Geotechnical Aspects of Underground Construction in Soft Ground, Kusakabe, Fujita & Miyazaki (eds)
© 2000 Balkema, Rotterdam, ISBN 90 5809 1 066

The Westerschelde tunnel: New shield technologies in Europe

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ABSTRACT: The 'Westerschelde Tunnel' underpasses the estuary of the Schelde in the Netherlands. The tunnel will consist of two tubes which are driven by two hydroshields (slurryshields). The tunnels will each have a length of approx. 6.6 km and a bore-diameter of 11.33 m. Demanding ground conditions had to be considered during the design of the shield machines. Loose sands, extensive clay formations and high ground water pressures of up to 6.5 bar will be encountered during the tunnel drive. As a result the shield machines are among the most sophisticated tunnelling equipment available today. Further developments in European shield technology include a Sonic Soft Ground Probing System with which a three-dimensional picture of discontiuities ahead of the shield machine can be achieved.

1 INTRODUCTION

In 1996 a contract was signed with the Kombinatie Middelplaat Westerschelde Consortium (KMW) to design and construct two tunnels which underpass the Westerschelde in the south of the Netherlands as well as the necessary infrastructure to operate the tunnel and to connect it to the existing road system.

The consortium consists of six partners: BAM Infrabouw BV, Heijmans NV, Voormolen Bouw BV (all Dutch), Franki BV (Belgian), Philipp Holzmann AG and Wayss & Freytag AG (both German). The tunnelling activities are scheduled to take place between the middle of 1999 and the end of 2001.

The tunnels will then be equipped and should be ready for operation in March 2003. The overall project value is 1.6 billion Dutch guilders (approximately $ 850 million).

2 CROSS-SECTION

The Westerschelde tunnel consists of two tubes with a length of 6.6 km, each will contain a two-lane road. Figure 1 shows the cross-section of the tunnel.

The internal tunnel diameter, including the associated clearance, will be 10.10 m. A segment thickness of 45 cm and a 16.5 cm layer of injected cement grout (annular gap injection) results in an external shield diameter of 11.33 m. The segment width shall be 2.0 m. The 53.000 segments needed for the tunnel lining are manufactured in a segment plant that has been specially constructed on site.

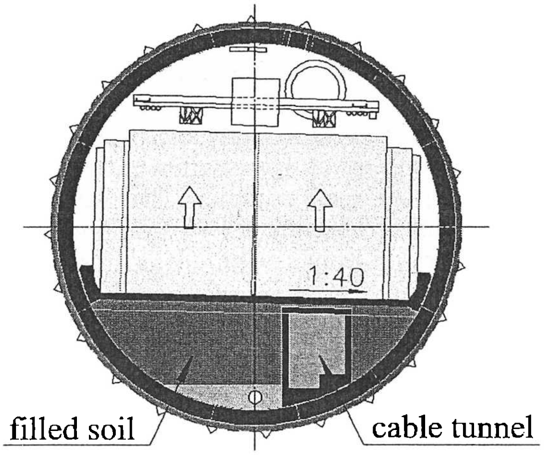

Figure 1. Cross-section of the Westerschelde tunnel.

A prefabricated cable canal/duct will be placed beneath the road level. The cable canal/duct will hold utilities that are needed for safety and for the operation of the tunnel. Maintenance work can be carried out by using specialised small vehicles which are able to travel in the cable canal.

The two main tubes will be connected with 26 cross-passages that are spaced at 250 m.

3 GEOLOGICAL CONDITIONS

The geology along the tunnels is made up by different sand and clay formations. Figure 2 shows the geology and a longitudinal section of the tunnel.

