FOUNDATION SUPPORT FOR NEW SAFE CONFINEMENT BUILDING, CHERNOBYL NPP

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ABSTRACT

Immediately after the devastating accident at Chernobyl Nuclear Power Plant (NPP), Unit 4, in 1986, short term measures were taken to reduce the release of radioactive particles to the environment. In 1997 a team of Western and Ukrainian experts developed a Shelter Implementation Plan (SIP) to convert the Object Shelter (or OS, as the damaged plant came to be called) into a safe system. A New Safe Confinement (NSC) conceptual design was completed in 2003 that consists of a metal arch structure that will completely enclose the OS. Urgent limited stabilization of the OS was designed and completed under the SIP Program in 2008, reducing the probability of collapse of the Shelter to an acceptable level for a period of 15 years, the time envisioned to complete the long term SIP objective: to convert Chernobyl into an environmentally safe site for the next 100 years. The overall design and funding for this multinational endeavor are discussed in other papers. The current paper discusses the foundation elements for the NSC.

The NSC will be constructed near the OS, in a low rad (radiation) area, and then slid into its final resting place supported on two long guide rails, each approximately 507m long, supported on three different foundation types: driven steel piles (during erection), continuous spread footings (en transit), and ultimately on continuous flight auger (CFA) piles. Ground beams in the Erection and the Service Zones support the guide rails and also function as pile caps. This paper discusses the three foundation support systems; their design, testing, and construction.

Relevant details in the design, analysis, construction and testing of these foundation systems proved to be a challenge on numerous engineering fronts, as well as provided the basis for an interesting story.

INTRODUCTION

The NSC will be constructed near the OS, in a low rad area, and then slid into its final resting place supported on two long guide rails, each approximately 507m long and separated by a distance of about 260m to support each side of the steel arch structure (see Figure 1). The rails are supported by ground beams about 10-11.5 m wide and 4 m thick and will accommodate the guide rail and the unique transport mechanism for sliding the NSC structure into place. The foundations are being constructed in phases and consist of three different types in three zones (see Figure 2): driven steel piles in the Erection Zone supporting a ground beam which also serves as a pile cap, where most of the NSC structure will be constructed; on a continuous spread footing in the Transfer Zone, which will provide only temporary support while the NSC is en transit to its final resting place; and on continuous flight auger (CFA) in the most highly contaminated Service Zone (see Figure 3). This paper describes the relevant details in the design, analysis, construction and testing of these foundation systems to support the concrete guide rails.
CFA Piles – Service Zone

Figure 1 – NSC structure, slide rails, and CFA pile support location in Service zone

Figure 2 – General site plan layout

Figure 3 – Steel arch encompassing Unit 4 in Service zone.

FOUNDATION CONDITIONS
The soil conditions in the vicinity of the OS consist mainly of loose to dense sands containing intermittent very dense, or lightly cemented layers, with groundwater at about 3-4m depth below Elevation +114.00. Cone penetrometer (CPT) tip resistances varied from as low as 2-4 MPa in the upper 3-5m to 40-60 MPa in the intermittent dense zones and generally about 15-20 MPa over the entire depth.

After the accident, much of the debris from the accident (and from the sand and concrete dumped by helicopters) was spread and covered with soil as a shield over the contaminated material. However, prior to constructing the guide rail foundations a 14.5m wide by 3-4m deep trench down to Elevation +113.5m with steel shell soldier-pile-supported walls was constructed along each guide rail alignment to remove the majority of potentially contaminated soil and debris. Subsequently, after the contract was awarded, the contractor pushed 46 CPTs, each to depths of about 30m at 25m intervals, along the centerline of each trench, and also drilled 24 boreholes including six for pressuremeter (PM) testing, as additional investigations to those performed by ChNPP (the plant owner) before 2005. CPTs were also routinely conducted at CFA test pile locations prior to test pile installation.

Figure 4 – Typical CPT logs a) North trench b) South trench

DESIGN AND TESTING CRITERIA

The NSC has a 100-yr design life. The design criteria were developed based on Ukrainian norms with consideration of acceptable displacements during transfer and adjustment capability of the support system. Table 2 shows the maximum design and test loads based on numerical modeling of the entire structural system using a 3D analysis and application of the local Ukrainian norms.
### Table 1 – Design Criteria

<table>
<thead>
<tr>
<th>Deformation</th>
<th>Unit</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Maximum settlement, $S_{\text{max,}U}$ for subsoil</td>
<td>mm</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>2 Relative difference between deformations $\Delta S/L_U$</td>
<td>–</td>
<td>&lt; 0.005</td>
<td>At erection stage $L$ – distance between the Arch supports (12.5 m)</td>
</tr>
<tr>
<td>3 The maximum horizontal displacement of the Arch supports:</td>
<td>mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>in the Transfer zone</td>
<td>mm</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>in the Erection zone</td>
<td>mm</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>in the Service zone</td>
<td>mm</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2 – Design and Test Loads

