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Detection of Anomalies in Diaphragm Walls

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Abstract. If a calamity with a retaining wall occurs, the impact on surrounding buildings and infrastructure is at least an order of magnitude more severe than without the calamity. In 2005 and 2006 major leaks in the retaining walls of underground stations in Amsterdam and Rotterdam occurred. After these cases had been thoroughly studied it was concluded that the diaphragm walls had anomalies in the joints between the D-wall panels. These anomalies are hard to locate using regular leakage detection systems and may cause major damage to the surroundings if an erosive leak progresses. Such a risk is hard to handle for a project and may stand in the way of the application of D-walls close to adjacent buildings. Between 2009 and 2014, within the GeoImpuls program, research was done to develop measurements to detect these anomalies. Three techniques have been found to be effective in evaluating the quality of the concrete in the joint area between D-wall panels. During D-wall production the slurry refreshing operation and concrete casting can be verified using Distributed Temperature Sensing (DTS). After curing of the concrete the Cross-hole Sonic Logging (CSL) method, applied to the joint area, can be used to assess the concrete quality in the joint. Anomalies can be localized both vertically and horizontally. The size and contents of the anomaly can be estimated based upon laboratory reference tests and site experience of several projects. If verification of anomalies detected with CSL or DTS measurements is required, Electrical Resistivity Tomography (ERT) can be considered to evaluate the hydrological parameters of the anomaly, although the reliability of these results is much lower than with the DTS and CSL measurements. Based upon the information of the tests, it can be decided if mitigating repair works prior to excavation of the building pit are necessary or that reparation of the anomaly can safely take place while excavating the building pit. The paper will give a short description of all three methods and the executed validation measurements. The paper concludes with practical recommendations for implementation of the measurements.

Keywords. diaphragm walls, quality control, anomaly detection, risk management

1. Introduction

Diaphragm walls have been widely used as retaining walls for deep excavations due to their risk reducing properties of vibration-less execution and high bending stiffness. A less favorable property of diaphragm walls is the uncertain quality of the joints between panels. Below par joints have caused severe problems during the construction of several underground projects all over the world. After calamities in Amsterdam and Rotterdam (the Netherlands) during metro construction works, it was decided to investigate the possibilities of detecting anomalies in the joints. Starting in 2009 from within the Municipality of Rotterdam and from 2010 onwards continuing at Delft University of Technology with support of the GeoImpuls program, research has been carried out in the laboratory and in several projects. In this paper, the main results of the research will be highlighted, including suggestions for execution of the measurements and interpretation of the results.

2. Measurement techniques

The research focused on the quality of concrete around the joints between D-wall panels. It is assumed that if the concrete in the joint is of good quality, the joint will be water and soil tight. The quality of the concrete within the panel itself is not considered to be causing calamities. The verticality of the panels has not been studied but must be guaranteed by good craftsmanship and measuring the inclination of the panels.

Within the research project, three techniques for determining the quality of concrete in the area around the joints have been found usable:

- DTS (Distributed Temperature Sensing)
- CSL (Crosshole Sonic Logging)
- ERT (Electrical Resistivity Tomography)

An indication of when the measurements can be applied is given in figure 1.

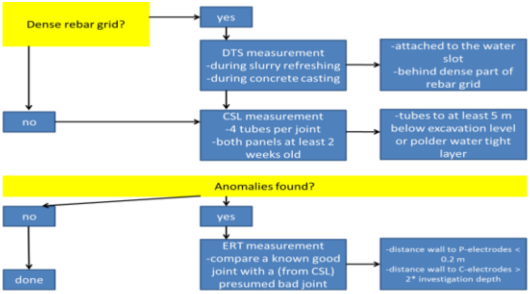

Figure 1. Flow chart measurement technique choice

2.1. Distributed Temperature Sensing

2.1.1. Measurement principle

Distributed Temperature Sensing (DTS) uses an optical fiber sensor to measure the local temperature as a function of the position within the sensor. As the different media in the D-wall trench (excavation-bentonite, fresh bentonite and concrete) will have different temperatures, the sequence of media in time (during slurry refreshing or concrete casting) can be registered using DTS. Incomplete or insufficient de-sanding of the bentonite slurry, concrete casting disruption and too dense rebar grid relative to concrete flow parameters (like viscosity) are considered to be the major parameters causing anomalies in D-walls. Theoretically, all of these can be verified using DTS.

