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Geotechnical Inspections and Applications in Underground Rail System Constructions: Halkalı - İstanbul Airport Metro Line Example

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Abstract: In this study, geological researches carried out before the construction of underground rail systems and geotechnical application methods preferred during the construction were examined within the scope of Halkalı-İstanbul Airport metro project. The metro line consists of a total of 66.2 km long underground tunnels, 31.3×2 km main line and 1.8×2 km repertorium connection line. 1006 soil and 1230 rock samples were collected for the main line whose geological research was carried out with 198 core drillings with a total length of 9588.5 m. The results of the laboratory tests on the samples and the field tests carried out in the boreholes were obtained. In addition, a total of four two-dimensional inverse resistivity model were obtained by using the Multi-electrode Electrical Resistance Tomography measurement method in the middle of two lines (Line-1 Km. 61+440 – 61 +660 /Line-2 Km: 61 +400 - 61+620), in the Olympic Stadium station (Km: 62+215 – 62 +490) and in the TBM route (Line-2 Km: 62 +835 – 63+050). The geological sections obtained from the drillings and the geophysical sections obtained by the electrical resistivity method were compared.

Yeraltı Raylı Sistem İnşaatlarında Jeoteknik İncelemeler ve Uygulamalar: Halkalı - İstanbul Havalimanı Metro Hattı Örneği

Anahtar Kelimeler
İstanbul Havalimanı Metro Hattı, Elektriksel Direnç Tomografisi, Elektrik Direnci

Öz: Bu çalışmada yeraltı raylı sistemleri inşası öncesinde gerçekleştirilen jeolojik araştırmalar ve inşası sırasında tercih edilen geoteknik uygulama yöntemleri Halkalı-Yeni Havalimanı metro projesi kapsamında incelenmiştir. Metro hattı 31,3×2 km ana hat, 1,8×2 km depo bağlantı hattı olmak üzere toplam 66,2 km uzunluğundaki yeraltı tünellerinden oluşmaktadır. Jeolojik araştırması toplam 9588,5 m uzunluğunda 198 adet karotlu sondaj ile gerçekleştirilen ana hat için 1006 adet zemin, 1230 adet kaya numunesi toplanmıştır. Numuneler üzerinde yapılan laboratuvar deneylerinin ve sondaj kuyularında gerçekleştirilen arazi deneylerinin sonuçları elde edilmiştir. Ayrıca TBM (Tünel Açma Makinesi) güzergahı iki hattın ortasında (Hat-1 Km. 61+440 – 61+660 / Hat-2 Km: 61+400 – 61+620), Olimpiyatköy Stadı istasyonunda (Km: 62+215 – 62+490) iki adet ve TBM güzergahında (Hat-2 Km: 62+835 – 63+050) olmak üzere Çoklu Elektrotlu Elektrik Özdirenç Tomografi ölçüm yöntemi kullanılarak toplam dört adet iki boyutlu ters çözüm özdirenç yeraltı kesiti elde edilmiştir. Sondajlardan elde edilen jeolojik kesitler ile elektrik özdirenç yöntemi ile elde edilen jeofizik kesitler karşılaştırılmıştır.

1. INTRODUCTION

Transportation problems occur due to the current urbanization in areas where circulation is concentrated such as new city centers, airports and touristic places in the rural areas of the city due to the increasing population and construction. For this reason, institutions turn to rail system public transportation, which is fast, permanent and ecological, to solve transportation problems in metropolitan areas. With the invention of the elevator, a jump similar to that seen in high-rise construction productions were observed with the invention of TBM (Tunnel Borring Machine) in underground rail systems and the use of NATM (New Austria Tunneling Method) in manufacturing.

Underground rail system projects are generally stations, route line, warehouse area, switches, emergency escape shafts, etc. It contains structures of very different sizes, each serving separate purposes. Along the route, geological mapping been made in the zone up to a distance of roughly 150 meters (300 m in total width) on both sides of the tunnel lines. In order to obtain accurate data in problematic areas with karstic cavities where the created geological section is not sufficient, geophysical studies using Multi-electrode Electrical Resistance Tomography method in four different locations have obtained 2-dimensional underground resistivity reverse solution sections. There are even 1 HST (High Speed Train) station and 7 metro stations, 11 switch structures, 8 service stations, 2 emergency escape shafts, 12 construction shafts and 106 cross-passage tunnels. The length of the tunnels in which TBM is used in the project is approximately 55.7 km, and the total length of the tunnels in which the NATM is applied is approximately 15.8 km.

