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NDT-Control of Injection of an Appropriate Grout Mixture for the Consolidation of the Columns Foundations of Our Lady's Basilica at Tongeren (B)

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ABSTRACT: With a grant of the Flemish government (IWT) and the support of a group of Belgian companies involved in restoration activities, a research project started in 2005, trying to control grout injections in masonry in a more reliable way. The study of appropriate grout mixtures and the application of geo-electrical measurements for restoration purposes are both parts of this research project. This paper discusses the analysis of the data, obtained during an on site measuring campaign, carried out to evaluate the injections of the columns' masonry foundations of Our Lady's Basilica at Tongeren (Belgium). The development of an appropriate grout for the injection is also briefly discussed in this paper. The selections of the grout composition, as well as the design of an effective injection procedure are based on laboratory and on site tests. It is demonstrated that a grout containing a specific mixture of slaked lime and hydraulic cement performed excellently within the preset boundary conditions.

1 GENERAL PURPOSE OF THE RESEARCH PROJECT

With a grant of the Flemish government (Institute for the Promotion of Innovation by Science and Technology in Flanders) and the support of a group of Belgian companies involved in restoration activities, a research project started in September 2005, trying to control grout injections in masonry in a more reliable way. The project was developed within a partnership between the Provincial College of Advanced Education of Limburg at Hasselt (B) and the Catholic University Leuven (B). The study of appropriate grout mixtures and the application of geo-electrical measurements for restoration purposes form the foundations of this research project and will be discussed in detail, using the case study of the injection of the column foundations of Our Lady's Basilica at Tongeren (B). The main objectives of the project are:

- *Inventory of knowledge*

Due to the wide spectrum of possible applications of grout injections, there is a lot of practical experience available, but this knowledge is widely spread throughout the building practice. The knowledge of injection techniques is fragmented and the structural inventory of all this knowledge is therefore very important. This classification will exceed the summary of existing techniques in the building practice. The outcome will be a well- argued decision matrix, which points out the correct grout mixture and evaluation sequence, given a specific grout problem and boundary conditions. This structuring forms the first part of the research project. Specific experiences with grout injections of a group of Belgian companies involved in restoration activities will be studied and expert aspects will be derived from them.

- *Integration of non-destructive techniques*

Secondly the integration of non-destructive techniques in the field of grout injections will be studied, not only for the evaluation of the quality of the deteriorated or injected massif (masonry or concrete) before and after injection. The aim is to develop the NDT-technology that hopefully makes it possible for on-line surveying of grout injections. The benefit is the possibility to alter the injection parameters during the injection itself so that the desired injection result can be obtained. Geo-electrical survey of masonry already proved to be a reliable non-destructive tool for this purpose (Janssens 1993, Keersmaekers 2003, Keersmaekers et al. 2004, Venderickx 2000, Van Rickstal et al. 2003)

- *Test programme*

The last objective of the project, indispensable as a support for the first goal, is a thorough investigation of the physical, physical-chemical, chemical and mechanical properties of different grout compositions and the correlation between the different parameters responsible for these properties. Special attention is hereby given to the bending strength of mineral grout mixtures.

2 CASE STUDY: OUR LADY'S BASILICA AT TONGEREN (B)

2.1 Introduction

Tongeren is an old Roman city, with a history of more than 2000 years. The city centre is an accumulation of remains of successive civilisations and cultures. Archaeological research in the Vrijthof-market at the south side of the church goes back to 1844 (Vanderhoeven and Van Gemert 1998). At that time a series of foundations were discovered, which were 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 10^{th} century and one from the 12^{th} century. At the same time a Roman town house with bathhouse from the 2^{nd} and 3^{rd} century was discovered, as well as a tower and connecting sections of the 4^{th} 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 Lady's Basilica.
The idea grew to disclose the remains under the church. However, religious life 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. Visitors will walk on bottom soil surface of the excavations, to keep the archaeological sensation as complete and as realistic as possible. 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 load carrying capacity of surface foundations is very limited and uncertain, and unconstrained rubble masonry of foundations has nearly no strength. Both effects significantly endanger the structure, leading to an almost certain collapse. Therefore the project was preceded by a preliminary investigation to reveal the composition and quality of the foundation masonry, and to study possible injection grouts for consolidation of the masonry, to strengthen it sufficiently to be able to transfer the anchoring forces of the micro piles (Fig. 1). The consolidation procedure was adapted according to the findings from the preliminary investigations.

