GEODATA

**Zurich, 10/12/2009** **Tunnelling in urban area**

# The new Anatolian Metro of Istanbul

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The new metro line of Istanbul from Kadikoy to Kartal is 21.7km long with 16 stations, crossing the densely-populated Anatolian side of the city and a significant part of the line is located beneath the E5/D100 motorway. The line is designed to be completely underground, with a variable cover of 25-35m, such that all the stations, the turn-out tunnels and more than 50% of the running tunnels are excavated with conventional methods.

Tunnelling in this densely-populated urban area is associated with a number of problems such as lack of space for stations and access shafts (more than 20 access shafts are required), interference with valuable buildings and the need to maintain traffic on critical roads during construction. Moreover, the complex contractual constraints, the heterogeneous geological conditions comprising mainly of sedimentary rocks with volcanic intrusions, and the high level of seismicity of the region, presents a great challenge for the Designers and Contractors.

In this article a number of examples are presented where an appropriate and agreed management of risks has allowed to face and to solve a number of critical design and construction issues during excavation works.

At the time of writing of this article, in a little more than a year and a half after the start of the construction, more than 60 excavation fronts are opened and a large part of the excavations have been successfully completed, allowing to meet contractual deadlines.

## 1. Introduction

Istanbul is a megalopolis with over 15-million inhabitants, still growing and expanding, characterized by a mixture of its historic heritage, natural beauty and uncontrolled urbanisation.

Istanbul's biggest problem is mobility, owed also to its unique location, divided in two by the Bosphorus, separating the Asian and the European side (Figure 1.1).

*Fig.1.1 Istanbul and the Bosphorus*

*Fig.1.2: The Second Bosphoru Bridge*

Currently, the only possibility of connecting directly the two parts of the city is to use its two bridges (Figure 1.2) that suffer from high congestion, or alternatively, to use the various ferry crossings between the two banks of the Bosphorus.

There are several plans to increase the infrastructure links between the two sides: the Marmara rail tunnel is currently at an advanced construction stage, while the construction of a third bridge and of a new highway tunnel under the Bosporus is expected. Just to address the increasing and urgent demand for mobility, there are over 130 km of public transportation routes including metro and tram systems under construction, which is a part of the very ambitious development program putting into operation over 500 km of new metro lines by 2025.

## 2. The project and the contractual context

The new metro line to Kadikoy on the Asian side assumes great significance for the public transport system of the city, as it is an important ferry port serving various locations of the Bosporus and is also part of the future extension to Sabiha airport (Figure 2.1). The first section is 21km long consisting of two single-track tunnels with 16 stations and crosses the densely populated Anatolian area of the city.

The stations are built with the cut & cover technique, while the platforms are constructed with conventional tunnelling from enlarging the running tunnel section. The project (including civil works and M&E systems) has been awarded in March 2008 to the Avrasya Metro Grubu J/V, led by the Italian Contractor Astaldi with Turkish Contractors Gulermark and Makiol, for a contract value of 750 million Euros and 900 days to complete all works, including the start-up of the system.

In the portion of the line between the Kadikoy and the Koziatagy station there is an uncompleted but excavated stretch of about 8.5km entrusted in the past to another local Contractor (Anadoluray). Considering the tight time schedule imposed by the Municipality, while waiting for the mobilisation of the tunnel boring machines for excavation of the portion between Altaycesme and Kartal stations (approximately 7.5 km), the section between Koziatagy and Altaycesme was excavated with conventional tunnelling method (approximately 5.0 kilometres). A few months after the award of the project, the contract of Avrasya Grubu Metro J/V was extended to comprise also the realization of the line till Kaynarka, Pendik, including an additional 4.5 km stretch and 3 intermediate stations, which led to a revised fee (about 1100 million €) and a revised time schedule (1260 days or 3.5 years).


*Fig.2.1: The alignment of the Kadikoy-Kartal line and the extension to Kaynarca*

In addition, substantial changes to construction planning were made: the TBMs would construct the new extention starting from Kartal, while the original 12km main line (i.e. 24 km of tunnels), should be constructed by conventional tunnelling.

Geodata is in charge of the design of all conventional tunnelling works by Avrasya Metro Grubu J/V (running tunnels, stations and connection works) and entrance shafts: in other words, the essential works of the project.

## 3. The alignment and the urban context

The project will be the new backbone of Istanbul’s public mass transport system in the Asian part of the city.

The line mainly runs beneath the E5/D100 corridor (Figure 3.1 and 3.2), the main urban highway linking the two parts of the city. The line is designed to be completely underground, with a cover varying between 25-35m.

*Fig.3.1: The traffic on the E5/D100*

*Fig.3.2: A metro worksite along the E5/D100*

As a result, all works, including stations, have been conceived as deep underground excavations in order to limit the impact to the surface, including the construction of shafts to access the excavation fronts.

## 4. The tunnelling works

The line consists of two single-track running tunnels and involves the construction of numerous and complex safety cross passages and train switches. These works combined with the station platform tunnels, forming practically large caverns whose cross sectional area can reach up to 175m$^2$. In detail, the typical layout of the underground spaces, to be excavated with conventional methods, is:

- Turn–out and switch tunnels: including the excavation of one or more shafts, the shaft access tunnel and the switch tunnels
- Stations: including platform tunnels, connection tunnels, stairs tunnels, ventilation tunnels, ventilation shafts and other underground spaces required.
- Main double-track tunnel: includes the access shafts, the running tunnels and the connections.

According to the design criteria, all these underground spaces constructed by conventional means should be completed before the passage of TBMs. In addition, in some points of the alignment, a number of further underground spaces are required, such as the Kartal node which will be the starting point of the TBMs. Inside these spaces the needs for TBM access gallery, mucking tunnel and other facilities are to be satisfied.
The needed internal dimensions of the various tunnels must be taken into account in the design process of the project. Alternatively, depending on the design criteria and the engineering decision taken for each situation, the external diameters can be defined so as to meet the project requirements. This has led to a complex condition where more than 15 geometrical typical sections are to be provided. Some examples of these typical sections are shown in Figures 4.1 and 4.2.

