Three-dimensional behaviour of a circular excavation in Nantes, France

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ABSTRACT: In the framework of a co-operation between the LCPC and Solétanche-Bachy, the behaviour of a circular retaining wall at the site "Ilot 7" in Nantes has been studied. The geometry of the excavation and of the retaining structure is symmetric and the ground conditions show horizontal soil layers. However, the measurements carried out during construction indicate that the deformations of the circular wall are not symmetric at all. Therefore, a three-dimensional finite element calculation (using CESAR-LCPC) has been carried out in order to clarify the influence of the construction sequence on the wall behaviour.

1 INTRODUCTION

Studying the real behaviour of constructions is one of the most important concerns in the domain of civil engineering: besides the design calculations carried out to assess the stability of the structure, it is necessary to anticipate the influence of the construction works on nearby structures, particularly in a dense urban environment. For that purpose, it is interesting to collect and analyse measurement data obtained by monitoring both construction process and service state of structures in order to validate and improve calculation methods.

The structure presented here has been built and monitored by Solétanche-Bachy in Nantes, France: it is a circular diaphragm wall constituting the outer structure of an underground car park. This kind of structure is quite complex in terms of design, since a circular wall does not behave like a plane wall. The wall panels can lean on each other, the geometry makes it possible for forces to develop in the direction perpendicular to the radius. Furthermore, the monitoring results show that the structure's deformations are not symmetric, which led to modelling the behaviour using a three-dimensional numeric finite element approach.

2 PRESENTATION OF THE PROJECT

The excavation has been carried out inside a 80 cm thick circular diaphragm wall having a diameter of 46.30 m. The wall is designed to be auto-stable for an excavation down to a depth of 14.70 m. Figure 1 presents a section of the retaining wall, also including the excavation steps and the stratification.

The subsoil is dominated by slightly consolidated clayey modern alluvium, silty in its upper part and containing peaty inclusions in the lower, overlying a rather thin deposit of fine to coarse sands. The substratum consists of mica-slates, the embedded part of the wall is driven down to the intact rock.

The circular wall being a special proposal of the contractor, a monitoring system has been installed, so

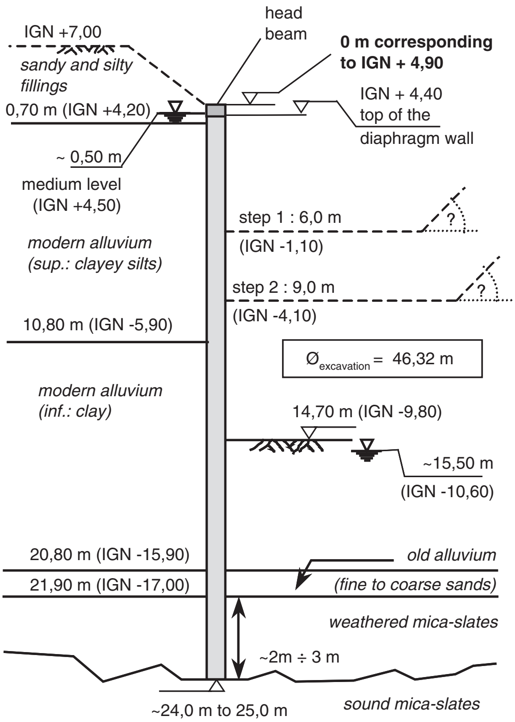

Figure 1. Retaining wall, stratification and excavation steps.

Figure 2. Dissymmetric soil excavation inside the diaphragm wall. Solétanche-Bachy, 2002.

as to keep track of the behaviour of the structure in four points placed each at 90 degrees of the circle.

These four points have been equipped with inclinometer tubes as well as topographic spots. Measurements were carried out during the excavation process, for three different depths: 6 m, 9 m and at the final depth of 14.7 m. For practical reasons, only three-quarters of the circular area are excavated in the first two steps: an earth platform has been conserved for the operation of the hydraulic excavator (figure 2).

