

Enhancement of geo-electrical techniques for NDT of masonry

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ABSTRACT: A geophysical resistivity measuring device was modified to perform automatic monitoring of historical masonry structures before, during and after grout injection for consolidation purposes. The obtained image is called a geo-electrical tomography. The technique was used to evaluate the deteriorated masonry of the recently partly collapsed Maagdentoren in Zichem, Belgium. The results of these measurements are discussed. An important improvement is the adaptation of the “cross-borehole” measurement technique for masonry. With this technique, a constant resolution in depth is achieved. Laboratory tests, using an adaptation of the “cross-borehole” technique, enabled to show the resistivity distribution changing during the injection of a test specimen with a hydraulic grout.

1 INTRODUCTION GENERAL PURPOSE OF THE RESEARCH PROJECT

With a grant of the Flemish government (IWT-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, aiming to improve control methods for grout injections in masonry. The project was developed within a partnership between the Provincial University College Limburg, Department of Architecture, Hasselt (B) and the Katholieke Universiteit Leuven, Department of Civil Engineering, Building Materials Division (B). The main objectives of the project are:

1.1 *Inventory of knowledge*

Due to the wide spectrum of possible applications of grout injections, a lot of practical experience is present, but this knowledge is partitioned, spread throughout the building practice and not readily accessible. The knowledge of injection techniques is fragmented and the structured inventory of all this knowledge is therefore very important. This classification will not only be the summary of existing techniques in the building practice, but it will also be a well-argued decision

matrix, which points at the correct grout mixture and evaluation sequence, given a specific grouting 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 out of these experiences.

1.2 *Integration of non-destructive techniques*

Secondly the implementation 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 massive (masonry or concrete) before and after injection. The aim is to develop the NDT-technology that should enable on-line surveying of grout injections. The benefit would be 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; Keersmaekers et al. May 2006; Keersmaekers et al. Nov 2006; Marchisio et al. 2002; Van Rickstal and

Vanhellemont 2002; Van Rickstal et al. 2003; Van Rickstal et al. 2006; Venderickx 2000).

1.3 Test program

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 relation between the different parameters responsible for these properties. Special attention is given hereby to the bending tensile strength of mineral grout mixtures, being the most representative for the bonding properties of the grout.

2 BASICS OF GEO-ELECTRICAL MEASUREMENTS

In the past, geo-electrical resistivity measurements were already used successfully in restoration projects by the Reyntjens Laboratory (Janssens 1993; Venderickx 2000). The interpretation of the geo-electrical measurements was based on the apparent resistivity value. The word “apparent resistivity” is used because this value is the resistivity value that would hold for a fully homogeneous and isotropic material. In reality this is not the case. Walls have a heterogeneous resistivity distribution.

In the recent past new developments were made in geophysics within the field of geo-electrical survey of soils. This was possible thanks to the growing effectiveness and power of numerical methods. Software was developed which can invert the measured apparent resistivity values to a distribution of absolute resistivity values of the subsoil. (Dey and Morrison 1979; Geotomo 2002; Lines and Treitel 1984; Loke and Dahlin 1997; Loke 2002) The resistivity measurement remains the same, but the sequence is different and the number of measurements is larger than previously common on masonry structures.

The technique is known in geophysics as geo-electrical tomography. Figure 1 shows the necessary measurements for a Wenner-alfa electrode-configuration with 20 electrodes. Each of these electrodes, mostly stainless steel nails, can be used to inject current (current electrodes C1, C2) or to measure potential (potential electrodes P1, P2). Conducting the first row of measurements, a distance “a” (n = 1) between C1P1, P1P2, P2C2 is kept constant, leading to 17 (20–3) measurements on this particular row. Raising the electrode distance to “2a” (n = 2) gives a bigger influenced zone of the masonry (i.e. more profound penetration of the potential field), resulting in an apparent resistivity value representative for a larger and deeper zone of the masonry. Conventionally, this apparent resistivity value is allocated to a physical

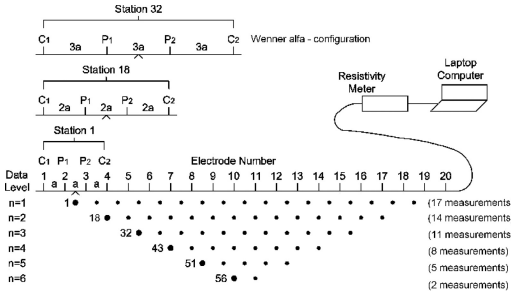


Figure 1. 2D geo-electrical tomography; Wenner-alfa electrode-configuration; subsequent measurements for building a pseudo-section.

point, centrally located between the four electrodes and on a depth equal to the average depth of the influenced zone of the potential field. Note that the second row of measurements (with an electrode distance “2a”) has only 14 (20–2 × 3) measurements. The number of measurements decreases with augmenting electrode spacing (i.e. higher penetration depth). In this way apparent resistivity values are gathered over the depth of the masonry structure and a “pseudo-section”, which is the graphical representation of the measured apparent resistivity values, is built.