2. LITERATURE RESEARCH

Electrical resistivity method, one of the geophysical research methods, has been used for many years in determining the parameters of the underground. The resistivity method which was first applied by Wenner in 1915, was developed by Schlumberger in 1920 and positive results were reached. With the development of computer and geophysical device technology, the electrical resistivity method allows the examination of underground resistivity changes in one, two and three dimensions. [1, 2]

The main purpose in the application of electrical resistivity methods is to reveal the geological structure by taking advantage of the horizontal or vertical electrical conductivity differences of the rocks. The electrical resistivity method is defined as sending electricity underground with two current electrodes and determining the potential distribution of this current by two potential electrodes through measurements made from the surface. [3] Based on this, some usage areas can be listed as determination of salt water inlets, determination of weathering zone boundary, determination of faults and fractures, karstic cavity and cave research, determination of underground structures for archaeological purposes, determination of mineral deposits and determination of contact places of geological units. [4]

Under what conditions and depending on which circumstances the electrical properties will vary in underground, the resistance of the measured environment depends on the different physical parameters of the rock (such as mineral or liquid content, porosity and degree of water saturation) and these parameters are important factors in the transmission of the current given into the underground. [1]

The transport of electrical load takes place according to two main transmission modes as electronic and electrolytic transmission. In electronic transmission, current flow occurs through free electrons as in a metal, while in electrolytic transmission, current flow occurs through ions. These types of transmission constitute a concept of self-conductivity for each environment. The movement of the electrical charge is a distinguishing feature for self-conductivity substances due to the presence of different physical parameters in each item and is used to distinguish the underground environments from each other. [1]

Table 2.1: Resistivity of some materials. [5]

Material	Resistivity(Ωm)	Material	Resistivity(Ωm)
Chalcopyrite	$1,5x10^{-5}$- $3x10^{-1}$	Soil (upper)	250-1700
Pyrite	$2,9x10^{-5}$-1,5	Dry sandy soil	80-1050
Pyrotite	$7,5x10^{-6}$-$5x10^{-2}$	Sand clay/clay sand	30-215
Galena	$3x10^{-5}$-$3x10^{2}$	Sand and gravel	30-225
Sphalerite	$1,5x10^{7}$	Gravel (dry)	1400
Hematit	$3,5x10^{-3}$-10^{7}	Gravel (saturated)	100
Limonite	10^{3}-10^{7}	Schist(limestone and mica)	20-104
Magnetite	$5x10^{-5}$-$5,7x10^{3}$	Schist (graphite)	10-10^{2}
Ilmenitis	10^{-3}-5x10	Marble	10^{2}-$2,5x10^{8}$
Quartz	$3x10^{2}$-106	Conglomerate	$2x10^{3}$-104
Rock Salt	$3x10^{2}$-10^{13}	Sandstone	1-$7,4x10^{8}$
Anthracite	10^{-3}-$2x10^{5}$	Limestone	5x10-10^{7}
Lignite	9-$2x10^{2}$	Dolomite	$3,5x10^{2}$-$5x10^{3}$
Granite	$3x10^{2}$-10^{6}	Clay	1-10^{2}
Soil (40% clayey)	8	Alluvium and sand	10-$8x10^{2}$
Gabro	10^{3}-10^{6}	Basalt	10-$1,3x10^{7}$
Sea water	$3x10^{-1}$	Clean underground water	10-100

Land consisting of easily meltable rocks that cannot resist abrasion is defined as karstic lands. Karstic regions are formed as a result of dissolution of soluble rocks such as gypsum, salt and limestone by external factors (for example, stream enriched with CO2 in the soil and gaining acidic property, rainwater enriched with CO2 in the air and gaining acidic property). Since the formation and expansion of these gaps depend on the flow of groundwater and surface waters and generally show an irregular spread, they pose a great danger in terms of construction and infrastructure works. Karstic cavities become interconnected during the dissolution process and allow surface water to reach the aquifer. For this reason, the melting process continues continuously and the karstic cavities expand over time. [6]

3. HALKALI-İSTANBUL AIRPORT METRO LINE GEOTECHNICAL EXAMINATIONS

This part of the metro line consists of approximately 31 km of tunnels, seven stations and storage areas in roughly double tubes. The parts of the route within Arnavutköy district center and Küçükçekmece district remain in the densely built area and the remaining parts remain in the areas that are not yet built or sparsely built. The line, which travels roughly north-south between Arnavutköy, Başakşehir and Küçükçekmece districts, ends in Halkalı district of Küçükçekmece District (Figure 3.1).In the project design, there are 104 passage tunnels, 11 switch tunnels, 8 service stations and 13 emergency escape shafts + construction shafts.

