The Blue Line Jerusalem LRT Underground Section – Public Transport in a challenging Project environment

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ABSTRACT: The 2 km long Blue Line Underground Section is part of a 20 km long LRT line currently being developed as part of the Jerusalem Mass Transit Master Plan. The Underground Section of the Blue Line is characterized by narrow streets, limited right of way, steep gradients, small alignment radii turns and crossings with other LRT lines. The geological conditions feature different formations of limestone and dolomite. Karst is a known frequent phenomenon in the Jerusalem region which must be considered in the design and construction process. This publication describes the key criteria to be addressed in the design, such as the overall design approach for the large span station tunnels, geological risks especially in relation to karst, the impact on existing buildings and the insertion of the underground stations in a highly sensitive urban environment with very limited available space.

Keywords: Tunneling, Underground, Karst, NATM, Monitoring.

1 PROJECT DESCRIPTION

The 20 km long Blue Line LRT is being developed by the Jerusalem Transportation Master Plan Team (JTMT) as part of the Jerusalem Mass Transit Master Plan, connecting the neighbourhoods Ramot in the north to Malha and Gilo in the south of Jerusalem. The section of the Blue Line in the city centre runs along principal urban streets featuring a mix of commercial, business, residential, public and religious institutional uses with very intensive pedestrian traffic along the entire alignment. In addition, this section of the Blue Line is characterized by narrow streets, limited right of way, high gradients, small radii turns, and crossings with the planned Green Line LRT and the existing Red Line LRT. To avoid these constraints, it was determined to adopt an underground alignment for the city centre section.

The Blue Line Underground Section is approximately 2 km long and stretches between Giv'at Moshe Street in the north and Jaffa Street in the south at the crossing with the existing Red Line LRT. The project also comprises a 350 m long branch tunnel connecting the Blue Line to the Green Line. The main underground structures of the Blue Line Underground Section include double-track running tunnels, three mined underground stations (Bar Ilan, Yehezkel and Strauss) including ventilation and emergency escape shafts, a large-span bifurcation cavern at the junction with the branch tunnel and three portal structures (north, south, branch).

The project fire safety concept provides for single tube double track running tunnels without separation wall and an additional emergency escape shaft between Bar Ilan and Yehezkel stations. Accordingly, the stations feature 5 m wide and 70 m long side platforms.

The design of the Blue Line Underground Section was carried out applying BIM and using state of the art software for BIM collaboration within an international multidisciplinary design team.

2 GEOLOGY

The geology in the project area is characterized by hard limestone and dolomite rocks. Layers of chalk may be encountered within limestone rock.

Karstic cavities are expected in both limestone and dolomite rock with sizes ranging from porous to several decimeters, but the existence of even larger cavities cannot be ruled out. Karstic cavities may be filled by clay or weathered dolomite (sand).

The rocks are overlain by quaternary and anthropogenic deposits (cohesive and non-cohesive soil, artificial fill) varying in thickness between 0.3 m and 5.8 m and are expected to be encountered mainly in the northern part.

The ground water table in the project area is several hundreds of meters below the surface and hence does not affect the construction of the underground structures of the project. Water inflow from perched aquifers or seepage water from the surface may occur.

3 MINED UNDERGROUND STATIONS

The three underground stations have a similar layout, comprising main platform tunnels with lengths between 140 m and 160 m depending on the station. The platform tunnels have a span of 22.5 m, 15.1 m height and a cross sectional area of about 294 m^2. The overburden of these caverns varies from around 9.0 to 23.0 m.

The main platform tunnels are connected to the surface by access shafts and adits as well as ventilation and emergency escape shafts. The number and alignment of accesses depends on the local surface conditions at each station. The adit tunnels vary in size based on passenger flow requirements and have a cross section of up to 45 m^2.

Bar Ilan station serves as interchange between the Green and Blue Line and features a 30 x 30 m large central shaft with four levels allowing for passenger transfer, ticketing and security facilities and accommodating technical rooms. Figure 1 shows the layout of Bar Ilan Station.

The excavation of the main caverns is sub-divided in two top headings and 3 bench levels. The initial support consists of a 25 cm thick shotcrete lining and rock bolts. The final inner lining is provided by a cast in-situ reinforced concrete lining of 60 cm thickness, which inter alia is a requirement for stations to be used as shelters.