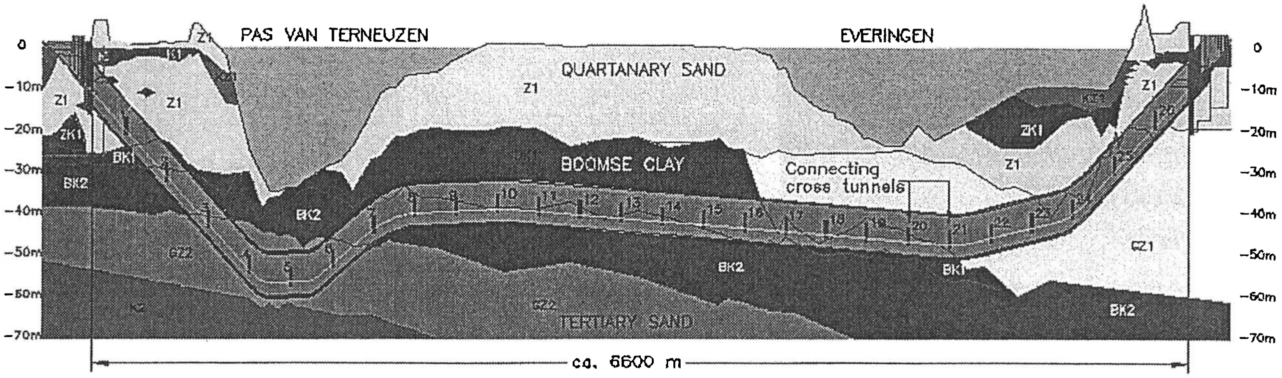

Figure 2. Geology and longitudinal section of the Westerschelde tunnel.

The uppermost 20 to 30 m consist mostly of medium to fine grained sands. The sands on the northern side of the Westerschelde have an underlying layer of tertiary, glauconitic sands.

'Boomse clays', overconsolidated stiff to firm tertiary clays are situated beneath the sands. These layers have a thickness of between 10 m to 30 m. The 'Boomse clays' are located at a greater depth in the north than in the south. According to their clay content and their mechanical properties the 'Boomse clays' can be divided into two layers: The 'upper Boomse clay' with an average clay fraction of 60% and the 'lower Boomse clay' with a clay fraction of roughly 40%.

Both clays can be expected to show sticky behaviour, demanding a consequent optimisation of excavation and handling of spoil material. The 'lower layer of Boomse clay' frequently shows sand bands with a thickness varying from several decimetres up to 1,8 m.

Tertiary, glauconitic sands are found beneath the 'Boomse clays'. The perched groundwater table in these sands corresponds with the sea level.

The Westerschelde has a width of approximately 5500 m at the tunnel location. The tunnel drives descend from the south side at a gradient of 4.5% towards the deepest point of the tunnel, which is located at the 'Strait of Terneuzen'. At this point the tunnel crown is up to 50 m and the estuary bed up to 35 m below sea level. Depending on tidal changes the necessary slurry pressure in the crown for the support of the tunnel face will amount up to 6.5 bar. Thus the slurry pressure in the invert of the shield's excavation chambers will be up to 8 bar. Underpassing the Strait of Terneuzen is therefore considered to be one of the special technical challenges of this project.

Thereafter the tunnel drive underpasses an extensive sand bank. After that the tunnel passes under the strait of Everingen in a depth of 40 m below sea level. Finally the tunnel ascends towards the receiver shaft, passing through different sands.

4 TUNNEL BORING EQUIPMENT

The construction schedule allows for a period of no more than 27 months for the tunnel drive. In order to meet this tight schedule two slurry shields will be implemented simultaneously, one for each tube. Due to organisational reasons the second shield will start roughly 3 months after the first. A further consequence of the limited construction time is that all necessary equipment for the construction of the fill beneath the road has to be included on the backup train.

The high level of support pressure and the extensive clay formations had to be considered carefully during the design of the shield machines. Figure 3 shows a section through the shield machine.

The fundamental decision of implementing either slurry shields, earth pressure balance shields or convertible machines (switching from slurry- to EPB-mode) was decided in favour of the hydro shield (slurry shield). The hydro shield features a submerged wall with an opening at the bottom separating the excavation chamber from the work chamber where the suction inlet is located. The support pressure in the slurry is controlled with a bubble of compressed air in the upper half of the work chamber. The following main aspects had to be carefully analysed in the process of choosing the best suitable shield:

1. Controlling large ground water pressure
2. Access to the excavation chamber under high pressure by using divers
3. Minimisation of wear
4. Consequent optimisation of the flow of material at the cutterhead and in the excavation chamber
5. Optimisation of the logistical systems

4.1 *Excavation*

The open cutterhead, as seen in Fig. 4, has six spokes with a peripheral rim. The shape of the spokes has been optimised to enhance the flow of

