A New Method of Quality Control for Construction Joints in Diaphragm Walls

Nikolaus Schneider, GuD Geotechnik und Dynamik Consult GmbH, Dudenstraße 78, 10965 Berlin, Germany, +49 30 789089-0, schneider@gudconsult.de

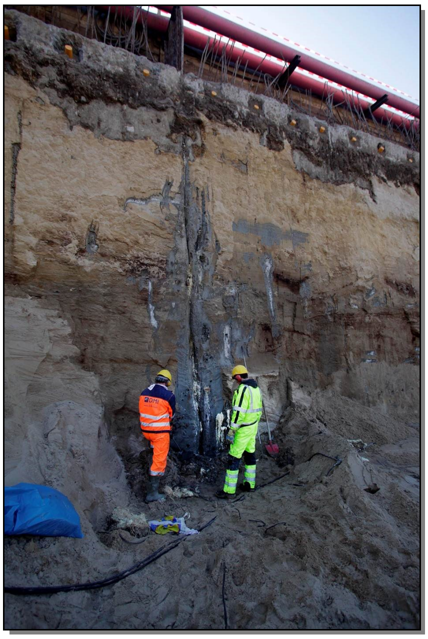
Abstract: Failure in the joints of diaphragm walls and their exposure to water pressure may have far reaching effects ranging from water leakage to the risk of catastrophic loss of stability for the retaining wall. Investigations of imperfect joints in diaphragm walls have led to the development and testing of a quality tool to monitor the joint integrity of diaphragm walls during construction. By applying independent mechanical sensors ("joint inspector") to the steel frame of hydraulic or mechanical grabs, it is now possible to record the surface of exposed primary joints during the construction of secondary panels. This allows for implementation of corrective action during the construction process if joint quality does not indicate a watertight connection to the adjacent panel. The joint inspector, used for different types of stop ends, was tested on a full scale test field and several construction sites. The implementation of this new quality tool drives a new quality standard for deep excavations in inner city areas.

General introduction to diaphragm walls

Diaphragm walls are reinforced concrete elements constructed using bentonite slurry to temporarily support an open trench in the ground. They are used in two main fields of application in civil construction: as foundation elements for vertical and horizontal loads (barrettes) and as retaining walls for excavation pits.

Barrettes are diaphragm elements designed in length and shape to transfer the load of high rise buildings into the ground. Under special requirements these barrettes are cross shaped to improve geometric characteristics for the load transfer. Barrettes are not being exposed laterally during the construction stage.

Particularly for deep excavation pits in inner city areas, diaphragm walls are used as temporary or permanent walls of retaining walls. Alternative retaining wall systems would be secant pile walls, sheet piles or soldier piles but these have disadvantages in structural strength when compared to diaphragm walls. If vertical load of existing buildings next to the excavation pit have to be accommodated, the most practical solution can be found using diaphragm walls supported by pre-stressed anchors, steel struts or slabs.



Picture 1: Repair work U2 in Berlin

The retaining wall of an excavation pit is constructed by adding single panels to each other in sequence to construct a continuous wall. Each panel is a construction unit, built in one work process. The minimum length of a panel equals one grab opening and can be increased to several grab units, depending on the trench stability supported by bentonite slurry.

Diaphragm walls are currently being designed and constructed with an excavation depth of more than 60 meters. This raises the question of how such panels of reinforced concrete may be joined and monitored for integrity at such a depth ?

The single panels of a diaphragm wall are interlocked by joints between the panels. These joints are inserted when constructing the primary panel and also provide guidance for the secondary panel. By this mechanism, the excavation tool for the secondary panel is led during the excavation process. Mechanical und hydraulic grabs are currently used for the excavation process and cutter units.

The type of joint used for the construction of the diaphragm wall depends on a variety of factors that reflect the different project requirements.

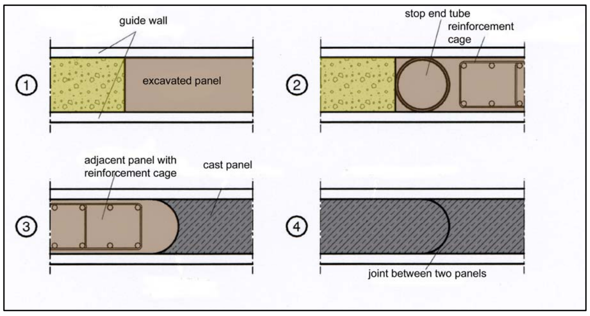
The catastrophic collapse of the Cologne Archive in March 2009 and the accident at the underground metro line U 2 in Berlin made it obvious, especially in Germany, that the joints of diaphragm walls exposed to water pressure constitute the weakest element in diaphragm walls and require special attention in design and quality control.

