İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

MARMARAY PROJECT AND PERFORMANCE OF A SLURRY TBM

M.Sc.Thesis by
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Programme: Mining Engineering

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JANUARY 2008

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TABLE OF CONTENTS Page

LIST OF FIGURES

LIST OF TABLES

SUMMARY

Tunnel constructions in urban play an important role in daily life. During constructions it may effect the city in negatif ways.

There are lots of tunneling method but tunneling with closed shield Tunnel boring machines (TBM) is the most reliable method in urban areas to minimize ground settlement. For engineering view ground settlements are very important subject in tunneling in urban areas.

In Istanbul there are lots of TBM projects now but one of them is very important for Istanbul and for the world. This project name is Marmaray project. This project being a design-build project.

Marmaray Project Contract BC1 is a part of Marmaray project which will pass crossing from the Istanbul Strait with the immersed tube tunnel technique and connection of the these tubes with Slurry Type TBM under 55 m of Istanbul strait. When this project completed , it will be a world-class facility.

In this thesis information about Marmaray Project background , some detailed information about Marmaray Project Contract BC1 , objectives of the Marmaray Project ,selections criteria of Tunnel Boring Machines which are being used in project , some detailed information about Slurry Type TBM and segment lining are given. Also the perfonmance of slurry type TBM is analysed and evaluated with this thesis also experiments are done for evaluate the perfonmance of TBM and rock properties of excavated materials and it is hoped that this study will show the correct way for the future TBM projects.

ÖZET

Günümüzde tünel projeleri çok büyük önem kazanmıştır. Tünellerin şehir hayatındaki getirdiği rahatlığı gözardı edilemez. Lakin tünneller inşaat sırasında şehirin gündelik hayatında olumsuz etkileri olduğuda bir gerçektir.

Bu sebeple şehirde tünel açmak için en güvenilir ve yeryüzü oturmalarına en az müsade eden kapalı tipli tünel açma makinaları şeçimi en doğru şeçimdir. Bu tarz makinların yeryüzü oturmaları için en güvenilir makina olduğu bilinmektedir.

Şu an istanbulda çok çeşitli tünel projeleri bulunmaktadır. Bu inşaatlarda çeşitli methotlar kullanılmaktadır. Tünel açma makinalarıda birçok projede kullanılmaktadır. Tünel açma makinaları kullanılan ve şu an devam etmekte olan Marmaray Projesi BC1 hem Türkiye için hem de dünya için en önemli projelerden biridir.

Marmaray Projesi BC1 kısmında İstanbul boğazının 55 metre derinliğinden batırma tüp metoduyla geçimini ve bu tüplere bağlanacak çamur tipli tünel açma makinasının kazısını kapsamaktadır. Bu proje tamamlandığında hem İstanbul'un hem de dünyanın en önemli yapıtlarından biri olacaktır.

Bu tezde Marmaray projesinin tarihçesi , Marmaray Projesi boğaz geçisi hakkında , Projenin hedefleri hakkında, tünel açma makinalarının şeçimi ve şeçilen çamur sistemli makina hakkında bilgi ve kazı tekniği hakkında bilgiler verilmiştir. Makinanın mekanik verileri değerlendirilmistir ve çeşitli karşılaştırmalar yapılmıştır. Ayrıca kazı malzemesinden alınan numunlere testler uygulanıp kaya özellikleriyle makinanın performansı arasında değerlendirme yapılmıştır.

Bu deneysel çalışmanın ileride yapılacak olan veya şu anda devam etmekte olan tünel açma makinalarıyla açılan tünel insaatlarına yol gösterici olması dileğiyle hazırlanmıştır.

1. INTRODUCTION

Mechanicazed tunnelling projects increasing very fast in Istanbul. For these excavations generally tunnel boring machines; slurry type tunnel boring machines, earth pressure balance tunnel boring machines are in use.

This thesis is prepared to give some information about slurry type TBM. The data in the thesis is taken from Taisei Corporation TBM division.

2. SUMMARY OF THE PROJECT

Istanbul is one the biggest city on the world and has significant traffic jam problem according to the population developing linearly. On the other hand, Istanbul is a city that has important cultural and historical sources. The main transportation way existing in this city causes a serious environmental problem. The railway is the most comfortable, trustworthy for this kind of the city, but it necessities a modern railway.

The Marmaray Project presents a real solution to this problem. The Project provides an upgrading of the commuter rail system in Istanbul, connecting Halkalı on the European side with Gebze on the Asian side with an uninterrupted, modern, high-capacity commuter rail system and it provides to citizens a comfortable displacement.

Figure 2.1 : The parts of the railway [1]

The Marmaray Project is the upgrading of approximately 76 kilometers of commuter rail from Halkalı to Gebze as seen on figure 2.1. The red alignment on the map shows the parts of the railway that are above ground and the white alignment shows the new railway system that will be constructed in tunnels under the Istanbul Strait.

Railway tracks in both sides of Istanbul Strait will be connected to each other through a railway tunnel connection under the Istanbul Strait. The line goes underground at Yedikule, continues through the Yenikapı and Sirkeci new underground stations, passes under the Istanbul Strait, connects to the Üsküdar new underground station and emerges at Sögütlüçesme.

