Water control for a rock-soil interface - infrastructure at a contaminated site

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Abstract. The conceptual model of the rock-soil (and future shaft) interface was confirmed (so far not rejected) using data from investigation boreholes. The location of a depression in rock (a likely deformation zone) was indicated and confirmed using borehole data. Wave-washed deposits (upper part of the stratigraphy) and a lower water-bearing strata (soil) coinciding with the depression are key water-bearing features in soil. The likely deformation zone is expected to be a key water-bearing feature in rock. Grouting design (curtain- and blanket grouting) and sealing of soil (jet-grouting and sheet-pile walls) focus on sealing these features. The wells (infiltration) that are planned between the shaft and a contaminated site may, if needed, further reduce the effect of the construction on hydraulic head and flow. Changes that are of interest since they may also influence the mobility of a contamination. A low grouting pressure is used in rock adapting to a shallow depth (curtain grouting) and a possible horizontal connectivity. The steps of the observational method, as described by Peck (1969), were found very useful. Its focus on "the general nature, pattern and properties" and "a working hypothesis of behaviour" is of particular interest, highlighting the understanding of the system at hand.

1. Introduction

Construction of infrastructures such as shafts and tunnels in a rock-soil interface, below the groundwater level and at a contaminated site, demand transdisciplinary collaboration (rock-, geotechnical- and environmental engineering as well as engineering geology and hydrogeology). A collaboration aiming at a relevant description of conditions as a basis for an understanding of behaviour and as a mean to provide an appropriate and site-specific design.

This paper presents a case study from an ongoing railway project integrating the above areas. Focus is on water control (hydraulic head and flow) using sealing (rock grouting, sheet-pile walls, jet-grouting), infiltration (adding water) and pumping (removing water). Simplified drawings of the shaft including technical measures (sealing), wells for observation and protective measures (wells) are shown in Figure 1. The description of geology and hydrogeology (the conceptualization) are presented and discussed in the framework of the observational method and Eurocode-7 [1].
The railway project and the contaminated site (contaminated by chlorinated solvents) are found in Varberg in the southwestern part of Sweden (Figure 2). The railway project has a total length of about 9 km (double track) including open concrete troughs, concrete tunnels and a 2.8 km long rock tunnel. The contaminated site is located by a stretch of the railway where an open concrete trough will be constructed. The water control measures described in this paper are focusing on the temporary stage Figure 1a,b of the project before the permanent concrete trough is casted (Figure 1c). At this final stage, walls will be removed (at least partially) and water will be flowing in permeable materials from left to right (east to west) below the trough (Figure 1c).

Chlorinated solvents are volatile organic compounds categorized as dense non-aqueous phase liquids (DNAPL). This means that they have a density larger than water allowing migration and accumulation below the groundwater table. Chlorinated solvents are chemicals with a low solubility that cause long-term contamination in soil and groundwater.

The purpose of infiltration wells is to introduce an additional possibility to reduce the effect of the construction on hydraulic head and flow, the purpose is not a remediation of the contaminated site. However, an observational approach and the same type of technical installations (boreholes and technical sealing measures) may very well be used as important components of a remediation strategy.

**Figure 1.** Simplified drawings of the shaft and technical- and protective measures for water control: sealing (rock grouting, sheet-pile walls, jet-grouting), wells for observation and monitoring, infiltration (adding water) or pumping (removing water). Drawings a) and b) - temporary stage. c) Casting of a concrete trough for the permanent stage. View from the north (elevated areas and contaminated site to the left).
2. Method

The objective of this paper is to compile and discuss investigations, conceptualization, design, and measurements (monitoring) within the framework of the observational method as presented by Peck [2]. Peck describes a procedure with eight different steps aiming at a closure of gaps in knowledge. For this case study, as well as for constructions in rock and soil in general, geology plays a major role.

The development of an early conceptual model allows for confirmatory (rather than exploratory) investigations, increasing understanding and closing the knowledge gaps. The following eight steps were formulated in Peck [2, p 173]:

1. “Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.”
2. “Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role.”
3. “Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.”
4. “Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.”
5. “Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.”
6. “Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.”
7. “Measurement of quantities to be observed and evaluation of actual conditions.”
8. “Modification of design to suit actual conditions.”

The focus of this paper is on the formulation of a first conceptual model of the conditions (general nature and properties) and its confirmation (or rejection) based on early investigation data. The construction of the trough by the contaminated site had not yet started (February 2021).

2.1. Geological setting – railway project and contaminated site

Varberg is located by the ocean (Figure 2), between valleys and on a sloping hill. The topography varies from 0 to 54 m.a.s.l. and depth to bedrock varies from 0 to 20 meter [3].