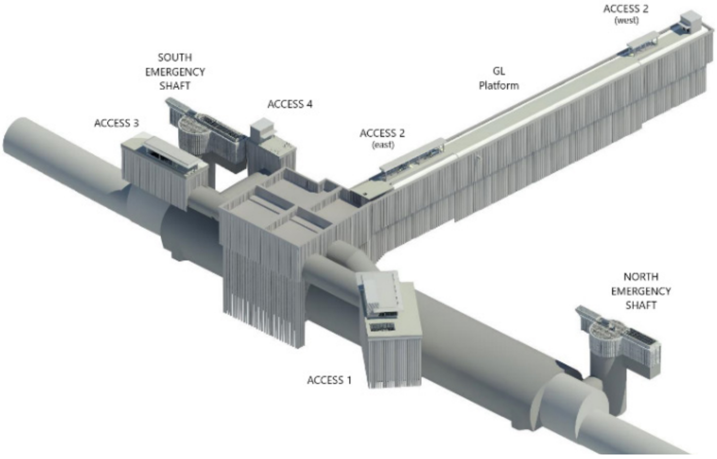

Figure 1. Layout of Bar Ilan Station (Cavern, "Big Box" and Accesses).

3.1 *Design approach*

The design of the mined station tunnels is based on the principles of the New Austrian Tunneling Method (NATM). The design of the underground station caverns requires an approach that addresses the specific criteria and limitations of tunnelling works in a highly sensitive urban environment.

One key factor is the need to minimize the impact of the underground works on the built environment which includes a considerable number of buildings in poor condition. This requires limiting and controlling settlements and vibration of buildings including a comprehensive instrumentation and monitoring scheme to be installed at underground level and on affected buildings within the zone of influence.

Tunnel excavation is performed by road header to minimize vibration and related damage to the existing structures. Drill and blast excavation is restricted to the bench excavation or exceptional cases only, in combination with close vibration monitoring of the affected buildings.

Additionally, the limited available space on the surface and the need to work during restricted night hours further complicate the design and construction process. The station design must also consider factors such as accessibility, ventilation, their usage as shelter, safety, and aesthetic considerations.

For the geotechnical and structural design of the station tunnels, both two-dimensional and three-dimensional numerical modelling was employed. Two-dimensional models were adopted for "regular" geometric conditions along the station length, whereas three-dimensional models were used to assess specific effects of intersections or multiple tunnel arrangements at close distance. The numerical analyses were performed in PLAXIS 2D and 3D respectively, based on the Mohr-Coulomb constitutive model and simulating all relevant excavation stages.

Figure 2 shows two models in Plaxis 3D performed for the Bar Ilan Station, where the influence of the "Big Box" and the various accesses and adits on the station cavern was assessed.

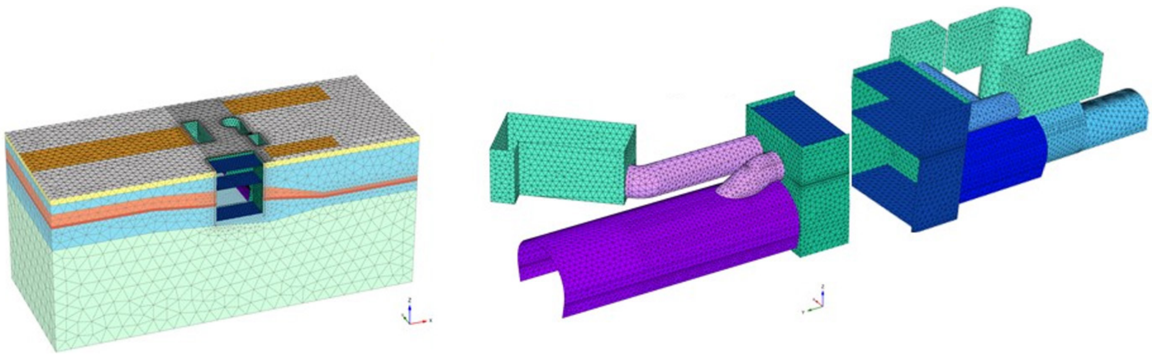

Figure 2. Plaxis 3D Models for Bar Ilan Station.

3.2 Design in Karst

The design of the station caverns in geological conditions with potential karst phenomena requires a careful approach. One of the main criteria for the design is the mandatory requirement of a detailed karst structure investigation during the excavation. The design approach also includes the definition of mitigation measures with the aim to minimize and control the risk imposed by karstic cavities on the tunnel structures and their environs.

In designing those measures, specific two-dimensional numerical models for the station cross sections were performed. Four different scenarios of potential karstic cavities in terms of their location relative to the station cavern were investigated with cavity sizes between 30 m² and 60 m². The investigated scenarios cover the existence of karstic cavities in the crown, in the side wall and underneath the final invert section as shown in Figure 3.

The objective of the analyses was to establish a safe minimum distance between the station cavern excavation line and the karstic cavity. Based on the results, the requirements for an underground exploratory program were defined along with mitigation measures for both construction and long-term stages.

