Automation at the Westerscheldt Tunnel

Ir. R.de Leeuw
Director Kombinatie Middelplaat Westerschelde

Ir. E. Oele
QHSE-officer Kombinatie Middelplaat Westerschelde

ABSTRACT: Terneuzen- On the 14th of March 2003, the Westerschelde Tunnel was opened after a construction phase of five and a half years. The tunnel was constructed using modern technologies which were partially supported by software and other automated equipment. It's uncommon to use highly automated technologies in construction projects because the unique character of projects reduces the economic feasibility of implementing automated techniques. In this article the following automated techniques will be described: measurement systems to measure the deviations of the used segments and the positioning of the Tunnel Boring Machine (TBM), and monitoring techniques with regard to the temporary frozen soil, which will be described in this paper. The saturation diving technique will also be described. The first part of this paper deals with the scope of the project and specific experiences gathered during the construction phase. The second part will deal with the automation techniques used will be described and finally a presentation of the conclusions will be made.

1. INTRODUCTION

The Westerscheldt Tunnel is one of the longest bored tunnels in the world. What makes this Tunnel unique is that the deepest point lies 60 m below MSL (Mean See Level) and because the soil is mainly weak ground the execution was rather daunting. The tunnel connects Zeeuwsch Vlaanderen to the other parts of the province Zeeland and has replaced the ferry lines. The new connection reduced the crossing time significantly and a twenty four-hour-connection is possible. The tunnel consists of two parallel tubes with a length of 6.6 km. The tubes are connected to each other every 250 metres by a cross passage. Fire protection cladding was placed on the tunnel walls and the energy facilities are located in thirteen "cellars" beneath the road surface. In the event of a calamity, victims can reach an emergency substation every 50 m and call for further assistance.

The Main Contractor of the project was a Joint Venture (Kombinatie Middelplaat Westerschelde; KMW) consisting of five participants; Koninklijke BAM NBM NV, Franki Construct NV, Heijmans NV, TBI Beton- en Waterbouw Voormolen BV and Wayss & Freytag Ingenieurbau AG. From logistical point of view, the boring process was carried out from Terneuzen. During the boring process, on the other side of the Westerscheldt (Zuid Beveland) receiving facilities for the boring machines were constructed. A caisson was constructed and sunk to 42 m below MSL in the soil. The prevailing soil conditions in Zuid Beveland made this solution the best option.

Rings

As mentioned earlier the construction activities with regard to the tunnel were carried out from Terneuzen.