This Project is one of the major transportation infrastructure projects in the world at present. The entire upgraded and new railway system will be approximately 76 km long. The main structures and systems; include the immersed tube tunnel, bored tunnels, cut-and-cover tunnels, at - grade structures, three new underground stations, 37 surface stations (renovation and upgrading), operations control centre, yards, workshops, maintenance facilities, upgrading of existing tracks including a new third track on ground, completely new electrical and mechanical systems and procurement of modern railway vehicles. [1]

3. PROJECT BACKGROUND

In 1860 : The idea of a railway tunnel under the Istanbul Strait was first raised. However, where the tunnel under the Istanbul Strait crosses the deepest parts of the Strait, the old-fashioned techniques would not allow the tunnel to be on or under the seabed, and therefore the design indicated a "floating" type of tunnel placed on pillars constructed on the seabed.

In 1902 : Such ideas developed further during the following decades, and a similar design was developed also showing a railway tunnel under the Istanbul Strait, but this design indicates a tunnel placed on the seabed. Since then, several different ideas have been tested and new technologies have allowed more freedom in the design.

Figure 3.1 : The view of the Mermaid tower

The technique that will be used in the Marmaray Project to cross the Istanbul Strait as seen on figure 3.1 - the immersed tube tunnel technique - has been developed since late in the 19th century.

In 1894 : The first immersed tube tunnel ever built was constructed in North America for sewer purposes.

The first tunnels for traffic purposes constructed using this technique were also built in the United States.

In 1906-1910 : The first one was the Michigan Central Railroad tunnel.

In 1942 : In Europe, Holland was the first country to adopt the technique, and the Maas Tunnel in Rotterdam was opened. .

In 1944 : In Asia, Japan was the first country to adopt this techniques and the two-tube road tunnel (Aji River Tunnel) in Osaka was opened.

In the 1950s : Such tunnels remained rare until a robust and well proven industrial technique was developed, thereby allowing the construction of large-scale projects in many countries.

In the early 1980s The desire to construct a railway mass transit connection from west to east in Istanbul and under the Istanbul Strait was becoming stronger and stronger

In 1987 : Consequently the first comprehensive feasibility study was carried out and reported. This study concluded that such a connection would be feasible and cost-effective, and the alignment we see in the project today was selected as the best of a range of alignments.

In 1987 : The project as outlined was discussed during the following years, and

Around 1995 it was decided to make more detailed studies and update the feasibility studies, including the passenger demand forecast from 1987.

In 1998 : These studies were concluded, and the conclusions underlined the earlier conclusions that the project would offer many advantages to the people working and living in Istanbul, and it would ease the rapidly growing problems regarding traffic congestion in the city.

The Project has another particularity. The new railway immersed tunnel will be constructed and will pass some 200 meters north of the Mermaid tower , being a famous landmark for ships, at a maximum depth of approximately 55 meters; and this is a world record!

4. OBJECTIVES OF THE MARMARAY PROJECT

When introducing major infrastructure projects such as the Marmaray Project, it is important to realise that it will influence not only the daily traffic pattern of Istanbul, but it will also influence the development of the city and the region.

It is therefore imperative that the objectives of the project are described in clear terms. The most important objectives are to:

- Provide a long-term solution to the current urban transportation problems of Istanbul;
- Relieve existing operating problems on the mainline railway services;
- Provide direct connection of railway system between Asia and Europe
- Increase capacity, reliability, accessibility, punctuality and safety on the commuter rail services;
- Reduce travel time and increase comfort for a large number of commuter train passengers;
- Provide an uninterrupted passenger and freight transportation across the Istanbul Strait;
- Reduce air pollution resulting from the exhaust gases and thereby improve the air quality of Istanbul;
- Reduce airborne traffic noise in the centre of Istanbul; and
- Reduce adverse effects on historical buildings and heritage sites by offering a potential for reducing the number of cars in the old centre of Istanbul. On figure 4.1 you can see a picture of traffic jam in Istanbul.

Figure 4.1 : Traffic jam of Istanbul [1]

4.1 Travel Time and Alignment

As it is said above, traffic problem in Istanbul is serious obstacle for urban life. It takes a lot of time and energy during the day and has effects on human's health. This Project will ameliorate the existing alignment and add other alignments. The alignment of the new Marmaray Railway Project will, outside the Istanbul Strait Crossing, be similar to the existing commuter rail line. This means that most of the existing stations between Halkalı and Yedikule and between Haydarpaşa and Gebze will remain where they are today, but they will be either re-furbished or completely new buildings.

In addition, Yenikapı, Sirkeci and Üsküdar are the new underground stations , and the railway technology will be upgraded using modern systems and rolling stock.

A trip today from Halkalı to Gebze will typically last a bit more than three hours, including the ferry trip from Sirkeci to Haydarpaşa. When the upgraded commuter rail system is in place, the trip will take one hour and forty-five minutes. In other words, passengers will save approximately one hour and fifteen minutes on the trip.

Other examples, including the above case, of travel duration are listed at table 4.1

Table 4.1 : Duration of trips [1]

Trips	Time taken by the new railway
Gebze to Halkalı	105 minutes
Bostancı to Bakırköy	37 minutes
Sögütlüçesme to Yenikapı	12 minutes
Üsküdar to Sirkeci	4 minutes

In general, this saving may not seem impressive, but it is the proof of the efficiency of the new railway system because if the daily savings per passenger is multiplied by the number of total trips, it will add up to tremendous amounts of time.

