Red Line tunnels in Israel – engineering highlights

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ABSTRACT: The Light Rail Red Line runs from the city of Bat Yam passing through the cities of Tel Aviv, Ramat Gan, and Bnei Brak reaching finally Petah Tikva to the northeast. In the present paper, some of the engineering challenges are described and analyzed. The main challenges were: (1) The crossing under Ayalon River, cutting heavily reinforced piles serving as retaining wall foundations between the railroad and the river. (2) The TBM crossed through the stations' shafts before they were excavated; a detailed program of excavation and dewatering stages was prepared for this purpose. (3) The alignment crosses under an existing bridge built more than fifty years ago, thereby cutting the foundation piles with the TBM cutter. (4) From the Herzl launching shaft the tunnels are in close proximity and under low overburden, crossing next to more than 100 year old buildings; protection works or other mitigations for buildings in critical or deficient conditions were performed before the TBM crossing.

1 INTRODUCTION

The Red Line has 12 km of at-grade alignment and 12 km of underground tunnels. There are 10 stations along the underground section of the alignment, at a distance of approximately 750 meters from one to the other.

The excavation of the tunnels was performed using 8 Tunnel Boring Machines (TBM) commencing works in 2017.

The Red Line tunnels are the first urban tunnels in soft ground and below the underground water table constructed in Israel and there was no previous experience to rely on. The alignment is located mainly under existing roads, bridges, utilities and close or under existing buildings, in Tel Aviv Metropolitan area.

The Client prepared three TBM launching shafts at strategic points along the alignment that allowed the beginning of the works in 2011 (See Fig. 1).

From the hydrological point of view, the Red Line is located mainly in the Mediterranean Coast Aquifer where the underground water level varies from approximately 0.0 m adjacent to the sea to the west, up to approximately +4.0 m at the Em Hamoshavot launching shaft to the east. Most of the tunnels are partially or entirely below the underground water level.

The geological formations consist mainly of sandstone, gravel, sand and lenses of clay. The types of sandstone existing in the Israeli Mediterranean coastal area are known as Kurkar, and they vary from a very soft rock (K1) to a rather hard rock (K4).

The alignment crosses through very populated areas of the Tel Aviv Metropolitan Area, including the cities of Bat Yam, Tel Aviv, Ramat Gan, Bnei Brak and Petah Tikva. The construction bid of the Red line, was divided into two segments, the West Segment starting at the Herzel Launching Shaft and ending at the Ben Gurion Station (See Fig. 1) and the East Segment from Ben Gurion Station to the depot. Each segment was constructed by different Contractors.