Figure 3.1: Halkalı – İstanbul Airport metro line satellite image and integration points.

Geological section of the line is formed by experiments conducted on 1006 soils and 1230 rock samples obtained from 198 cored research drillings with a total length of 9588.5 m. Drilling drills were carried out under the tunnel excavation base to obtain information up to a depth of 5 - 6 m. SPT (Standard Penetration Test) was performed at 1.5 m intervals in ground-like parts including completely weathered rock and disturbed soil samples were taken during the tests. Samples of undisturbed samples (UD) were also taken at appropriate clayey levels of consistency.

Key	Formation	Member	Definition
Yd	Artificial Filling		Off-white, beige colored rock fragments and blocks as well as gravel, sand, clay size intermediate material.
Qal	Alluvium		Gravel, sand, mile, clay.
Tik	İstanbul	Kıraç	Reddish, light brown, gray, mostly gravel and lesser sand-clay unattached material.
Tdg	Danişmen	Güngören	Greenish, dark gray, purple mottled, claystone-shale, sandstone, tuff, tuffite and fine lignite interbedded.
Tda	Danişmen	Ağaçlı	Gravel, sand, clay, coal intermediate level.
Tc	Ceylan		Unallocated; marl, claystone dominant, clayey limestone, calcareous claystone interbedded; calrenite and sparse tuff interbedded.
Tsğ	Soğuçak Limestone		White, cream, ash gray colored reefal limestone, abundant algae, coral, nummuilit, micrite-biomicrite.
TK	Koyunbaba		Sandstone; conglomerate, clayey-sandy-gravelous limestone, limy claystone, marl; coal intermediate level.
Ksgb	Garipçe	Boğazköy	Grey, purplish ash color. Andesitic with mica and feldspar phenocrysts, porphyritic texture.
Ct	Trakya		Black, dark gray, degraded light brown, olive green; thin medium bedded claystone-siltstone-sandstone alternation.
Tçb	Çekmece	Bakırköy	White, beige, thin-medium bedded limestone dominant, clayey limestone, claystone and marl intercalated.
Tçç - Tçg	Çekmece	Güngören Çukurçeşme	Tcç: Yellowish gray, gray mica flakes, medium-sized, cross-bedded, unconsolidated coarse sand and gravel. Tcg: Sand, mile intercalated, green gray clay; interlayer at higher levels.

Figure 3.2: Halkalı – İstanbul Airport metro line stratigraphic columnar section [7, 8, 9 and 10].

In a significant part of the soil samples, only physical and index experiments such as sieve, hydrometer, specific gravity, consistency (Atterberg) limits, water content, unit volume weight were carried out, while in some of these experiments, mechanical experiments such as free pressure and cutting box were carried out. On rock samples, mechanical-elastic tests such as physical and point loading index, poison ratio, uniaxial pressure, and elasticity module was performed. In addition, the geological formations seen in the drillings along the line are listed in Figure 3.2.

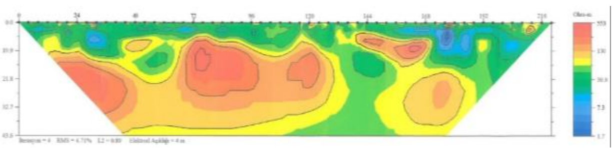

Figure 3.3: Two-dimensional (2D) inverse resistivity model of ERT-1 measurement profile calculated as a result of evaluations [11].

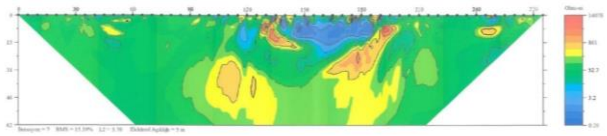

Figure 3.4: Two-dimensional (2D) inverse resistivity model of ERT-2 measurement profile calculated as a result of evaluations [12].

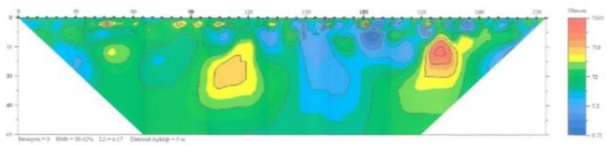

Figure 3.5: Two-dimensional (2D) inverse resistivity model of ERT-3 measurement profile calculated as a result of evaluations [12].