Types of stop ends and specifications for diaphragm walls

The contractors for special geotechnical work are aware of the importance of joints in diaphragm walls and have used their experience to improve the construction sequences and the details of the stop ends and water stops. These improvements reflect the ground conditions, the groundwater level behind the joints, the intended use the exposed diaphragm wall and quality standard set in the specifications.
They also must consider the degree of reinforcement, the width of the diaphragm wall and the intended depth of the wall. These factors go along with the type of grab used on site; i.e. mechanical or hydraulic grabs or rotating cutter blades.

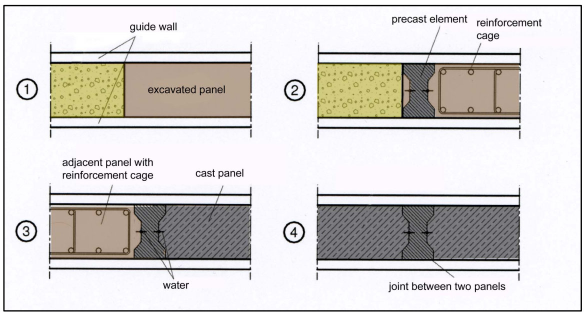
The author interviewed several German and European contractors of diaphragm walls. The most common types of stop ends in diaphragm walls, supplemented with inserted water stops, are listed below. This variety of different technical solutions for stop ends developed over time according to site needs, the experience of the construction company and the equipment available.

Commonly used stop ends for diaphragm walls



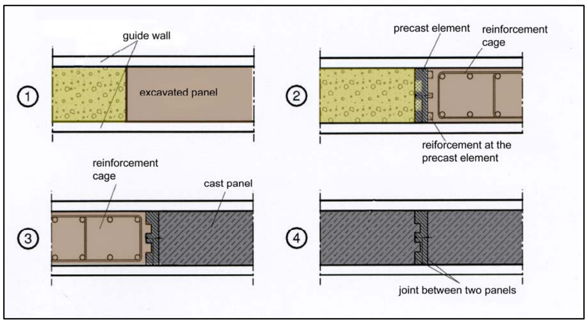
- Different angles of panels are easy to combine
- Shape of the joint creates a long path for leakages
- Shape provides good guidance for adjacent panel
- Timing for pulling the tubes requires long experience
- Upgrading with post grouting tube possible
- Spacing of reinforcement cages requires attention

Figure 1: Type of stop end – stop end tube



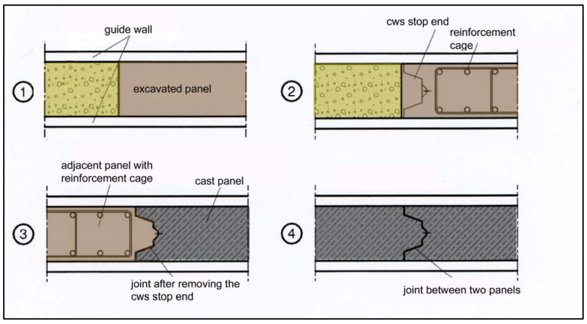
- Permanent element that remains in the panel
- Water stops can be installed
- Application possible to a depth of 60 m
- Stiff element against deflection and torsion
- Possible to cast on site
- Powerful cranes required on site
- Difficult to remove excess concrete
- Double number of joints
- Difficult to join separate elements

Figure 2: Type of stop end – precast element by Bauer



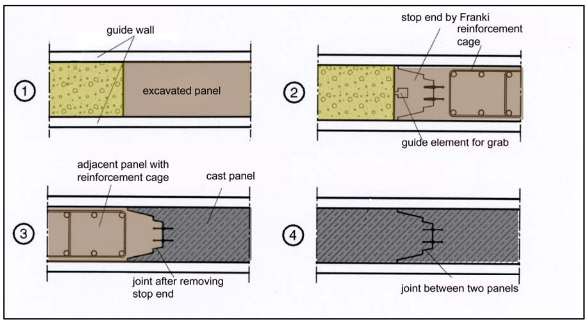
- Permanent element that remains in the panel
- Reinforcement cage is close to the joint
- Improved load transfer due to special reinforcement connection
- Good guidance for the chisel
- Water stop with expansion can be installed
- Post grouting possible if required
- Powerful cranes required on site
- Difficult to join separate elements
- Width between 1,0 to 1,50 m

