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Pile tests in nuclear area: case of Chernobyl

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ABSTRACT: The explosion of reactor 4 at Chernobyl Nuclear power plant was a major disaster affecting both humans and the environment. The decision to cover the sarcophagus, which was built in appalling conditions at the time, led to the construction of an arched structure covering the old structure. Given the site conditions, it was essential that the structure had to be erected in a lower-risk area and the moved alongside to the structure to be dismantled. This move could only be carried out on concrete "rails" resting on several rows of piles, but the site conditions required the development of specific construction concepts and methods.

This paper presents the principles and the necessary innovations used for implementing of certain tests carried out on driven tubular and bored piles near the sarcophagus (static instrumented vertical, lateral, coupled lateral head loading tests). Additional elements relating to vibration measurements and integrity control are also presented, as well as the conditions for on-site intervention considering the need to reduce the risk of contamination to a minimum.

KEYWORDS: Static tests, Dynamic tests, lateral, compression, vibration, nuclear.

1 INTRODUCTION

The explosion of reactor number 4 at the Chernobyl nuclear power plant on April 26, 1986, was a dramatic event of major environmental significance that initially led to the creation of a protective sarcophagus (object shelter). This was built under highly complex conditions and have been gradually deteriorated under the influence of weather and radiation, leading to the need of a new containment structure.

This structure is a vault (Figure 1.) aiming to protect the existing structure from the weather elements and to ensure the containment of radioactive dust. It must also allow enough space for the partial dismantling of the existing structure and the removal of radioactive waste.

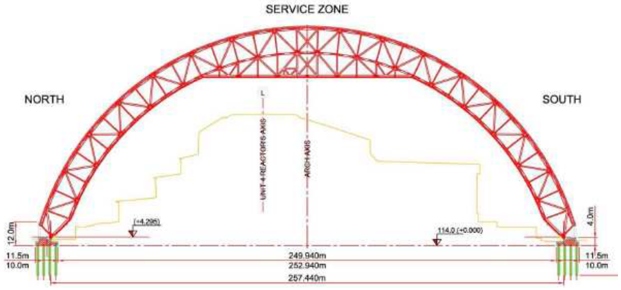

Figure 1. Arch elevation (source: Novarka)

For safety reasons, the contractors Vinci Grand Projets (leader) and Bouygues TP, constituting the Novarka JV, were required to construct this structure weighing nearly 20,000-tonne structure on concrete rails (ground beams) resting on piles, then to move it directly above the sarcophagus and reactor 4. Designing and installing these piles required numerous types of tests to be carried out, which are described here.

2 GENERAL PRESENTATION

2.1 *Construction process*

Three different areas are to be considered as shown in Figure 2.:

- Erection zone.
- Transfer zone
- Service zone

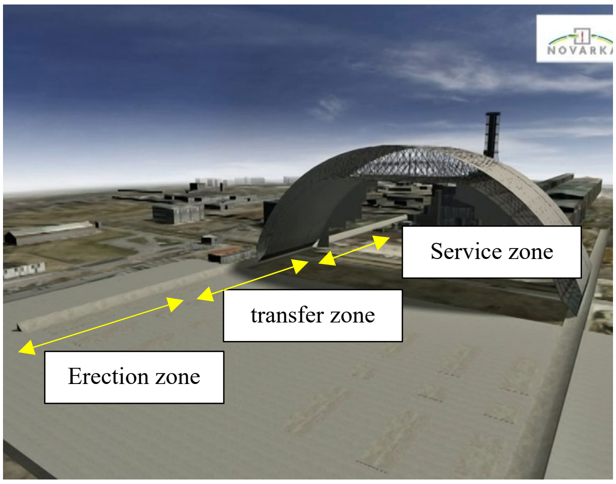

Figure 2. Different Zones (source: Novarka)

The construction of this tremendous structure can be broken down into the following main steps:

- Construction of a foundation slab of about 250m wide covering the erection area
- Excavation of two trenches parallel to the existing sarcophagus, protected by retaining walls
- Installation of driven tubular piles in the erection area
- Installation of CFA piles from the trenches in the service area
- Construction of the two ground beams (North and South) used to move the vault. They are supported by piles except in the transfer zone.
- Supply and assembly of the prefabricated metal parts of the first section of the vault in the erection zone, with various lifting phases.
- Movement of this first section of the vault by sliding it on the ground beams to the transfer zone (Figure 3)
- Assembly and lift of the second and final section of the vault in the erection zone, then assembly with the first section.
- Movement of the entire assembly onto the sarcophagus after dismantling of the chimney common to reactors 3 and 4.