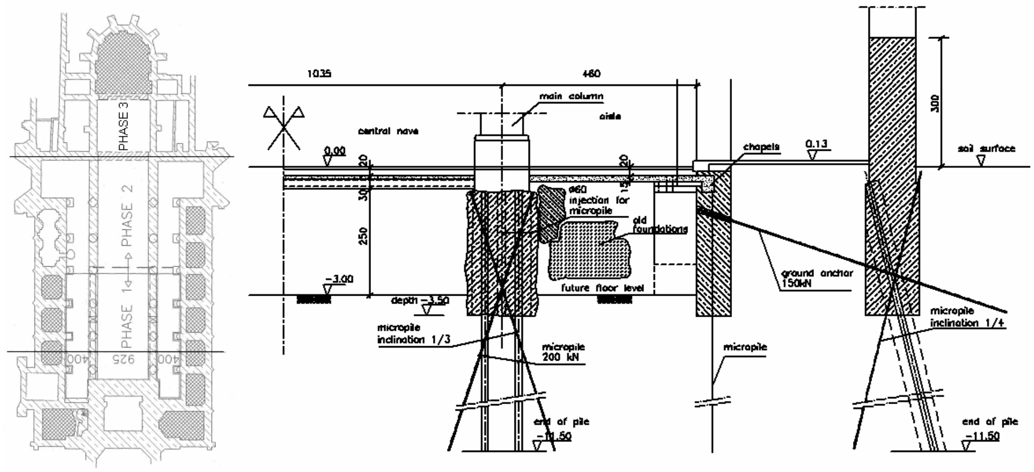

Figure 1 : Left: Plan of the church with excavation phases I and II.
Right: Cross-section of the archaeological cellar.

2.2 Consolidation and strengthening: concept

The whole project was 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 central part of the church. Excavation works and consolidation and strengthening as well as re-arrangement works are going on simultaneously. This means a lot of organisation and compromise between archaeologists, contractor, designers and users. Fig. 1 left shows a plan of the nave, aisles and chapels of the church. The massive west tower is not shown. More information about the consolidation of the tower can be found in (Van Gemert et al. 1995). Fig. 1 right gives half of the 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 per pile. 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 (Van Gemert et al. 2000). This heavy soil 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. 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. The micro piles must be anchored in a stable masonry, able to take up the concentrated forces from these piles. Therefore the masonry walls are injected with mineral grout.

3 CONSOLIDATION AND STRENGTHENING: EXECUTION

3.1 Phase I: (1999-2001), injection with cement based grout

The injectability of a cement grout depends amongst other on the fineness of the dispersion of the cement particles in the water phase. The addition of stabilizers and superplasticisers prevents the dispersion from coagulation and segregation. The injected cement-based grout was a mixture of cement, admixtures and water (see also Table 1).

Table 1 : Compositions of the binary grouts for the injections during phase II.
Remark: composition 1 is used as a reference, it is the cement-based grout used in phase I.

Component:	CEM IIIA 42.5 kg	Bentonite kg	$Ca(OH)_2$ kg	W/B ratio	Water litres	Glenium 27 kg
Composition 1	100	2		0.675	67.5	1
Composition 2	50		50	0.675	67.5	1
Composition 3	60		40	0.675	67.5	1
Composition 4	70		30	0.675	67.5	1
Composition 5	80		20	0.675	67.5	1

Although the main objective concerning the consolidation and strengthening of the foundation masonry was successfully executed with the cement based grout in phase I of the project, there were some disadvantages using this type of grout. Cement based grouts tend to remain very fluid for several hours, causing damage. Some valuable inscriptions on lime stone fragments were lost and even a skeleton was accidentally injected (see Fig. 2(b)).