Unfortunately, the 2D pseudo-section does not enable direct interpretation of the apparent resistivity values. No conclusions about the real resistivity distribution in the substrate (internal structure of the masonry) can be drawn based on apparent resistivity values. To build the real resistivity distribution it is necessary to numerically invert or transform the pseudo-section values into real resistivity values. Forward modelling enables the calculation of the apparent resistivity values (pseudo-section), starting from a given resistivity distribution. The idea is to construct a numerical model with a resistivity distribution whose calculated pseudo-section corresponds with the measured pseudo-section. The section of the wall is therefore numerically divided into blocks or elements, where every element is given a resistivity value. A least square approximation between the calculated and measured pseudo-sections determines how the model parameters (i.e. the resistivity values of the model blocks) must change in the next iteration, resulting in a better correlation between calculated and measured pseudo-sections.

In practice, a measuring campaign starts by positioning the electrodes. Stainless steel nails are used for masonry structures. The electrodes are connected to the automatic scanning module which switches the nails as current or potential electrode. In this research project, the geo-electrical measuring device Terrameter SAS1000 was used.



Figure 2. After the collapse on June 1st, 2006.

3 CASE STUDY: MAAGDENTOREN ZICHEM (B)

3.1 History

The “Maagdentoren” or “Tower of the Virgins” is located at the bank of the Demer river and is a 26 meters high, 15 meters wide ferruginous sandstone tower. The walls have a thickness of 4,2 meters at the base and 1,8 meters at the top. Over history, numerous reparations, renovations and restorations were done. This exceptional piece of medieval architecture was built in 1380. The original function is unclear, but it can be assumed that the tower served multifunctional purposes. It was used residentially, military and prestigiously. The tower was partly destroyed during the Eighty Years' War around the 16th century. The upper level and the entrance were demolished.

A series of necessary repairs were executed in 1863 and 1905. After that, the tower deteriorated for the rest of the century, resulting in a partial collapse of a part of the outside parament in 1995. The biggest catastrophe occurred on June 1st, 2006, when a huge part of the outside wall collapsed (Figure 2).

Figure 3 shows the location on the tower where a dipole-dipole electrode configuration was used to perform a geo-electrical tomography (white line). The survey line of the tomography was deliberately

partially placed over a visually good looking part of the wall and a bad looking zone. This visually bad looking zone is caused by the demolition of an historic defence platform that was situated there (Figure 3).

3.2 Geo-electrical measurements

Figure 4 shows the inverted section of the measured survey line, using the dipole-dipole electrode configuration. Remark that the inversion result does not lead to the same conclusions as would be drawn from a visual inspection of the surface only. A dark colour represents a high electrical resistivity, meaning a deteriorated zone in the masonry. From the outside visually good looking zones of the masonry show high resistivity values on a depth of 30 to 40 centimetres on the tomography. This depth corresponds with the thickness of the outer leaf of the wall. These high resistivity values continue over a thickness of 50 to 60 centimetres. After that the resistivity values decrease, meaning less deteriorated and less eroded masonry. This conclusion was verified with an endoscopic (borehole 1) examination. The following damage mechanism can explain this phenomenon. The ferruginous sandstone of the outer leaf absorbs rainwater like a sponge. This water penetrates the outer leaf by capillary forces, wetting the inner core of the three leaf masonry and dissolving lime from the mortar. When the wall dries, leaching of the dissolved lime from the inner core takes place. After several centuries, this led to a severely deteriorated zone of approximately 50 centimetres thickness behind the outer leaf. Deeper in the wall, the masonry is less deteriorated and shows better cohesion (lower resistivity values). The masonry that visually looks the worst (zone of the defence platform), shows lower resistivity values on the tomography (indicating a better cohesion) compared with the adjacent masonry. An exception can be observed at borehole 2, where a more deteriorated zone is seen on the tomography. This zone was verified by the endoscope. Borehole 3 confirmed the overall better state of the masonry. The explanation for the fact that the bad looking masonry from the outside is less deteriorated and has a better cohesion than the good looking masonry is the following. At this place there was a defence platform which protected the now exposed masonry for centuries for deterioration.

