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# Wallslotrobot: a new method of deep braced excavation in compact spaces

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## ABSTRACT

*This paper outlines the first development stages of Wallslotrobot: a new method of deep braced excavation. Wallslotrobot is a technological response to the established manual technique called "beschoeide sleuven" (BE) or "fouilles blindées" (FR) which is geographically limited to the Benelux countries. The result is a prototype machine which is basically a vertical tunnel boring machine. The device consists of a ground cutter that is pushed vertically into the ground by a jacking system. The shaft lining consists of hollow rectangular precast concrete segments.*

*At present the technical feasibility of Wallslotrobot has been successfully demonstrated. The prototype machine and lining segments have been tested on the field. Three 15m deep adjacent trenches were excavated from a 2,5m diameter tunnel. In response to this positive evaluation, the joint venture Future Foundations was set up to commercialize Wallslotrobot by 2019*

***Keywords: deep braced excavation, deep sheeted trenching, deep foundations***

## 1. INTRODUCTION

Deep braced excavation or deep sheeted trenching is a construction technique to build deep reinforced concrete walls in dry, soft soil conditions. These are manually created by specialized personnel, using a shovel, bucket and pulley system. This process is slow and workers are exposed to significant safety risks.

Its field of application is mainly situated on construction sites where there is little clear working height and space available, like tunnels or basements. Thus where other competing techniques as slurry walls, soilmix or secant piling are not applicable.

A particular example where this technique was used is the Schuman-Josaphat rail tunnel (2008-2012), during which the idea for mechanizing the technique arose. From 2011 until 2013 the general conception of the idea was developed and named Wallslotrobot.

Subsequently a nationally funded project was set up to demonstrate the technical feasibility of constructing these deep sheeted trenches mechanically and with an economical advantage compared to the existing method. The main project objective was to design, build a prototype machine and demonstrate it in a realistic operating environment.

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In June 2015 the first field tests were conducted, the overall test program consisted of the excavation of three 15m deep adjacent trenches from a 2.5m diameter concrete pipe anchored at ground level.

## 2. TRADITIONAL METHOD OF DEEP BRACED EXCAVATION

### *2.1. Description of execution*

Deep braced excavations occur typically in adjacent slots of 3m in length, dimensions range over 15m in depth and between 1m and 1.5m in width. The trench is sequentially dug out, by shovel in soft soil or pneumatic tools in case of hard discrepancies, over a height of 0.4-0.5m. The soil is removed by a bucket and pulley system installed at the top of the trench. Hereafter the exposed soil is sheeted by precast concrete elements which are fixed in place by horizontal struts at predefined distances, see Figure 1.

Figure 1: Deep braced excavation by hand

Once the desired depth is reached, rebar is put in place. Especially where little clear working height is available (<3m) this is done manually by workers located inside the trench (see Figure 2). To conclude the trenches are poured with concrete.

Figure 2: Rebarred trenches

Due to the complexity of this specialized technique it is mainly used and established in the Benelux countries: Belgium, the Netherlands and Luxemburg.

### *2.2. Case study: Schuman-Josaphat project*

To illustrate the practical use of deep braced excavations the case study of the Schuman-Josaphat rail tunnel (Brussels: 2008-2012) is briefly described next.

The Schuman-Josaphat rail tunnel is a mined tunnel and junction to an operational line beneath an avenue, residential and commercial buildings. Because of the low soil cover of only 3-4m normal TBM driving was not applicable. In addition the environmental consequences of cut-and-cover were unacceptable. Therefore it was decided to adopt sequential excavation combining, microtunneling with traditional deep braced excavations and compensation grouting to construct a tunnel envelope as described next and presented in Figure 3.

1. Construction of an access pit (6mx6m) with pipe jacking galleries.
2. Horizontal pipe jacking (DN3000) aligned with the top corners of the tunnel.
3. Deep braced excavations (20m depth), forming the tunnel walls.
4. Transverse pipe jacking, forming the tunnel roof.

Following the completion of the boundary structure (concrete filled pipe-roof and reinforced concrete walls) the intermediate soil is removed and the concrete floor is installed.