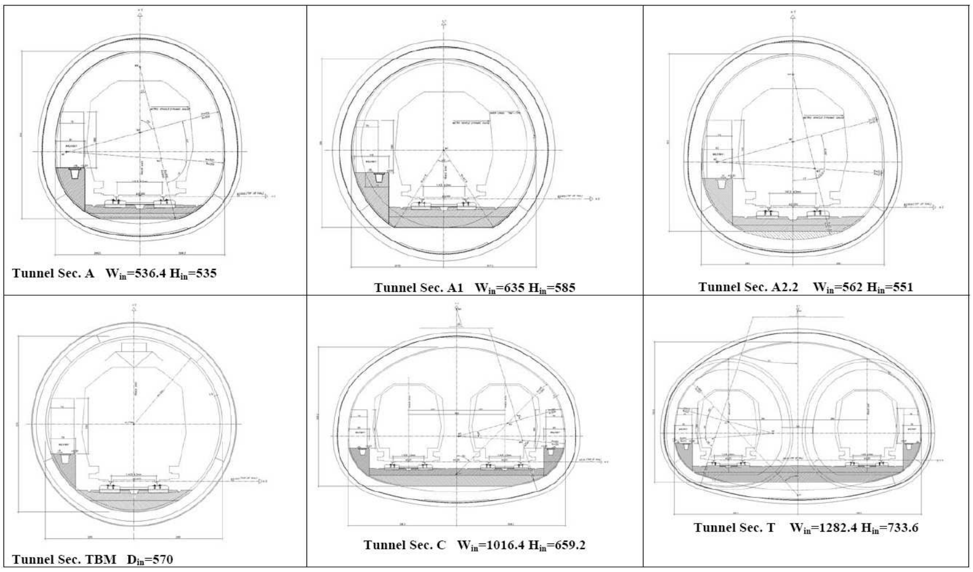


*Fig.4.1: Typical sections for running tunnels and switches*

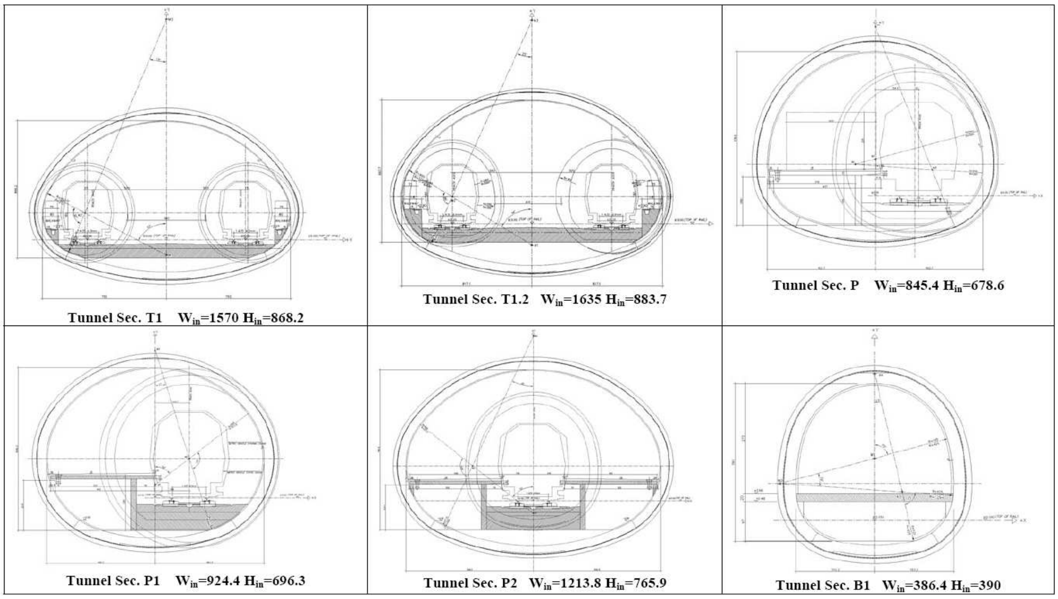


*Fig.4.2: Typical sections for switches and platform stations*

Figure 4.3 below illustrates schematically the three-dimensional complexity of a typical station with the various underground spaces mentioned above.

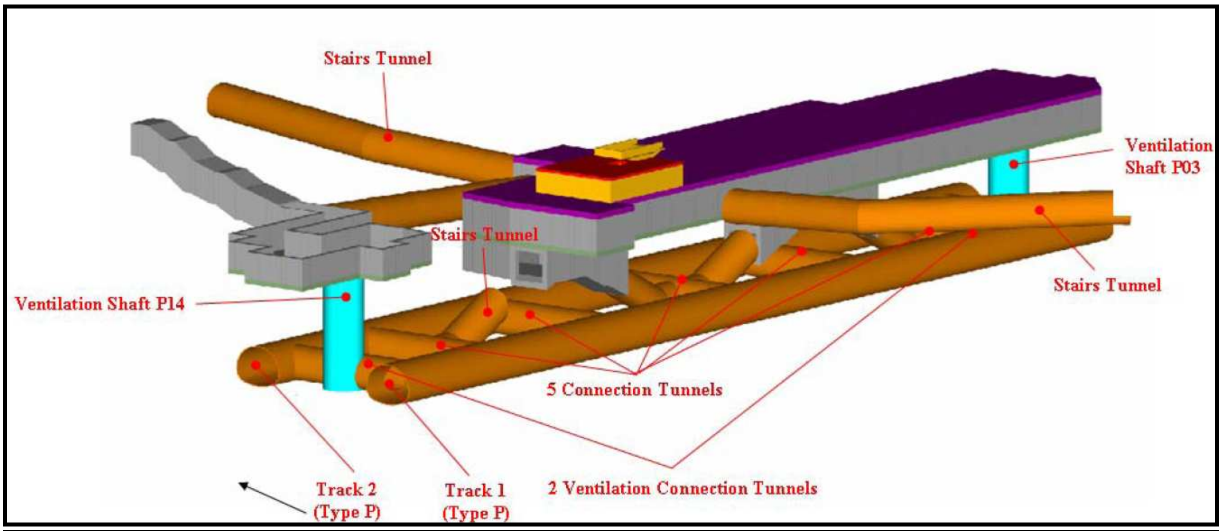


*Fig.4.3: Typical 3D layout of stations and its components*

## 5. The constraints and the main issues

The following aspects were considered for the design of the underground structures:

– The urban context described earlier, with limited available space for construction of the access structures for the stations and heavy interferences both with traffic and amongst the different underground structures

– The geological and hydrogeological context, characterised by complex and heterogeneous conditions, comprising mainly of sedimentary rocks with volcanic intrusions. The initial part of the alignment crosses the Trakya formations (Kadikoy side), consisting of sandstone, siltstone and claystone layers, to a transition zone with limestone and shale layers in the Kartal formation, followed by the Dolayoba formation consisting of limestones. The alignment also passes through various intrusions of magmatic rocks and andesites. Groundwater presents another critical issue for some areas such as Kadikoy, where the station and switch tunnels are located in the close vicinity of Marmara Sea, with the rail level being at approximately 30m below the sea level. All underground structures in the Kadiköy-Kartal Metro alignment are designed to be full-round waterproofing.

– Seismic resistant design due to the high level of seismicity in Istanbul, despite the fact that it is not commonly used in tunnelling. Seismic actions have been modelled as free-field shear deformations for the design of the final lining. Seismic joints are provided to absorb seismic deformations. However, the risk of having a seismic event during the construction period of about four years is accepted by all parties and is thus not considered in the design of temporary support.