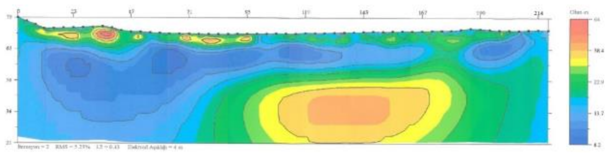

Figure 3.6: Two-dimensional (2D) inverse resistivity model of ERT-4 measurement profile calculated as a result of evaluations [13].

Within the scope of the Halkalı-İstanbul Airport metro line project; a total of four Two-dimensional (2D) inverse resistivity model (Figure 3.3, Figure 3.4, Figure 3.5, Figure 3.6) were obtained by using the Multi-electrode Electrical Resistance Tomography measurement method, two of which were in the middle of lines (Line-1 Km. 61+440 – 61 +660 /Line-2 Km: 61 +400 - 61+620), two of which were in the Olympic Stadium station and in the route of TBM (Line-2 Km: 62 +835 – 63+050).

With the Multi-electrode Electrical Resistance Tomography measurement method applied to determine the lateral and vertical changes of the geological units underground in the study area, the resistivity changes depending on the conductivity of the geological units underground can been mapped in two dimensions.

In the measurements, 56-channel AGI brand Superstring R1 model multi-electrode resistance measuring device and equipment been used and dipole-dipole sequencing method was applied. Electrode range (a) was measured with a total 56 electrodes by selecting a =4 m for ERT-1 and ERT-4 and a=5 for ERT-3. In the measurements, the parameters for each sequence and point were automatically recorded as voltage (millivolts), given current (amperes), calculated resistivity (ohms-m) and error rate (%).

4. COMPARISON OF GEOTECHNICAL AND GEOPHYSICAL SECTIONS OBTAINED IN THE HALKALI-İSTANBUL AIRPORT METRO LINE

Under this heading, the four resistivity reverse solution sections obtained as a result of the multi-electrode electrical resistance tomography measurement method on the line will be compared and interpreted by comparing the geological sections formed with the help of the drillings corresponding to these sections.

Figure 4.1 shows the ERT-1 section formed by geophysical examination at the location of Line-1 Km: 61+440 – 61+660 /Line-2 Km: 61+400 – 61+620 in the middle of two lines on the TBM route and the geological section obtained from HHS-60, HHS-60A and HHS-61 drillings corresponding to this section.

In the HHS-60A drilling at the Km: 61 +514 location, the electrical resistivity value was measured as 30 ohms on average in the artificial filling consisting of gravel units without water for 10 meters. In the continuation of the drilling, it is seen that the electrical resistivity values for water-free, fractured cracked limestone units with a depth of approximately 35 meters increase up to 553 ohms. In the last 5 meters of the drilling, the increase in the fracture crack rate and the presence of groundwater caused the resistivity values to decrease.

In the region where the HHS-61 (Km: 61 +674) drilling of the same resistivity reverse solution section coincides, the electrical resistivity method cannot be displayed after the first 20 meters due to horizontal data loss. The electrical resistivity values measured in the first 20-meter unit analyzed and the unit represented by artificial filling observed in the HHS-60A drilling show parallelism. Another indication of this parallelism is the characterization of approximately the first 20 meters in the HHS-61 drilling log as artificial filling.

The zone with low electrical resistance values between Km: 61+570 - 61+590 can been explained by the possible increase in clay or underground water level and the filling of limestone cracks with water.

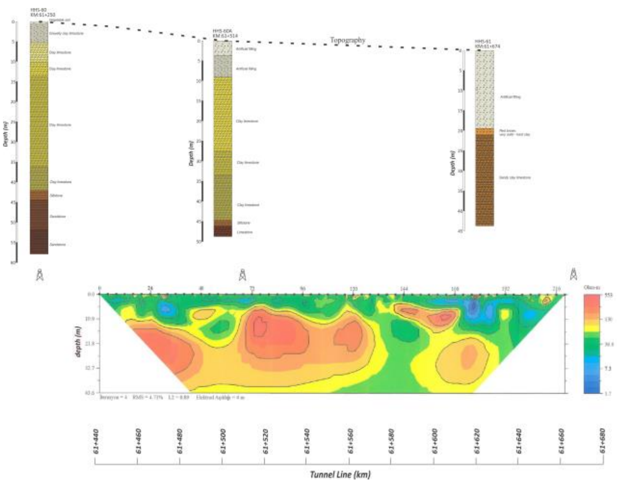

Figure 4.1: ERT-1 reverse solution section and geological section obtained from drillings in the same location.

