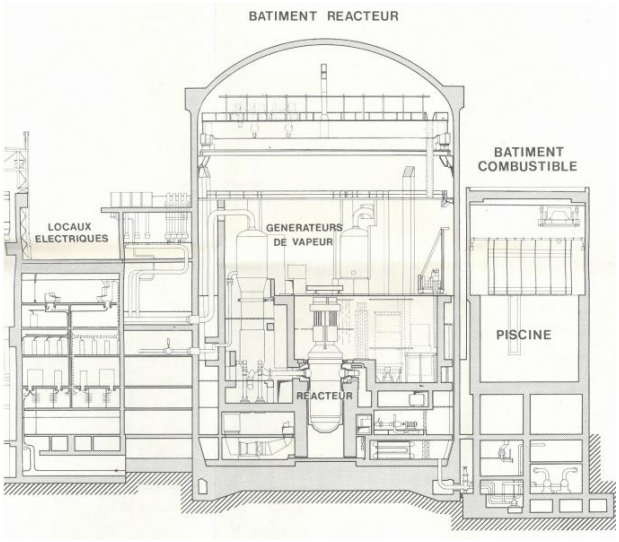
This paper aims to present the findings of a comparative analysis of instrumented response and envelope assumptions made during design studies, in order to draw lessons that will enable a better assessment of the raft behavior on soft soils for different situations regarding Nuclear Power Plant (NPP) design: during the periodic structural integrity tests and during normal operation conditions.

The dedicated study on which this paper is based has been focused on the measurement analysis from six French existing sites, including five on soft soils, generically referred to as sites A, B, C, D, E and F. This paper presents an overview of the design approach adopted in the 1970's for old-generation Nuclear Power Plants, a brief description of available measurements on rafts, a comparison between the instrumented response and the envelope design assumptions and the identification of potential over-conservatism factors for design, and finally the useful feedbacks for anticipated evolution of NPP and design of reactor buildings rafts on soft soils

DESIGN ASSUMPTIONS FOR OLD NUCLEAR POWER PLANTS

The reactor building of a French 900 MWe nuclear power plant is composed of the cylindrical prestressed concrete containment with metallic liner, reinforced concrete inner structures and the circular raft. The containment and the raft constitute a safety system which requires 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 of the raft during the life of the power plant and during the periodic integrity tests under internal pressure.

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



Thanks to the standardization of EDF NPP 900 MWe series named CP1-CP2, the geometry, the gravity loads distribution and the pressure level are the same for the reactor building rafts of this series, the only difference concerning soil characteristics. In the scope of CP1-CP2 series, 24 units were built between 1975 and 1986. During the design stage in 1970's, dedicated complete calculations were carried out on two pilot sites. The other sites could then be treated by analogy, based on soil characteristics and anticipated raft behavior.

A particular feature of the 900 MWe NPP design is that the reactor pit was untied from the raft during construction, which means that all the weight of inner structures is distributed through the skirt of inner structures. Therefore, the distribution of vertical loads does not depend on the raft deflections. The dead load is approximatively 540 MN and the average soil reaction under the raft is 0.45MPa.