Around the tower, evidence of foundations of three of these defence platforms were discovered during archaeological surveys conducted in the eighties of the past century. When these platforms were removed is not clear until the present day (Oost and Geyskens 1982).

3.3 Conclusions for the case study

Based on the geo-electrical tomography and the endoscopic examination of some boreholes, it can be concluded that the overall state of the “Tower of the

Virgins” is seriously deteriorated for a significant part of its thickness. Keeping in mind the collapse on the first of June 2006, a consolidation injection with an appropriate hydraulic grout is urgently needed to preserve this monument for the next generations.

4 LABORATORY TESTS: CROSS-BOREHOLE

Geo-electrical tomographies, as described above, have the disadvantage that the resolution decreases with the penetration depth of the measurements. Nevertheless,

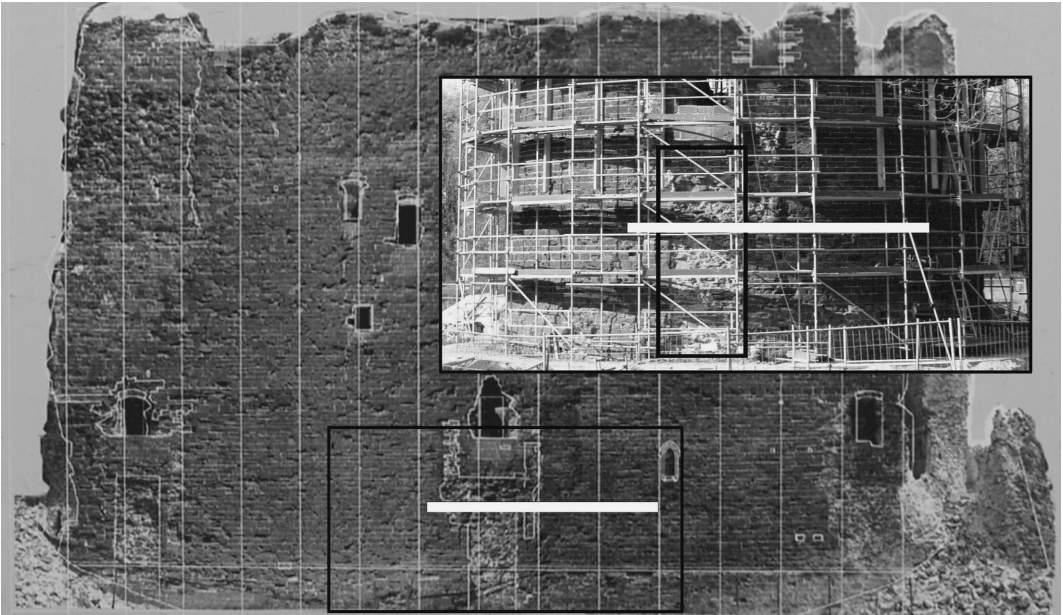


Figure 3. Position of the survey line on the tower; Insert: detail with in white the position of the electrodes and in black the position of the historic defence platform, removed in an unknown past.

