Hard Rock Caverns with low overburden in urban environment – a case study

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ABSTRACT: The design and the construction of underground caverns with low overburden in an urban environment is a sophisticated task. The project of an urban parking garage, which is built within a large span cavern construction is presented. Due to its low overburden, combined with the dominating behaviour of the jointed rock mass, there was a need of complex modelling techniques and considerations in design. The contribution gives an overview over the project, including the morphology, the ground investigation and classification and special risk scenarios. It also provides an insight in the design of the excavation process, the support measures and the accompanying monitoring process.

Keywords: Cavern, urban environment, low overburden, analysis and design, jointed rock

1 INTRODUCTION

The construction of a cavern structure with low overburden in an urban environment requires careful evaluation of the geological and geotechnical situation to minimize risks and to ensure the safety of nearby structures. In this article, we will present the geological and geotechnical conditions of the planned project of a parking garage in an urban area in Italy as a case study.

The newly built parking garage consists of a main cavern with nearly 170 m of length and a cross cavern with about 60 m length. It has cross section dimensions of about 20 m in width and 30 m in height. Beside the cavern, which is shown in Figure 1, there are several access tunnels and side constructions, which influence the mechanical behaviour of the rock mass around the cavern which need to be considered in the design process. The cavern has a low overburden of about 30-35m and lies within a formation of quartz-rich paragneiss. The mechanical behaviour is dominated by the properties of the jointed rock.

Based on the knowledge of the geology, the ground behaviour type (GVT) and the resulting system behaviour (SVT), following the recommendations of the ÖGG guidelines (Austrian Society for Geomechanics), are investigated. To consider the combination of the complex mechanical behaviour and the large complex geometry within the urban area, a combination of different 2D and

3D finite element calculations are performed. The calculation parameters are based on laboratory tests as well as in-situ observations. The assumptions of the mechanical rock behaviour are validated during the design process by a simultaneously built bypass tunnel (under construction during the design of the cavern) lying parallel to the cavern axis. The whole construction process is accompanied by a dense monitoring program which allows for a re-evaluation of the assumptions made during the design process. The start of the excavation is planned for 2023.

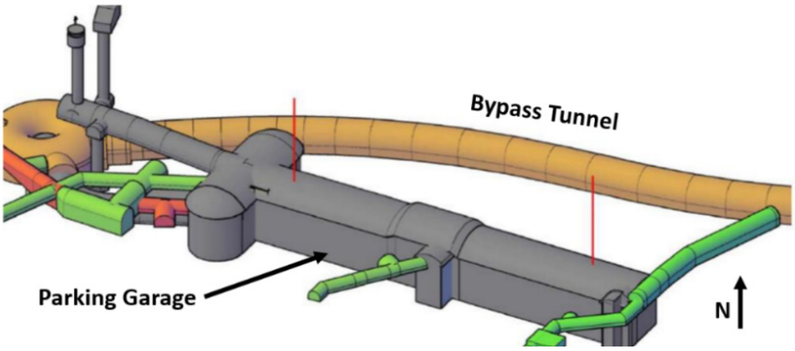

Figure 1. Overview of the geometry of the parking garage.

2 GEOLOGICAL AND GEOTECHNICAL SITUATION

The underground explorations consisted of surface mapping, two core drillings (S1 and S2) with borehole tests, geophysical investigations, and an extensive laboratory program. Based on this information, a better understanding of the subsoil conditions and the rock mechanical properties could be created. The findings were supplemented by the experiences from the construction of the bypass traffic tunnel, which was driven approximately 60m northeast, see Figure 1.

The project is in an area of quartz-rich paragneiss with alternating layers of mica schist. Basically, it is a stable rock mass, in which the rock behaviour is dominated by potential of discontinuity controlled block fall (GVT 2, according to ÖGG Guideline 2021). The cavern axis is oriented towards the northwest at approximately 300°. The main joint planes run parallel to the schistosity, steeply dipping to the northwest. In some places, few decimetres to meters thick fault zones were found, which appear as strongly fragmented areas. No continuous groundwater body was found nearby, but occasional water ingress through joints is possible.

Table 1. Mechanical properties of the rock mass.

Parameter	σ_c	σ_t	E_{rm}	ν	c	φ
	(kPa)	(kPa)	(MPa)	(-)	(kPa)	(°)
S1	1200	20	2000 – 4000	0,2	250	45
S2	3900	60	4000 - 6000	0,2	700	50

Particularly critical are regularly occurring, almost vertical joints with apparently low joint friction. The quality of the rock mass decreases towards the northwest. The investigation yields two parameter sets for the description of the rock mass, based on the two core drillings S1 and S2. Values of the uniaxial compressive strength of intact rock range from UCS=15-45 MPa with a GSI of about 55 and a stiffness $E_i = 15 - 45$ GPa. The resulting material parameters for the rock mass of the two areas S1 and S2 are obtained using the Hoek-Brown classification (Hoek, 2002) with the software RocLab and are given in Table 1. Results obtained from laboratory and field investigations of the joint properties are given in Table 3.