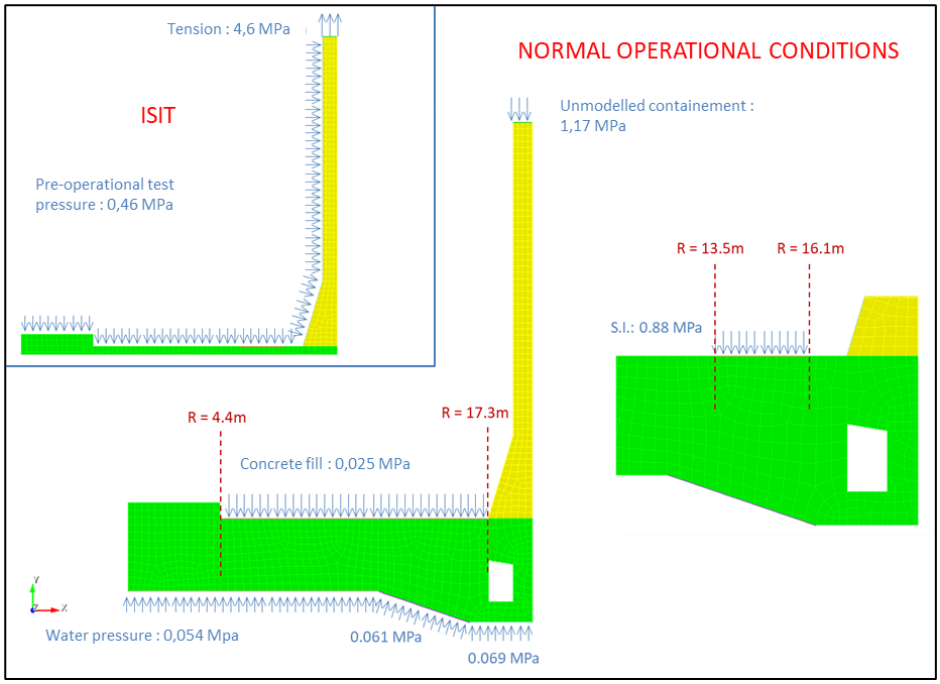
Fundamental load cases to be included in the analysis of the reactor building raft are decomposed into elementary external forces, integrated to a dedicated asymmetric model of the reactor building raft: weight of inner structures, weight of the containment, earth pressure, hydrostatic pressure, pre-stressing, SIT pressure, shrinkage, seismic loads.

Inner structures are uncoupled from the raft but are conserved in the raft modeling in order to model correctly the distribution of axial loads between the skirt of inner structures and the raft: the weight of the inner structures and their equipment (approx. 21650 t) is therefore integrated as an equivalent pressure applied to the concrete fill (béton mort) and through the support skirt. The containment is modeled up to a height of 14.5m, since it was previously shown that there was no bending of the section plane above this height. The weight of the dome and of the non-modeled part of the annular portion (between 14.5m and 49.3m) has been integrated as a pressure distributed over this section of the containment.

For the ISIT load case, a pressure of 4.6 bar (pre-operational test) is applied to the upper face of the raft and to the inner face of the containment, as well as a tensile load on the top of the modelled part of the containment, in order to integrate the pressure on the dome.

A view of the representative model of the reactor building raft and the elementary external forces integrated into the model is shown in Figure 2. The reinforced concrete raft is 3.50m thick in central part and 5m thick in the periphery, including the prestressing gallery.

Figure 2: Equivalent axisymmetric model of the reactor building raft – Description of external forces for permanent load cases and initial structural integrity test



In addition to the loading case, the definition of the boundary conditions to be considered on the underside of the raft is another important aspect of raft modeling. The way that soil structure interaction (SSI) is estimated, influencing stress and strain distributions, can have a major impact on the overall behavior of the raft.

Several methods can be adopted to model SSI, and have been explored during design phase for the two pilot sites:

- Application of a soil reaction profile, that does not require soil modeling but lies in the choice of the law of variation of reactions depending on estimated raft and soil interaction;
- Independent springs below the mat operating in tension-compression, reflecting a soil modeling without shear resistance (Wrinkler method), requiring a choice of rheological model;

- Finite element modelling including soil as continuous medium: this approach requires assumptions on soil behavior law (linear elastic, elastoplastic, consideration of effect of soil confinement, etc…) but enables to introduce a more precise assessment of SSI including the geometric specificities of the raft, load distribution, possible stratification of the subsoil …

For the spring model and the finite element model, soil reaction profile is obtained as a result of the modeling whereas the first method requires to determine the reaction profile. For the design phases of the studied CP1-CP2 units, according to regulations on the date of dedicated studies, the forces developed in the reactor building raft, resulting from gravity loads, prestressing or internal pressure are calculated by considering two conservative assumptions:

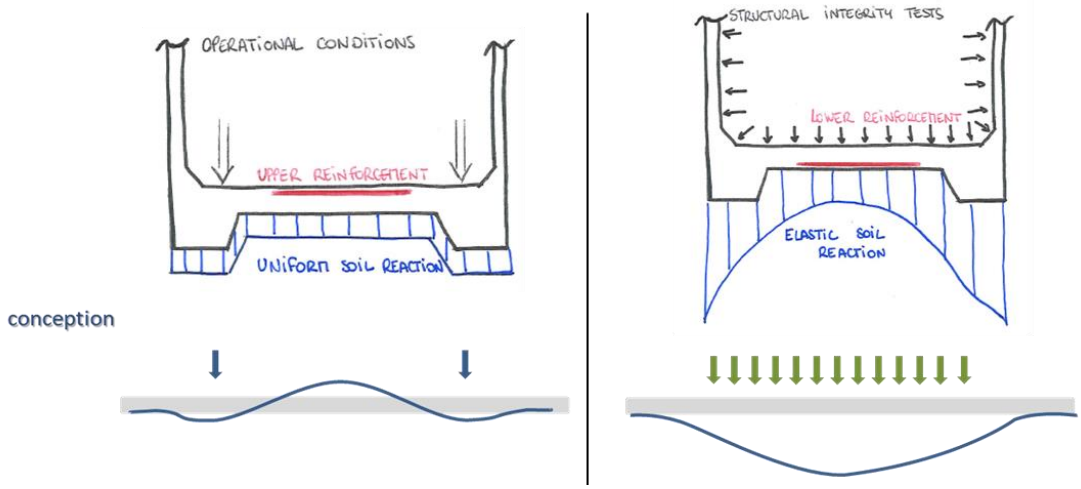
- Elastic soil reaction profile, similar to the shape analytically calculated with the Boussinesq solution assuming a uniformly loaded rigid plate lying on semi-infinite linear elastic soil (uniform reaction under the central part of the raft and very sharp at the periphery)
- Uniform soil reaction profile

For some of the six sites studied in this paper, a third configuration has been studied including a vertical spring model, considering a higher stiffness at the periphery, reflecting a limitation of Boussinesq soil reaction, due to local loss of soil elastic properties.

Among the load cases studied in the design phase (including construction, normal operational conditions, structural integrity tests ISIT and SIT and accidental increased loads such as seismic loads), two specific load-cases stand out as penalizing with respect to the raft behavior. These cases, in combination with soil assumptions adopted in compliance with regulations at the design date, have led to consider the two following envelope assumptions corresponding to two distinct soil reaction profiles for the central part of the raft:

- The load-case corresponding to normal operation conditions, considering a uniform soil reaction profile, which maximizes soil reactions at the center of the raft, and thus governs the design of the reinforcement requirement for the upper face of the raft, given the fact that gravity loads are essentially transmitted in peripherical part of the raft;
- The load-case corresponding to structural integrity test considering an "elastic" type of ground reaction, stronger at the periphery of the structure, which minimizes soil reactions at the center of the raft and thus governs the design of the reinforcement requirement for the lower part of the raft.

Figure 3: Schematic behavior of the reactor building raft and deformations under envelope design assumptions



COMPARISON BETWEEN REACTOR BUILDING RAFTS DESIGN AND MEASUREMENTS – CONSERVATISM FACTORS

The reactor building rafts are equipped with extensometers in upper part and lower part of the raft, leveling pots and settlement gauges, in order to follow the evolution of raft behavior since the beginning of construction (except for leveling pots) and during the life of the power plant.

Interpretation of available measurements, especially for normal operation conditions and for each periodic structural integrity test, is described in detail in reference 1. More specifically, the interpretation of measurements from extensometers, leveling pots and settlement gauges allows the estimation of curvature and deflection of the raft in several radii during the periodic tests and during the life of NPP. By calibrating the concrete Young's modulus with an instantaneous value during SIT and a long-term value for normal operation, it is also possible to estimate forces and bending moments from the measurements and compare them with the internal forces used in the design.

In this paper, we focus on bending moments in the central part of the raft, which govern the reinforcement requirement for upper face and lower face of the raft for periodic structural integrity tests and during normal operation conditions. Table 1 presents the bending moments estimated from measurements in the central part of the raft for the six studied sites, with five on soft soils, together with the moment values retained according to the design assumptions. A focus on site A design values is detailed further on reference 1.

