

# Comparison of geological conditions predicted from tunnel boreholes and found in situ

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**Abstract** The information available on five tunnels was assessed prior to construction and geological long sections prepared. These were compared to sections prepared as the excavations were undertaken. The tunnels involved were the Bolu tunnel, the Zincirlikuyu tunnel in the Istanbul Metro, the Moda wastewater tunnel, the Beykoz highway tunnel and the derivation tunnel of the Yayladağı dam in Turkey. The paper briefly discusses the variable geology encountered. In an area where extensive faulting has taken place, the subvertical faults were frequently not predicted from the boreholes. The work has shown the importance of undertaking a full investigation, possibly involving oblique boreholes and/or the use of geophysical and other downhole photographic methods to ensure the most accurate sections can be produced. The paper notes that in the case of these five tunnels, the investigation costs varied between 1 and 2% of the total cost of the projects.

**Résumé** Les informations disponibles concernant cinq tunnels ont permis la réalisations de coupes géologiques prévisionnelles. Celles-ci ont été comparées aux coupes établies en suivant l'excavation de ces tunnels: les tunnels de Bolu, de Zincirlikuyu du métro d'Istanbul, de Moda, le tunnel autoroutier de Beykoz et le tunnel de dérivation du barrage de Yayladağı en Turquie. L'article présente sommairement les conditions géologiques rencontrées. Dans les régions intensément fracturées, les failles subverticales ont été rarement identifiées en sondage. Il est en fait très important de réaliser une reconnaissance

géologique détaillée, avec si nécessaire des sondages obliques, des diagraphies géophysiques et des photographies en sondage permettant d'établir de bonnes coupes prévisionnelles. L'article souligne que pour ces cinq tunnels les coûts de reconnaissance ont représenté de 1 à 2% du coût des ouvrages.

**Key words** Predictions · Site investigation · Tunnels · Turkey

**Mots clés** Prévisions · Reconnaissances géologiques · Tunneles · Turquie

## Introduction

Geological sections of tunnels are prepared on the basis of information obtained from field observations and drilling activities conducted prior to the commencement of the tunnel excavation. The reliability of these geological sections affects the design and cost of the tunnel and whether it can be completed in the projected time. It is important therefore that the ground conditions anticipated from the investigation boreholes are similar to those encountered during the tunnel excavation.

This paper discusses five excavations: part of the Bolu tunnel, the Zincirlikuyu tunnel in the Istanbul metro, the Moda wastewater tunnel, the Beykoz highway tunnel and the derivation tunnel of the Yayladağı dam in Turkey (Fig. 1). The geological conditions and construction details of the five tunnels are given in Table 1. The geological sections prepared from the investigation boreholes are compared with observations made during the excavation of these tunnels and the similarities/differences between them are discussed.

The site investigation may account for a significant proportion of the project budget; typically 1–2% of the total cost, but in some cases as much as 12–20% may be required for geotechnical services in order to properly consider the geological, geophysical, engineering, soil and

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**Table 2**

Estimated cost of site investigation (SI) and construction for the tunnels studied

Tunnel	Site investigation cost (€)	Construction cost (€)	SI as % of construction cost
Bolu	63 350	6 271 650	1
Zincirlikuyu	12 000	600 000	2
Moda	3 500	411 760	0.85
Beykoz	20 300	1 691 600	1.2
Yayladağı	21 100	2 131 310	0.99

North Anatolian fault zone (Dalgıç 1994). In this study, the section of tunnel between the Yedigöller and İkizoluk formations is examined.

#### Zincirlikuyu tunnel, İstanbul metro

The Zincirlikuyu tunnel was the first excavation stage in the İstanbul metro between Taksim and Levent and encountered the Trakya formation of Carboniferous age. This formation is composed mainly of alternating sandstone and mudstone. Both horizontal and vertical facies changes are very common. A number of andesite, diabase and micro-gabbro dykes cut the Trakya formation, generally perpendicular to the bedding. The width of dykes varies from a few meters to 100 m (Biberoglu and Dalgıç 1996). In addition, there are quartz and calcite veins of between 200 and 300 mm thickness.

#### Moda wastewater tunnel

As in the first excavation stage of the İstanbul metro, the Moda waste tunnel passes through the sandstones and mudstones of the Trakya formation and hence encountered natural materials with very different geomechanical properties, above which there was much fill.

#### Beykoz tunnel

The oldest rocks in the Beykoz tunnel are part of the Kurtköy formation of Ordovician age. In the vicinity of the tunnel this formation consists of conglomerate, sandstone and mudstone. Overlying these strata as a result of tectonic activity is the Aydos formation also of Ordovician age and comprising quartz conglomerate and quartz arenite. Andesite dykes up to 10 m thick are common along the tunnel route, generally trending NW-SE.

#### Derivation tunnel of the Yayladağı dam

The derivation tunnel of the Yayladağı dam is constructed within the peridotites and serpentinites of the Kızıldağ ophiolite. Harzburgites are the dominant peridotitic rock found within the tunnel axis. They are greenish-black in colour with only rare serpentinitisation. Where the orthopyroxenes change to bastite, the harzburgites have a spotted appearance with a silvery brightness of light yellow and light green colours. It was noted from some samples collected at the dam site that as the amount of olivine crystals increased, the harzburgites changed to dunitites, while

with an increased proportion of clinopyroxenes, they changed to lherzolites. Serpentinites within the peridotites are another important lithological unit in the drainage tunnel. The greenish-grey serpentines comprise peridotite pebbles and blocks.