– In addition, typical of tunnelling projects in urban area, significant difficulties involve the complex contractual conditions described earlier, due to the simultaneous working of different Contractors for the same project, which is interfering and often conflicting. This situation does not facilitate either the construction planning or the design choices. Moreover, to respect the deadlines, a large number of local subcontractors and low cost, not always adequately experienced in tunnelling in urban area, are involved.

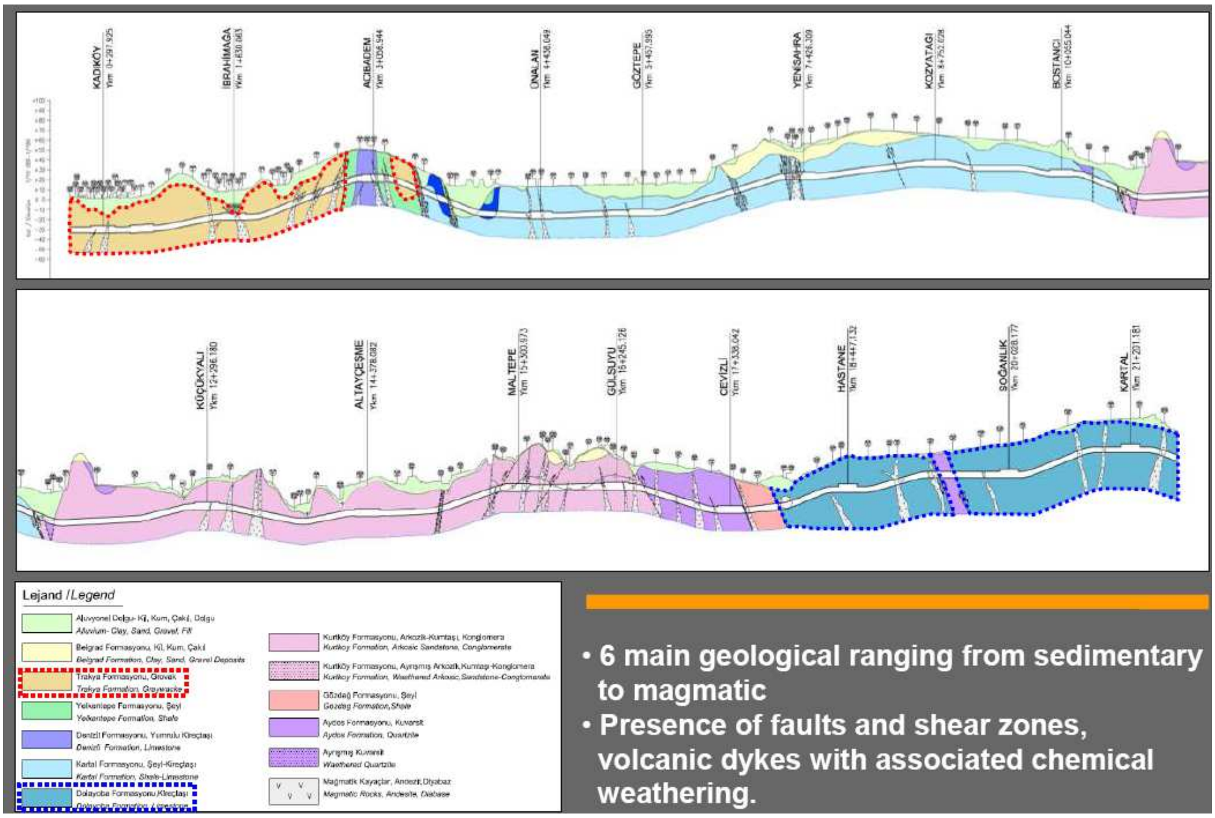


*Fig.5.1: The geological profile of the Metro Kadikoy- Kartal*

## 6. The design approach

The expectations and the pressure of the municipality of Istanbul have brought all involved parties to the strenuous and shared task of guaranteeing two fundamental requirements:

- Highest possible advance rates
- Maximum possible limitation of costs

These requirements, clearly expressed in the terms of the contract with the Contractors, must be balanced with the fundamental requirement of safety, particularly in tunnelling under densely-populated urban areas (where the safety must be ensured both in underground and in superficial space).

These often conflicting and contrasting requirements have presented a significant challenge to the Designer, accentuated in this case due to the professional relationship of working as the Contractor's Designer.

Aiming to fulfil these objectives, the Designer has had to propose an optimized design with provisions for the simplest possible construction techniques having a level of reliability that is appropriate for the local subcontractors who apply their own preferred techniques.

Considering all these issues, a risk management approach has been adopted, using the 'Observational method' (Peck., 1969) in which the design is constantly reviewed during construction (Eurocode 7) after the constant interpretation of construction feedback.

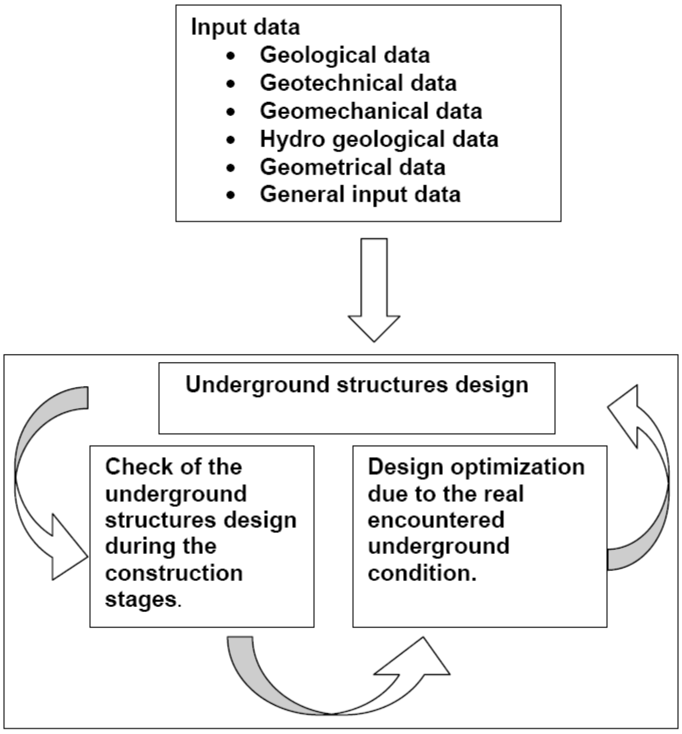


*Fig. 6.1: The Observational method*

The design developed is based on analysis, such as finite element; however, analysis cannot replace engineering judgement.

One of the fundamental elements of the Observational Method is to overcome the limitations of analysis by examining real conditions with engineering judgement. Feedback from observations and monitoring data should be timely collected and interpreted in order to confirm predictions or to provide adequate warning of any undue trends in ground movements or loading.

