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# The Shazar caverns – Design challenges and construction experience

The Shazar caverns (width 19 m, height of 29 m, length 270 m) are part of the first phase of a larger project called the "Jerusalem Gateway". They will accommodate a road in the upper level and five parking floors in the lower levels. The geology in the project area is characterized by dolomite and dolomitic limestone, overtopped by decayed rock including significant clay masses and artificial filling. Overall, the rock mass is weathered due to strong karst activity. The peculiarities of the project are the small overburden (7 to 10 m) under poor ground conditions, the close vicinity between the caverns and existing/future buildings (2 to 5 m), the vicinity between the two caverns (3 to 5 m), the intense earthquake activity in the area and the presence of large karstic cavities. The resulting challenges require unique engineering solutions. This paper gives an overview on the project, it presents the adopted design approach and the elaborated design solutions and, finally, it shows the construction experience.

**Keywords** mega caverns; caverns–building interaction; urban project

**Die Shazar Kavernen – Herausforderungen bei der Planung und Erfahrungen im Bau**
Die Shazar Kavernen (Breite 19 m, Höhe 29 m, Länge 270 m) sind Teil der ersten Phase des Projekts "Jerusalem Gateway". In der Kalotte jeder Kaverne wird im Endzustand eine dreispurige Straße verlaufen, während im unteren Bereich fünf Parkebene vorgesehen sind. Die Geologie im Projektgebiet ist charakterisiert durch Dolomit und dolomitischem Kalkstein, überlagert mit verwittertem Felsgestein, einschließlich Tonen und künstlicher Verfüllung. Insgesamt ist der Fels aufgrund starker Karstaktivität verwittert. Die Besonderheiten des Projekts sind die geringe Überdeckung (7 bis 10 m) unter schlechten geologischen Bedingungen, der geringe Abstand zwischen den Kavernen und bestehenden/zukünftigen Gebäuden (2 bis 5 m), der geringe Abstand zwischen den beiden Kavernen (3 bis 5 m), die intensive Erdbebenaktivität in diesem Gebiet und die Nähe großer Karsthohlräume. Die daraus resultierenden Herausforderungen erfordern einzigartige technische Lösungen. Dieser Beitrag gibt einen Überblick über das Projekt, stellt den gewählten Entwurfsprozess und die ausgearbeiteten Lösungen vor und zeigt schließlich die gesammelten Erfahrungen beim Bau auf.

**Schlüsselworte** Großkavernen; Interaktion zwischen Kaverne und Gebäude; städtisches Projekt



## 1 Introduction

The Shazar project consists of two caverns excavated in the urban area of Jerusalem (Figure 1a) and are part of a larger project called the "Jerusalem Gateway" (Figure 2a). The Owner of the project is the Moriah Jerusalem Development Corporation, responsible for the development of civil infrastructures in the Jerusalem area.

The caverns have a width of 19 m, a height of 29 m and a length of 270 m. They run underneath the Shazar Road and will accommodate a road in the upper part and 1,300 parking places distributed over five floors in the lower part. The traffic between the caverns will be ensured by six connection tunnels (Figure 1b). At the end of all construction works, the caverns will be connected to the major nearby structures – as the Convention Centre of Jerusalem and the Hauma railway station (Figure 2b) – as well as to other nearby structures by means of twelve pedestrian/vehicle exit shafts. The caverns are excavated by means of drill and blast at very small depth (3 to12 m) trough weak sedimentary rocks. The big size of the caverns, the small distance between them (only 4 m), the small overburden, the difficult ground conditions, the interferences with the nearby structures, and the intense earthquake activity of the area, make the Shazar Project technically very challenging.

The design of the caverns has been carried out based on the quantitative assessment of the main geotechnical hazards (as e.g. inadmissible surface settlements and collapse of the rock pillar). Several computational approaches have been applied; from 2D dynamic FE analyses of seismic events to 3D FE static analyses (Figure 3).

## 2 Geological conditions

The geology of the project area mainly consists of dolomite and dolomitic limestone of the Bina–Weradim formation. Due to a strong karst activity, the upper portion of the rock mass is highly weathered; the weathering of the rock mass decreases with the depth (see geological model in Figure 4a).