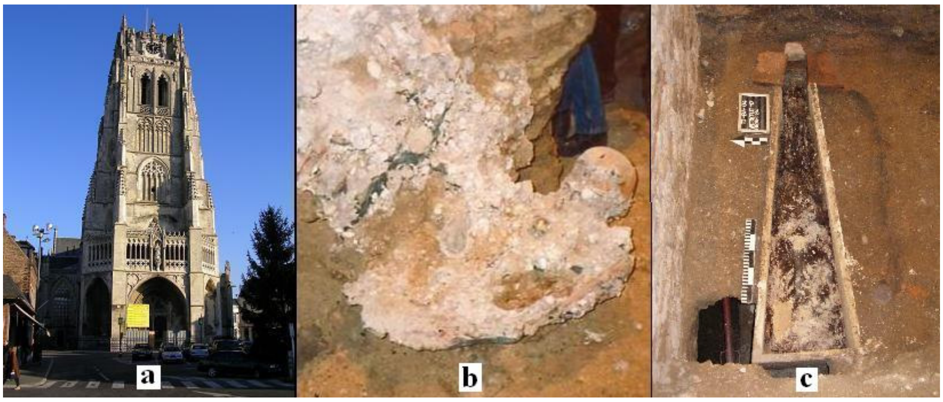

Figure 2 : (a) tower of Our Lady's Basilica et Tongeren (Belgium)
(b) unwanted "consolidation" of a skeleton (injected with cement based grout of phase I)
(c) sarcophagus next to the chain wall (excavated in phase II)

3.2 Phase II: injection with binary grout

In phase II it is attempted to prevent this unwanted filling of sarcophaguses, skeletons and inscriptions by using a different grouting material. The aim was to develop a mixture that not only satisfied all the requirements needed for structural strength but also limits the fluidity in time. In that way, the unwanted consolidation of valuable artifacts is reduced to a minimum.

3.2.1 Grout requirements

Tomazevic (Tomazevic 1992) and Toumbakari (Toumbakari 2002, Van Gemert et al. 1999) indicated that the mechanical properties of the grout hardly influence the final compressive strength of injected masonry in case of comparable injectability. Adhesion of grout to stone and mortar is more important. Therefore, it is preferable to focus on rheological properties of the grout and on tensile or adhesion strengths instead of on compressive strength. A second category of requirements could be named "compatibility" with the original material. The grout needs to be adapted to the original material with regard to three aspects: chemical (including durability), mechanical/structural and physical compatibility. Special attention is paid to the aspect of historical compatibility keeping in mind the original composition of the mortars.

- *Physical compatibility*

The physical compatibility of the grout concerns properties such as stability, fluidity and the injectability in the masonry structure. Stability is a first requirement for a grout to be admitted for injection purposes. A grout can be unstable in two major ways: bleeding and segregation and are prevented by composition and mixing procedure (Van Rickstal 2000). The fluidity of the grout is a rheological property (including thixotropy) commonly measured using a flow time test. It measures the time needed for a fixed amount of grout to flow through a hole out of a standardized recipient. Mostly used is the Marsh funnel providing the Marsh viscosity expressed in seconds, according to (ASTM C 939_(1987)) or (NF P18-358 (1985)). The injectability of polymer or mineral grouts is mostly checked by injecting a glass tube filled with fine or coarser sand according to the French standard: (NF P18-891 (1992)) "sand column test". For testing the injectability of mineral grouts it is better to adapt this test to produce a situation representative for the on-site boundary conditions. The viscosity and yield stress and hence the injectability of mineral grouts, highly depend on the water content. The dry masonry absorbs water from the grout. The injectability of the grouts should rather be checked in a column filled with crushed bricks to simulate a water absorbing action comparable to the real situation.

- *Mechanical and chemical compatibility*

The most important mechanical properties that apply in this particular case are the tensile and adhesion strength. Chemical compatibility is also very important. There is the possible growth of ettringite crystals when injecting cementitious grouts. This is why blast furnace slag cement is preferred over ordinary Portland cement.

3.2.2 Grout development

In order to fulfill the requirements, it was decided to examine several mixtures of binary grout using cement and air hardening lime as basic materials. Table 1 shows the different mixtures that were tested. Table 1 mentions the W/B (water/binding agent – ratio) in stead of the W/C because the binding agent is a mixture of cement and air hardening lime. This W/B and the amount of superplasticiser (Glenium 27, polycarboxylic ether superplasticiser) were kept constant. Practical experience showed that higher amounts of superplasticiser increased shrinkage; lower amounts require too much water (Van Rickstal 2000). The following mixing procedure was used: dry mixing of cement and calcium hydroxide, addition of 90 % of the water and 2 minutes mixing (2400 r/min), after 2 minutes rest, addition of 5 % water with 50 % of superplasticizer amount and mixing for 3 minutes (2400 r/min), after 2 minutes rest, addition of the final amount of water (5%) with the last 50 % of superplasticizer and mixing for 2 minutes (2400 r/min).