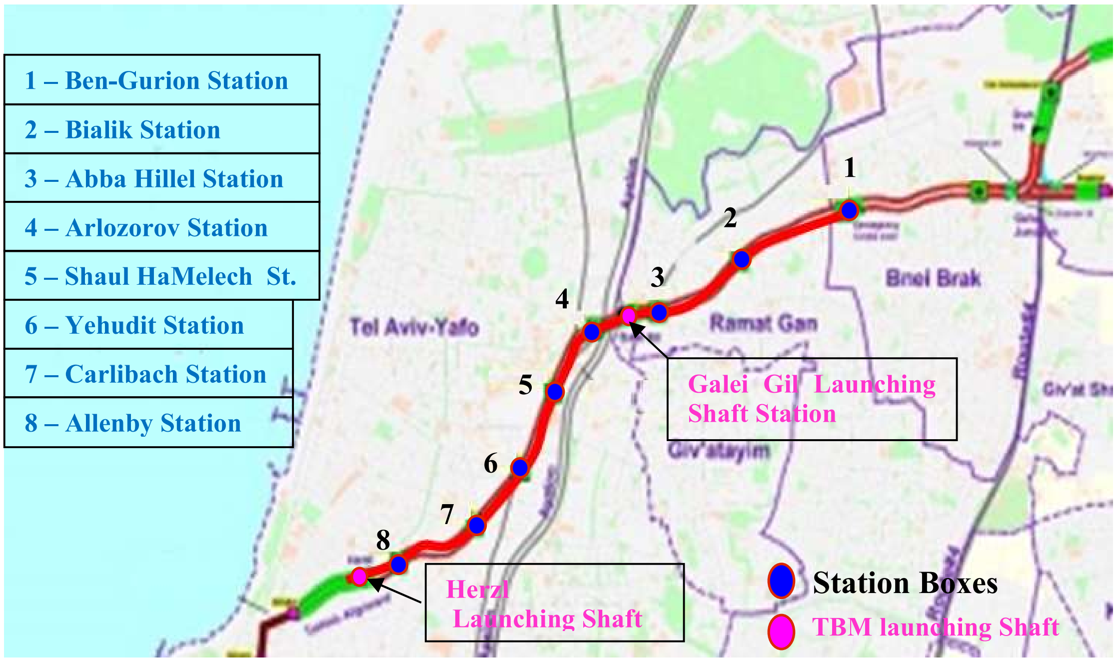

Figure 1 - Red line West Segment alignment map

The present paper will refer to the Western Segment that begins crossing the Tel Aviv Metropolitan area, Ramat Gan and reaching Bnei Brak. The contract was granted to a joint venture between Shikun Binui from Israel, and CRTG from China. Colaborating with the design and as design checker was Eng. Nicola Della Valle from TunnelConsult.

Building Survey Conditions (BSC) and Building Risk Assessment (BRA) reports were prepared in order to advise the Contractor on monitoring programs and risk mitigation measures for each building within the zone of influence (ZOI) of the planned route. More than three hundred buildings and about five thousand apartments were surveyed and documented in the Western Segment.

The BSC was performed in two stages; first external surveys were prepared for each Building including available existing plans, review of the structure and nonstructural elements conditions, pictures, determination of the vulnerability index, etc. Afterwards, and according to Client's request, most of the apartments (more than 80%) were surveyed and documented. The completion of these works, by at least three survey teams, took more than one year.

The BRA was determined according to Burland's criteria, using at first an empirical approach to determine the green field movements, and where necessary additional calculations were performed using the PLAXIS numerical program.

After finishing the BSC and BRA documents, visits to the different sections of the alignment were performed together with the contractor in order to decide which risk mitigation measures were necessary to reduce the impact on buildings to an acceptable minimum.

Automatic monitoring instruments were installed in all of the buildings in addition to other mitigation measures.

