Complex piled raft foundations designs for Expo 2015 Arcs Viaduct

L. Castellani, G. Furlani & A. Lucarelli
Studio Sintesi, Rimini, Italy

A. Lucarelli
Politecnica, Bologna, Italy

ABSTRACT: The Arcs Viaduct that will give the new Expo 2015 area its distinctive skyline is made of three different parts and based on several foundation shafts. These shafts actually have been designed as piled raft. Pile spacing is variable under the plinth: it’s closer along the border and wider internally. The resulting global stiffness of such a foundation is then part-way between a foundation shaft and a classic piled raft, so that complete 3D modeling is necessary to investigate pile stress and global displacements. Moreover, unconventional plane shapes could be studied, allowing difficult pile group effects to be found. Finally, up to four neighboring piled raft foundations and their interactions could be examined in order to evaluate the vertical and horizontal effects on the neighboring piles.

1 INTRODUCTION

Better access to the new Expo 2015 area in Milan is granted by the new junction between the A4 Milan-Turin motorway and a primary municipal road (under construction) in the city. The junction overpasses the A4 motorway, the Expo pedestrian access area and the A8 motorway making up the 3 Arcs Viaducts (see Fig. 1). As far as structures are concerned, while the A4 Viaduct is a proper arc viaduct with stay cables, the Expo area Viaduct is actually sustained by piers, as shown in Figure 2, and the so-called Expo Arcs have just an aesthetic function, without bearing the deck loads. Finally, the A8 Arc Bridge is a single roadway bridge sustained by the cable-stayed arc and the supports on the pass-through-pier and the final abutment.

Figure 1. Arcs Viaduct rendering. Aerial view.
Among the formerly described viaduct foundations, only the Expo Viaduct, a standard pier viaduct, has standard piled raft foundations with well-space piles below it. This foundation can be analyzed with simplified methods, like matrix analysis which is currently used in pile design.

Other foundations are part way between a shaft and a piled raft: a piles lane that is narrowly spaced is set at the perimeter of each foundation, and a well-spaced piles distribution is arranged inwardly. Figure 3 shows the piles plan and cross section of the Arcs foundations.

3D structure-soil interaction analysis is essential for the Arcs foundations for several reasons. First of all, just for the complexity of the single foundation alone, because of the thin slice of soil between two consecutive 1.2-m diameter piles along the perimeter are spaced at about a 1.3- to 1.5 m in diameter. Thus, the usual simplified hypothesis of substituting soil with elasto-plastic springs cannot be assumed. Moreover, with simplified methods, unreliable assumptions are required for taking into account both horizontal and vertical group effects that are very important for narrowly spaced piled-raft foundations (see Berezantzev 1965, Brinch Hansen 1961, Poulos & Davis 1990, Reese & O’Neill 1988). All of these difficulties are intrinsically overcome by a FLAC\textsuperscript{3D} (Itasca 2012) full-interaction model.

Figure 2. Arcs Viaduct rendering. View from the Expo pedestrian area.

Figure 3. Expo Aesthetic Arc. Plan and cross section.
However, that is not the only issue for these foundations. Due to the geometrical restrictions at the site, some unconventional shapes are necessary. As far as the Expo Arcs are concerned, they have to bear mostly horizontal loads because of their aesthetical function, owing to wind pressure rather than vertical loads due to self-weight. Thus, the optimal pseudo-elliptical shape of the foundation could be designed, verifying it to be the better way to avoid stress peaks on the corner piles and to bear the prevalent horizontal loads direction.

As for the A8 Arc Bridge, two very wide areas are occupied by the foundations. The bridge deck is sustained by the pier supports, by the abutment supports and by the cable-stayed arc. Thus, foundations receive relevant contributions both from the arc bases and from the pier/abutment bases (see Fig. 4). Therefore, non-convex polygonal shapes and several loads application areas have to be implemented in these 3D models.

Finally, three of the four A4 Arc Bridge foundations are the more geometrically restricted ones. Several plinths, characterized by plan circular shapes, are close enough to other distinct foundations to involve mutual interaction between neighboring piles. As shown in Figure 5, Plinth n.4 of the A4 Arcs is very close to the Pier n.1 plinth of the Expo Viaduct. Furthermore, Plinths n.1 and n.2 of the A4 Arcs are very close to the abutment of the Expo Viaduct and to the bordering abutment of the Stephenson Viaduct that will connect a future expansion area of Milan.