Figure 4.3 shows the ERT-2, ERT-3 sections formed as a result of the geophysical examination made in Olimpiyatköy station and the geological section obtained from the YHH-81, YHH-81A, YHH-81C and YHH-81E drillings corresponding to these sections.

In ERT-2 and ERT-3 section, there is no difference in electrical resistivity values in the analyzes corresponding to YHH-81A and YHH-81E drillings. This situation is related to the continuity of the fractured cracked structure at a very high rate, as can be seen in the drilling crate photo in Figure 4.2.

In ERT-2 and ERT-3 section, there is no difference in electrical resistivity values in the analyzes corresponding to YHH-81A and YHH-81E drillings. This situation is related to the continuity of the fractured cracked structure at a very high rate, as can be seen in the drilling crate photo in Figure 4.2.

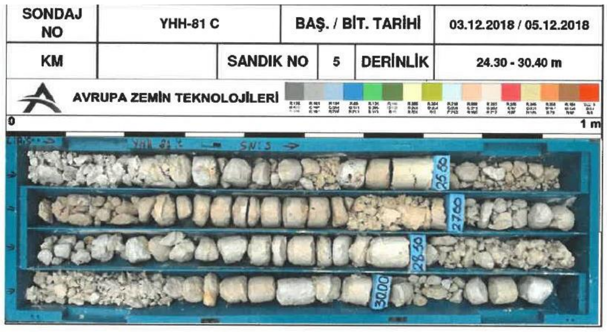

Figure 4.2: YHH-81C drill 24.30 m – 30.40 m caisson image (Soğucak limestone formation) [9].

On the other hand, the distinction between filler and limestone is clear in the regions corresponding to YHH-81C drilling in resistivity reverse solution sections. The electrical resistivity values in the filling part were 10 – 15 ohm.m due to the fact that the filling consisted of clayey silty units, while it was 50 – 70 ohm.m due to the cracked structure in the limestone.

The remarkable in these two sections are the inclusions with relatively high electrical resistivity values at the levels of 7000 ohm.m and 14000 ohm.m, which emerge close to the surface and at a depth of 30-30 meters from the surface. The high electrical resistance values that occur suddenly in limestone can been explained by the decrease in conductivity due to the possible karstic gaps. The karstic gaps observed during the production of Olimpiyatköy station support this interpretation.
By scaling the positions of ERT-2 and ERT-3 measurements performed in parallel with each other, the horizontal extensions of the possible karstic spaces are approximately shown in Figure 4.4.

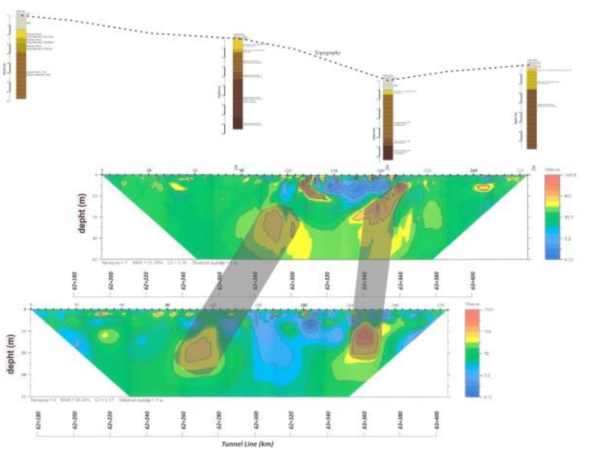

Figure 4.4: ERT-2/ERT-3 reverse solution sections and geological section obtained from drillings in the same location.