Figure 3: Type of stop end – precast element by Porr



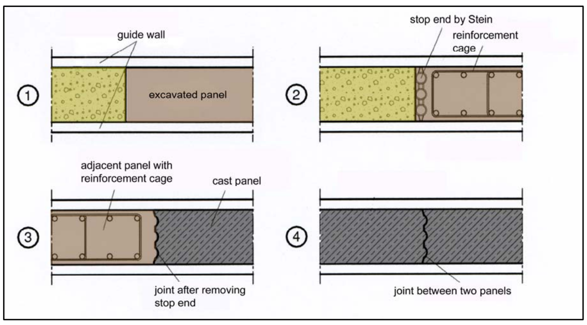
- High reliability in terms of water tightness
- Water stop can be installed
- Extracted during the excavation of adjacent panel
- Guidance for the grab in the stop end
- Stop ends are retrievable
- Shape of the stop end element gets affected by the concrete pressure
-Weight of stop ends require powerful cranes

Figure 4: Type of stop end – CWS stop end by Bachy



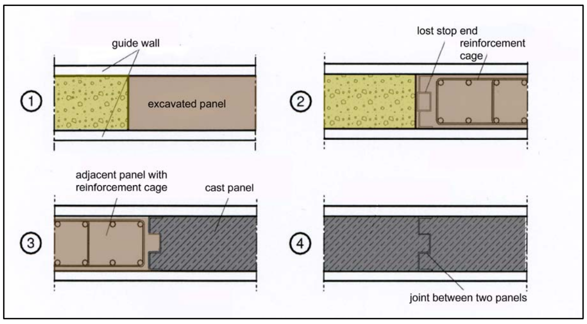
- High reliability in terms of water tightness
- Two water stops
- Extraction during the excavation of adjacent panel
- Guidance for the grab in the stop end
- Stop ends are retrievable
- Difficult to remove excess concrete
- Weight of the stop end requires powerful crane

Figure 5: Type of stop end – stop end by Franki



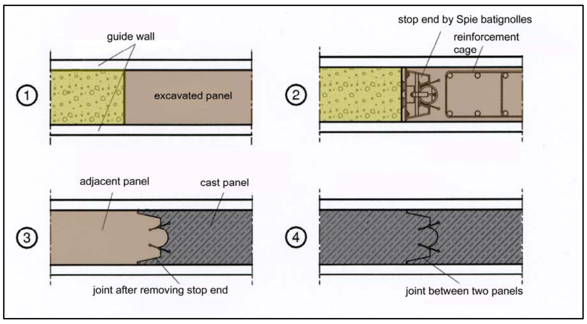
- Stop ends are retrievable
- Relatively light stop ends
- Long path for the leakages
- Short distance of reinforcement gages
- Extraction requires an independent work procedure
- Water stops are not integrated
- Hydraulic jack required

Figure 6: Type of stop end – stop end by Stein



- Remains in the cast panel
- No additional work sequence
- Light stop end construction
- Guidance for the grab
- Protected during the excavation of adjacent panel
- Short distance of the reinforcement cages
- Easy to extend different elements on site
- No water stop installation
- Very flexible stop end

Figure 7: Type of stop end – lost steel joint



-Two water stops provide reliable water tightness
- Removal of stop end possible at any time
  by horizontal hydraulic jack
- Retrievable stop end
- Adjustable in width
- Time intensive to extend the stop end
- Requires powerful cranes
- Long distance between the reinforcement cages

Figure 8: Type of stop end – stop end by Spie Batignolles

Specifications for diaphragm walls refer to the code of practice and refer to the national or European Standards. They define the quality of work that has to be performed by the contractor in conjunction with the contract and as provided by the client´s engineer.
The contractor usually produces a method statement and shop drawings with panel layout, waterproofing details and recesses for anchors in the diaphragm wall. Nearby buildings may have to be monitored depending on the panel width and the panel excavation sequence.
In terms of the joint quality, the Engineer asks for reference projects of diaphragm walls with comparable stop ends in similar ground conditions. If required, a trial panel or trial pit may be built and exposed prior to actual construction in order to approve the type and installation sequence for the stop ends. During construction, the Engineer usually allows for a number of independent checks of the verticality of panels.