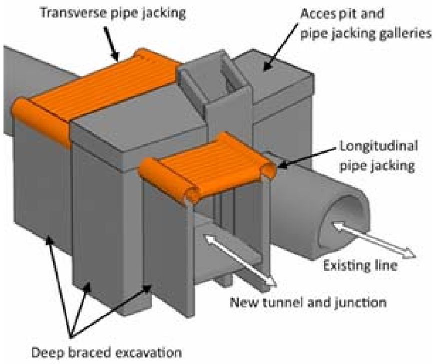


Figure 3: Josaphat Schuman rail tunnel construction

## 3. WALLSLOTROBOT CONCEPT

### *3.1. Idea*

During the construction of the Schuman-Josaphat rail tunnel over 10,000m³ of deep braced excavations were performed. The execution of these excavations was determinative for the total project duration because of the slow rate of progress and shortage in specialized personnel.

Because these excavations were highly repetitive, the idea arose to mechanize this technique. This would not only be beneficial for the project duration and cost but also a higher overall safety and better ergonomic working conditions for the workers would be achieved.

### *3.2. Design goals*

Following general design goals for the Wallslotrobot development were predefined:

- Excavation time: 5x faster
- Maximal depth: 30m
- Width: 1.200mm
- Min. clear working height: Ø2.5m
- Geology: silt layers on top and Tertiary dense sand below, including sandstone concretions. Situated above ground-water level.
- Safety: minimal human presence in the trench
- Cost effectivity: competitive with manual method
- Quality: excellent water tightness and high surface finishing.

### *3.3. Conception*

The general conception was developed during 2011-2013 according to the design goals described in 3.2.

The result is a method, illustrated by Figure 4 , in which the trench is formed by pressing precast concrete sheeting elements downwards while loosening the soil at the base by means of a soil cutter. The removal of loosened soil from the trench is done by a grab.

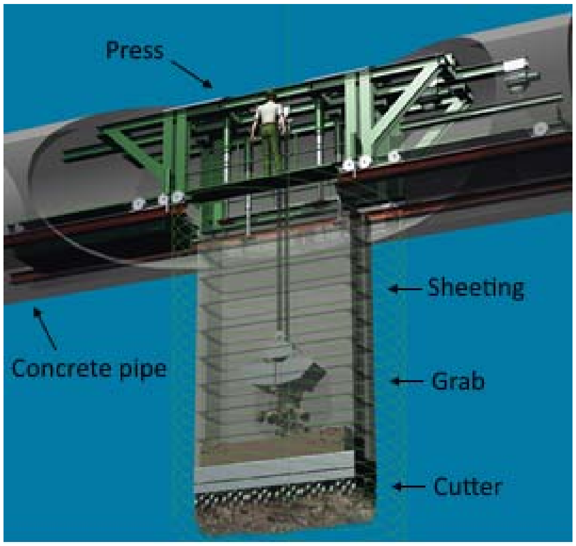


Figure 4: Wallslotrobot concept

When the desired trench depth is reached the soil cutter is recovered and rebar cages are installed, whereafter the trench is poured with concrete. Multiple interlocked adjacent trenches eventually form a reinforced concrete wall.

The method is patented and published with number EP2535462B1 on the ninth of March 2016.

## 4. PHASE 1: TECHNICAL FEASIBILITY

### *4.1. Goal*

Following the conception stage a nationally funded IWT project was set up in order to assess the technical feasibility (2014-2015). The final goal was to construct three adjacent 15m deep trenches in a realistic operating environment and relevant geology. To achieve this goal a prototype machine and concrete sheeting element had to be designed and built, with a predominant focus on technical feasibility and a minor focus on process speed and/or automation. This design process included multiple iterations.

### *4.2. Test setting*

The test setting is discussed first since the design of the prototype machine is partly based on this.

## Testsite geology

As Brussels is the primary market for this new technique it was chosen to obtain a test location with a similar geology as for the Schuman-Josaphat project. Thus a silty and clayey Quaternary top layer with underneath sandy Tertiary layers commonly classified as Brusseliaan. It typically contains sandstone concretions and possible decalcified zones.

