Detecting defects in diaphragm walls prior to excavation

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1 Abstract

Recent incidents with leaking diaphragm walls during construction of subway lines in Amsterdam and Rotterdam (Netherlands) have led to reconsideration of the diaphragm wall as a retaining wall construction for deep excavations. In our opinion the joints between the panels are the weak spot. During concrete pouring the concrete should replace the bentonite slurry. If it fails to do so, bentonite inclusions occur (mainly) in the joints. These inclusions are almost impossible to detect with a pumping test or EFT/ERT measurements because the hydraulic resistivity of the inclusion is very high. After excavation however, the bentonite inclusion may become unstable, causing leakage and settlements in de surroundings.

Therefor two research projects were initiated at TU Delft, one focusing on optimizing the production process of diaphragm walls and one (as described in this paper) on developing measurement techniques for early (before excavation) detection of defects in the joints.

In two projects with deep excavations in the Netherlands, field tests with five different measurement techniques have been carried out. In a scaled test with a known anomaly the basic response of the measurements has been tested. The tested techniques are: Distributed Temperature Profile, Natural Gamma Radiation, Cross-hole Sonic Logging (CSL), Single-hole Sonic Logging (SSL) and Direct Conductivity. In this paper the results so far will be presented and discussed. Preliminary conclusions will be drawn. A detailed setup in a diaphragm wall of the most promising method, Cross-hole Sonic Logging, will be shown together with recommendations for the interpretation of the field measurements. An outlook on the upcoming research steps and expected results will be given.

2 Introduction

Traditionally, diaphragm walls were considered a safe and proven technology for constructing the wall of a deep excavation. Due to recent uncontrollable leakages occurring in metro building projects in Amsterdam and Rotterdam, the risk profile of the diaphragm wall has changed.

As there is a clear need to reduce the uncertainty of the quality of in-situ formed construction elements, a research project has been started to determine if areas with a high risk of leakage can be detected before excavation takes place. Like in borehole geophysics, it was assumed that the combination of several measurement techniques will lead to a reliable conclusion. Therefor five different measurement techniques were investigated. These are: Distributed Temperature Profile, Natural Gamma Radiation, Cross-hole Sonic Logging (CSL), Single-hole Sonic Logging (SSL) and Direct Conductivity. Measurements were carried out on site as well as on scaled test samples.

3 Test locations

Underneath the ‘Kruisplein’ in the center of Rotterdam a 6 stores underground parking facility is being constructed. Diaphragm walls to a depth of 42 m minus surface level (at which level a clayey layer with high hydraulic resistivity is present) will ensure a robust and watertight ground retaining construction.

Several measures to improve the quality of the diaphragm walls were included in the contract (e.g. every truck load of concrete has been tested on consistency levels). To reduce the uncertainty of the final build quality, the hydraulic resistance of the wall is also tested by lowering the water table inside the building pit.

Still, in case of bentonite inclusions in the joints between the diaphragm wall panels, potential weak spots in the wall will not be found in the pumping test, as the bentonite inclusion has a high hydraulic resistance and will therefor prevent water inflow through the diaphragm walls. During excavation however, the bentonite inclusions may become unstable, due to the change in horizontal ground and water pressure. After gradual degradation of the bentonite inclusion, a sudden major leak can occur, resulting in large volumes of water and (possibly) sand flowing into the building pit. If transport of sand occurs, subsidence outside the building pit will occur, causing damage in case of neighboring buildings and infrastructure.

It was therefore thought worthwhile to investigate the possibilities to detect bentonite inclusions prior to excavation. Measurements on site on four diaphragm wall joints and on two laboratory sized blocks were performed in fall 2009 and spring 2010.

After the first positive results from the tests in Rotterdam, the contractor of the railway tunnel project ‘Spoorzone’ in Delft decided to implement one of the techniques (Cross-hole Sonic Logging). In this ‘Spoorzone’ project the existing railway viaduct will be replaced by a 3 km long 4 track cut and cover tunnel. The complete diaphragm wall adjacent to the buildings on the eastern side of the tunnel is being tested (2010-2011) and a special testing section with 10 joints (spring 2011) has been set up to further optimize the measurements. The diaphragm walls in this project reach till a depth of 25 m minus surface level.

