Geotechnical analysis of a gallery under a large concrete base slab. A case study of the European Spallation Source project in Sweden

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1 Abstract

Following the geotechnical assessment of the existing design of a gallery structure situated below two buildings prior to the placement of a large concrete base slab, it was found that the gallery structure had insufficient ULS and SLS capacity.

As a mitigation, it was suggested to install compressible layers at the outer side of the gallery walls.

The structural design of the gallery walls and base slab was found to be significantly impacted by the stiffness of the backfill material, in this case modified Swedish clay till, surrounding the gallery.

This paper presents the argumentation used to select suitable stiffness parameters for the modified Swedish clay till backfill, and the geotechnical analysis carried out to assess the performance of the backfill, when subjected to forced horizontal movements due to temperature variations and shrinkage of the large concrete base slab.

2 Introduction

The development of the European Spallation Source is driven by the research needs of the European scientific community, leading to the design and construction of a large complex of different purpose buildings. The ESS site will be safe with regards to radiation, environmentally sustainable, and will be a world-class research centre with an innovative architectural design in tune with the surrounding landscape. This paper analyses the performance of the installation galleries, IG, under the Target Buildings D01 and D03, galleries which are located under a large concrete base slab. The installation galleries are subjected to forced horizontal movements as a result of shrinkage and temperature effects in the large concrete base slab. A conceptual sketch of the typical cross section of the installation galleries is depicted in Fig. 1.

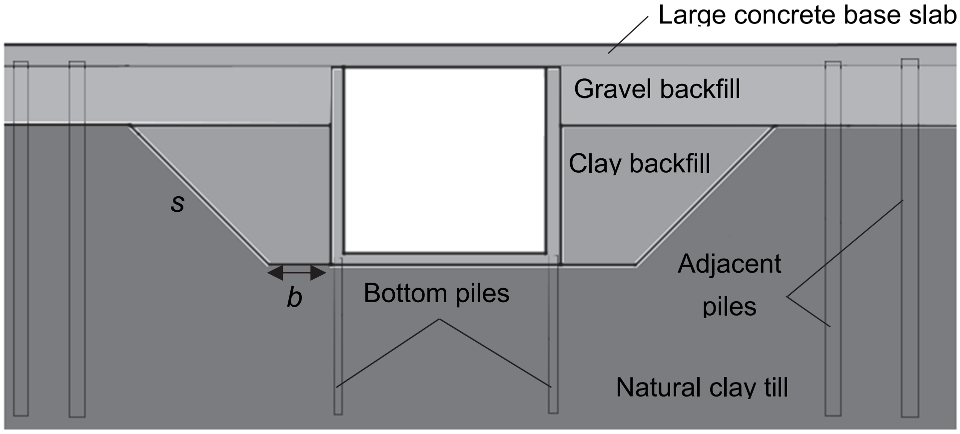

Fig. 1: Conceptual sketch of the installation galleries under D01 and D03

The performance of the gallery structure is analysed by 2D finite element modelling technique using the geotechnical commercial software PLAXIS 2D. In the following sections the structural properties of the typical cross-section of the installation galleries is presented, followed by the discussion on the derivation of the most relevant geotechnical parameters. Then, the methodology and assumptions are listed together with a short discussion on the material model selected before the results and conclusions are drawn.

The main reference codes for geotechnical design for static loads are EN 1990 and EN 1997-1 with Swedish national annexes.

