

Underpinning and consolidation of the foundations of St. Mary's Basilica at Tongeren (Belgium).

Approfondissement en renforcement des fondations de la Basilique Sainte Marie à Tongeren (Belgique)

J. Maertens, Jan Maertens BVBA and KU Leuven

D. Van Gemert, KU Leuven

M. Jansen, architect

W. Loosen, Libost Groep NV

W. Cromheecke, Denys NV

ABSTRACT

The foundation walls and column footings of the Basilica of our Lady Mary are made of rubble stone masonry, partly of three leaf masonry with rubble core. The central nave and the aisles of the church are being excavated to make an archaeological cellar underneath the church. The loss of bearing capacity due to the decrease of the weight of the soils above the foundation level has been compensated by an underpinning of the strip foundations, initially founded at a depth of 3 meters. Furthermore the foundation masonry has been strengthened by means of cement based grout injection, and cemented steel anchors. During the whole working period a detailed monitoring of the displacements has been performed by means of a total station measuring the location of a certain number of points every hour. From the obtained results the influence of the different activities could be deduced.

RÉSUMÉ

Dans la Basilique de la Sainte-Marie les murs de fondation ainsi que les massif sous les colonnes sont constitué de maçonnerie de pierres et partiellement de parements en maçonnerie avec un remplissage central. Pour la réalisation d'une cave archéologique le sol est excavé dans la partie centrale de l'église. Parce que l'enlèvement d'un grand volume de terre donne lieu à une diminution de la capacité portante des fondations il a été nécessaire d'approfondir les fondations directes existantes. En plus la maçonnerie a été traitée par injection d'un coulis de ciment et par mise en place de barres d'armature scellées au ciment. Pendant toute la période de la phase II les déplacements ont été contrôlés tous les heures à l'aide d'un total station. De cette façon l'impact des différentes opérations a pu être déterminé.

Keywords: Restorations, Underpinning, Masonry injection, Micro piles

1 INTRODUCTION:

Tongeren is an old Roman city, with a history of more than 2000 year. The city centre is an accumulation of remains of successive civilisations and cultures. Archaeological excavations in the 'Vrijthof' market place next to the church indicated that the gothic church was built just on top of a most interesting and crucial archaeological site [21]. Archaeological research in the Vrijthof-market at the south side of the church goes back to 1844. At that time J.L. Guijth discovered a series of foundations, which he and his successors in the 19th century interpreted as the remains of a Roman fortress. At the re-arrangement of the Vrijthof site in 1994-1996 extensive excavations revealed that these remains are parts of two different defensive walls of the medieval Minster, one dating from the 10th century and one from the 12th century. At the same time a Ro-

man town house with bathhouse from the 2nd and 3rd century was discovered, as well as a tower and connecting sections of the 4th century town wall. The archaeologists were convinced that the remains of the bathhouse were only the southern exterior walls of a rich urban residence, of which the remaining parts are situated under Our Ladies Church.

The idea grew to disclose the remains under the church. However, religious live in the church is very active, and the church is an important monument as well. One had to look for a solution that could combine the desires and needs of all parties involved. The proposed solution was the construction of an archaeological cellar under the church. This cellar will be an underground archaeological field. The cellar will have no solid concrete bottom floor. People will walk on bottom soil surface of the

excavations, to keep the archaeological sensation as complete and as realistic as possible.

The Church-fabric of St. Mary's Basilica initiated the excavation project in 1994-1995. The project is designed by the architectural office Janssen and Loix in Tongeren. Libost-Groep consulting engineers, in collaboration with engineering consultant J. Maertens, make the structural design. The Reyntjens Laboratory of K.U.Leuven gives technological support. The project is supported by the Church-fabric, by the City Council of Tongeren and by the Department of Environment and Infrastructure of the Flemish Government. Excavations are made by the Institute for the Archaeological Patrimony IAP. The consolidation and underpinning works are executed by Denys n.v.

From the beginning on it was clear that the excavation of an archaeological cellar underneath the existing church structure would cause great structural problems. From existing small cellars it was estimated that foundation depth of walls and columns would be about 2.7 to 3.0 m. The necessary excavation depth for an accessible cellar, taking into account the necessary space for a roof plate and new flooring system for the church, would be 3 m. To give the visitors the real feeling of an archaeological site, and not of a crypt under the church, it was decided to excavate the central nave and the adjacent aisles as well as part of the choir. This presents a surface of about 20 m by 40 m, in which the column footings and the wall foundations would be stand-alone elements. Removing of the soil around the foundations also takes away its constraining action on the foundation masonry. Moreover, the direct foundations at depths of about 3 m than become direct foundations on the soil surface.