This calculation is done for the future years:

- For the opening year : the total time savings will be of the order of 13 million
- By the year 2015 : the savings will be of the order of 25 million hours.
- By the year 2025, when the capacity of the systems is fully utilised, the savings will be of the order of 36 million hours per year or approximately 100.000 hours (11.4 years) saved by people every single day all year round.

Such an improvement in efficiency will have other repercussions on the general transportation pattern of Istanbul. The efficiency of railway systems in major cities around the world is often monitored via the percentage of all trips made via railway and subway systems against the total number of trips made.

Some years ago, this percentage was 60% in Tokyo, 31% in New York, 22% in London, 25% in Paris, but only 3.6% in Istanbul (Graphic 1). These figures clearly indicate that Istanbul has a serious backlog when it comes to the possibility of allowing people to use efficient train systems for the daily transportation needs of the city. The percentage estimated, when the Marmaray Project has been completed and people become familiar with using the new systems, may rise 28% If this happens, Istanbul's transport efficiency and environmental solutions will be comparable with those of other major cities around the world.

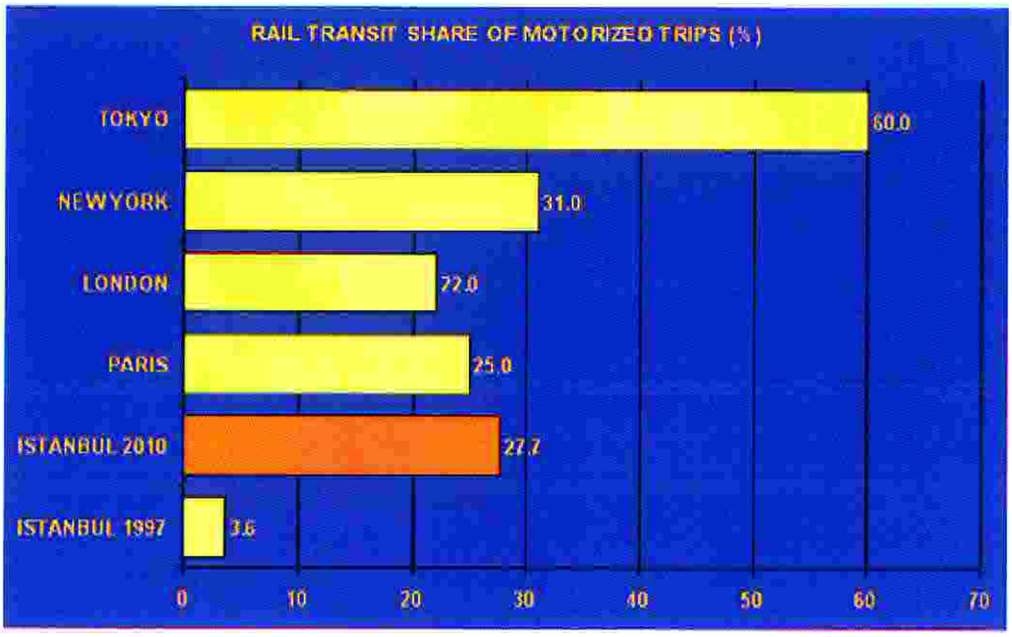

Figure 4.2 : Rail Transit Share of Motorized Trips (%) [1]

Figure 4.2 shows how many percent of the motorized trips is done by rail traffic in big modern cities around the world. It can be seen that in Tokyo 60 out of 100 trips are by train, whereas in Istanbul today only 3.6 trips out of 100 are by rail, but after the Marmaray Project and the related railway lines have been opened, the trips by train could be as high as 28 out of 100.

4.2.Environment

The Marmaray Project, as the major infrastructure projects, assess the impacts in two different periods: the impacts during the construction period and the impacts after the operation of the railway has been initiated.

The impacts from the Marmaray Project are generally similar to those of other recently built modern projects in Europe, Asia and in the United States. Whereas, generally, the impacts during construction are negative, but after the operation has begun, these negative impacts will be completely neutralized within a very short time. The impacts during the long remaining period of the project's lifetime will be very positive as compared to the situation of the situation as it is today if the Marmaray Project were not to be undertaken.

For example, it is estimated that the reduction in air pollution as a consequence of the Project compared with the situation that will develop if we do not build the Project will be approximately as follows:

- The reduction of air pollution gasses (NMHC, CO, NOx etc) will be an annual average of approximately 29,000 tons/year over the first 25 years of operation.
- The reduction of green houses gasses " mainly CO2 " will be an annual average of approximately 115,000 tons/year over the first 25 years of operation.

These types of air pollution all have negative effects on the global and local environments.

- The non-methane hydrocarbons and the carbon-oxides contribute negatively to the general heating of the globe (the "greenhouse effect", and furthermore CO is a very toxic gas),
- The nitrogen-oxides are very disturbing for people who suffer from allergic reactions and asthmatic diseases.

Once operation has begun, the modern and efficient techniques used in the Project will reduce other negative environmental problems currently affecting Istanbul, such as noise and dust. It will also make railway transport much more reliable, safe and comfortable. However, the construction period of the Project will be the initial compensation and the negative impacts paid to obtain these major advantages to the environment.