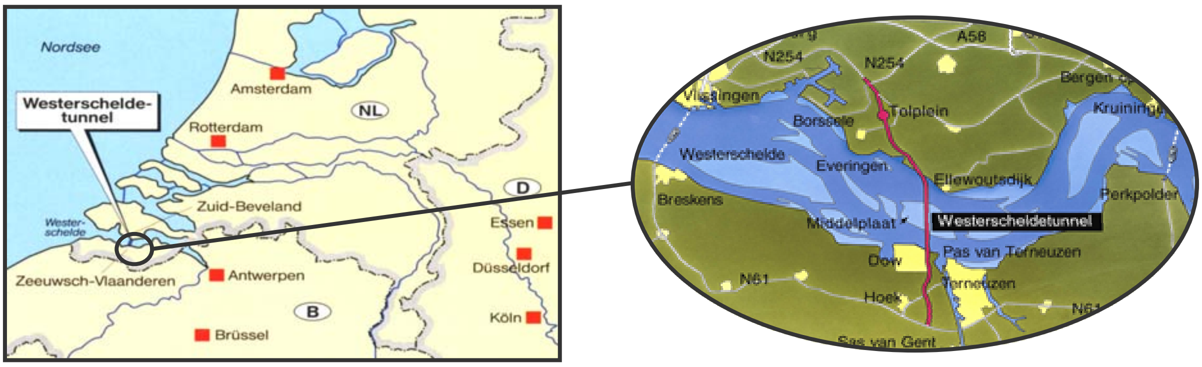

Figure 1: Geographical location Westerscheldt Tunnel

Therefore a site of about 300 ha was needed to carry out the boring process and support it. The contract required a hundred year life cycle and therefore meant that the basic construction of the tunnel had to meet stringent requirements. During the boring of the tunnel, rings were produced to form the tunnel. One ring has a length of 2 metres and consists of 7 segments. The last segment of a ring was a keystone, which completed a ring. Due to the high requirements (low tolerances in length and angles) of these rings and segments, the construction of the segments took place in a temporary concrete factory in Terneuzen, so the quality requirements and aspects could be kept under control. Approximately 53.000 segments were used in both tubes.

Due to the fact that the rings were constructed by seven segments and a keystone, tolerances of the segments were low, which meant that the quality requirements were more complicated. Tolerances, deviations and measure techniques are described later in this paper. After the segments are produced and approved for use, they are transported to the Tunnel Boring Machine (TBM). The heavy weights and large forms of the segments made it necessary to move the segments by train. A train traction of two 52 tons locomotives, 100 tons material and the transport equipment it self resulted in approximately 250 tons transport. The trains must cross the dike with a sharp curve and afterwards enter the tunnel on a 4.5 degrees slope. The original maintenance program for these locomotives wasn't enough and after some near misses occurred, preventive maintenance was extended. Each tunnel tube was serviced by one railway with a siding every kilometre. Sidings were extended as well, so the delivery of segments could be controlled. Besides the delivery of segments to support the boring process, personnel and materials needed for other activities (cross passages f.i.) used the rails as well. Although originally only railway traffic was allowed.

Acceleration

After some major set backs occurred, and a delay of almost one year was estimated, KMW mobilised eighteen work groups to study the acceleration of the project. The main issue to accelerate the completion, was that the fitting out phase should be started during the boring process and that as many activities as possible could be carried out in parallel. This method was worked out in detail and the largest bottleneck that had to be solved, was the logistical support for all fitting out activities.
While the boring process could only be supported by railway traffic, it was necessary to allow wheel traffic in the tunnel as well. The use of wheel traffic in the tunnel caused other problems. Formation of dust and the increased amount of carbon sooth in the tunnel were the important factors to deal with. Besides the boring process and the construction of cross passages, the main fitting out activities where:

- Construction of (Electrical) cellars
- Fire protection cladding
- Electrical & Mechanical Installations

As a result of the integration of the fitting out activities, the logistic movements in and to the tunnel increased while both access ramps had to be finished as well. Safety measurements for important facilities were temporary installed in order to be able to carry out the activities in this area. Fitting out during the boring process meant an increased number of employees in the tunnel. Due to the fact that the "climate" in the tunnel differs from the usual working area, safety facilities in the tunnel were even further extended. Additional education to the employers was organised and the success of the training became clear when a starting fire was directly smothered.
The effects of all measurements taken to accelerate the completion were great. The remaining (estimated) lead-time of three years was reduced to two years. All measurements, which had increased the costs for the Contractor, became economic feasible due to the fact that the terms of the contract were changed after the estimation of one year delay. A no-claims bonus system was added to the terms of the contract and additional investments could be made.