2 SOIL CHARACTERIZATION AND CONSTITUTIVE LAW

Subsurface soil characterization comes mainly from boreholes with Standard Penetration Tests (SPT) and Down-Hole tests. SPTs results have been correlated through Ohta & Goto (1978) and Yoshida et al. (1988) in order to determine shear wave velocity \( V_S \) and subsequently shear modulus \( G_0 \) for very small deformation rate (see Cestari 1990). DH tests directly output \( V_S \), but because these tests are a little far from the Viaduct foundations site, they have been considered just to confirm the design modulus profile with depth (see Fig. 6) (see Seed et al. 1970 and Lai et al. 2000).
Soil at the site is mainly gravelly sand, with a homogeneous stratigraphy over the whole area of interest. Three main geotechnical layers have been identified, named GS-A, GS-B and GS-C, plus an upper layer of backfill named R. Design water level is about 5 m below the ground surface. Strength parameters have been estimated mainly through SPTs and laboratory tests (see Bellotti et al. 1989, Bolton et al. 1986, Kulhawy et al. 1990, and Cestari 1990). The best fit of the shear modulus design profile can be obtained well through CHSoil – Simplified Cap Yield – constitutive model of FLAC$^3$D v5, as shown in Figure 7. Furthermore, several sensitivity analyses have been performed in order to validate soil model behavior.
Three main steps are used to perform $FLAC^{3D}$ initialization. First, a temporary material with Mohr-Coulomb constitutive law and high strength parameters is set in order to generate initial stress in volume elements; then, maintaining the MC law, real strength parameters are assigned in order to refine the horizontal stress state; and finally, the CHSoil constitutive law is assigned with the same strength parameters that were used in previous step, but with the calibrated modulus profile. The CHSoil parameters for the modeled units are reported in Table 1.

Table 1. Geotechnical parameters (see $FLAC^{3D}$ manual [Itasca 2012]).

<table>
<thead>
<tr>
<th>Unit</th>
<th>$z$ [-]</th>
<th>$\gamma_{sat}$ [kN/m$^3$]</th>
<th>$k_{o,NC}$ [-]</th>
<th>$c^\prime$ [kPa]</th>
<th>$\phi_\ell$ [deg]</th>
<th>$n$ [-]</th>
<th>$m$ [-]</th>
<th>$G_{ref}$ [kPa]</th>
<th>$K_{ref}$ [kPa]</th>
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</thead>
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<tr>
<td>R/S</td>
<td>0.0 ÷ 1.1</td>
<td>18.0</td>
<td>0.500</td>
<td>0</td>
<td>30°</td>
<td>0.25</td>
<td>0.30</td>
<td>226</td>
<td>637</td>
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<tr>
<td>GS_A</td>
<td>-1.1 ÷ -6.5</td>
<td>18.0</td>
<td>0.426</td>
<td>0</td>
<td>35°</td>
<td>0.57</td>
<td>0.62</td>
<td>447</td>
<td>1076</td>
</tr>
<tr>
<td>GS_B</td>
<td>-6.5 ÷ -15.0</td>
<td>22.0</td>
<td>0.426</td>
<td>0</td>
<td>35°</td>
<td>1.09</td>
<td>1.14</td>
<td>699</td>
<td>1550</td>
</tr>
<tr>
<td>GS_C</td>
<td>-15.0 ÷ -40.0</td>
<td>22.0</td>
<td>0.441</td>
<td>0</td>
<td>34°</td>
<td>0.38</td>
<td>0.43</td>
<td>487</td>
<td>1042</td>
</tr>
</tbody>
</table>

Figure 7. Vertical stress state after initialization.

