Concrete Flow in Diaphragm Wall Panels: A Full-Scale In-Situ Test

Jan H. DALEN VAN [a,b], Johan W. BOSCH[b], ir. Wout BROERE[b]
[a] *Strukton Civiel Projecten, the Netherlands*
[b] *Geo Engineering, Civil Engineering, Delft University of Technology, the Netherlands*

Abstract. Flow processes, taking place during the concreting of diaphragm wall panels (D-wall panels), are of great importance for the quality of the wall. During this phase, the bentonite, present in the excavated trench, should be completely replaced by concrete in a controlled way. In literature several cases are described in which this process resulted in bentonite inclusions in the panel. These inclusions often lead to severe problems, like leakages, for the building pit to be excavated within the diaphragm wall panels. Beside the risks for the building pit, leakages caused by bentonite inclusions can also have large consequences for nearby constructions. In this article, set up and results of a full-scale diaphragm wall test are described. Conclusions are drawn with regard to the influence of several parameters on the flow process and subsequently on the quality of the wall and the risk on bentonite inclusions.

Keywords. Diaphragm walls, Building pit, Concrete flow, Bentonite, Reinforcement, Full-scale test

1. Introduction

During the construction of a diaphragm wall, the role of the flow processes involved is decisive for the risks. Especially the process in which the concrete needs to replace the bentonite is important, because remaining bentonite inclusions in the concrete can lead to hazardous situations during excavation of the building pit. In the Amsterdam North-South metro line project, a bentonite inclusion near the joint between two diaphragm wall panels of the Vijzelgracht underground station, led to unacceptable settlement of a row of historic houses. The houses became temporary uninhabitable. This settlement resulted in an enormous delay and cost overrun of the project.

To prevent this kind of inclusions, several recommendations regarding design and construction of Diaphragm walls are given in CUR 231. Important factors mentioned in this publication are the fluidity properties of the concrete and the bentonite, which should be adequately controlled prior and during the concreting phase. Another important aspect is the presence of reinforcement bars, which slows down the flow. Apart from the slowing down, distances between reinforcement bars should be sufficiently large, in comparison to the largest grain diameter of the concrete used to prevent blocking of openings between bars by clogging grains.

As part of research at TU Delft, a full-scale field test has been performed in Delft. For this field test, two diaphragm wall panels have been constructed in the middle of the building pit for the project Delft Spoorzone. Because the two panels are no part of the retaining walls around the building pit, it was possible to excavate and inspect them on all sides. Also, measures that would normally pose too much of a risk for a functioning retaining wall, could in this case be taken. To be able to evaluate the effect of several conditions, those conditions have been chosen in such a way that no perfect diaphragm wall could be expected.

The expectation of this field test is to reduce risks for future projects by obtaining a better understanding of the flow processes in diaphragm walls.

Also, as part of the research, a numerical model in which the concreting process can be simulated has been built in OpenFoam, open source software which can be used to simulate various kinds of flow problems. The results of the full-scale test will be used to help validate this model. In this article the setup and results of this field test are described.