The adopted solution consists of the underpinning of the existing foundations by means of micro piles and the consolidation of the masonry by means of cement injection and cemented steel bars.

The whole project is divided in several phases. Phase I is the excavation and re-arrangement of the west part of the church (1999-2001); phase II concerns the east part of the church (2003-2005) and phase III the choir (2006-2008). Excavation works and consolidation and strengthening as well as re-arrangement works are going on simultaneously. This means a lot of organization and compromise between archaeologists, contractor, designers and users.

2. SUBSOIL CONDITIONS:

Before the start of the works a general site investigation has been performed consisting of 6 CPT tests of 200 kN outside the church. From the results of these

tests the following composition of the subsoil could be deduced:

- filled and/or disturbed soil layers from groundlevel till 3 or 5m depth
- very dense tertiary sand layers ($q_c > 20$ MPa) till 15 or 20m depth

A typical CPT diagram is given on figure 1.

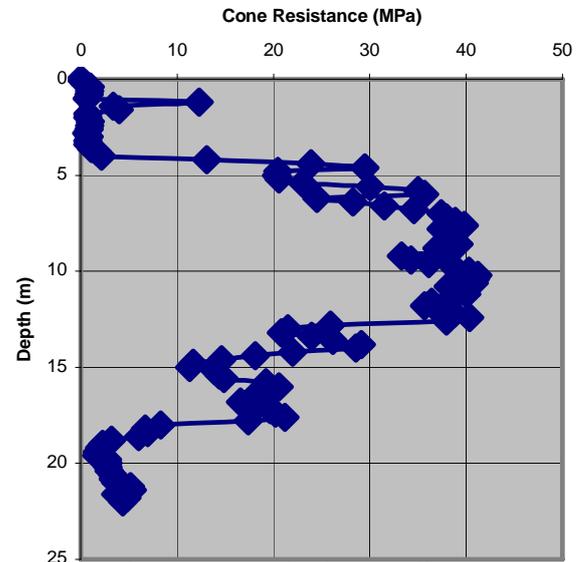


Figure 1: Typical CPT diagram

Before the start of each phase a detailed ground investigation has been performed consisting of:

- CPT tests in and outside the church
- 1 or 2 borings with prelevation of disturbed and undisturbed samples
- laboratory tests
- destructive borings with registration of the drilling parameters and/or Menard type pressuremeters tests.

Further on several cone drillings are performed through the foundations to be strengthened and underpinned. As there is always a real risk that the loose material within the rubble stone masonry is washed out during core drilling one has to be very careful with respect to the representativity of the obtained cores. For this reason several preliminary injection tests are performed in each phase before the start of the works to check the injectability of the existing foundations. The injection tests consists of the injection of a cement grout on three verticals situated on a triangular grid and of the execution of a core drilling in the middle of the grid after sufficient hardening of the grout.

3. CONSOLIDATION AND STRENGTHENING CONCEPT AND EXECUTION:

Figure 2 shows a plan of the nave, aisles and chapels of the church. The massive west tower is not represented. The first phase of the excavations is shown in the left part of the plan.

Figure 3 gives a cross-section of the archaeological cellar. The micro pile system under the columns and walls is also presented. The load bearing capacity of the micro piles is 200 kN pro pile. As can be seen also the exterior walls are supported by micro piles, although no excavation will be made next to these walls.

The underpinning of the columns and uncovered walls is needed because the strength of the foundation soil becomes insufficient after removal of the soil layer of about 3 m, representing a surface load of 50 kN/m². This heavy load will be removed over a large area of about 20 x 40 m, and by that the strength of the foundation soil drops drastically under the column footings and under the foundation walls. Also the stress distribution in the soil all over the church surface changes considerably, and as a consequence also the deformations of the soil will change. This might lead to excessive differential settlements of structural elements, leading to cracking of walls and vaults. The underpinning of all the columns and walls in and adjacent to the excavation will avoid such differential settlements.