<table>
<thead>
<tr>
<th>Location</th>
<th>Vertical [design (test)], kN</th>
<th>Horizontal [design (test)], kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>North trench, steel piles</td>
<td>4111 (5139)</td>
<td>830 (1040)</td>
</tr>
<tr>
<td>South trench, steel piles</td>
<td>4250 (5310)</td>
<td>810 (1020)</td>
</tr>
<tr>
<td>North trench, CFA piles</td>
<td>4179 (5015)</td>
<td>1271 (1525)</td>
</tr>
<tr>
<td>South trench, CFA piles</td>
<td>4191 (5029)</td>
<td>1179 (1415)</td>
</tr>
</tbody>
</table>

### FOUNDATION SUPPORT SYSTEMS

The design-build contract was awarded on Sept. 10, 2007, and final sliding of the arch is currently scheduled for September 2015. Due to the potential risks from radiation exposure, concerns regarding internal stability of the OS structure, and costs, the supporting elements for the concrete guide rails were varied in each of the main zones.

#### Erection Zone

Driven piles were selected to support the ground beam in the Erection Zone. Initially, the contractor estimated that the design load could be achieved using 18m long 1016mm diameter open-ended steel (S 355 grade) pipes with wall thicknesses 30mm in upper 6m and 16mm below. The piles were installed in two phases. The first 12m section was installed by vibration using an ICE 815C vibro-hammer, then upper section(s) were welded on and installed by driving with an IHC S90 hydro-hammer.

Field testing associate with steel piles included vertical and lateral static, dynamic testing and vibration monitoring. This paper only discusses the static tests.

A number of full scale field tests were performed to assist in the final design and to confirm vertical as well as lateral pile capacity. The general arrangement of piles for a set of vertical and lateral static tests is shown in Figure 5. The center pile is tested for vertical capacity using the four corner piles for reaction and two pairs of adjacent piles are used to perform two lateral tests. Dynamic analyses were also made during driving using PDA (pile driver analyzer) methods. Generally, the contractor attempted to perform two sets of vertical and lateral static load tests under both the Ukrainian norm and European norm, which were significantly different in terms of test load levels and length of time to hold those loads. Five phases of pile load testing were conducted for the steel piles.

In September 2009 two vertical load tests were performed. A maximum vertical load of about 3700 kN was achieved when 12000 kN was planned. Both tests experienced excessive movement, over 90mm, before the tests were halted. A single lateral test was performed which achieved only about half of the planned load (1263 kN versus 2500 kN) at which point excessive deflection occurred. The Contractor recognized that they were not getting the end-bearing resistance they had anticipated. Potential solutions were identified to increase pile capacity, including lengthening pile, adding a bottom cap, or adding an interior ring to increase end bearing. The third method was selected for additional testing.
In March 2010 one of the earlier tested piles (P5) was lengthened with a welded on extension and an internal ring plate, then retested. This arrangement proved insufficient since the internal ring was placed too high in the pile and did not develop the end bearing increase desired.

Also in March 2010 a report was produced that included analysis of a new pile, P7, which had a diaphragm installed 12m above the toe, and an uplift test on the earlier installed pile, P5. There were no static load tests performed on P7; only dynamic PDA (pile dynamic analyzer) testing was performed on this pile. The pile driving behavior of P7 was compared to that of P5 to justify a higher end bearing capacity, which then led to another round of full scale pile load tests.

In August 2010 a new pile load test setup was built in the North foundation trench in which two vertical and two lateral tests were performed. The test piles were embedded 25m with a diaphragm located 12m above the toe, and achieved the desired vertical and lateral test results. The vertical load test was applied to a maximum of 5366 kN for the Ukrainian standard test and 8050 kN for the European standard test (Note that the test loads were reevaluated and reduced from that used for the earlier test).

In December 2010 a new pile load test setup was built in the South trench in which two vertical and two lateral tests were performed. The test piles were embedded 25m with a diaphragm located 12m above the toe, and achieved the desired vertical and lateral test results. A vertical load test was applied to a maximum of 5300 kN for the Ukrainian standard test and 10750 kN for the European standard test.

The installed pile were 27m long and 1020mm diameter steel pipe, with 30mm thick walls in the upper 7m and 16mm thick walls below, with an interior welded diaphragm annulus containing a 350mm opening positioned at 12m above the toe. The piles were installed by vibration for the first 12m, then driven the remaining distance using the equipment described earlier. A total of 396 production piles were installed in the North and South trenches between August 2010 and October 2011.