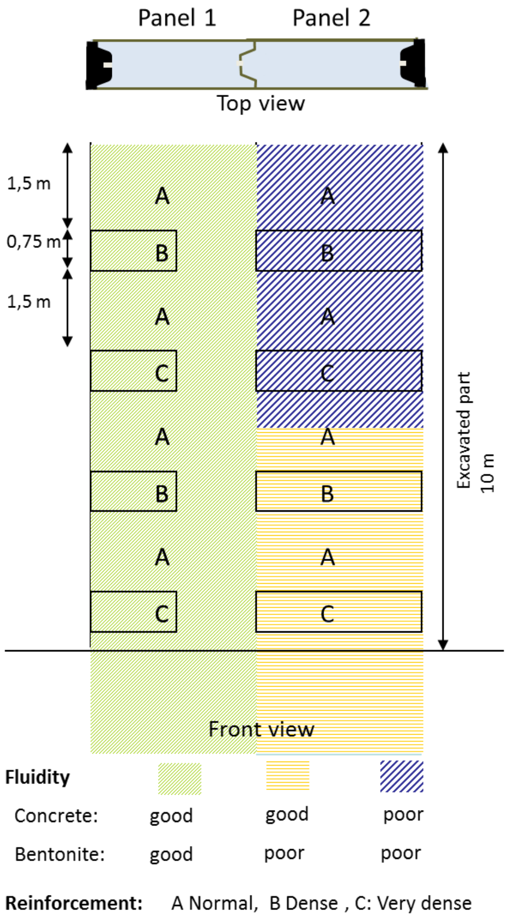

Figure 1. Schematic layout of both test panels.

2. Test setup and monitoring

The reinforcement cages of the two panels differ at various places. In certain areas distances between bars have been chosen smaller than allowed according to CUR 231, see Figure 1. In the case of “very dense” the probability of gravel in the concrete passing the reinforcement is <<1, based on Roussel (2009). Both fluids (concrete and bentonite) can be conceived as Bingham fluids, with a given viscosity and a yield stress, which are important parameters for the flow process. Another essential parameter for this process is the difference in volumetric weight between the two fluids. In the first panel the fluidity of bentonite and concrete were chosen according to CUR 231. In the second panel the bentonite has not been desanded, leading to higher values for volumetric weight, yield stress and viscosity. On top of that, the concrete used in the last part of the second panel was less fluid, i.e. had a larger yield stress and viscosity. According to the original plan, after the concreting of the first half of the second panel, a waiting period has been adapted in an effort to cause the concrete already present in this panel to gain the same fluidity properties as the concrete later added. However, in reality this goal was not achieved; the fluidity of the first load of concrete was still relatively high during the pour of the less fluid second half.

During the concreting process, the rise of the concrete level in the diaphragm wall panel has been recorded at multiple positions in- and outside the reinforcement cage by means of mechanical automatic level devices and glass fibre cables (Spruit et al, 2015).

To be able to evaluate the flows, each concrete truckload has been coloured differently, by using additives. Additionally, for a more detailed view of this aspect, in total about 2000 RFID chips have been added to the concrete. These chips all look identical, but have a unique identity code, which can be detected from a distance with an electromagnetic scanner. These chips were added to the concrete during the concreting phase, by throwing them directly in the tremie pipe, recording the time of entry for each individual chip. After excavating the panel, it was possible to find the final position of the chips, by scanning the surface of the diaphragm walls. Since the reinforcement cage acts as a Faraday cage, it was expected that only (part of) the chips that accidentally ended up outside the reinforcement cage would be found back. Assuming the chip only migrates with the concrete and not within the concrete, this way start- and endpoint of flow lines of the concrete are made visible for flow lines which end near the outside of the panel.

During excavation of the building pit, the panels became visible. Samples of the bentonite cake, present on the outside of the panel were taken for laboratory testing. After cleaning of the surface of the panels by removing soil and bentonite remains, the concrete was visible.

Pictures were taken, the surface was inspected for irregularities and the electromagnetic scanner was used to track down RFID's under the surface. Also in this phase, the panels were 3D laser scanned, to record the exact shape visible on the outside. Due to the phasing of the surrounding building pit, the described inspection happens in stages. Per phase, after inspection, the visible part of the wall was demolished.

3. Results of the RFIDs

Table 1 gives an overview of the amount of RFID chips found after completion of the wall.

Table 1: Overview of RFIDs

Panel	Amount of RFID's		Real % found	Expected % found	Found / Expected
	Total inserted	Later detected			
1	950	149	16%	17%	95%
2	1015	131	13%	19%	69%

Beforehand it was expected that most of the chips outside the reinforcement cage per scanned surface would be found back and those inside not. The percentages mentioned in the column 'Expected percentage' is based on that principle. For panel 1 there is only a limited difference between the real and the expected percentage found; for panel 2 there is a clear difference. An explanation for this difference between the two panels, apart from randomness, is the fact that the concrete of panel 2 had a rougher surface, containing more small bentonite inclusions. These inclusions cause the concrete for panel 2 to dry out slower than for panel 1. The fact that a high moisture content has a negative influence on the amount of RFID's found was also observed during the scanning process. Short after excavation less RFID's were found then after a rescan, just a day later, when the surface of the wall had had time to dry. The final scans were all performed after a waiting time of at least 1 day after cleaning of the wall with high water pressure.