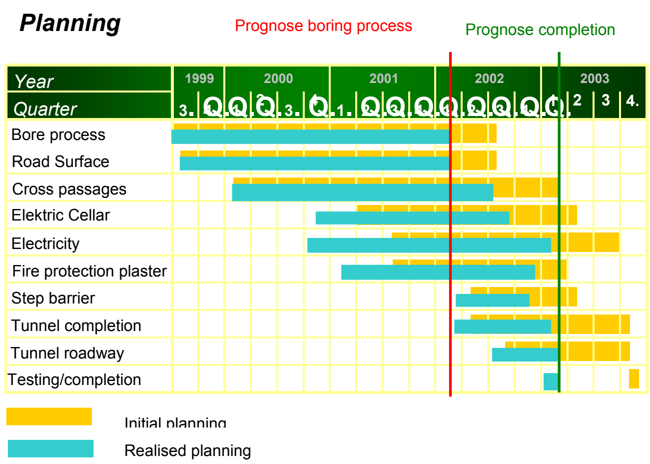

Figure 2: Planning Westerscheldt Tunnel Project

Segments

Due to the low tolerances of the segments, the requirements for the production system of the segments were high. The production system was intensively monitored by the QA department of the Main Contractor. Scrap had to be minimised, while the tolerances were decimals of millimetres. Angles had a tolerance of 0.1° degrees over a length of 2 metres! Many data had to be measured to decide if a segment is to be approved or rejected. Therefore it was necessary to purchase a highly sophisticated measuring system to cope with exacting demands. Due to the fact that approximately 130 segments were required to be produced each twenty four hours, the measure system had to be accommodated user friendly and above easy processing of the data.

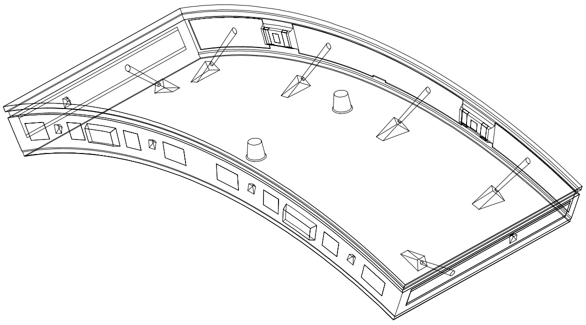

Figure 3: 3D image of a segment

Various measuring systems were evaluated and all advantages and disadvantages were carefully analysed. The essential requirements of the measuring system that the Contractor was looking for had to have:

- High accuracy
- Minimal disturbance to production cycle
- Easy in use
- 3D measurement
- Readily available

In the final analysis it was decided that a "photo-metric" system was the best solution according these requirements. Photometric measuring systems are very precise and easy to work with. As the system is independent of vibrations photos could be easily made by hand. Another advantage is that a measuring laboratory is not required. The Photometric system consists of:

- one digital camera (6.0 mega pixels)
- one laptop
- one orientation-stabilisation block
- one software module
- object marking points

Once a segment is ready to be measured, it is installed on the stabilisation block. After the placement on this block the object marking points are added on the segment. The more marking points are added the more precise the measurement is. After the pictures of the marking points are made with the camera, an infrared receiver on the laptop receives the transmitted data from the camera. After all the data is received the special purpose software module processes this data and carries out an analyses. The software can transfer the data to CAD stations when further processing is carried out. The analysis of the data is based on IST-SOLL. This means that values that exceed the "SOLL"-value, the segment will be rejected as unsuitable.

Upper and Lower boundaries

As the segments are eventually fitted in place, it is possible that the linked segment of the same ring, or following ring can compensate the excessive tolerance of one segment. For instance a positive deviation of +0.8 mm can be compensated by a negative deviation of –0.5 mm. This making the overall deviation: +0.8-0.5=0.3 mm. Replacement of such segments is possible when the overall tolerance between two segments is less then the tolerance of one segment. This is only valid for segments of the same type ("Left" <u>or</u> "Right" rings and the same code in the configuration, A1-segment or C-segment). Therefore rejected segments, which failed the dimensional check, were not rejected. All segments were monitored by using a barcode system. Every segment has a unique barcode with all relevant data of the segments collected facilitating tracking of segments.

