Project Modernizace trati Praha-Výstaviště – Praha-Veleslavín

Expert Assessment

on behalf of Správa Železnic

Part I – Technical Assessment of Geotechnical Investigation Programme

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1 Introduction and Objective

1.1 Executive Summary

The geotechnical investigation programme has been assessed with respect to feasibility and sufficiency for the current design stage of the Project. It was found that

- The geotechnical investigations conducted so far and the results available are sufficient to recommend a preferred alignment variant.
- Further geotechnical investigation should be performed in the next design phase, once the final alignment variant has been selected.
- A list of additional questions for clarification has been included in this Report, all of which have been answered by the designers.

1.2 Project Introduction

As part of the train connection between the centre of Prague and Prague International Airport and the City of Kladno, respectively, a modernisation and expansion of the existing railway track between Praha-Dejvice and Praha-Veleslavín (hereinafter referred to as Project) is currently investigated.

Five variants have been taken into consideration in a current feasibility study: (1) a widening of the existing single-track at-grade alignment; (2) a close-to-surface underground alignment following the existing alignment (CUT-AND-COVER variant); and (3) three different bored tunnel variants (NORTH, CENTRE, and SOUTH) that will deviate from the current alignment and will be located deep below the ground surface.

For reasons of potential interference with the surrounding residential areas along the railway track, the at-grade variant has mostly been ruled out. At present, four remaining variants (CUT-AND-COVER, NORTH, CENTRE, and SOUTH) are still in consideration (see Figure 1).

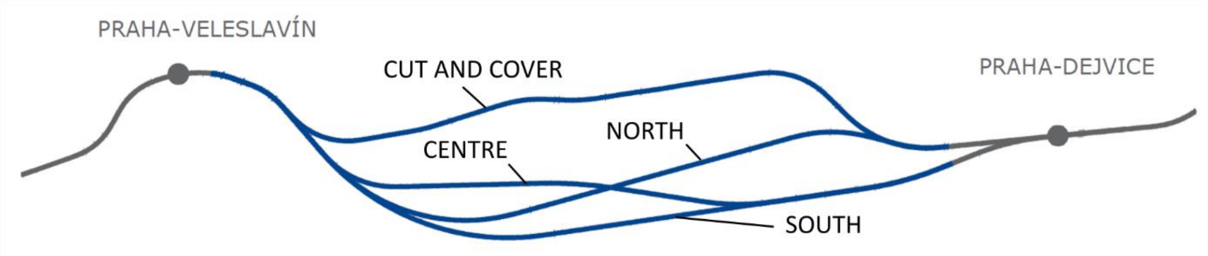

Figure 1: Alignment variants (sketch taken from [2], markers added)

The CUT AND COVER variant follows the current alignment of the rail track. The bored tunnel variants follow three different alignments south of the existing rail track.

1.3 Objective and Scope of this Report

The Authors of the Report have been selected by Správa Železnic, the Owner of the Project, to provide an expert assessment of the four tunnel variants currently considered for the railway track between Praha-Dejvice and Praha-Veleslavín.

In particular, the Authors have been asked to provide their opinion regarding the following three items:

1) The sufficiency of the ground investigations and their interpretation so far conducted for the preliminary design stage and for the selection of the preferred tunnel alignment option.
2) A technical assessment of all four variants regarding geotechnical risks, impact on the surroundings, and technical suitability. As a results of this assessment, a preference for one of the variants is to be provided.
3) An answer to several questions on specific topics that have been provided by the Owner.

This Report addresses the first of the aforementioned items by assessing the geotechnical investigations regarding their feasibility and sufficiency. The further two items will be covered in the second part of our Report.

Note that for the scope of the Report, the current stage of design covers the excavation process only. In the present design stage, neither the tunnel lining nor the tunnel equipment has been designed so far. Hence, the assessment of the geotechnical investigation programme focusses on those investigations that are necessary to rank and assess the four variants with respect to excavation works and their impact on the surroundings. Tunnel equipment does not significantly differ between the alignment variants.

2 Reference Documents

2.1 Design Documents of the Feasibility Study

[1.1] Studie proveditelnosti Železniční spojení Prahy, Letiště Ruzyně a Kladno, Metroprojekt Praha, 2016 (in Czech language), Document ID: 16 7021 007 01 03 00 000.

[1.2] Modernization of the line Prague-Výstaviště (excl.) - Prague-Veleslavín (excl.) - Study "Comparison of variants of tunnel solutions in section Praha-Dejvice - Praha-

Veleslavín", Metroprojekt Praha, 02/2020, English version of Document ID: 18 7461 22 01 00 00 000.

[1.3] Amendment of preliminary design 03/2009 Modernization of Prague - Kladno line with connection to Ruzyne airport, Phase I, Joint venture Metroprojekt Praha and SUDOP for PRaK Phase I, 03/2009, Parts D (Geotechnical Exploration) and E (Construction Part) for CUT AND COVER variant.