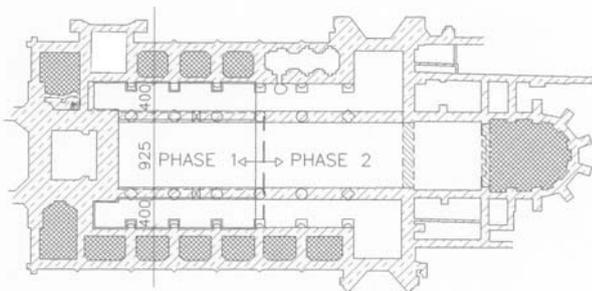


Figure 2: Plan of church with intended excavations

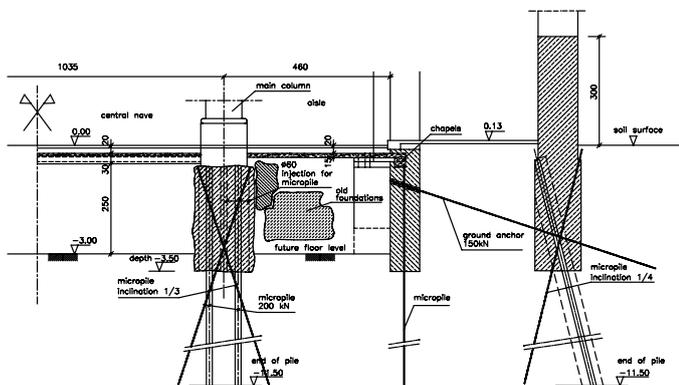


Figure 3: Cross-section of archaeological cellar

Ground anchors with tension capacity of 200 kN are installed in the north and south wall of the cellar. They secure these walls during the excavation, when exterior horizontal soil pressures are acting on the freestanding walls, not yet supported by the roof plate.

Micro piles and ground anchors must be anchored in a stable masonry, able to take up the concentrated forces from piles and anchors. Therefore the masonry walls are injected with the cement-based grout. The injection is made through vertical or slightly inclined boreholes, with a diameter of 50 mm. The grout consumption is calculated for an average filling rate of 25 % of the foundation masonry. Compressive strength tests on control coring indicated strength of 3 to 6 MPa for the injected masonry. The injection holes are drilled at the same location as the micro piles.

The following procedure is followed to place the micro piles. First a hole with 100mm diameter is drilled through the injected masonry. At the onset of the foundation, an auger type-drilling rod (type Ischebeck 40/16) is used to extend the borehole in the foundation soil to a depth of 12 m. The drilling rod is a thick walled tube with internal diameter of 16 mm and external diameter of 40 mm. With four screw-connected elements of 3 m the desired length of 12 m is obtained. The cutting bit has a diameter of 90 mm. The borehole is made under simultaneous injection of cement grout through the central hole of the drilling rod, with an injection pressure of ± 5 bar. At reaching the depth of 12 m the injection is continued until the grout is flowing out of the borehole. In this way a complete filling of the borehole with cement grout is guaranteed. The drilling bit makes a hole with a minimum diameter of 100 mm.

In order to check the bearing capacity of the micro piles a preliminary load test has been performed on a micro pile installed outside the church. Over the upper 3m the load transfer to the soil has been eliminated by means of a PVC tube. The obtained load settlement diagram is given in figure 4.

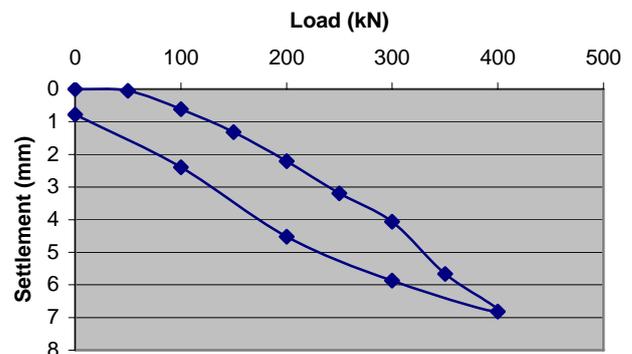


Figure 4: Maintained load test on a micro pile

The columns transfer a concentrated load of 1800 kN to the foundation footing. These footings are connected with a chain wall, as shown in Figure 5.

The position of the columns on their footings and on the chain wall is mostly eccentric. This eccentric position introduces additional bending stresses in the masonry. The available strength of 3 to 6 MPa after the first injection is not reliable enough to secure the arising compressive and splitting stresses. Therefore, an additional strengthening is executed in the column foundations, Figure 6.