3 The structure

The structure consists of a rigid concrete U-shape structure placed on top of the excavated soil at 75.5 m above the reference level, +75.5 mRL, and supported on piles. Before the excavation is backfilled a 200 mm thick prefabricated concrete slab is placed on top of the gallery walls, and the space between the slab and the walls is grouted. The excavation is then backfilled adjacent to the structure using a modified clay till material and further compacted. Finally a 400 mm gravel layer is placed on top of the backfill up to a level of +78.9 mRL and on top of the gravel the 0.5 m thick concrete base slab is cast. Before casting the concrete a blinding layer is placed. The connection of the gallery walls with the cast concrete base slab is constructed so that shear and axial forces can be transferred, whereas bending moments cannot be transferred. The installation gallery bottom slab is supported by a series of piles which carry the weight of the structure. A typical cross-section of the gallery structure is presented in Fig. 2. Regarding the excavation geometry as shown in Fig. 1, the slope, *s*, is 1:1 and the distance, *b*, from the gallery bottom slab to the excavation slope is 2 m.

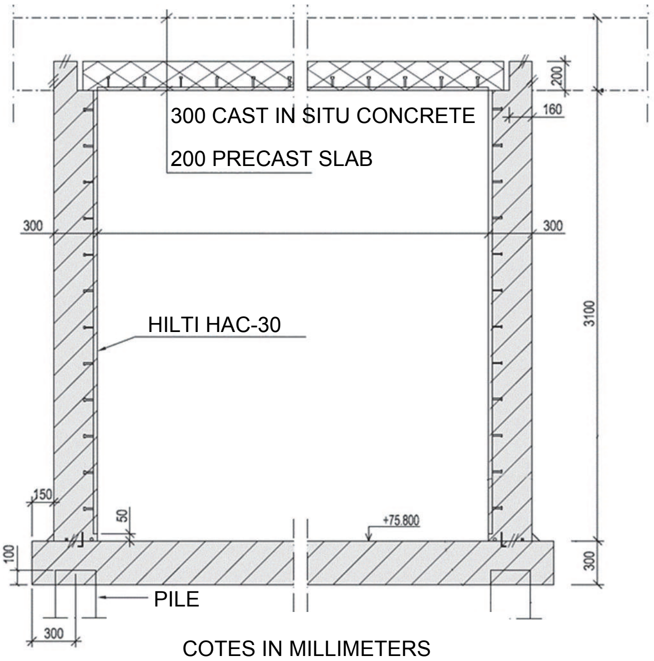

Fig. 2: Typical detailed cross-section of the installation gallery structure

For construction stages and SLS, the ground water level is located at +74.7 mRL, which is located below the gallery bottom, and for ULS at +79.0 mRL corresponding to the top of the gallery walls.

4 Geotechnical properties of soil

The most relevant geotechnical properties of the different soil materials, modified clay till backfill, gravel backfill and natural clay till, are discussed in the following. Finally, the geotechnical properties for each soil material are summarized.

4.1 Modified clay till backfill

It is evaluated that an accurate assessment of the geotechnical properties of the modified clay till backfilling material is critical for this analysis.

4.1.1 Stiffness

The most important parameter affecting the performance of the installation gallery is the stiffness of the modified clay backfill. Therefore, this geotechnical parameter has been carefully assessed. The backfilling process is described below:

- The backfill clay is placed in thin, 30 cm, layers. After placing, the material is homogenised by various means.
- In case the fill is too dry it is watered and again homogenised.

- A certain amount, 0.5 to 1 % by weight, of quick lime is spread on top of the backfilled layer.
- The lime and backfill clay is thoroughly mixed.
- The layer is levelled by a grader and compacted by a vibratory compactor roller.
- Plate load tests are performed from the surface of the layer. The requirement is that the unload/reload stiffness modulus, E_{v2}, is to fall between 40 and 90 MPa.
- In case E_{v2} is smaller than 40 MPa, additional lime is added, backfill and lime is re-mixed, the surface is levelled by a grader, followed by compaction and testing.
- In case E_{v2} is larger than 90 MPa, the amount of lime for the next layer is reduced to achieve 40 MPa $\leq E_{v2} \geq$ 90 MPa.

It is based on the above considered that the backfill is characterised by E_{v2}, from the surface of each layer, being between 40 and 90 MPa. However, based on engineering experience it is the mass property of the modified clay backfill is expected to fall in a more narrow range such as 50-80 MPa.