## Borehole investigations

#### Bolu tunnel

A total of 33 boreholes were drilled in the Bolu tunnel section of the Anadolu motorway. Some of these were continued to the tunnel elevation while some were terminated at shallow depths for correlation purposes. The six boreholes considered in this study extended from 57.5 to 257 m.

#### Zincirlikuyu tunnel

The general investigation for the İstanbul tube tunnel and metro route included 60 boreholes. These provided information on the lithology, groundwater and structural features. In order to determine the geotechnical properties of the rocks and soils along the metro route, samples were collected and tests carried out in the boreholes. Additional investigation boreholes were undertaken during the construction of the metro. Some of these boreholes were drilled for more detailed investigation of the strata and some to obtain in situ measurements. Five of the initial investigation boreholes were undertaken in the Zincirlikuyu tunnel section of the İstanbul metro, extending to depths of between 24.75 and 30.75 m.

#### Moda tunnel

As the route of the Moda wastewater tunnel was entirely below fill/residential development, the only exposures that could be observed were in a limited number of cliffs and construction holes. This background information on the engineering geology of the region was evaluated together with the underground data obtained from the investigation boreholes. In total, some 649 m of core drilling was undertaken in 35 boreholes along the route, in some of which pressure-meter testing was undertaken (Dığış 1990).

#### Beykoz tunnel

The investigation for the Beykoz tunnel included nine rotary-cored boreholes but only a limited number of in situ permeability measurements and amount of laboratory testing. In areas where clay-filled faults and joints existed the recovery tended to be poor, hence the occurrence of these features during the tunnel drive was underestimated.

#### Yayladağı dam

The Adana Branch of State Water Works (DSI) drilled five investigation boreholes on the line of the derivation tunnel for the Yayladağı dam. The depth of these varied between 21 and 60 m. Features of rock mass were determined and Packer tests were undertaken in the boreholes to assess water absorption.

rock mechanical aspects. However, in some cases, even when an investigation costing 20% of the budget has been undertaken, there may be significant differences between the predicted and encountered geological conditions, for instance heavy localised inflows of groundwater, or the extent and position of karstic formations less than 60 m long (Nagel 1992) which were not identified during pre-construction investigations. The site investigation and construction costs of the five tunnel schemes considered here are given in Table 2. The figure in the last column of the table is the site investigation cost expressed as a percentage ranges from 0.1 to 2%. In some parts of the Bolu tunnel (not evaluated in this study) the investigation costs amounted to 20% of the construction costs as a pilot study was subsequently undertaken.

## Brief details of the studied tunnels

The Bolu tunnel is the most important motorway tunnel in the İstanbul–Ankara area. The project involves twin tunnels at an elevation of 800 m above sea level and with a maximum thickness of overburden of 250 m (average 50–100 m). The excavated width of the tunnels is 16 m and the height 11.5 m. When completed, the horizontal opening and height of the tunnels will be 14 and 8.6 m respectively. The tunnels are between 30 and 60 m apart. The length of the right-hand tunnel will be 3326 m while the left-hand tunnel will be 3287 m. To date, the tunnels have been excavated to a length of some 1200 m from the Asarsuyu and 400 m from the Elmalık entrances.

The first stage of the İstanbul metro is still under construction between Taksim and Levent. It began from Taksim and for much of its 7040 m length this section passes at a depth of some 22 m beneath an intensely developed housing area. The remaining 880 m, known as the Zincirlikuyu tunnel, will connect Şişli and Levent.

The Moda wastewater tunnel was constructed in Kadıköy on behalf of the İstanbul Water and Sewage Management (İSKİ) as part of the İstanbul sewage project. The majority of the 1226 m long, 3.96 m diameter tunnel was excavated using a full-face tunnel boring machine (TBM). The Beykoz road tunnel is located in İstanbul city. The horse-



Fig. 1  
Location of tunnels

shoe-shaped tunnel has a finished span of 10.6 m, a length of 625 m and a height of 50–65 m. The tunnel is being excavated using the bench method, the excavation of the lower bench following the upper bench along a distance of 50 m.

The Yayladağı dam is being constructed 8 km north of Yayladağı where the city of Hatay is located at the confluence of the Gökpınar and Kızlaroğlu rivers. Constructed for drinking water and irrigation purposes, Yayladağı is a rock-fill dam with a height of 47.4 m from the basement and 44.4 m from the thalweg (river profile). The crest length is 191 m. The volume of the dam is 360,000 m<sup>3</sup> while its lake volume is 7.55 million m<sup>3</sup>. Its 310 m long derivation tunnel is on the right-hand side and is circular in shape with a diameter of 3 m.