The design has been developed in the following stages:

- Quantification of geological conditions by means of geomechanical classifications;
- Running tunnels: prediction of excavation behaviour classes based on probabilistic analysis due to the uncertainty in the rock mass (Russo, 2007-2009). With this approach the factor of safety is evaluated as distribution curves, where the safety margin S is defined by the difference between capacity (C) and demand (D). Consequently, the inadequacy of a design may be quantified by the negative portion of the safety margin distribution (the probability of failure Pf), see Figure 6.2.
- Station and Switch tunnels: excavation behaviour classes based on probabilistic analysis due to the uncertainty in the rock mass (Russo, 2007-2009). Carrying out of parametric numerical analyses (two and three-dimensional) in order to:
  - ➢ model the construction sequence of excavations and their effect, particularly on the evaluation of ground movement and estimation of surface settlements;
  - ➢ analyse the response of the structures to seismic actions;
  - ➢ Estimation of three-dimensional effects in various types of intersections, in particular in the stations.

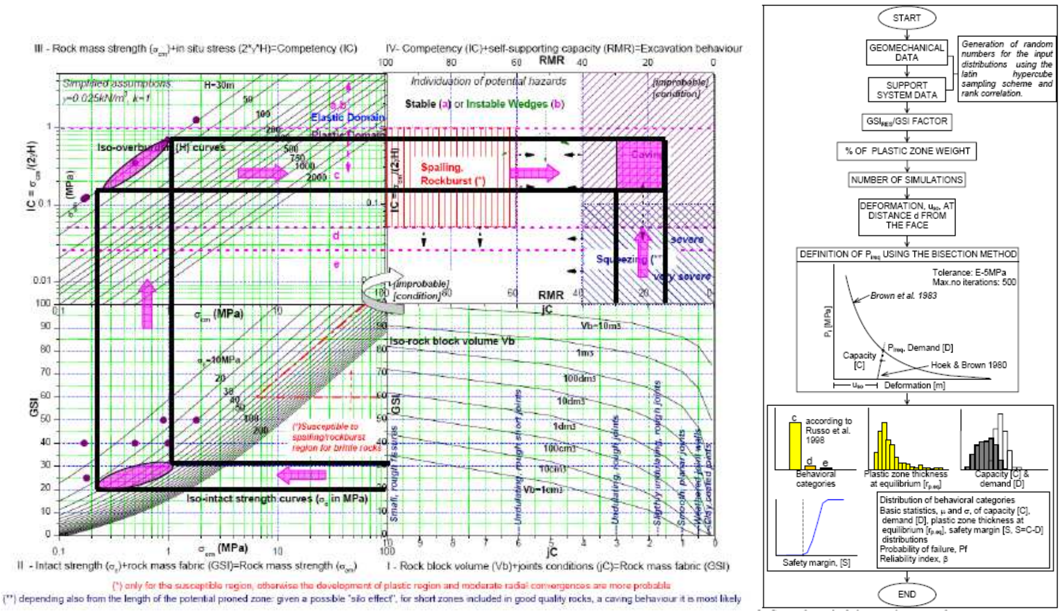


*Fig.6.2: Excavation behaviour and methodology risk related to the excavation evaluation approach*

In coherence with the Observational Method, the design has been checked by constant on-site control of the excavation face.
The aim of this activity is to assist the Contractor in the carrying out of modifications and optimisations during construction based on the real conditions encountered at the excavation faces. Due to a close collaboration with the General Contractor, this activity has been a "tutorial" process aimed to optimise and homogenise the quality of the excavation works along the entire line. This has been a key element in guaranteeing the application of the design and at the same time to ensure compliance with the contractual schedule.
Considering the simplicity and the non-redundant factors of safety of the design, the management of risk has allowed to foresee and apply adequate countermeasures where the effects of a failure are deemed as unacceptable in terms both of safety and of delays for small accidents even if the probability is minimum.
As an example, systematic support has been applied to the shallow excavations for stairs and elevators, independent from geological-geomechanical conditions.
In fact, for the construction of Ayrilikcesme station the Geodata design was not followed due to the subcontractor habits and a little accident occurred during the excavation works (Figure 6.2).

*Fig. 6.2: Ayrilikcesme station – Little accident during Stair tunnel excavation*

In addition, significant modifications to the design have been carried out, including the revision of the functional layout of the tunnels, where the factor of safety of the original design or where the reliability of the works done by local subcontractors was considered inadequate for the success of the project.

## 7. Examples

Kadikoy Switch (M1-M4) is a clear example of the application of the risk management plan during the design.
Kadikoy is a very crowded zone with significant interference problems with traffic, buildings and public utilities. In addition, the switch is excavated in the Trakya formation, one of the worst geological formations encountered along the entire metro line, and it is located near the sea (minimum distance of 60-70m).

*Fig. 7.1: Kadikoy area – interferences between M1-M4 site and facilities at the surface.*

The Contractor (Avrasya Metro Grubu J/V) took over the previous one (Anadoluray) where some underground structures had already been partially excavated according to the approved Tender Design, (access shaft, access tunnel and part of Track 2 of the running tunnel – Figures 7.3 and 7.4).