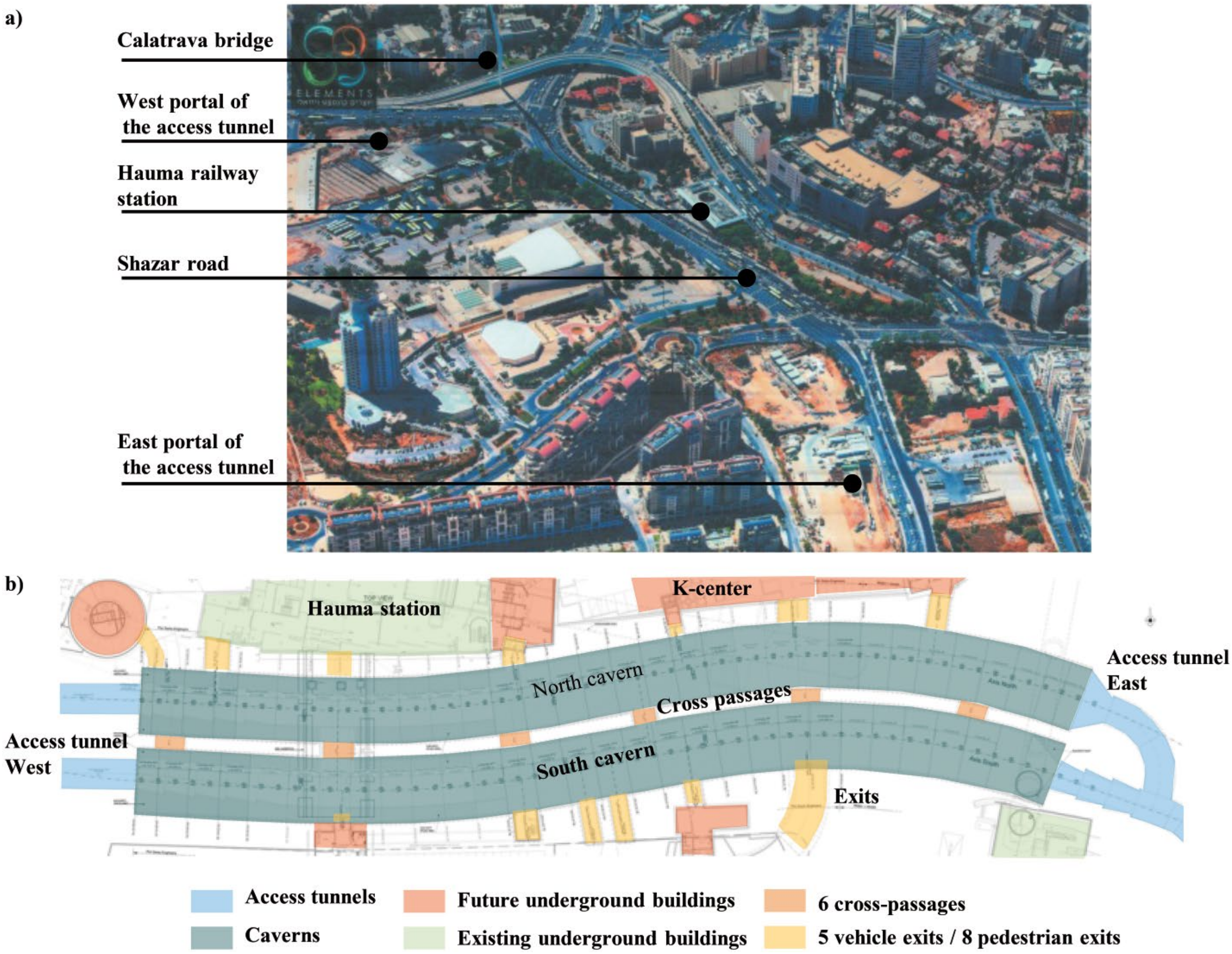


**Fig. 1** a) Overview over Jerusalem; b) plan view [1]
a) Überblick von Jerusalem; b) Grundriss [1]

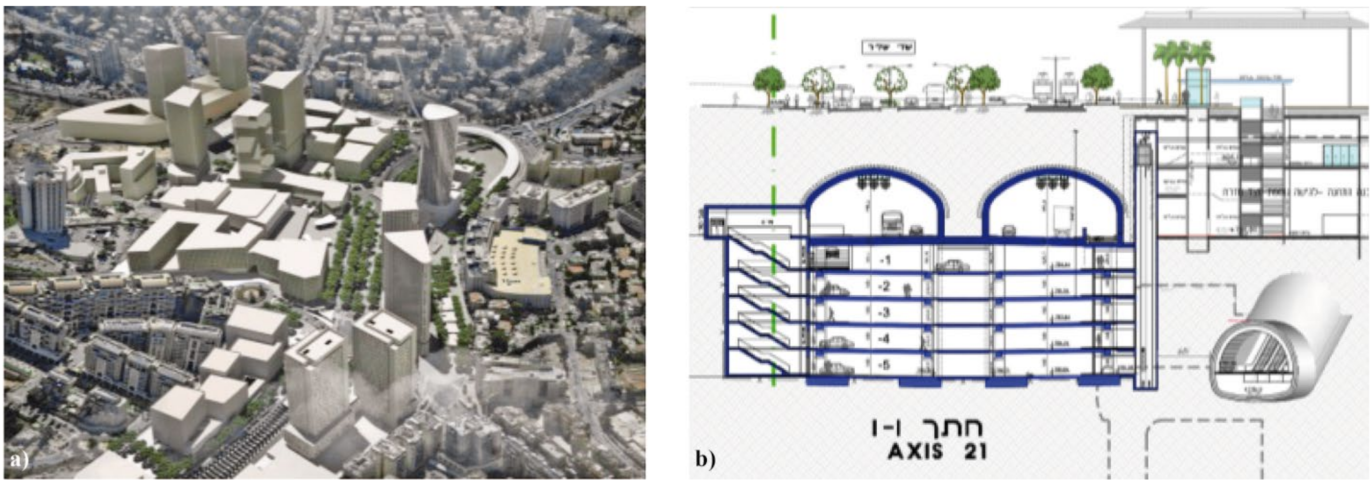


**Fig. 2** a) Jerusalem Gateway; b) Caverns in the area of the Hauma Station [1]
a) Jerusalem Gateway; b) Kavernen im Bereich Hauma Station [1]

A layer of artificial filling was located just below the ground surface (from 0 to 3 m depth). The top rock mass layer (from 3 to 7 m depth) was so weathered that it was assumed to behave as soft ground. Below a depth of 7 m, both intact rock and poor rock (i.e. jointed, fractured, crushed) have been encountered. Sound dolomitic limestone appeared at a depth of about 30 to 40 m. Major karst cavities (empty or filled with clay) have been encountered during excavation. Those features are typical for this kind of rock formation and were expected according to the construction experience in the Jerusalem area.