Figure 3. First section of the vault placed in the transfer zone and the second one's beginning

2.2 *Geology*

Several units from the platform elevation (114m) have been identified ranging from backfill, clayey sand, fine to medium sand and marl clay. The top layers consist of alluvial deposits down to an elevation of approximately 82m, i.e. about 32m thick, counted from the platform level. Below 82m, the soil is predominantly marl clay.

The water table is found at an elevation of around 110.00m, with a margin of +-1.0m, i.e. 4m below the ground beam of the foundations (114.00m)

It is important to bear in mind the presence of this contaminated surface water table, located in the backfills and surface sands. The underlying marl layer constitutes an impermeable horizon that protects the underlying, uncontaminated water table.

2.3 *Foundations*

After soil investigation using pressuremeter tests, core drilling, with laboratory testing and CPT, an initial theoretical design was established, followed by load in situ tests.

To reduce contamination risks and ensure compliance with dosimetry criteria, a test area, located several hundred meters from the reactor, was initially used to conduct preliminary tests on the driven piles. These tests consisted of dynamic load tests with vibration measurements, followed by horizontal and vertical static load tests.

However, this required the systematic decontamination of the concrete slabs protecting the ground. This was done using a truck equipped with a watering system (Figure 4.)

Figure 4. Watering device for soil decontamination in remote areas

These tests on driven piles were continued in the erection zone during the production phase

The tests on CFA specific piles were vertical and horizontal static tests. They were carried out from both North and South trenches. CFA piles coupled together subjected to horizontal forces were also tested, as well as integrity tests using sonic coring and mechanical impedance. Vertical static load tests were also performed on production piles.

3 DRIVEN PILES

The driven piles are tubular steel piles, 1016 mm in diameter. It is clear that 198 piles were planned for the North Zone and the same number for the South Zone. These were open tubular steel piles.

The loading tests, carried out by Rincent BTP Service Research and Expertise company, consisted in:

- Dynamic and static vertical load tests
- Horizontal static load tests
- Vibration measurements

3.1 *Vertical tests: bearing capacity*

Following an initial series of tests, it was found that the driven tubular open piles behaved as purely coring-based, with no ability to stress the pile tip. Furthermore, it was not possible to modify the pile layout or their numbers because they had to be constructed in a trench protected by existing retaining walls. It was necessary to develop a method of improving the pile behaviour at toe.

This was achieved by installing a diaphragm whose height was determined based on the soil's capacity to mobilize an optimal void ratio. This diaphragm had an annular shape that reduces the impact of water pore pressure (Figure 5)

Figure 5. diaphragm

The dynamic tests were likely to be strongly affected by the reflection generated by the diaphragm. For this reason, it was decided to implement a SIMBAT-type dynamic measurement. This methodology enables the approximation of a static bearing capacity in the absence of a model, with the sole utilisation of measurements.

It should be noted that this technique necessitates the installation of an accelerometer and strain gauges in close proximity to the pile head. In addition, a target must be observed by means of a high-speed/high-resolution camera. This methodology allows the measurement of the displacement of the pile during the impact of the driving hammer (Figure 6).

This dynamic displacement measurement facilitates recalibration of the double integration of the acceleration, consequently enabling the determination of recalibrated velocity, which is necessary for the estimation of driving resistance. However, this necessitated the implementation of measurements at regular intervals of one metre. Furthermore, it is imperative to equip the test pile at each of these depths to conduct a series of approximately 15 individual impacts.