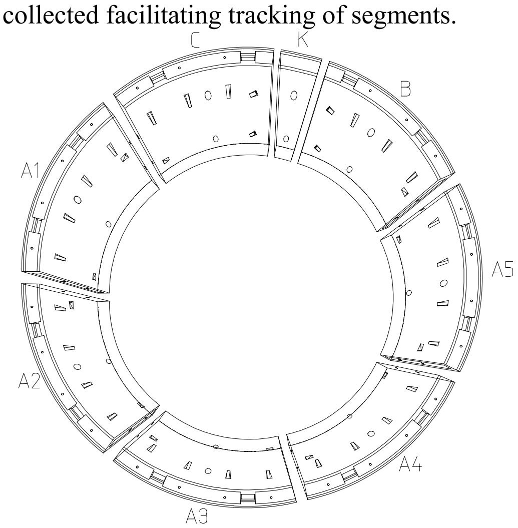

Figure 4: Configuration of a tunnelling

Formworks

Once a segment was failed the dimensional check, the following segment, which was produced with the same formwork, was measured and analysed. If same deviations were found, the formworks themselves had to be measured (and where necessary adjusted). This review was not part of the regular cycle. The *primary* review is carried out before the production is started. After a number of production cycles the *secondary* review was carried out. The review resulting by rejected segments was called the *tertiary* review.

Positioning Tunnel Boring Machine (TBM)

Due to the minimum tolerances of the segments and the minimum tolerance of the boring direction (10 cm on a length of 6.6 km!) an additional highly sophisticated measuring system was necessary. The differing curves in the tunnel alignment complicated earlier mentioned factors. As to reach Zuid Beveland within the tolerance, this could only be done by permanently measuring the three dimensions in which the TBM moves. To measure these movements of the TBM in the three dimensions, the position of TBM in relation to constructed part of the tunnel and the design axis is permanent measured. The so-called the design axis is programmed in the computer and with an automated measuring system the position of the TBM in relation to this axis (and specially the deviations to the axis) is measured, interpreted and corrected. The TBM moves by cutting the soil in front of the machine away and pushes itself forward on the last constructed ring by jacks. As soon as the tunnel moved two metres the jacks were rejected to build in a segment. The jacks were controlled separately and became the steering mechanism of the TBM.

Measuring of the TBM's position

The positioning of the TBM was done by measuring the movements, compared to a (known) constructed tunnel (see figure 3). A Laser Receiving Shield measured the deviations, which was permanent installed at the TBM. At the rings a Laser Transmitting Instrument (LTI) was installed to shoot the laser on the LR Shield. On this shield, the movements of the tunnel in two dimensions could be measured. The third dimension was calculated by using the Laser frequency. The movements of the TBM, compared to the bored tunnel, were compared to the design axis and corrections could be made. Small deviations were automatically handled, and in the event another ring configuration was needed to meet the required design axis, the PC in the control room of the TBM automatically calculated the adjustments. Deviations were graded as major as soon the deviation was 10 cm or more from the design axis. In this case the computer calculated a correction curve with a radius of 3000 m till the design axis was met again. Due to the limited tolerances of the segments such a wide curve was necessary to maintain the required tolerances.

Review of measurements

Another issue to be considered were the (potential) movements of the tunnel. When, for example, the fixed LRS at the TBM moves in one direction and the tunnel with the LTI moves in the same direction, it appeared that no deviations took place elsewhere. To eliminate these failures, the last part of the constructed rings was daily measured following a strict protocol:

- Each 50 rings; every three days before tunnel boring
- Each 20 rings; daily before tunnel boring