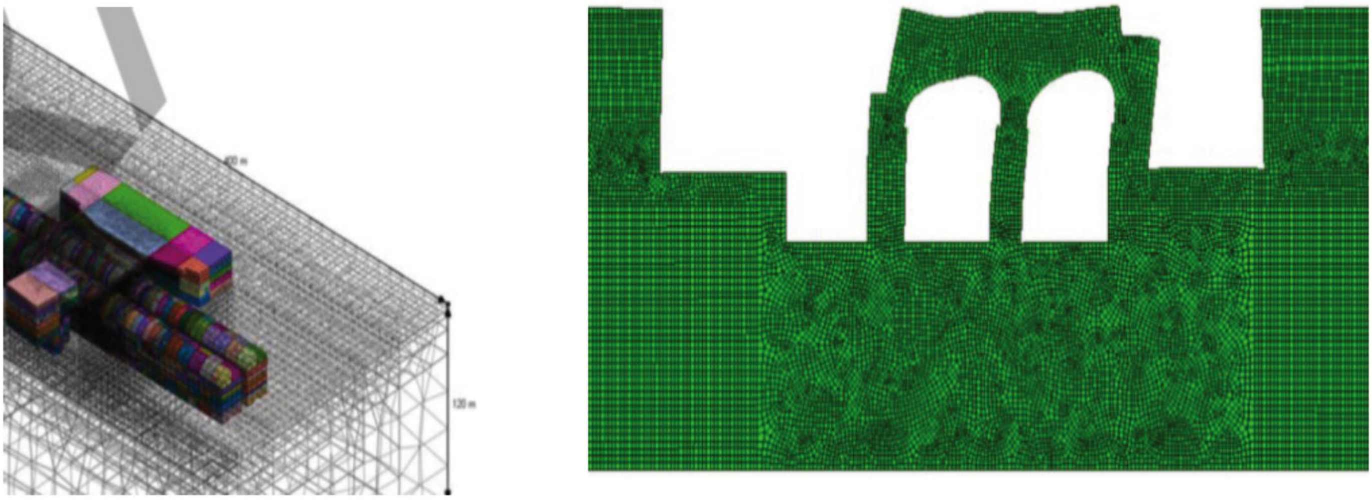


**Fig. 3** Example of computational models [1]
Beispiel von Berechnungsmodelle [1]

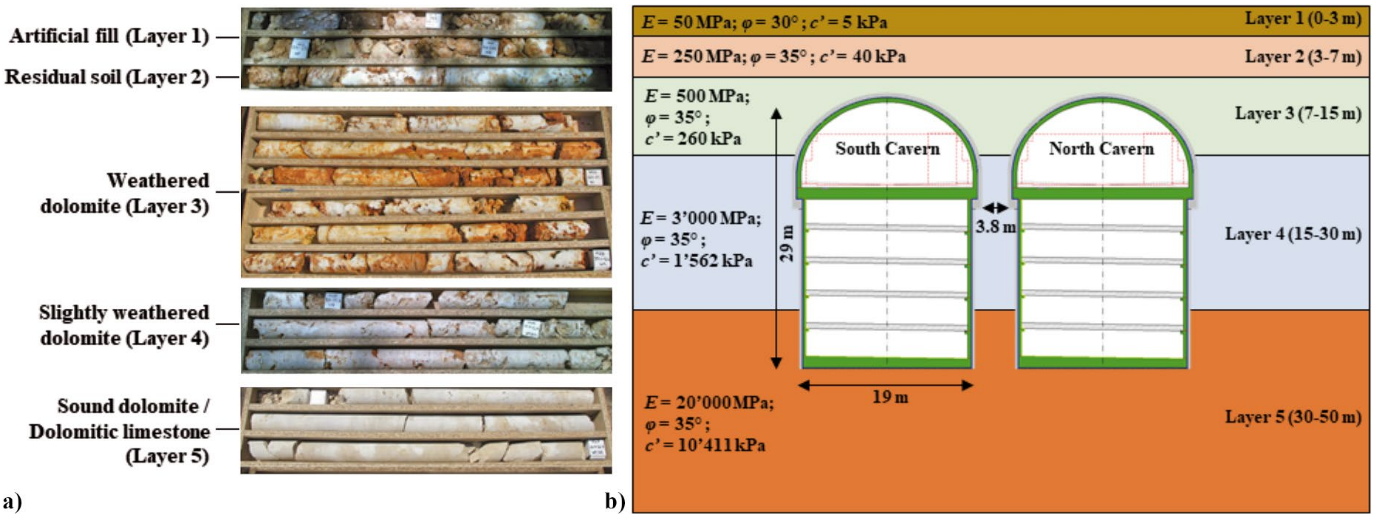


**Fig. 4** a) Representative drill cores; b) geotechnical model and dimensions [1]
a) Repräsentative Bohrkerne; b) geotechnisches Modell und Abmessungen [1]

## 3 Main hazards and mitigation measures

Figure 5 shows the main geotechnical hazards identified for the project. Due to the low overburden, the poor ground conditions and the large cavern span, large settlements – and in the worst case crater formation at the ground surface – have been identified as the major geotechnical hazards to be expected during the excavation of the top heading. In order to mitigate this risk, a pre-support system consisting of a pipe umbrella in combination with full face excavation was applied over the majority of the caverns length. Partial excavation of the top heading – central drift enlarged with two side drifts – was indeed applied over the most critical areas (Figure 6a). The primary support of the top heading consisted in a combination of steel ribs and a 45 cm thick shotcrete lining (Figure 6b).

The instability of the rock mass underneath the top heading foundation was another significant hazard of the project. In order to mitigate this risk a longitudinal foundation beam has been installed at the bottom of the top heading (Figure 6c and Figure 7a). The beam was reinforced with a longitudinal coupled reinforcement and had a cross section of 1 m$^2$. In order to avoid the instability of the rock mass underneath the foundation and reduce the risk of vertical settlements of the top heading, pre–stressed bolts have been installed just underneath the top heading foundation (see Figure 6c).