The quaternary deposit map of Varberg (Figure 2) shows the presence of till (blue), glaciofluvial deposits (green), glacial clay (yellow), wave washed deposits (orange), postglacial sand/clay, peat and flood sediments [4]. Moreover, the bedrock map (Figure 3) identifies the presence of charnockite (deep red), granodiorite granite gneiss and monzodiorite granodiorite gneiss (beige and pink) and gabbro (green) [5].

The study area is widely dominated by those Precambrian crystalline rocks, the charnockite being very rare in Sweden, the gneiss being more common. Further, the region consists of pre-last glacial sediments as well as sediments from the latest glaciation. The deposition of till (blue areas in Figure 2) and the formation of end moraines are related to the action of the ice itself. To the east of Varberg some of the Halland coastal moraines are seen (blue, thin lines, mainly oriented northwest-southeast (Figure 2). These were formed about 18000 to 16000 years ago [6]. The deposition of glaciofluvial sediments (green) is related to the waters of a melting ice [7].

Yellow areas identify marine clay, the deposition of which happened following the deglaciation period and was due to a high sea level (75 m above present level). After the withdrawal of the sea from higher to present day levels, the wave washed sediments were left behind (orange areas).
3. Results and discussion

3.1. Conceptual model (hydrogeology) by the trough and the contaminated site

The level of the ground by the future concrete trough (identified by pit 3.4 and 3.3 in Figure 4) is found at approximately +2 m (m.a.s.l.). Increasing to approximately +4 m by the contaminated site east of a group of observation wells (black symbols, well U47G01GV etc). An expected (simplified) stratigraphy at higher elevations (east) would be wave washed deposits on till on rock. At lower elevations (west) wave washed deposits on clay on till on rock are expected. A depression in rock was identified by borehole 14T3091U (Figure 4) and a stratigraphy may contain wave washed deposits on clay (silt/sand) on till (or glaciofluvial material) on rock (likely a deformation zone). To the east an open aquifer (wave washed deposits on till) is expected and to the west, two aquifers, a lower and confined (in till and below clay) and an upper unconfined (wave washed deposits) are likely. By the depression in rock, a transition from two aquifers (west) to one (east) is expected. In the area of the trough the groundwater levels (both upper and lower aquifer) are at approximately +1 m increasing towards the east. The level of the bottom of the shaft (to be constructed) is at -8 m to -10 m.

As a mean to confirm (or reject) the above descriptions, Figure 4 presents investigation boreholes and intervals of hydraulic conductivity for soil (green symbols > 3 $\times$ 10^{-5} m/s, yellow symbols below 3 $\times$ 10^{-5} m/s but above 1 $\times$ 10^{-6} m/s). For rock, Figure 4 shows two cored boreholes drilled at an angle at the location of the trough (blue symbols).

Hydraulic conductivity of shallow soil (upper aquifer) varies (moderate to high) with an identified maximum of 5 $\times$ 10^{-4} m/s. In addition, high values were found also for the boreholes located by the expected depression of rock (lower aquifer). For boreholes 14T3091U and 14T3090U, 1 $\times$ 10^{-4} m/s and 3 $\times$ 10^{-5} m/s respectively. For 14T3092U (adjacent to the previous two) the hydraulic conductivity was 6 $\times$ 10^{-6} m/s. The depression in rock was investigated and confirmed also by the aligned group of observation wells to the east of these two boreholes (black symbols).

Water loss measurements were performed for 3m-sections of the cored boreholes in rock. For borehole KBHG114 (north, drilled at an angle towards the south), the deeper sections of the borehole were identified as the most permeable sections (33-36 m, 36-39 m, 39-42 m, 42-43.9 m). The hydraulic conductivity of these sections is above 3 $\times$ 10^{-5} m/s. The lower sections of the borehole are located below the identified depression in rock and are characterized by moderate hydraulic conductivity (1 $\times$ 10^{-5} m/s).
conductivity of these sections had a range between $1 \cdot 10^{-7}$ and $1 \cdot 10^{6}$ m/s (transmissivity, $T$, of $3 \cdot 10^{-7}$ to $3 \cdot 10^{6}$ m$^2$/s for 3m-sections). Lower for the remaining sections.

For KBHG115 (southern cored borehole, drilled towards the north), the most water-bearing sections were identified between 9-12m, 18-21m, 21-24m, 24-17m, 33-36m and 36-39m). The hydraulic conductivity was about $1 \cdot 10^{6}$ m/s ($T$: $3 \cdot 10^{6}$ m$^2$/s for 3m-sections). Using a cement-based grout (Injektering 30) we assume penetration of grout into individual fractures having a transmissivity exceeding $5 \cdot 10^{-7}$ m$^2$/s (corresponding to a fracture with an aperture of approximately 90 µm, $3d_{50}$ for the grouting material).