The testing station of the Belgium Building research Institute at Limelette is an ideal location with a comparable geology. Clayey tertiary layers down to 8m below ground level with underneath the sandy Brusseliaan. A CPT diagram and soil classification is given by Figure 5.

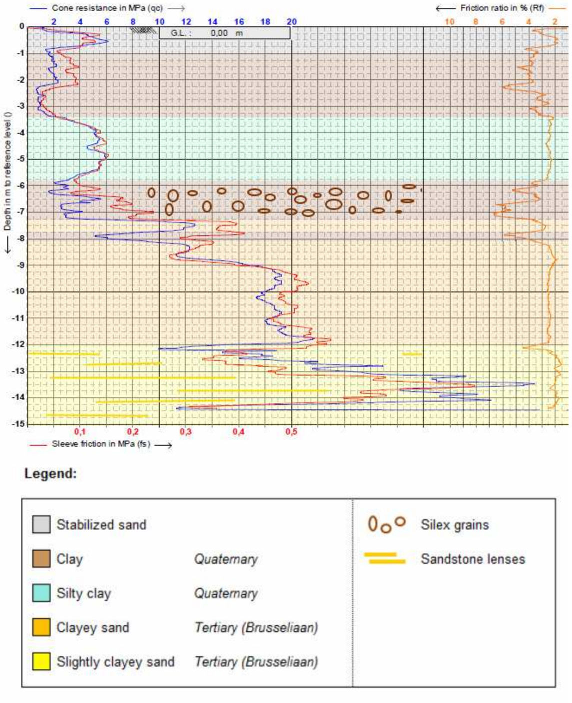


Figure 5: Soil classification and CPT (C3-BBRI) at the test location for slot 1

In most of the CPT's that were available, sandstone concretions were encountered between 12m-14m below ground level. Taking this information into account it was decided to perform tests to a depth of 15m below ground level in order to maximize the probability of encountering the sandstone concretions. The groundwater level is located well below this depth so no additional measures for drainage were necessary.

## Test setup

To demonstrate the Wallslotrobot method it was essential to create a realistic setting. In this case four aligned concrete pipes, with an internal diameter of 2.5m and a total length of 11.5m, were anchored at ground level on a bed of stabilized sand. Four anchors were installed on either side of the pipe at an angle of 17° away from the longitudinal symmetry plane in order to minimise soil disturbance prior to excavation. A side- and cross view of the test setup is given by Figure 6 and Figure 7 respectively.

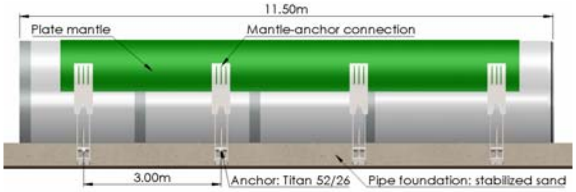


Figure 6: Side view of the test setup

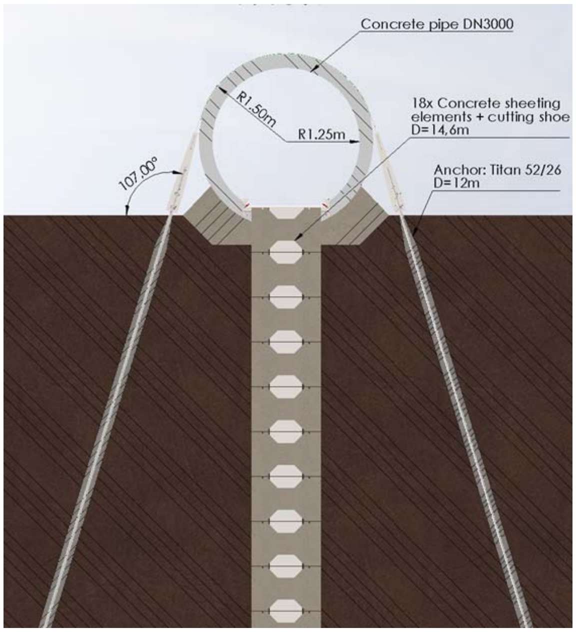


Figure 7: Cross section of the test setup

After installation, the anchors were connected to a steel plate mantle resting on top of the pipes and prestressed to fix the pipe in place. Subsequently a 1.3m by 10m slot was cut out and strutted in the bottom of the pipe to allow passage of the machine. Lastly rails were installed to facilitate horizontal transport of the machine itself, sheeting elements, and excavated soil.