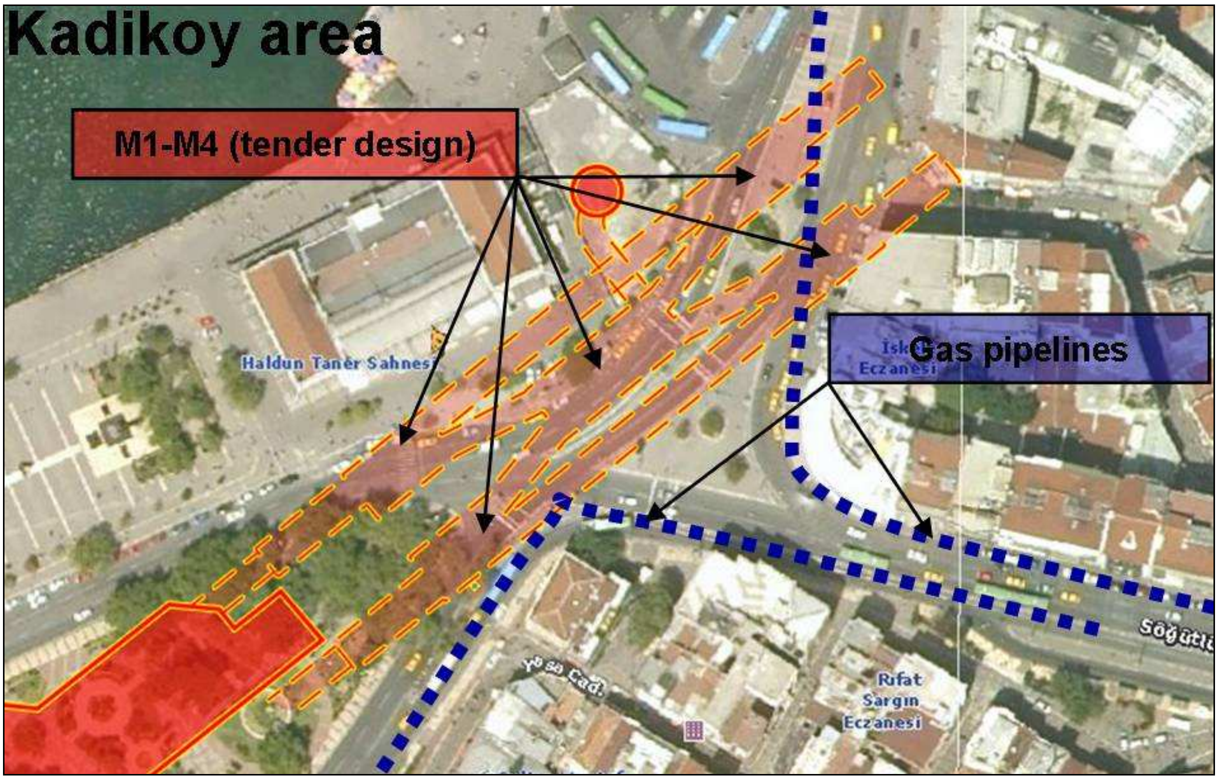


*Fig. 7.2: Kadikoy area –M1-M4 Tender Design lay-out.*

According to the critical analysis of Geodata, the design and the situation 'inherited' from the previous Contractor involved a number of critical issues posing safety risks to the project, amongst which:

- The particular geometry of the switch, which due to a limited pillar between two caverns must be considered as a single very big cavern;
- Impossibility to operate from the surface to grout the rock mass due to the interference with public utilities and the impossibility to interrupt traffic;

- A resulting uncertainty in the stability of the pillars between the underground structures (Figure 7.3); due to the development of very extended plastic zones;
- Expected large displacements in the tunnels (see Figure 7.4);
- Unacceptable expected settlements at utilities and surface structures (Figure 7.4).

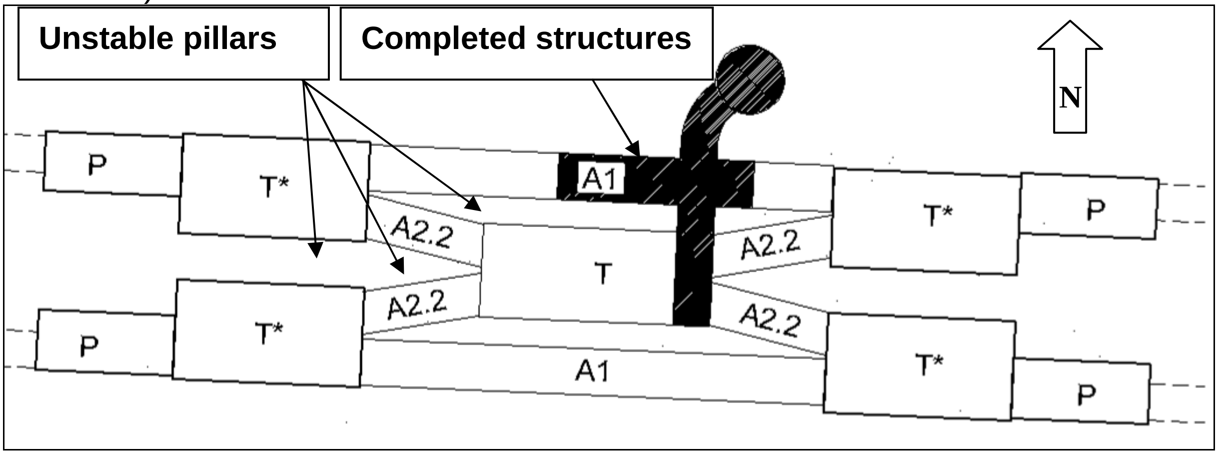


*Fig. 7.3: Kadikoy area –M1-M4 underground works completed by the old contractor (note the several thin pillars in the area of the switch).*

Facing these issues, a series of analyses were carried out in order to examine the stability of the excavations at various stages and their effect on buildings, roads and public utilities. The analyses were developed considering different scenarios based on geological conditions and different rock support types and excavation methodologies, aiming to investigate all possible solutions that could be adopted for Switch M1-M4.

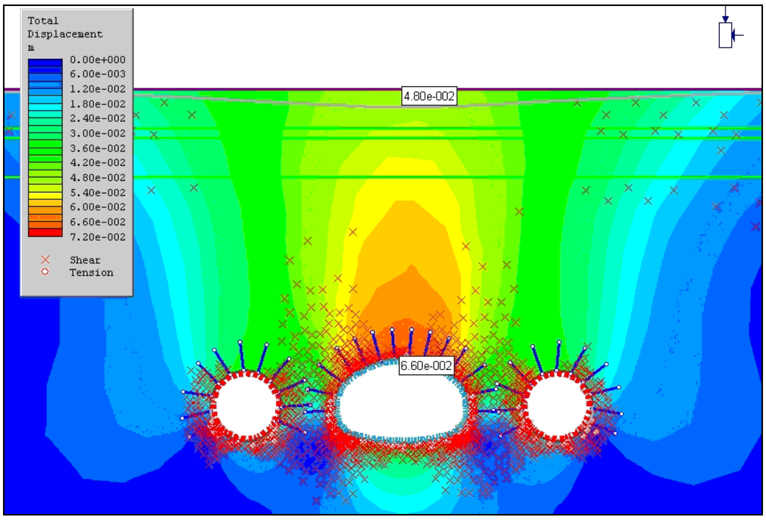


*Fig. 7.4: Kadikoy area – Tender design lay-out. Numerical analyses.*

Even though the project was already approved and in an advanced stage of construction with pressure exerted by the Municipality and the Supervising Engineers to complete the project, the careful evaluation of the situation with its associated risks, performed in cooperation with the Contractor and the Municipality of Istanbul, resulted in a critical revision of the Tender Design.

The revision concerned not only the construction aspects of tunnel excavation, but also some fundamental modifications to the functional aspects of the railway system.

During the period of preparation of the new design excavation works were halted and a monitoring system was installed in order to follow the excavation step by step and define any extra countermeasures. Emphasis was put on surface monitoring and especially on the two nearest buildings.

The result has been an optimised design providing a new layout:

1. The Tender Design provision for Switch M1-M4 was 1 "T type" and 4 "T* type" tunnels disposed at a diamond pattern, in addition to the two running tunnels (Figure 7.3). In the revised layout (Figure 7.5) only one "T1.2 type" tunnel was necessary (incorporating the running tunnels) with a total length of approximately 90m, which is much shorter than the total length of the tunnels of the Tender Design (approximately 200m).
2. The new lay-out avoided thin pillars between the underground structures minimizing the disturbing effects due to their excavation.