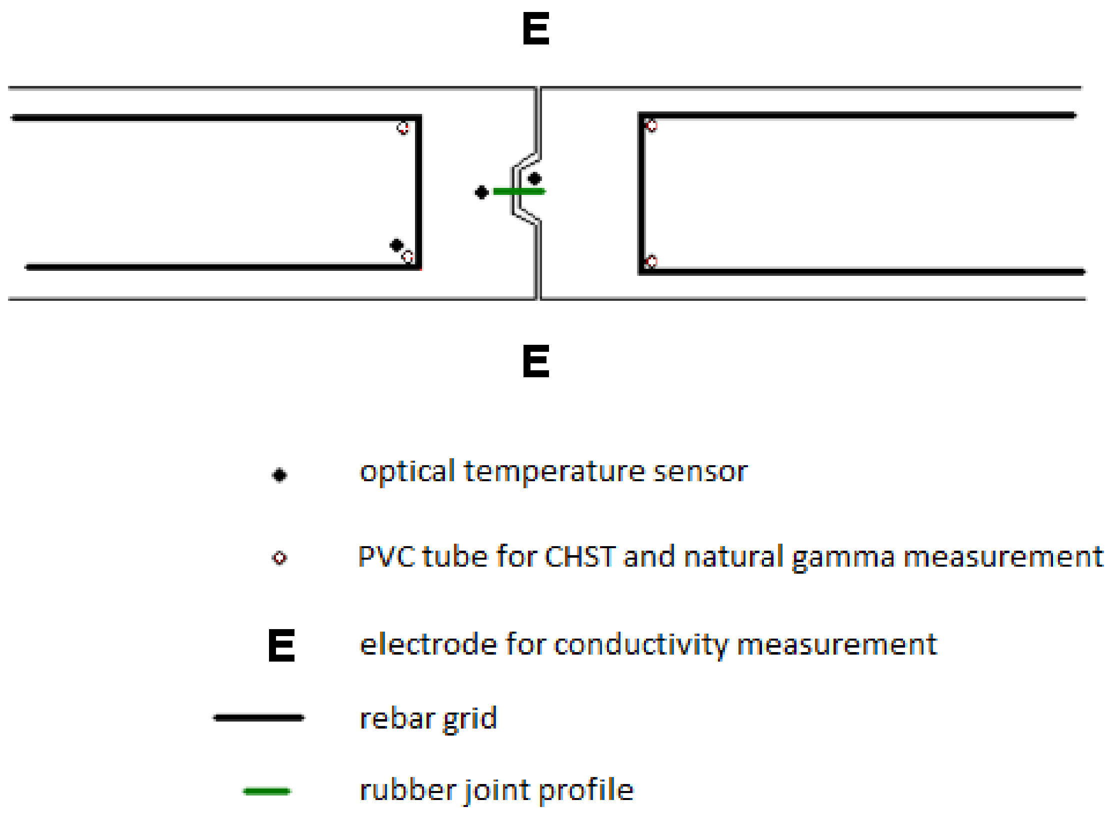

Figure 1: Top view of test configuration as used in Rotterdam

4 Description of the tests and results

4.1 Temperature

During fabrication of a diaphragm wall panel the volume in the excavated trench is being replaced several times. After reaching the final depth with the excavator the excavation bentonite has to be replaced by fresh (lighter) bentonite which in the next stage has to be replaced by concrete. Each material has a specific temperature when entering the trench. By using a vertically positioned distributed temperature sensor, it is possible to keep track of the different materials in the trench. The temperature has been measured with optical fibers (Del Grosso et al. 2001). With a Sensornet Oryx

DTS (Sensornet 2009), the temperature distribution along the fiber could be measured. The temperature accuracy is around 0.01 °C whereas according to the specifications of the manufacturer the accuracy of the position of the measurements is 1 m. From the projects in Rotterdam and Delft it became clear that the most interesting location to measure the temperature profile is in the joint with the previously excavated panel. The optical fibre can be lowered into the excavated trench by attaching a weight at the closed end of the sensor. The replacement of the excavation bentonite with fresh bentonite could be monitored in detail (Figure 2). The excavation bentonite contains relatively large amounts of sand and is therefore harder to replace by concrete. If in the desanding procedure excavation sand remains in the trench (is not replaced by fresh bentonite), this increases the chances of bentonite inclusions to occur. Also during concreting we were able to monitor the concrete front rising in the trench. Figure 3 shows (indicated with an arrow) how a short break in the concreting process is detected in the measurement.