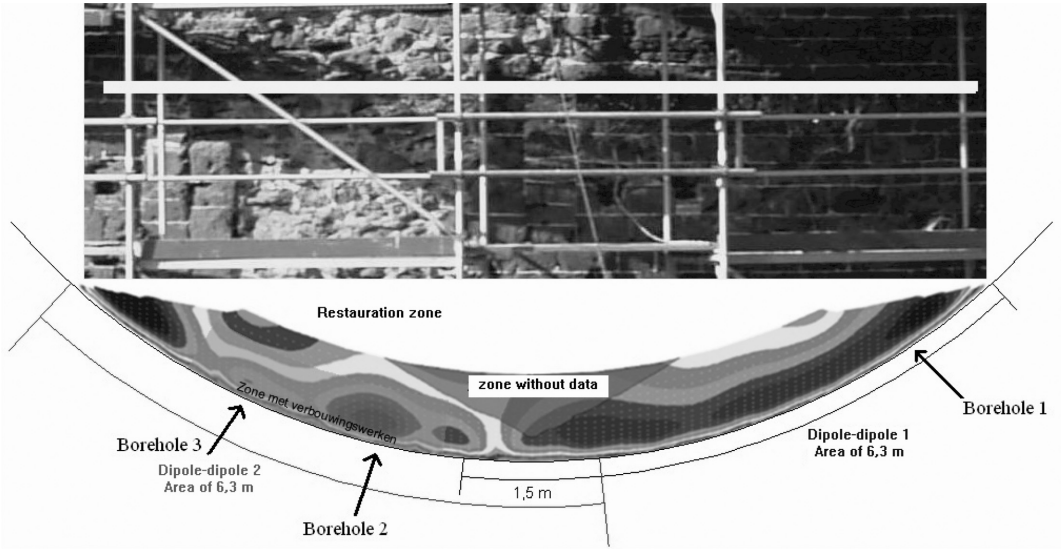


Figure 4. Above: position of the electrodes on the wall (white line); Below: inversion result of dipole-dipole measurements and the location of the boreholes for the endoscopic survey.

very interesting conclusions can be drawn based on these tomographies as was clearly shown in the case study above. In the research project, another existing technique was adapted for masonry, based on a two sided approach of the wall, whereby on both sides electrodes are placed. In geophysics this technique is referred to as “cross-borehole”. Theoretical research and numerical simulations showed that this approach leads to a constant resolution over the depth of the wall (Bernaerts and Moens, 2006; Stroobant and Verkest, 2007). Figure 5 shows the result of a successful cross-borehole measurement, without going into the technical aspects. A replica of a three leaf masonry wall was built in the laboratory, containing a piece of insulation simulating a void in the wall. The inversion result (Figure 5 Right) clearly shows that the insulation

is detected as a high resistivity within the graphical representation of the resistivity distribution.

5 LABORATORY TESTS: ON-LINE MONITORING OF A GROUT INJECTION

The cross-borehole technique seemed suitable for on-line follow up of hydraulic grout injections. This means that it can be used during injections in a way that an image can be constructed showing the grout flow in the masonry. This would be a useful appliance to evaluate the effectiveness of the injection. Also the detection of grout leaching in unwanted directions and the incomplete filling of voids could be detected in real time.

To accomplish this, a customized sophisticated data logger had to be built. This was necessary because the system must be capable of reading, filtering and processing the data fast enough to evaluate the injection in real time. A Labview-based (National Instruments) system was built using 48 analogue input channels which can be sampled parallel with each other. The principle is as follows. On one side of the wall 3 parallel rows of 16 current electrodes are placed and connected with the automatic switching module. This is the active side of the wall. Likewise, on the backside of the wall 3 parallel rows of potential electrodes are placed and connected to the data logger. This is called the passive side and here the response to the injected currents is measured. In this way it is possible to measure 9 cross borehole tomographies in 90 to 120 seconds (see Figure 6: Left). After inversion the nine 2D-images are combined to a single 3D-image of the resistivity distribution (Stroobant and Verkest, 2007).

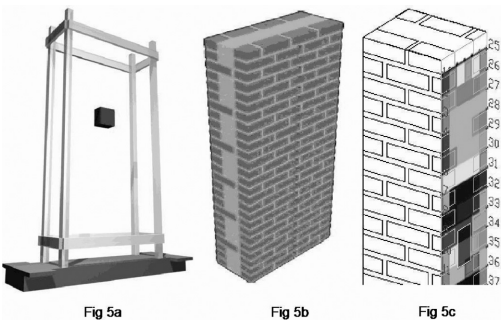


Figure 5. (a) Position of insulation as a simulation of a void; (b) Position of the electrodes; (c) Inversion result of the cross-borehole survey, with the high resistivity at location of insulation block.

