SOIL AND BEDROCK CONDITIONS TO BE EXPECTED IN TALLINN – HELSINKI TUNNEL CONSTRUCTION

Ossi Ikävalko, Geological Survey of Finland, ossi.ikavalko@gtk.fi
Ilkka Vähäaho, Geotechnical Division, Real Estate Department, City of Helsinki, Ilkka.vahaaho@hel.fi
Sten Suuroja, Geological Survey of Estonia, s.suuroja@egk.ee

ABSTRACT

The capital areas of Helsinki in Finland and Tallinn in Estonia have grown enormously during the last 20 years. The about 80 km wide Gulf of Finland separates the cities and restricts movement of people and goods. The idea of a tunnel between Tallinn and Helsinki was presented in early 1990’s and has been a subject to a lively debate. The tunnel will be an extension of the future Rail Baltica railway, which is a project to improve north–south connections among European Union Member States. This project is already accepted by the Council of EU as a first priority EU project.

This paper discusses the bedrock construction conditions and the methods to be used in tunnel construction. The focus of this paper is to provide an overview of the geological and geotechnical properties of the construction environment and to describe the possible difficulties in building the world’s longest undersea tunnel. The information is based on a co-operation project between the Geotechnical Division of Helsinki, the Geological Survey of Finland and the Geological Survey of Estonia in 2012.

The tunnel area is located at the border between the East European Platform and the Fennoscandian Shield. In the Helsinki area the exposed old Precambrian hard bedrock is overlain with a thin layer of loose Quaternary sediments. Near Tallinn the old crystalline basement meets the about 1.2 billion years younger sedimentary rocks. The tunneling project will be challenging especially in the area of its southern end due to limited experience of conditions near the interface between these two formations.

Possible methods for tunnelling are drilling and blasting techniques specific to hard rock conditions such as in Finland, or use of tunnel boring machines (TBM) as an alternative on Estonian site. Both methods are shortly described and compared in this paper.
INTRODUCTION

Taking into account traffic connections and passenger movements, Finland can be considered as an island. About 80 per cent of freight traffic leaving Finland nowadays goes by sea. The cities of Helsinki and Tallinn on both sides of the Gulf of Finland have grown enormously during 20 years and at the same time traffic by the sea has also increased. Today some 7.3 million passenger cross the sea each year, and the number is growing. Because of the importance of good connections from Finland to Europe, new ideas of logistics have arisen in the development of broader frameworks of accessibility of the Baltic Sea region. Rail Baltica is a project to develop a new railway connection from Warsaw to Tallinn. Only about 50 – 60 km strip of water obstructs a direct rail connection from Finland to Europe.

In the early 1990's, the Geological Survey of Finland published the geological maps of the Baltic Sea’s Geology [1]. It was evident that old and hard crystalline bedrock continues below the Gulf of Finland and sinks gently under younger sediments in Estonia. This generated the idea of the possibility to construct an undersea tunnel from Finland to Estonia, especially taking into account good experience in developing long undersea tunnels in Finland. The idea was first proposed in 1992 at the Nordic Geotechnical Meeting (NGM92) in Aalborg [2].

The idea of the tunnel construction has been submitted and discussed in several contexts in seminars and congresses held by the experts of tunnel construction [2,3]. A feasibility study of a railway tunnel under the Gulf of Finland was submitted by Antikoski in 2007 [4] A Helsinki-Tallinn Feasibility Study Working Group was established in 2008 on the basis of the meeting of the mayors of the cities of Helsinki and Tallinn. Later in 2010, a Euregio Helsinki -Tallinn Transport and Planning Scenarios Project (H-TTransPlan) was developed. The final report of the project was published at the beginning of 2012 [5].

During the years 2011 – 2013, debate about the tunnel construction has been intensive. Critical voices have been strong and several negative statements have been given. At the beginning, the tunnel idea initiators did not receive attention from politicians or transport planning authorities [6]. Nowadays the tunnel alternative is considered as a good alternative for the transport of people and goods. For the rapidly developing area several economic and technical facts favoring the tunnel alternatives can be proven.