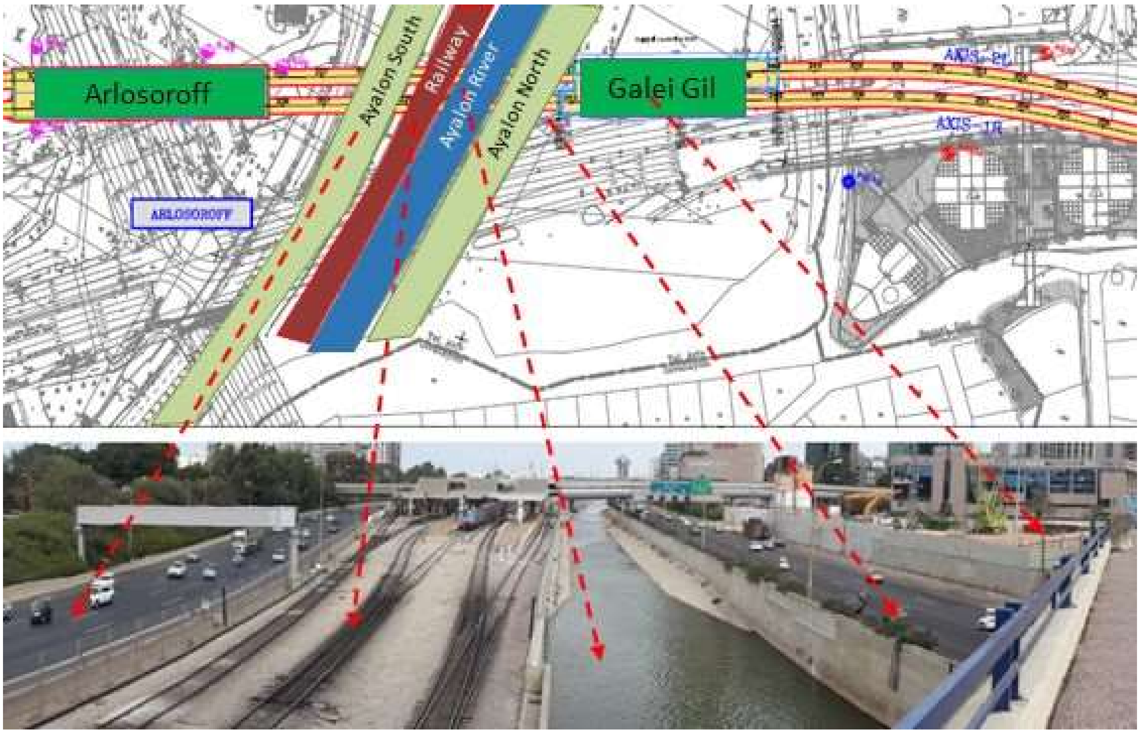

Figure 2 – Ayalon Crossing

2 CROSSING UNDER AYALON RIVER

The Ayalon River crossing was a very complicated task from a design and construction standpoints.

TBM 5 and 6 were the first to be launched in the project, from the Galei Gil launching shaft in Ramat Gan, and immediately crossing under the Ayalon Highway with very heavy traffic, railways, sewage pipes, and the Ayalon River in order to reach the Arlozorov Station in Tel Aviv. The Ayalon river is bounded on both sides by two retaining walls founded on piles, which were constructed at different stages, and strengthened later to allow the placing a railroad immediately behind the walls.

The tunnel crown is located about 8 meters under the river bed and about 12 meters under the railway and the highway.

2.1 *Cutting Piles Methodology*

One of the main design and technical issues was to cut the piles under the retaining walls without major impact to the railways, the highway, and the walls. Many possible solutions were considered including grouting, jet grouting, and shaft construction to engage the piles from the river and others.

Ultimately, a very challenging approach was adopted; the piles were cut by the TBM during the crossing. At first, it was considered that a small underwater chamber will be implemented from the TBM chamber using air pressure, bentonite and/or grout to allow reaching the piles and cutting them, but this solution was considered too risky. Afterwards, the contractor suggested the possibility of constructing a special, heavy duty cutterhead capable of demolishing the piles.

The question was how the cutter would deal with the heavily reinforced piles and cross through them without causing major damage to the machine, the structures or the surroundings. To demonstrate the feasibility of the proposed solution two decisions were taken: first to make a simulation test at the TBM factory showing that the cutter would be able to cut the reinforced piles and secondly to improve the ground conditions by injecting jet grout between the piles in order to avoid any possibility that the piles would move during cutting. The grouted block would prevent possible pile movement during cutting and also serve to strengthen the existing foundation after cutting the piles, thus protecting the tunnel. (See Fig. 4)

The simulation test took place in China and the proposed cutter was used to cut reinforced concrete as shown in figure 3. The simulation test allowed the following conclusions to be reached:

- Using either disc cutters or drag bits it is possible to cut reinforced concrete piles.
- Discs are very efficient in cutting but the length of the cut rebars is not uniform. The length of rebars after cutting with drag bits is more uniform

Figure 3 – Reinforced concrete, cutting simulation equipment

It was recommended to operate at an excavation speed of 3 to 5 mm/min and a rotation speed of 1 to1.3 radian/min. The concept is that low excavation speed combined with a high rotation velocity produces fewer disturbances and a smaller length of cut reinforcement.

Another recommendation was to add more quantities of foam and bentonite slurry in order to reduce the cutter head temperature and increase tool's lubrication.

In order to enter the river bed and perform jet grout operations, a small dam was constructed between the site and the sea in order to work in dry conditions.

It was necessary to inject about ten thousand cubic meters of grout in a rather short time. Two sets of grouting equipment were used in parallel in order to meet the deadline of finishing the works before the start of the rainy season and water flow in the river. It was impossible to add more equipment because of the space limitation of the site. (See Fig. 4)

There were several issues that arose during the jet grouting process due to the above mentioned reasons and the very limited working site, especially regarding the backflow control of the grout. The backflow entered through an existing drainage layer under the river concrete floor, producing the uplift of the floor which was necessary to repair.

Monitoring instruments on the retaining walls and the railway tracks showed very small movements of no more than three millimeters.

Drilling to extract samples from the jet grout was performed. The samples UCS (Unconfined Compression Stress) had a mean value of 25 MPa more than required in the specifications.

The Jet Grout work was completed a few days before the site was flooded due to continuous rains.