### *4.3. Wallslotrobot prototype*

The design of the prototype machine is subdivided in three main components: the press unit, the ground cutter and a method for vertical soil removal. Figure 8 illustrates the prototype assembly in operation, here the mechanism for soil removal is not displayed since multiple systems were designed and tested.

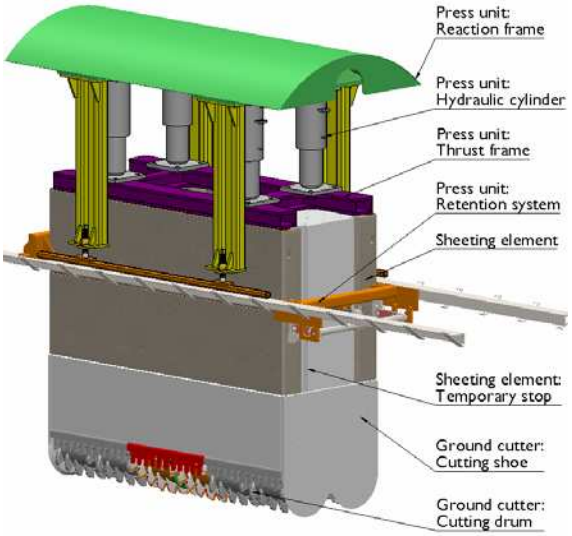


Figure 8: Assembly of the prototype machine in operation

### Press unit

The press unit can translate in the longitudinal axis of the pipe on the rails. When positioned on a desired location the press is fixed and aligned in the pipe by a rail locking system. Four hydraulic cylinders are installed in order to press the concrete sheeting elements downwards. The reaction forces are transferred to the pipe roof via the reaction frame.

The presence of underground cavities due to decalcification for example has been taken into account in the design. To anticipate on this loss of frontal resistance, possibly resulting in uncontrolled descent, the ground cutter, the sheeting elements and the press are continuously interconnected mechanically. This link is broken only during the placement of a new sheeting element, therefore a static retention system is installed to temporarily hold the concrete shaft and the cutter.

### Ground Cutter

The ground cutter is designed to minimize frontal resistance and loosen the soil to facilitate vertical removal. In the first stage the soil needs to be transported from below the cutting drums to above them. This is achieved by the combination of the rotation of the cutting drums and the presence of soil scrapers as displayed on Figure 9. In addition the cutter needs to be capable to cut through local sandstone concretions (UCS <50MPa).

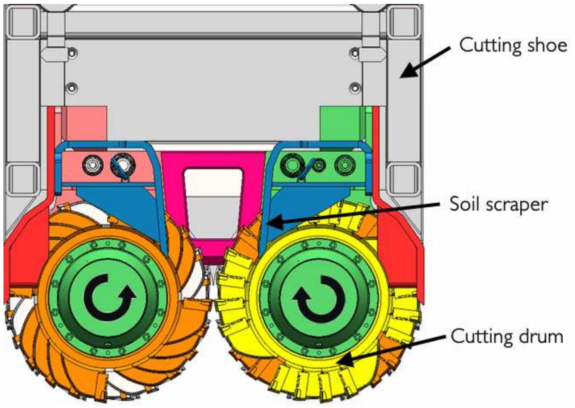


Figure 9: Cross section of the ground cutter

The cutter itself consists of six identical modules, each equipped with two hydraulic powered cutting drums, which are mounted on the cutting shoe. An overcutting value of 3mm was empirically determined, based on the following considerations:

- A minimal overcutting is needed to allow for steering.
- Settlements need to be within an acceptable range, resulting in an upper limit for the value of overcutting.
- When the overcutting value is higher, soil relaxation is higher resulting in a decrease of lateral earth pressure on the sheeting. This has two advantages: a decrease in thrust forces due to lower wall friction and a decrease in strength specifications of the sheeting elements.