As a result we consider the distributed temperature measurement an important tool to be able to monitor the production process of the diaphragm wall panels. In the desanding stage it is even possible to act based upon the measurements: if incomplete refreshing of the bentonite is being observed it is still possible to brush the joint or somehow stir the bentonite in the joint.

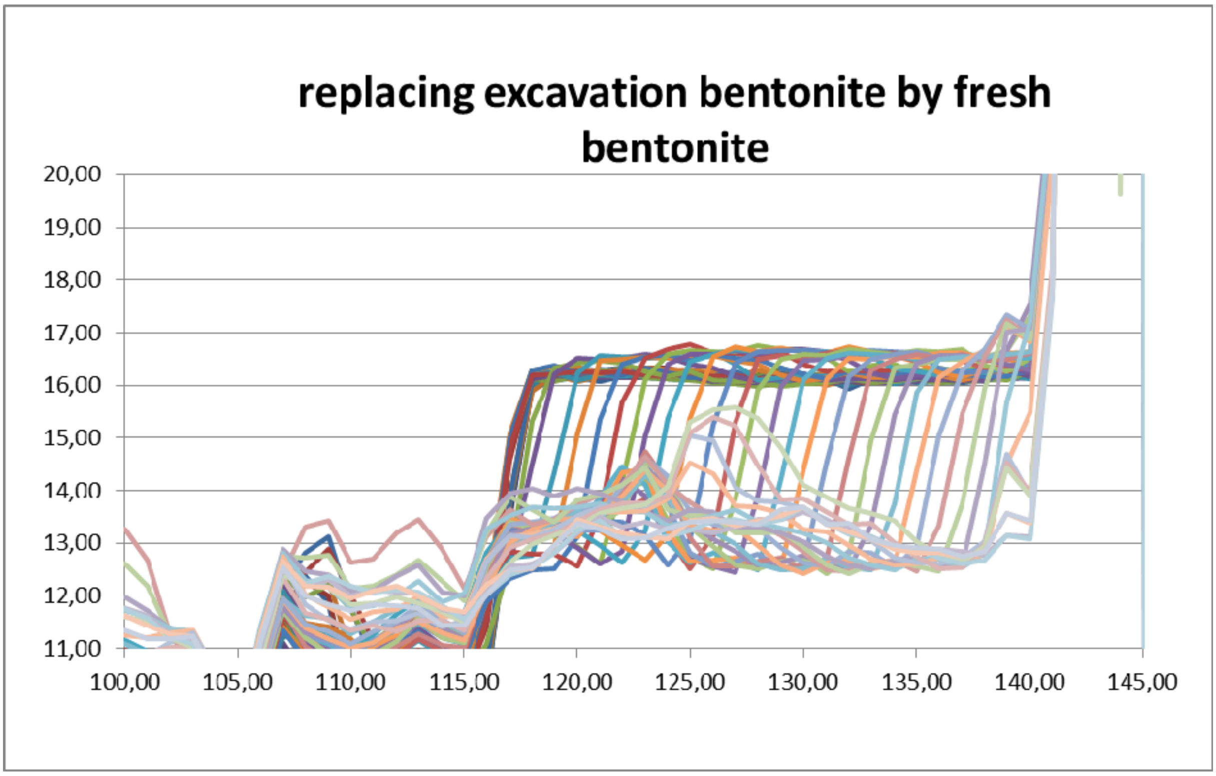

Figure 2: Fresh bentonite (12.5 °C) replacing excavation bentonite (16.3 °C), 117 m till 140 m along the sensor is in the trench

The test blocks were also equipped with optical temperature sensors. The full analyses of those results is elaborated by Doornenbal et al (2011).