## Geology of the tunnels

### Bolu tunnel

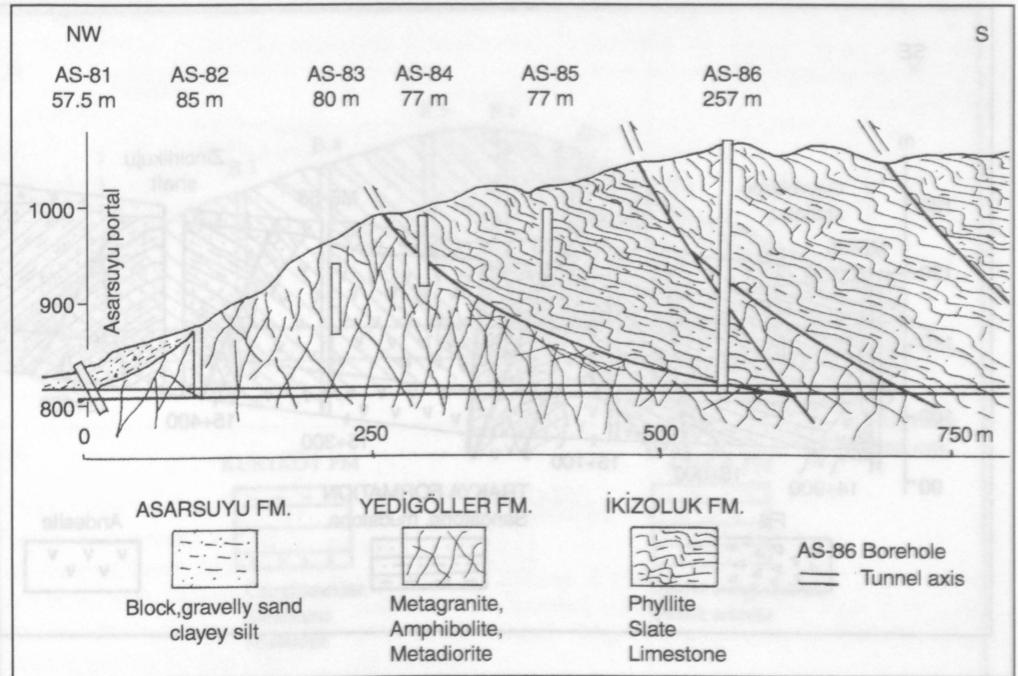
The Yedigöller formation consists of metamorphic rocks and is the oldest unit present at the Asarsuyu entrance of the Bolu tunnel. It is tectonically overlain by the metamorphic İkozoluk formation of Devonian age. Above these strata are the upper Cretaceous to upper Eocene sedimentary units. The tunnel route passes through weak zones related to paleotectonic thrust faults and the neotectonic

Table 1

Geological and construction details of the tunnels studied

Tunnel	Purpose	Geology	Length (m)	Dimensions of opening (m)	Depth of cover (m)
Bolu	Motorway	Metagranite, amphibolite, metadiorite and phyllite slate	3326	11.5 × 16	50–250
Zincirlikuyu	Metro	Sandstone and mudstone	3287		
Moda	Waste	Sandstone and mudstone	880	24–100	22
Beykoz	Highway	Sandstone and quartzite	1226	3–6	5–20
Yayladağı	Derivation	Peridotite and serpentinite	625	10.6	50–65
			310	3	40–70