For the city and the people living in the city the negative impacts during construction will, amongst others, be as listed in table 4.2

Table 4.2 : The negative impacts in the city and their sources and how to mitigate. [1]

Impacts in the City	The Sources and how to Mitigate
Traffic Congestion	To build the three new deep stations, it will be necessary to occupy large construction sites in the heart of Istanbul. Traffic diversions will be put in place, but congestion problems will occur at times.When constructing the third track and when upgrading the existing tracks, it will be necessary to limit or even close down the existing commuter rail service at certain periods. Alternative means of transport will be provided in the form of bus services serving the affected areas. These services, when combined with traffic diversions around the affected station areas, may create congestion problems during these periods.The Contractors will have to use the road systems near the deep stations for the transport of materials to and from the construction sites using large trucks and this activity will from time to time overload the capacity of the road systems.It will not be possible to avoid disruption completely, but careful planning combined with comprehensive information to the public and support from the relevant authorities will limit the adverse impacts.
Noise and vibrations	Construction activities required for the Marmaray Project are noisy activities. In particular, the activities required to construct the deep stations will produce loud and continuous daily noise over the duration of the construction period.The underground works will normally not create noise in the city. However, the tunnel boring machines (TBMs) will create a low-frequency vibration of the soil surrounding the TBM. This may create a rumbling type of noise in the properties nearby, and this noise will persist 24 hours a day, but should not affect any one area for more than a few weeks.To avoid closing down the existing commuter rail service for longer than is absolutely necessary, some of the work will be carried out at night. It can be expected that the activities that will take place during these periods will be quite noisy and may from time to time exceed the limitations normally acceptable for such works.It will not be possible to avoid noise disturbance completely, but extensive requirements have been imposed on the Contractors to do what is possible to limit the noise level caused by the construction activities.

Table 4.3 : The negative impacts in the city and their sources and how to mitigate. [1]

Dust and mud	Construction activities will result in dust in the air and mud and soil on the roads around the construction sites. This will also occur on the Marmaray Project. Although it will not be possible to avoid these problems altogether, in general much can and will be done to reduce their impact - for example, watering the roads and paved areas and cleaning the vehicles and the roads.
Disruption	Before construction works start, all known utilities will be identified and diverted as necessary. However, many of the existing utilities will not be positioned exactly where they are supposed to be, and there will be utilities no-one even knows about. Therefore it is not possible to avoid disruption from time to time of the power supply, water supply, sewer systems, and communication systems such as telephone and data cables. Whilst it may not be possible to avoid such disruption completely, careful planning combined with comprehensive information to the public and support from the relevant authorities will limit the adverse impacts.

For the marine environment and the people using the navigation channel in the Istanbul Strait, there will also be some negative impacts during construction. The most important are listed in table 4.4 and table 4.5:

Table 4.4 : The negative impacts for the marine environment and their sources and how to mitigate. [1]

Impacts, Marine	**The Sources and How to Mitigate**
Contaminated materials	The investigations already carried out in the Istanbul Strait have documented that contaminated material exists on the seabed where the Golden Horn meets the Istanbul Strait. The amount of contaminated material that has to be removed is of the order of 125,000 m^3.DLH has requested the Contractors to use proven and internationally recognized techniques to take the material out from the seabed and bring it to a Confined Disposal Facility (CDF). Such facilities will typically be an on-shore confined and controlled area that will be sealed with clean material or it may be a confined pit in the seabed covered by clean protective material. Contamination problems can be eliminated completely if the correct methods and equipment are used for the operations. Furthermore the cleaning of a substantial area of the seabed of contaminated materials will have a positive effect on the marine environment.
Navigation	There will be a period lasting about three years when a substantial amount of marine activities related to the construction of the immersed tunnel will take place in the Istanbul Strait. Most of these activities can be performed in parallel with the normal marine traffic passing through the Istanbul Strait, but there will be periods when constraints will be put on the traffic, and there may even be shorter periods when the traffic has to be completely stopped. Mitigation will be to ensure careful and timely planning of all the marine activities in close cooperation with Harbour Master and other authorities. Furthermore, all possibilities of utilizing the modern Vessel Traffic monitoring Systems (VTS) will be explored and initiated.
Pollution	When heavy marine operations are ongoing, there will always be a risk of accidents that may cause pollution problems. Typically, such accidents will be the spillage of limited amounts of oil or gasoline in the waterway of the Istanbul Strait or the Marmaray Sea. The risk can not be fully eliminated, but the Contractors will have to adhere to strict and internationally well proven standards and maintain a readiness to deal with such situations to limit or neutralize the impacts on the environment

Table 4.5 : The negative impacts for the marine environment and their sources and how to mitigate. [1]