[1.4] Modernizace trati Praha-Výstaviště (mimo) – Praha-Veleslavín (mimo), dílčí plnění předkládající technické řešení a geotechnický průzkum pro variantu raženou SEVER, „Společnost MP+SP – Výstaviště-Veleslavín“, (02/2019, in Czech language) and English translation of Geotechnical Survey report for NORTH variant (03/2019), Document ID: 18 7461 06 08 01 004.2.

[1.5] Geotechnical exploration report for bored tunnel, SOUTH variant (08/2019), English translation of Document ID: 18 7461 04 02 01 07 006.01

[1.6] Geotechnical exploration report for ventilation shaft, SOUTH variant (11/2019), English translation of Document ID: 18 7461 04 02 01 07 009.01.

[1.7] Three geological cross-sections through all alignment variants (scale 1:1000/500) including a situational plan, per e-mail by Metroprojekt on May 18, 2020.

[1.8] Clarification of questions concerning regional geology of Prague, Metroprojekt, 05/2020, Document ID: 18 7461 23 00 00 00 000.

[1.9] Table summarising laboratory and field testing carried out in each of the boreholes - for variants bored tunnel SOUTH and NORTH, Metroprojekt, 05/2020.

[1.10] Jiří Hudek: “Determination of Rock Massif State of Stress Using the Stress-relief Gellery Method for the First Passage of Metro Tunnels under the Vltava River in 1973”, in: Tunel, 25, pp. 51 to 60 (2016).

2.2 Relevant Codes, Standards and Recommendations

[2.1] DIN EN 1997-1:2014-03, Eurocode 7: Geotechnical design – Part 1: General rules; German version EN 1997-1:2004 + AC:2009 + A1:2013.

[2.2] DIN EN 1997-2:2010-10, Eurocode 7: Geotechnical design – Part 2: Ground investigation and testing; German version EN 1997-2:2007 + AC:2010Eurocode 7: Geotechnical design – Part 2: Ground investigation and testing; German version EN 1997-2:2007 + AC:2010.

[2.3] ČSN EN 1997-1, Eurokód 7: Navrhování geotechnických konstrukcí - Část 1: Obecná pravidla

[2.4] ČSN EN 1997-2, Eurokód 7: Navrhování geotechnických konstrukcí - Část 2: Průzkum a zkoušení základové půdy

[2.5] DIN 4020:2010-12: Geotechnical investigations for civil engineering purposes – Supplementary rules to DIN EN 1997-2

[2.6] DIN 18196:2011-05

[2.7] DIN 18312:2016-09: German construction contract procedures (VOB) – Part C: General technical specifications in construction contracts (ATV) – Underground construction work

[2.8] ITA Report on Strategy for Site Investigation of Tunnelling Projects

[2.9] Deutscher Ausschuss für unterirdisches Bauen e. V. (German Tunnelling Committee (ITA-AITES)): Empfehlungen zur Auswahl von Tunnelbohrmaschinen (Recommendations for the selection of tunnel boring machines, in German), 2020.

3 Assessment Baseline

The assessment of suitability and sufficiency of the geotechnical investigations conducted in the current stage of the Project is based on international codes, standards, and recommendations, such as:

- Eurocode 7 [2.1, 2.2, 2.3, 2.4]
- DIN 4020 [2.5]
- ITA Report on Strategy for Site Investigation of Tunnelling Projects [2.8]
- DAUB Recommendation for the Selection of Tunnel Boring Machines [2.9]

As a general principle, codes and recommendations indicate that "geotechnical investigations" or "site investigations" need to be sufficient to provide the designers with enough information to perform their tasks in course of the project's design evolution.

The amount of required site investigations as well as the expected depth of interpretation therefore depends on the design phase of the project. Since different standards and recommendations employ a slightly different classification of design phases, it is important to define an assessment baseline to properly assess the sufficiency of geotechnical investigations so far conducted.

Hence, the assessment baseline starts with determining which design phase the Project is currently in. Considering the level of design so far performed, it is our impression that the Project is already beyond the feasibility study phase, but not yet in the pre-design phase.

The reason for the design level being beyond the typical feasibility study phase is that the Project is located in an urban environment, which raises concerns regarding the tunnelling impact on the surroundings and the environment. The risks and the potential impacts will most likely be the determining factors of the selection of a variant, whereas boundary conditions of the technical design are of secondary concern. As a result, pre-design will most likely not be conducted in full extent unless the alignment variant is determined.

The geotechnical exploration in the current phase therefore needs to accommodate the requirements of the variant selection by means of sufficient information to evaluate the potential impact on the surroundings and the environment for each variant. It does not, however, currently have to fulfil all requirements of the pre-design phase regarding the tunnel lining, the technical installations, or detailed solutions for technical challenges.