Figure 2 shows the levels at which RFID chips were found back, in relation to the time of entry. In panel 1 it can be observed that most of the chips are found back at levels around the concrete level in the trench at the time of entry.

For panel 2 this is different; many of the early RFIDs are found back at high levels, and many later inserted RFID at deeper levels, although in all cases at levels higher than the level of the tremie pipe. This indicates that the concrete of the first loads has been pushed up by the later added less fluid concrete.

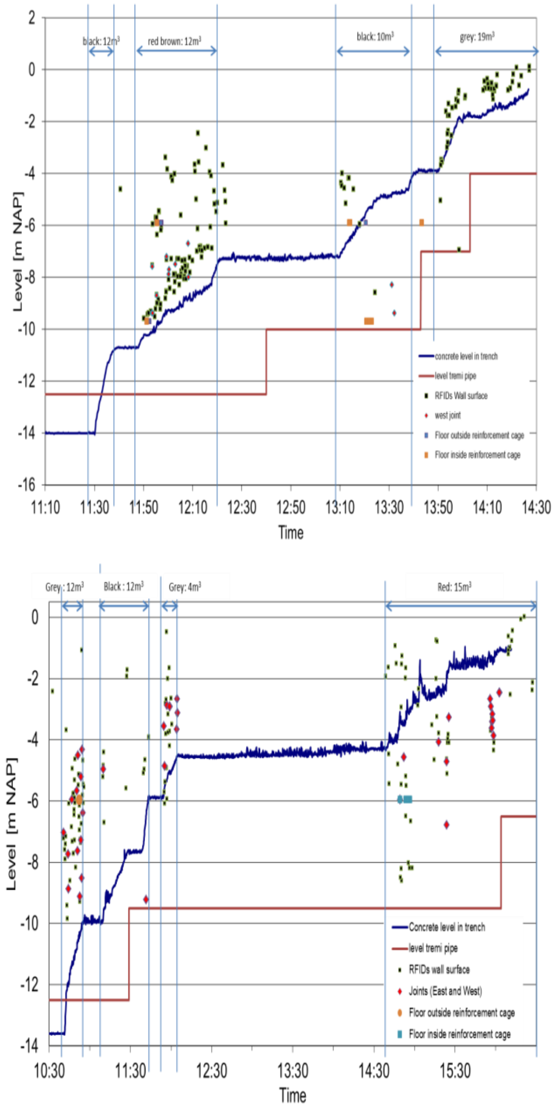

Figure 2. Relation between scanned level RFIDs and concrete level at time of insertion for panels 1 and 2.

In the case of panel 1 is observed that for deeper levels the average time of insertion of

RFID's found near the joint is about 6 minutes earlier than those found in the middle area of the panel (see Figure 3). In this amount of time on average about 3.5 m^3 of concrete will have passed the tremie pipe. For levels, higher than halfway the depth of the panel, the time difference diminishes to about zero at surface level. For Panel 2 this is completely different; in this case the difference in insertion time between RFIDs near the joint and in the middle of the panel is much more extreme for deeper levels: several hours. This supports the observation from Figure 2 that the early concrete in the middle area was pushed up by concrete poured in after the interruption.