2.1.2. Verification tests

To investigate the usability of DTS in this application, it was necessary to determine the response curve of a DTS system (sensor and interrogation device). The typical response curve of the Sensornet Oryx DTS combined with an ACE-TKF CTC 8xMM sensor to an interface between two media with different temperatures is shown in figure 2. Although the Sensornet Oryx DTS has a spatial resolution of 1 m (as stated in the manufacturers documents), it can be seen in figure 2 that the influence of a temperature change stretches over a length of 3 m (1.5 m before and after the actual interface between the two media).

Each DTS device will have its own characteristic response curve, which is often not supplied by the manufacturer, but the general shape will be comparable.

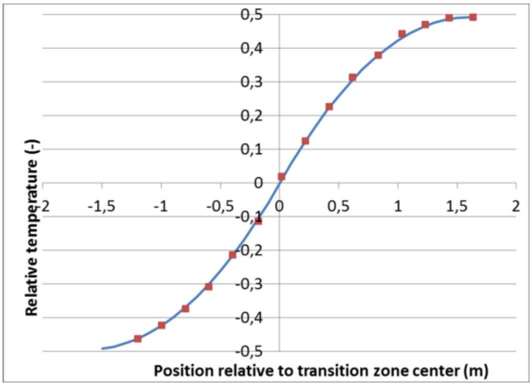

Figure 2. Typical DTS response curve (Sensornet Oryx DTS)

If the measured temperature profile recorded with a Sensornet Oryx DTS is simulated with the response curve of figure 2, the position of an interface between two media with different temperatures can be determined with an accuracy of about 0.05 m. This is much more accurate than expected, based upon the 1 m spatial resolution of this specific DTS device. This accuracy has been verified with both laboratory and field tests (Spruit 2015).

2.1.3. Measurement setup

Most DTS recorders have 4 or more channels. If 4 channels are available it is advised to use fibers to the full depth of the trench at the following locations:

- Attached to a rubber water slot in both joints (2 pcs)
- Inside the rebar cage, near the tremie pipe
- Outside the rebar cage, near the tremie pipe, on the side with the most dense rebar grid (generally the excavation side of the building pit)

2.1.4. Interpretation guidelines

2.1.4.1. Detecting casting interruption

Interruption of the concrete flow is generally considered to be causing the most severe defects in diaphragm walls.

If two or more profiles overlap, the concrete front has not risen during the interval between the measurements, indicating a casting stop. The number of overlapping profiles times the measurement interval determines the duration of the casting interruption.

2.1.4.2. Bentonite inclusion after casting interruption

If casting restarts after an interruption, the DTS sensors outside the rebar cage and especially those in the joint areas could show a large initial offset compared to the DTS sensor close to the tremie pipe. This is caused by the concrete which has stiffened due to the standstill and which has difficulty regaining the flow through the rebar grid. If the casting interruption was long enough, the fresh concrete could break out of the previous casting front, forming a new front and locking up the sandy bentonite slurry that was collected on top of the previous casting front. This will become visible in the DTS recordings in the joints: the concrete temperature will suddenly appear above the area where the bentonite temperature remains. Before this sudden 'jumping up' of the concrete level, a period of increasing offset between the DTS sensor near the tremie pipe and the DTS sensors in the joints should be visible.

2.1.4.3. Tracking the interface between materials

DTS measurements offer the possibility to monitor the position of the interface between two or more media with different temperatures.

With the typical response curve of the DTS device it is possible to simulate the response of the DTS device based upon assumed temperatures of the two media and an assumed position of the interface. By comparing the recorded temperature profile with the simulated profile, the actual interface position can be determined iteratively. With the Sensornet Oryx DTS an accuracy of 0.05 m can be obtained.

If the shape of the measured temperature profile does not fit the response curve shape of the DTS device, this means a system with more than two phases has been present (figure 3).