The following factors predominantly affect the quality of joints in either temporary or permanent walls and ought to be defined in the specifications for diaphragm walls:

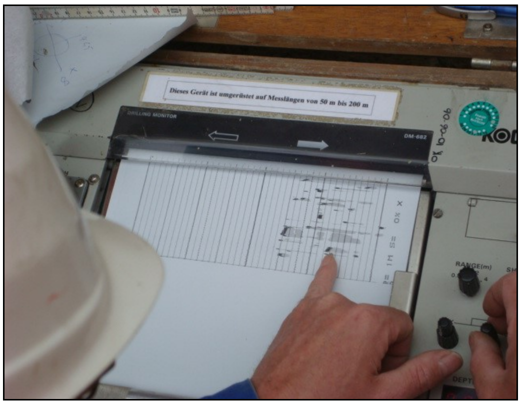
Specifications for stop ends: Shape of stop ends
Material of stop ends
Stop end with or without water stops
Stop end that are extracted (vertically or horizontally)
Stop ends that are lost
Verticality check of stop ends
Quality check for the removal of over break concrete

Quality control for stop ends in diaphragm walls

Experienced engineers, qualified supervisors, operators and foremen on site make a major contribution to facilitate the technical success of diaphragm walls.
Supporting factors are the equipment used and the implemented QS/QC standards on site in combination with project schedule. Beside these factors, the type of joint used to combine adjacent wall panels determines to a major extent the quality of the exposed joints.
Project developers request highest quality standards and minimum risk involvement, therefore, they increasingly demand extended production records of diaphragm joints.
The type of joint element implemented together with the assessment of the field engineer regarding the removal of the excess concrete is not sufficient information to comply with the specifications. Therefore, two independent quality routines have been established and are used to check the joint quality.

Ultrasonic readings by the use of Koden monitoring units
Koden is a word wide operating supplier for marine electronic products .The basic unit of these naval ultrasonic reading tools has been adapted for the application of quality control during diaphragm works.
The principle is based on sending ultra-sonic waves through the bentonite slurry, after the panel was excavated. To obtain best results, the slurry should be de-sanded for the purpose of taking readings.

Picture 2: Ultrasonic unit installed at the panel



Picture 3: Readings taken

The ultrasonic head is being lowered into the open panel and waves are sent out while lowering the Koden unit into the panel. The system is attached to a frame and moved by a precision winch that monitors the depth during the readings. The waves are sent to the front side of the excavated panel. Once the distance is set between the reading unit and the exposed joint, all readings taken should show the same distance.
Those areas which show significant differences indicate the likelihood of excess concrete along the joint. In most cases, this is a clear sign that the concrete must be removed by a crane operated chisel.
These ultrasonic readings are very easy to integrate into the production process, since there is enough time to place the Koden unit and lower it into the panel during de-sanding of the slurry in the panel.
Special attention has to be given to the interpretation of the readings, since the unit measured is the time for the ultrasonic wave that travels from the sender back to the sender after reflection at the exposed joint. The travel time of the ultrasonic waves through the bentonite slurry depends on the specific weight of the slurry that might differ over the depth of the panel. Therefore, adjustments have to be given to receive clear results for further decisions.
The most significant advantage of the Koden readings is that the results are available before concreting the panel and therefore, correction along the joints is possible while the panel is still open and the equipment is on site.

Ultra sonic cross-hole logging

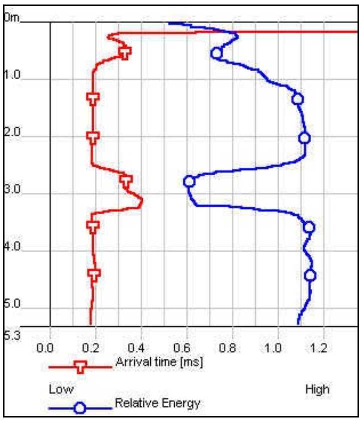
This commonly used measuring system is based on the travel time of ultrasonic waves travelling through concrete, not through bentonite slurry.