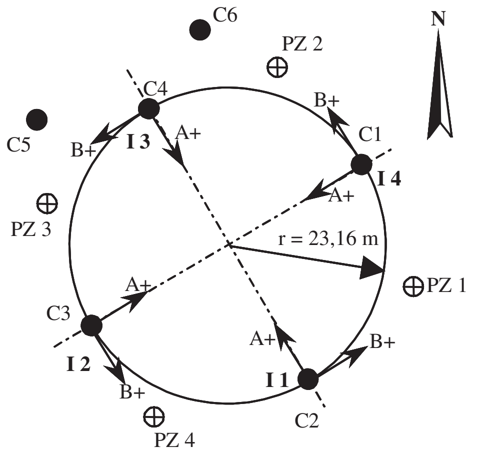

Figure 3. Schematic of the instrumentation: Inclinometers (I1–I4), Piezometers (PZ1–PZ4), Topographic spits (C1–C6).

3 MONITORING DEVICES

3.1 *Presentation of the instrumentation*

The monitoring devices are presented in figure 3.

Measurements started in April 2002 and were carried out for all excavation steps. The final depth was reached after 4 weeks at the end of April. Measurements were carried out until the end of July 2002.

The machine used for the excavation is based in the Northeastern part of the cylindrical enclosure, in the vicinity of inclinometer 4 and the topographic spot C1. The arrows on the sketch show the orientation of the inclinometer tubes, indicating a positive displacement towards the excavation (A+) and in anti-clockwise direction (B+).

3.2 *Measurement results*

The measurements obtained by the available devices clearly show the following displacement pattern: the whole structure tends to lean on the not yet excavated side of the cylinder. This general movement can be observed after an excavation of 5 to 10 m. Additionally, the whole structure exhibits a slight rotational movement in an anti-clockwise direction.

Figure 4 resumes the results of the final topographic measurements. They prove the tendency of the structure to move in Northeastern direction and to take an oval shape. The scale of the figure is increased in order to better visualise the head displacements, which do not exceed 1 cm.

The inclinometer results presented in figure 5 confirm the observations obtained by the topographic survey. The different behaviour of the opposite wall panels in the SW-NE-axis can be seen quite clearly.

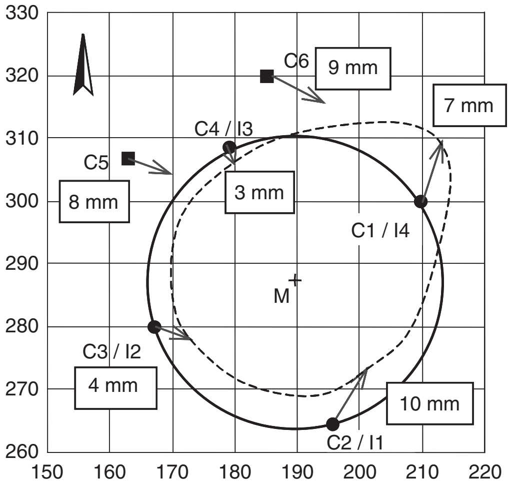

Figure 4. Final displacements of the diaphragm wall head, measured by the topographic survey. Coordinates X-Y of the Lambert-System: X + 306 000 and Y + 253 000.