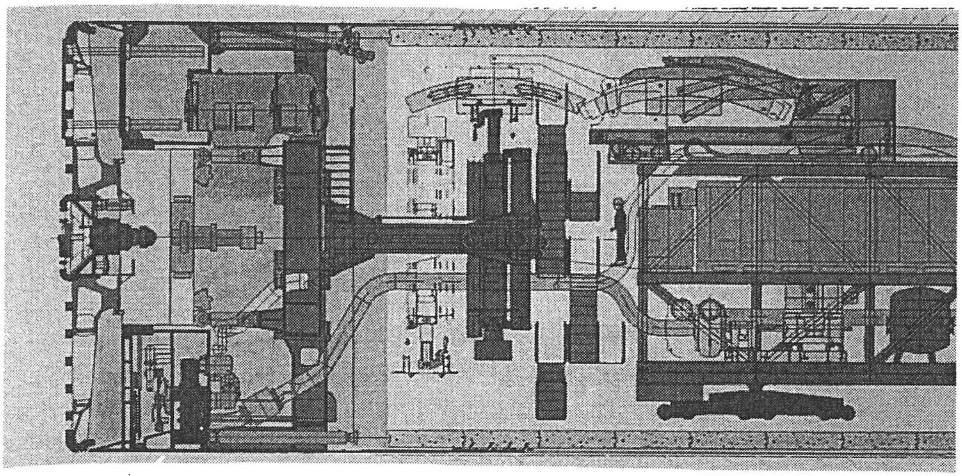

Figure 3. Section through the shield machine for the Westerschelde tunnel.

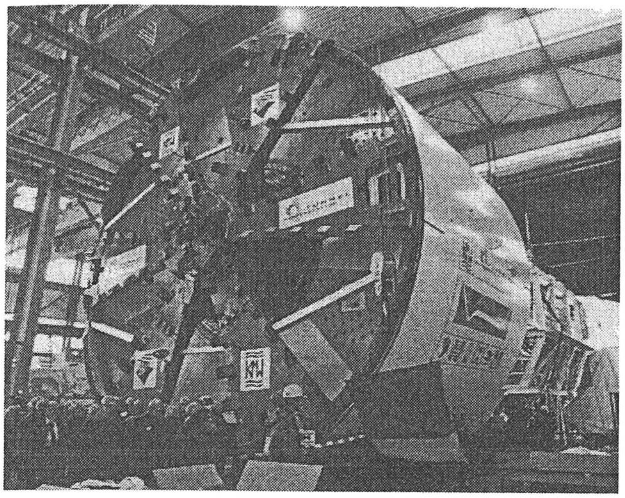

Figure 4. Shield machine in the workshop.

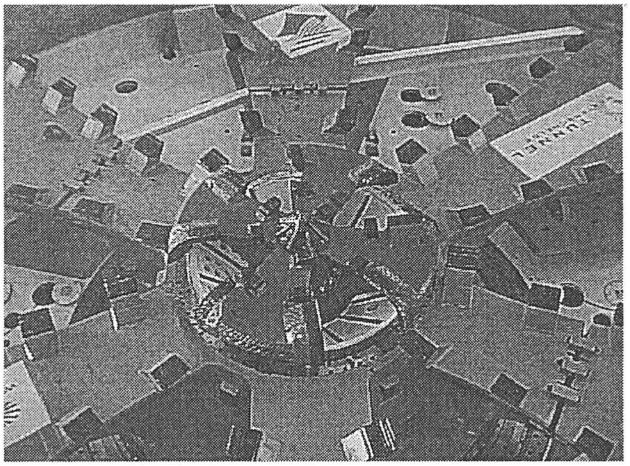

Figure 5. Detail of the centre cutter.

excavated material. Two plows on the backside of the cutterhead will shove the spoil towards the opening of the submerged wall and the suction inlet.

The cutting plane of the excavation tools lies 200 mm in front of the steel body of the spokes. Clay chunks that are cut during the tunnel drive are supposed to be isolated rapidly in the support fluid instead of adhering to each other and to the structure of the cutterhead. The material of the cutting tools, their geometry and their equipment with teeth of hardened steel are designed to ensure lasting performance.

The centre of the main cutterhead is equipped with a separate centre cutter of 2.5 m diameter (see Fig. 5). It is able to turn with or against the direction of the main cutterhead while rotating approximately three times as fast. The centre cutter is equipped with its own slurry feeding system feeding fresh suspension and extracting the spoil loaded slurry. It is also equipped with high pressure water jets for clearing clogged soil.

Behind the submerged wall in front of the suction inlet a rotary cylinder crusher and two fast-running agitators are installed (see Fig. 6). A crusher of this type has been installed although it is unlikely that large stones will be encountered along the given geological situation. The advantages of the crusher are its ability to reduce large chips of firm clay to small pumpable pieces as well as its supporting action for the suction inlet because of its cylinder rotation.

The chosen combination of rotary crusher and agitators guarantees that slurry flow blockages caused by static obstacles, as known from other types of crushers, will not occur. The strong turbulences created by the rotary crusher and agitators will prevent spoil from settling in front of the suction inlet.