The mitigation measures consist mainly in mass concrete backfilling in combination with rock bolting, while for the long-term stability, a related inner lining design is provided.

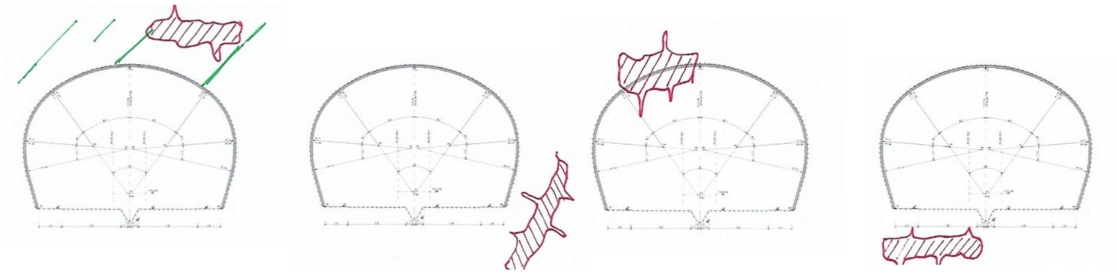

Figure 3. Investigated scenarios for karstic cavities around the station cavern.

4 PROJECT ENVIRONMENT AND LIMITATIONS

The Blue Line Underground Section is located in the district of Mea Shearim, a densely populated religious neighborhood in the historic center of Jerusalem. The main challenges posed by the project environment are extremely limited space, acceptance of the project by the local community and the built environment with numerous buildings in poor condition.

Designing the underground structures within this special urban environment required careful and intense coordination with all stakeholders, particularly the station entrances, shafts and portals connecting the underground structures to the public space at the surface. Space to implement the project is very limited all the way along the underground alignment. Along the main streets, road closures are not permitted, and traffic flows must be maintained via temporary traffic arrangements throughout the construction period.

The construction strategy consists of two separate tunnel headings, one from the north portal to the junction with the branch tunnel and the second one from a temporary shaft located along the branch tunnel in Pituhei Hotam Street to the south portal. The mined stations will be excavated through the running tunnels. This strategy requires two main mobilization areas for the underground works, one near the north portal and Bar Ilan station and the second one at the temporary shaft in Pituhei Hotam Street. The available space at these mobilization areas is very limited, posing special challenges for the site logistics. Sheds and barriers are required for noise and dust protection of the vicinity.

Working time for construction will be restricted to 5.5 days per week, whereby at-grade works and underground excavation will be limited to 12 hours per day. Certain “non-noisy” underground works may be performed by the contractor at nighttime. The current project schedule is based on these constraints.

5 IMPACT ON EXISTING BUILDINGS

Along the Blue Line Underground Section, a total of 228 buildings were subject to a building risk assessment. Building condition surveys were undertaken to determine the pre-construction condition of these buildings. During the construction phase ground movements (vertical and horizontal) and vibration impact due to underground excavation works will occur, which were analyzed for all affected buildings in respect of the structural condition of each. The zone of influence of tunnel construction was defined based on the results of the settlement and vibration analyses i.e. the boundary of negligible settlement and vibration impact along the underground alignment.

For classifying the buildings within the zone of influence, the collected building condition survey data were analyzed together with the expected impact of settlements and vibration caused by the excavation works. The results of the impact during construction were superposed and clustered into three groups (categories) in terms of the recommended instrumentation and monitoring regime during construction. A classification into categories C1 to C3 was proposed, with category C1 representing buildings with a low and category C3 buildings with a high degree of sensitivity against ground movements and vibration due to tunnel construction. The instrumentation and monitoring program for each category provides different combinations of two-dimensional level points, three-dimensional targets, vibration measuring equipment, crack meters, tilt meters and visual inspection during construction.

Based on the results for each single structure or building, trigger values and related measures during construction were specified. The trigger values were defined for underground and surface displacements in horizontal and vertical direction. In addition, trigger values for vibration impact were defined.

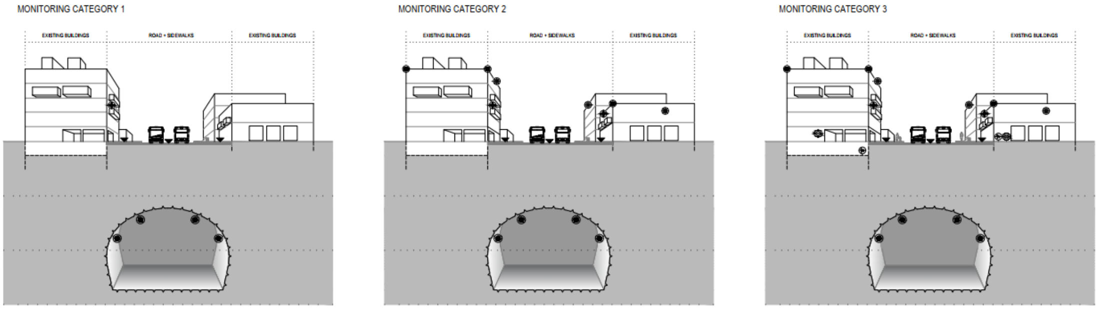

Figure 4. Typical monitoring cross sections.