Besides the financial and functional feasibility studies, also technical feasibility has been assessed [2, 4], but it has been in a minor role. This paper contains a review of what we know of the construction suitability of the bedrock in Finland and Estonia and what kind of technical challenges are to be expected for the construction.

TUNNEL ALTERNATIVES AND TECHNICAL SOLUTIONS

Two alternatives for (Figure 1) excavated rock tunnels under the Gulf of Finland [4] are proposed. In both options, the track would link with the Muuga coastal railway on the Narva main road in Maardu, Estonia. On the Finnish side, the Porkkala track option would link with the
coastal railway in Jorvas in the municipality of Kirkkonummi. The Pasila track option would link with the main railway line after the Pasila depot. The undersea tunnels will be railway tunnels. The lengths of the undersea tunnel section are 58 km and 73 km, respectively, and about 12 – 15 km is required for the other tunnel sections. The tunnel system would use two track tunnels with cross-sections of about 80 square meters, and one possible maintenance tunnel (Figure 2).

The maximum tunnel longitudinal inclination could be about 1.2 – 2.0 %. The depth of the Gulf of Finland is 90 – 100 meters. The lowest point of the tunnels is estimated to be about 220 meters below the sea [4]. This is based on predictions of the depth of the hard bedrock surface.

The tunnel lines are planned to go through islands and shallows at the Gulf of Finland. At sea, entrances to the work tunnel and work bases would be built on islands along the route. In addition, manmade islands with service shafts to the tunnels would be created on sea banks, where water depth is less than 10 m. Service shafts and ventilation exhaust systems will be constructed on the man-made islands. The islands will offer possibilities for house maintenance facilities [4]. The islands would serve also as wind power stations.

Figure 1. Proposed two tunnel alternatives from Finland to Estonia, 85 km long Helsinki – Tallinn connection and 70 km long Kirkkonummi – Tallinn tunnel [4] on a geological map of Fennoscandian shield [1].
INVESTIGATION AND REVIEWS OF THE GEOLOGICAL DATA

Geological data of the Finnish area is obtained mainly based on mapping made in the coastal area and islands. The geology of the Precambrian in the surroundings of the Gulf of Finland is given by Koistinen [1]. More detailed data is gathered in some undersea sewage tunnel projects reaching a few kilometers to the sea. Also seismo-acoustic profiling and echo soundings are made, but the information of the depth of the crystalline bedrock is not available in this description. The general features of the bedrock can also be estimated from the aerogeophysical small scale maps.

The description of investigation and geological setting of the Estonian area is based on the report made in 2012 by the Geological Survey of Estonia (EGK) for the City of Helsinki and Geological Survey of Finland (GTK) [7]. In that work, the data was collected from different databases of a predetermined area within the Estonian Exclusive Economic Zone (Figure 3). On the basis of the data, a 3D –model (Figure 4) of the main geological units was compiled and explanation of the physical properties of the soil and bedrock units was given [7].

On the Estonian side, the marine geological data are based mostly on marine geological mapping in the scale 1:200,000. Data for the Tallinn Bay is mostly interpreted with data from islands and mainland drill cores. Wells reaching the Precambrian crystalline basement were drilled on some islands (Naissaar, Prangli, Aegna). Low-frequency seismo-acoustic continuous profiling (0-450 Hz) with echo sounding (24 kHz) was used as geophysical method in mapping. Distance between profiling and sampling was ca. 2 km.
Figure 3. The data used in compiling the 3D model of the Estonian site [7]. Lines – seismoacoustical profiles, bold lines – seismoacoustical profiles used in this project, dots – drill holes (red ones reach the crystalline basement).

Figure 4. The 3D surface of the Quaternary sediments of the Estonian site according to the compiled 3d-model [7].
Geological setting

The Gulf of Finland is 50 - 60 km wide. Along the north coast (i.e. Finnish coast) the 1.8 – 1.9 Ga old Precambrian crystalline basement is exposed. It forms a sedimentation basement for much younger Ediacaran (Vendian) sediments in Estonia. The sedimentary cover comprises rocks belonging to Ediacaran (Vendian), Cambrian and Ordovician systems (bedrock), and loose Quaternary deposits (i.e. Estonian coast). The sedimentary cover in the Tallinn area reaches up to 200 meters in thickness. Bedding in the sedimentary cover is close to horizontal (in average, dipping southwards 2–3 m/km), but there are some linear dislocations (Figure 4 [7]).