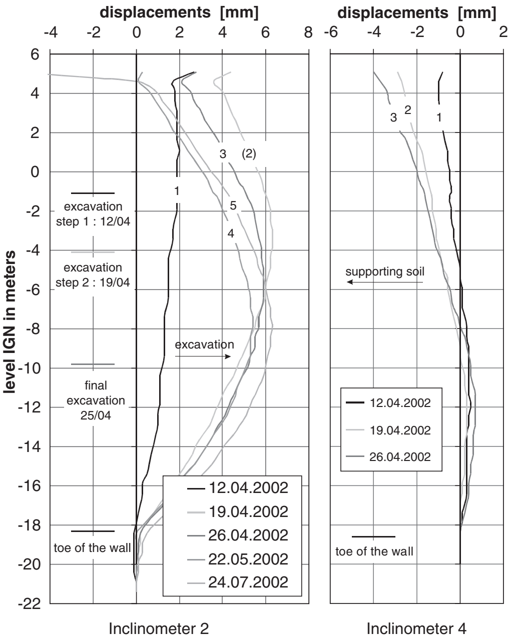

Figure 5. Results of the inclinometer measurements in the radial direction (A+). Positive values indicate a movement towards the excavation.

The deformations obtained by evaluating the results of inclinometers 1, 2 and 3 is similar to those caused by a linear wall supported in its upper part, inclinometer 4 however corroborates the tendency of the cylindrical wall to lean on the soil on the non-excavated side of the structure. The specific shape of the deformation may partly be due to the reinforced concrete head beam redistributing compression, but mainly it is caused by the three-dimensional geometry of the shaft and the earth pressure growing with depth.

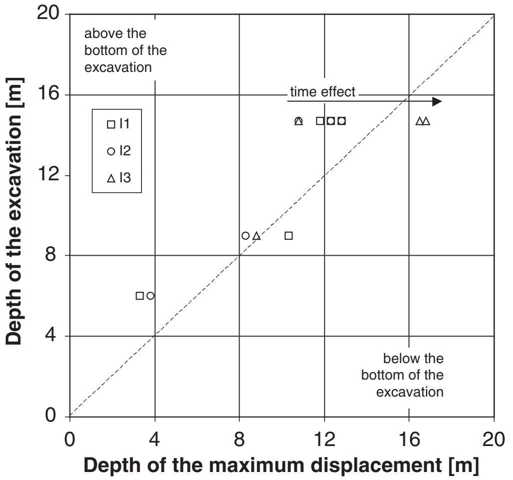

Figure 6. Depth of the bottom of the excavation vs. depth of the maximum displacement for inclinometers 1, 2 and 3.

After reaching the final excavation depth (measure 3, 26/04/2002), the displacements indicated by inclinometer 2 remain close to 6 mm, however the following measurements in May and July show that the depth of the maximum displacement approaches the bottom of the excavation. A similar behaviour, still less pronounced, is recorded by inclinometers 1 and 3.

In figure 6, the depth of the maximum displacement is summarised for inclinometers 1, 2 and 3. The diagram shows clearly that maximum deformation occur approximately at the bottom of the excavation.

A similar behaviour has been observed by Walter & Tarallo (1985) for cylindrical diaphragm walls in Zeebrugge (subsoil dominated by fine and clayey sands), where three 20 m deep excavations have been monitored during their construction process. However, the authors did not concentrate on the excavation technique, and no three-dimensional behaviour is reported.

Two other interesting examples of diaphragm wall shaft excavations are presented by Muramatsu & Abe (1996) as well as Anagnostopoulos & Georgiadis (2001).

The former investigate an about 60 m deep and 28 m wide shaft in alternating layers of sand, clay and silt. The observed deformation is quite different from what is observed in Nantes, since the maximum displacement occur at the top of the wall (2 cm). Two possible reasons for these differing behaviour can be identified. Firstly, the authors indicate that a movement of the inclinometer base is possible due to chemical grout injection carried out before reaching the final excavation depth, and secondly, thin mud films between the wall panels probably gibe the whole wall a different behaviour than that of the excavation in Nantes. Generally, the role of the joints of diaphragm walls is yet not very well known.

The second two authors present a 9 m deep shaft excavation in loose silty sand. Strain gages were welded on the reinforcement bars of one of the 26 wall panels and survey measurements were carried out. Measurements results indicate negligible displacements of the head of the wall, an observation comparable to the wall at Nantes. Particularly interesting is the distribution of compressive forces (as this is seldom reported), calculated from the strain measurement results. For all excavation steps, high compressive ring forces developed close to excavation level. However, again, no three-dimensional behaviour is discussed.