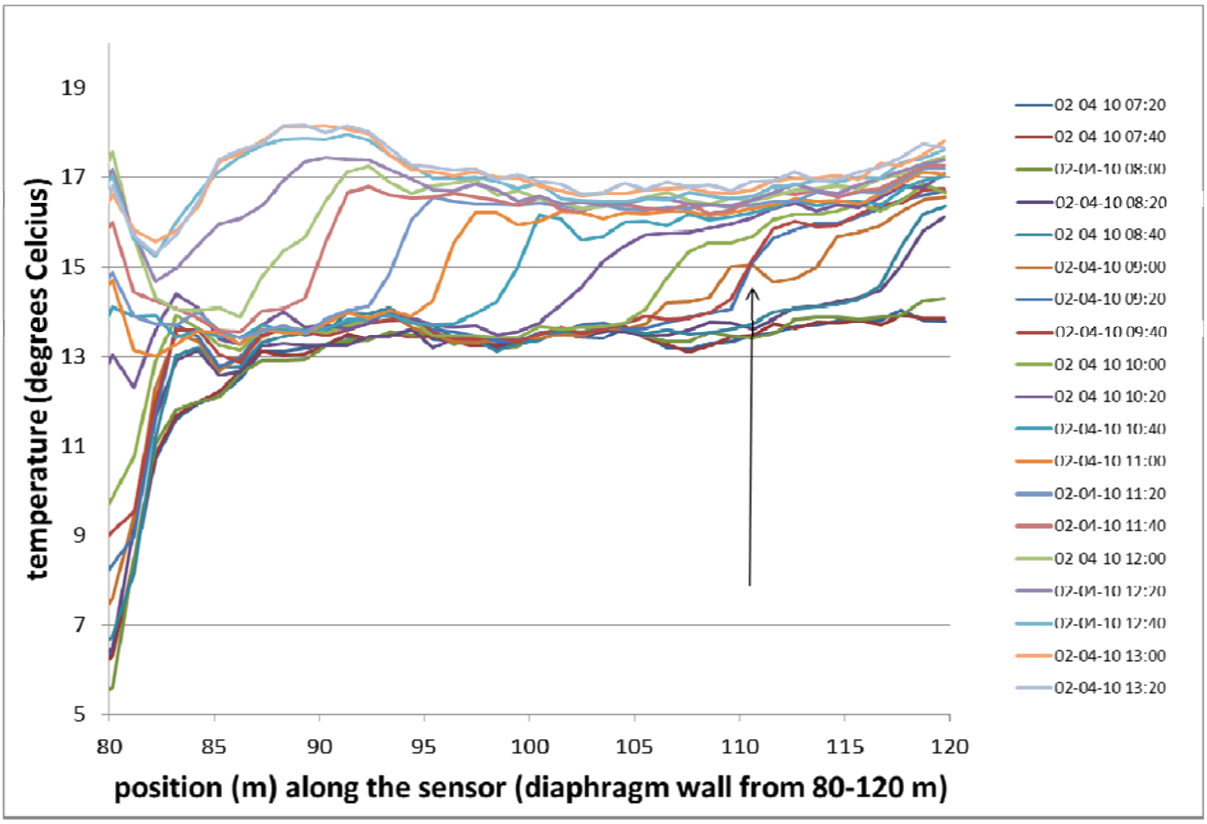

Figure 3: Temperature profile during concreting

4.2 Natural gamma radiation

Normally, clay minerals tend to have a higher natural radioactivity than the ingredients of concrete. It was therefore assumed that areas with high amounts of bentonite remaining in the trench after the pouring of concrete might be detected by measuring the natural radioactivity. Using a gamma ray detector, the radiation along the joint was measured, using the PVC tubes indicated in Figure 1.

Unfortunately, the natural radioactivity of the concrete came out to be higher than the radioactivity of the bentonite. Even with a gamma spectrometer no detectable differentiation between bentonite and concrete could be made.

Table 1: Radioactivity of concrete and bentonite as determined using samples originating from the site

Specimen	^{40}K (Bq/kg)	^{232}Th (Bq/kg)	^{238}U (Bq/kg)
Concrete	215	20	30
Bentonite (dry)	160	12	15
Bentonite (wet)	107	9	7

As it will be almost impossible to detect a small amount of material in the joint with a relatively low radioactivity when the majority of the material has a relatively high radioactivity, this detection method is not further investigated.

4.3 Cross-hole Sonic Logging (CSL)

The speed of sound in a solid medium depends on the density and the stiffness. Because concrete and bentonite have a different density and stiffness, it must be possible to discriminate between concrete and bentonite using an acoustic signal. By attaching tubes on the rebar cages on both sides of the joint (Figure 1), it is possible to send an acoustic signal across the joint.

This method is already commercially available for testing the integrity of large diameter bored piles (Amir et al. 2008). In the test we used the CHUM equipment of PileTest (PileTest 2009).

In advance it was unknown what influence the joint would have on the signal transmission as there is little experience in similar situations.