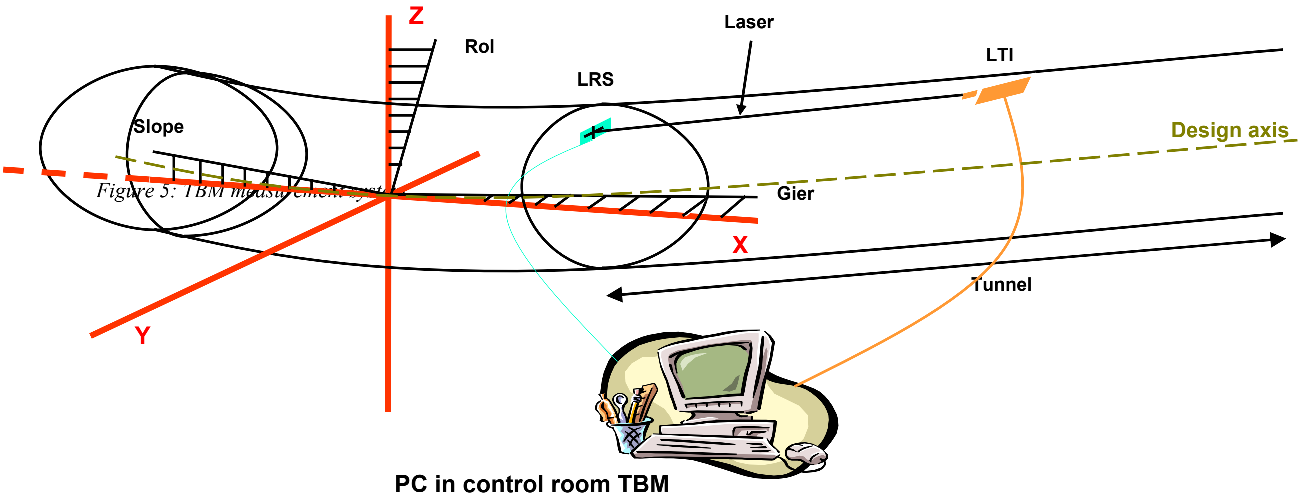

Figure 5: TBM measurement system

- Each 10 rings; every 3 days after the tunnel boring, to review the settling of the tunnel
- Each 4 months; review measurements to check the settling of the tunnel
- In the event deviations exceeded the accuracy, this period of one year could be extended

At each 750 metres the whole fitting of the tunnel was measured. All these measurements resulted in a deviation of 2.0 cm for the Western TBM and 3.0 cm for the Eastern TBM. Both deviations were measured from the centre of the TBM. The fitting of both tubes related to each other was also measured. This measuring was carried out trough the opened cross passages. To check the measurements of the Contractor the Employer had mobilised an external measuring company. This company measured if the deviations of the TBM's measuring system were within the allowed tolerances.

Saturation diving

The geology of the soil beneath the Westerscheldt consists of different layers. The main layers are (different kinds of) sand and (Boom) Clay. Every layer has its advantages and disadvantages. Sand is a medium trough which the boring progress is better as the fixed Boom Clay, but has a larger impact on the wearing factors of the bits and blades in front of the TBM. At a length of 6.6 km, bits and blades were periodically inspected and where necessary replaced. The deepest point of the whole trace was 60 metres below MSL, which means that the maximum local pressure in front of the TBM was equal to 7.5 bars. Execution of work activities at such a pressure level required the use of professional divers to carry out the inspection and replacement activities. Notwithstanding that the activities were carried out by professionals, one has to bear in mind that maximum saturation times are dependent on pressure tables. These tables describe the maximum processing time at a certain pressure. In addition to relative simple activities, divers had to carry out welding and cleaning activities with high-pressure tools as well. The high pressure made it necessary to carry out these activities by saturation diving. As this kind of work is unique in tunnelling business various safety requirements were put in place. These requirements weren't limited to technical aspects only, the whole diving organisation had to meet strict requirements which in turn had to be approved by the Labour Inspection Services.

Execution

To reduce waste of production time, diving activities were carried out by two teams divided over a sixteen hours each working day. While decompressing is more time consuming than the increasing to local pressure, divers were transported out of the tunnel in a saturation transport capsule (l: 3.10 m; w: 1.50 m; h: 1.70 m) and shifted to a larger saturation space on site. On site two saturation tanks, provided with the primary needs for a living, was the recreation area for the divers when the other diving team was working. These tanks were under permanent control by medical specialists.