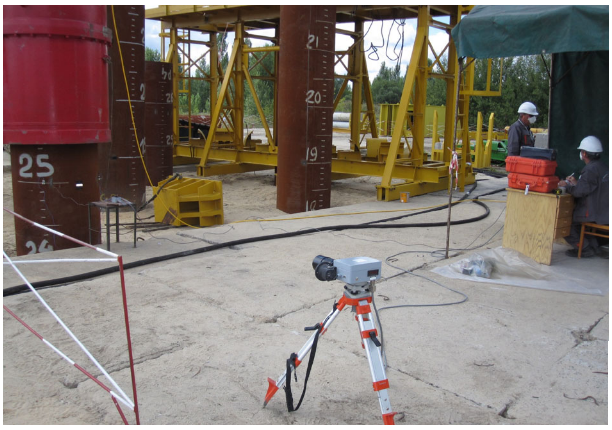

Figure 6. High speed camera on remote test area

Conventional vertical static loading tests were also carried out in compression as well as a pull-out test. The step tests were conducted with force/displacement measurements at the pile head via a data acquisition unit.

For these test piles, the reaction was ensured using 4 dedicated driven piles. The metal framework has been welded to these reaction piles and allowed the installation of jacks that apply the load to the test pile.

These static and dynamic data were then compared to assess the evolution of the static resistance of the piles in compression as a function of depth. This is expressed in the summary graph shown in Figure 7.

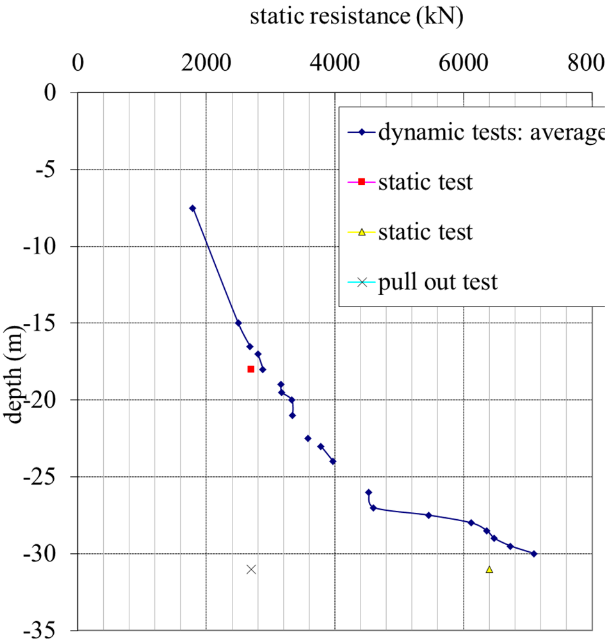

Figure 7. Summary of data from vertical loading tests

3.2 *Lateral tests*

Concurrently with the vertical behaviour of the piles, it was also necessary to verify the lateral behaviour: the abutment being mobilised considering the inclination of the force provided by the base of the vault.

In order to examine this aspect, lateral loading tests were carried out on pairs of driven piles. Each of these piles was instrumented at two different levels so that translation and rotation at the head could be judged (Figure 8).

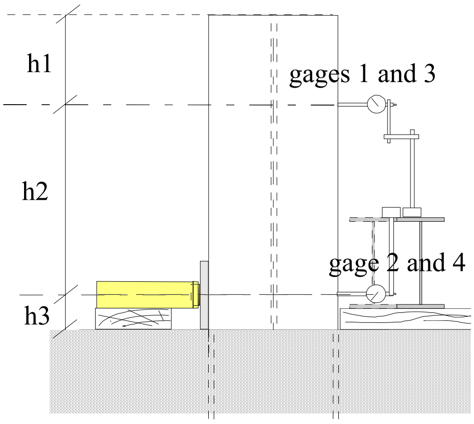

Figure 8. Sensor arrangement : lateral load tests

These lateral tests were conducted by steps, with force/displacement measurements recorded via a data acquisition unit designed specifically for these tests. A specific driven pile was used for reaction (Figure 9). Of course, the measurements concerned both the test pile and the reaction pile.