In literature (Likins et al. 2004, Amir et al. 2008) different opinions on the tube material to be used were found. For robustness and better bonding with the concrete, steel tubes should be chosen. Another research (Likins et al. 2004) indicates that debonding will not occur if the PVC tubes are filled with water prior to concreting. In the field tests (mainly with PVC tubes) no signs of debonding were discovered.

As the reinforcement cages in Rotterdam were not prepared for the tubes, they had to be retrofitted. PVC tubes are much easier to handle and cheaper than steel ones. Therefore 14 out of the 16 tubes in Rotterdam were chosen PVC, the 2 remaining ones were chosen steel, making it possible to compare the different materials. From the field tests it became clear that the signal measured in the PVC tubes contains less noise (ringing) than in the steel tubes.

The measurements on site could be performed very fast especially considering a 42 m wall depth (Rotterdam). Within 30 minutes all 6 cross-hole combinations could be measured. This is the time needed for the simple ‘horizontal’ measurement in which both source and receiver are on the same level and are pulled up simultaneously. Theoretically it is also possible to vary the source/receiver position in such a way that 2D tomography is performed. In the signal there was generally no hint for the need of this extra measurement density.

In two joints anomalies were found. Both anomalies were only visible in one out of six CSL profiles of that specific joint. It was therefor expected that the anomalies would only show on one side of the diaphragm wall. At the depth the anomalies were expected, clayey layers are present outside the excavation. Therefor no further measures were taken to prevent leakage as the soil itself acts as a barrier. After excavation one anomaly proved to be a rock pocket. Further investigation on the material is planned to be undertaken in a later stadium of the building process. The other anomaly consists of bentonite.

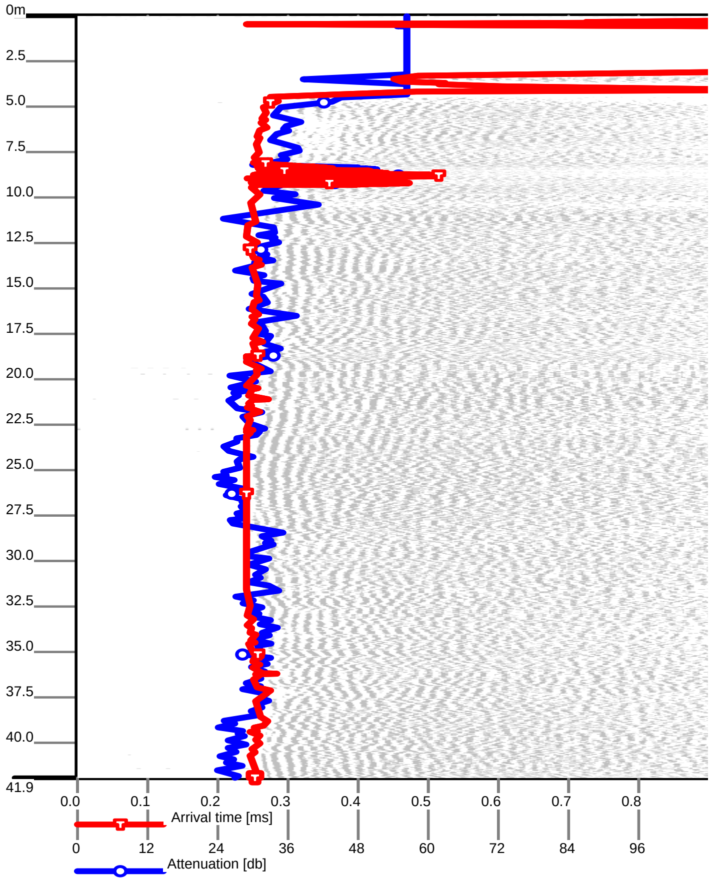

Figure 4: Cross-hole seismic profile with anomaly from 8 to 9.5 m

In Figure 4 the anomaly at 8-9 m minus surface level can clearly be seen. The upper 4 m consists of low grade concrete due to pollution with bentonite (1 m) and bentonite, as the upper 3 m were not concreted to facilitate easy construction of the concrete beam coupling the wall panels.

From the laboratory tests (Fig. 8) a first indication of the anomaly size can be deducted. The test blocks were poured in a normal formwork with a steel joint profile as the lower boundary of the formwork. After curing of the first half, the block was inverted, an anomaly was sculptured in the joint area, the formwork was attached again and the upper block was poured. Instrumentation was set up similar to the in-situ tests.