In summary and from a qualitative and hydrogeological perspective, the most water-bearing (so far identified) units were found in soil by the depression in rock (locally confined) and in shallow soil at higher elevation (an open aquifer). The boreholes in rock drilled at an angle towards the depression identified permeable sections also at depth suggesting an intersection of a deformation zone (or its damage zone).

3.2. Conceptual model and the observational method
The section below aims at discussing investigations and conceptualization, design, and measurements (monitoring) within the framework of the observational method as presented by Peck (1969) [2]. The eight steps quoted in Section 2 are indicated by the numbers 1 to 8 below.

So far, the trough was not yet constructed. This means that step 7 “Measurement of quantities to be observed and evaluation of actual conditions” and step 8 “Modification of design to suit actual conditions” will not be described here. However, the evaluation of actual conditions (confirmation or rejection and revision) is continuously dealt with, going from an early description using maps and geological history, adding confirmatory (rather than exploratory) investigations.

3.2.1. Exploration - general nature, pattern and properties (1). Topography, maps of quaternary geology and rock (Figure 2 and Figure 3), soil depth (depth to rock surface) and basic geological history of the site (Nordic conditions including a history of glaciation) provided a conceptual model of the general geological pattern, constrained likely hydraulic properties (ranges) and possible continuity of important water-bearing strata (structures) in soil and rock. A deformation zone was assumed based on the topography of the rock surface (a depression). Wave-washed deposits (gravel, sand) underlain by silt (sand) and, for a greater soil depth, clay, was expected. Below these layers and on top of rock, a layer of till (and in depressions of the rock surface, sand/gravel) were anticipated. Data from investigation boreholes (drilling, hydraulic testing, groundwater levels) confirmed (or did not, so far, reject) this general pattern.

3.2.2. Assessment - most probable conditions & most unfavourable conceivable deviations (2). The “desktop” conceptualization, the confirmatory data sets (with coordinates) together with the geometry of the construction (coordinates - length, width, depth) allowed for an assessment of the most probable conditions (and most unfavourable conceivable deviations) at the construction – geology interface. Wave washed deposits on till on rock and wave washed deposits on clay on till on rock are suggested as the basic and most frequent conditions (stratigraphy). Wave washed deposits on clay (silt/sand) on till (or glaciofluvial material) on rock (deformation zone) is expected to be a more unfavourable condition (stratigraphy) in terms of flow, influence on hydraulic head and sealing. As mentioned previously, the seven boreholes (black symbols in Figure 4), drilled as a preparation (observation boreholes) prior to installation of infiltration- and pumping wells, confirmed the expected depression in rock.
Figure 4. Location of the future trough (excavation pits, 3.4 and 3.3), investigation boreholes and intervals of hydraulic conductivity. Boreholes in soil (green symbols $>3\cdot10^{-5}$ m/s, yellow $3\cdot10^{-5}-1\cdot10^{-6}$ m/s). Cored boreholes in rock KBHG114 och KBHG115 (blue symbols). Observation wells (hydraulic head, black symbols) to the east show the area where installation of infiltration- and pumping wells is planned. The main contaminated area is found to the east of these wells. Depression in rock (east to west) was identified by borehole 14T3091U and confirmed by the observation wells. Figure 1 represents drawings of a cross-section of the trough seen from the north.
3.2.3. Establishment of the design (behaviour - most probable conditions) (3). The description above forms a basis for a qualitative assessment of differences in behaviour (where do we expect most or least inflow to the construction and most or least influence on the surrounding groundwater levels). This relates to step 3 and a “working hypothesis of behaviour”. The parameters for rock grouting design that we have used, e.g. [8,9,10], are directly related to quantities that could be observed within the framework of the observational method (presence of water-bearing strata/structures and their hydraulic properties, evaluated based on groundwater levels and flow). The effect of a grouting (sealing) campaign can be estimated or modelled (analytically, numerically) using reduced hydraulic conductivities. Infiltration or pumping and the effect thereof can be investigated using sources or sinks in a model. Grouting design aim at sealing deformation zones, host rock and shallow rock (close to the rock surface). Jet-grouting and sheet-pile walls are used for sealing of soil. Further, infiltration and pumping focus on the rock depression in the area of the observation wells (black symbols, Figure 4). Main reasons are the proximity to the contaminated site (to the east) and the greater influence on the hydraulic head that is expected for these more permeable geological materials seemingly connecting the trough and the contaminated site. Rock grouting, sheet-pile walls and jet-grouting (sealing) are considered technical measures whereas infiltration and pumping are here looked upon as protective measures. In this case, we have the contaminated site to the east and infiltration (adding water) in the area by the observation wells aim at (if needed) further reducing the effect of the construction on head and flow that could influence the mobility of the chlorinated solvent.