**Fig. 4**  
Observed geological section of the Bolu tunnel (Dalgıç and Gözübol 1996)



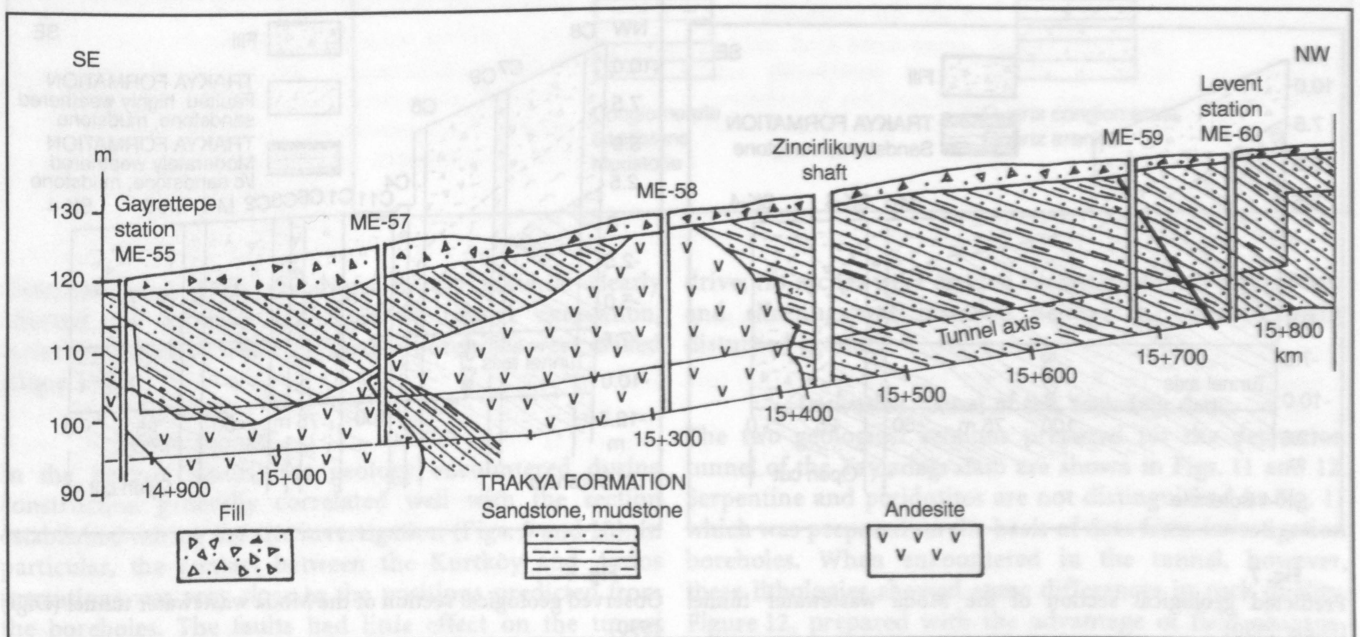
**Zincirlikuyu tunnel**

The presence of a dyke (Fig. 5) in the Zincirlikuyu tunnel section of the İstanbul metro was determined on the basis of borehole data (IRTC 1988). The geological section of the tunnel which was prepared on the basis of field observations and data of Köksal et al. (1996) is shown in Fig. 6. The dyke predicted from the borehole data was identified during the tunnel works; as can be seen from the two figures, the only difference in the two sections is the geometric shape of the dyke. In the prediction, the hypabyssal material was shown to be more of a sill-like feature. In reality, however, as indicated by the tunnel, the intrusive material was more vertical and hence dyke-like. The

number of boreholes, their depth and the experience of the person who prepared the borehole log and geological section are clearly important factors when predicting the likely geology along a tunnel. As shown, the prediction is likely to be as good as the background of the person who undertakes the work.

**Fig. 5**

Predicted geological section of the Zincirlikuyu tunnel in the İstanbul metro (IRTC 1988)



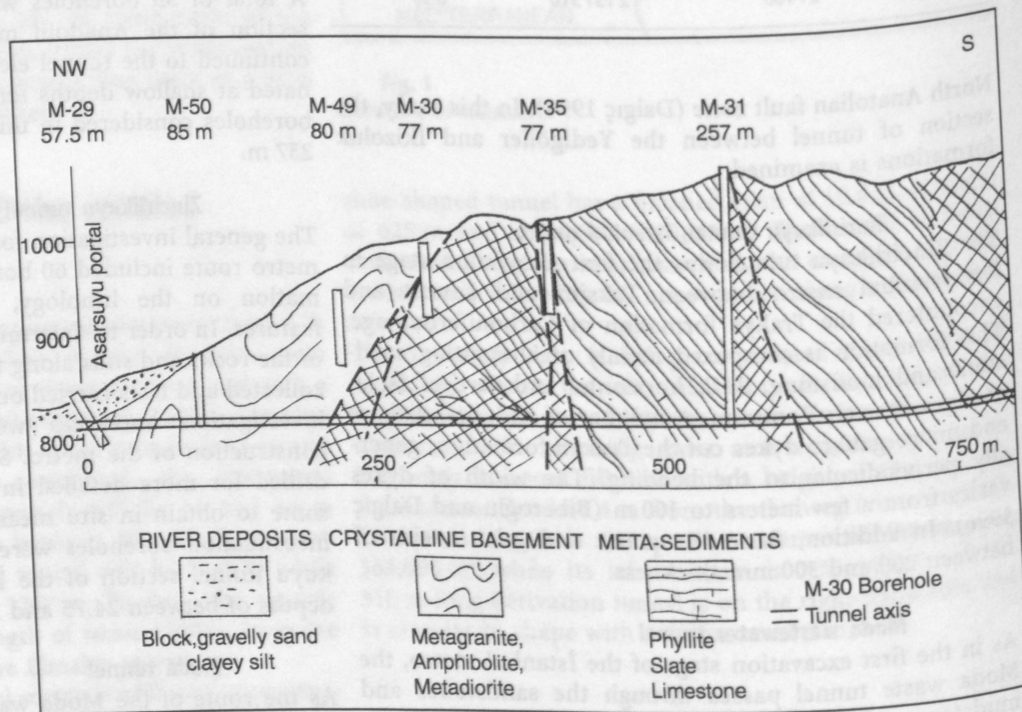
## Comparison of predicted and observed geological conditions

### Bolu tunnel

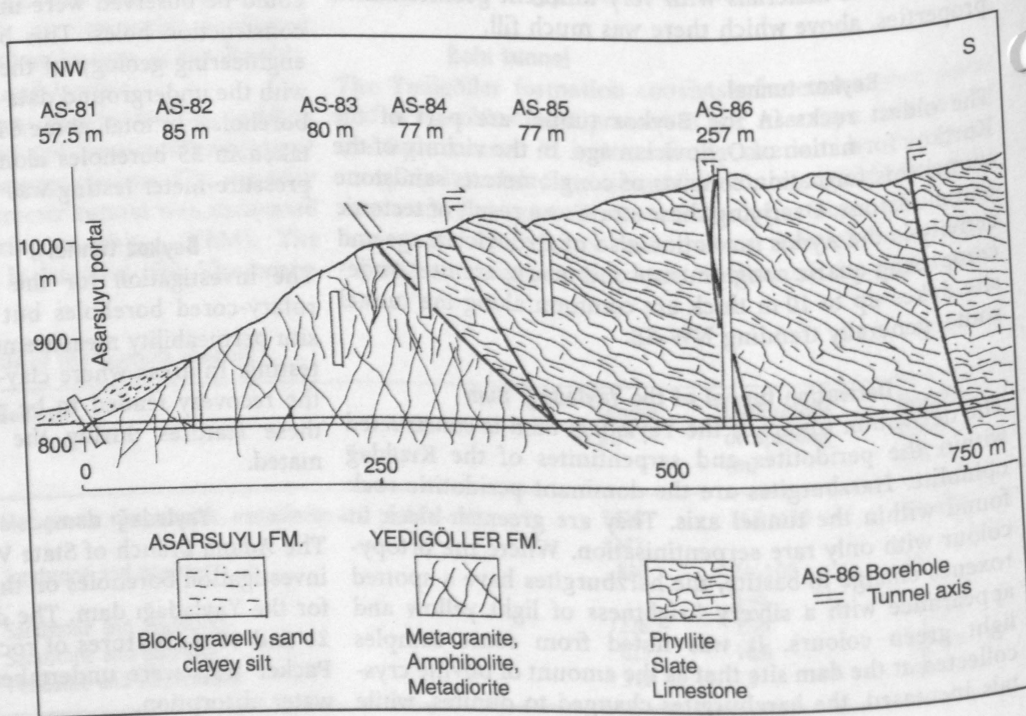
Geological sections for the Bolu tunnel, based on the borehole data, are shown in Figs. 2-4. Figures 2 and 3 were prepared by Kleberger (1992) and Dalgıç (1994) respectively prior to the opening of the tunnel, while the section shown in Fig. 4 was prepared after completion of the