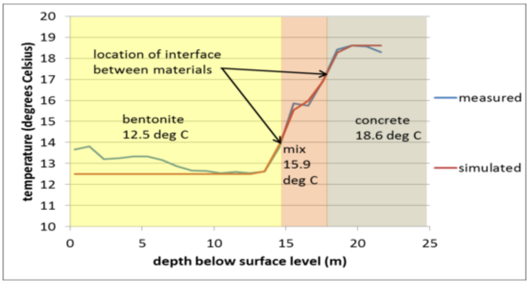

Figure 3. Measured and simulated temperature profiles for a three phase system

By superimposing n response curves, a system containing n+1 phases can be simulated. Figure 3 illustrates successful simulation of a three phase system.

A sequence of temperature profiles can be used to simulate the concrete level in time (figure 4). This shows a far more detailed registration of the casting process than manual measurements.

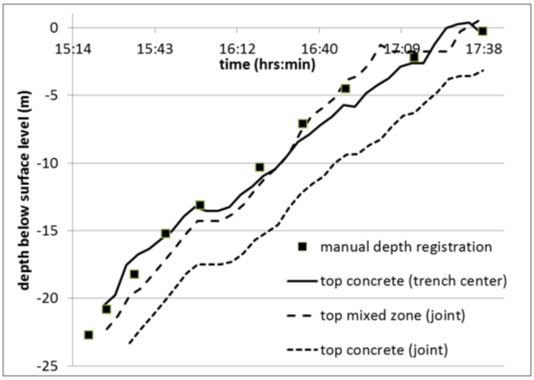

Figure 4. Concrete casting progress based upon DTS and manual measurements

2.2. Cross-hole Sonic Logging

2.2.1. Measurement principle

Cross-hole Sonic Logging (CSL) uses an ultrasonic source and receiver to determine the travel time and signal loss between source and receiver. As the speed of sound in a medium depends on density and shear-stiffness, anomalies containing bentonite or soil can be differentiated from concrete. PVC tubes are attached to the outer corners of the rebar cage to provide access of the source and receiver in the area around the joint. After concrete casting and curing the panels on both sides of a joint, the joint can be scanned by simultaneously lowering source and receiver in all permutable combinations of access tubes.

2.2.2. Verification tests

A full description of the executed verification tests has been reported in Spruit et al. 2014.

For several fill materials in an anomaly, the change in First Arrival Time (FAT) and the attenuation of the signal have been determined. The delay in arrival time (DAT) is linearly proportional to the anomaly size (figure 5).

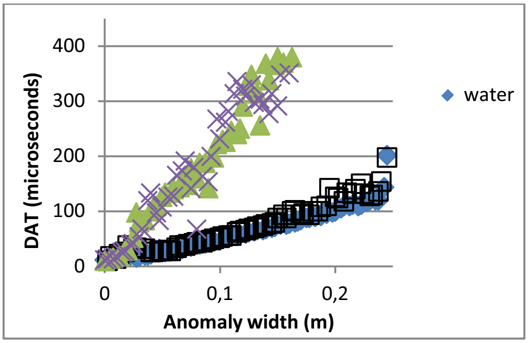

Figure 5. DAT versus anomaly size

In a similar way, the attenuation also has a correlation with anomaly size (figure 6).

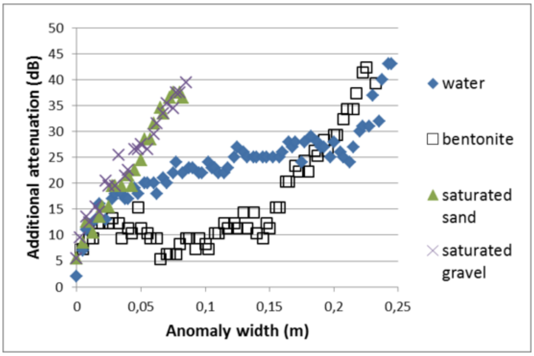

Figure 6. Attenuation versus anomaly size

2.2.3. Installation of measurement tubes

The preferred material to be used for the tubes is regular PVC. This provides the cleanest signal and has shown to be less vulnerable than steel tubes.

The best survival rate for the tubes is obtained when they are attached to the rebar cage on site, just before installation of the rebar cage in the trench. If the rebar cage consists of more than one section and below the top section CSL is still required, PVC offers the possibility to couple several sections quickly and easily using PVC glue and sleeves. The tubes can be attached to the rebar grid by applying tie wraps each meter.