In order to anticipate on deviations in verticality each cutting drum is designed to be individually adjustable in rotational speed. By adjusting the relative speeds of specific drums one can theoretically provoke a steering motion in any direction.

Eventually, once the trench has the desired depth, the cutter is disassembled. Ideally this is done automatically which is not yet incorporated in this prototype design. On disassembly the cutting shoe is left behind, functioning as sheeting.

### Method for vertical soil removal

Regardless of the grabbing concept, multiple options for vertical soil removal were considered. Eventually it was chosen to develop and test two independent methods: the original grabbing method and soil removal by air transport as presented in Figure 10. The airflow is invoked by means of a rental vacuum suction excavator.

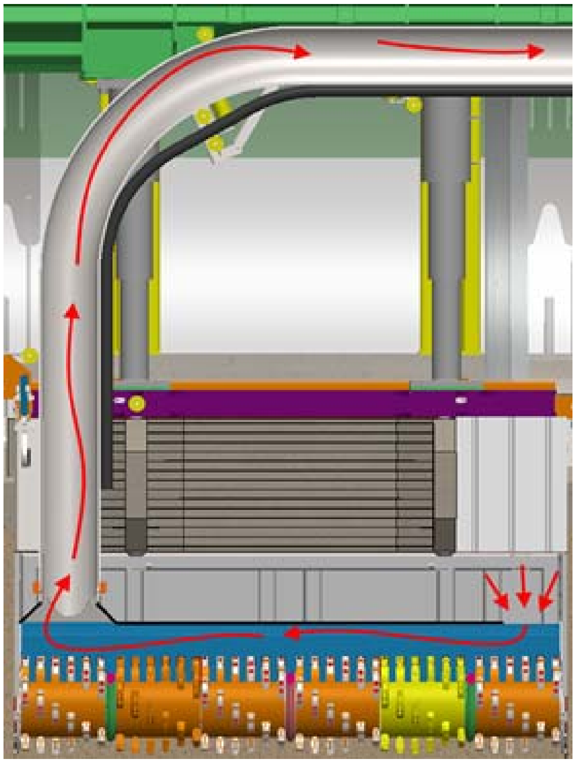


Figure 10: Soil removal by air transport, airflow represented by arrows

### Process control and instrumentation

The prototype machine is controlled via an operating console which allows control of diverse process parameters and observation of process data registered by multiple measurement sensors. The most important sensors and their function are listed in Table 1.

Table 1: Installed measurement sensors

| |
|---|
| 1. **Press:** cylinder pressure sensors (4x)<br>→ Total thrust force |
| 2. **Press**: cylinder stroke sensor (1x)<br>→ Thrust frame position, depth and progress rate |
| 3. **Press:** inclinometers (2x)<br>→ Yaw and pitch of the thrust frame |
| 4. **Cutter:** inclinometers (2x)<br>→ Yaw and pitch of the cutter |
| 5. **Cutter:** force sensors (4x)<br>→ Front pressure and wall friction |
| 6. **Cutter:** drum speed sensors (12x)<br>→ Rotational speeds |
| 7. **Cutter:** drum pressure sensors (12x)<br>→ Cutting torque |
| 8. **Cutter:** cameras (3x)<br>→ Process observation |
| 9. **General:** Target laser (1x)<br>→ Depth and lateral drift of the cutter |

## *4.4. Sheeting element prototype*

The main functionality of the sheeting element consists in retaining the soil, thus preventing the trench from collapsing during construction. Because these elements are left behind their function is temporary and therefore a minimal production cost is a major design condition. This resulted in the use of hollow prefabricated concrete blocks as sheeting elements.

### Design load

To assess the technical feasibility it was necessary to determine a "worst case" design value for the lateral earth pressure. The design assumption was made to use the standard lateral earth pressure envelope for braced excavations according to Terzaghi and Peck (1967). However, due to a difference in execution and the presence of an annular space in contrast with standard braced excavations there is no 1-to-1 relation. Finally the design load was set at 300kPa uniform pressure, for a worst case scenario of 30m deep trenches in dry, fine grained soils with low cohesion.