The study area is located between the border of the East European Platform and the Fennoscandian Shield (Figure 1). The geological section consists of two principal elements in the platform area, the Precambrian crystalline basement and sedimentary cover. The crystalline basement contains younger formations of the Subjotnian rapakivi granites and remnants of Jotnian sediments and diabases. The whole crystalline basement is eroded quite flat during long lasting continental erosion and dips gently to the south below Ediacaran rocks at the depth of about 130 – 140 meters below sea level near the coast of Estonia (Figure 5).

![Figure 5. A cross-section through the Gulf of Finland from Helsinki, Munkkisaari to Tallinn, Vimsi (Figure 1) according to the compiled 3D-model [7] and the data of Geotechnical Division of the City of Helsinki. J22 is the cleaned wastewater outlet tunnel, which was built in the 1980s and extends from the Viikinmäki wastewater treatment plant to the area south of Katajaluoto. The tunnel measures 17 km, of which 8 km are in the sea area.](image)

The Precambrian crystalline basement occurs on the Finnish side in the islands of the varying and broken coast. No observations of the bedrock are made in deeper water areas. In the undersea sewage tunnels excavated some kilometers to the sea, typical gneisses and granitic rocks are seen [1]. The geology of the crystalline basement does not change in this area dramatically, according to available small-scale geophysical maps. On the Estonian side, crystalline basement is represented by different complexes of metamorphic and intrusive rocks. The crystalline basement has been subjected to intense denudation during pre-Ediacaran time.
Therefore, the crystalline basement is covered by a 1–20 m thick weathering crust under the sedimentary rock cover and its surface is quite smooth. The weathering crust is absent in the sea bottom areas, where only postglacial loose deposits cover the crystalline basement, and the surface of the crystalline basement is uneven (such as roche moutonnée features).

The crystalline basement is characterized by the stratified Jägala complex of intercalating sillimanite - cordierite and biotite gneisses, felsic, intermediate and mafic metavolcanites, and leucocratic gneisses [7]. The physical-mechanical properties are illustrated in Table 1.

Intrusive rocks are represented by the Naissaar and Neeme rapakivi massifs. They consist mainly of porphyritic rapakivi granite of homogenous texture. Physical-mechanical properties of the rapakivi granites of the Neeme Massif are seen in Table 1.

Table 1. Physical-mechanical properties of different formations along the Tallinn-Helsinki tunnel [8,9]. 1= volumetric weight, 2= compressive strength, 3= porosity, 4= P-wave velocity ca. 6000-6500 m/s, 5= thickness of formation.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G/cm³</td>
<td>Mpa</td>
<td>%</td>
<td>m/2 m</td>
<td>m</td>
</tr>
<tr>
<td>Precambrian gneisses</td>
<td>A</td>
<td>2.65-2.75</td>
<td>110-240</td>
<td>0.1-0.2</td>
<td>6000-6300</td>
</tr>
<tr>
<td>Rapakivi granites</td>
<td>B</td>
<td>2.65</td>
<td>100-200</td>
<td>0.1</td>
<td>6000-6500</td>
</tr>
<tr>
<td>Weathered crystalline basement</td>
<td>C</td>
<td>2.0-2.6</td>
<td>1-100</td>
<td>1-20</td>
<td>2000-5000</td>
</tr>
<tr>
<td>Sandstones</td>
<td>D</td>
<td>2.0-2.3</td>
<td>1-25</td>
<td>10-20</td>
<td>2000-3000</td>
</tr>
<tr>
<td>Siltstone</td>
<td>E</td>
<td>2.25-2.35</td>
<td>5-25</td>
<td>10-15</td>
<td>2500-3500</td>
</tr>
<tr>
<td>Sandstones</td>
<td>F</td>
<td>2.1-2.2</td>
<td>1-5 Mpa</td>
<td>20-25</td>
<td>2500-3000</td>
</tr>
<tr>
<td>Blue clay</td>
<td>G</td>
<td>2.3-2.4</td>
<td>2-4 Mpa</td>
<td>8-10</td>
<td>2000-2500</td>
</tr>
<tr>
<td>Limestone</td>
<td>H</td>
<td>2.55-2.65</td>
<td>100-150</td>
<td>0.1-5.5</td>
<td>4000-5500</td>
</tr>
<tr>
<td>Glaucnoite sandstone</td>
<td>I</td>
<td>1.95-2.1</td>
<td>1-20</td>
<td>1-10</td>
<td>2500-3000</td>
</tr>
<tr>
<td>Alum shale</td>
<td>J</td>
<td>1.9-2.0</td>
<td>40-50</td>
<td>1-10</td>
<td>3500-4000</td>
</tr>
<tr>
<td>Sandstones</td>
<td>K</td>
<td>2.1-2.8</td>
<td>1-40</td>
<td>1-20</td>
<td>2500-3500</td>
</tr>
<tr>
<td>Quaternary loose sediments</td>
<td>L</td>
<td>1.5-2.2</td>
<td>&lt;1</td>
<td>10-30</td>
<td>1500-2000</td>
</tr>
</tbody>
</table>