3.1 Requirements for geotechnical investigations acc. to EC7

As a general design code, valid throughout the European Union, Eurocode 7 (EC7) in its Czech implementation ČSN EN 1997-1 [2.3] and ČSN EN 1997-2 [2.4] needs to be followed. In Germany, as an addition to EN 1997-2, DIN 4020 [2.5] needs to be considered, which provides supplementary rules for geotechnical investigations and will be considered in this Report as well.

EC7 typically does not quantify requirements for geotechnical investigations but rather requires geotechnical investigations to comply with the risk associated with the project [2.1, Section 2.1 (8)]. For the determination of the level of requirements, Geotechnical Categories are defined in EC7. Tunnels fall in Cat. 2 at minimum, if they are fully embedded in hard, intact rock without requirements of water tightness. Since requirements are higher than that in this Project, Cat. 3 applies, for which EC7 requires geotechnical investigations that exceed those specified in EN 1997-1 [2.1, Section 2.1 (21)].

Part 2 of EC7 [2.2, 2.4] specifies geotechnical investigation and testing. EN 1997-2 differentiates between preliminary investigations and main investigations. Preliminary investigations need to provide sufficient information for the following assessments [2.2, Section 2.3]:

- General stability and feasibility of the designated area.
- Suitability of an alignment and its relation to alternative alignments.
- Potential influence of the works on its surroundings.
- Determination of the probing locations.

- Possible construction methods and ground improvement measures.
- Preparation of main and control investigations including a description of the extension of significant ground types in the investigated area.

Preliminary investigations shall provide information on:

- Rock and soil types and their layering along the alignment.
- Ground water table and properties.
- Rock and soil strength and deformation characteristics.
- Potential occurrence of contaminations in the ground.

Main investigations comprise field and laboratory tests to determine geotechnical parameters for the design. EC7 does not specifically distinguish the project’s design phases. For the determination of the alignment variant, preliminary investigations may be sufficient. Some elements of the main investigation like, for example, field and laboratory tests may be required at early stages of the design, however, if preliminary investigations do not already provide sufficient information for this decision.

DIN 4020 [2.5] specifically requires boreholes and the appointment of a geotechnical expert for projects of Cat. 2 and higher. Note that a Geotechnical Report according to DIN 4020 comprises characteristic parameters and technical recommendations in addition to the requirements of a Geotechnical Investigation Report according to EC7 (see Figure 2). Design calculations and proofs of stability and serviceability are not part of the Geotechnical Report acc. DIN 4020 but need to be included in the Geotechnical Design Report according to EC7-1. The latter is certainly beyond the scope of what is required in the current phase of the Project between feasibility study and pre-design.

from: DIN 4020:201012, Figure A 7.1

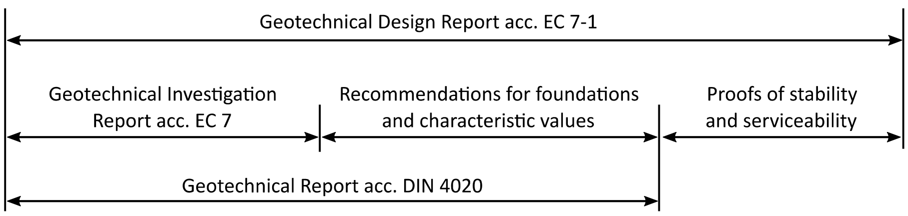

Figure 2: Extent and classification of geotechnical investigation reports, translation of Figure A 7.1 in DIN 4020 [2.5]

The density of boreholes along the alignment is not strictly determined in EC7. There are recommendations, however, to have exploration points every 20 to 200 m along the alignment of tunnels [2.2, Appendix B3]. The actual density of boreholes depends on the stage of design, on the heterogeneity of the ground and on the preliminary knowledge of the geology.

3.2 VOB/C – DIN 18312

As a tunnelling-specific code for contractual requirements for technical descriptions, DIN 18312 [2.7] lists requirements regarding the description of the ground, the determination of excavation classes and homogeneous sections. While intentionally being a contractual code, DIN 18312 can be considered in this Report to specify state-of-the-art requirements in the ground description for tunnelling works.

Based on the geotechnical properties of the encountered ground, the project is to be separated into homogeneous sections, which describe sections that are consistent regarding their mechanical behaviour, their requirements for excavation and disposal, and their hydraulic properties. For each homogeneous section, the following list of parameters shall be provided. For reference reasons, the respective German standard is listed here in parentheses:

- Parameters of soils:
  - Particle size distribution (DIN EN ISO 17892-4)
  - Content of cobbles, boulders, and blocks (DIN EN ISO 14688-1)
  - Unit weight (DIN EN ISO 17892-2 or DIN 18125-2)
  - Undrained shear strength (DIN 4094-4 or DIN EN ISO 17892-7 or DIN EN ISO 17892-8)
  - Water content (DIN EN ISO 17892-1)
  - Plasticity index (DIN EN ISO 17892-12)
  - Consistency index (DIN EN ISO 17892-12)
  - Relative density (DIN EN ISO 14688-2, DIN 18126)
  - Abrasivity (NF P18-5792)
  - Soil category (DIN 18196)
- Additional parameters for bored tunnels:
  - Organic content (DIN 18128)
  - Mineral composition of cobbles and blocks (DIN EN ISO 14689)
  - Cohesion (DIN EN ISO 17892-9 and DIN EN ISO 17892-10
  - Sensitivity (DIN 4094-4)
- Parameters of rocks:
  - Rock identification (DIN EN ISO 14689)
  - Unit weight (DIN EN ISO 17892-2)
  - Weathering and modifications (DIN EN ISO 14689)
  - Uniaxial compressive strength (DIN 18141-1
  - Joints, joint orientation, joint spacing (DIN EN ISO 14689)
  - Joint opening and joint filling (DIN EN ISO 14689)
  - Abrasivity acc. DGGT Recommendation No. 23

3.3 ITA Report on Strategy for Site Investigation of Tunnelling Projects

The Working Group 2 of the International Tunnelling Association (ITA) has published a research study on strategies for site investigations of tunnelling projects [2.8] that contributes an international point of view to the assessment.

In accordance with EC7, the ITA report states, as a general principle, that site investigations are an integral part of the risk assessment of a tunnelling project. It is emphasised that in order to serve its purpose, the reliability and robustness of information is to be continuously reviewed and new information and findings need to be incorporated accordingly.

The ITA report identifies five components of site investigations that are ranked based on their effort from less to more costly:

1. Desk study
2. Field mapping
3. Field investigations
4. Laboratory tests
5. Exploration tunnels/shafts

Unlike EC7, the ITA report specifies three project phases: feasibility studies, preliminary design and detailed/final design. To classify the current stage of the Project into these phases, it can be stated that although the technical feasibility of the proposed alignment variants is still under investigation, the Project is currently in a phase between feasibility studies and preliminary design. Being in the process of identifying risks and technical challenges, it is necessary to already determine quantitative characteristics of the ground. Thus, the sought preference for a tunnel variant can be based on substantial information.

The ITA recommendation lists investigations means and expected results for each project phase [2.8, Tables 1 and 2], which are compared to the available information from the geotechnical site investigations in Chapter 4.

3.4 DAUB Recommendation for the Selection of TBMs

The recently revised Recommendation for the Selection of Tunnel Boring Machines by the German Tunnelling Committee (DAUB) [2.9] provides guidance in the selection process of tunnel boring machines (TBM). It does so by giving a technical description of various types of TBMs and a multitude of associated technical and procedural topics.

One of the most important and often decisive aspect in the selection process is the geotechnical properties of the ground. Hence, the appendices of the Recommendation list a large number of ground parameters that are relevant in the tunnelling process and for the selection of the most suitable TBM type.

Of particular importance in soils are the particle size distribution, the permeability, the confinement pressure, and the abrasivity in terms of the equivalent quartz content. In rock, the most relevant parameters are the compressive strength, the rock mass quality (RQD, RMR), the presence and inflow of water (and required support pressure, respectively), the abrasivity and the swelling potential. Also, the tendency of rock to weakening and disintegration upon contact with water and mechanical stirring is of importance for the operation of a TBM.

For the bored tunnel variants, these parameters need to be determined in the pre-design phase in order to support the TBM selection process. In the current stage of selecting an alignment variant, however, they are not of utmost importance because all three bored tunnel variants would likely encounter very similar conditions.

3.5 Required Information for Assessment of Settlements and Alignment Variants

For the assessment of alignment variants, all relevant boundary conditions such as the geological longitudinal section and cross-sections in relevant areas, geotechnical and hydrological conditions, vulnerable structures in the vicinity, and important non-technical requirements and boundary conditions need to be known.

Part of the subsequent assessment of the alignment variants will be the numerical analysis of three cross-sections per variant in order to estimate the tunnelling-induced ground deformations and settlements. For these analyses, material properties and the geometrical layout in significant cross-sections are required, which include:

- Unit weight
- Stiffness
- Strength
- Initial in-situ stress state
- Ground surface, layer boundaries and fault zones (spatial position, extent, length)
- Ground water level

Where the aforementioned information is not completely available, plausible assumptions can be made. In such cases, however, the assumptions will need to be verified in later design stages.

4 Available Geotechnical Investigations

Throughout the 15 years of the Project's history, several preliminary investigations have been conducted, starting with desk studies (Technical Passports and Preparatory Documentation as mentioned in [1.1]). Four underground variants were selected for further evaluation, part of which is the alignment variant assessment in the second part of our Report, for which Geotechnical Exploration Reports were compiled. Currently, the following reports are available for review:

- CUT AND COVER [1.3]
- NORTH [1.4]
- SOUTH [1.5]
- Ventilation Shaft SOUTH [1.6]

Another Geotechnical Exploration Report for the CENTRE variant is currently pending as two more boreholes for that alignment have been recently drilled.