Turbidity	It will be necessary to dredge more than 1,000,000 m^3 of soil from the bottom of the Istanbul Strait to prepare the trench for the immersed tunnel. It is unavoidable that this operation will release natural sediments in the water and thereby increase turbidity. This may have adverse effects on fish migration in the Istanbul Strait.During spring, fish migrate northwards near the bottom of the Istanbul Strait where the current flows towards the Black Sea, and during autumn they migrate southwards in the upper layers where the current flows towards the Sea of Marmara. However, because these contra-flowing currents are relatively stable and coexist, it is expected that the plume of increased turbidity that is created will be relatively narrow - most likely of the order of 100 to 150 metres. This has been the experience in other similar projects, for example the Oeresund immersed tube tunnel between Denmark and Sweden. If the width of the plume generated is less than say 200 metres, it is not likely to have significant effects on fish migration because there will be good opportunities for the migrating fish to find paths in the Istanbul Strait where the turbidity is not increased. It will be possible to avoid these adverse effects on the fish almost entirely, and the mitigation measure will simply be to restrict the Contractors' options regarding the timing of the dredging operations. They will therefore not be allowed to perform dredging in the deep parts of the Istanbul Strait in the spring migration period, and they will only be allowed to perform dredging in not more than 50% of the width of the Istanbul Strait during the autumn migration.

Figure 4.3 : Typical dredging operation in white limestone, Oeresund, Denmark. [1]

Dredging works in the Istanbul Strait will be a necessity. Fortunately the current of the Istanbul Strait is quite constant and almost always present. Figure 4.3 shows the well-defined plumes that are expected to evolve during dredging works in the Istanbul Strait under similar conditions. The migrating fish will therefore easily find a path where the water will be free of sediment and unaffected by the construction activities. (The picture shows a typical dredging operation in white limestone, Oeresund, Denmark)

4.3 Passenger Demand and Planning

The Marmaray Project is a result of a certain demands. The basis for all major infrastructure projects will always be a study of the expected demand - "How many passengers can be expected, from where to where, and when during the day will people use the commuter train system?".

- In 1985, the first systematic studies were performed and the studies have been updated regularly ever since.

The latest traffic forecasts of the Marmaray Project have been made by using a conventional transport model.

- In 1996, the model was initially calibrated with the data collected as a part of the Istanbul Transport Master Plan (IUAP) that was prepared by Istanbul Technical University (ITU) between 1995 and 1998.
- Between 2002 and 2003, the model has been revised and the validity of the model results have been checked by using data collected.

The city is divided by the model into 211 zones, and the zones are based on the smallest administrative district available - the "mahalle". The model also uses base data such as population, employment and the number of students in each zone. All other public and private transport systems, including the highway systems, have been evaluated and form another important part of the "backbone" of the model. The future land-use pattern, the number of trips per person per day, the type of each trip and the trip matrix (from which zone to which zone) and the trip-generating factors are other important aspects that have been evaluated and used in the model.

Once these factors and many others have been established and the model calibrated, a number of different scenarios - "what happens if" - can be developed, and as a result of all these exercises, the most likely traffic demand can be forecast.

Some key results are given below:

- The total number of trips per day in year 2015 is estimated to approximately 1,500,000 passengers and in year 2025 this figure will have increased to some 1,700,000 passengers.
- The maximum number of passengers per hour per direction using the system will in 2015 be some 65,000 and in 2025 this figure will have increased to some 75,000 passengers.
- The total number of saved hours for all passengers per year will in 2009 be approximately 13 million hours, in year 2015 approximately 25 million hours and in 2025 approximately 36 million hours.

5. MARMARAY PROJECT CONTRACT BC1

Main purpose of this thesis is to analyze the performance of Slurry type of TBM's which are used in MARMARAY PROJECT Contract BC1 .

MARMARAY PROJECT Contract BC1 constructed by TAISEI CORPORATION (Japan) and GAMA-NUROL (Turkey) Joint Venture. Employer of this project is DLH General Directorate and the Employer's Representative is Avrasya Consult JV. This is one of the most challenging tunneling projects in the world. This project is joins Asian and Europe as seen in figure 5.1. In this project there are 5 Closed Type TBM machine and their routes are shown in figure 5.2. TBM 1 is EPB Type TBM machine from Lovat Company. TBM 2 ,TBM 3 ,TBM 4 ,TBM 5 are Slurry type TBM machine from Hitachi Zosen.

