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Westerscheldetunnel – Use of brine freezing for the construction of the cross passages

Tunnel de Westerschelde – Utilisation de la congélation de saumure pour la construction des passages transversaux

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ABSTRACT: In the western part of the Netherlands the Westerschelde Tunnel is under construction. The road tunnel will connect Zuid-Beveland and Zeesch-Vlaanderen and will replace the two current ferry links. The main advantages of the new link will be a gain in time and a better reliability. Special attention is paid to this project as the tunnel with a length of 6.6 km is constructed in clay. This is a new challenge as such a long tunnel was never performed before in soft ground in Western Europe. The tunnel contains two parallel tunnel tubes. The tubes will be connected by cross passages every 250 m. Tunnel boring machines with slurry supported work faces are used for the drilling of the two main tubes whereas the cross passages will be excavated under protection of a frozen soil body. Artificial ground freezing is used as sealing against water inflow and as temporary structural support. The design of the frozen soil cylinder is the subject of this paper.

RÉSUMÉ: Le Tunnel de Westerschelde est en cours de construction dans l'ouest des Pays-Bas. Le tunnel routier reliera le Zuid-Beveland et le Zeesch-Vlaanderen et remplacera les deux liaisons de bac actuelles. Un gain de temps et une meilleure fiabilité seront les principaux avantages de la nouvelle liaison. Une attention particulière est accordée à ce projet étant donné que le tunnel, long de 6,6 km, est construit dans de l'argile. Il s'agit d'un nouveau défi puisqu'un tunnel si long n'a jamais été construit auparavant dans un sol meuble en Europe occidentale. Le tunnel contient en fait deux tunnels parallèles. Les tunnels seront reliés par des passages transversaux tous les 250 m. Des tunneliers avec bouclier à bentonite sont utilisés pour percer les deux tunnels principaux, tandis que les passages transversaux seront excavés sous la protection d'un sol congelé. La congélation artificielle du sol est utilisée comme scellement contre la pénétration d'eau et comme support temporaire de la structure. Le présent article est consacré au design du cylindre pour sol gelé.

1 INTRODUCTION

In the western part of the Netherlands the Province Zeesch-Vlaanderen is cut off from the Continent in the south-west by the Westerschelde (Fig. 1). The Westerschelde is the port entrance to Antwerpen. Presently both parts are connected by two ferry links. In order to save time and to install a link of better reliability it has been decided to replace the current ferry links by a tunnel.

The tunnel will contain 2 lanes in each direction and the provided safety areas. Taking into account the fire protection sheathing and constructional tolerances the clear diameter comes up $d = 10.10$ m. Providing a segment thickness of 0.45 m and an annular gap grouting of 0.165 m the outer diameter of the tunnel boring machine results in $d = 11.33$ m (Fig 2).

Each tunnel tube will have a length of 6.6 km and the lowest point will be located below the shipping passage "Pas van Terneuzen" in a depth of approx. 60 m below MSL.

Every 250 m the tunnel will be connected by cross passages. These cross passages are provided for safety reasons. 26 passages with a clear cross section of 6.25 m² and an average length of 12 m will be built in total.

Due to the clay formation being close to the surface the southern tunnel access is built in an artificial polder with permanent water control. Sheet piling extending down to the clay formation is used for the construction of this polder. As the clay formation does not reach the northern end of the tunnel a concrete caisson is sunk to approx. 20 m below the Amsterdam Ordnance Datum (NAP) and durably re-anchored against buoyancy. For the built-up and the operating of the Westerscheldetunnel the public limited company N.V. Westerscheldetunnel has been set up and is financed by the central government supported by the Province of Zeeland.

The order for design and the associated works, tunneling and construction as well as the maintenance for ten years was given to the joint venture "Kombinatie Middelplaat Westerschelde" consisting of the six companies: BAM Infrabouw BV, Heijmans



Figure 1. Westerscheldetunnel, location

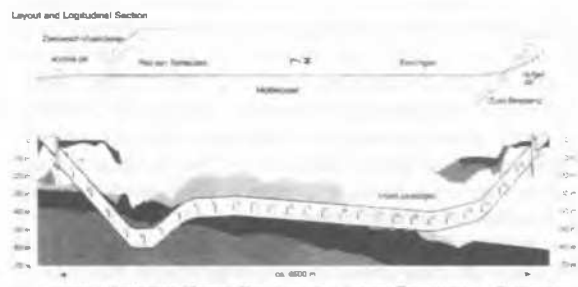


Figure 2. Schematic longitudinal section and geology

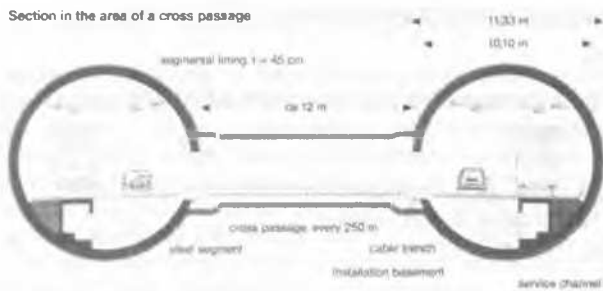


Figure 3. Section in the area of a cross passage

NV, Voormolen Bouw NV (Netherlands), Franki NV (Belgium), Philipp Holzmann AG and Wayss & Freytag AG (Germany).