A typical CSL graph from the test blocks is shown in Figure 5. The known anomaly is present from 0.1 m to 1 m and varies in thickness from 0 to 0.3 m.

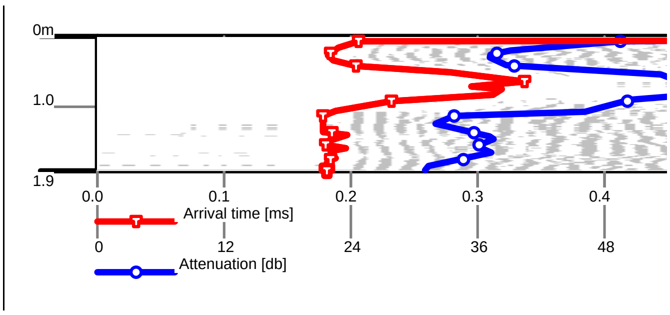

Figure 5: Typical CSL profile of the laboratory block, straight across the joint

Figure 6: Laboratory block

The average (from two test blocks) extra arrival time for a joint contaminated with 0.3 m bentonite is straight across the joint 0.23 ms and 0.35 ms diagonally across the joint. Because the ‘straight’ signal can partly bypass the inclusion, the expected extra travel time will be around 0.1 ms per 0.1 m bentonite inclusion.

The average damping of the signal is 20 dB for a joint with 0.3 m bentonite. 7 dB damping per 0.1 m bentonite is expected.

For further interpretation we are working on a frequency domain analyses of the signal passing through the joint. From the results of the test blocks (Figure 7) it seems that the higher frequency components of the signal are absorbed by the inclusion to a higher degree than the lower frequency components. The spectral analyses of the recorded signal could help identifying the material in the inclusion. Materials with low stiffness (e.g. bentonite) tend to filter the high frequencies more than stiffer materials like sand of even low strength concrete.

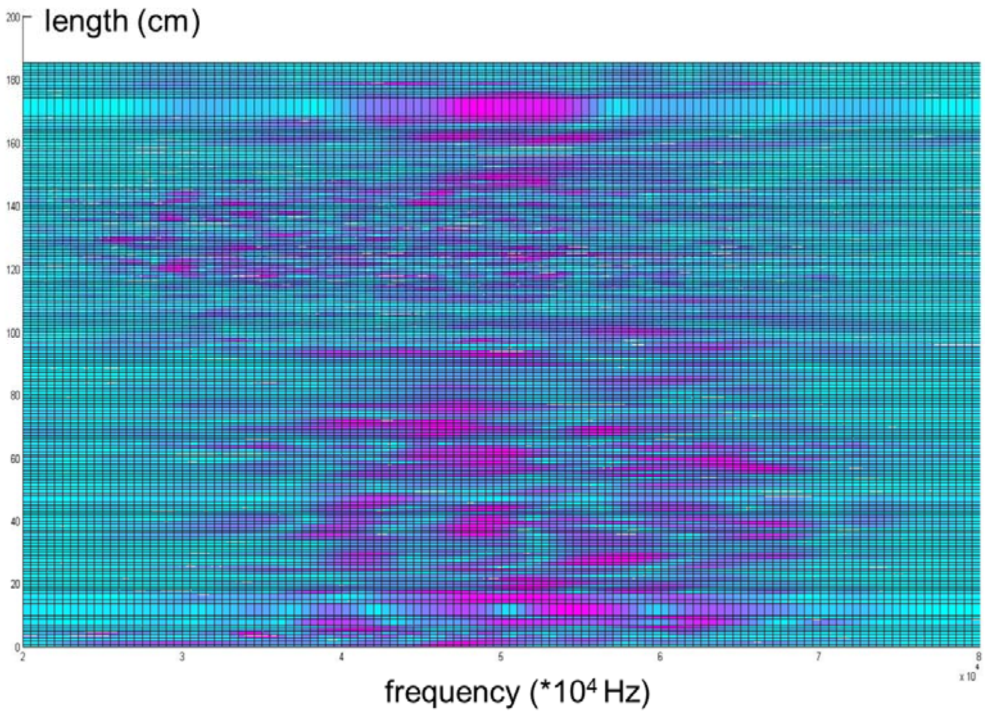

Figure 7: Spectral analyses of the CSL signal

The anomaly found in the in-situ profile of Figure 4 shows 0.25 ms extra arrival time combined with 24 dB damping. If the laboratory samples prove to be representative, the size of the anomaly could be in the order of 0.25 m (based upon arrival time) and 0.35 m (based upon damping). When we combine the extra arrival time with the damping, we expect around 0.3 m of bentonite in the joint.