excavation (Dalgıç and Gözübol 1996). The information shown in Fig. 2 does not reflect the preconstruction evaluation of the regional tectonics. When thrust faults were encountered during the works, it was necessary to change the design based on Fig. 2. This caused a 1-year delay to the Bolu tunnel project and was explained as an unexpected geological situation. However, squeezing and swelling associated with the thrust zone had in fact been predicted before the excavations took place (Dalgıç 1994; Dalgıç and Gözübol 1995).

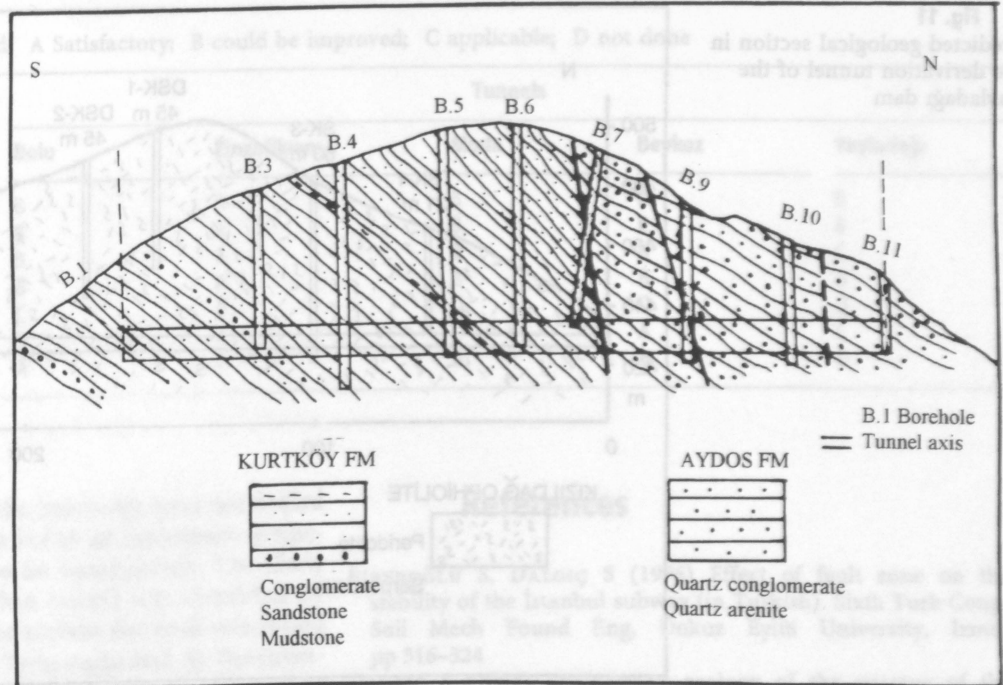
**Fig. 2**  
Predicted geological section of the Bolu tunnel (Kleberger 1992)



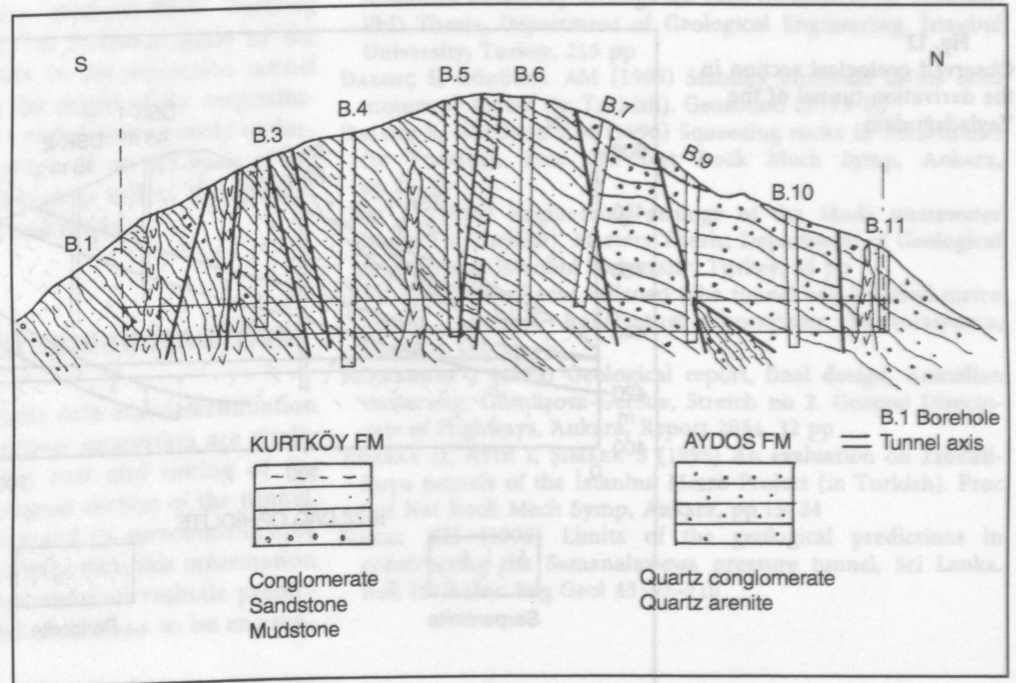
**Fig. 3**  
Predicted geological section of the Bolu tunnel (Dalgıç 1994)