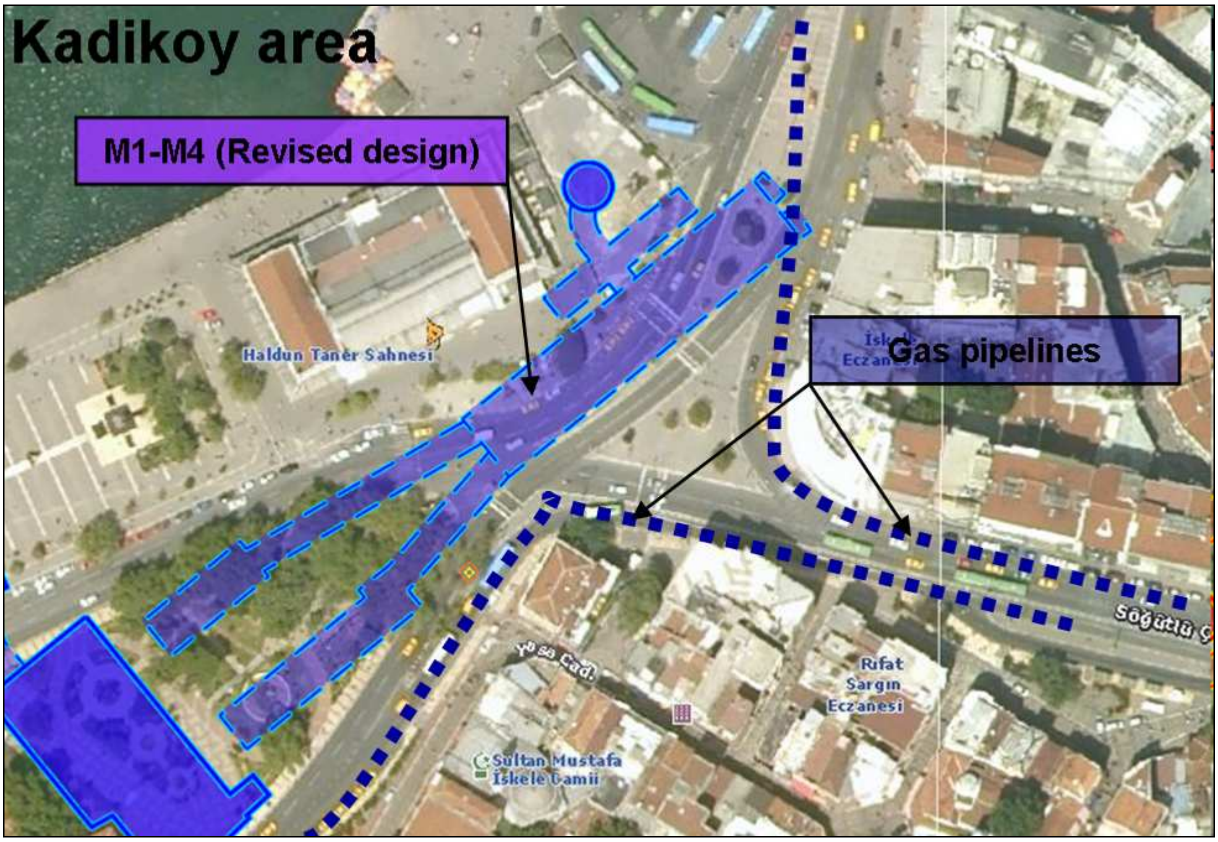


*Fig. 7.5: Kadikoy area – M1-M4 revised lay-out.*

In addition to the extensive optimisation of the lay-out, the primary objective to minimise settlements with their associated risk has led to the adoption of a sequential excavation technique for the cavern with use of grouting from inside the tunnel in order to limit the effects of rock mass relaxation. Various parametric numerical analyses were performed to support this design choice (Figure 7.6).

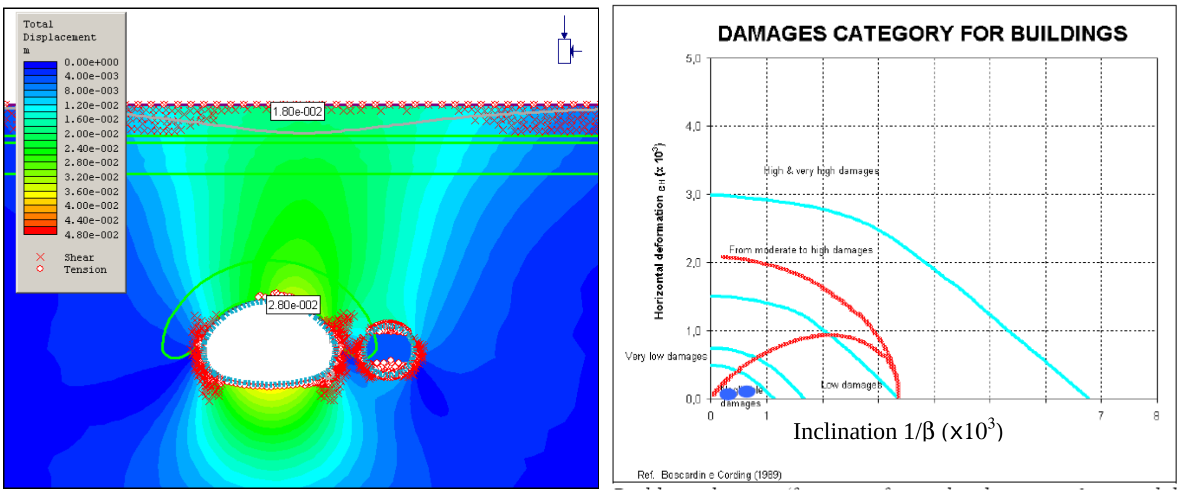


*Fig. 7.6: Kadikoy area – Revised design lay-out. Numerical analyses and evaluation of the effects on the existing structures following the methodology of Boscardin & Cording(1989).*

Grouting was performed from inside the first side drift (Figure 7.7) with grout injections designed directly on site by the Geodata team based on the actual absorption capacity of the rock.