Table 1: Comparison of bending moments at the center of the rafts between design and measurements – Sign convention: positive moments indicate tensioning of the lower face, while negative moments indicate tensioning of the upper face

Sites	Design moment under pressure Periodic test (MNm/m)	Estimated moment from measurements under pressure Periodic test (MNm/m)	Design moment Normal conditions (MNm/m)	Estimated moment from measurements Normal conditions (MNm/m)
Site A	15	10.6	-8	3
Site B	15	5.35	-9	1.78
Site C	13	7	-9	1.67
Site D	15	5.9	-10	0
Site E	15	4.9	Not communicated	0.8
Site F	7	3.1	-6.8	-1.2

The analysis of the curvatures and bending moments in the center of the raft allows to characterize the general behavior of the raft, which appears to be different from design assumptions especially for normal operation conditions, as illustrated by the schematic views presented in Figure 4.

For all CP1-CP2 sites, the gravitational loads of the containment and inner structures are essentially transmitted in peripherical part of the raft, the pit being disconnected from the raft during the construction. As a result, under normal operational conditions, the raft is quite sensitive to soil reaction assumptions. The most unfavorable case is when the soil reaction is greater at the center of the raft while the load is quite limited, i.e. the case of uniform soil reaction profile, inducing tension at the upper face of the raft. This translates into negative values for the bending moments at the center of the raft.

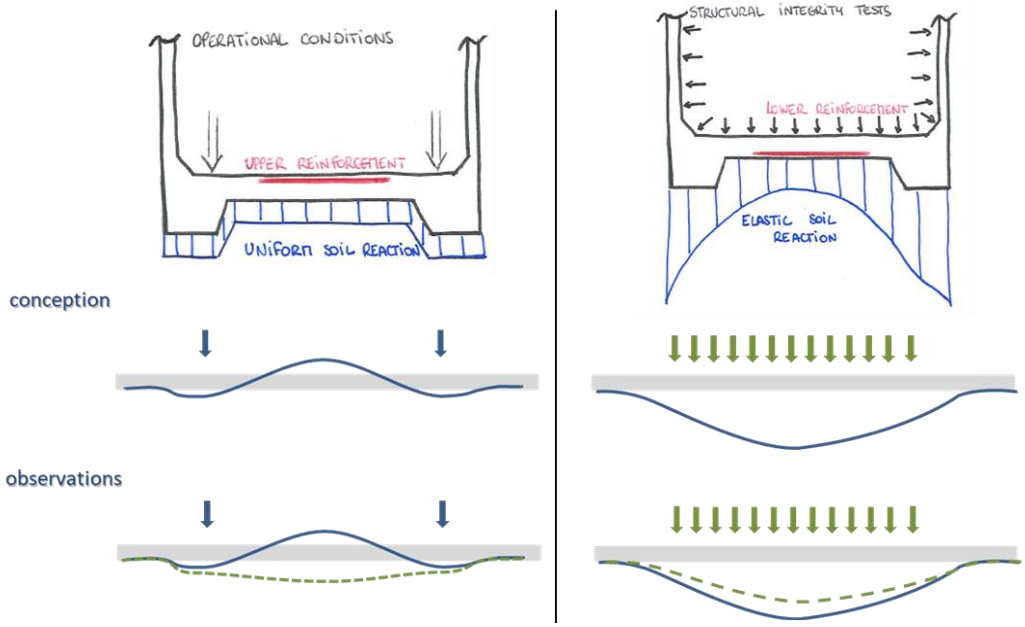
According to measurements interpretation, the deformation of the rafts reflects for all sites on soft soils (site F is not on soft soil conditions) a slight deflection when a "reversed plate" behavior was expected in design. This phenomenon can be explained by an overestimation of soil reaction at the center of the raft (average reaction of 0.45MPa).

For the case of periodic SIT under uniform pressure, the raft develops a deflection. The lower the soil reaction at the center, the greater the deflection (this is when the soil reaction profile is close to an idealized Boussinesq elastic reaction profile). In this case, the lower part of the raft is in tension, be-

havior that is consistent with observations. According to measurements interpretation, a certain conservatism can nevertheless be noted in the design, leading to almost constant moment values (13 to 15 MNm/m) regardless of the site considered, while the observations show a more contrasted pattern (4.9 to 10.6 MNm/m). This phenomenon can be explained by an underestimation of soil reaction at the center of the raft (for site A, the elastic soil reaction displays a value equal to 0.27MPa in the center part of the raft). In fact, we find comparable values to the design if we treat the case of a beam on supports without taking the ground reaction into account. This variability also highlights a strong dependence of the results on site-specific soil conditions, which did not appear on resulting design (N.B. some sites have been treated by analogy, based on complete calculations carried out on the two pilot sites).