The construction impact assessment for displacements was carried out in general following the theoretical approach after Burland and Wroth. The methodology to assess the impact of the excavation on neighboring structures is based on limiting tensile strains and incremental building damage. Ground movement profiles obtained from numerical models were used as input to this assessment. Figure 5 below shows the schematic arrangement of sagging and hogging zones forming in a typical symmetrical settlement trough caused by tunnel excavation, which qualitatively resemble the shape of the settlement troughs obtained from the numerical models.

According to Burland and Wroth, a building can be idealized as a deep beam with a span L and a height H deforming under a central point load to give a maximum deflection Δ. The height H is taken as the height from foundation level to the eaves. The roof of the building is usually ignored.

Buildings, when affected by a settlement trough, are assumed to follow the ground displacements at the foundation level. The settlement trough (typically simulated as a Gaussian distribution curve) consists of a sagging and a hogging zone, which are delimited by the point of inflection of the trough curve. A building can be considered separately at each side of the point of inflexion. Therefore, the assessment of building tensile strains can be carried out separately for the area of the building within the sagging and the hogging zone respectively.

For the section of the building in the hogging zone, it is assumed that the restraining effect of the foundation will lower down the neutral axis, which can therefore be taken to coincide with the lower extreme fiber of the beam. Then, all strains due to bending are tensile.

For the section of the building in the sagging zone, however, it is reasonable to assume that the neutral axis is in the middle of the beam. In this case, bending will generate both tensile and compressive strains.

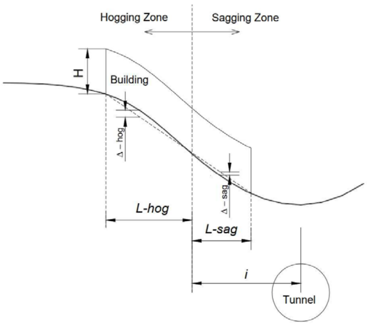

Figure 5. General case of a building affected by a settlement trough.

The assessment of building strains was based on ground movement profiles obtained from numerical models as shown in Figure 6 performed for the station cross sections. Similar analyses were carried out for all underground structures (running tunnel and bifurcation structure, branch tunnel, ramp structures at the portal areas, shafts). For buildings affected by displacements from multiple underground excavation works a superposition of the effects was considered.

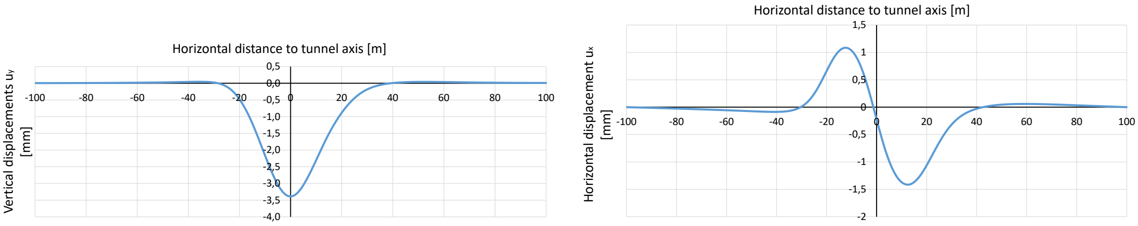

Figure 6. Typical vertical settlement and horizontal displacement.

6 SUMMARY

The Blue Line Underground Section is to be implemented in the historic city center of Jerusalem. The main challenges posed by the project environment are extremely limited space, acceptance of the project by the local community and the built environment with numerous buildings in poor condition.

The design approach for the large span mined station tunnels of more than 290 m² cross sectional area follows the principles of NATM considering the boundary conditions and limitations imposed by the urban environment with the objective to ensure safe and economic construction.

The design for potential karst cavities includes comprehensive karst investigation during construction and a toolbox of measures to ensure stability of the underground structures throughout the operation phase of the infrastructure.

A detailed building risk assessment was carried out at the design stage considering the pre-construction condition of the affected buildings. This included a classification of buildings, the definition of a building instrumentation and monitoring scheme and related trigger values as well as criteria for strengthening measures during construction.

REFERENCES

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