The TBM crossing and cutting of the piles were performed without any problems. The methodology worked as planned, producing minor settlements of the retaining walls and without affecting their stability.

2.2 *Authorities Authorizations*

This was the first TBM works performed in an urban area in Israel, so there was not any previous experience on this subject. The authorities were very reluctant to provide the required approvals, needed time to study the submitted documents, and required additional explanations and reports, thus producing delays at the beginning of the works.

The Highways Authority (Netivei Ayalon) considered the possibility of stopping vehicular traffic before the crossings, but ultimately the highway remain opened.

The Railroad stopped train transit in this section before the first TBM crossing and only during the second TBM crossing the railroad was opened.

The sewer pipes of the Shafdan were closed during the crossings and a large number of monitoring instruments were installed.

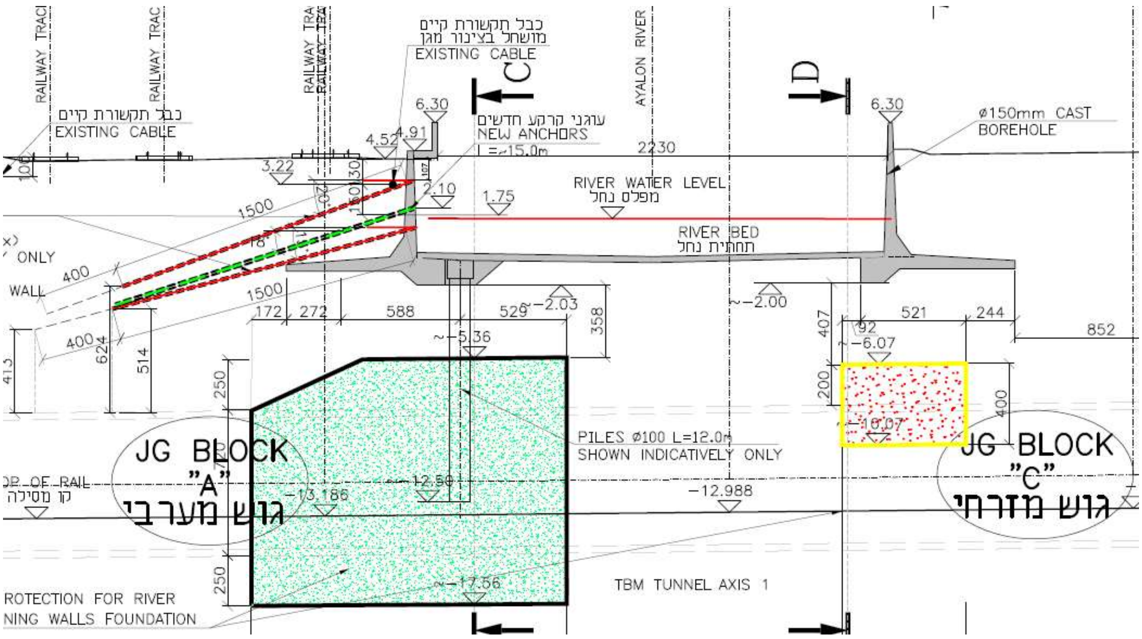

Figure 4– Piles, Ground Anchors and Jet Grouting under the retaining walls.

The crossings were performed without any damages or problems of any type. The measured subsidence was only a few millimeters on any point of the alignments.

3 TUNNEL ANTECEDENT

The original design was to construct and excavate the stations' external box walls at a first stage and afterwards to cross with the TBM through the stations' walls. The advantages of this method are that the stations are constructed in parallel with the tunnelling and enable possible checking and maintenance of the TBM at the stations during the crossing. In most of the tunnel projects, this is the preferred and adopted methodology.

In the present project, the stations' construction was very time consuming due to utility relocations and traffic arrangements. If the TBM had to wait until the stations' excavations were completed, more than a year would be added to the timetable.

For this reason, the tunnel antecedent methodology was proposed by the Contractor and approved by the Client. In this case the TBM crosses through the stations after all the external shaft diaphragm walls were cast, or at least partially cast. The excavation of the stations was performed after the TBM crossing and the tunnel segments inside the stations were demolished. (See Fig. 5)

3.1 *Stations verification*

When the tunnel antecedent methodology was adopted, parts of the stations were already under construction. In this situation, it was not possible to introduce any modifications, and it was necessary to verify that the existing diaphragm walls had sufficient reinforcement to stand the new construction stages.