4.1 Investigation Methods

4.1.1 Variant CUT AND COVER

For the CUT AND COVER variant, a Geotechnical Exploration Report was provided [1.3]. Therein, findings from the preparatory studies are amended by site investigations that comprise

- core drilling,
- field tests (penetration tests),
- rock and soil sampling including laboratory testing, and
- geodetic surveys.

Along the alignment of approx. 3.7 km, 37 boreholes were drilled (average distance: 100 m, in line with the EC7 recommendations), to verify the thickness of quaternary layers. Site investigations were combined with desk studies of pre-existing geotechnical investigations in the area.

The evaluation of site investigation data is amended by broad experience from previous construction projects in the area. In particular, two tunnel projects have been constructed in the vicinity, which provide insight into geotechnical properties of the subsoil.

4.1.2 Bored Tunnel Variants

Individual Geotechnical Exploration Reports were prepared for each of the bored tunnel variants. Since their alignments are not located far from each other, however, the findings in the individual reports do not differ a lot. With respect to the investigation methods, it is therefore possible to assess the reports for the bored tunnel variants simultaneously.

The following investigation methods have been conducted by the geologists:

- Desk studies,
- rock and soil sampling from boreholes,
- field tests,
- hydrogeological investigations,
- geophysical measurements in boreholes,
- hydrogeological pumping tests,
- vibration measurements.

In total, 14 new boreholes (plus two additional boreholes for the CENTRE variant) were drilled. This is much sparser than for the CUT AND COVER variant and some boreholes are spaced up to 700 m. However, also existing information from previous activities in the area has been taken into consideration by the geologist.

From all but one borehole laboratory samples were extracted and analysed by means of different testing methods. Among the laboratory tests, there are direct shear tests, uniaxial compression tests, and oedometer tests to determine the mechanical properties of the samples.

Desk studies take the least effort but provide valuable information from geological maps and experience from previous projects in the area. In case of the current Project, this information is already available to a large extent due to the location in the vicinity of two previously built tunnels (Tunnel Blanka and a Metro tunnel). In addition, cadastral information about wells and geothermal boreholes was reviewed, which may have significance for the selection of preferred variants.

4.2 Presentation and Evaluation of Geotechnical Information

The geotechnical information compiled in the individual reports for each variant is clearly and transparently presented in general.

The Geotechnical Exploration Report for the CUT AND COVER variant [1.3] gives a very brief introduction to the extent of investigations, before listing the various geological formations to be encountered, followed by a geotechnical evaluation regarding soil behaviour, workability, and recyclability. Afterwards, the ground along the alignment is divided into homogeneous sections each of which is described in detail regarding their geotechnical characteristics. Selected geotechnical parameters are given in form of tables for each characteristic layer in each homogeneous section.

For the bored variants, each report [1.4, 1.5, 1.6] starts with the explanation of investigation methods. Afterwards, the individual geological formations and their arrangement are discussed. A very large set of appendices in the Czech version of the document lists all available results from the various field tests, boreholes and laboratory tests. Some of these results, however, seem not to have been directly considered in the main reports. For example, the stratification of shales in various boreholes and the results from dynamic tests in the vicinity of the Institute of Physics of the Czech Academy do not seem to be interpreted in the report.

Another aspect that is not completely clear is the upscaling of results from core sample tests to rock mass parameters, for instance the influence of anisotropy in the shale formations. The stratification shown in the borehole mappings is not explicitly interpreted in the Geotechnical Explotation Report [1.4]. See Section 6.2 for some remaining questions, which should be provided an interpretative answer to from the authors of the Geotechnical Exploration Report.

Geotechnical implications of the results for the tunnel construction are provided both in the reports for the CUT AND COVER variant and for the bored tunnel variants. Therein, aspects of usability and disposal of the excavated material are discussed for each expected type of material. Also the potential presence of contaminations is covered. Also potential difficulties regarding workability and stability are discussed in [1.3].

The Geotechnical Exploration Reports for the bored tunnel variants are not strictly focused on the intended use of an Earth Pressure Balance (EPB) TBM. Therefore, also geotechnical interpretations for conventional tunnel excavation are included. As a major challenge, the presence of tectonic fault zones is expected. While their exact amount, orientation and extent is not fully known, there is a confirmation that fault zones parallel to the alignment are not expected [8].

5 Assessment of the Geotechnical Investigation Programme

5.1 Comparison of Available Geotechnical Investigations with EC7 Requirements

Table 1 lists the requirements of EC7 regarding the information preliminary geotechnical investigations need to provide in the current phase of the Project. For each requirement it is assessed whether the information is available in the four reports [1.3 to 1.6] to a sufficient extent.