Another interesting point about design assumptions is the similarity between reinforcement requirements for the upper and lower fibers results from the design. Considering a uniform soil reaction of 0.45 MPa (4.5 bar) for normal conditions with a minimal load (at the center of the raft) is indeed quite comparable to the pressure of 4.6 bar applied during ISIT, which explains why the resulting reinforcement requirements are similar. Depending on the site considered, reinforcement requirements may actually vary according to the stratigraphy encountered, under both normal or periodic SIT load conditions.

Figure 4: Schematic behavior of the reactor building raft and deformations in normal operation conditions and during periodic SIT – comparison between design (in blue) and observations (in green)



IDENTIFICATION OF INFLUENCING PARAMETERS FOR DESIGN OF REACTOR BUILDING RAFTS ON SOFTS SOILS

Different methods for taking SSI into account were explored during the design studies of the two pilot sites A and B and it is noticed that the case of FE calculation on continuum elastic soil was identified as the most realistic. Indeed, the possibility to include the soil domain as continuous medium, with consideration of the geometric specifies of the raft, the load distribution and any stratification of the subsoil into the definition of the soil reaction profile, provides results closer to reality. However, it appears that slight “reversed plate” behavior could be expected for some sites on very soft soils, even with FE model on elastic soil, which underlines that other parameters can have a significant role on raft behavior.

This paper presents additional complementary analyses using specific 2D axisymmetric finite element modeling for each site to simulate soil-structure interaction, in order to estimate the distribution of forces and the evolution of soil reactions and settlements and identify the factors of conservatism in design and also the most influencing parameters. By carrying out these sensibility analyses, considering notably the geotechnical and stratigraphical specificities, the variability of the raft response can be highlighted, directly linked with the stratigraphy encountered (multi-layer effect with varying moduli of the different layers, thickness, spatial heterogeneity, etc.), which can have an impact on the distribution of soil reaction.

Even if FE calculation on elastic soil is closer to real raft behavior, approaching the orders of magnitude of calculated moments based on measurements, this does not lead to conservative results and it does not cover all influencing parameters. It is therefore important to identify the parameters that can influence the definition of the soil reaction profile, in order to propose appropriate SSI methodology that can anticipate the real raft behavior and reduce over-conservatism.

The influencing parameters identified in the scope of this work are the following:

- The consideration of stratigraphy seems to be the most important parameter which explains the variability between the six studied sites. In the case of highly stratified soils, in particular, for contrasting stratigraphy or in presence of complementary foundation (or soil reinforcement), other effects impact on the distribution of soil reactions, new shapes of soil reaction profile can be observed, minimizing again the reaction at the center of the raft and increasing reaction at the periphery (whereas the shape is smoothed when considering a more homogenous soil). This phenomenon is called “slab effect”.

- Constitutive law of soil below the raft

  In the case of a uniformly loaded raft on homogeneous soil, the creep mechanism can be considered for the most loaded area, capping the soil reactions in periphery of the loading area, transferring the load to the center, and smoothing the soil reaction curve compared to a Boussinesq-type elastic reaction. This phenomenon occurs faster for softer soils, without the soil reaction tending towards a uniform ground reaction. This phenomenon could partly explain that we have larger soil reaction for SIT than calculated with a FE model including elastic soil modeling, but could not be highlighted in our work due to the multitude of mechanisms involved (choice of resistance parameters, stratification…).

  Another aspect concerning soil behavior is relative to granular soils for which a densification can be initiated depending on encountered stress levels. This phenomenon can also explain an underestimation of soil reaction.

  For some sites, 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. The effect of this delayed soil behavior can be seen in measurements of average deformations or radius variations, which stabilize slowly compared to other sites for which the stabilization occurs as early as the pre-operational structural integrity test.