In general, the installation process was uneventful except for one location where a buried track of a bull dozer was encountered and required removal. Also, vibrations from driving near an existing guard house necessitated its eventual demolition.

Figure 5 – Typical pile test arrangement

Transfer Zone

The continuous footings in the Transition Zone were designed as a single unit with expansion joints on either end where the continuous footing meets the pile supported sections. A 2D numerical model was developed to check that deformations were within the design criteria allowances. No field verification was performed for the Transfer Zone foundation. However, plate loading tests were performed to characterize the upper soil layer quality, which appeared to be of better quality than originally envisaged by CPTs. The Transfer Zone foundation construction began in Spring 2012 and is planned to be completed by Spring 2013.

Service Zone

The CFA piles supporting the Service Zone ground beams which, in turn, support the guide rails, proved to be the most problematic of the three foundation types. Figure 6 shows the typical procedure followed for installing CFA piles. The 1000 mm diameter CFA piles were installed using a Llamada P-145 installation rig equipped with a Lutz automated pile installation recorder. A typical Lutz log is
presented in Figure 7. Relatively high ground water conditions, as well as the presence of loose to medium dense zones of clean sands, resulted in difficult challenges, both from installation, as well as performance, points of view, and resulted in a long testing program (currently over two construction seasons and still ongoing, see Figure 8) to confirm that the CFA piles could provide the required vertical and lateral resistance. These tests consist of full scale vertical and lateral tests. The project interpretation of the local code regulations did not allow consideration of pile head fixity benefits in reducing lateral deformations without direct testing. Therefore, two-pile fixed head tests were also performed to confirm adequacy in foundation lateral resistance. As Figure 8 shows, there was a long and tortuous path of load testing, with many failures (shown as red filled symbols) for pile installation as well as testing.

Figure 6 – Installation methodology for CFA piles
Pile integrity testing (PIT, Figure 9), crosshole sonic logging (CSL, Figure 10), and pile coring, as well as compression break testing on concrete cube samples, were all performed to varying degrees during the testing program to check the structural integrity of the pile itself.

Installation and testing of the CFA piles has proved to be a significant challenge. Five of the 27 test piles installed to date could not be installed successfully, due primarily to improper installation procedures. These included three of five piles with 1020mm diameter casings in the upper 5m to 7m in an
attempt to increase lateral capacity. Of the 15 load tests performed to date only five have fully achieved the design testing criteria.

Initially, the contractor placed two arrays of piles (10 total; P11-P20), similar to that used for steel pile testing (Figure 5) just west of the edge of the Service zone in both trenches. Two other piles (P20 and P21) were installed within the Service zone, but both had installation problems and were abandoned and not tested. These first 12 piles were all installed by first installing a temporary steel casing to 5m depth, then removing the interior soil and replacing it with a mix of sand and dry cement, then removing the casing before installing the CFA pile to 20m depth. The reason for this procedure was to protect against potential contamination of the auger rig and/or to remove debris that might impede the auger penetration. As it turned out, no contamination or significant debris was encountered.

Vertical tests were performed on the center piles and two lateral tests were done on the two pair of outer piles (see Figure 11). All 6 of these initial tests failed to achieve the test load criteria defined in Table 2 (although the vertical tests did not fail by much, Figure 12). The primary reason appeared to be due to installation procedures and the use of the temporary casing. The automated pile installation records indicated that the auger was inserted too slowly using too many revolutions. In accordance with FHWA (2007), the auger should only rotate about 1.5 to 2 revolutions per a depth equal to the pitch of
the auger. In this case the auger pitch was 0.5m, so the total revolutions for a 20m CFA pile should be on the order of 60 to 80 total spins, yet they were installed with as many as 800 revolutions. This likely mined the saturated sands around the auger creating a weaker zone around the auger. Also, the concrete pressure was too low – on the order of only 0.2psi, when it should have been one atmosphere, or greater. Additionally, the temporary casing procedure was creating a loose zone around the upper 5m of the CFA pile reducing the lateral resistance, which is predominantly controlled by the upper 8 to 10 pile diameters.