## Geometrical design

In Figure 11 the prototype sheeting element is presented. The length and width of the elements are based on the current practice. The height was chosen in function of the available working height and was set to 0.75m for this project.

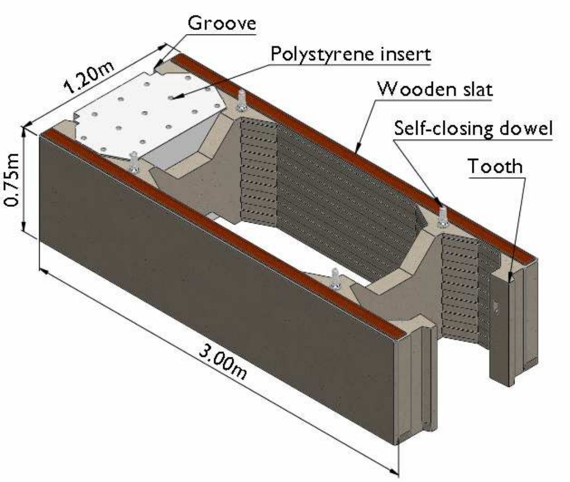


Figure 11: Concrete sheeting element

The H-shape results in an optimal force distribution and a low wall thickness. In addition there is no need for decoupling power lines for the cutter every time a new sheeting element is placed. Furthermore the shape contributes to a better water tightness and makes structural continuity of adjacent slots possible.

The sheeting elements are equipped with a tooth-groove connection to ensure alignment of neighboring trenches. The elements themselves are vertically centered and interconnected by self-closing dowels used in the tunneling segment industry. Vertical pressure forces are transmitted through wooden slats.

The polystyrene insert at the end face has a double functionality. On the one hand it retains the soil during excavation. On the other hand it divides adjacent slots, acting as formwork for the concrete in the final construction stage, whereafter it is removed by cutting. In a later design stage the polystyrene inserts will be replaced by a more sustainable and practical solution.

## Destructive testing

The sheeting element is designed for a uniform lateral pressure of 300kPa. However, the hypothesis of uniformity will in practice only occur for very soft soils (e.g. peat) and hydrostatic pressures. Instead a favorable 3D soil arching mechanism will emerge horizontally between the struts, the size of the arching effect is dependent on the soil properties, depth, strut center distance and the deformation of the sheeting (Piaskowski & Kowalewski, 1965).

To assess the influence of the arching effect, the sheeting elements were subjected to real scale destructive testing in the Magnel laboratory for concrete research. Two test setups were built, one to simulate uniform loading where the element is placed on a mortar bed and subjected to five equal line loads (Figure 12a). For the other setup the element was placed on a 0.90m sand bed where it is pushed against the bed by introducing forces via the struts (Figure 12b).

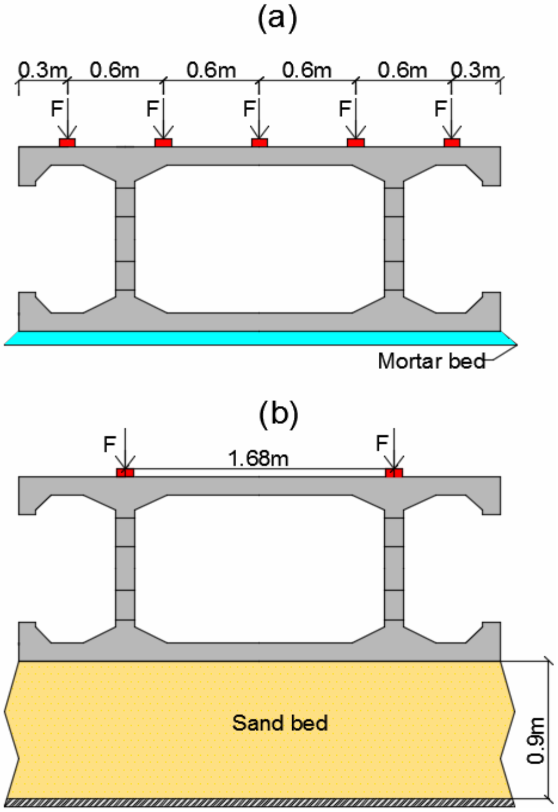


Figure 12: Real scale test setup for (a) uniform pressure simulation and (b) soil arching simulation