The apparent lack of data on the three-dimensional shaft excavation behaviour has led to the idea of carrying out a 3D-finite element analysis in order to simulate the observations acquired at Nantes.

4 THREE-DIMENSIONAL FINITE ELEMENT SIMULATION

4.1 *Motivation*

It is quite natural that the bi-dimensional calculation method used for the design of the structure is not able to predict this dissymmetric wall deformation. The design was carried out using the subgrade reaction modulus method, and the cylindrical shape of the structure was taken into account through a cylindrical rigidity ($k = e \cdot E/r^2$) simulating the interaction between panels, but beside this, the eccentric construction sequence has not been considered.

Therefore, it is interesting to carry out a three-dimensional finite element calculation in order to discuss whether the dissymmetric construction sequence is the crucial factor for the observed behaviour.

In the following, we present the modelling carried out by using the FE-code CESAR-LCPC.

4.2 *Mesh and construction phases*

The aim of the numerical simulation is to discuss the hypothesis that the excavation process can be responsible for the observed dissymmetric shape of the final geometry of the structure: the anti-clockwise movement of the wall is left outside the scope of the analysis. Thus, only half of the structure is taken into account in the numerical model. Since we assume that the presence of the earth platform inside the circular enclosure has an influence on the deformation of the wall, the geometry of the earth platform and of the zones excavated at each construction step must be taken into account in the generation of the mesh.

The initial stress state is assumed to be geostatic, in the wall as well as in the ground: in other words, it is assumed that the wall is "wished in place" and that its construction does not modify the stress state in the surrounding ground. The ground volume weight is taken equal to 20 kN/m^3, and the lateral earth pressure coefficient is assumed to be equal to $K_0 = 0.5$. Given what is known about the construction process, the numerical simulation is carried out in three successive computation steps (figure 7):

(1) the first step corresponds to the excavation of a part of the area limited by the wall down to a depth of 6 m;
(2) the second step is the simulation of the excavation down to a depth of 9 m around the earth platform where the machine is located;
(3) the last step consists in simulating the final stage of excavation down to the depth of 15 m (the wall toe being 25 m deep).

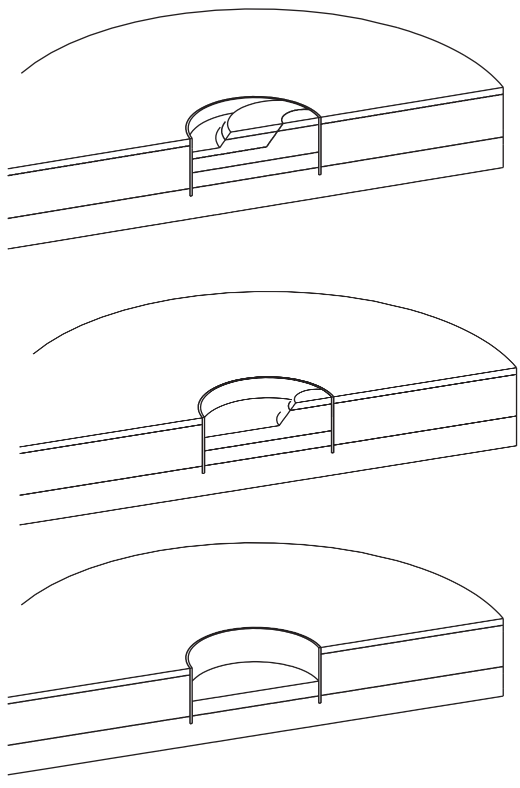

Figure 7. Steps taken into account in the numerical simulation.