**Fig. 9**  
Predicted geological section of  
the Beykoz tunnel



**Fig. 10**  
Observed geological section of  
the Beykoz tunnel



disturbed zone. Such variations in the material clearly affected the method and cost of tunnel excavation, including the delay while the further boreholes were drilled (Dığış 1990).

#### Beykoz tunnel

In the Beykoz tunnel, the geology encountered during construction generally correlated well with the section established during the site investigation (Figs. 9 and 10). In particular, the contact between the Kurtköy and Aydos formations was very close to the positions predicted from the boreholes. The faults had little effect on the tunnel

drive; rib arches were erected each time a fault was crossed and sheeting was installed behind the ribs in badly disturbed ground.

#### Derivation tunnel of the Yayladağı dam

The two geological sections prepared for the derivation tunnel of the Yayladağı dam are shown in Figs. 11 and 12. Serpentine and peridotites are not distinguished in Fig. 11 which was prepared on the basis of data from investigation boreholes. When encountered in the tunnel, however, these lithologies showed some differences in rock quality. Figure 12, prepared with the advantage of field observa-

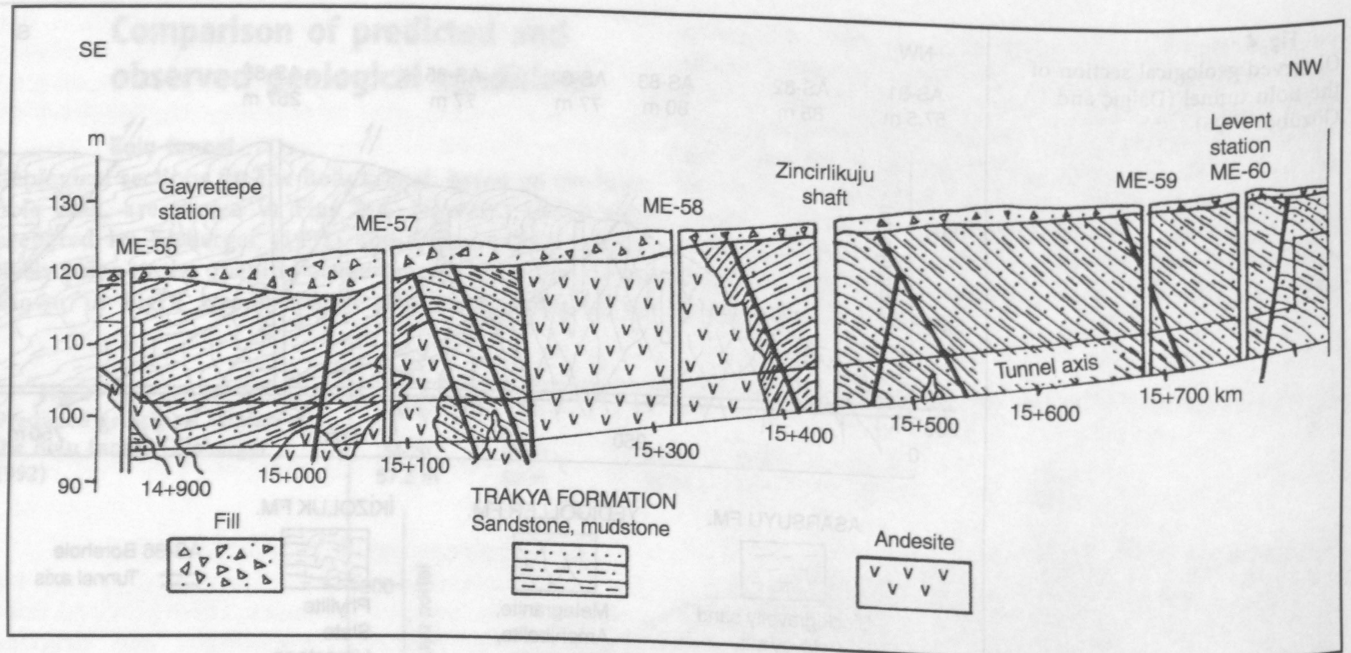


Fig. 6

Observed geological section of the Zincirlikuyu tunnel in the İstanbul metro

**Moda wastewater tunnel**

Some 68 m from the entrance shaft of the Moda wastewater tunnel, weak soil conditions were encountered in the upper part of the panel and the material moving in from the crown decreased the operational efficiency of the full-face TBM (Fig. 7). Pulling the machinery back resulted in subsidence in the area where the excavation had taken place and the loose material in front of the TBM hindered its rotation.