2 GEOLOGY

Preliminary ground investigations during the design phase showed medium dense quaternary sands at the top 20 up to 30 m (Fig 3). In this sand clay lenses containing sea silt and peat are embedded. In the northern part glauconitic sands are found underneath the quaternary sands. They are underlain by tertiary clay layers of rigid consistence containing sea silt (Boonse clay). The thickness of the dense clay varies from approx. 8 m under the "Pas van Termeuzen" to approx. 28 m under the Middleplat (Fig. 3). Underneath the Boonse clay tertiary glauconitic sands of high density are found. This sand layer is hydraulically linked to the sand layers at the top.

Due to the salt content in the groundwater the behaviour of the subsoil is influenced and has to be taken into account in the design of the frozen soil cylinder.

During high tide a maximum water pressure of approx. 6.5 bar at the lowest point of the tunnel.

3 GROUND FREEZING

3.1 Generals

In this project brine freezing will be used for the built-up and maintenance of the frozen soil cylinder.

The frozen soil has to fulfill two requirements:

- temporary structural support from the beginning of opening until the lining is installed
- prevention of water inflow into the cross passage until the lining will provide protection

These requirements can only be met if the designed cross passage is completely enclosed by the frozen soil cylinder and if this soil cylinder provides the required thickness and average temperature.

Immediately after the tunnel boring machines have passed a branch to a cross passage and the opening is stabilized and supported the works for the construction of the cross passage are commenced. At first the drillings for the installation of the freeze tubes and temperature measurement holes are performed. Drilling starts from one tunnel tube towards the opposite tunnel tube and is finished a few centimeters in front of the opposite tunnel lining. After the installation of the whole freezing system the built-up of the frozen soil cylinder begins. As soon as the required thickness of the soil cylinder is achieved the tunnel lining is opened and the cross passage is excavated following the principle of the New Austrian Tunneling Method. The design provides a step-by-step excavation and an immediate application of a 0.25 m thick shotcrete lining. After completion of the excavation and shotcrete lining the final lining will be constructed

Section of cross passage during ground freezing

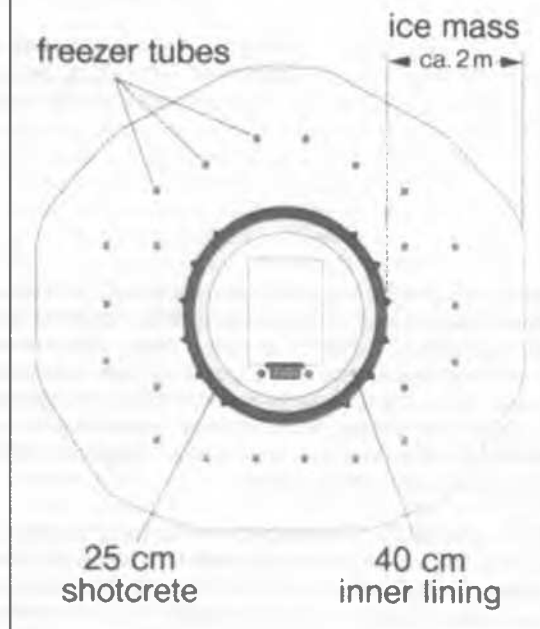


Figure 4. Section of cross passage during ground freezing

(Fig. 4). After finishing the construction works the freeze aggregate is turned off.

3.2 Specific ground investigations

As only little information about the soil behaviour was available the joint venture "Kombinatie Middelpaat Westerschelde" ordered physical and mechanical tests of the material taken from the areas of the ground freezing.

The test program was performed by Jessberger + Partner based on the test results of previous investigations of Grondmechanica Delft in order to investigate the behaviour of the soil during freezing, the influence of the salt content on the behaviour and the changes of the geological features after thawing.

In addition to the determination of the physical soil parameters

- grain size distribution
- water content and density
- porosity
- degree of saturation
- plastic limits
- ignition loss
- particle density
- salt content of the groundwater

the test program provides

- uniaxial compression tests at temperatures of $T = -5\text{ }^{\circ}\text{C}$, $-10\text{ }^{\circ}\text{C}$ and $-20\text{ }^{\circ}\text{C}$
- uniaxial creep tests at a temperature of $T = -10\text{ }^{\circ}\text{C}$
- triaxial test at a temperature of $T = -10\text{ }^{\circ}\text{C}$ and thawed samples
- frost heave tests
- compression test on unfrozen and thawed samples

in order to characterize the behaviour of the soil. The tests are performed for the soil layers BK1, BK2 and GZ2. The highly plastic Boonse clays BK1 and BK2 are less to medium silty clays of semi-rigid consistence. BK2 additionally contains very thin silty to clayey sand lenses. The glauconitic sand GZ2 un-

derlying the Boomse clay is characterized as dense to very dense and clayey to less silty.