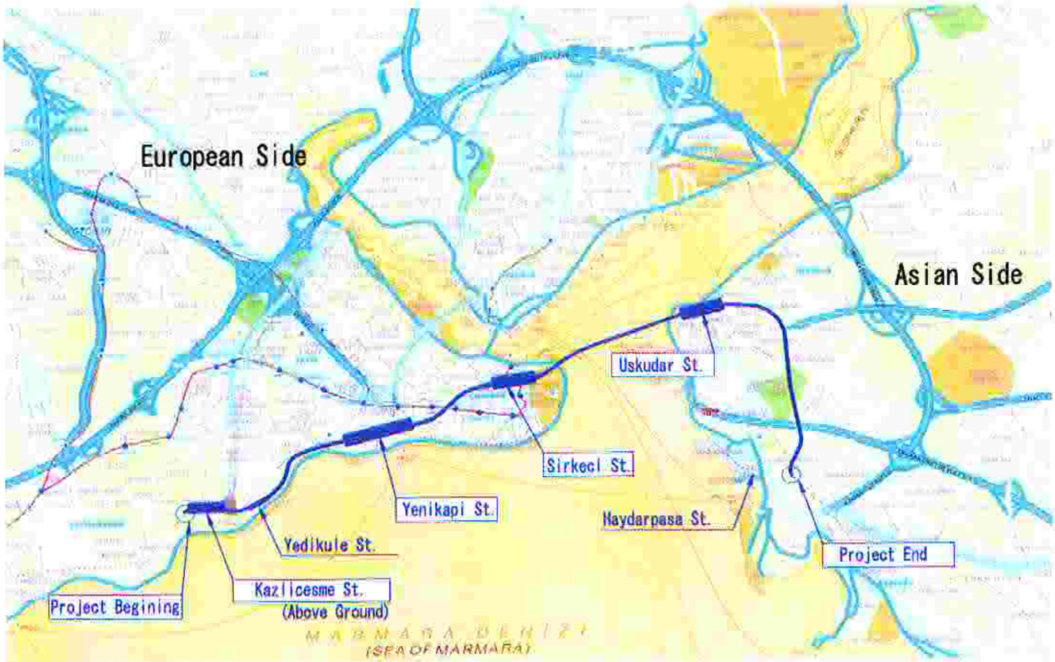

Figure 5.1 : Map of Project Marmaray Contract BC1 [2]

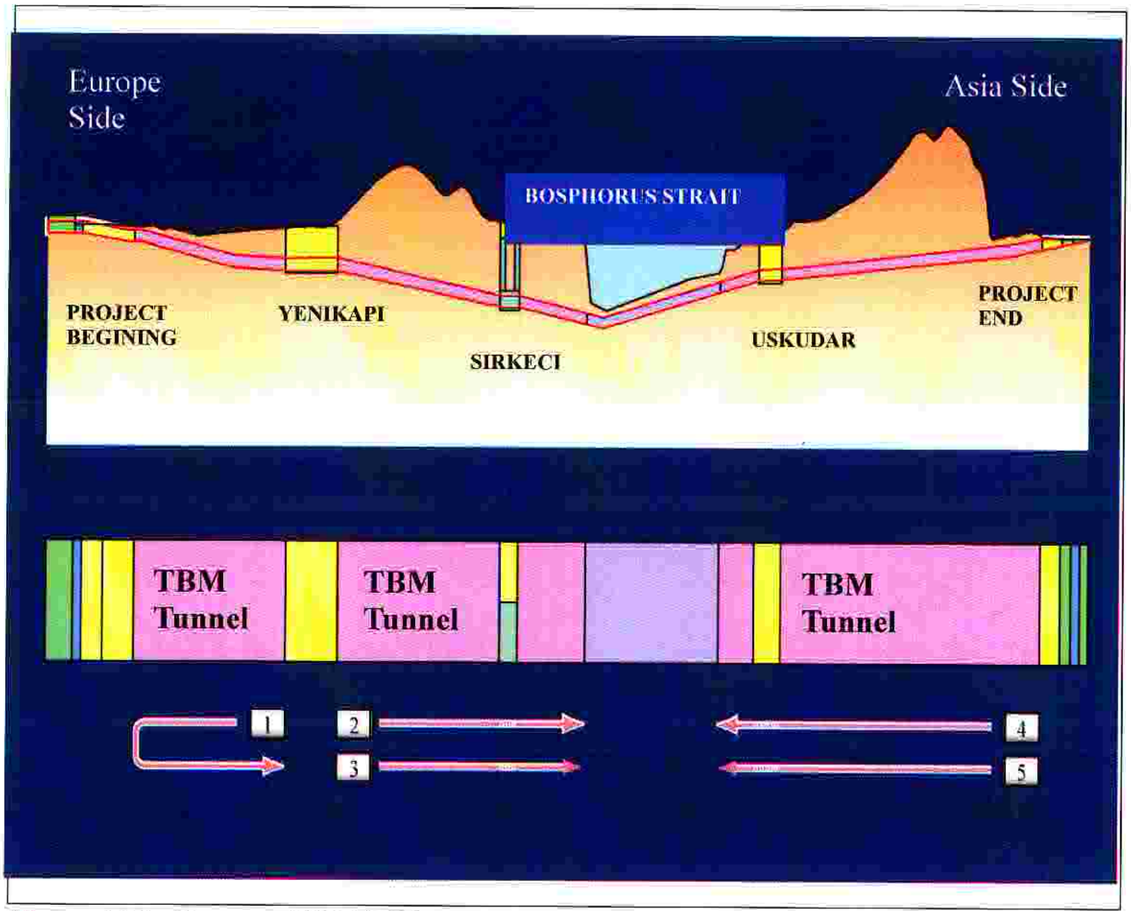

Figure 5.2 : Routes of TBM [2]