The results showed that the arching effect in highly compacted sands has a significant advantage in force distribution. Because the maximal thrust force of the setup was reached before structural failure was observed, the exact advantage could not be quantified. However, it can be concluded that the deflection capacity of the sheeting elements is adequate for arching to occur. A minimal load capacity increase of 45% was observed, which is in line with the 3D-arching theory of Piaskowski & Kowalewski, 1965.

### *4.5. In situ testing*

In total the test program consisted of five stages: three test stages (A,C,E) and two design iteration stages (B,D) as presented by Figure 13. The total program had a duration of six months starting from June until November 2015. A detailed description of the test geology and test setup can be found in paragraph 4.2.

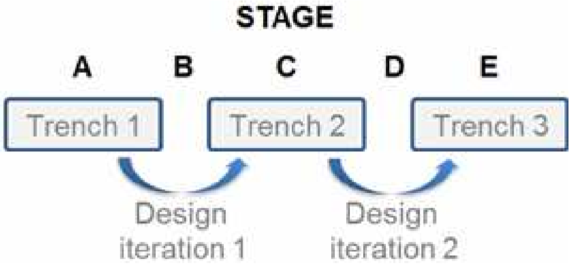


Figure 13: Test program Wallslotrobot

Before testing, the following operational risks were identified:

- Need for excessively high thrust force.
- Insufficient steering capacity to ensure verticality.
- Inefficient vertical soil removal, resulting in too low productivity
- Inefficient soil cutting mechanism, resulting in low progress rates.
- The capability to cut through sandstone concretions.
- Bad alignment of adjacent trenches.

### Evaluation of the thrust force

The necessary thrust force was well below the expected value's which were estimated according to EC7, pile design. An explanation lies in the presence of the annular space, the occurrence of soil arching and the short execution time, which all contribute to a lower lateral earth pressure and thus a lower wall friction.

Moreover the thrust force tends to be quasi constant, regardless of the execution depth. This means that the increase in dead weight of the sheeting tends to be in equilibrium with the increase in shaft friction. Thus the lateral earth pressure doesn't seem to increase at greater depths, which corresponds to the theory of arching according to Piaskowski & Kowalewski, 1965.

### Ground cutter performance

The excavation effectiveness of the ground cutter was well above expectation in soft soils. It literally digs itself in even at very low rotational speeds. Peak progress rates of 48 mm/min were recorded during testing. When encountering sandstone concretions progress rate dropped, but the cutter eventually got through. It was concluded that by optimizing the teeth configuration and tooth type, the efficiency can be increased significantly.

### Effectivity of vertical soil removal

The performance of the air transport system was very variable, depending on soil conditions. In course grained soils a good productivity was achieved. However, for fine grained, slightly cohesive soils multiple problems were encountered. The main issue was clogging of cohesive particles, obstructing the horizontal suction channel in the cutter. During the first design iteration, improvements were made to the geometry of the suction channel and air inlets were installed to add compressed air. This improved the efficiency but not enough, the clogging problem was displaced to the vertical suction tube (Figure 14).

Figure 14: Free 10'' suction tube (a), clogged suction tube (b)