A two years test programme was implemented to study the long term effects of the grout mixtures of Table 1. The tests were done on samples 40x40x160 mm³ according to the standard (NBN EN 1015-11 (1999)) for compression and flexural strength. The environmental conditions of the samples were kept constant for the first 90 days at R.H. higher then 96%; CO_2-amount 3 % (using a CO_2-incubator) and temperature of 20 °C. Than the samples were divided into two groups A and B, corresponding to a relative humidity higher than 96 % (group A) and 85 % (Group B) for a two years testing period. The idea is to study the long term effect of delayed carbonation of the air hardening lime on the cement-matrix (instantly formed during the hydraulic reaction). Therefore a CO_2-amount of 3 % is used (normally the CO_2-content in the atmosphere is 0.03 %) to accelerate the carbonation process. In (Van Balen 1991) it was stated that the carbonation rate reduces dramatically with increasing relative humidity. By keeping the R.H. high (> 96 %) for the first 90 days, the hydraulic reaction of cement will dominate the curing process. By reducing the R.H. to 85 % after 90 days (group B), the carbonation process will take part in the curing process and the long term effects on the mechanical properties can be studied.

- *Physical properties*

The stability is checked by measuring the bleeding which can be read from the scale on a lab tube in which the grout is poured. The bleeding was measured after 0', 15', 30', 60', 90' and 120'. It is concluded that the higher the content of cement, the higher the bleeding will be. Air hardening lime seems to function as a very good stabilizer. Composition 1 produces the most bleeding, but still keeps bleeding under 3 %, which is regarded to be tolerable for grout mixtures. The fluidity test is performed with a Marsh funnel Viscometer (cfr. ASTM C 939 (1987)). The Marsh cone used was an OFITE and is calibrated so that it takes 26 ± 0.5 seconds for 947 ml of water (21 ± 3°C) to pass the funnel. Fig. 3 gives the Marsh cone flow times of the different compositions tested for phase II. The flow times were measured after 0', 15', 30', 60', 90' and 120'. As mentioned before, it is the aim to develop a grout who's fluidity stays constant the first one and a half hour and then decreases rapidly. Fig. 3 clearly shows that compositions with an air hardening lime content above 30 % fulfill this special condition needed to prevent the filling of the valuable artifacts. The injection test consisted of the injection with grout (composition 3), under a constant pressure of 1 bar, of a Plexiglas column, which was filled with gravel (broken bricks). The crushed bricks show a water absorbing action comparable to the real situation. The size of the brick particles varies between 1 mm and 2 mm. The grout proved capable of consolidating the gravel.