Figure 11 –CFA pile test setups: left) vertical and right) horizontal

Figure 12 – Results of initial tests at edge of Transfer Zone: left) vertical and right) horizontal

These deficiencies were corrected in subsequent tests. A larger pump was added and the auger was inserted more rapidly. In addition, the temporary casing was abandoned and replaced with a permanent casing. Installing through a permanent casing (5m and 7m lengths were tried) proved very difficult for the contractor and only two of five installations were successful. The test results on the cased piles (N P25 [with 5m casing] and N P31 [with 7m casing]) and an uncased pile (NP 37) are shown, along with the previous test results on temporary cased piles, in Figure 13. Note that the permanent cased and uncased piles performed much better. However they still did not achieve the design criteria. Additionally, the uncased pile (N P37) behaved very oddly and failed suddenly after about 1000kN of lateral load. This was later found to be due to a buried concrete slab near the pile.
Subsequent vertical pile load tests were performed on isolated piles in the north and south trenches with improved installation methods (N P36 and S P38). A comparison of these results with the earlier vertical pile load tests is presented in Figure 14. Note that the traces with square markers, signifying the later piles installed, produced significantly higher loads than the earlier vertical tests for a given deformation.

In the final structure, CFA piles will all have a fixed-head condition due to the large ground beam (about 11 m wide, 4 m high and 175 m long with two expansion joints) which acts as a pile cap. It is common practice to test piles laterally as free-head piles, and then apply theory to calculate the lateral deformation (which will be significantly reduced) under the fixed head condition. However, the project interpretation of the local codes do not allow this and the deformation criteria had to be shown directly by testing. Therefore, a new test campaign in the second half of 2012 was performed on CFA piles without casings. This included the two vertical tests mentioned in the previous paragraph, and lateral fixed head tests conducted on CFA pile pairs connected with a single pilecap in the North and South trenches. The two tests in the North trench (P35/P36 and P32/P33) produced almost identical results and met the lateral design test criteria, while the two tests in the South trench have experienced higher displacements, which require more analyses and potentially re-design (see Figure 15).
CFA production piles in North Trench are planned to begin in Spring 2013 on the basis of successful lateral tests performed on P35/P36 and P32/P33, though taking also into account the lateral test performed in the South trench on P28/P38.

The issue related to the South Trench is most likely due to weaker soils in the upper 4-6m caused by poorly compacted backfill around existing 2 meter-diameter underground water cooling pipes that cross the South Trench at numerous locations (see Figures 16 and 17). Tests P28/P38 and P40/P41 were performed at a distance of 2 meters and 1.3 meters, respectively, from these pipes, and tend to indicate poorly compacted backfill of the upper layers, as CPTs performed at these pile locations demonstrated.
In addition to the presence of poorly compacted soils, there is a risk of deterioration of these pipes over the service life (100 years) and it is possible the soil could become de-compacted in the upper 4-6m. Removing these pipes was not the preferred solution due to the potential for presence of highly contaminated water inside these pipes. The 3D model incorporates the effect of this weaker zone by excluding soil resistance (lateral and vertical) in the upper 6.3 m.

Additional soil investigations (to better define the extent of loose zones near the circulation water lines) and pile tests in the South Trench are expected to be conducted before Summer 2013, and it is expected to define an updated pile design/layout shortly thereafter.

CONCLUSIONS

To date, the project has faced many challenges:

- Erection Zone driven steel pile tests have proven that assumptions on pile tip resistance were not sufficiently conservative, which resulted in the addition of a unique internal diaphragm to increase vertical resistance.
- The presence of saturated loose to medium dense sands created a major challenge for installation of CFA piles. First attempts in installing CFA piles in such difficult conditions initially failed. After more than 20 CFA test pile installations, there is now consistency in CFA pile construction resulting from lessons learned on the earlier attempts.
- After several lateral load tests, the method of testing a free-head pile were deemed unsuitable for pile acceptance by the project interpretation of the local code, which did not allow the benefit of pile fixity to reduce lateral deformations to acceptance levels by calculation – the deformations had to be proven by direct testing.
- Fixed-head tests performed on pile pairs connected with a single pile cap provided adequate deformation levels in the North Trench, but not the South Trench.
- A number of the South Trench CFA piles adjacent to the existing circulation water pipes will have reduced lateral resistance due to loose backfill which must be taken into account in final analysis and design.

Currently, the contractor is investigating the cause of the South Trench failures and more field testing and pile load testing is planned in early Spring 2013. Additionally, CFA production piles are planned for the North Trench in Spring 2013 on the basis of the successful testing performed on two lateral fixed-head tests and a vertical test in the North Trench.

While all challenges have been tackled one by one, the project had to go through a long learning curve. Due to high radiation it is difficult to make additional investigations and it is always preferred to engage experts in determining potential causes of all the issues encountered before deciding on remedial actions. These challenges and assessments led to a multi-year testing program, but has ultimately resulted in acceptance by all the parties involved.

More challenges are likely ahead. In particular, the issue around circulation water pipes in the South Trench is the most significant and challenging for the immediate future.

REFERENCES