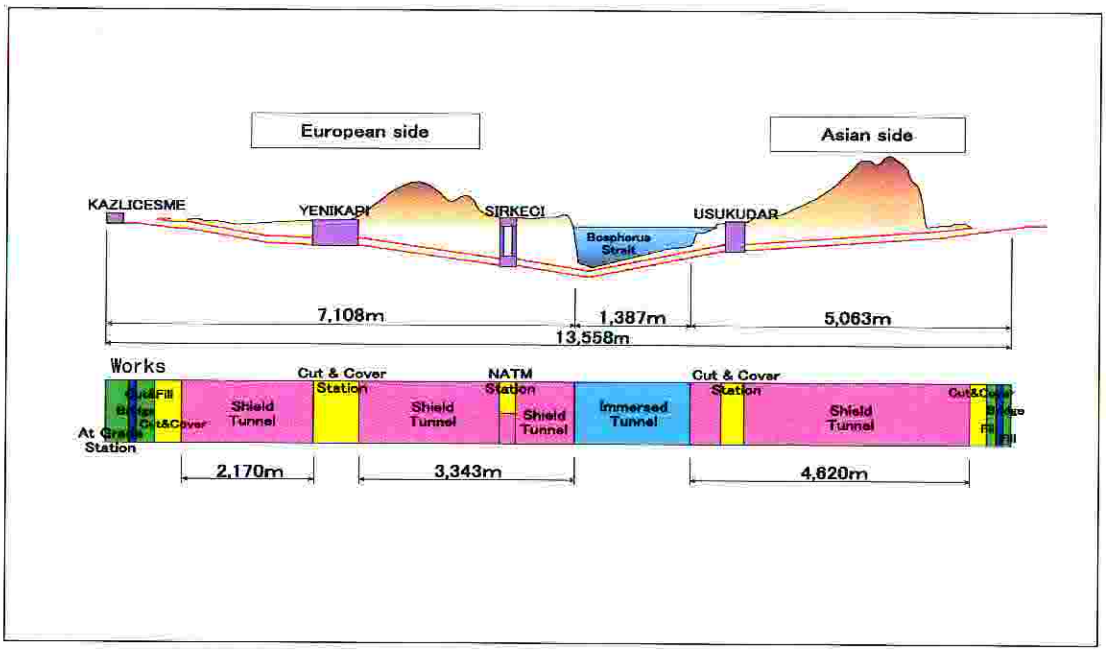

Figure 5.3 : Map of Project Marmaray Contract BC1 [2]

In Marmaray Contract BC1, They construct the railway tunnel with some construction methods in urban area and under the sea as seen in figure 5.3.

When this project will complete, we can pass through under sea, from Europe to Asia with railway system.

In this project they construct this tunnel with four tunneling methods.

Open Cut tunnel, NATM conventional tunnel, Immersed tunnel and TBM tunnel.

Yenikapi and Usküdar stations are constructed with open cut tunneling method.

NATM conventional method tunnel applies for Sirkeci station.

Sirkeci station locates under the world heritage area in the centre of old Istanbul.

So that work area is quite limited, first deep vertical shaft is constructed and extend the NATM tunnel in underground horizontally.

Under Bosphrous strait they apply Immersed tunnel method.

The depth of immersing is very high, maximum depth reaches 60m from the sea level.

Under high water pressure, immersing work is performed. Depth of the sea current of the water also make the job difficult.

Under high current condition, immersing work has to be carried out.

TBM tunnels connect each method of tunnels including connection with immersed tunnel.

Taisei & Gama-Nurol JV construct two lines tunnels and 4 stations.

For TBM tunnel, inner diameter of segment ring is 7.04m

In the project total length of Slurry TBM tunnel is at asian side 4260 m and at Europe side 3120 m. For EPB TBM tunnel length is at european side 2485 m.

6. SELECTIONS OF TBM'S

To plan and to select TBM type, they have to consider many factors, soil condition, above ground condition, ground water level, work area, construction period, environmental condition, and so on.

For this project many infrastructures and buildings are locating above ground and under the ground. Basically to get wide construction area is difficult. Also they have to consider about environmental aspects. Noise and vibration, air pollution, waste water and dust. TBM tunneling method can work with smaller work area than open cut method. Environmental issue also can minimize compare with other method.

In Istanbul, we have a huge number of residents living over their tunnel alignment.

There are a lot of buildings and a lot of historical or regional structures standing.

If they cause some amount of ground settlement or soil collapsing while the tunneling works, serious accident may occur and we have to prevent such situation.

To minimize the ground settlement, closed-face type TBM is most reliable.

They planned with closed-face type TBM. There are mainly 2 closed-face types TBM. In Marmaray Contract BC1 project, they apply both closed-face type TBM.

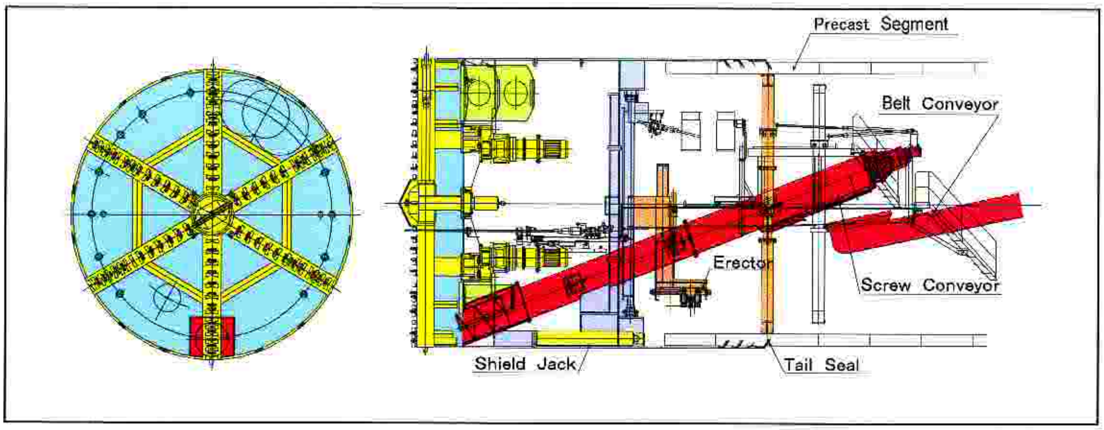

Figure 6.1 : Typical drawing of EPB Type TBM. [2]