Table 1: Available site investigations for the Project vs. EC7 and DIN 4020 requirements

Information requirement (EC7)	**Associated investigation methods**	**Available in [1.3-1.6]?**
Requirement for assessments		
General stability and feasibility of the designated area	• Desk studies • Experience from adjacent projects • Field tests • Exploration points • Laboratory testing	✓
Suitability of an alignment and its relation to alternative alignments.	• Interpretation of geotechnical investigation results • Experience from adjacent projects	✓
Potential influence of the works on its surroundings	• Interpretation of geotechnical investigation results • Field tests • Geophysical testing	✓
Determination of probing locations for main investigation phase	• Desk studies • Experience from adjacent projects • Field tests • Exploration points • Laboratory testing	✓
Possible construction methods and ground improvements	• Interpretation of geotechnical investigation results	✓
Preparation of main investigations including quantification of significant ground types in the investigated area	• Interpretation of geotechnical investigation results Note: This step requires the selection of a preferred alignment variant and parts of the pre-design.	✗ Not part of current project phase
Geotechnical information		
Rock and soil types and their layering along the alignment	• Interpretation of geotechnical investigation results	✓
Ground water table and properties	• Interpretation of geotechnical investigation results	✓
Rock and soil strength and deformation characteristics	• Interpretation of geotechnical investigation results	✓
Potential occurrence of contaminations in the ground	• Desk studies • Laboratory testing	✓

5.2 Comparison of Available Investigations with ITA recommendations

Table 2 provides a comparison of available geotechnical information and site investigation means recommended by ITA [2.8]. It should be noted that the ITA recommendations are very general. The actual site investigation programme needs to account for the specific requirements, risks and boundary conditions of the Project.

Table 2: Available site investigations for the Project vs. ITA recommendation

<table>
<tr><th>Investigation means (ITA)</th><th>Expected results (ITA)</th><th>Available in [1.3-1.6]?</th></tr>
<tr><td colspan="3">Feasibility study stage</td></tr>
<tr><td rowspan="5">• Desk studies
• information from field studies and adjacent projects
• Geophysical investigations
• Limited site investigations</td><td>Geological and hydrogeological maps</td><td>✓</td></tr>
<tr><td>Natural risk map (when appropriate)</td><td>✓</td></tr>
<tr><td>Longitudinal geological profiles</td><td>✓</td></tr>
<tr><td>Longitudinal geotechnical and geomechanical profile with qualitative identification of ground behaviour</td><td>✓</td></tr>
<tr><td>Preparation of risk register</td><td>(✓)[1]</td></tr>
<tr><td colspan="3">Preliminary design stage</td></tr>
<tr><td rowspan="6">• Geophysics and boreholes at the portals and along the alignment
• Water sources and groundwater monitoring
• Laboratory tests
• Outcrop and surface mapping
• In-situ stress measurements and permeability tests, when appropriate
• Exploratory galleries/shafts, if needed</td><td>Longitudinal geological profile (1:5000 to 1:2000)</td><td>✓</td></tr>
<tr><td>Longitudinal geotechnical-geomechanical profile (1:5000 to 1:2000) with quantitative characterisation of ground behaviour</td><td>✗</td></tr>
<tr><td>Geological and geotechnical cross-sections (1:500 to 1:200)</td><td>✓</td></tr>
<tr><td>Geological and geotechnical cross-sections at access/ventilation shafts</td><td>✓</td></tr>
<tr><td>Preliminary characterisation of the hydrogeological regime</td><td>✓</td></tr>
<tr><td>Update of risk register</td><td>(✓)[1]</td></tr>
</table>

Annotations:

()[1]: Both geological risks and risks associated with EPB tunnelling are discussed in the reports [1.3 to 1.6]. While this does not fully qualify as a risk register according to ITA recommendations [2.8] it is consirered sufficient for the variant assessment.

The risk associated with the Project's alignment variants has not been specifically in the scope of the reports [1.3 to 1.6]. It will be part of the assessment of the alignment variants in the second part of our Report.

5.3 Comparison of Available Information with our Requirements for Part II

The available amount of information provided in the reports [1.3 to 1.6] and associated documents of the current design phase is large and has been provided in much detail along all alignment variants. There are, however, some parameters and boundary conditions that need to be made assumptions for. This mainly applies to geomechanical parameters such as un-/reloading stiffness and anisotropic properties of the different ground types as well as quantified information on the fault zones. Table 3 lists the required specific information and its availability for the CUT AND COVER and bored tunnel variants, respectively.

Table 3: Available information for further assessment tasks

Required information	**Available in in [1.3-1.6]?**	
	CUT AND COVER	**Bored tunnels**
Geotechnical properties of the ground / rock layers		
Unit weight	✓	✓
Stiffness soil/rock	✓/-	(✓)[1]
Strength	✓	(✓)[1]
Stress state		
In-situ stress state	(✓)[2]	(✓)[3]
Geometrical boundary conditions		
Ground surface	✓	✓
Layer boundaries	✓	✓
Fault zones (orientation, extent)	-	(✓)[4]
Hydraulic conditions		
Ground water level	✓	✓
Permeability	✓	(✓)[4]

Annotations:

()[1]: UCS and stiffness from uniaxial compression testing on rock samples; no triaxial testing; missing clarity regarding upscaling of sample results to rock mass, influence of discontinuities, and anisotropy (see Chapter 6.2); assumptions have to be made concerning rock mass behaviour.