3 MODELING APPROACH

Full 3D models have been developed for all the Arcs foundation described above. In all models (see Fig. 8), plinths are implemented with volume elements – zones – with elastic constitutive model. Piles are always generated through $FLAC^{3D}$ “embedded pile” structural element type, which is a beam type element with pre-configured soil interaction parameters. Hence, embedded piles have mechanical proprieties of reinforced concrete (1.2 m diameter) circular section beams, while as for lateral interaction properties they have no cohesion, 26° friction angle, $1\times10^5$ kPa shear modulus and $1\times10^4$ kPa normal modulus. Links to zones are set at top and bottom of piles; while piles heads have an extra-length of about 1.0 m with translational and rotational restraints, pile bottoms are linked with elasto-plastic springs 4500 kN base strength and a $2\times10^5$ kPa modulus (see $FLAC^{3D}$ manual [Itasca 2012]). Such lateral interaction parameters and base link were determined by sensitivity analyses, and observed pile behavior in similar geotechnical conditions during load tests.

Piles and plinths density is applied gradually to avoid sudden acceleration in $FLAC$ computing. To ensure that no stiffness overlapping is considered, since the embedded pile element has no volume, the stiffness of the soil between piles is reduced considering the actual soil/pile volume ratio. Furthermore, the lateral interaction of the border piles has been reduced to 50% (considering half perimeter) as a design precaution due to the close pile spacing.

$Interface$ elements are inserted at the surrounding surfaces of the plinths, with very low shear strength and moduli, to ensure that no reaction could arise between the plinth and the soil elements that are located both below and at the side of the plinth.

As previously mentioned, plinths n.1 and n.2 of the A4 Arcs interact with the abutments foundations of Expo Viaduct and Stephenson Viaduct (see Fig. 9). The interaction analysis of these foundations with plinths at different levels highlighted the importance of a good backfill between plinths after their construction. This requirement was written on the design technical drawings. Thus, their sideways interface elements must behave differently from the ones
beneath: good stiffness and friction properties have been assigned to let lateral pressure be transferred to the backfill-soil elements and to the neighboring plinths. Otherwise, with “soft” interface elements, i.e., with poor quality backfill material between plinths, unrealistically high stress levels on the neighboring piles would arise due to the horizontal contrasting loads at different levels. Finally, between the two abutments plinths, pure friction behavior is assumed to simulate the concrete contact.

Figure 8. Structural elements implemented in FLAC$^{3D}$ models.

Figure 9. Embedded pile elements, interface elements and backfill zones implemented in FLAC$^{3D}$ model with A4 Arc foundations close to abutments foundations.
4 LOADS APPLICATION

Loads are applied at the upper surface of plinths in the actual application areas given by the base sections of the elevated structures through boundary stress linear distribution.

Several load combinations came from the elevated structures analyses. Italian Code, which follows general norms of the Euro Codes, requires at least five Limit States that are the Ultimate Limit State both in static and seismic conditions, and three different Service Limit States depending on the accidental load combination factors. Furthermore, considering the two main application directions for wind and seismic loads, and maximizing or minimizing vertical loads, not less than ten load combinations can be obtained with some filtering efforts.

As for the Expo Aesthetic Arcs, due to their prevalent horizontal load direction and their length of about 200 m, loads are obtained from complex studies in the wind tunnel, so no less than 24 load combinations have to be implemented.

In a non-linear analysis of such foundations, this could be computationally expensive. Considering the several attempts needed to optimize the design solutions, results could be achieved in good time through automatic procedures that were specifically studied for this design through FISH and Visual Basic routines. Figure 10 shows an example relative to A8 Arc, where arc base loads, wing-wall loads and front-wall loads are applied at different loading areas. Figure 11 shows an example that emphasizes the interaction between loads applied A4 Arc plinths n.1 and n.2 and loads applied to the adjacent abutments of Expo and Stephenson Viaducts.

5 MAIN INTERACTION RESULTS

Principal results for the foundations design concern horizontal group effects and mutual interaction between neighboring foundations. Horizontal group effects that arise implicitly from such 3D models were not easily predictable by preliminary simplified analyses. As shown in Figure 12, shear stress distribution at pile heads is highly influenced by the main direction of horizontal loads and torque. In the upper diagram, rotational and translational effects can be seen on a top prospective view of the deformed geometry. In particular, the black and white scaled deformed plinth is partially overlapped to its undeformed position. Higher shear-stress piles are the ones that are horizontally pushed against the surrounding soil, while other piles are “dragged” and less stressed. The difference between the maximum and minimum shear-pile force is around 400 kN, while the bending moment difference is around 1000 kN.