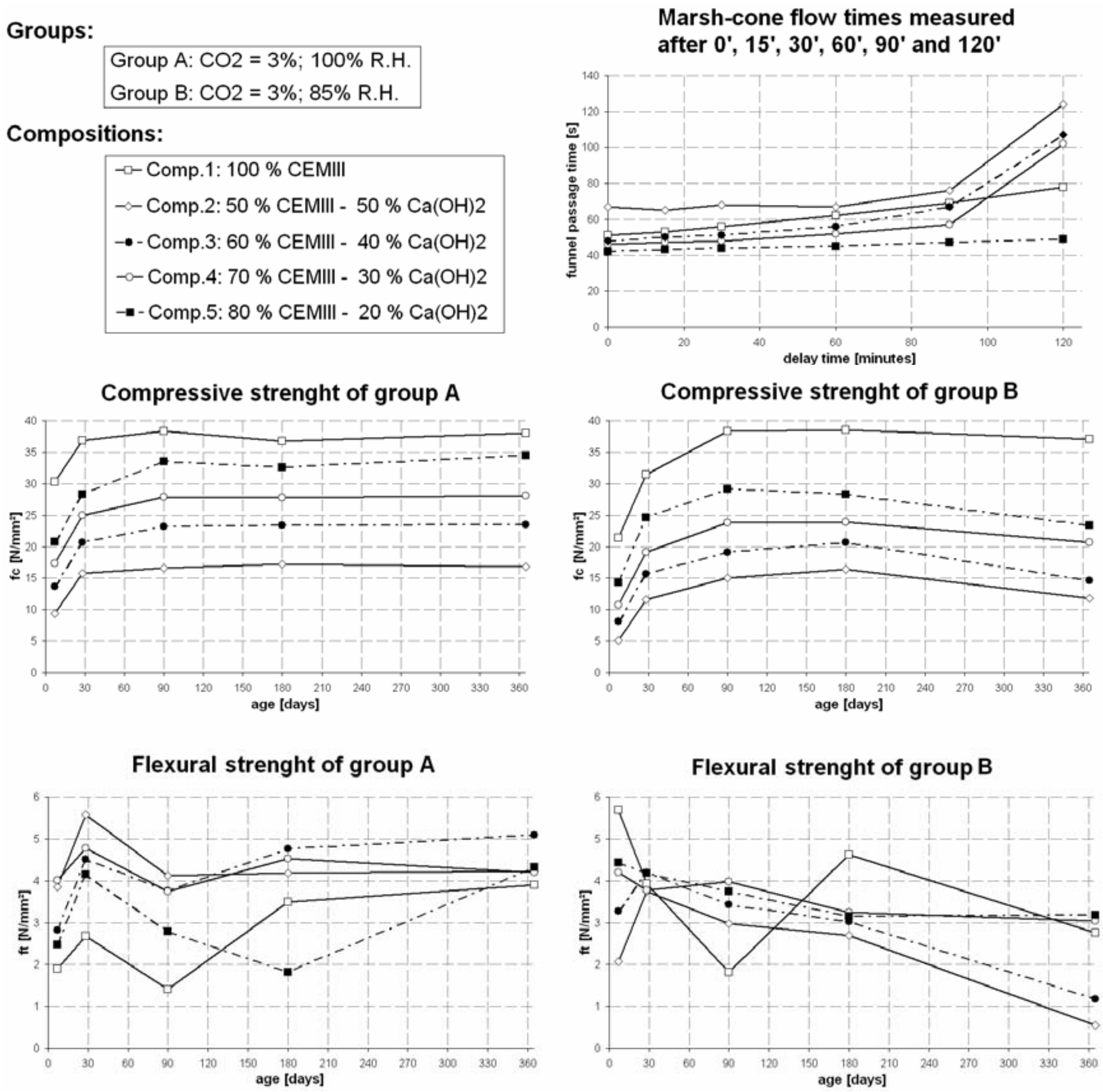

Figure 3 : Mars-cone flow times and compressive and flexural strength of the different compositions

- *Mechanical properties*

The compressive and flexural strength test are being executed after 28, 90, 180, 365 and 730 days. At the time of writing, the tests were executed after 7, 28, 90, 180 and 365 days. Fig. 3 gives the evolution of the compressive and flexural strengths of the different compositions of both groups. Higher cement content results in higher compressive strengths. The compressive strength of group B tends to decrease slightly after a year. The flexural strength depends on the amount of cement and the relative humidity. Group A (R.H. > 96%) shows no decrease of the flexural strength after 365 days. For group B, a cement content of 70% is observed to be a minimum to prevent dropping of the flexural strength. The drop of flexural strength is probably due to microcracking occurring at the interior of the samples. It is assumed that the reason of this microcracking is caused by drying or by the difference between areas of the grout situated towards the exterior of the specimen that are carbonated and other areas towards the interior, that are still hardening. Hydration causes chemical shrinkage and induces tensile stresses (and thus microcracking) at the interface of a carbonated (and thus inert) part of the material and a non carbonated (and thus hydrating) part of it. A similar phenomenon was already observed and described in (Toumbakari 2002) for grouts containing silica fume. This phenomenon is the topic of an extensive research at the Catholic University of Leuven. After considering all the objectives, it was decided that composition 4 (70 % cement, 30 % slaked lime) corresponded best with all the requirements stated above and therefore was used on site.

4 ON SITE TESTING AND VERIFICATION OF THE INJECTIONS

4.1 Destructive tests

Some test injections were performed on site with composition 4. Three injection holes were drilled, forming an equilateral triangle with a distance of 60 cm, and filled with grout under atmospheric pressure. After curing, a core was drilled in the equilateral triangle. Due to the presence of very hard stone material in the foundations and the resulting difficulties experienced during drilling of the core, the core itself did not present a good image of the injection degree of the masonry (Fig. 4 top left). To verify the injection, an endoscopical survey of the drilled holes for the micro piles was executed, showing high degrees of consolidation. The injected grout itself was also tested and controlled. The Marsh funnel flow time evolution was checked for every day’s grouts and every 3000 litres some samples of 40x40x160 mm were moulded for compression and flexural strength (cfr. NBN EN 1015-11 (1999)). The physical and mechanical properties of these samples correlated with the laboratory tests.