()[2]: Stress state is assumed to be lithostatic, normally consolidated.

()[3]: The in-situ stress state was not investigated by the geologist. However, information for the general situation in the Prague area can be found in [1.10].

()[3]: The exact amount and orientation of fault zones is not known. According to [1.8], fault zones parallel to the alignments are not expected. The general presence of fault zones will be considered in subsequent assessments. Fault zone properties comprise mechanical properties as well as permeabilities.

In general, the subsoil for the near-surface CUT AND COVER variant is better known and explored than for the bored tunnel variants, which results in a higher remaining ground-related risk. Precise settlement predictions, however, are of particular importance in the shallow soft-ground or weathered-rock sections close to the portals.

In the Project, there are delicate stretches mainly in the east portal area, where the bored tunnel variants will be underneath sensitive infrastructure and built-up areas with shallow soft-ground overburden. In the design phase, these sections will require much increased exploration effort, which has also been stated in the respective reports [1.3 to 1.6].

In soft-ground areas, in-situ stresses as well as un-/reloading stiffness are important parameters for the use of high-quality material models, which in turn would provide better predictions of settlements. Where these parameters are currently not available, numerical analyses based on limited parameters and, where required, assumptions will deliver qualitative results rather than exact quantifications. In the current project phase, this is reasonable. For the later design phases, however, additional investigations and, eventually, updated settlement analyses may be required.

The present data in the four reports [1.3 to 1.6] regarding the stiffness of the ground basically refer to one stiffness parameter, the "deformation modulus" or "elastic modulus", in some cases with a large scattering range, and are only sufficient for simple linear-elastic perfectly plastic material laws without reversal of loading direction (e.g. according to Mohr-Coulomb). In the oedometer tests, only the initial loading was carried out and examined. Also triaxial tests were not performed.

In rock, joints and interfaces usually dominate the mechanical behaviour during the excavation of the tunnel. Here, there are some remaining questions regarding the rock-mass upscaling of sample tests (see Chapter 6.2). However, the influences on surface settlements in areas with high overburden and in good rock are considered insignificant and can be adequately covered by conservative calculation assumptions.

Summarising, the lack of some parameters does not impede the possibility to conduct the upcoming settlement predictions and the assessment of alignment variants. Where required, suitable assumptions will be made that can be verified in subsequent design phases. It has to be noted, however, that conclusions drawn from assumptions are associated with uncertainties. The fact that all three bored variants are located close to each other, on the other hand, imposes very similar conditions on either of them.

5.4 Assessment of the Extent of Geotechnical Investigations

With exception of the CENTRE variant, all Geotechnical Exploration Reports are currently available. The CENTRE variant follows the SOUTH variant along a large part of its alignment and later intersects the NORTH variant. For a remaining stretch, two additional boreholes have been drilled and are currently being evaluated.

For an assessment of the situation, it is important to mention that from the geotechnical investigation point-of-view, the project is between the phases of feasibility study and pre-design. On the other hand, however, lots of considerations regarding construction methods have already been made by the design team. The CUT AND COVER variant is already separated into sections of cut-and-cover, NATM, and “Tortoise” methods whereas for the bore tunnel variants, an Earth Pressure Balanced (EPB) TBM has already been identified as the preferred solution. Hence, the comparably mature status of the investigations and the design consideration is no surprise.

For the upcoming task of assessing risk and technical issues associated with the different tunnelling methods in the different alignment variants, the geotechnical information so far available is sufficient. For the CUT AND COVER variant, the Geotechnical Exploration Report [1.3] is already based on a large number of exploration points that may be sufficient to enter the preliminary design stage with a few additional tests.

For the bored tunnel variants, the density of exploration points is still sparse and will have to be increased when the preferred alignment variant has been fixed. As already stated in the Geotechnical Exploration Report [1.4] for the NORTH variant, particularly in the soft ground areas near the east portal the extent and geotechnical properties of the difficult aeolian soils must be investigated more thoroughly. All three variants, however, will face similar geotechnical challenges and with the EPB technology, a tunnelling method has already been proposed that is likely to be able to deal with these challenges. Hence, the sparsity of the current geotechnical investigations does not prevent considerations of preferred variants and the compilation of risks associated with each of the alignment variant.

It is of particular importance to emphasise the experiences of the geotechnical experts with the local and regional geology. In close vicinity of the bored tunnel alignments, the Tunnel Blanka was excavated through similar rock formations. Experience from this project has certainly been used in the preparation of the present Geotechnical Exploration Reports.