This means that less suspension has to be injected through nozzles in front of the suction inlet in order to create strong liquid jets to keep excavated spoil from settling.

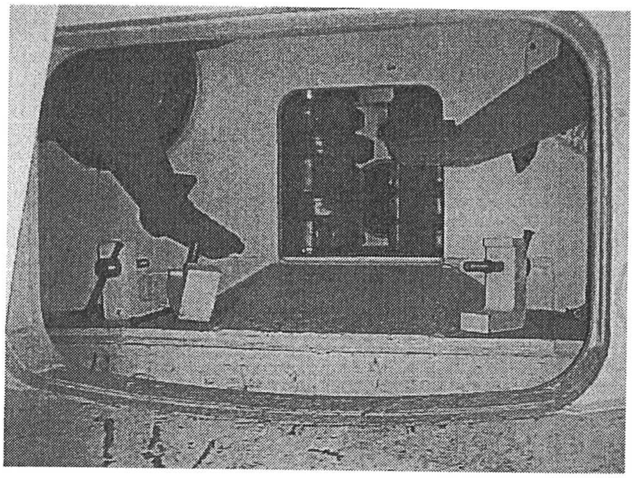

Figure 6. Submerged wall opening with agitators, stone crushers and suction inlet.

A new concept for the distribution of the fresh suspension in the excavation and working chamber has been developed. It has substantial improvements compared to older hydro shields and enables the feed flow to be directed to numerous points in both chambers:

1. the centre of the main cutterhead
2. the independent centre cutter
3. the peripheral area and central area of the excavation chamber
4. the area in front of the submerged wall opening
5. the area in front of the suction inlet

In addition a recirculation pump is integrated in the shield, drawing suspension from the work chamber and re-injecting it at the top section of the excavation chamber. The overall circulation through the two chambers is thus increased by up to 30 %.

A large number of valves and pumps are required for the above described multiple-inlet-feed in order to control the suspension flow. The valves will be switched in groups following a number of scenarios which have previously been programmed in order to allow the tbm operator to continously supervise all of them. The program will allow the operator to direct the feed flow in front or behind the submerged wall or to divide it between both areas in several steps.

4.2 *Maintenance under high pressure*

The tunnel drive will incorporate long sections where maintenance works under compressed air will not be possible because of the high support pressures and because of unacceptable chances of blowouts. In these sections the excavation chamber will be entered by off-shore divers. These men have been trained to do maintenance on the cutterhead while diving in the bentonite suspension. The required personnel from off-shore diving contractors will be integrated in the tunnelling crews and therefore will always be on site.

4.3 *Machine data*

The recorded and visualised data of the shield machines is supplemented by data that can be related to the development of clay clogging in different areas of the shield. All relevant data will be monitored and analysed regularly during the tunnelling process. This allows the detection of clogging at an early stage where countermeasures can still be undertaken. The cutterhead pressure and cutterhead torque as well as the pressures in different areas of both chambers will be some of the available data that will be monitored.

4.4 *Tail skin seal*

The seal of the shield tail consists of four rows of wire brushes in order to cope with the high ground and water pressures. The four rows of brushes provide for three chambers to be filled with tail skin sealing compound. The pressure in the sealing compound is monitored directly along the circumference of all three chambers. Local irregularities, such as leakage's in the wire brushes can thus be detected at an early stage.

4.5 *Annular grout injection*

Four double-piston pumps are used to inject grout through eight grout lines, in the tail skin, into the annular gap around the segment lining. Iin the clay sections of the tunnel the mortar could have difficulties to consolidate by dissipating filtrate water to the surrounding ground due to the high impermeability of the clay. Therefore, a fast build-up of an effective bedding of the tunnel might be impaired. Should this be the case, incompatible deformations of the segments rings could result. However the joint venture will be able to use results of a research program, that was carried out by Philipp Holzmann AG and Herrenknecht GmbH, in order to prevent this.

In this program, large scale tests were conducted with a new system that quickly improves the properties of the injected mortar. A large test rig was built for these tests, simulating a continuously developing gap of realistic dimensions that could be injected under pressures of up to 3 bar. An additive that enhances the stiffness within a few minutes is added to the mortar just in front of the tail skin.