Based on the test results and experiences of the behaviour of comparable soils Jessberger + Partner determined the characteristic soil parameters and design values. These parameters are used as basic data for the static and thermal design of the frozen soil cylinder.

3.3 Drilling

For each cross passage the following number of holes has to be drilled:

- 22 freeze tube holes
- 2 temperature measuring holes

The freeze tubes are located around the excavation line. The average distance between freeze tube and excavation line is 1.10 m.

For all types of holes the main important criterion is the accuracy of drilling. Non-accurately drilled freeze tubes may increase the required freezing time.

With an average length of the cross passages of 12 m the boring length is not the problem. The difficulty is boring against the extremely high water pressure. To achieve a watertight passage through the tunnel lining a special sleeve has been designed.

3.4 Design of the frozen soil cylinder

The design of the frozen soil cylinder is divided into static and thermal part.

Basic input data for a structural analysis are the strength properties of the soils. These properties are temperature and stress dependent. As the actual loading of the frozen soil cylinder results from the structural calculations and the temperature distribution in the frozen soil depends on the actual frozen diameter which is determined in the thermal calculations the two design parts depend on each other and an interactive solution is necessary.

Assuming a required frozen soil diameter of $d = 2.0$ m the thermal calculations are being performed.

Due to the salt content of the groundwater the boundary of the frozen soil cylinder is defined as the -3 °C isotherm.

The thermal calculations are performed in order to determine:

- the time dependent development of the frozen soil cylinder
- the temperature distribution in the frozen soil cylinder at particular times
- the freezing time for the built-up of the required frozen soil body diameter
- and the required capacity of the freeze plant according to the time dependent heat flux.

For the thermal calculations performed by Jessberger + Partner the Finite-Element-Method (FEM) is used as this method can meet all the criterions mentioned above.

The structural calculations performed by Philipp Holzmann AG are done by using the FEM as well.

These calculations consider that caused by the deformation during excavation an arch will be formed in the soil and that this arch will take a part of the soil load.

3.5 Watertight connection of the frozen soil body to the tunnel lining

The tunnel segment around the openings towards the cross passages are made of steel, a material of high thermal conductivity. Therefore an increased heat transport through these segments towards the frozen soil will occur. As the freeze tubes already

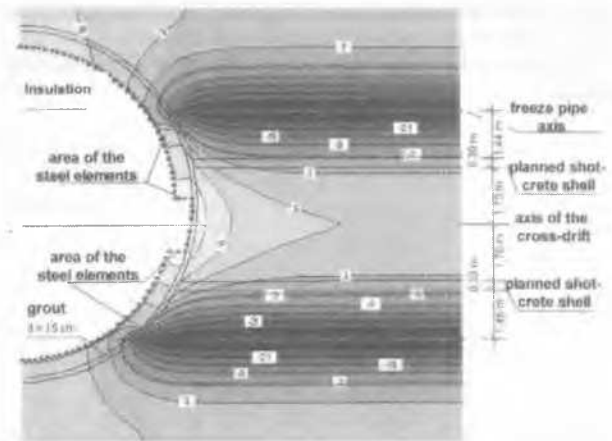


Figure 5. Calculated temperature distribution after a freezing time of 46 days

end in front of one tunnel tube in a distance of approx. 0.2 m additional thermal FE-calculations are performed in order to study the influence of the increased heat transport on the development of the frozen soil body as a watertight connection between frozen soil cylinder and tunnel lining has to be insured on the side of the tube ends as well (Fig. 5). Based on these calculations an insulation of 0.10 m thickness is provided on the tunnel lining in the opening area.

3.6 Refrigeration plant

Based on the thermal calculations, the theoretical frozen soil volume and an operating freezing temperature of $T = -37$ °C the installation of a freezing capacity of 94 kW per cross passage was decided.

For each cross passage a refrigeration plant with the required capacity built in container size is positioned inside the tunnel directly beside the cross passage in order to avoid long conduits causing heat losses.

3.7 Monitoring and Quality assurance

Temperature measurements are very important for successful performance of ground freezing projects. It is absolutely indispensable to know the temperature within and at the boundary of the artificially frozen soil cylinder.

For each cross passage the installation of 2 longitudinal temperature measuring holes are planned for the monitoring of the temperature development in forming frozen soil cylinder.

In order to check the watertight connection between the frozen soil cylinder and the tunnel lining on the ending side of the freeze tubes 5 additional measuring chains each of them containing 3 transducers are implemented in the tunnel lining.

The temperature readings are taken computer aided. The interval can be adopted to the freezing progress.

In order to check a possible influence of the ground freezing on the tunnel lining extensive deformation measurements at the tunnel lining are provided.

4 CONCLUSIONS

In the Netherlands the Westerscheldetunnel is currently being constructed. The construction of this tunnel is a new challenge as such a long tunnel was never performed before in soft ground in Western Europe.

The tunnel consists of two parallel tunnel tubes. For safety reasons cross passages are provided every 250 meters.

Each of the 26 cross passages will have an average length of 12 m and a clear cross section of approx. 6.25 m². The cross pas-

sages will be excavated using the New Austrian Tunneling Method under the protection of a frozen soil cylinder.

Currently the first two cross passages have been finished successfully.