Make sure the position of the measurement tubes relative to the corners of the rebar cage is constant. It is easiest to attach the tubes on the outside of the cage, which also provides for the best signal for imaging the joint. This has not shown to increase the failure rate of the tubes.

After immersion of the rebar cage in the trench, it is recommended (Likins et al. 2004) to fill the measurement tubes with water and to cap them. The water in the tubes will reduce bentonite in-flow in case of a leak in a coupling sleeve. During concrete casting, the water in the tubes will damp the temperature fluctuations, supposedly reducing the chance of debonding.

After the concrete casting has finished, check if the caps (used to prevent unwanted objects from entering into the PVC tubes) are still on the measurement tubes. They sometimes pop off due to compression of the PVC tubes and/or heating up due to concrete curing.

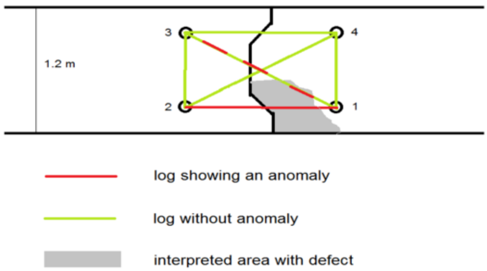

Figure 7. Typical access tube configuration relative to joint between panels

Experiments with 2 additional tubes in the center of the panel have not shown a better understanding of the geometry of the joint, while increasing the chance of obstructing the concrete flow in the center of the panel, towards the central rubber water slot.

2.2.4. Gain

The CSL signal will suffer severe loss in amplitude while crossing the joint. Not all auto-gain algorithms are able to cope with this phenomenon. It is therefore recommended to start with a few tests to evaluate the auto-gain system. If on some scans of the same joint, no useful signal is recorded, manual gain control should be chosen.

With manual gain, it is important to use a fixed gain for each type of crossing. Generally, the gain for the scans perpendicular to the joint should be double the gain for the scans parallel to the joint. The scans that run diagonally through the joint generally need a gain three times higher compared to the parallel scans.

These values could be influenced by site specific parameters like the type of concrete and bentonite applied in the production of the wall. It is therefore necessary to test these settings on a few joints before setting them for the large scale production tests. To make comparison between joints possible it is required to keep the gain factors fixed within the project.

2.2.5. Interpretation guidelines

For a first evaluation of the CSL results, FAT recordings without deviations can be interpreted as 'there are no anomalies present'.

If severe deviations are noticed, the attenuation at the same depth must be considered in conjunction with FAT. It is also necessary to combine with the other logs of the same joint to assess the volume of the anomaly relative to the cross section of the panel.

If the anomaly seems to affect even the scans parallel to the joint, the CSL logs of the joint on the other side of the same panel should be examined in detail as well. If the anomaly was caused by a long term stop of the concrete casting process, there could be a horizontal sandy layer extending to the full cross section of the panel.

To estimate the volume of the anomaly, figures 5 and 6 can be used. Generally, it is safest to derive the anomaly size upon the DAT assuming bentonite as fill material. By combining all scans of one joint, the affected area and anomaly thickness can be plotted. This information can be used to assess the risk of leakage and/or the need for repair.

2.3. Electrical Resistivity Tomography

2.3.1. Measurement principle

Electrical Resistivity Tomography forces an electrical current through a current electrode at a distance from one side of the wall to a second current electrode at a distance at the other side of the wall. With two (or more) additional electrodes the local potential very close to the suspected joint is measured. If concrete of a good quality is present in the joint, the electrical resistivity will be high (large potential difference), if the cross section of the joint contains an anomaly (consisting of soil or bentonite), the local resistivity will be lower. The resistivity results of a sound joint are compared to the results of a suspected joint. Local differences indicate an anomaly.

2.3.2. Verification tests

A test wall consisting of the reference blocks that were cast for the CSL measurements has been built upon a plastic sheet (figure 8).

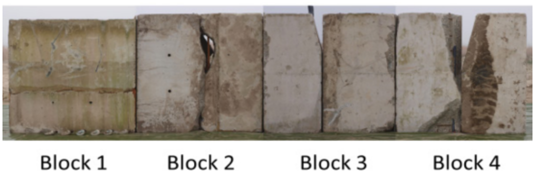

Figure 8. ERT test wall

Around this wall, a basin with mega-blocks and a plastic sheet has been built and filled with water taken from a nearby canal (conductivity = 1340 μS/cm).