This is an effective countermeasure against mortar flow within the annular gap, and therefore also minimises tunnel displacements. The test rig made it possible to visualise the spreading of the grout, in the annular gap, through the injection of different coloured mortars. Further, valuable information were

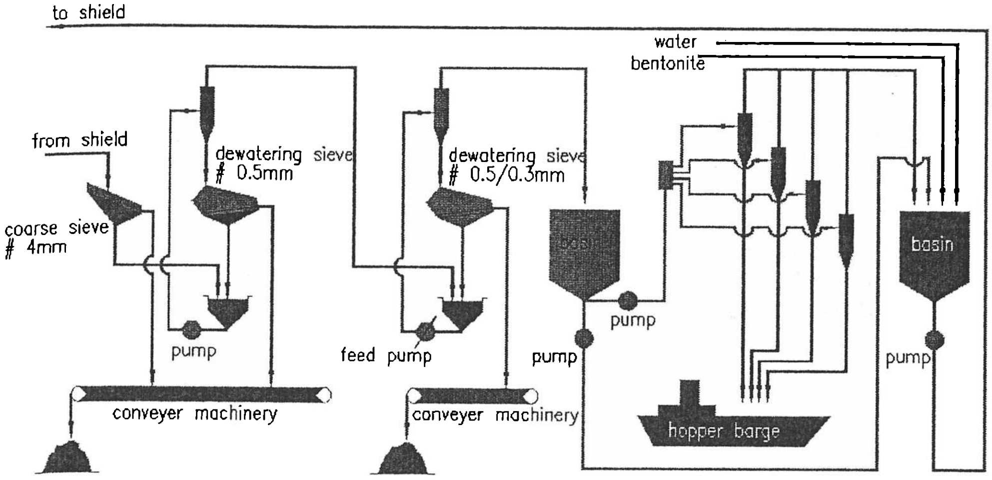

Figure 7. Scheme of the separation process.

won over the pressures losses from the grout pumps to the annular gap as well as the pressure gradients in the annular gap itself.

4.6 *Separation plant*

Figure 7 shows a scheme of the separation process. The separation plant has been designed to manage approximately 2000 m³/h for each TBM. This allows a peak performance of 2 m/h with approx. 100 m³ of material excavated per m tunnel.

Separating out the clay particles in the Boomse clay is a particularly difficult problem, as the grain-size distribution of these clays exhibits an affinity for the grain-size distribution of the bentonite. Therefore, extensive preliminary separating experiments were carried out.

At first the cuttings are run through the classical two-stage separator, which is made up of a preliminary screening machine for separating out clay chips greater than 4 mm in size. The first cyclone stage then cuts of grain sites of approx. 100 µm and a second hydrocyclone stage separates out the particle fraction with sizes up to approx. 30 µm.

The remaining ultra-fine particles in the suspension must be separated out in a further separating stage. As a result of intensive investigations, together with specialist companies, a third hydrocyclone stage, with a capacity of 800 m³/h, is to be installed. This third hydrocyclone is charged with some of the circulating suspension in which thickening of the silty grain fraction takes place. This makes it possible to separate additional fine particles from the regenerated bentonite suspension economically. The cut achieved is less than or equal to 10 µm. The thickened suspension is loaded onto barges and discharged into the Westerschelde or treated for reuse at a different location according to a new concept devised by the client.

5 FURTHER DEVELOPMENTS IN EUROPEAN SHIELD TECHNOLOGY: THE SONIC SOFT GROUND PROBING SYSTEM

When a tunnel is drilled it is highly desirable to recognise any change in ground properties in advance that could effect the safety or advance speed of the drilling process. In sonic soft ground probing (SSP) a seismic measurement system that is mounted on the cutting wheel of a tunnel bore machine operates while drilling.

An electromagnetic shaker excites a broad-band high-frequency (kHz range) P-wave sweep in the forward direction that is recorded by accelerometers. In a noisy environment, under limited angular coverage, and in a difficult wave propagation regime data are acquired automatically.

With a minimum of prior information on elastic ground properties automated real-time processing yield a three-dimensional reflection image of the nearest few ten meters ahead of the cutting wheel. This allows to recognise potentially dangerous obstacles or voids and to adjust drilling parameters in time.

Automation is required because in general no geophysicist will be available full time at the tunnel site, because the prediction must be available within hours or at least within a day, and because the large amount of raw data doesn't allow for detailed visual inspection. Heavy machinery like pumps and compressors add to the noise of the drilling process itself and cause high noise levels at all signal frequencies.