Figure 9. Lateral test using 2 piles, one acting as reaction

In addition to these measurements, surface observations were made. It was observed that the soil detached from the pile depending on the amplitude of the displacement. The data obtained provide significant insights into the characteristics of the cracks, including their opening and depth, at this particular location.

The rupture of the soil that appears at a loading step can affect the soil/foundation behaviour and, consequently, its lateral bearing capacity, depending on the type of calculation carried out following these tests.

3.3 *Vibration measurements*

During the driving of the test piles, a measurement of the ground velocity at different distances from the impact point was required, in order to evaluate the waves' attenuation.

The measurements were carried out for numerous piles using different hammer energy for each pile. To precisely determine the vibration influence according to depth and distance from impact, records were performed in the following manner:

- measurement when pile toe is located at depth of 2, 5, 8, 10, 12, 15 and 20m
- measurement at soil surface at distances of 3, 5, 7m

The sensors used for vibration measurement consisted of blocks of 3 geophones placed in the 3 space directions: x, y and z directions. They had a cut-off frequency at 4,5Hz but were electronically corrected to 1Hz.

They were connected to a specific equipment created by Rincent BTP Services Recherche Expertise. This equipment allows for the recording of the following required data and post analysis :

1. Maximum value of each measured particulate velocity,
2. Spectral amplitudes of these same signals (Fourier),
3. Fourier Amplitudes of the signals obtained at the output of the one-third- octave band filters centred on the frequencies $F_C = 1000\ [2^{1/3}]^N$ for N varying from - 30 to - 10, (filters were disposed in entry for each measured particulate velocity signals).

1. And 2. refer to French 1986 recommendation that sets out velocity limit values as a function of frequency and the sensitivity of nearby structure. These recommendations consider two cases: sustained vibrations and impulse vibrations. One of the graphs resulting from these recommendations is shown in Figure 10: the velocity measured in each of the three directions of space and according to their frequency must be below the indicated criteria.

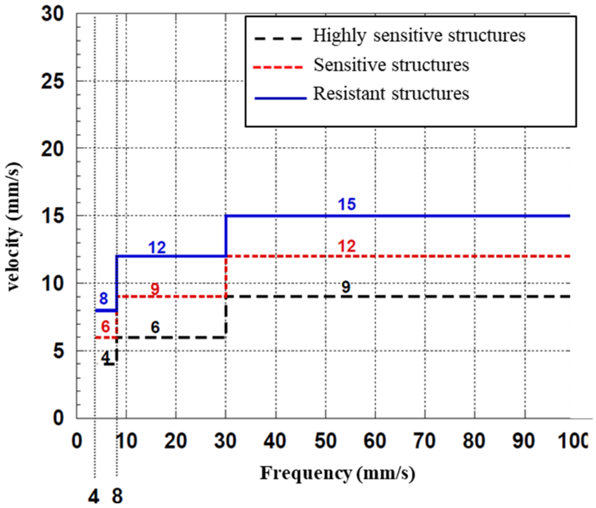

Figure 10. French recommandations

3. refers to the Ukrainian standard. An example is given in Figure 11 showing the vibration measurement results during driving at 3; 5 and 7m from pile side, according to vertical axis, when pile toe is located at 5m deep from the surface.

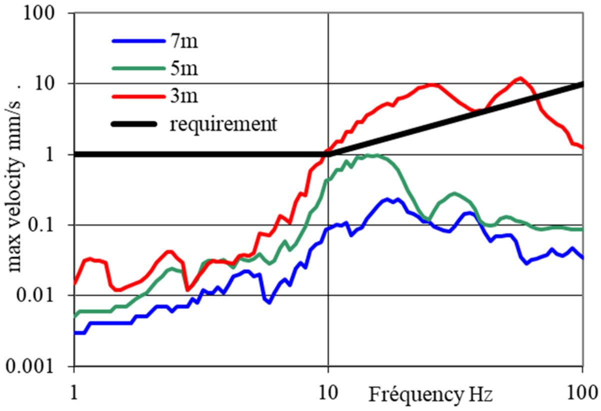

Figure 11. Example of vibration analysis according to Ukrainian standards

These measurements were supplemented with visual observations, among which it was relevant to measure the visible spacing between surface waves appearing during driving and the settlement after pile driving (Figure 12.).