Pipes are installed before concreting the panel .These pipes are placed in the primary panel and in the secondary panel and once the concrete is hardened, these pipes take the sender and readers at the same time to read the time needed for ultra-sonic waves to travel from the sender to the receiver.

The position of the senders and readers can be exchanged and altered so that a qualified picture of the joint can be concluded. If the integrity of the joint does not reflect the specifications, there would be a significant difference the ultra-sonic readings.

If joint systems are implemented which are not being extracted and intentionally lost in the joint, it becomes more difficult to understand the readings (since several materials with different specific travelling speeds have to be interpreted).

Picture 4: Measuring procedure

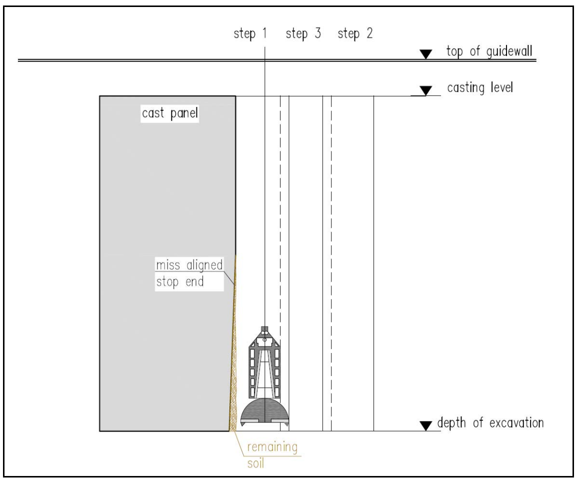


Picture 5: readings taken

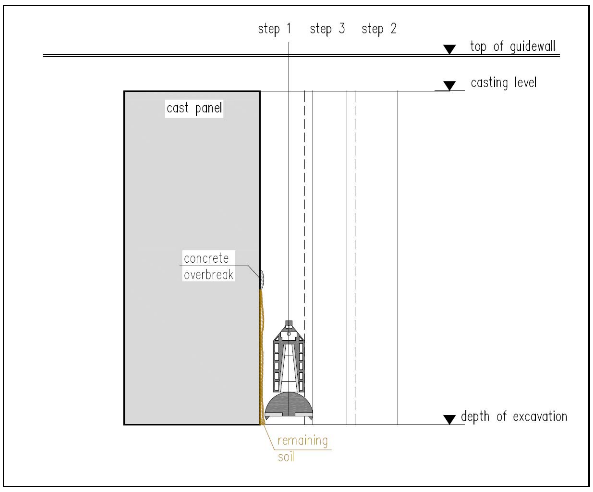
The ultra-sonic cross-hole sonic logging is a post construction quality check on the joints, usually taken prior to excavation and exposure of the joints. If the quality deficits are detected, the remedial work cannot be executed by the equipment used for diaphragm work, rather by additional technique like grouting , jet grouting or freezing.

Details of excavated and exposed joints in diaphragm walls

The vertical position of the joint construction as well as the clean surface of the exposed adjacent panel is essential for the interlock of panels. If these criteria are not fulfilled, the excavation of the panel is very likely to suffer severe quality defaults and miss relevant areas as the grab gets diverted.



Picture 6: deviation due to miss aligned joint element



Picture 7: deviation due to excess concrete

Those water pressure exposed areas along the joint construction, in which excess concrete was not removed properly, remain an uncontrolled risk during the excavation. These construction joint have no qualified transition between the concrete cured in two different panels. The exposure to atmospheric conditions during excavation might lead to fault in material due to different behaviors and properties. As a precautionary measure, it is recommended to cover these areas with steel plates and hard foam from the detected height down to the final excavation level.