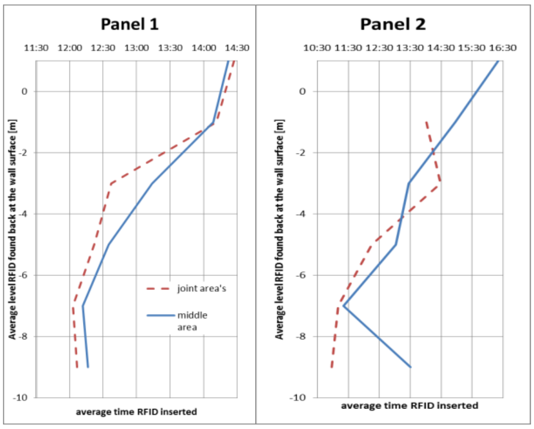

Figure 3. Relation between scanned level of RFIDs, averaged per 2 m height and time of insertion.

4. Observations from laser scans and photos

Panel 1, which has been made with normally fluid concrete and bentonite has a relatively smooth surface, also at the locations with the extremely concentrated reinforcement. However the concrete level at the time of the 47 minutes interruption of concrete supply (see Figure 2) a horizontal inclusion of sand and bentonite is visible in the middle area of the panel, see Figure 4.

The concrete underneath and above are from the same truckload, which was poured in just before the interruption. The times of insertion of the RFIDs found are sequential, indicating that concrete, already present in the middle area is being pushed outside the reinforcement cage when new concrete is added. This process was not influenced by the interruption, but the visibility of the interruption is likely to be caused by instability of the bentonite suspension near the concrete surface, leading to sagging of sand particles and bentonite cake forming at the surface between fresh concrete and bentonite.

The fact that the main part of vertical flow takes place in the middle area within the reinforcement cage is also confirmed by the horizontal cross section of panel 1, which was taken about 1 m higher than the interruption (see Figure 5)

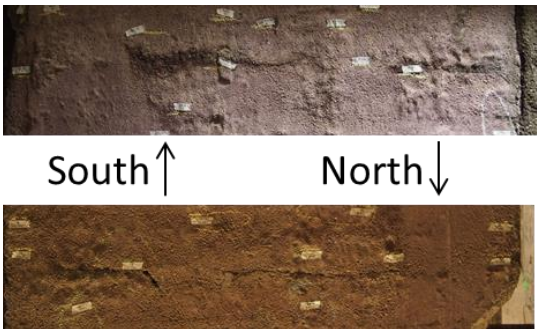

Figure 4. Panel 1 at level NAP-7m, showing a concrete interruption in the middle area (horizontal line)

It is clearly visible that the later black concrete has pushed the earlier red concrete outside of the reinforcement cage.

Figure 5. Cross section of Panel 1 at level NAP-6m, showing different truckloads of concrete in- and outside the reinforcement cage.

Remarkable is that the much longer lasting interruption in Panel 2 (see Figure 2) of almost 3 hours did not lead to a visible horizontal line at the level reached at the time. In panel 2 however, at this level, mainly concrete of later truckloads is found, indicating that in that case at these levels there has been a flow outside the reinforcement cage.

In Panel 2 at several locations (totally about 50% of the panel) an effect as shown in Figure 6 is observed. Clearly visible at the surface is the location of reinforcement bars. This indicates that those bars influence the horizontal flow of concrete perpendicular to the net of bars. Also it indicates that on those locations, in the space between reinforcement bars and surrounding soil no flow of importance parallel to the plane through the reinforcement net takes place.

Figure 6. Location of reinforcement bars visible in Panel 2

Another pattern is observed in locations with an extreme amount of reinforcement, see Figure 7. The red concrete, visible in the middle area origins from the last truckload, the grey concrete surrounding it from the first truckload. During the first truckload the level of the tremie pipe was 3.5 m deeper than this location, during part of the last truckload this level was 0.5 m under the reinforcement concentration.

Figure 7. Pattern visible at locations with a strong reinforcement concentration

A plausible explanation for what is seen here, might be the fact that during the first truckloads, this area was not completely filled with concrete, due to the reinforcement concentration. From simulations this was also expected. During the last truckload, however the pressure in the concrete near the outlet of the tremie pipe must have reached much higher values, since the overall concrete level in the trench was higher. Probably with that pressure, the gap in the concrete was filled from underneath, suppressing the (grey) concrete present at the edges of the formerly non filled area. The latter would explain the circular lines of grey concrete which are alternated with lines of dark grey bentonite, surrounding the circular red area. Area's similar to this one are found at 3 different locations in the panel, all where concentrations of reinforcement are present.