Figure 12. Measurement of distance between surface waves

4 CFA PILES

The CFA Piles technology was selected in the service zone considering the loads applied to the structures and the mitigation of induced vibrations, which could threaten be hazardous for the Object Shelter's stability.

The permanent piles are made of reinforced concrete type C40/50 (concrete cover: 75 mm), with a diameter of 1 000mm and a total length 19 m for both ground beams located north and south.

Numerous tests were performed per Ukrainian and European standards, to check and confirm the calculations made based on the available data, consisting of:

- Static vertical load tests.
- Static lateral test on single piles and coupled piles.
- Integrity testing (sonic coring and impedance tests).

4.1 *Bearing capacity*

Static load tests on specific CFA test piles required the installation of 4 reaction piles supporting the reaction beam. A general view is given in Figure 13.

These piles were equipped with vibrating wire lines embedded at various depths in order to determine the lateral friction for each of the soil layers identified during the preliminary geotechnical investigations.

They were therefore not placed at equal distances from each other, but at varying depths. They were connected to a data acquisition system that also collected data from sensors placed at the pile head (displacement sensors, load cells).

Figure 13. Static test on specific test pile

For the production piles, vertical static loading tests were also carried out; nevertheless, vibrating wires were not included as the forces applied at the head were significantly lower. To ensure the reaction, only two piles were needed to absorb the traction forces. A casing connected to their reinforcement cage allowed the connection with the reaction steel structure, as shown in Figure 14.

This vertical arrangement enabled the transfer of forces via the jacks to the previously concreted test pile head without the need of cutting the reinforcement cages.

Figure 14. Device specific to the production pile loading test

4.2 *Lateral test*

Conventional static lateral tests were performed using a reinforced concrete beam placed on the retaining wall supporting the trench in which the ground beam was to be constructed. It acts as reaction (see figure 15. The measurement principle employed was consistent with that utilised for steel piles.

Figure 15. Reaction device for lateral test on CFA pile

The results obtained led to a specific examination of the behaviour of two piles coupled at the top. The ground beam is characterised by its substantial width, which is a consequence of its intersection with the four piles that constitute a row. The beam is also notably thick and has undergone extensive reinforcement to ensure its capacity to absorb the forces exerted by the arch. Furthermore, the presence of subterranean obstructions complicated the process of accurately characterising the terrain.

It was therefore determined that an examination of the behaviour of test piles coupled at the top by a reinforced structure would be undertaken (Figure 16)

Figure 16. Re-bars placed for a lateral coupled test

Apart from the force measurement provided by a load cell, the instrumentation included at the head of the installation 8 displacement sensors, arranged in 4 units per face of the piles cap (Figure 17)

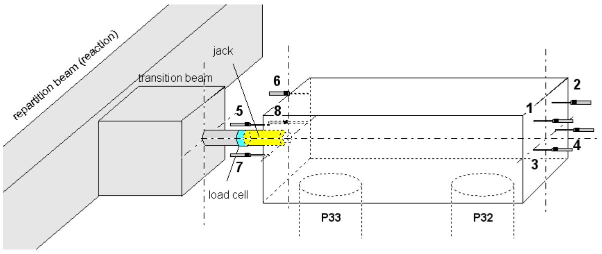

Figure 17. Displacement sensors disposition

Each sensor was of course based on independent reference beams and therefore the supports were located far from the zone of influence (Figure 18).

Figure 18. Setting up the device

The loading tests were conducted in accordance with a step loading procedure that adhered to both European and Ukrainian standards. The acquired data (force/displacement) were processed to obtain data relating to the inclination of the top of the pile cap. An illustration of this phenomenon is provided in Figure 19, which provides supplementary information regarding the observed translations.