The unloading/reloading stiffness, E_{v2}, is determined after each of the load increments that have acted for a relative short period of time, few minutes. Due to this effect, the measured value is considered to be larger than the "true" value.

The fact that the value to be used is related to shrinkage of the large concrete base slab means that a long-term value is to be used for the present purpose. This would imply that the value should be somewhat smaller than E_{v2}.

However, quick lime is used to modify the properties of the soil, see Westesson (2015), which has a stiffening effect on the backfill material. This effect is considered to develop with time, meaning that the stiffness measured immediately after placing the backfill represents a low estimate of the stiffness after some months/years.

According to the discussions above, E_{v2} may represent an upper value or by contrary may represent a lower value of the "true" stiffness of the backfill. It is therefore, based on engineering judgement considered that the measured value E_{v2} represents a conservative estimate of the stiffness of the fill, upper value in this case since it leads to larger pressures on the gallery wall.

4.1.2 Initial stress conditions

Relatively large horizontal pressure due to compaction will exist at the top of the fill. This phenomenon is, however, not modelled because the change in active and passive earth pressure at the analysed displacements are negligible.

4.1.3 Stress path during loading

The fill is built in with a few percent of air content. This air will, even if the water level is raised to the underside of the large concrete base slab, only partly disappear resulting in a pore water/air mixture, which has a very small stiffness relative to the stiffness of the backfill soil skeleton. The assumption of constant volume, i.e. undrained condition, can therefore not exist, and the material is treated as drained in all the analyses.

4.2 Gravel backfill

The gravel layer is considered as a drained material as the material is composed of coarse grains up to 63mm. The strength and stiffness of the gravel does not have a big impact on the overall model, since it is a thin layer located beneath the concrete base slab. Therefore, they will not be discussed here.

4.3 Natural clay till

The stiffness of this material, upper and lower clay till, is determined according to the Danish experience on Scandinavian clay till.

4.3.1 Stiffness

The oedometer modulus for clay till may be described by (1), see Hansen (1978).

$$E'_{oed} = E'_{oed,0} + \Delta E'_{oed} \cdot \sigma'_{v,a} \tag{1}$$

Where:

- $\sigma'_{v,a}$ is the minimum vertical stress after glaciation. In case of an excavation the value of $\sigma'_{v,a}$ corresponds to the stress after this excavation.
- E'_{oed} is the oedometer modulus.
- $E'_{oed,0}$ is the oedometer modulus for $\sigma'_{v,a} = 0$ kPa.
- $\Delta E'_{oed}$ is the increase of the oedometer modulus per increase of $\sigma'_{v,a}$.

In Hansen (1978) common stiffness values for clay till are reported and used for the analysis. These values are $E'_{oed,0}$ =20000 kPa and $\Delta E'_{oed}$ = 1500. Young's modulus, E', is derived based on linear elastic theory from the oedometer modulus, E'_{oed},

4.3.2 Initial stress conditions

It is known that the horizontal stresses in undisturbed clay till can be significantly larger than what is a result from a K_0-condition. This phenomenon is, however, not modelled here due to the fact that these stresses will disappear due to the excavation and also because the elastic properties are not influenced by this fact.

4.3.3 Stress path during loading

Undrained shear strength is not considered relevant, because it is experienced that the consolidation time for clay till is limited, partly due to the large stiffness and partly because the field mass value of the permeability is many times larger than the laboratory value due to fissures in the clay. Therefore, being that the shrinkage time of the concrete relatively long compared to the consolidation time, it is assumed that clay till behaves under drained conditions.

4.4 Summary of geotechnical properties

The geotechnical properties of the different soil materials are summarized in Tab. 1. Geotechnical parameters for natural clay till are in good agreement with the values proposed in the guidance notes in Danish Geotechnical Institute (1985).