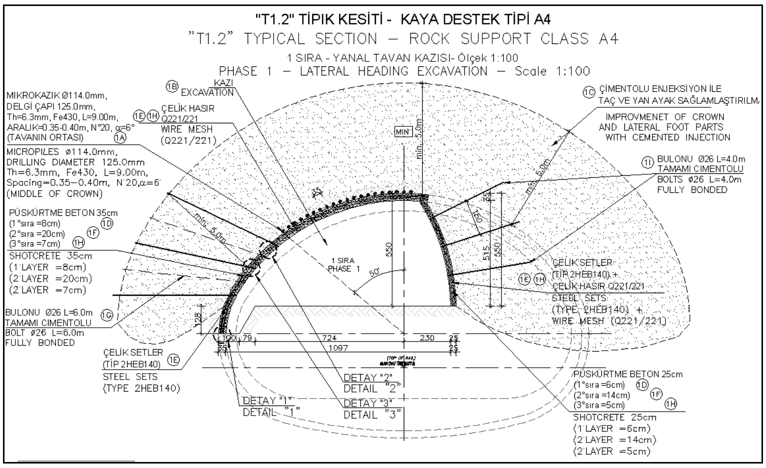


*Fig. 7.7: Kadikoy area – M1-M4 revised project - Grouting from the first side drift.*

Excavation works according to the revised design of Kadikoy Switch commenced in January 2009 and were successfully completed at the end of June 2009, with minimal displacements inside the tunnel and settlements at the surface.

In Figure 7.8 the M1-M4 complete section is shown.

*Fig. 7.8: Kadikoy area – M1-M4 complete excavated sections.*

The design methodology applied to the Kadikoy switch and the successive experience acquired in guiding the subcontractors to minimize interference between the underground excavation and the surface facilities was also adopted for the following two complex underground structures:

1. Acibadem station;
2. Bostanci station.

The provision of the Tender Design for these two stations was cut and cover construction, but due to different problems such as difficulties in expropriating areas, interference with motorway (it is not possible to interrupt even partially traffic without creating big problems to the entire traffic system), interference with buildings and public utilities, it was necessary to review these structures as mined caverns.

- **Acibadem station**

The revised design provides for minimum interference to structures and facilities at the surface, as there are only three shafts (access and technical shafts) and two openings for stairs.

One of the challenges of Acibadem station design was to construct the access tunnel passing below the motorway and a water pipeline (aqueduct) ensuring that no damage would be caused to them.

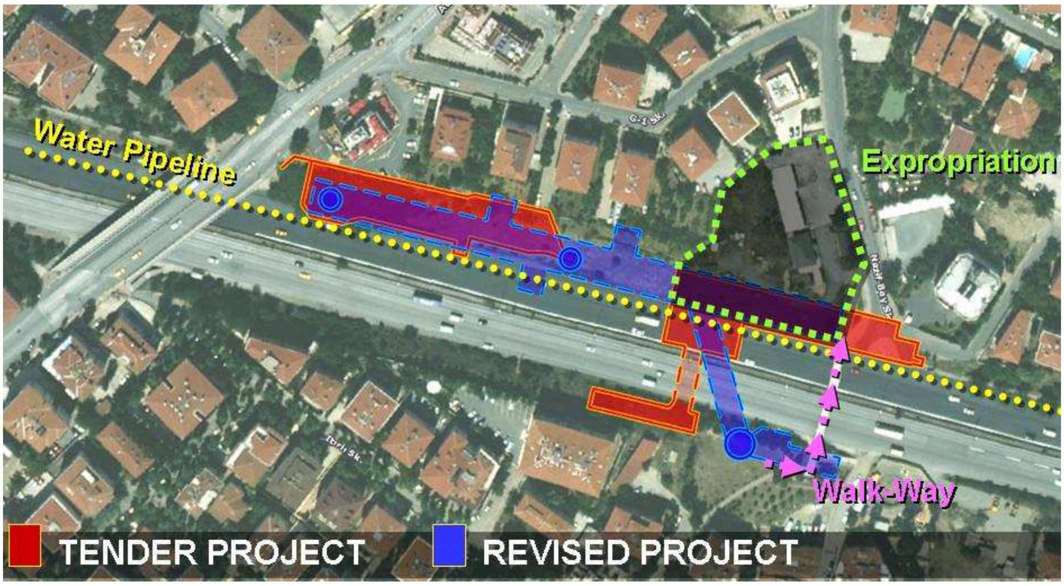


*Fig. 7.9: Acibadem station – comparison between Tender Design (cut and cover structures) and revised design (shallow mined cavern).*

In Figure 7.10 the longitudinal profile of the access tunnel is shown where umbrella arches were systematically used (where the geometrical curvature of the access tunnel route made the installation of micropiles impossible, but where the station typical section would be opened later on the umbrella arch technique was substituted by spiling) in order to:

- Prevent rock mass relaxation;
- Minimise displacements inside the tunnel and in the surrounding medium;
- Protect the water pipeline running parallel to the motorway.

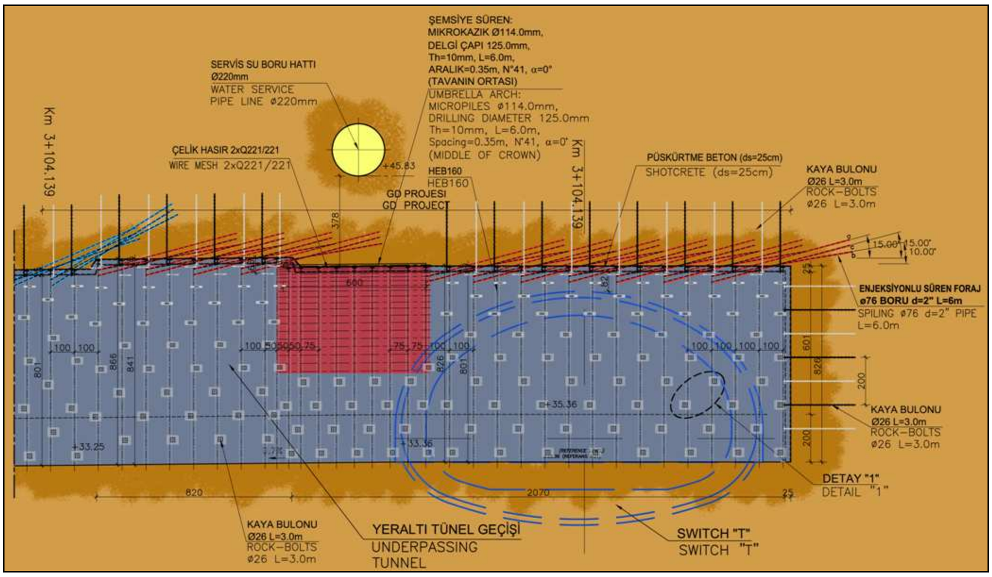


*Fig. 7.10: Acibadem station – Temporary support of the access tunnel - longitudinal profile.*

The Acibadem station was excavated using “T type” tunnel section. Also in this case a risk management plan was developed with constant designer supervision on site in order to apply the best solution evaluated by the Design Team.