The planned construction project is located in an urban area, in a sloping terrain, with an overburden of approximately 30 - 35m. Due to the nearby structures, special attention must be paid not only to the risk of block failure, but also to the deformations at the ground surface. An overview of the geological situation is given in Figure 2.

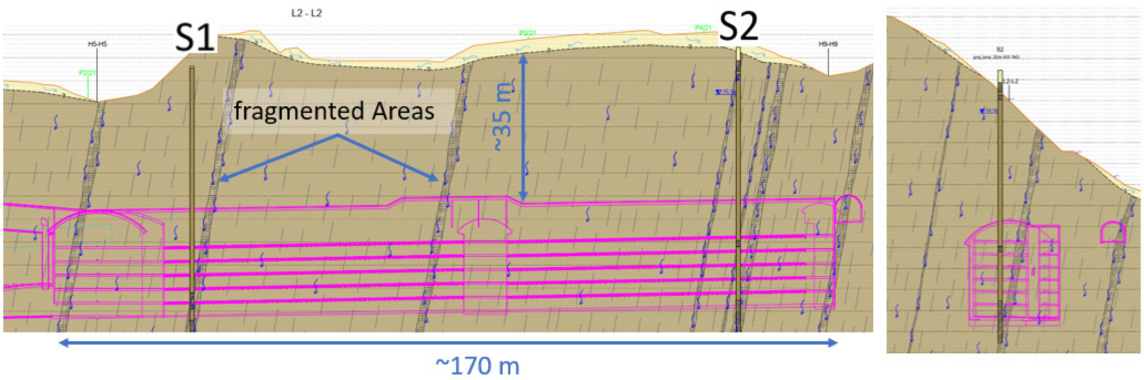

Figure 2. Cross section through the cavern with the drillings S1 and S2. Source: Geological Report, M. Jesacher.

Table 2. Joint orientations of the areas S1 and S2.

		K1	K2	K3	K4
S1	[°]	N350 / 60	N210 / 75	N010 / 75	N 280 / 90
S2	[°]	N310 / 70	N270 / 60	N000 / 60	N 280 / 90

Table 3. Joint set properties of the Areas S1 and S2. (Characteristic shear values in bold brackets).

	Friction	Cohesion	Spacing	Joint Length	Persistence
	(°)	(kPa)	(cm)	(m)	(%)
S1	28 – 30,5 **(30)**	0 – 120 **(0)**	60 – 200	3 – 10	50
S2	28 – 45 **(32)**	0 – 80 **(0)**	60 – 200	3 – 10	50

3 ANALYSIS AND DESIGN

Based on geological and rock mechanical findings, an excavation scheme for the cavern is developed according to different support classes. The excavation starts with a core tunnel in the crown followed by an enlargement of the entire crown section. Subsequently, the benches are excavated at three levels of about 5 – 7 m.

For immediate protection against block failure, frictional rock bolts are used, which are installed immediately after the excavation. The shotcrete lining during the excavation process consists of a first layer of fibre-reinforced shotcrete and an additional layer of 15cm steel reinforced shotcrete.
Frictional bolts cannot be used as permanent support measure. Therefore, an additional system anchoring consisting of SN-25-250 morter anchors with lengths up to 7,5 m are installed. As permanent lining, an additional, reinforced shotcrete layer of 10 cm is applied. An example for a permanent shotcrete lining, employed in caverns can be found at the Obervermuntwerk II (Diech, 2016).

Three support classes were developed, based on the expected system behaviour. The decision of a class depends on the actual rock mass, described by the RMR rating from Bieniawski (1989). The round length varies between 1,0 m and 3,0 m and the anchor pattern of temporary bolts between 1,0 x 1,5m and 1,5 x 1,5 m.

The design of the support measures is carried out in accordance with the Italian standard NTC 2018. Due to the complex geometry and the different relevant system behaviours (block failure, surface deformations), different calculation methods are used for the design of the excavation and the support measures. The first dimensioning of the shotcrete lining and anchors is carried out using block analysis with the software Unwedge 4.0, based on the discontinuity-dominated behaviour. A combined consideration of the block failure and the deformations in the rock mass is carried out using the 2D Finite-Element program RS2 with explicit consideration of the jointed networks.

The time-dependent non-linear behaviour of the shotcrete line is considered using two different parameter Sets for *young* and *old* shotcrete (HME, hypothetical modulus of elasticity). This allows for a more realistic approximation of the deformation behaviour, as well as the strength evolution within the shotcrete layer. Immediately after the current excavation step, the parameters for the young shotcrete are employed, and they are increased to properties of old shotcrete for further excavation steps.