Due to the narrow distance between the caverns as well as between the caverns and other underground structure (minimum distance of only 4.64 m in the area of the new Hauma Station) the instability of the rock pillars represented the major hazard during excavation of the benching. In order to mitigate this risk, the maximum height of the excavation levels of the benching was bounded to 3 m (se Figure 6c). Four bolt layouts have been designed in order to cope with all possible geological scenarios. The layouts included cross–bolting between the caverns by

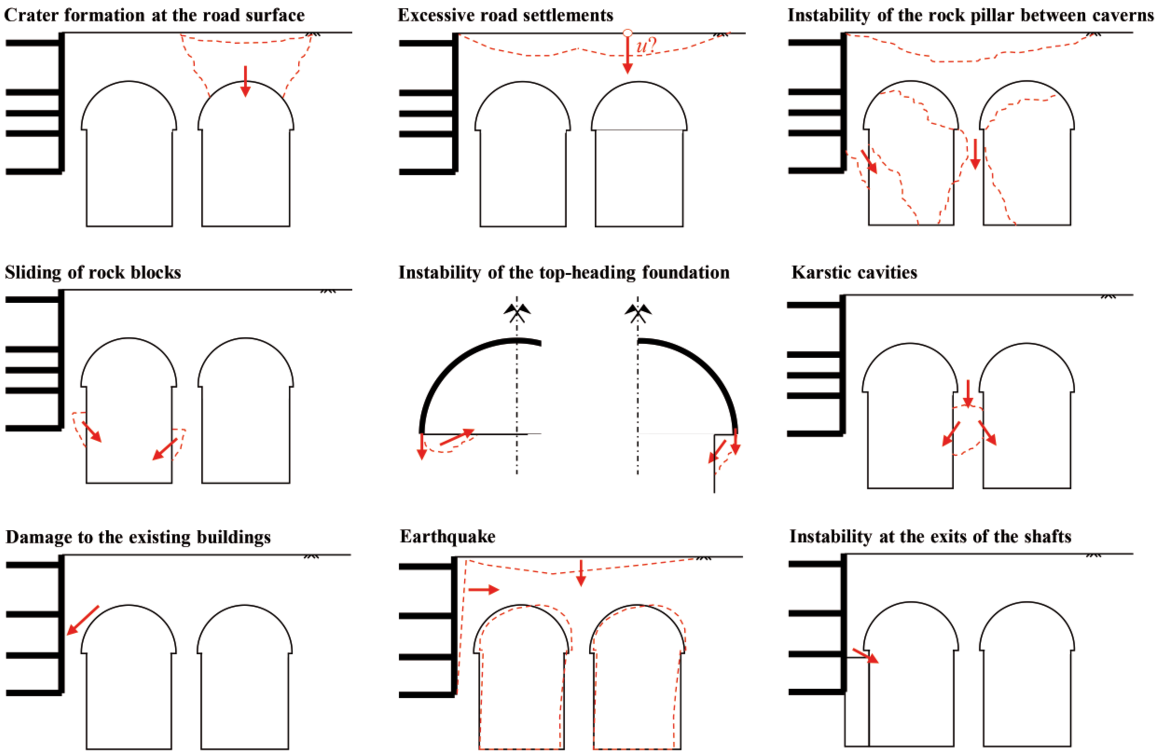


**Fig. 5.** Main hazards [1]
Gefährdungsbilder [1]

means of Gewi bolts. The primary support of the benching walls consisted of a 30 cm thick shotcrete lining reinforced with two layers of steel meshes. Additional strengthening was applied in the areas of the connection passages and of the exit shafts (see Figure 6b).

All geotechnical hazards are amplified in case of an earthquake event. The systematic study of the impact of earthquake activities during both the construction and operation phase of the caverns has been investigated by means of by pseudo–static and dynamic FE analyses. The result of the seismic design impacted not only the reinforcement of the caverns and of the pillar but also the excavation sequences and the supporting systems to be adopted during the excavation of the nearby shafts of the "Jerusalem Gateway" project.

The caverns behaviour during construction has been monitored by installing optical prism combined with total stations, load cells and extensometers as well as by monitoring the force in the pre–stressed bolts. Moreover, in order to timely identify the presence of karst cavities (in the pillar and beneath the excavation levels), systematic probe drilling has been carried out during excavation. In case of detected voids, cementitious grouting was applied as mitigation measure. The longitudinal foundation beam of the top–heading was designed in order to cope with the worst–case scenario of a badly filled karst cavity extending underneath the top heading foundation.