Additional investigation in the soil profile yielded significant differences which had not been predicted from the

previous studies. In particular, it confirmed the presence of a fault zone in the area where the subsidence occurred (Fig. 8). The variation between the strong sandstones and the weaker mudstones, clearly evident from the drilling, made it difficult to draw sections as no distinctive marker horizons were observed. The initial ground investigation and subsequent investigations showed the bedrock to dip towards the river with a gentle slope. The thickness of the bedrock above the tunnel crown was considered to vary with probably only some 2 m of bedrock above the tunnel as it progressed from the shaft entrance. However, very altered and disintegrated rock fragments were observed some 60 m from the area where the subsidence had occurred, where these materials were present in a fault-

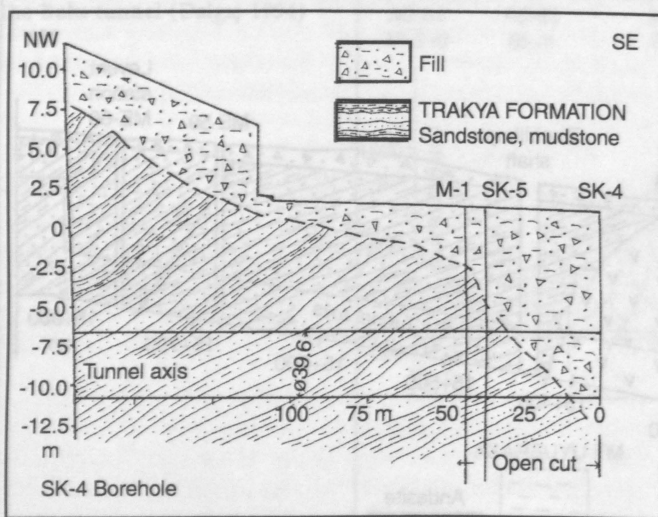


Fig. 7

Predicted geological section of the Moda wastewater tunnel (Diğış 1990)

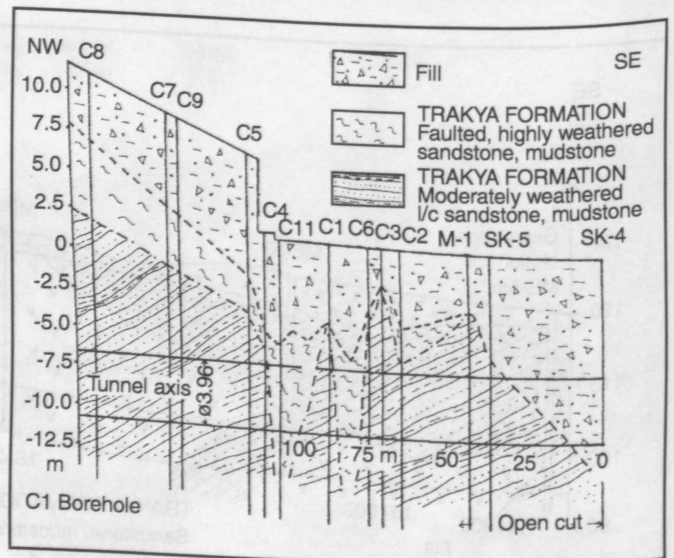


Fig. 8

Observed geological section of the Moda wastewater tunnel (Diğış 1990)

Table 3

Evaluation of the tunnels studied. A Satisfactory; B could be improved; C applicable; D not done

Item	Tunnels				
	Bolu	Zincirlikuyu	Moda	Beykoz	Yayladağı
Preliminary information	B	A	B	B	B
Boreholes and samples	B	A	B	B	C
In situ and laboratory tests	B	A	B	B	B
Use of test results	B	A	D	D	D
Geophysical survey	C	D	C	A	C
Geological interpretation	B	A	B	B	D
Construction records	A	A			

the Moda wastewater tunnel, the boreholes were not drilled in the correct direction, which led to an inaccurate prediction of the rock conditions to be encountered. The likely presence of faults in the Beykoz tunnel was identified by the boreholes, but during construction the rock was found to have more faults than had been suggested by the investigation data. This was inevitable, as although the vertical boreholes would intersect the medium-thick bedding planes, they would be unlikely to intersect many of the vertical or steeply inclined faults. In the derivation tunnel of the Yayladağı dam, because the origin of the serpentinisation and the tectonism of the region were poorly understood, the geological sections prepared on the basis of the investigation data did not adequately reflect the ground conditions encountered in the excavations.

### Conclusions and recommendations

Correct evaluation of the borehole data and determination of problematic areas prior to tunnel excavation are vitally important in terms of both the cost and timing of the project. When preparing a geological section of the tunnel, the tectonics history of the route and its surrounding area must be carefully considered as only with this information can the borehole data be interpreted and realistic predictions made of the likely ground conditions to be encountered during the tunnel drive.