New method of quality control for construction joints ("joint inspector")

The intensive investigation of several failures in joints of diaphragm walls has led to a new approach in the quality control of joints between diaphragm panels. It is imperative to obtain information on site of the joint quality during special geotechnical work to enable execution of remedial work while the appropriate equipment is on site. Prior to excavation, the quality of joints has to be measured and corrected if necessary. The optimal time to check and assess is when the adjacent panel is excavated and the joint to the neighboring panel is exposed. After excavating a panel, during the de-sanding period, a time slot of several hours is available to investigate the joint to the adjoining panel.
At that time, the new method of quality control may be implemented. A mechanical device, mountable to the frame of the mechanical grab, shall check the exposed contact zone of the adjacent panel. The crawler crane with the grab runs one more excavation cycle in the excavated panel, utilizing a special measurement tool attached to the grab.
Starting from the bottom to the top, the grab is lifted at a defined distance to the joint and takes readings during this ride.
The tool attached to the grab has mechanical distance sensor which works completely independent from the hydraulic system of the crawler crane. Like fingers that are pre stressed and bend down at the frame of the grab, they "feel" the surface and the profile of the exposed surface once they are released. While pulling back the grab, these mechanical sensors measure the angle to the contacted surface and, as such, measure the profile of the exposed joint.
All readings are stored in an electronic unit which is incorporated in the measuring unit. Once the grab and the measuring unit (called "joint inspector ") is extracted from the slurry filled panel, the recorded data is sent by blue tooth technique to the computer of the site engineer.

Picture 8: The "joint inspector" mounted to the grab
.

Picture 9: Modular units of the "joint inspector" without distance sensors

Picture 10: Modular units of the "joint inspector" in full set up

Picture 11: "Joint inspector" in touch with the joint

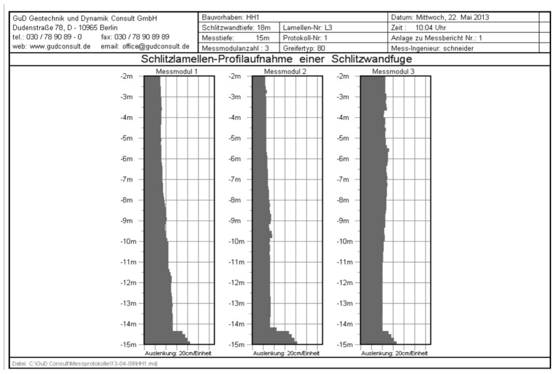

Picture 12: "Joint inspector" with fully released distance sensors

9. Site application on different types of stop ends and grab systems

The following descriptions refer to field tests that were conducted from April 2013 to September 2013 in Germany. The "joint inspector "was tested on 4 different sites in Berlin and nearby Magdeburg. The purpose of these tests was to approve the suitability on different mechanical and hydraulic grabs as well as on different types of stop ends. At one site a profiled steel plate was additionally attached to the stop end to check for accuracy.

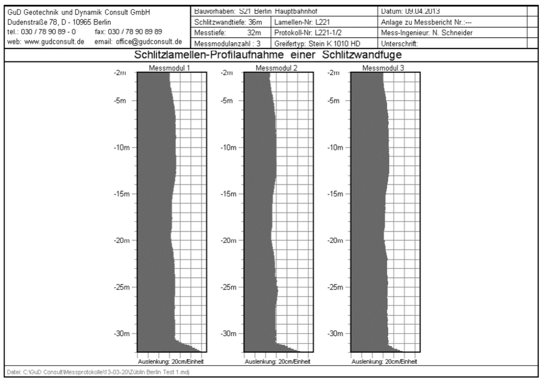
All tests were carried out by taking two measurement readings and confirming that the data collected was reliable.

Picture 13: Test on stop ends by Bachy



Picture 14: Print out of readings taken

Picture 15: Test on lost stop ends



Picture 16: Print out of the readings taken

The mounted “joint inspector” has an electronic memory box that stores the depth and the angle of the different distance sensors along test run. When the grab with the joint inspector comes out of the slurry, a blue tooth connection transfers the data to a field computer that immediately displays the results.
The immediate availability of data allows the field engineer to take necessary decisions, for example, if the plots displays that excess concrete was not removed according to specification.

Since the removal of the excess concrete in most cases requires a special chisel that hangs at the main winch of the base crane, the mounting of the “joint inspector “to the regular grab is not on the critical path. Therefore, the time span for mounting is not relevant with respect to construction time.