Tab. 1: Summary of the geotechnical properties of the soil materials

Soil material	γ, [kN/m^3]	c', [kPa]	φ', [degree]	E_0', [MPa]	$\Delta E'$, [MPa/m]	ν', [-]
Modified clay till backfill	21	20	32.5	80	0	0.3
Gravel backfill	18	0	43.0	25	0	0.3
Upper natural clay till	20	25	32.5	15	23	0.3
Lower natural clay till	21	20	32.5	15	22	0.3

5 Methodology, assumptions and constitutive model

In order to perform a correct simulation of the earth pressures, an integration of the realistic construction stages that the structure and soil have been subjected to have been modelled. For this purpose, the commercial finite element program PLAXIS 2D was used.

The typical cross-section is analysed under 2D plane strain conditions. The calculation consists of a simulation of the realistic construction stages followed by a pushover analysis of the large concrete base slab simulating the forced installation gallery movements due to shrinkage and temperature effects of the large concrete base slab.

The U-shape installation gallery concrete structure is modelled as three plate structures with the sectional properties of the concrete rectangular sections. A linear elastic material constitutive model has been used to simulate the concrete. The gallery walls and installation gallery bottom slab are considered to crack due to the large deflections. In order to model this, the moment of inertia of the cross-section has been considered as half of the non-cracked concrete section.

The piles below the bottom slab of the installation gallery are modelled as fixed-end anchors in the horizontal and vertical directions with an axial stiffness equal to the force exerted by 10 mm movement of the piles that have a horizontal stiffness of 8 MN/m and a vertical stiffness of 170 MN/m, with spacing of 1.25 m.

The prefabricated concrete slab placed at the top of the installation gallery before the backfilling process is modelled with a node-to-node anchor structure, which is removed once the large concrete base slab is placed. The anchor will act in compression, which is a valid assumption since the prefabricated concrete slab has been grouted to the gallery wall.

The large concrete base slab is modelled by a plate element connected to the top of the installation gallery by free-rotation connections. The plate element is modelled with linear elastic material with the concrete section properties. Further, it should also be considered the effect of the adjacent piles that take the weight of the large concrete base slab. The piles are expected to settle maximum 3 mm and its effect on the base slab is simulated by a surcharge of 20 kPa on top of the large concrete base slab.

The pushover analysis is simulated by a prescribed displacement of the entire large concrete base slab.

The interface of the gallery walls with the backfill soil material are considered to be smooth ($\delta' = ⅔\cdot\varphi'$ and $a' = ⅔\cdot c'$) assuming the wall is cast with smooth surfaces, while the interface of the large concrete base slab with the gravel is considered to be rough ($\delta' = \varphi'$ and $a' = c'$), since the slab is cast on blinding which is placed directly on the gravel.

The installation gallery bottom slab is assumed to not be in contact with the soil, therefore the soil below it is not resisting the vertical loads, which are fully transmitted to the piles. This is modelled by introducing a very soft cluster of soil of 20 cm height just below the installation gallery bottom slab.

Due to the short distance of the ground surface to the water table, the capillarity effects in the soil above the water table will (partly) saturate the clay till above ground water level. Further, the air content in the clay backfill is only few percent, but even with a high ground water level the pores of the clay backfill will not be fully saturated. Therefore, the bulk unit weight of these materials above ground water level and below water level is assumed to be the same.

A linear-elastic model is used for the structural materials, while a linear elastic-perfectly plastic, Mohr-Coulomb, model is used for all soil materials. The reasoning behind the selection of a simple material model for the natural clay till and the modified clay till backfill is that these can be interpreted as over consolidated and therefore simple elastic properties are valid.

The structural properties of the different elements are summarized in Tab. 2, where thickness, weight and spacing are represented by *t*, *w* and *l*, respectively.