The final lining was designed neglecting the favourable effect of primary lining and support (Figure 7). In order to face all hazards and load combinations, the final lining consisted of a 45 cm thick cast in place steel reinforced concrete arch in the top heading, a 90 cm thick concrete slab at the bottom of the top heading, a 30 cm cast concrete benching walls and pre–cast parking slabs (designed in order to support the ground pressure under both static and dynamic conditions). The final lining is executed bottom–up after the end of the cavern's excavation.

## 4 The Hauma Railway Station

One of the most critical sections of the projects was represented by the area of the new Hauma Railway Station where, over a length of 80 m, the northern cavern runs at close proximity to the station (minimum distance of 4.64 m). Previous analyses from preliminary design stages, carried out by other Designers, have shown that the excavation may create unacceptable stresses in and around the narrow rock pillar between the cavern and the station. These stress levels, combined with the fact that the station walls are unsupported over a height of 8.5 m (vertical span), was judged unacceptable for the serviceability and ultimate state of the station, thus questioning the technical feasibility of the entire project.

In order to demonstrate the technical feasibility of the project, two solutions were developed and studied with sophisticated structural behaviours models:

- Increase of the resistance of the Hauma Station by means of carbon laminates or steel plates (application from inside the station),

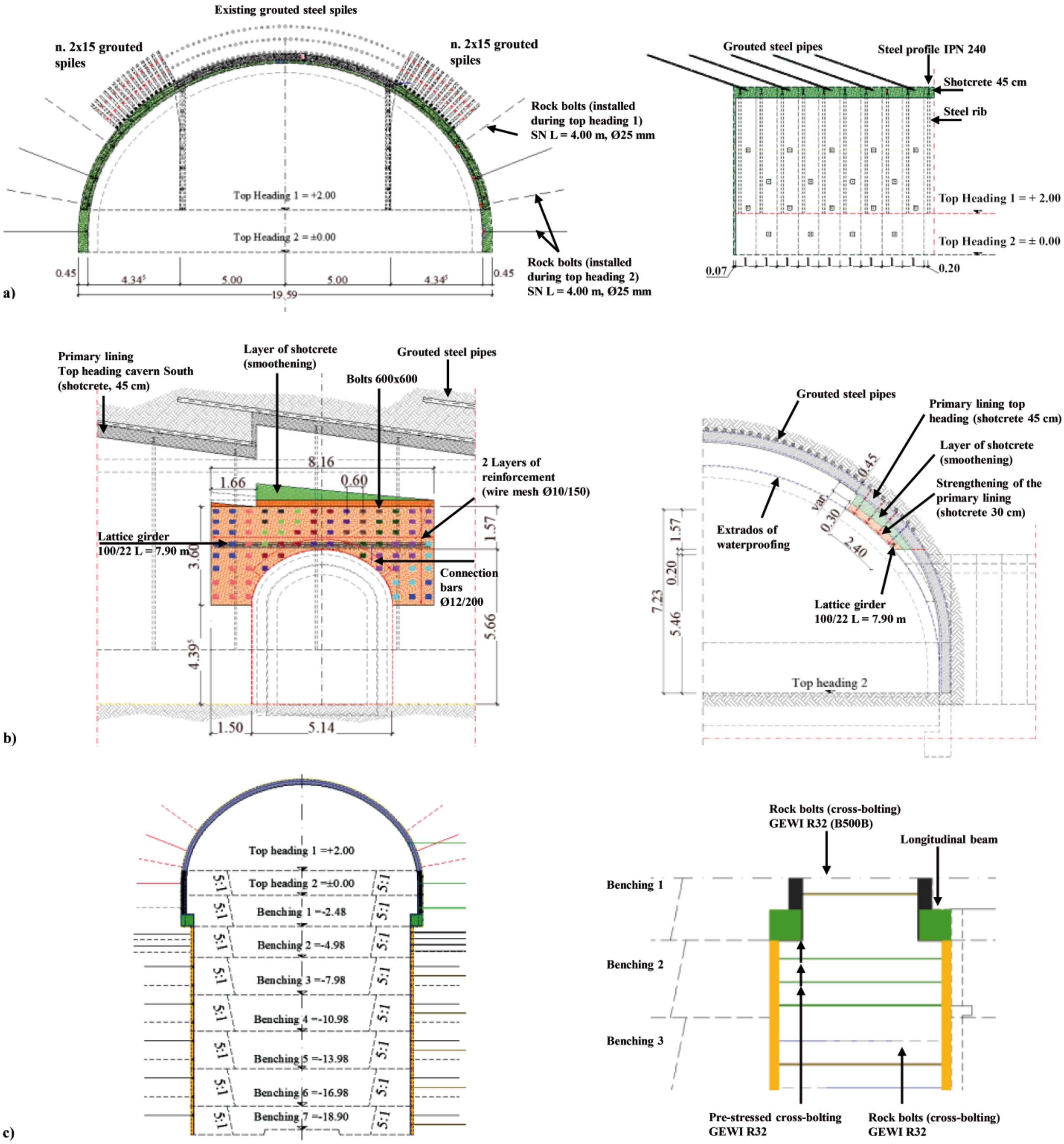


**Fig. 6** a) Partial excavation of the top heading; b) strengthening in the area of the exits; c) benching levels and cross bolting [1]
a) Teilausbruch der Kalotte; b) Versteifung der Spritzbetonschicht bei den Ausgängen; c) Strossenabbau und Verankerung [1]

- Reduction of the additional lateral load caused by the excavation of the caverns by decreasing the stiffness of the narrow rock pillar between the cavern and the station structure (intervention from outside the station) by installing a compressible layer from a side drift or by disconnecting the rock mass from the Hauma's wall through the construction of a compressible pile wall from the surface or also from a side drift (see Figure 8).

The solution adopted in the final design consisted of the intervention inside the station with a reinforcement of the Hauma's wall by means of steel plates. This solution was combined with a partial excavation of the top heading (central drift in a first phase and enlargement in a second phase) and a risk management plan based upon the intensive monitoring of the wall behaviour during excavation (by means of tiltmeters, extensometers and high–precision laser distance meters).

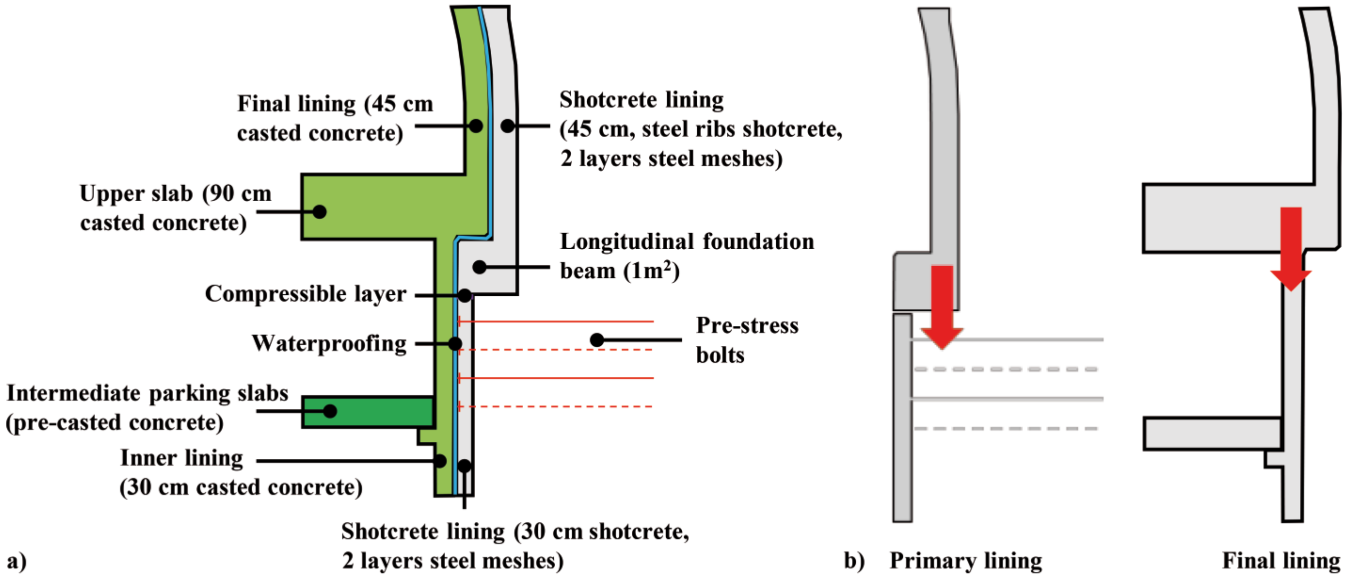


**Fig. 7** a) Primary and final support of the caverns; b) load transfer in the area of the top heading foundation [1]
a) Ausbruchssicherung und Innenausbau; b) Krafteinleitung der vertikalen Lasten [1]