3.2.4. Quantities to be observed (during construction) - calculation of values (4 & 5). Having selected the quantities to observe (flow and groundwater levels related to the presence of water-bearing strata/structures), calculations of these values for most probable (4) and most unfavourable conditions (5) should be made. A basic estimate of inflow was done using a cross-section of the trough (Figure 1) assuming a width of 45 m and a depth of 8 m. The upper boundary of the model was set to a constant level and the east, west, and lower boundaries of the model were assumed to be no flow boundaries. Finite difference estimates of the groundwater level (pressure) were made using Excel (pressure in a cell equals the average value of adjacent cells). Further an assumed residual transmissivity, \( T \) (following sealing measures) in the order of \( 5 \times 10^{-7} \text{ m}^2/\text{s} \) was used (hydraulic conductivity, \( K \), of \( 6 \times 10^{-8} \text{ m/s} \), \( T \) divided by the depth 8 m, if equally distributed). This transmissivity would, for example, correspond to the ability of a residual, non-grouted, 90 µm fracture to transmit water. The above resulted in an inflow in the order of 0.16 litres/second/100m or 2 litres per second for 1250m length. For the entire trough (1250m) the permitted inflow during construction is 8 litres/second (given the whole excavation is open). As shown in Figure 4, those two values (\( T: 5 \times 10^{-7} \text{ m}^2/\text{s} \) and \( K: 6 \times 10^{-8} \text{ m/s} \)) are exceeded in soil in the area of the trough (green symbols, \( K > 3 \times 10^{-5} \text{ m/s} \), yellow symbols \( 3 \times 10^{-5} > K > 1 \times 10^{-4} \text{ m/s} \)). In rock some of the 3m-sections have a transmissivity, \( T \), of \( 3 \times 10^{-7} \) to \( 3 \times 10^{-6} \text{ m}^2/\text{s} \). The continuity of the water-bearing strata in soil and an indication of continuous structures in rock (shallow fractured rock and horizontal fractures) highlights a need for a systematic and continuous (not selective) approach.

3.2.5. Selection in advance of course of action or modification of design (6-8). For rock, curtain- and blanket grouting is used. Focus is on using a cement-based grouting material (diameter of 30 µm) and for shallow depths, a low grouting pressure is applied to decrease the risk of jacking. Split-spacing (primary and secondary grouting boreholes) and hydraulic testing before grouting (water loss measurements) allow a densification of grouting boreholes when the water loss exceeds a pre-defined value (relates to the ability of the specific grout to penetrate a fracture of about 90 µm, see section above). Measurements of inflow and groundwater levels during and following excavation will allow further evaluation of actual conditions (7) and allow a modification of design (to suit actual conditions, 8) if needed. Densification (or removal) of grouting boreholes is a course of action that was selected in advance. A densification is expected for deformation zones and fractured, shallow rock.
4. Conclusions
The conceptual model of the geological conditions (general nature and properties) was confirmed (or so far not rejected) using data from investigation boreholes. The location of a depression in rock (a likely deformation zone) was indicated and confirmed using borehole data. Wave-washed deposits (upper part of the stratigraphy) and a water-bearing strata (soil) coinciding with the depression of the rock surface are key water-bearing features in soil. The likely deformation zone is expected to be a key water-bearing feature in rock.

Grouting design (curtain- and blanket grouting), sealing of soil (jet-grouting and sheet-pile walls) and wells, all focus on these features. The wells (infiltration or pumping) that are planned east of the shaft and west of the contaminated site may, if needed, further reduce the effect of the construction on hydraulic head and flow. Changes in head and flow are of interest since these changes may also influence the mobility of the chlorinated solvent. A low grouting pressure is used in rock adapting to a shallow depth (curtain grouting) and a possible horizontal connectivity.

The steps of the observational method, as described by Peck (1969) [2], were found very useful. Its focus on "the general nature, pattern and properties" and "a working hypothesis of behaviour" is of particular interest, highlighting the understanding of the system at hand.

The focus of this paper was on the formulation of a first conceptual model of the conditions (general nature and properties) and its confirmation (or rejection) based on early investigation data. The construction of the trough by the contaminated site had not yet started (February 2021) and a discussion on the remaining steps of the procedure will be presented in future work.

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