Tab. 2: Summary of the structural properties of the different elements

Structural element	*EA*, [kN/m]	*EI*, [kN.m^2/m]	*t*, [m]	*w*, [kN/m/m]	*EA*, [kN]	*l*, [m]
IG wall and bottom slab	9.90e6	3.71e4*	0.3	7.5	-	-
Large concrete base slab	1.65e7	3.44e5	0.5	12.5	-	-
IG horiz. anchor (pile)	-	-	-	-	8.0e3	1.25
IG vertical anchor (pile)	-	-	-	-	170.0e3	1.25
IG node-to-node anchor (prefab. slab)	-	-	-	-	6.6e3	1.00

*Assumption of cracked section.

A representation of the soil-structure 2D model is shown in Fig. 3.

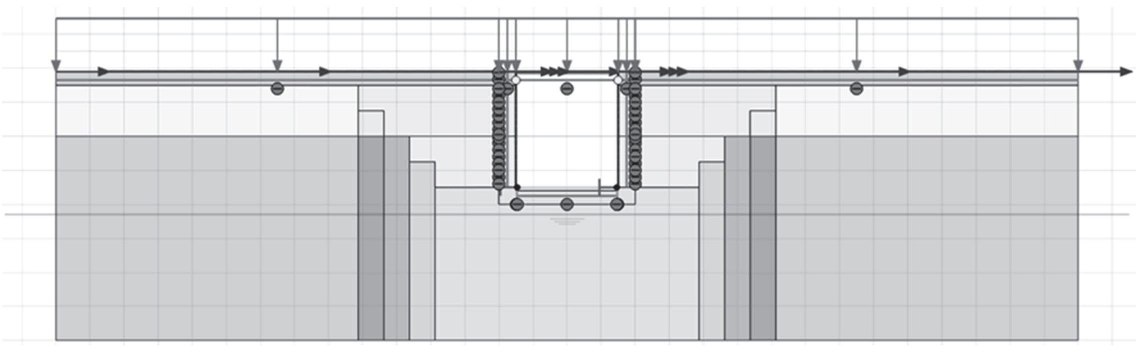

Fig. 3: Representation of the 2D model

6 Results

The pressures at rest conditions and the active/passive pressures developed due to the forced displacement of the large concrete base slab during SLS and ULS conditions are presented in Fig. 4. And Fig. 5. In this paper it is only presented the pressures acting on the wall moving towards the soil. Two sensitivity studies are presented in these graphs, which assess the impact of the flexibility of the wall and the impact of the modified clay backfill stiffness.

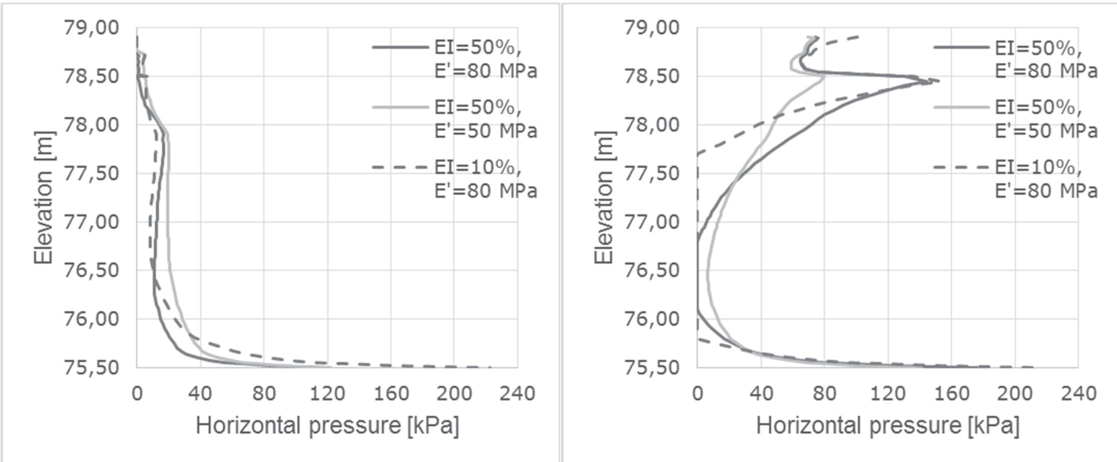

Fig. 4: SLS horizontal pressures acting on the gallery wall. Left: Pressure before forced displacement. Right: Total horizontal pressure after 10 mm forced horizontal displacement of the large concrete base slab.