This was verified using Plaxis 2D software. The new design bending moments' envelope and shear forces that were calculated considering the different construction stages and loadings were compared with the capacity bending moments and shear forces of the existing reinforcement. Small changes in the positions of struts and the construction stages were necessary to reach an adequate safety factor in all of the stations.

3.2 *Uplift forces*

In order to ensure the stability of the tunnels during the excavation it was necessary to verify that the groundwater uplift forces were less than the counterweight to avoid buoyancy.

The stages of excavation, strut construction and dewatering were redesigned in order to obtain a sufficient safety factor. The groundwater level was maintained high enough to avoid excessive pumping and low enough to avoid buoyancy at the different stages of construction.

3.3 *Segments stability*

The inner diameter of the tunnel is 6.5 meters and each ring is composed of six segments. The rings have good stability due to compression forces introduced by the surrounding soil pressure. When the compression forces are large enough, the eccentricity due to moments in the ring is small, and all the connections between the segments are in compression.

During the excavation, the compression forces are reduced due to smaller overburden and the bending moments at the segment connections produce greater eccentricity. As a result, at a certain level of the excavation, the connections behave similarly to hinges reducing the ring rigidity. This problem should be checked and properly calculated to avoid an early collapse of the tunnel.

The following protection measures were taken to reduce the risks:

- After the excavations reach two meters above the crown no entrance to the tunnels underneath was permitted, and no traffic of heavy equipment was allowed.
- When the excavation reached one meter and twenty centimeters above the crown no equipment above the tunnel was allowed.
- The excavation shall be performed in parallel on all the sides of the tunnel.
- No asymmetric excavation was allowed.
- The groundwater level inside the stations was maintained under the bottom level of the tunnel.

Figure 5– Demolishing one of the tunnels at Shaul Hamelech Station

4 SHEFA TAL BRIDGE CROSSING

The Shefa Tal Bridge is located at the limit between the cities of Tel Aviv and Ramat Gan, and very close to the Galei Gil launching shaft. The road above the bridge has a very large traffic volume serving as a main connection between the two cities. The bridge was constructed in two stages; in 1930 an arch structure was built and in 1960 the bridge was widened by adding two lateral bridges at the southern and northern sides.

The superstructure of these bridges has continuous pre-stressed girders, and the foundation consists of driven piles. According to the design drawings from 1960, the length of the piles was 7 meters, but before the crossing, the length of the piles was measured using sonic tests with the result that the piles are 12 meters in length instead of the designed 7 meters.

This increase in the length has serious consequences for the tunnel crossing under the bridges because if the piles were 7 meters the TBM would cross under them, but because the piles are 12 meters long, the TBM crosses through the piles.

Many utilities were found between the foundations of the bridge including electricity, drainage pipes, communication cables, sewage pipes and others complicating the possible treatment of the foundations.

Only one of the two parallel tunnels, the southern one, crossed under the bridge; the northern one crossed very close to the bridge but not cutting any pile.

The selected construction methodology consisted of the following:

4.1 *Jet Grouting*

Soil treatment with jet grouting was performed under the bridge having two purposes. The first one was to treat the soil under the pile caps in order to strengthen the foundation, allowing the cutting of the piles without causing major settlements or weakening of the foundation support.

The second purpose was to allow the TBM to cut the piles with a minimum impact on the bridge.

A detailed design was prepared for the jet grouting including bridge monitoring, tests, and traffic arrangements.

4.2 *Settlements compensation*

Settlements calculations showed that ground treatment combined with limited volume loss will reduce the differential settlements in the longitudinal and transversal directions of the bridge to a maximum of 8 mm. The expected additional tensile stresses in the bridge beams, due to these settlements, will be 0.94 MPa.

Extensive continuous monitoring was performed during the crossing.

Superstructure differential settlements of more than 8mm were to be compensated using hydraulic synchronized jacks during Jet Grout works and during tunnelling works.

4.3 *Design vs. Reality*

According to the design, the first TBM crossing near the bridge was to be the southern one that crosses under the bridge. But due to a delay of the jet grout works the Contractor decided to cross first with the northern one, before completing the ground treatment under the eastern pier.