Three layers of cemented anchors with diameter of 25 mm are placed to take up the horizontal splitting forces caused by the concentrated column load. The layers are placed when the excavation reaches the corresponding depth. After drilling the anchor holes a second injection of the cement grout is made through these holes, to improve the consolidation of the adjacent masonry. The number of anchors per layer decreases with increasing depth.



Figure 5: Chain wall between collars

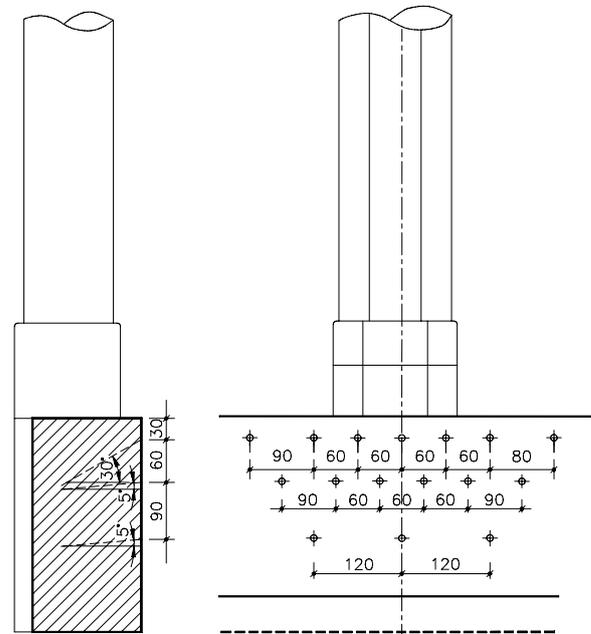


Figure 6: Cemented anchors in column foundations

4. GROUT SELECTION AND EXECUTION OF INJECTION:

The injectability of a cement grout depends in an important way on the fineness of the dispersion of the cement particles in the water phase. To prevent the dispersion from coagulation and segregation, the addition of stabilizers and superplasticizers is necessary. The effect of a superplasticizer lies in the generation of a positive ζ -potential on the surface of each cement particle, strong enough to disperse them. Furthermore, the attraction between the positive particles and the water molecules strengthens this effect and finally, the sterical disturbance of the molecules on the surface of the cement particles prevents the dispersion from coagulation. The materials used in the preliminary test program are:

- Cement: CEM III A 42.5
- Additives: Bentonite Bentonil CV15
Superplasticizer Rheobuild 716
(sulphonated naphthalene with polyhydroxylated polymer)
- Water

The mixing procedure is determining for the physical and mechanical properties of the cement grout. The following routine was adopted:

- dry mixing of cement and bentonite
- addition of 50 % of the water and mixing
- after 2 minutes, addition of 50 % water with 50 % of superplasticizer amount and mixing
- addition of 50 % superplasticizer and mixing

Component	Quantity
Cement IIIA 42,5	100 kg
Bentonite CV15	2 kg
Water	67.7 kg
Superplasticizer Rheobuild 716	1.0 kg

Table 1: Composition of the injected grout mix

The mixing procedure is determining for the flow of the grout and the final mechanical properties. The flow time of the mix through the AFNOR funnel n° 4 only reached 13 seconds. The final mechanical properties of this grout, measured on prisms 40 mm by 40 mm by 160 mm are given in table 2.

	Tensile strength MPa	Compressive strength MPa
After 7 days	4.4	26.8
After 28 days	4.0	31.8

Table 2: Mechanical properties of the injected grout (NBN B12-208)

5. MONITORING:

During phase I the following measurements have been performed:

- topographic measurement of the settlements and the verticality of the columns
- displacements at different depths in the soil by means of two rod extensometers
- very precise distance measurements by means of an invar band extensometers.

From the topographic measurements it could be deduced that settlements of about 1cm have occurred during phase I of the works. However, as the measurements have only been performed every 2 or 4 weeks it was not possible to determine exactly the origin of the settlements.

The two rod extensometers have been damaged during the installation of the micro piles.

The measurements with the band extensometers have been performed when an over excavation was made by the archeologists over almost the whole length of the foundations. As during a period of 1 week the distance between the two chain walls decreased with almost 2mm it has been decided to install steel struts between the walls in order to limit the possible horizontal displacements of the column.