The main difficulty in the constitution of a suitable mesh for three-dimensional geotechnical structures lies in the fact that not only the structure must be discretised, but also the surrounding ground: the meshes of the ground and of the retaining wall must have nodes located at exactly the same points. This difficulty does not exist in bidimensional problems, but in the case of three-dimensional analyses, it remains a strong limit to the complexity of the problems that can be dealt with. In the case of the structure discussed here, it is assumed that in the first two stages, the machine excavates the ground from a platform of circular shape, but the centre of the platform does not coincide with that of the wall.

The stability of the ground under the platform implies that the slope can not exceed a given value. This slope was taken equal to 45 degrees, for lack of more detailed information.

Thus, the mesh must include the intersection of two cones of vertical axis with the vertical cylinder that is constituted by the wall (figure 8). Eventually the mesh has to be completed with the ground outside the wall. The final mesh includes 23000 nodes and 6200 quadratic elements. The construction sequence and the geometry of the soil layers leads to the definition of ten different groups of elements in the mesh. The meshed zone has a radius of 90 m, and a height of 35 m. The boundary conditions prescribe zero displacement in the three directions for the lower and outer limits of the model. On the plane of symmetry, the displacement is zero in the direction perpendicular to the plane.

4.3 *Mechanical data*

In the simulation, the ground is divided into three horizontal layers. The constitutive law associated with each layer is elastic-perfectly plastic, with a linear isotropic elastic law, and an associated flow rule defined by the Mohr-Coulomb model. The values of the corresponding parameters are given in Table 1.

The wall itself is considered as linear elastic; its Young's modulus is equal to 10000 MPa and the Poisson's ratio is 0, 2.

The mechanical characteristics of the second layer do not exactly correspond to the values that can be found in the geotechnical file, because the slope of 45 degrees of the earth platform is not stable with these values. Given the fact that the actual slope angle is unknown and that the aim of the simulation is to confirm that the non-symmetric deformation of the wall can be explained by the construction sequence, the resistance characteristics taken into account in the computations are slightly greater than the values of the geotechnical file, in order to ensure the convergence of the elastoplastic computations.

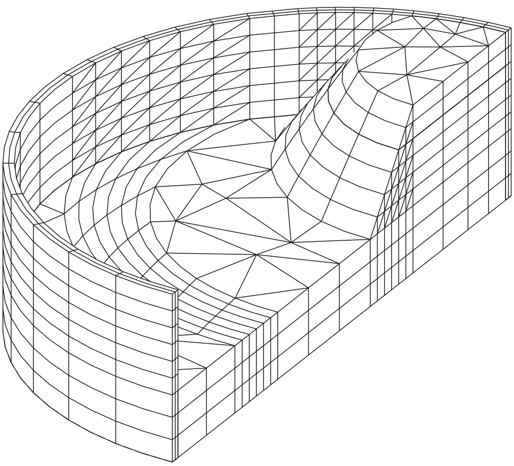

Figure 8. Detail of the mesh illustrating the geometry of the elements used for the platform and the wall.

5 RESULTS

The computed deformation (figure 9) shows that the wall behaviour is different from that of a plane wall: although there is no support, the maximal displacement is not obtained at the head of the wall, but a little above the base of the excavation. This is due to the three-dimensional nature of the problem, and is also reflected by the measures of the inclinometers (figure 5). Besides, the computations clearly show the

Table 1. Mechanical data.

depth [m]	E [Mpa]	ν [−]	c′ [kPa]	$\varphi' = \psi$ [−]
$z \in [0; 3.0]$	10	0.3	5	25
$z \in [3.0; 21.7]$	15	0.3	8	30
$z \in [21.7; 35.0]$	500	0.3	100	45

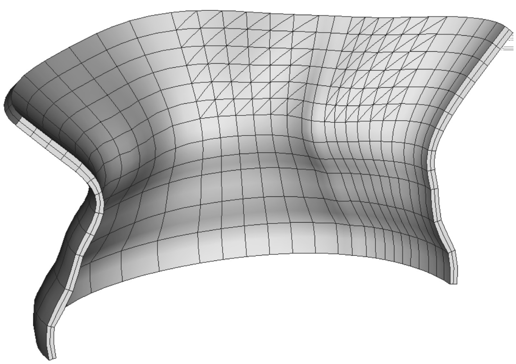

Figure 9. General view of the deformation of the wall alone (the platform is on the right).