5. Conclusions

Using coloured concrete can help to increase insight in the flow process of concrete in diaphragm wall panels. However special attention is needed for the colours used. The difference between black and grey concrete turned out to be not very well visible. The difference between red or red/brown versus black or grey is much easier to recognize. Also the addition of colour has an influence on the flow ability of the concrete, since most colouring powders consist of very fine particles, which has to be compensated for in other ingredients. If fluidity is an important issue for the test performed, it is advisable to make a test mixture prior to the test to establish the effect.

The use of 125 MHz RFID chips to trace start and endpoints of flow lines in Diaphragm walls works quite well, providing much more detailed information about the flow process than the use of colours. Although with the equipment used -a standard scanner, generally used for contactless entrance cards and relatively cheap standard chips-, only chips outside the reinforcement cage could be detected and the concrete had to be relatively dry. It would be worthwhile investigating if extension of this method to scanning chips deeper in the concrete would be technically possible. Further extension might be to find ways to track the chips during the pouring process, providing an even better image in place and time.

In contradiction to what has always been assumed, local large concentrations of reinforcement in a diaphragm wall panel which can’t be passed directly by the concrete, do not necessarily lead to bad spots. Important however, is that there is an alternative path for the concrete to pass to that location and that the concrete pressure near the location can reach values high enough to obtain the flow via this alternative path. Also it has to be ascertained that the concrete already present at the alternative path, has not lost too much of its fluidity to make a new flow possible. Higher concrete pressures can be reached by keeping the tremie pipe at a relatively low level, preferably near the location of the alternative path. This suggests that with special care and quality control during construction, issues with local reinforcement concentrations can be overcome.

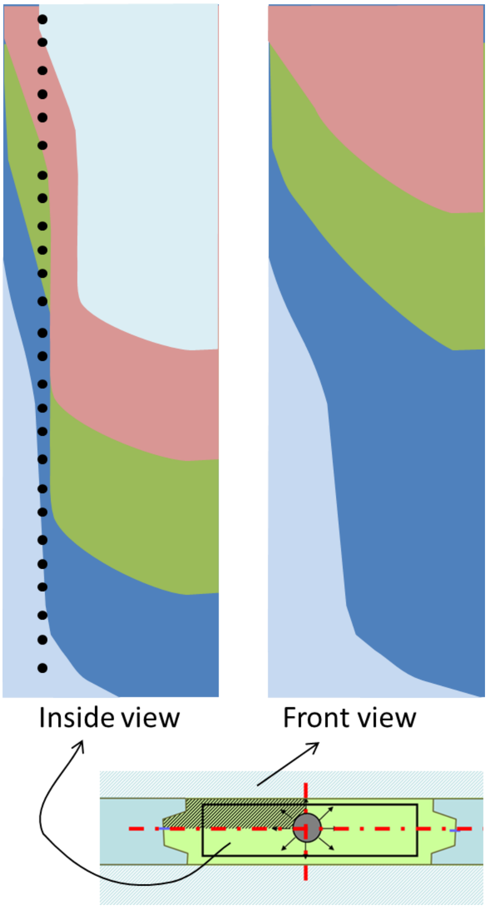

Figure 8. Pattern visible at locations with a strong reinforcement concentration

In panel 1, a generalized flow pattern has been observed as shown in Figure 8. It is very likely that in a general situation, in which the fluidity of the concrete stays about equal during the pouring process, or the fluidity of concrete of new truckloads is better than the ones already been poured in, the flow pattern would show the same characteristics. The observations from panel 2 have showed that in the case later added concrete is less fluid than earlier added concrete, and the tremie pipe remains at a deep level, it is possible to suppress older concrete to higher levels, even in areas outside the reinforcement cage.

It is expected that the results of both panels will enable the verification of the OpenFoam model, also used in this research.

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