Much of the signal processing therefore aims at (precorrelation) noise suppression. Special care must be taken to limit the acquisition footprint, because we have only a limited number of fixed offsets and rotational acquisition symmetry. We need high-frequency waves to allow for large spatial resolution but we also should take into account that they expe-

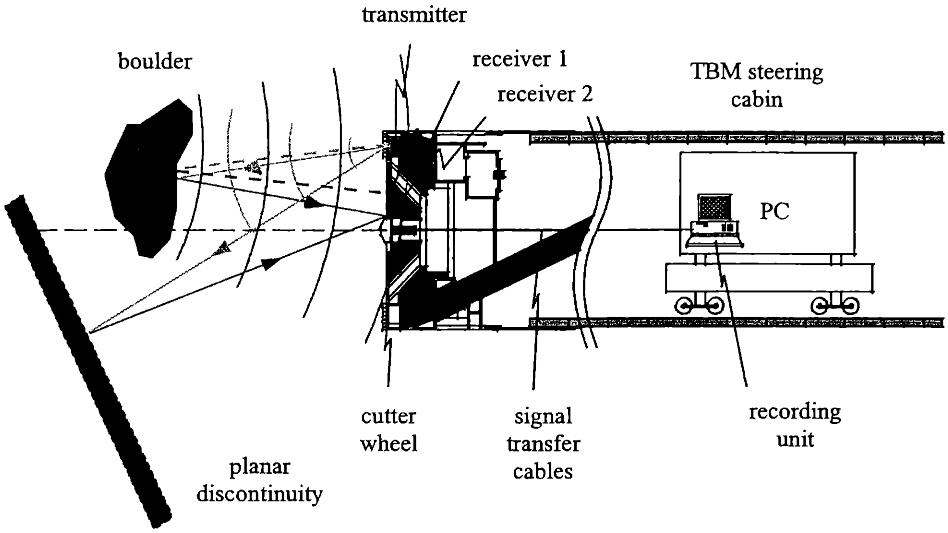

Figure 8. Measurement principle Sonic Soft Ground Probing system (SSP).

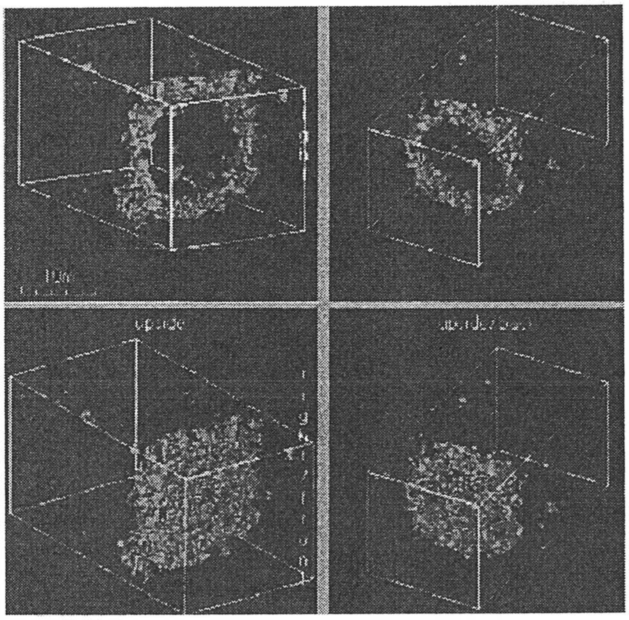

Figure 9. Image of an injection block before and after the simulation of the advance.

rience considerable attenuation in less consolidated rock or ground. Since a large amount of data must be processed in real time efficient implementations are essential. Migration velocity field and other processing parameters are extracted automatically from the seismic data. An interactive graphics tool assists the civil engineers in the interpretation of the final 3-D model. Figure 2 shows the final reflection image of an injection body before (lower) and after simulation of the advance (upper).

Sonic soft ground probing (SSP) is a novel seismic system that is mounted on the cutting wheel of a tunnel bore machine and records seismic energy excited by a high-frequency electromagnetic vibroseis shaker. Unfavourable conditions imply on the one hand the need for powerful processing tools and on the other hand call for simple and robust methods. Acquisition and processing are fully automated and yield a 3-D image of reflection energy ahead of the tunnel face in real time.

The SSP system has been developed in cooperation by Amberg Messtechnik AG (Switzerland), Herrenknecht AG, Philipp Holzmann AG and Züblin AG (all from Germany).

6 CLOSING REMARK

The technical standard of shield tunnelling equipment has made some remarkable progress with the last several years. This progress has been boosted by such challenging tunnel project such as the Westerschelde tunnel.

Building the Westerschelde tunnel is an extraordinary assignment for of those involved in the project and is setting new standards as for mastering geotechnical challenges.