3.1 Block analysis

The design of the rock bolt support is obtained performing block analysis with Unwedge 4.0. Within the calculation, the different excavation phases are considered, as well as time dependent strength of the shotcrete. For the block analysis, the behaviour of the two obtained rock mass types S1 and S2, according to Table 2 are used. The calculation was performed within the crossections of the main cavern and the cross cavern and results in the necessary distribution and length of the primary bolt pattern.

3.2 2D Finite-Element calculation

Because of the low overburden of the cavern, and the urban situation, a focus lies on the surface deformation. Additional 2D Finite-Element calculations are performed, as a combined approach of joint dominated behaviour and the consideration of the rock mass. Therefore the so-called 'Jointed Networks' of the software RS2 from Rocscience are employed. Within this approach, the discontinuities within the rock mass are approximated using explicitly defined joints and the intact rock mass is considered with an continuum mechanical approach.

Within these calculations, the bolts as well as the shotcrete lining are considered. The shotcrete lining is applied according to the planned excavation process using the stiffness and strength parameters of the *young* and the *old* shotcrete. For the consideration of the 3D excavation behaviour within a 2D calculation, the stress redistribution is controlled by pre-relaxation factors.

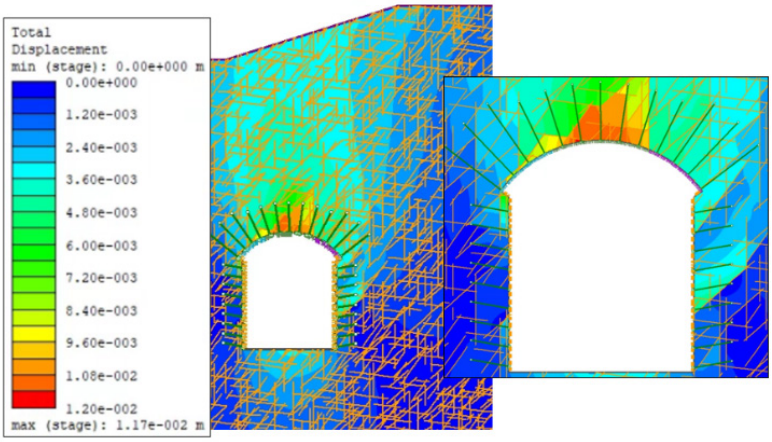

Figure 3. Total deformation within the 2D-finite element calculation, BQ2, final step.

Based on the results of the calculation, only small surface settlements of about 1 – 3 mm are expected. The calculated crown settlement lies in a range up to about 1 cm. The deformation field in Figure 3 shows the strong influence of the discontinuities on the deformation behaviour.

3.3 3D-Finite-Element calculation

The whole construction, consisting of the main cavern and the cross cavern as well as several connecting tunnels, has a complex geometry. To consider the geometrical effects the whole construction is investigated in additional 3D-Finite-Element calculations. A linear elastic-ideal plastic material using a Mohr Coulomb failure criterion is used for the rock mass. To consider the results of the discontinuity approach, the maximum deformation of the 3D model was calibrated on the results of the 2D models. The shotcrete lining is modelled with linear elastic plate elements with a different stiffness for young and old shotcrete. The rock bolts are not considered within these continuum calculations. Because of the size of the model, two partial models, with each an approximately size of 120 x 150 m are used, see Figure 4a. The resulting models consisted of about 110.000 to 150.000 10-noded elements. We modelled the excavation process of the cross-section areas with the actual advancement length of 1,5 m. In standard cross sections, bigger sections are excavated *Whished in Place* (WIP), see Figure 4b.