- Modeling choices

  Another result of interest concerns the non-negligible effect of load distribution on raft deflection and curvature, when a simplified inner structures model is adopted. According to sensibility analyses performed for sites A and B, it appears that the application of a progressively more evenly distributed loading leads to in inversion of the sign of the curvature, moving from negative curvature for a very local distribution, to a positive curvature for the

extreme case of load distribution over whole area of concrete fill. To ensure adequate distribution of the loads transmitted by the inner structures, it is essential to be able to characterize the stiffnesses and loads during the design phase.

Sensitivity analyses had been performed for sites B and C concerning the modeling choice of the interface between the raft and the subsoil. The results show, unsurprisingly, that a smooth interface condition increases the deflection and moments at center compared to a model with a rough interface. The actual configuration certainly lies between these two extreme conditions, which could explain the overrated design values (in conjunction with other aspects) observed for the ISIT load-case.

- Impact of surrounding buildings and construction phasing

  The presence of neighboring buildings around the RB can impact the soil response, and therefore the soil reaction profile to be applied under the RB raft, in different ways depending on the phasing of construction. In particular, if these buildings are built prior the RB, they may affect the initial state of ground and increase the soil reaction at the center of the raft. If they are built after or during the RB, the soil reaction profile may concern a more global footprint, minimizing the soil reaction at the center of the raft. Sensitivity analyses have been performed for site E, illustrating a significant dependence of soil reaction profiles to loading assumptions for neighboring structures. In particular, soil reaction at the center of the BR is reduced if neighboring structures are built simultaneously.

FEEDBACK FOR ANTICIPATED EVOLUTION OF NPP DESIGN

The behavior of the reactor building raft is highly sensitive to the studied load-cases, as well as to the assumptions regarding the SSI, which determine the deformation and forces developed in the raft, and therefore the reinforcement requirements.

In terms of methodology, the analysis of the available measurement's shows that the two envelope assumptions for soil reaction profile were too restrictive and did not correctly transcribe the reality of raft behavior leading to oversizing the reinforcement requirement, especially for the upper part of the raft (conservatism of 40% to 300% for ISIT and tensioning the upper fibers).

Generally speaking, it should first be noted that in the design phase, beyond the methods used, the moments calculated for the ISIT case were estimated on the basis of a short-term static modulus, which was subsequently re-evaluated on the basis of initial measurements during REX studies, thus identifying the first explanations for the discrepancies between measurements and design assumptions. Analysis of FE calculations on elastic calculations taking these reassessments into account highlighted their impact on the moments estimated for the ISIT load-case used to size the lower reinforcement of the raft.

Since the date of the design studies performed for the sites presented in this work, evolutions have gradually been incorporated into the regulations, for static SSI. At the date of CP1-CP2 series design stage, it was recommended to calculate the RB raft by considering two conservative hypotheses, represented by Wrinkler springs method reflecting a mean reaction distribution and Boussinesq theory. Then, specifications about soil constitutive law, which should take into account the level of stresses due to the analyzed building, as also about surrounding buildings effect have been integrated. The actual regulation code insists on the direct influence of the distribution of ground reactions on the forces in foundations and structures and advises to evaluate soil reactions under the buildings of the Nuclear Island using global models that simultaneously represent the realistic behavior of soil and building structures, considering three types of action: permanent, variable and accidental, leaving open the possibility of using equivalent models for quasi-permanent load cases.

Design methods incorporate a high level of conservatism and are conditioned by the principle of linearity (which allows several load cases to be studied cases separately and to combine them a posteriori according to a very large number of combinations of actions). In order to transcribe the behavior of rafts on soft soils, without over-conservatism, soil reaction assumptions typically considered for design purposes remain relevant, but each assumption must be used in conjunction with the action combinations that are most relevant to it (e.g. avoid using the homogeneous profile scenario with an action that does not load the center of the reactor building). Secondly, it may be possible to refine the most unfavorable combinations of actions with more advanced calculations that take into account a number of important factors such as: soil modeling, consideration of the phasing and evolution of soil moduli, presence of eventual foundation system …The majority of load cases can therefore be handled using decoupled calculations (reaction profiles, static impedances etc.), but it is recommended to carry out analyses of unfavorable cases using coupled methods (SSI) taking into account refined (nonlinear) modelling.

A good knowledge of the site's geotechnical model is essential, and a distinction must be made between short and long-term static moduli in correlation with the loading case considered. In particular, short-term moduli are used for construction situations, prestressing, periodic SIT for non-earthquake accident situations. Long-term moduli are used for normal operating situations and long-term settlements studies.