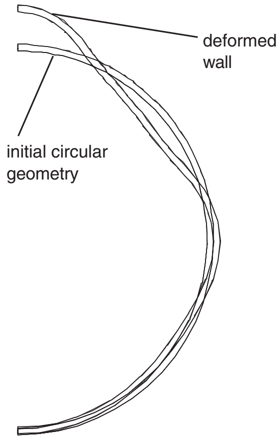

Figure 10. Displacements in the horizontal plane of the wall head (the excavation machine is located on the top of the figure; displacements are magnified by a factor 300).

interaction of the wall toe with the lower, stiffer layer: the wall remains vertical in the lower part of the mesh.

Figure 10 shows the computed displacement of the wall head, in the horizontal plane (with the initial circular geometry). The wall has clearly taken an oval shape and moves towards the side where the machine was located during the excavation (upper side of the figure). The maximal displacement given by the simulation is 6.9 mm, which is close to the measured values.

6 CONCLUSION

The geometry of the excavation discussed here is simple, but it shows a complex three-dimensional behaviour, caused by the apparition of plastic zones in the ground around the wall during the construction (that are not symmetric with respect to the wall vertical axis). This result provides an interesting insight in the behaviour of circular walls, and brings to light the influence of the construction sequence: it is not unlikely that it may have an influence even in the case of plane walls.

The three-dimensional analysis presented here confirms the fact that the finite element method makes it possible to investigate questions that lie out of the scope of traditional design methods.

The cause of the final oval shape of the wall is the combination of a plastic ground behaviour and a complex construction process (in terms of the geometry of the zones that are excavated at the various stages). It must be emphasised that the results could not be obtained if this geometric effect is disregarded, even with much more complex constitutive laws than the usual Mohr-Coulomb used here: taking into hardening effects without including the excavation process would not be of any help.

Nevertheless, although the computations account, both qualitatively and quantitatively, for the observed oval shape of the wall at the end of the construction, it must be recalled that the use of three-dimensional computations is generally not necessary in day-to-day practice and that it remains difficult to carry out a thorough investigation of the influence of geometric parameters in three dimensional conditions: in the example discussed here, a parametric study of the influence of the slope of the earth platform would not be easy, since a new mesh must be created for each computation. On the contrary, a parametric study of the influence of the geometry is common practice in bidimensional conditions. Moreover, the duration of three-dimensional computations (several hours) still remains incompatible with parametric analyses of the influence of soil parameters.

It must be underlined that back analysis of case studies like the one presented here are an important tool to better understand the soil-structure interaction of geotechnical constructions. The measurement data has been obtained by "ordinary" site monitoring. It is important to emphasise the knowledge and data transfer between contractors and research institutes in order to profit more frequently of such studies.

ACKNOWLEDGEMENTS

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REFERENCES

Anagnostopoulos, C. & Georgiadis, K. 2001. Behaviour of an instrumented circular diaphragm wall. *15th International Conference on Soil Mechanics and Foundation Engineering, Istanbul.* Vol. 2: 1061–1064.

Muramatsu, M. & Abe, Y. 1996. Considerations in shaft excavation and peripheral ground deformation. *Geotechnical Aspects of Underground Construction in Soft Ground*. Mair & Taylor (eds): 173–178. Rotterdam: Balkema.

Walter, J.P. & Tarallo, F. 1985. Soutènement d'une fouille par une paroi cylindrique. *11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco*. Vol. 4: 2141–2144.