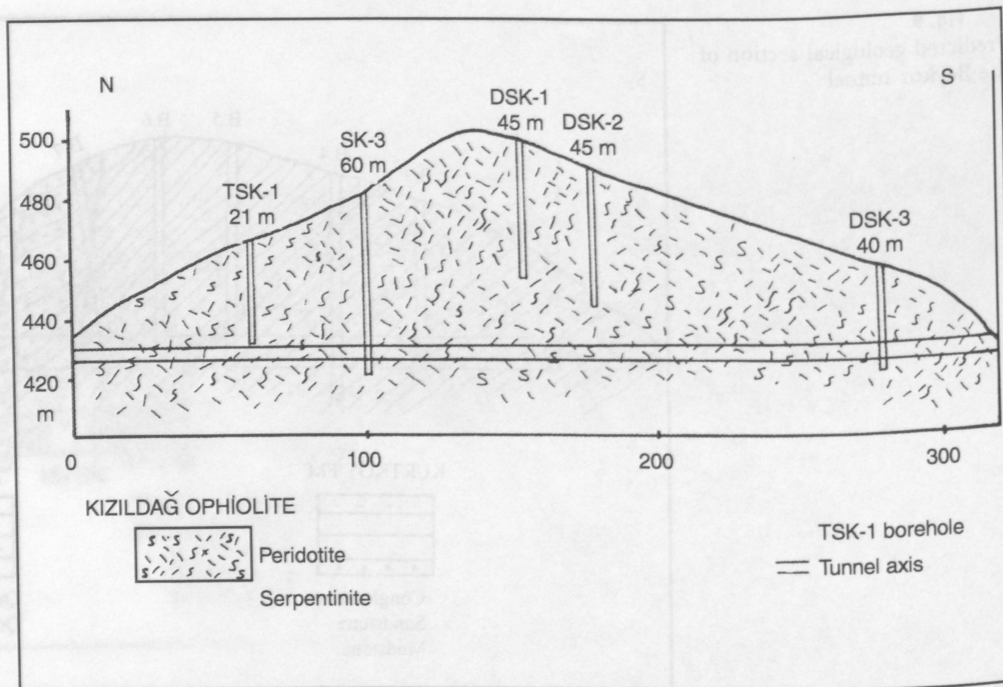
The case studies have indicated that the best use was not always made of the opportunity for site investigation and testing. For the investigation in rock, further information on the rock mass properties could have been obtained by use of downhole cameras, while in some circumstances the use of inclined boreholes, geophysical survey and trial shafts would also have been beneficial.

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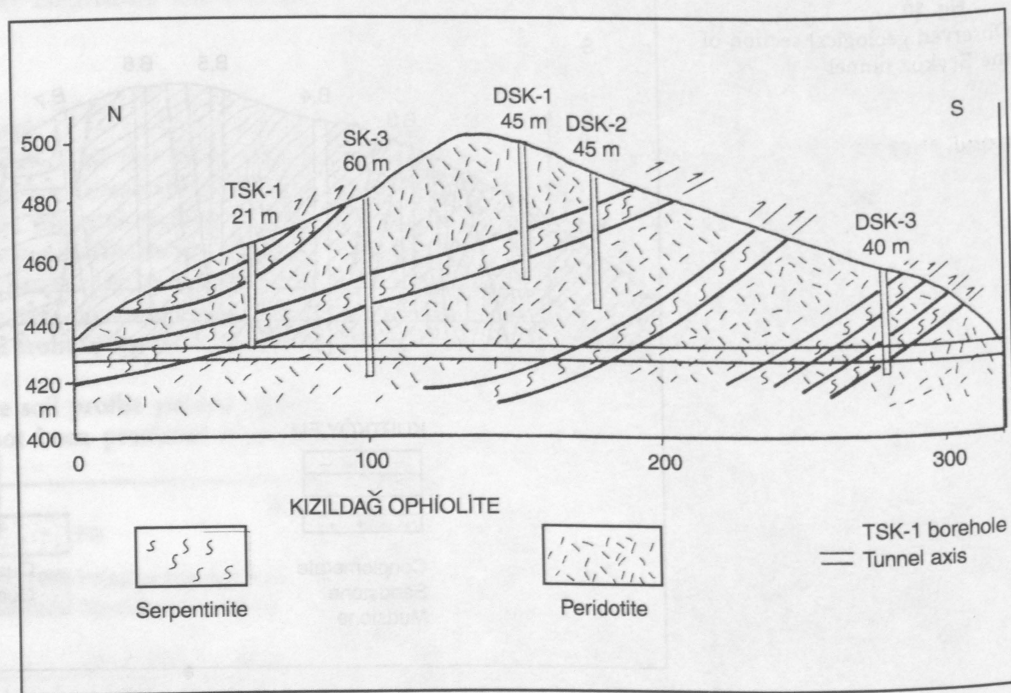
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**Fig. 11**  
Predicted geological section in the derivation tunnel of the Yayladağı dam



**Fig. 12**  
Observed geological section in the derivation tunnel of the Yayladağı dam



tions as well as the regional tectonic features interpreted from the borehole data, clearly indicates that the serpentinisation seen in the investigation boreholes (Fig. 11) can be related to the north-south tectonic lines.

### Evaluation

The results of the case histories are summarised in Table 3. It is emphasised that this is to some extent a subjective

assessment, but it indicates some interesting points. In view of the tectonic regime of the region, the boreholes drilled in the Bolu tunnel were insufficient in both number and depth and, as a consequence, there were significant differences between the predicted and observed rock conditions. However, for the Zinirlikuyu tunnel section of the İstanbul metro the conditions encountered were similar to those predicted. The number and depth of the investigation boreholes were appropriate and led to the construction of a more accurate geological section and a better evaluation of the ground conditions. In the case of