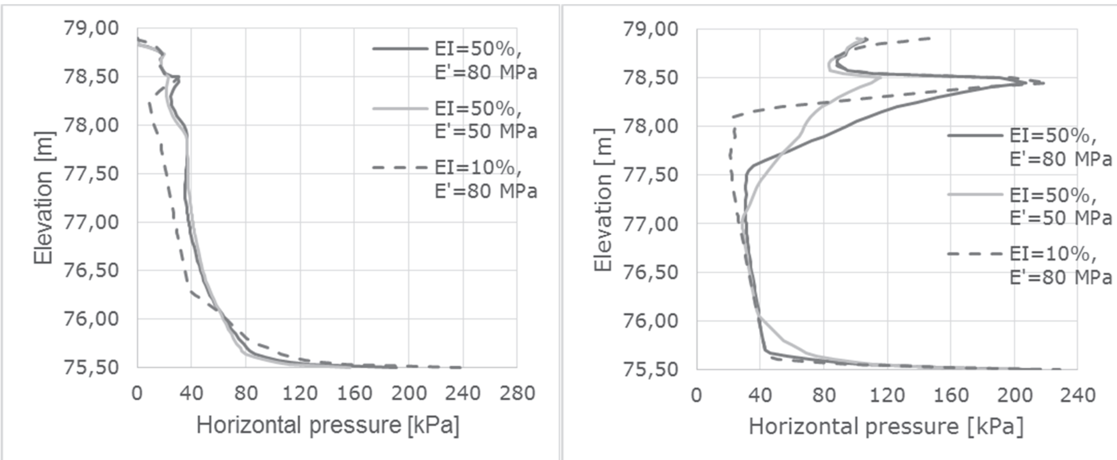

Fig. 5: ULS horizontal pressures acting on the gallery wall. Left: Pressures after raise of ground water level. Right: Pressures after 10 mm forced horizontal displacement of the large concrete base slab.

7 Conclusions

This paper presents the geotechnical analysis of the installation galleries under D01 and D03, which are located under a large concrete base slab. The installation galleries then become subject to forced horizontal movements due to temperature and shrinkage in the large concrete base slab. The typical cross-section is analysed for ULS and SLS cases.

When a numerical model is used for solving complex geotechnical problems, it is of outmost importance that the inputs to the model are correctly understood by the engineer. In this paper, a detailed discussion on the derivation of the most relevant geotechnical properties of the modified clay till backfill and of the natural clay till has been presented. Moreover the methodology, all the different assumptions and the reasons behind the selection of the soil material models need to be detailed to facilitate a quality review from internal and external geotechnical experts.

A sensitivity analysis was performed to assess the impact of the stiffness of the modified clay till backfill. This analysis shows that the stiffness of the modified clay till backfill has a high impact on the largest value of the horizontal pressures, which occurs at the level where the largest wall deflection in the clay backfill occurs. This implies that the stiffness of the modified clay till backfill plays an active role on the magnitude of the shear forces in the gallery wall.

A sensitivity analysis of the impact of the flexibility of the gallery wall on the pressures was performed. The analysis shows that the flexibility of the gallery wall influences the total area of the largest pressures on the wall, and therefore plays an active role on the magnitude of the bending moments in the gallery wall.

It is therefore concluded that the relative stiffness of the combined gallery wall and modified clay till backfill is dominating the magnitude and distribution of the total horizontal pressures on the wall and therefore controlling the magnitude of the shear forces and bending moments resulting in the gallery wall structure.

8 Literature

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