Figure 6: Transport Capsule to the TBM

A working day of a diving team is divided as follows:

- Shift from saturation tank to transport shuttle: **1h**
- Transport to the TBM and shift to the saturation area on the TBM: **1h**
- Increase the pressure (by 2 bar) to local pressure in front of the TBM: **0.5 h**
- Effective working time at the cutting wheel in front of the TBM: **4.5h**
- Decompressing time by 2 bar in the transport shuttle: **2h**
- Resting in saturation area on site: **16h**

This production cycle was repeated till all inspections and replacements were carried out and the boring process could be continued. The longest "diving" cycle was ~21! days.

The specific circumstances that characterised these diving activities meant that special diving equipment was needed. Divers needed a mixture of three gases to breath (12% O_2; 48% N_2 and 40%He). To do so this mixture was connected by cables to the helmet. Diving equipment was provided by two connectors for breathing equipment, one water connector, to clean the breathing connectors, communication, light and depth measurement equipment and a video cable. To minimise illnesses and maximise hygiene, every diver had his own equipment. After each dive all equipment components were double checked with regard to the functionality and operational prepared.

In case of failures, the items were repaired or replaced. Therefore spare parts were held in stock on site to secure saturation diving wasn't postponed due to lack of spare parts.

The circumstances in front of the TBM were difficult as it was a dark area in which 55 kg cutting tools must be inspected and replaced. After a tool was removed, it was knotted on a line. This line had many knots to lift the tool up. When there were to less knots or the line was greasy, the tool could fall down and major injury to the divers down the working area could occur. Communication to the supervisors was difficult and a known “diving language” was used. Tools for example were classified by ”1” for very good and a “6” for very poor. Major accidents didn’t occur, while at pressure levels of 3.6 bars or higher N_2 narcosis was monitored. An implication of such a disease is tire and divers start making failures. In 672 divings, only 3 decompression diseases occurred, which were all solved safely.

Saturation diving in tunnelling processes has proven to be a cost saving technique. Whereas Japanese tunnel contractors use several TBM's to deal with the wearing problem of bits and blades, the Westerscheldt TBM’s were inspected by an innovative, preventative and timely replacement methodology that is far more economical in replacement costs and labour time then replacing whole new TBM’s.

Cross passages

As mentioned earlier in the introduction the tunnel consists of two parallel tubes linked every 250 m by a cross passage. The initial design was made with escape routes to the other tunnel tube every 500 m. Due to high level of accidents in tunnels during the design phase, the number of cross passages was doubled. A cross passage can be opened in case of emergency. The operator in the control room must unlock the doors as soon as he get a signal something is wrong in the tunnel. The cross passages have a length of approximately 12 metres and contains appropriate emergency facilities.

Construction

Due to the limited length of these “tunnels”, the link to the other tube was made by digging. Digging a hole in weak soil is only possible when the soil is temporary stabilised. There are different ways of stabilising soil and at the Westerscheldt tunnel, the soil was temporary frozen. To freeze the soil between the two tunnel tubes a kind of “heat”-exchanger must be temporary installed between the tunnels. To achieve this 22 freezing lances were drilled trough the segments in the soil until they reached the other tube at a maximum distance of 20 cm. The internal distance between two lances was approximately 1 m. A liquid salt solution from –37° C was pumped trough the lances. The lance construction was designed to ensure that no chemicals would leak into the soil. The lances were drilled with an accuracy of 0.5%. Another restriction was that the drilling must be carried out with a maximum use of a half tunnel tube, to minimise disturbances to the logistics of the railway traffic. Besides the freezing lances two temperature lances and a de-watering lance were drilled as well. These temperature lances measured the temperature at two metres from the beginning of the frozen soil.