6 Recommendations for the Geotechnical Investigation Programme

6.1 General Recommendations

For the upcoming task of assessing risk and technical issues associated with the different tunnelling methods in the different alignment variants, the geotechnical information so far available is sufficient. For the CUT AND COVER variant, the Geotechnical Exploration Report [1.3] is already based on a large number of exploration points that may be sufficient to enter the preliminary design stage with a few additional tests. For the bored tunnel variants, the density of exploration points is still sparse and will have to be increased when the preferred alignment variant has been fixed. AS already stated in the Geotechnical Exploration Report [1.4] for the NORTH variant, In particular the soft ground areas near the east portal requires the extent and geotechnical properties of the difficult aeolian soils to be investigated more thoroughly.

Furthermore, the geotechnical interpretation of the bored variants is partly focused on conventional excavation. Once the pre-design phase starts, further investigations of TBM-relevant geotechnical parameters such as abrasivity and clogging potential will be required. This does not, however, impede the possibility to assess the alignment variants, since they are close enough to each other not to expect significant differences in terms of technical feasibility.

As a prerequisite for the design phase, however again not crucial for the current stage of alignment variant assessment, the mechanical properties of soils and rocks should be investigated by means of oedometer tests examining the un- and reloading behaviour (for soils) and triaxial tests in order to provide better information for simulation of ground behaviour. In addition, a quantification of potential blocks and boulders in the diluvial sediments will be required as well as information on the in-situ stresses.

According the longitudinal sections of the bored variants, four tectonic fault zones have been identified, which will be intersected by all bored tunnel alignments. Since these fault zones bear an inherent technical challenge for the excavation process as well as for the lining design, a detailed exploration of these zones is recommended as part of the main geotechnical investigation programme.

With respect to potentially vulnerable structures in the vicinity, the Tunnel Blanka in the east and the heating plant in the west, detailed investigations will be necessary in the pre-design and design phases. It is likely, that prior to these design stages, additional geotechnical investigations need to be performed.

Independent from the selection of the variant, it is recommended to appoint a dedicated tunnelling expert already in the pre-design phase, who can support the further site investigation programme and provide technical consultancy regarding the tunnelling methods. During this upcoming phase, the Geotechnical Design Report, which includes procedures for proofs of stability and serviceability as well as more detailed boundary conditions for the design of the tunnelling methods and the design of the tunnel lining, will follow.

In addition to this, a dedicated technical expert report on the tunnelling methods and their associated design works and risk analyses is recommended. This expert report will amend the geotechnical findings and provide guidance throughout the design, procurement, and construction phases.

In case of the bored tunnel variants, for the design of the tunnel lining, more detailed information on the ground water pressures and the actual permeability at a high resolution along the alignment will be required. For the selection of a suitable tunnel boring machine, excavation-related parameters considering clogging potential and abrasivity will be required.

6.2 Additionally Required Information for Variant Assessment

While the overall extent and quality of the Geotechnical Exploration Reports [1.3 to 1.6] is very high given the current stage of the Project, there are a few particular aspects that may affect the assessment of the alignment variants and that should be addressed by the geotechnical designers of the Project:

1. Regarding the aeolian loess layers near the east portal, the technical feasibility may depend on the tendency of mechanical degradation upon stress redistribution or contact with water. Furthermore, loess soils sometimes exhibit leeching and cavities. Can this risk be estimated based on the currently available information or based on previous experience in Prague’s geology?
2. Since no swelling tests have been performed in the tunnel horizon, is there a notable risk of swelling ground behaviour in the tunnel horizon anywhere along the different alignments?
3. Regarding the three-dimensional orientation of the rock/soil boundary: is there a high risk of glancing intersections between rock and soil that might cause problems with steering and tool wear in TBM tunnelling? This statement falls in line with the already answered question of whether fault zones are expected parallel to any of the alignment variants.

4. What is the probability to encounter further fault zones that have so far not been explored?
5. What are the properties of the fault zones in the tunnel horizon compared to closer to the surface?
6. Are there experiences from comparable materials in the area regarding the triaxial behaviour of rocks and soils in the area?
7. Are there any statements regarding the anisotropy of the shale formations? The stratification angle and the anisotropic strength/stiffness characteristics are of high importance for the excavation process.
8. How have the geophysical measurements been interpreted and considered in the reports [1.3 to 1.6]? Which parameters were directly or indirectly determined based on geophysical tests?
9. Appendix 8 of the Geotechnical Exploration Report for the NORTH variant [1.4] contains detailed information on dynamic testing that was performed close to the Institute of Physics of the Czech Academy. Has any significant vulnerability to tunnelling-related vibrations been found? If yes, we would like to ask for a translation of this appendix.
10. Are there significant differences regarding the aforementioned open questions (1 to 9) between the three bored tunnel variants?

The aforementioned requests do not impose the necessity to conduct further field tests or exploration drilling. They are mainly questions of additional interpretation of existing information by the geotechnical designers. In case a question cannot be answered at present, respective assumptions will be made in the variant assessment.