Figure 10. A8 arc base and abutment foundation. Load application.
Figure 11. A4 Arcs plinths n.1 and n.2, Expo Viaduct abutment and Stephenson Viaduct abutment. Load application.

Figure 12. Roto-translational deformed geometry and pile shear force in X direction.
The two analyzed cases of adjacent foundations have highlighted two different aspects of mutual interaction of close piled rafts. In plinth n.4 of the A4 Arc interaction with the Pier n.1 of the Expo Viaduct, vertical interaction effects are very clear: Pier n.1 has a larger vertical load than Plinth n.4, whose neighboring piles are subjected to negative skin friction, such that some tensile stress arises in the nearest piles to the adjacent foundation, see Figure 13.

Horizontal interaction then is highlighted mostly by the piled raft foundation of the Abutment of the Expo Viaduct, which is adjacent to the A4 Arc Plinth n.1 and n.2, and to the Stephenson Viaduct Abutment. Figure 14 shows longitudinal distribution of shear in the abutment piles, i.e., in the X direction. Longitudinal bending moment is not reported here, but would show a similar diagram. As illustrated, the most stressed piles are those that are nearer to Plinth n.2, which is closer to the abutment foundation than Plinth n.1. This happens because prevalent horizontal loads of the abutment and of the arcs push in opposite directions. For this complex case, 3D interaction analysis was the only methodology capable to determine with some level of confidence the shear force and bending moment on the piles.

![Figure 13. Pile axial force in plinth n.4 of A4 Arc.](image)

![Figure 14. Expo Viaduct abutment. Pile shear force in X direction.](image)
6 PILE DESIGN METHOD

In order to optimize reinforcement along the pile length and to manage the several design load combinations better, exporting pile stresses to a spreadsheet was required. In order to do that, a specific automated procedure was performed to export, filter, graph and verify the reinforced concrete sections through FISH and Visual Basic routines.

Figure 15 shows examples of the bending moments of the Expo Arc piles and reinforcement technical drawing at the side. Bending moments come from several load combinations at Ultimate Limit State; SLU is in static conditions and SLV is in seismic conditions according to the Italian Code. Max and Min refer to the maximum and minimum axial load at constant global moment. There is no significant difference between SLU max and min, as well and between SLV max and min. However, pile bending moments are slightly higher with the minimum axial load.

Figure 15. Example of pile reinforcement design, with additional reinforcement added at the top.
7 CONCLUSION

Full 3D soil-structure interaction modeling has proved essential for the Expo 2015 Arcs Viaduct foundation design, for several reasons. The shape complexity of plinths and piled rafts, the unconventionality of the perimeter line of narrowly spaced piles, the global shaft deforming behavior and – the valuation of the group effects – would have been impossible to analyze with commonly used simplified methods, like matrix analysis of piles.

Furthermore, thanks to flexible and automated procedures, the $FLAC^{3D}$ models could have been performed in a good design time, and led to some optimized solutions such as the elliptical Expo Arc piled raft. Thus, 3D models were used as more of a “design” tool than as a “validating” tool.

As a final point, all mutual interaction issues between neighboring foundations have been investigated and the model has allowed full understanding of the mechanics.

In the first case, where Plinth n.4 of A4 Arc interacts with Pier n.1 of Expo Viaduct, a strong vertical interaction was observed and some piles were subjected to negative skin friction.

The second case, where the mutual interaction concerned four different foundations (i.e., Plinths n.1 and n.2 of the A4 Arcs, the Abutments of the Expo Viaduct and of the Stephenson Viaduct), a strong horizontal interaction has been highlighted, due to the different levels where the piles heads are set. For these plinths, good interaction properties have been given laterally to the interface elements, to let lateral pressure be transferred to the soil elements. Otherwise, stress levels that are too high on the neighboring piles would have occurred. Thus, a backfill with good mechanical properties between plinths is very important and such an ordinance requirement has been written on the design technical drawings. This 3D model, with regard to the Expo Viaduct Abutment foundation, finally pointed out shear and bending moment peaks on the nearest pile to the adjacent foundation.

REFERENCES