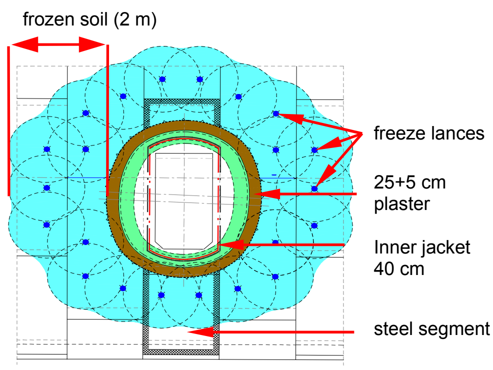

Figure 7: Frozen soil

To reduce the increased water pressure, caused by the frozen soil, the de-watering lance was drilled. All lances were drilled from the Eastern tube.

After the lances were drilled, the freezing equipment was connected. To reach the temperature of –37° C, a special purpose Ammonium based freezing machine was developed. The minimum amount of Ammonium was 80 kg and in combination with the limited space in which the machine is installed, additional safety facilities were also installed. Sensors measured the amount of Ammonium and as soon as the concentration exceeded it’s MAC value, the ammonium flow was closed and any leaked ammonium was neutralised by a water installation.
Approximately 26 temparature measuring instruments were installed in the Western tube faciliting a controlled formative of frozen soil. A mean temperature of -20° C and an ice thickness of 2 m must be strong enough to construct the cross passage. To reduce the waste of energy, isolation folie was placed inside both tunnel tubes to keep the temperature between both tubes low and no less heat exchange to the tunnels took place. Although most circumstances were known, some major safety facilities were installed. The largest is the emergency door in the West tube. The opening of a cross passage was all done from the West tube. As soon as the freezing installation had a blow out, this

emergency door could be closed and repair of the installation could be carried out.

Once the soil was strong enough (thickness > 2m), the soil could be removed. To remove the soil a special purpose cutting machine was developed. Every two metres progress, the opened part was sprayed with a 25 cm thick plaster. This was repeated till the East tube was reached. This layer of plaster was sealed with a plastic folie, which protects the cross passage against water. The last step was to finish the cross passage by a 40 cm reinforced construction concrete. The folie was covered by reinforcement and afterwards the formworks could be placed and concreting could be carried out. During the start of the drilling of lances till the end of drying period of the concrete the temperature was measured and controlled permanent.

All 26 cross passages were carried out as written above. The lead time to construct a cross passage decreased during the processing time and depends on the medium in which a cross passage is constructed and the depth beneath the Westerscheldt.

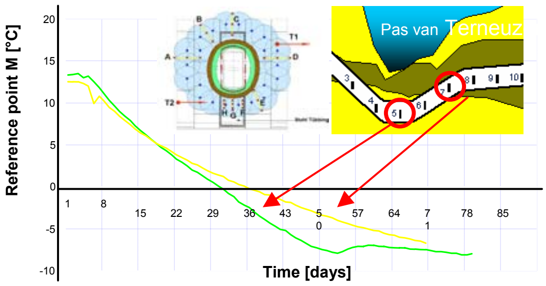

Figure 7: Freezing times

Cross passages constructed in Boom clay took more time to reach a 2 m thick Soil as cross passages in sand The deeper the cross passage was constructed the less time it took to reach the necessary thickness.

2. CONCLUSIONS

The use of automation in project oriented production areas is increasing. Usually automation isn't used at construction activities. The unique character and mostly limited scope of work (outsourcing of work packages to subcontractors) is the main reason for not even analysing automation systems. Actually in large scaled projects investments in automation systems can be very useful and economic feasible as well. In cases many different data must be stored, due to contract requirements f.i., the use of computer systems is very useful. Complex calculations, which must be carry out frequently, is also a good issue to analyse the profitability of automated systems.

Another issue that became clear from this paper is that contractors should be aware of using innovative techniques. The use of saturation divers for instance, to carry out maintenance and inspection activities, in front of the TBM wasn't carried out elsewhere in the World on such a scale as at the Westerscheldt Tunnel. Many preparations and studies took place before these activities could take place in a safe manner. Eventually using innovative techniques could save a lot of costs.