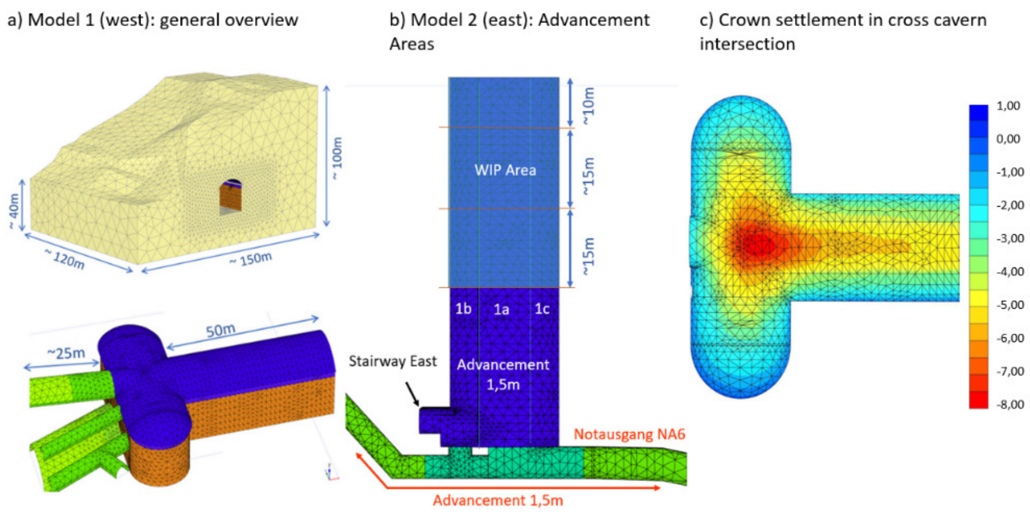

Figure 4. 3D FE Model: a) 3D overview of model 1 (west). b) plan view advancement areas in the model.

The results of the 3D-Finite-Element calculation were used for the design of the shotcrete reinforcement using M-N interaction diagrams. For the analysis, a full bond between the first and the second shotcrete layer is considered, as they are modelled as one layer. As the calculation was performed employing characteristic ground parameters, the necessary partial factors were directly applied on the actions on the lining and on its resistance. Using the 3D calculations, critical sections could be identified and reinforced, while the support on the standard cross sections was optimized. Especially within the cross section of the caverns, an increase of the support measures was necessary.

4 MONITORING PROGRAMM

The geological investigations and the calculation results show the complex mechanical behaviour within the rock mass. The highly discontinuous behaviour carries significant uncertainties regarding the actual joint properties, which cannot be fully covered by the numerical and analytical calculations. To be able to detect irregularities in the rock mass behaviour early on and to avoid damages on structures on the ground surface as well as hazardous situations during the construction, an intensive monitoring program is required.

For the underground monitoring, geodetical targets, extensometers and instrumented anchors are installed in regular monitoring cross sections. Each 40 m of excavation, the main monitoring cross sections (H-MQ) are installed within the caverns opening. In between, a “reduced monitoring program”, only with geodetical targets, is used.

This measurement program allows for an interpretation of the actual system behaviour and thus a verification of the design assumptions. In addition, on the ground surface, in the cross sections of the H-MQ, geodetical targets are installed to allow for the monitoring of the ground surface deformations, see Figure 5. In case of strong deviations of the monitored system behaviour to the design assumptions, the design needs to be updated. The verification of the design assumptions and the monitoring of the system behaviour in sense of an observational method ensure a safe construction of the cavern.

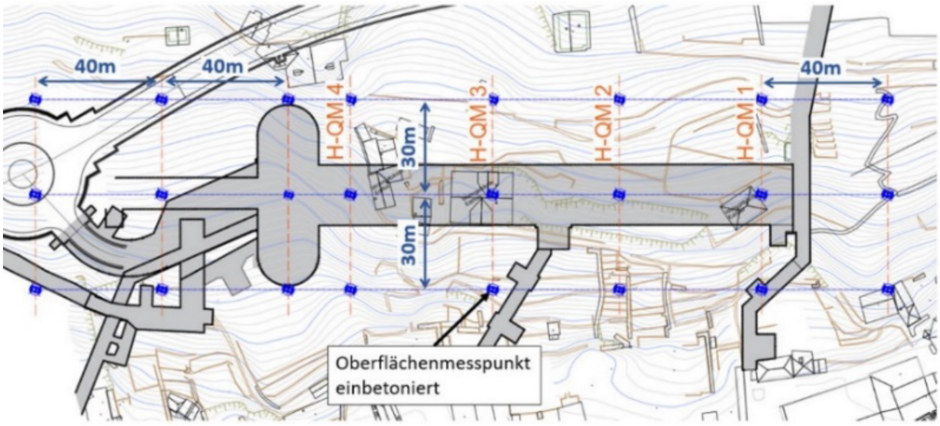

Figure 5. Overview of the monitoring concept with the main monitoring cross sections (H-MQ).

5 CONCLUSION

The current contribution shows the complexity of the design of a large cavern construction with low overburden within an urban area. Because of the discontinuity dominated behaviour, combined with the high risk of surface deformation, a complex calculation program was performed.

In conclusion, a thorough evaluation of the geological and geotechnical situation is essential for the successful realisation of a cavern project of this type. The findings from the laboratory program, geophysical investigations, and underground explorations provide important information about the subsoil conditions, rock mechanical properties, and the behaviour of the rock mass. The excavation scheme and the support measures are based on the geological and rock mechanical findings, and are designed to minimize the risks and ensure the safety of nearby structures. Despite the extensive laboratory program and design process, there is always some uncertainty involved in such a tunnelling project. Therefore, monitoring is a critical aspect of the construction process, as it enables early detection of any potential issues and allows for corrective measures to be taken before any significant damage occurs.

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