After excavation it became clear that the area affected by the rock pocket was larger than expected based upon the laboratory tests. The material in the joint area was however low quality concrete (with a higher speed of sound than bentonite) instead of bentonite. The anomaly containing bentonite showed a size in accordance with the laboratory test results.

4.4 Single-Hole Sonic Logging (SSL)

In Delft a special testing section was facilitated in which 3 PVC tubes were used on each side of the joint. From the central tubes Single-hole Sonic Logging (SSL) tests were carried out. SSL measurements are only possible in plastic tubes. The SSL method is assumed to be complementary to the CSL measurement. When much signal is lost in de CSL measurements, the energy that is not passing through the joint must have been reflected, giving a presumably strong reflection in the SSL measurements.

The SSL measurements were only carried out from extra tubes that were positioned in the heart of the panels. These central tubes were needed because the tubes near the wall-soil interface will mainly show the reflection on the outside of the diaphragm wall and no reflection on the joint of the wall. It became clear that interpreting the SSL data is less obvious than the CSL data. The SSL field data of the Spoorzone project seemed to contradict the CSL data. In the upcoming laboratory tests with known geometry the SSL measurements will be further investigated.

4.5 Resistivity

Based on the principle that cured solid concrete has a high electrical resistivity (compared to soil), it is expected that an imperfection in the joint could be made visible in an electrical resistivity measurement along the joint (Hwang et al. 2007). For this measurement a reference electrode (steel rod) was pressed into the soil with a CPT truck outside the building pit. With a resistivity cone attached to the CPT truck, an electrode was gradually pressed into the soil inside the building pit.

The local electrical soil resistivity was measured with the CPT cone (CONE in Figure 8), the electrical resistivity from the cone to the reference electrode outside the building pit was measured (REF in Figure 8) as well as the resistivity between the cone and the rebar grids on both sides of the joint (RBG_N, RBG_S in Figure 8).