During phase II the topographic measurements have been performed by means of a total station. In this way the displacements could be determined every 15 min. From the obtained data it could be deduced that:

- settlements mostly occur during the installation of the micro piles, however not during the drilling into the ground, as is expected normally but during the drilling of the hole through the existing foundation. Also rather surprising was that destructive drilling with a down the hole hammer and by core drilling produced the same settlements. The total settlements of the columns due to the installation of the micro piles varied between 4 and 8 mm. An example of the displacements measured during the installation of the micro piles underneath a column are given in figure 7.

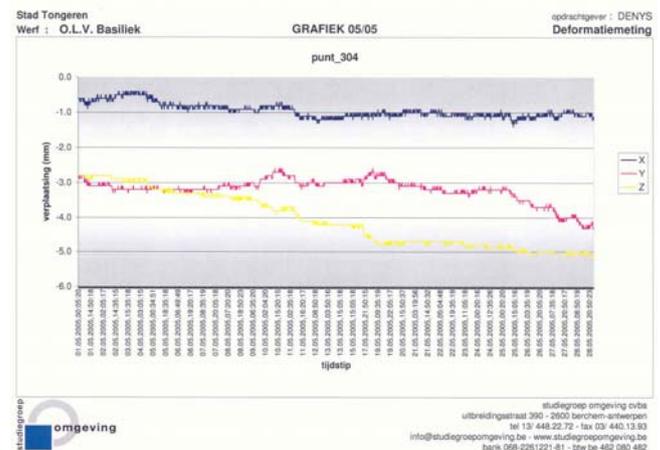


Figure 7: Observed settlements during the installation of micro piles (z = vertical direction, x and y = horizontal direction)

- during the excavations only very small settlements (= about 1mm) have been measured. This means that the load transfer to the micro piles has been rather small.

Long term settlement measurements are performed to check the variation of the settlements with time. Over a period of more than 1 year no substantial increase of the settlements has been observed.

A general view of the excavations is given in figure 8.



Figure 8: General view of the excavations

6. CONCLUSIONS:

Making an archaeological cellar under an existing monument is a challenging project, in which both archaeologists and engineers must discuss, persuade and compromise. The presence, location and magnitude of archaeological remains are unknown beforehand and archaeologists tend to excavate more, deeper and wider than originally planned. The design engineer must protect the monument as well as the archaeologists, but he also has to give them all the necessary help to discover and uncover as much as possible of the hidden objects, evidence and magnitude.

During the realization of the archeological cellar underneath the St Mary's Basilica much attention has been given to a detailed monitoring of the displacements. The topographic measurements by means of a total station during Phase II of the works provided extremely valuable information. From these measurements it could be deduced that:

- underpinning of the chain wall foundation produced some settlements. However these settlements are mostly due to a rearrangement of the rubble stones within the masonry, and much less to the drilling into the ground;
- almost no settlements occurred during the excavations.

It has to be stated that although the load transfer to the micro piles is probably rather small, their role is very important in stiffening the soil underneath the foundation and in providing the necessary ultimate bearing capacity and safety factor.

Consolidation injection and strengthening of masonry seem to be rather simple techniques, but practice proves that consistent quality can only be obtained through constant quality control of procedures and materials, and constant involvement of dedi-

cated and skilled designers. The production of stable grouts with appropriate flow and mechanical properties is a science as well as an art. The design engineers must acquire the science, the art must be taught to the technicians who execute the work.

REFERENCES:

- Van Gemert D. 1988, "*The use of grouting for the consolidation of historic masonry constructions*", Stable-Unstable, (Ed. R. Lemaire and K. Van Balen), Leuven University Press, pp. 265-276
- Van Gemert D., Ladang C., Carpentier L., Geltmeyer B. 1995, Consolidation of the Tower of St. Mary's Basilica at Tongeren, *Int. Journal for Restoration of Buildings and Monuments*, Vol. 1, no. 5, pp. 371-392
- E. Toumbakari E., Van Gemert D. 1997, Lime-pozzolana-cement injection grouts for the repair and strengthening of three-leaf masonry structures, *Proceedings 4th International Symposium on the Conservation of Monuments in the Mediterranean*, Rhodes 6-11 May 1997, Vol. 3, pp. 385-394