During the crossing of the northern TBM, due to lack of adequate protection, the eastern pier settled about 6mm at the northern column, close to the tunnel and a negligible settlement occurred at the southern column. The settlement under the northern column was very close to the threshold of 8mm as explained above, and it was expected that additional settlements would happen during the second TBM crossing. The bridge was thoroughly checked and no additional damage was found at this stage.

After finishing all the ground treatments, the southern TBM crossed under the bridge cutting the foundation piles, with only very small settlements of about 3 mm. This proved that the jet grouting solution provided good protection, even better than predicted.

After the TBM crossing, it was required to compensate settlements at the eastern pier and to replace the neoprene bearings that were already in poor condition.

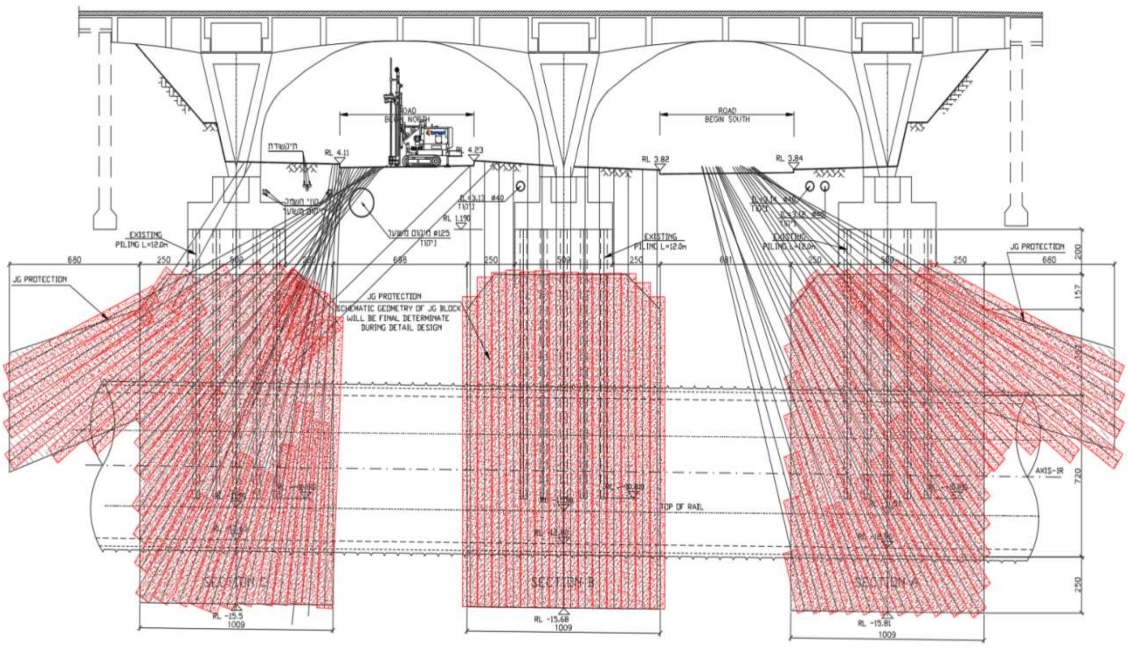

Figure 6– Shefa Tal Bridge including jet grouting design.

5 TUNNELS IN CLOSE PROXIMITY

The western underground section of the Red Line originates in southern Tel Aviv. This is one of the city's oldest and more crowded areas, with narrow streets and buildings about one hundred years old. Only a small part of them have been refurbished and/or strengthened over the years.

The TBM works started at the Herzl launching shaft, which is very narrow and surrounded by old and partially unstable buildings. During the construction of the shaft by the client at a previous stage, the residents of one of the buildings were temporarily evacuated from their homes.

As noted earlier all the buildings along the alignment were inspected (BCS), a risk assessment report (BRA) was prepared, and in this area, special precautions including monitoring, mitigation works, and emergency programs were implemented.

5.1 *Close proximity*

Tunnels in close proximity, means that the distance between two parallel tunnels is very small in relation to their diameter. Normally a minimum distance equal to twice the tunnel diameter center to center is kept and preferable two and a half diameters, depending on the type of soil or rock.