This kind of data was used in the modelling process to evaluate the abutment and the horizontal stiffness that could be considered. Indeed, the lack of direct information regarding the rotation along the entire pile length did not prevent defining the boundary condition at the pile head by knowing its displacement and rotation.

Thus, by considering pile's inertia and the couple: restraint at the foundation base/displacement + rotation at the head for each load step, the only remaining unknown was the horizontal stiffness. This parameter was crucial for accounting the horizontal force applied by the vault.

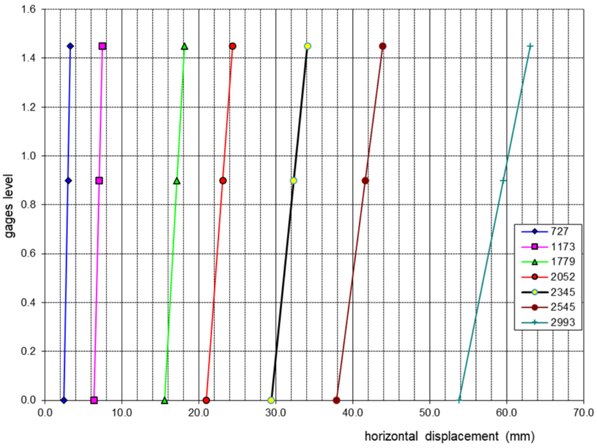

Figure 19. Inclination of pile cap at end of each step

4.3 *Integrity testing*

Two types of integrity tests were implemented. These were sonic coring (also referred to as cross-hole sonic logging) and mechanical impedance tests, which were conducted utilising Rincent BTP equipment. The selection of the mechanical impedance method was motivated by the understanding that the stiffness of the pile/soil can be determined using this method, in contrast to the echo method.

The sonic coring method was implemented utilising two parameters to leverage the signals: the propagation time between the transmitting and receiving probes, and the amplitude of the signals. The final parameter serves to refine the initial parameter, thereby facilitating the more efficient exploitation of the signals and enabling the determination of the presence or absence of an anomaly (Figure 20).

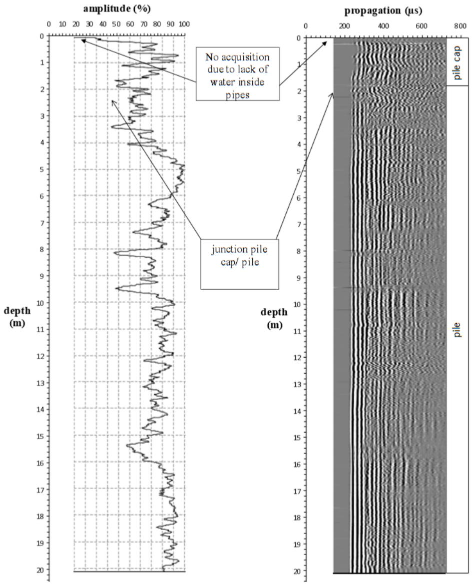

Figure 20. Example of sonic coring test results: propagation time and amplitude

5 PERSONNEL PROTECTION

The project's distinguishing characteristic was, naturally, the context associated with the potential for contamination and radiation hazards. This necessitated meticulous medical observation of personnel, in conjunction with the proactive involvement of radiation protection services.

Consequently, a range of measures were implemented, including the provision of lead shelters to ensure the protection of personnel (Figure 21).

Figure 21. Protection against radiations and contamination

This category of lead protection also encompassed the shelters of the personnel responsible for conducting static loading tests (figure 22).

Figure 22. Shelter protection against radiations and contamination

In addition to the afore mentioned devices, the exposure periods were meticulously regulated on both a daily and annual basis.

6 CONCLUSION

This project was rendered exceptional due to the complexity of its structure and the specific conditions of the site. This necessitated the development of numerous innovations in the fields of civil engineering, foundations, and their control. The present document addresses several of the afore mentioned aspects.

This project also demanded close collaboration between all the stakeholders working on site. The successful completion of this project, which is designed to last for 100 years, was made possible by the active involvement of radiation protection and site personnel of various nationalities.

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