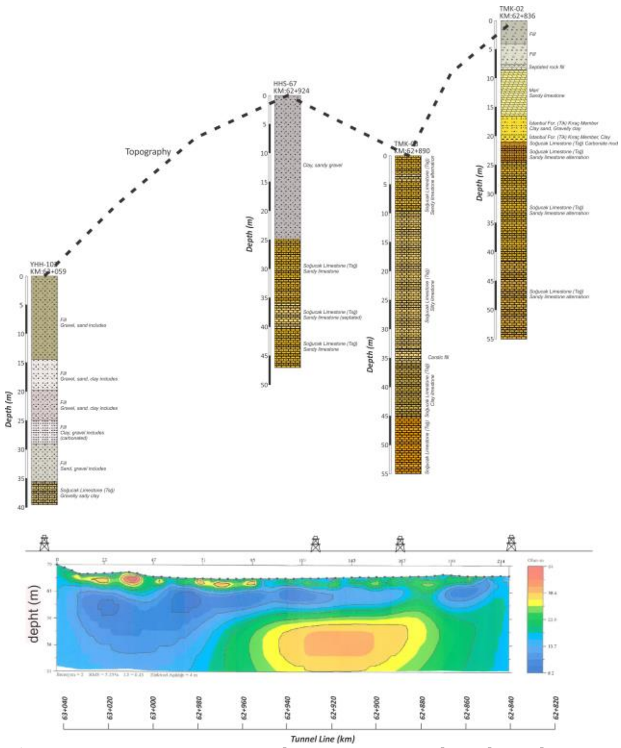

Figure 4.5: ERT-4 reverse solution section and geological section obtained from drillings in the same location.

Figure 4.5 shows the ERT-4 cross-section created as a result of the geophysical examination performed on Line-2 Km: 62 +835 – 63+050 on the TBM route and the geological cross-section obtained from TMK-02, TMK-03, HHS-67 and YHH-102 drillings corresponding to this cross-section.

In HHS-67 drilling in Km: 62 +924 location, the electrical resistivity value of the first 25 meters corresponding to the clayey sandy gravel unit been represented in the range of 8 – 20 ohms in the resistivity reverse solution section. The electrical resistivity value, which is observed to increase up to 64 ohms in the continuation, is represented by the different degrees of decomposed structure of the soğuçak limestone.

The electrical resistivity values corresponding to the TMK-03 drilling 35 m behind the HHS-67 drilling are similar for the ongoing units. In addition, the karstic gap observed in the drilling log at a depth of approximately 35 meters corresponds to the area where the maximum resistivity values at the same depth are measured in the resistivity reverse solution section.

Filling ground seen in YHH-102 drilling gives electrical resistivity values of 8 – 13 ohms at the end of ERT-4 section. Relatively low resistivity values can been explained by the highly hollow structure of the ground seen in Figure 4.6.

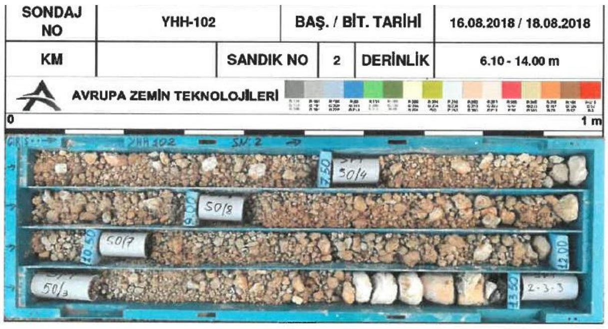

Figure 4.6: YHH-102 drilling 6.10 m – 14.00 m caisson image (Artificial filling) [10].

5. RESULTS

In this study, geotechnical studies conducted within the scope of Halkalı-İstanbul Airport metro line project been examined with the help of geological and geophysical survey reports. Geophysical sections and the geological sections obtained with the help of the drillings corresponding to the regions where these sections been formed were compared with each other.

As a result of this comparison, it was seen that karstic gaps could not be detected in the drillings made at Olimpiyatköy station. In addition, it is clear that the use of geophysical methods will provide effective time use and savings in order to predict and prevent possible problems in the manufacturing phase. Because it will be very costly and time-consuming to determine areas that are quite small compared to the project area, such as karst voids, by means of drilling in projects that require production in kilometers of different depths and sizes, such as underground rail systems.

In rail system projects where the production is concentrated on a line, the drilling plan mostly follows this line. Geophysical methods can been resorted to because the data obtained from the drillings in the regions where the production is intense in the second dimension, such as station structures, may be insufficient. In addition, data can be obtained by geophysical methods in regions where drilling cannot be performed due to topography or dense construction.
On the other hand, it is a fact that geophysical methods performed indirectly should been supported by drilling or different methods. In order for the interpretation of electrical resistivity values to approach the truth, basic data that can been obtained by drilling such as presence of groundwater level, stratification of soils, rock quality are needed.

Accurate, fast and clear sharing of the necessary data in underground rail system constructions, which require many different disciplines to work together, is of great importance under the headings of time and cost.

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