The Ediacaran system is represented mainly by weakly cemented sandstones with relatively thin (up to 1–2 m) layers of varicolored (red-brown-grey) clayey siltstones of the Kroodi formation. Composition and the physical-mechanical properties of the Ediacaran rocks depend from this composition. For the sandstones, the properties are illustrated in Table 1.

The Cambrian system is represented mainly by its lower series (thickness ca. 100 m), which consists of siliciclastic rocks (clay-, silt- and sandstones). The upper part of the Cambrian section crops out up to the thickness of 20 m at the foot of the Cambrian–Ordovician escarpment of the
Baltic Klint. The outcropping section includes an up to 15 m thick layer of weakly and moderately cemented fine-grained quartzose sandstones of the Tiskre formation and up to 5 m thick sequence of blue clays of the Lükati formation. Physical-mechanical properties of the rocks are given in Table 1.

Blue clays are the oldest (ca. 530 Ma) clays in the world that have retained the plastic properties of clay (Table 1), although being more consolidated than young glacial clays. The complete succession of blue clay is ca. 60 m thick and consists of (from top to bottom): ca. 15 m thick blue clay stratum with quartzose sandstone interlayers of the Lükati formation and ca. 45 m thick stratum of pure blue clay of the Lontova formation. The lower part of the Lontova stage is represented by a more than 20 m thick stratum of the Sämi member, where there is a ca. 10 m thick bed of weakly cemented quartzose sandstone inside of a ca. 10 m thick sandy blue clay layer. The content of blue clay in the Sämi member decreases and the content of sandstones increase towards the west. By composition, two complexes can be distinguished inside the Cambrian system: upper – sandstones of the Tiskre formation, and lower – blue clays.

The Ordovician system, covering the Baltic Klint limestone plateau in the southern part of the area, is represented mostly by up to 20 m thick stratum of Middle-Ordovician carbonate rocks (limestones). The physical-mechanical properties of the Ordovician limestone are quite stable (Table 1). Lower Ordovician is represented mostly by more than 10 m thick stratum (from top to bottom): ca. 2 m glauconite sandstone of the Leetse formation; ca. 3.5 m alum shale (graptolite argillite) of the Türisalu formation; 3–8 m thick stratum of quartzose sandstones with phosphatic brachiopod detritus of the Kallavere and Ülgase formations. Physical-mechanical properties are varying (Table 1).

The Quaternary deposits cover most of the area. Their thickness varies between some tens of centimetres on alvars and up to 150 meters in buried valleys (bedrock surface elevation -135 m. b.s.l. in well no. 174), reaching in places up to the crystalline basement and thus cutting through the complete bedrock complex. Merivälja, Ülemiste, Kopli and Harku buried valleys can be observed from east to west, and they extend tens of meters into the crystalline basement. They are filled with till and loose silt, sand and gravel deposits.

The thickness of the Quaternary deposits is 20–60 m on the sea bottom. They consist of up to five strata (from top to bottom): contemporary marine deposits (mud) – up to 15 m; post-glacial deposits (clays) – up to 5 m; late-glacial (Baltic Ice Lake) deposits (varved clays) – up to 20 m; glacial deposits (till) – up to 60 m.