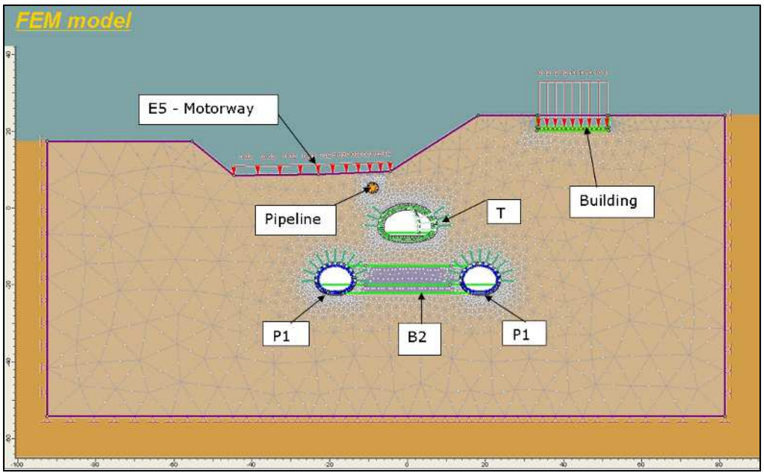


*Fig. 7.11: Acibadem station – numerical model.*

The excavation works according to the revised design started in the spring of 2009 and are now completed (Figure 7.12 is representative of the excavation works at the beginning of summer 2009).

*Fig. 7.12: Acibadem station – Excavation inside T type section.*

- **Bostanci station.**

The original station design (cut and cover structures) has been revised (see Figure 7.13), providing now for a series of mined tunnels to connect the optimized cut and cover structures. This revision was done in order to avoid any adverse condition that could arise from traffic deviations along the E-5 Motorway.

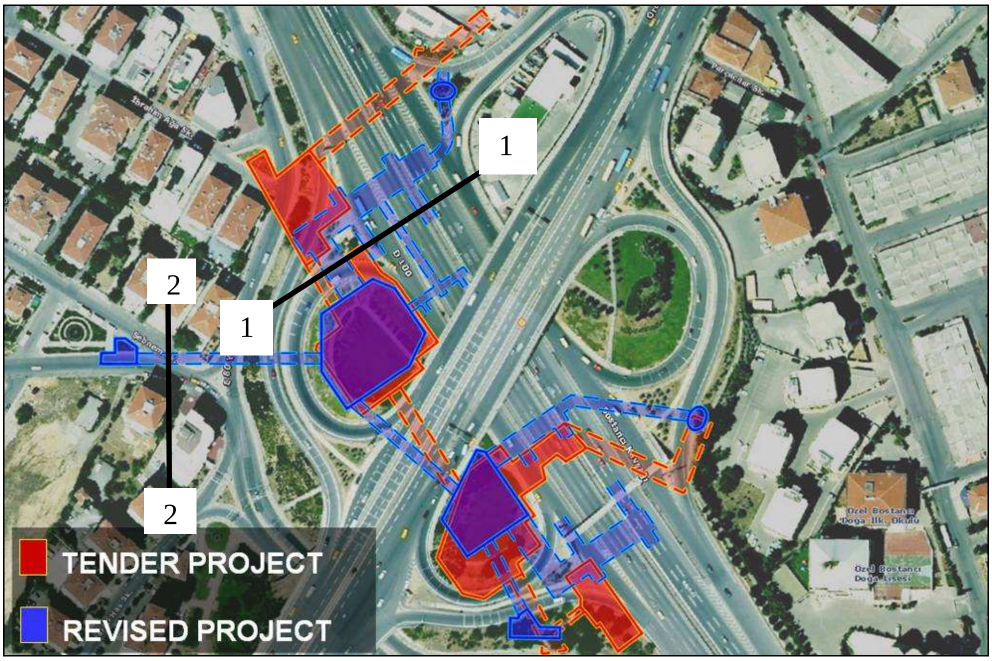


*Fig. 7.13: Bostanci station – comparison between Tender design (cut and cover structures) and the revised design (shallow mined caverns and tunnels).*

In this revised design several mined tunnels connect the cut and cover structures. Each tunnel was studied considering the presence of the other tunnels. Different rock support classes and special extra support systems were predefined in order to solve the problems that could be encountered during the excavation works. In Figure 7.14 two of the numerical models are shown, where the support system for the underground structures (Section 11) and the interference between the underground structures and the near buildings (Section 22) are shown.

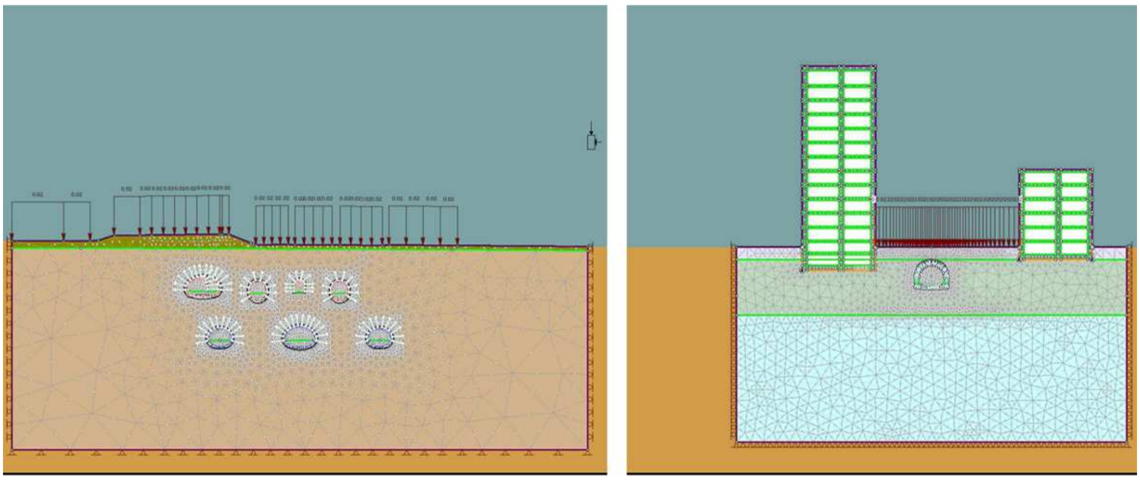

*Fig. 7.14: Bostanci station – Sections 11 and 22 - numerical models.*

## 8. Conclusions

Istanbul Metro has been a successful and extraordinary experience of design-construction of large-scale infrastructure projects in a complex and dense urban context.

Despite the presence of significant obstructions and very demanding contractual terms, a significant revision of the tender design including modifications in the alignment, layout and position of stations was made.

Furthermore, despite the numerous difficulties in organising the construction sites, more than 70 conventional excavation fronts have been working simultaneously in the city, involving only local manpower. At the time of writing this article all difficult excavations have been completed without accidents or delays, reaching an average progress of 150m per day.

The case of Istanbul Metro reported in this paper demonstrates that even in the new era of extensive use of mechanized excavations especially by TBMs, construction by conventional techniques remains as an efficient, economic and safe means for realizing underground infrastructures provided that a risk management plan is implemented earlier from the design stage.

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