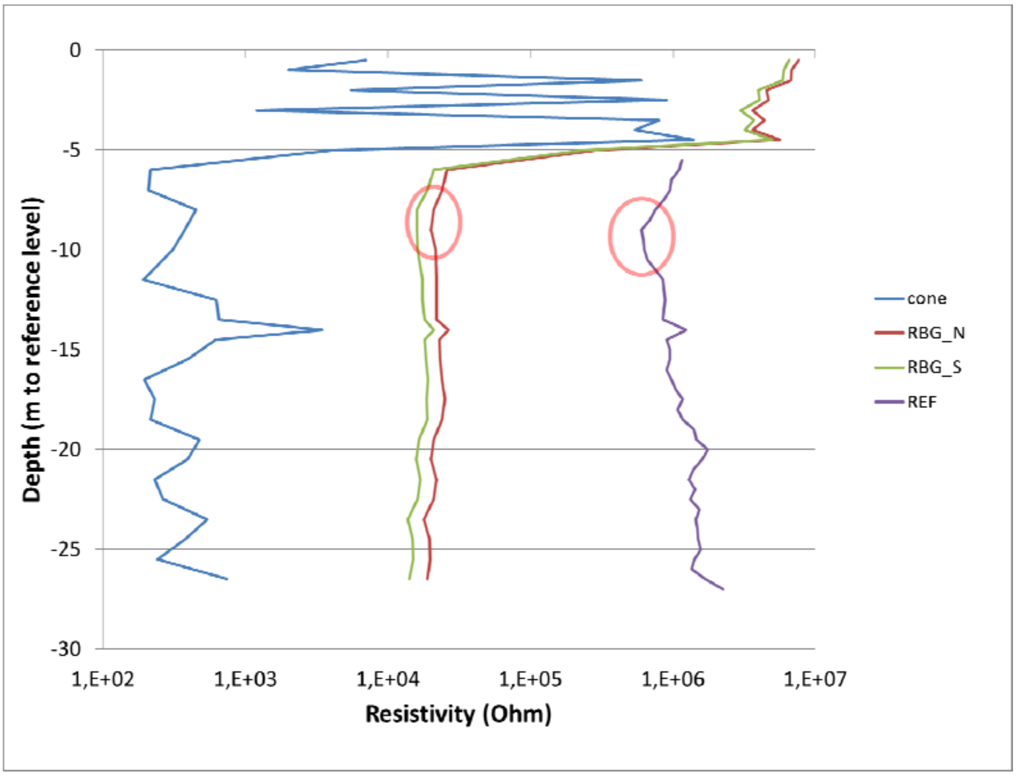

Figure 8: Resistivity profile

The resistivity profile was measured at the same joint as the CSL profile of Figure 4 in which an anomaly was detected at 8 to 9.5 m minus reference level. In Figure 8, at the same depth, there is a 30% (relative to the average 1 MOhm resistance) decrease of the resistivity over the diaphragm wall (REF in Fig. 9). The anomaly probably reaches to 1/3 of the wall thickness, based upon a decrease of the resistivity of 30%. The depth of the visible 'defect' has not yet been established because the defect is exactly at a strut level and is not accessible until the struts are removed.

5 Recommendations for field tests

The CSL measurements are at this point in the research process the most promising method for detecting defects in diaphragm walls. The main reasons are the availability of equipment, the short measurement time per joint and the resulting relatively low costs of measurement. Although the interpretation can be improved much and a lot of effort is still needed in acquiring reliable reference data from known defects, the technique can already be implemented in a project environment. If the CSL profile shows only straight lines indicating a very constant and homogeneous material in between the measurement tubes and the signal shows low degradation, it can be assumed that the joint has no defects. If local deviations show up, the extra time needed for the signal to arrive at the receiver in combination with the attenuation of the signal are the first indicators to quantify the defect. For more detailed analyses a Fourier transformation of the signal can provide extra information about the consistency of the material in the joint as the lower frequencies are filtered out of the spectrum passing through softer material. In case of a large defect the SSL measurements could theoretically be useful to better define the shape of the defect. From a measurement quality point of view, the best material for the tubes is PVC as this produces less noise in the measurements compared to steel. If the possibility to use the SSL techniques should not be excluded in advance, PVC is the preferred material as SSL measurements cannot be performed in steel tubes.

The preferred position of the PVC tubes for CSL measurements is on the outside of the outer corners of the rebar cages. In case of (additional) SSL measurements extra PVC tubes in the middle of the panel on both sides of the joint should be added.

6 Conclusions

The measurements performed on the ‘Kruisplein’ location in Rotterdam, the ‘Spoorzone’ location in delft as well as in the laboratory generally improved our understanding of the concrete pouring process of diaphragm walls.

The natural gamma radiation measurement did not function as intended as a result of the high natural radioactivity of the concrete. In case the ingredients of the concrete could be screened on low radioactivity, this method could be useful.

The temperature measurements can be used to monitor the efficiency of the refreshing of the bentonite mixture prior to the concrete pouring. During the pouring of the concrete, the process in which the bentonite is replaced by concrete can be monitored. With the distributed temperature measurement it is already in the production stage possible to indicate areas that have a higher chance of showing defects. During the desanding operation it is even possible to react: if sub-optimal desanding is detected, with for example brushing of the joint the desanding might be improved.

The CSL measurements proved to provide detailed information about the quality of the joint. Using the first reference information of the laboratory blocks, it is possible to estimate the volume of the anomalies that were found in the test area. Exposing these areas during excavation of the building pit proved that there were indeed anomalies. One anomaly does not consist of bentonite but of slightly decomposed concrete of lower strength. The other anomaly is indeed bentonite. The size of the bentonite inclusion was as expected based upon the scaled tests.

The resistivity measurements proved to be useful for investigating the depth into the wall of an anomaly.

Further investigation on the CSL method will focus on the change in signal (frequency domain) during passage of the joint. The change in stiffness from concrete to the material in the joint might be visible as a change in the characteristics of the signal, providing extra information about the contents of the joint material. Also additional reference measurements will be performed.

Further investigation of the resistivity measurement will focus on the improvement of the measurement setup, as to reduce operating time in the field and at the same time improving resolution.

7 Acknowledgements

The tests were cofounded by the Municipality of Rotterdam and the contractor Besix/Franki. Some of the measurements were sponsored by Deltares, Medusa Exploration, Gemeentewerken Rotterdam-VLG, Fugro and Brem.

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