CONSTRUCTION SUITABILITY

The Quaternary sediments are water-saturated loose and soft deposits and pose a challenge for the tunnel penetration [7]. In buried valleys, the Quaternary sediment thickness may reach up to 150 m. With the high groundwater pressures it is a construction environment that has to be avoided. Supposedly also the rocks of the Ordovician system stay outside of the tunnel project. The blue clay stratum is a steady aquitard and good environment for tunnel penetration. The
Ediacaran water-saturated silt- and sandstones, reaching up to 60 m in thickness, are an important source of water supply for the Tallinn city and its surroundings, and one of the main challenges for tunnel penetration. The crystalline basement consisting of very hard solid rocks is a firm and protected environment for the tunnel constructions. In Finland, several large projects have been developed in these rocks.

In this study, the geological succession is divided into seven complexes, according to geotechnical and hydrogeological properties of rocks and deposits, which mostly coincide with the lithostratigraphical units (Table 2).

Table 2. Physical-mechanical properties of the rocks divided into 8 groups [7]. Complexes from 2 to 6 represent the sedimentary rocks, collectively called bedrock. Bedrock is, partly or completely, eroded by later processes.

<table>
<thead>
<tr>
<th>Complex no.</th>
<th>Thickness m</th>
<th>Properties tbl. 1</th>
<th>Construction conditions</th>
<th>Tunnel km incl. 1.5 %</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 - 60</td>
<td>L</td>
<td>Very difficult</td>
<td>outside tunnel</td>
<td>Quaternary deposits;</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>H</td>
<td>Good</td>
<td>outside tunnel</td>
<td>Ordovician limestones;</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>J, I</td>
<td>Very challenging</td>
<td>outside tunnel</td>
<td>Lower-Ordovician alum shale and glauconitic sandstone</td>
</tr>
<tr>
<td>4</td>
<td>15 + 10</td>
<td>I, K</td>
<td>Very challenging</td>
<td>2</td>
<td>Lower-Cambrian and Lower-Ordovician sandstones;</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>G</td>
<td>Good</td>
<td>4</td>
<td>Blue clays (Lükati and upper part of Lontova formations);</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
<td>D, E</td>
<td>Very challenging</td>
<td>4</td>
<td>Ediacaran silt- and sandstones (Kroodi formation);</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>C</td>
<td>Challenging</td>
<td>1</td>
<td>Weathered crust of basement</td>
</tr>
<tr>
<td>8</td>
<td>(km)</td>
<td>A, B</td>
<td>Very good</td>
<td>63</td>
<td>Precambrian basement metamorphic and igneous rocks</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Helsinki – Tallinn tunnel will be constructed in varying rock conditions. Most of the tunnel will lie in hard crystalline Precambrian bedrock starting from the Finnish site. Close to the south coast of the Gulf of Finland the tunnel will rise to younger Ediacaran and Cambrian rocks. The physical and mechanical properties are quite different from that of crystalline bedrock. The tunnelling will be very challenging in an about 6 km long segment in very porous and water-leaking sand- and siltstones. Also the possibly weathered surface of the Precambrian crystalline basement in contact with Ediacaran sediments might be challenging. In water-leaking and weak rock sequences the tunnel can be excavated by tunnel boring machine (TBM) with reinforcing the tunnel by concrete-steel lining.

Most of the tunnel will lie in the old Precambrian crystalline gneisses and granitoids, along about a 63 km long stretch in the Helsinki City alternative. Because of missing investigations, it is uncertain to predict the construction suitability. But experiences on the Finnish side of the Gulf of Finland have shown that the conditions are usually very good. In the old bedrock, fracture and weakness zones are usual, but normally they are not very wide or insurmountable.
For the tunnelling under the sea, the most important issue is to maintain the rock roof. Therefore, in the future lots of investigation to locate the bedrock surface are required. That will be done with seismo-acoustic sounding in the first phase and by drilling in the second phase. Weakness zones also have to be located. For this, geophysics and interpretation of sea bottom (bedrock) relief maps will be useful methods.

REFERENCES