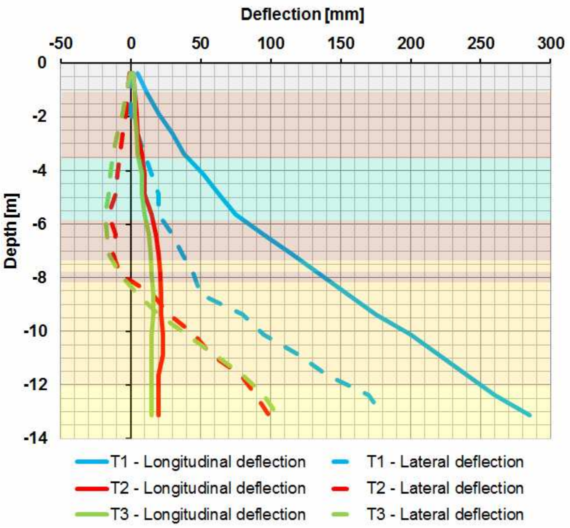
The grabbing mechanism was tested in stage C. The performance was good and small cycle times could be achieved. Unfortunately, the tests were aborted prematurely due to insufficient torque of the drum cutters. In comparison to air transportation the soil is stacked above the cutter and is funneled from the sides to the center, requiring a higher torque.

It can be concluded that the method for vertical soil removal determines the overall productivity. Air transport is only viable for course grained soils. However, the power requirement and installation size are a major downside. The grabbing mechanism is efficient and independent of soil conditions. However, the ground cutter design needs to be attuned with this system of vertical soil transport.

## Steering performance

Due to the high effectivity of the ground cutter, there was too little frontal resistance to induce a steering motion by adjusting the cutting drum speeds. Most of the time the frontal resistance was even negative, indicating that the ground cutter hung on the shaft. The verticality of the trenches is given by Graph 1.

Graph 1: Verticality of trenches T1, T2 & T3



The second and third trench (T2 and T3) were equipped with a steering compartment with four cylinders, situated above the cutter. By retracting or extending these cylinders one creates an angle between the cutter and the sheeting, introducing a steering motion. However, there are still teething problems to overcome since steering is a delicate operation which effect is dependent on local soil conditions.

A good alignment was achieved between adjacent trenches T2 and T3, which were not placed directly next to T1 because of the excessive longitudinal deflection of T1.

## Evaluation of the Sheeting elements

As stated, there was little to no frontal resistance. This in combination with a low wall friction lead to higher tensile forces in the sheeting dowels than anticipated. During in situ testing these connections broke, leading to uncontrolled descent (Figure 15). This was fixed by installing screw plates. The top view of T1 is given in Figure 16.

Figure 15: Disconnection of sheeting dowels

Figure 16: Final result of T1, top view

## General performance

The technical feasibility has been successfully demonstrated. Production rate was doubled for each trench, starting from 20 days for T1 down to 5 days for T3. The design goal of quintupling the excavation time is certainly feasible.

## 5. PHASE 2: COMMERCIALIZATION

### *5.1. Goal*

Future Foundations, a joint venture between Denys and the Participation Company Flanders (PMV) has been set up to commercialize Wallslotrobot. This phase consists of a three year action plan for increasing the technology readiness level (TRL) from 6 to 9 (Figure 17) to finally bring Wallslotrobot on the market.

Figure 17: Technology readiness levels (TRL)

In the first year, which started on January 2016, a beta version of the Wallslotrobot will be developed and tested (TRL 7). In this stage the focus lies on increasing the efficiency, productivity and overall cost effectiveness.

The second and third year will focus on further fine-tuning of the technique, standardisation (TRL8), marketing and actual execution of Wallslotrobot trenches in a first commercial project (TRL9). In parallel new applications will be developed for Wallslotrobot including trench excavation below groundwater level.

### *5.2. Market and applications*

The main market for the Wallslotrobot lies in underground project development in dense urban areas. Here surface area is getting really scarce and the socio-economic impact of open-pit techniques is no longer sustainable.

Future applications for Wallslotrobot are: tunnels (e.g. Schuman-Josaphat), parkings, stations, multi-functional spaces including shopping malls, cinema’s, nightlife activities and sports infrastructure (e.g. the AMFORA project Amsterdam), and many more.

## 6. CONCLUSION

In this paper, a new method of deep braced excavation, Wallslotrobot, is presented. The conduct and result of the first development phase, i.e. the assessment of the technical feasibility, are described. It can be concluded that Wallslotrobot method is technically viable and that a fivefold productivity increase in comparison with the manual method is achievable. The joint venture Future foundations is set up to commercialize Wallslotrobot by 2019.

## 7. ACKNOWLEDGEMENTS

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