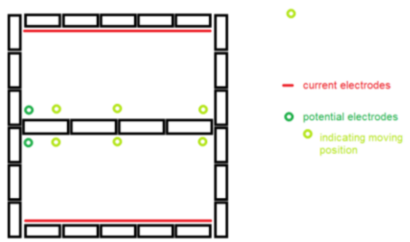

Figure 9. Schematic overview of ERT test

Following the schematic configuration of figure 9, the test wall has been examined for several distances between the potential electrodes and the test wall.

Figure 10 illustrates the impedance results for all measurements with a 0.2 m distance between the potential electrodes and the test wall. The full report on the verification tests is to be found in Spruit (2015).

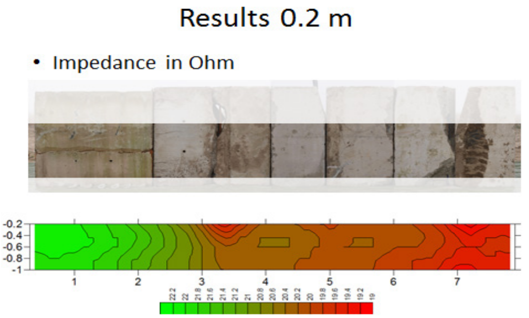

Figure 10. ERT test results, potential electrodes 0.2 m distance to the test wall

Figure 11 has been constructed using the estimated anomaly cross sections and their detection in the different measurements (0.1, 0.2, 0.4 and 0.8 m distance between potential electrodes and test wall). Even though the number of measurements is limited, it is undeniable that the ability of the ERT technique to detect anomalies, is strongly influenced by the distance between the potential electrodes and the wall to be tested.

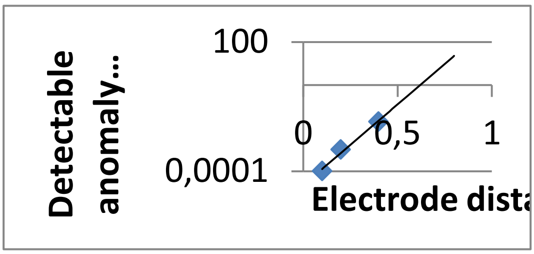

Figure 11. Ability to detect anomalies depending on potential electrodes distance to the test wall

Generally speaking, for detecting anomalies that could cause a calamity, the potential electrodes should be closer to the test object than 0.2 m. This results in practical limitations of this technique when push-in electrodes are used. For bored electrode strings such small distances might be realizable between potential electrodes and the object to be tested.

2.3.3. Preferred setup

Even though the method is limited, in some cases where repair works with jet grouting are less desirable, ERT could be useful for verifying the anomaly estimations made with CSL measurements. In such cases the setup outlined in figure 12 could be used.

However, in most cases repairing with jet grout will be more cost effective.

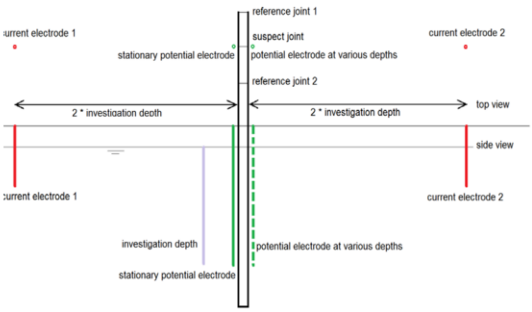

Figure 12. Suggested electrode configuration

3. Conclusion

Generally, CSL must be applied in all projects regardless of the risks in the surroundings. Because of the low measurement costs of CSL, the technique is already cost effective if the only benefit is preventing project delay.

DTS measurements will (for the moment) be primarily useful in research settings and for verifying the concrete flow through dense rebar cages. If dense rebar cages are necessary, DTS measurements within the first panels can be used to optimize the concrete characteristics and rebar configuration.

Bentonite inclusions in the joint area could be detected if the DTS sensor is included in the rubber water slot.

ERT measurements should not be relied upon as primary tool for detecting anomalies in D-walls. As a confirmation tool or to assess the permeability of the wall, it can provide useful information if the potential electrodes are placed close to the wall, in fact closer than 0.2 m.

References

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