In any case, it appears that the assumption of an equivalent homogeneous soil, even if it well represents building settlements, is a risky assumption to adopt for soft soils, as stratigraphy can play a significant role in the distribution of soil reactions. It is important to take soil stratification into account. If a simplified soil reaction profile is applied, it must be confronted and if necessary calibrated with an iteration based on a model that considers soil stratification and the possible presence of a complementary foundation system.

It should be noted that the above considerations about raft behavior, made by comparing design assumptions and observations are valid for the CP1-CP2 RB rafts on soft soils studied in the scope of this work, presenting among other things the specificity of load distribution at the raft periphery. Nevertheless, major conclusions about the design methods for SSI are valid, and the main highlights on raft behavior can be extrapolated for other geometries.

Load distribution, modeling choices, the presence of the RB's immediate environment and construction phasing are all parameters that influence the behavior of the raft. In order to draw the appropriate conclusions from the comparative analysis of measurements in the reactor building rafts (BR) of CP1-CP2 sites and envelope design assumptions, in anticipation of design evolution of future NPP, the following remarks can be made:

- In the case of the CP1-CP2 series, the reactor building is independent from the other buildings of the nuclear island, the raft is circular and loaded by the weight of the inner structures on the periphery by the weight of the containment. Curvatures and moments in the raft are therefore strongly influenced by the assumption of distribution of ground reactions under normal operating conditions or during periodic structural integrity tests. For different configurations, in particular if the raft is common to several buildings, it is possible that the raft un-der the reactor building area will be much less sensitive to “reversed plate” behavior whereas the junction with surrounding buildings may be a singular point to control. The same consideration can be made if the weight of inner structures is less localized. For this common raft hypothesis, the solidarization or not of the buildings will be also an influencing parameter for the raft behavior since it impacts the global rigidity.

- The average soil reaction value for CP1-CP2 is equal to 0.45MPa. For heavier configurations of NPP, soft soils may develop more non-linearity than seen in this study, which may also impact the soil reactions profile, and generate more settlements (global and/or differential) to mitigate together with raft deflections.

- If heavy buildings are planned in the neighboring of the RB, they can have a non-negligible impact on the overall deformations of the raft. Depending on whether these structures are built prior to, during or after construction of the Reactor Building, different raft behaviors can be anticipated, requiring more detailed studies on the effect of construction phasing on raft design.

Depending on future NPP design evolution, the interpretation of such type of measurements could be of great value in confirming the mechanisms anticipated for a common raft in an EPR configuration, for example. It could also be valuable to interpret measurements on a site that has undergone significant settlements, in order to exploit the soil reaction profiles and resulting moments.

In any case, the monitoring devices installation and follow-up in reactor buildings rafts is very valuable in order to re-evaluate the initial estimation of the soil model (in particular short-term static modulus, but also for long-term settlement monitoring) and for a better understanding of the behavior of rafts on soft soils.

CONCLUSIONS

The analysis of the available measurements allows to interpret the behavior of the reactor building rafts through parameters such as curvature, settlements, elongation, rotations which have been com-pared to the envelope design assumptions adopted for the construction between 1974 and 1981 of the six studied NPP 900 Mwe reactor buildings.

The comparison highlights some conservatisms. In general, the moments estimated based on measurements for periodic structural integrity tests are significantly lower than those calculated in design (40% to 300%). For normal operating conditions, the moments estimated based on measurements are mostly positive, with an elongation of lower fibers and shortening of upper fibers of the raft, whereas the opposite behavior was expected with the range of soil reactions considered at the design stage. The only exception is site F, for which the moments estimated based on measurements for normal operating conditions are negative but still lower than the maximum design values.

Beyond the methods used for SSI modeling, load distribution, modeling choices, presence of the RB's immediate environment and construction phasing are all parameters that influence the anticipated behavior of the raft, together with a great knowledge of the soil characteristics.

In this respect, instrumentation is an invaluable source of recalibration, enabling us to refine soil and structural models directly after the measurements, to monitor real structural stresses and strains developed over the life of the NPP and, ultimately, to improve our design methods.

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