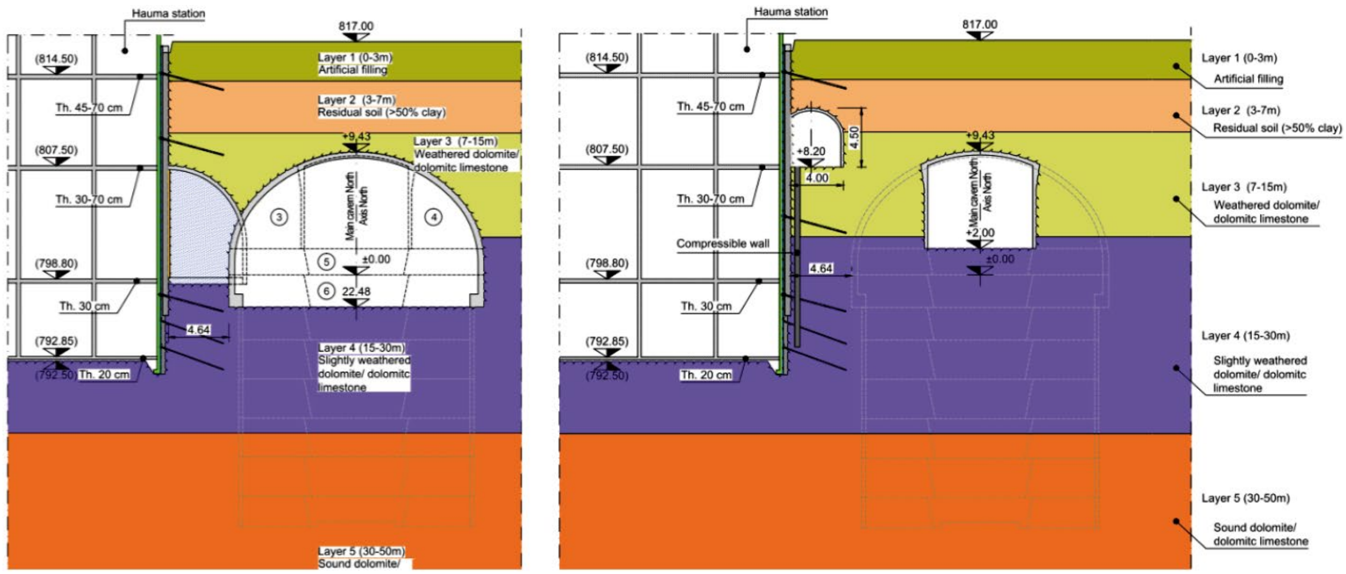


**Fig. 8** Construction alternatives in order to reduce the lateral load on the Hauma wall
Konstruktive Möglichkeiten/Alternativen zur Verringerung der seitlichen Belastung auf die Hauma-Wand

## 5 Construction experience

The excavation of the top heading started in April 2017 and was completed in August 2018. The excavation of the benching started in February 2018 and was completed in July 2019. During the excavation works several major karstic cavities have been encountered. Those cavities required the interruption of the excavation works and the execution of grouting operations and, successively, control drilling (required in order to confirm the success of the grouting operations). The deformations measured in Hauma Station remained within the expected ranges and no cracks appeared in the station walls. The successful construction experience showed that the design solutions were suitable for the encountered geological conditions (Figure 9).

The construction of the inner lining started in August 2019. The caverns are expected to be operative at the end of 2022.

## 6 Conclusions

The unicity of the Shazar Parking is due to the large size of the caverns, the small distance between them and their strong interaction with existing and future building/infrastructures.

Due to relevance of the project and its feasibility concerns, the entire project was set from the beginning under extreme pressure. The key factors leading to the successful completion of the excavation works were: the ability


**Fig. 9** Impressions of the construction phase [1]
Bilder aus der Bauphase [1]

of thinking different of the engineering team – by elaborating a completely new structural concept within an extremely short time – , the experience of the supreme site supervision (carried out from the Designer) allowing to ensure the correct implementation of the design solutions; the excellent and target focused collaboration between Designer, Project manager, Owner and Contractor.

## References

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