4.2 Non-destructive test, geo-electrical tomography

A geo-electrical tomography was performed for controlling the efficacy of the injection under a representative column. 48 stainless steel nails, spacing 10 cm, are used as electrodes, placed on a survey line (Fig. 4 left) approximately spread out 1 meter under the column. This method is an adaptation for masonry structures of a technique in geophysics within the field of geo-electrical survey of soils (Van Rickstal 2003, Keersmaekers 2003, Keersmaekers 2004).

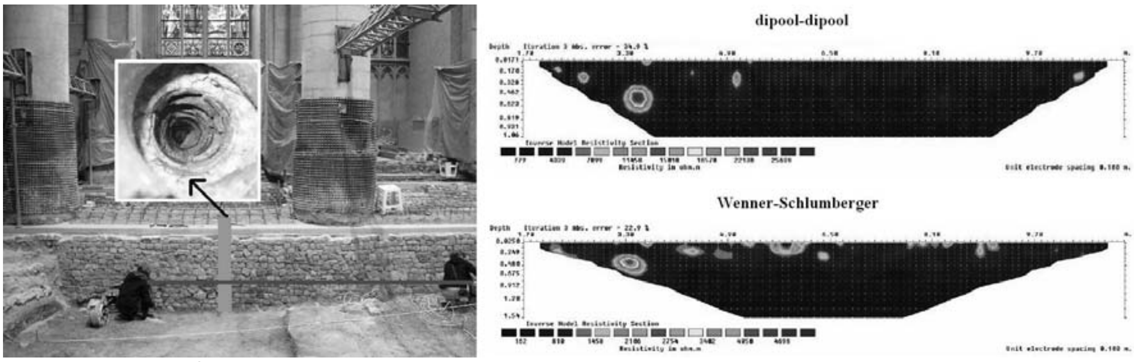

Figure 4 : left: black line = survey line; grey tube = borehole; right: dipole-dipole and Wenner-Schlumberger geo-electrical tomography showing the presence of the borehole.

The electrodes are connected in different combinations, performing several hundreds of measurements, to construct a pseudo-section, which is the graphical representation of the apparent resistivity values for a 2D-section of the masonry wall. The word “apparent resistivity” is used because this value is the resistivity value that would be measured in case of a perfectly homogeneous material. In reality this is not the case. Therefore, it is not possible to draw conclusions about the real resistivity distribution of the substrate (internal structure of the masonry) based on the measured pseudo-section. Inverse modelling enables to reproduce the resistivity distribution in the masonry structures that results in the obtained pseudo-section. The philosophy is to construct a model representing a certain distribution of the underground (wall) resistivity of which the calculated pseudo-section is the same as the measured pseudo-section. The underground is therefore divided in blocks or elements and each block is given a certain resistivity value. A least-square fitting between the calculated and the measured pseudo-section determines how the the resistivity values of the different blocks have to change in the next iteration in order to improve the least-square fitting of the calculated and the measured pseudo-section (Loke 2002, Keersmaekers 2003). Fig. 4 at the right shows two “inverted” cross-sections of the measured survey line, using respectively the dipole-dipole and the Wenner-Schlumberger electrode configurations. Both representations show the presents of a round anomaly which was verified on site as the remains of a borehole made for the evaluation of an injection test. It was left open during the excavations, filled itself with rubble and sand and was then closed by the concrete base for the floor slabs (Fig. 4 left). Furthermore, the geo-electrical survey showed a good consolidation of the masonry under the column.

5 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. Stability reasons made grouting inevitable, and the specific conditions required some special properties for the grout. The fluidity of the grout must be sufficient during injection, but has to decrease rapidly after a predetermined period. The binary grout developed is able to fulfill the physical, chemical and mechanical requirements. An extensive test programme including laboratory and on site experiments, both destructive and non-destructive, proved that grout mixtures of cement and slaked lime act complementary, producing the requirements needed in this project.

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