The problem with tunnels being in close proximity is that after the crossing of the first TBM, the second one affects the stability of the first tunnel, since the excavation is executed at a short distance; this problem should be properly addressed or avoided.

At the Herzl launching shaft, the net distance between the tunnels is only 0.8 meters, and the close proximity continues for 220 meters between chainage 14+060 to 14+280. In this alignment section, the minimum overburden is approximately 6.5 meters (at Herzl launching shaft) and the maximum 10.75 meters.

Due to the close proximity of the tunnels, special mitigation measures were implemented including construction of a wall of concrete piles of 0.8 meter diameter and 1.0 m spacing between the tunnels. In some places this solution of pile walls was not adequate due to existing utilities that were not possible to relocate. Instead of pile walls, it was necessary to inject grout from the first tunnel, before the crossing of the second one. The permeation grouting was performed using small dimension equipment in order to allow the continuation of the tunnel works.

Fig. 7 Section with tunnels in close proximity

5.2 *Building protection*

As stated above, many of the buildings in this section were in poor condition. As an example, near the Herzl shaft, a two story building was strengthened by the owners with steel struts in or-

der to provide stability, without any connection to the project. The ground floor of the building contains commercial space, and the first floor residences. Considering the critical situation of the building it was decided to protect it by a wall of piles to reduce settlements produced by the TBM. The crossing was scheduled for a weekend when the stores are closed, and the residents were temporarily evacuated.
Risk mitigation measures for buildings in this area included among others: pile walls between the tunnel and the buildings, continuous monitoring with several control parameters, continuous inspection of the buildings by a certified engineer, evacuation of residents, emergency programs, etc.

5.3 *Detailed calculations*

Detailed calculations of the settlements at each section were performed, using PLAXIS 2D software. The model included the different layers of the soil, the protection piles and loads due to building foundations and traffic.

The results of these calculations were used to determine tensile strain induced in each building and the expected damages according to Burland classification.

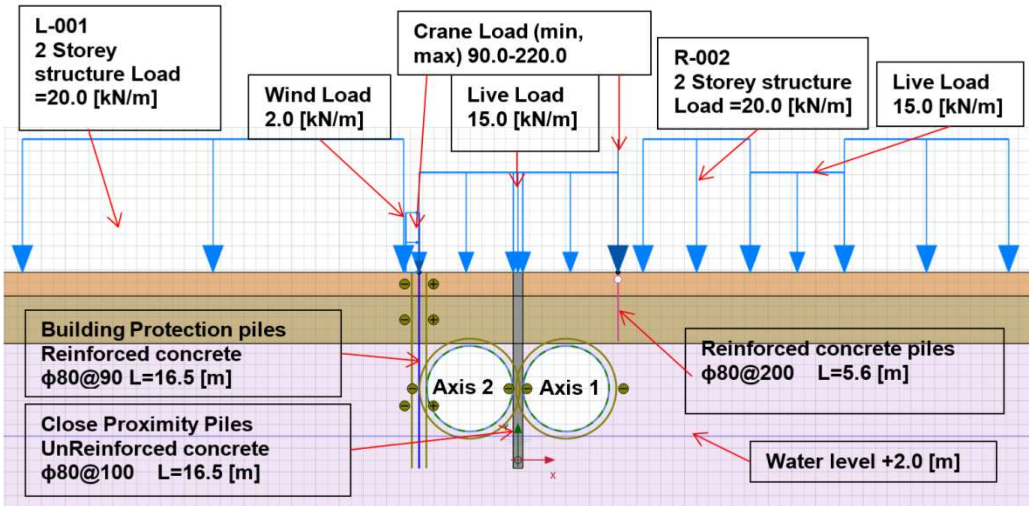

Fig. 8 Calculation of a cross section of tunnels in close proximity using PLAXIS 2D software

6 CONCLUSIONS

Tunnelling in urban areas has a variety of challenges and problems that shall be properly treated in all stages of the design and the construction. It is necessary to take special care of existing structures as buildings, bridges, tunnels, utilities, etc. Other problems could be receiving the authorities' approvals and dealing with complicated approach from the surface or even not having such an approach.

In the present paper there is a description of some difficulties and problems during the design and construction of the tunnels for the light-rail Red Line in Tel Aviv. We hope that the way they were treated and finally successfully solved will serve as an example that maybe used in other urban tunnels in the future.

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