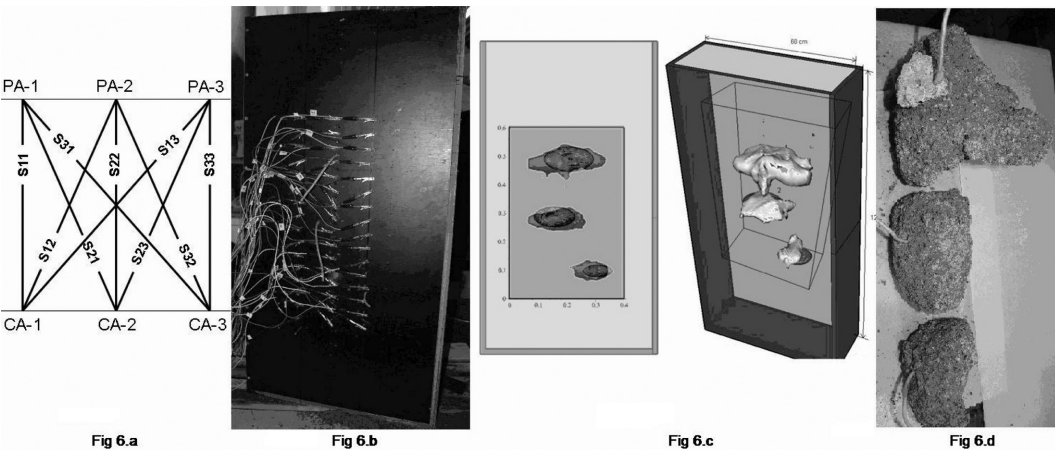


Figure 6. (a) 9 cross-borehole tomographies used to construct a 3D image of the inversion; (b) 3 x 16 current electrodes, the potential electrodes (3 x 16) at the backside; (c) Position of the volumes of gravel to be injected and the result of the inversion 3D-inversion result at the end of the injection; (d) Injected volumes, excavated after hardening of the grout.

A laboratory test was built in order to test new procedures for on-line follow up of grout injections. Three zones with high resistivity (representing deteriorated, little cohesive masonry) were placed in a volume of sand. This was done by inserting three volumes of tennis court gravel (different sizes) in the sand volume (Figure 6: Middle). Gravel consists of crushed bricks, an easily injectable material. A reference measurement was done before the injection started. Then, every gravel volume was gradually injected with a hydraulic grout. Simultaneously, the set of 9 cross borehole tomographies was measured every two minutes. Drawing of the relative difference charts, which gives graphic representation of the difference in resistivity between two subsequent 3D-tomographies, clearly shows the gradual filling of the different gravel volumes. The good electrical conductivity of the grout leads to local resistivity drops creating a big contrast with the former high resistivity of the gravel. This provides an excellent condition to detect the injected area on a relative difference chart. Figure 6 (Middle right) gives the 3D relative difference chart between the last measurement (at the end of the injection of the three volumes) and the reference measurement before injection. Notice how clearly visible the injected zones appear on the image. The three volumes were excavated after hardening of the grout (Figure 6: Right). A good correlation between these volumes and the inversion result was observed.

Drawing of the relative difference charts, which gives graphic representation of the difference in resistivity between two subsequent 3D-tomographies, clearly shows the gradual filling of the different gravel volumes. The good electrical conductivity of the grout leads to local resistivity drops creating a big contrast with the former high resistivity of the gravel. This provides an excellent condition to detect the injected area on a relative difference chart. Figure 6 (Middle right) gives the 3D relative difference chart between the last measurement (at the end of the injection of the three volumes) and the reference measurement before injection. Notice how clearly visible the injected zones appear on the image. The three volumes were excavated after hardening of the grout (Figure 6: Right). A good correlation between these volumes and the inversion result was observed.

The above technique seems very suitable for on-line follow up of grout injections. Conventional geo-electrical tomographies (like in the case of the Tower of the Virgins, or cross-borehole), used to determine the internal structure of the masonry, can not always be interpreted unambiguously. Therefore, the conclusions based on conventional topographies should always be verified with destructive tests, like endoscopic survey or core drilling. This disadvantage disappears when the technique is used for on-line follow up of grout injections. When composing a difference chart, relative to

a reference measurement before injection, the contrast is caused by an external influence (the injected grout). This definitely simplifies the interpretation, because the difference in resistivity can only be caused by the added grout.

6 CONCLUSIONS

With a grant of the Flemish Government (IWT) and the support of a group of Belgian companies involved in restoration activities, a research project was started in September 2005, aiming to control grout injections in masonry in a more reliable way. One of the objectives was the implementation of non-destructive techniques in the field of grout injections. The project showed the feasibility of performing geo-electrical tomographies (one side approach and two sided approach by means of cross-borehole) for the evaluation of the quality of deteriorated or injected masonry before and after injection. An adapted new NDT-technology has been developed for on-line surveying of grout injections. The benefit is the possibility to adapt the injection parameters during the injection so that the desired injection result can be obtained.

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