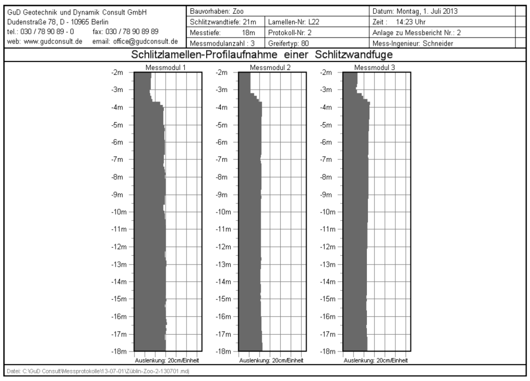
Once the extended arms are pushed back into the vertical position, the “joint inspector” is ready for the next test run.
It takes approximately 10 minutes to attach the “joint inspector” to the mechanical grab.
The first site statistics show that it takes about 1- 2 minute to test run the length of 10 meters exposed diaphragm wall.

Regardless of the width of the excavation, preset steel plates allow to attach the joint inspector to grabs ranging from 60 cm to 150 cm. The basic frame of the “joint inspector “was designed in aluminum to enable transportation by air freight, if necessary.

The mechanical solution was designed to carry out the test runs always from the bottom to the top. That way, the wear and tear is minimal to the system. Rollers at the end of the arms

run over the exposed surface of the adjacent joint.
The “joint inspector “was designed to be water tight to a depth of 100 meters. All the distance sensors are detachable and - if necessary – the joint inspector can be upgraded with up to 5 arms, if the width of the diaphragm wall requires additional profiles.


Picture 17: Test on stop end tubes



Picture 18: Readings on stop end tubes

After the completion of the test runs, the mechanical parts can be sprayed off with water and dismantled.
The readings taken do not require a defined distance to the exposed joint. All site tests were carried out with a distance of 40 cm to 70 cm.
The accuracy from the field test taken shows that 3 cm elevations are detectable.
The connection of the arms to the main unit of the “joint inspector” are laid out to allow for a break at this joint if some unforeseen circumstances arise.

Improved quality standard for deep excavation

The most significant advantage of the quality control using the “joint inspector” is the immediate availability of the profile taken. Should excess concrete be detected, all necessary equipment is still on site to continue the cleaning process of the joint. This enables the contractor to prevent quality failures by in-process monitoring, rather than to repair quality defaults at a later stage.
The verticality of the stop end can also be monitored using the “joint inspector”, just by checking the profile readings over the depth.
The test runs do not require a certain quality of the bentonite slurry. It is possible to take the measurement during the de-sanding process. The readings are completely independent from the purity of the bentonite slurry.

The principle of the measurements are straight forward and independent from any interpretation. The results can be discussed since all project partners can develop a clear picture of the elevations measured. If necessary, the test run may be repeated –within minutes - to double check the results.

Both the client and the contractor have independent documentation that reflects the quality of the joint. This could allow for clear contractual agreements regarding the handling of the sensitive issue of diaphragm joints.
The engineering team of GuD Consult GmbH are proud to offer this state-of-the-art method for quality control of construction joints in diaphragm walls. This development has the potential to improve the quality of basements in a way that inner side facing walls of underground car parks might become replaceable for appropriate projects.

As follow up step, GuD Consult GmbH is committed to attribute the” joint inspector “to a complete project during the entire stage of diaphragm wall works to ensure highest quality on joints for diaphragm walls.

Acknowledgments

The engineers of GuD Consult GmbH acknowledge the funding that was made available via EUREKA and the Bundesministerum für Wirtschaft und Technologie. We greatly appreciated the help of J.M. and E.I. Amir as well as the support of E. Niederleithinger of BAM, Bundesanstalt für Materialforschung und-prüfung.

References

Niederleithinger E. (2014): Advanced methods for quality assurance of diaphragm wall joints. Proceedings of the DFI- EFFC International Conference on piling and Deep Foundations, Stockholm, Sweden.

Jäkel, H. (2011) Ausgesuchte Schlitzwandfugensysteme und die Möglichkeiten der Qualitätsüberwachung

Neuenhaus, H. und Krutwig, R. (2010) Herstellung von tiefen Schlitzwänden und DSV-Andichtungen für Tunnelvortriebe

Borchert, K.-M. und Linder, W.-R. (2007) Erfahrungen mit Leckagen an Schlitzwänden und Unterwasserbetonsohlen bei Trogbaugruben

Triantafyllidis, Th. (2004) Planung und Bauausführung im Spezialtiefbau, teil 1: Schlitzwand und Dichtwandtechnik. Verlag Ernst & Sohn, Berlin