Figure 6.1 shows Earth Pressure Balanced type TBM. EPB type TBM feature that

Figure 6.1 shows Earth Pressure Balanced type TBM. EPB type TBM feature that balanced pressure by using mud of excavation soil and excavated soil is transported through screw conveyor and disposal. This type of material is chosen for excavation between Kazlıcesme to Yenikapı. The general reasons are plant facility for EPB type TBM is smaller than Slurry type TBM , plastic flow in chamber due to predominant cohesive soil and appropriate Earth Pressure Balance type shield without blowing of slurry caused by thin cover.

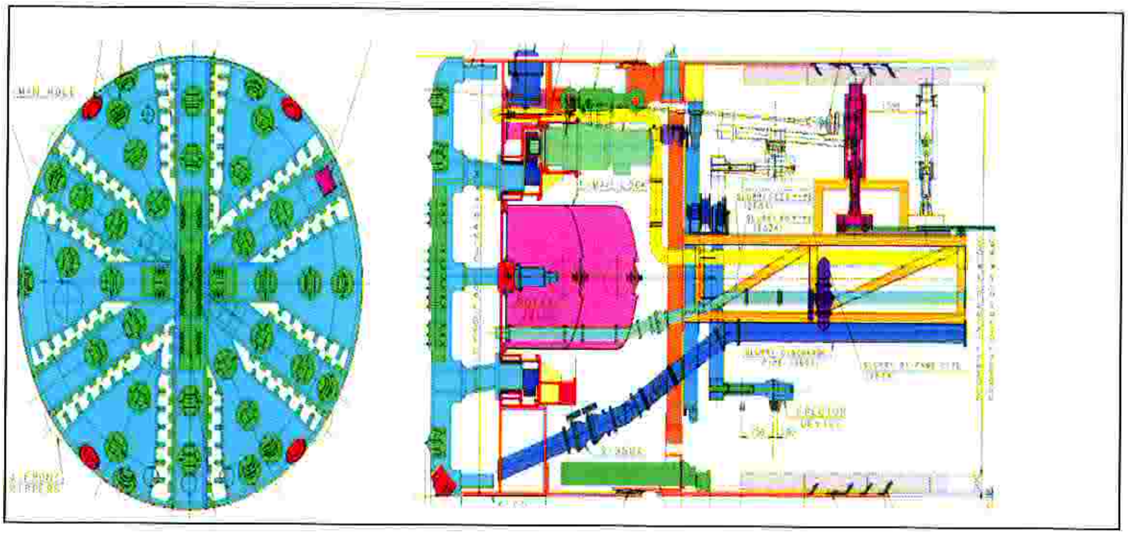

Figure 6.2 : Typical drawing of Slurry Type TBM. [2]

Figure 6.2 shows Slurry type TBM. Slurry type TBM feature that face pressure is balanced by slurry. This machine is chosen between Ayrılıkcesme to Uskudar and Yenikapı to Sirkeci. The general reasons are Slurry Pressure type shield suitable for fluctuation of water pressure caused by high water pressure in immersed connections and rock zone, high excavation performance, high soil discharge capacity, and high-efficiency construction.

Excavated soil discharged by slurry circulation. Generally, larger plant is required for Slurry type TBM compare with EPB type TBM. Slurry is produced with Slurry treatment plant.

In TBM tunneling route, there are some high water pressure zones. Under Bosphorus strait, TBM tunnelling works have to carry out under water pressure of 600kpa. On land portion maximum water pressure reach to 850kpa.

To get rid of high pressured water condition, they select slurry type TBM.

Slurry type TBM can manage to sustain the face pressure with slurry control system relatively easy.

EPB type TBM, face pressure control is relatively difficult.

EPB type TBM takes the excavated soil with screw conveyor from opening chamber hole.

Under high water pressure, this opening portion becomes weak point, to control the stable of face pressure.

Usually, during excavation with EPB type TBM in the high water pressure condition, they need some auxiliary measures such as special gate equipment to attach screw conveyor for keeping face pressure, soil improvement or soil support system.

On the other hands, Slurry TBM is more suitable under high water pressure condition, because face pressure is controlled by combination of feeding and discharging pumps with mechanized slurry control system.

With using closed-face type TBM, they can carry out the tunneling work rapidly.

This is the one of advantages to use closed-face type TBM.

Closed-face type TBM is suitable for a large kinds of soil condition.

But, with open type TBM, they need some auxiliary measures.

For example probe drilling, soil improvement or some sustain system while tunnel construction. It takes time and cost.

In urban area, usually there are not enough space to carry out such measure from ground surface. And generally they may say it is better to pass excavation rapidly.

It is better to be covered by lining segment as soon as possible to reduce the possibility of settlement above ground.

Therefore, the closed-faced type TBM is selected for this project.

7. SLURRY TYPE TBM

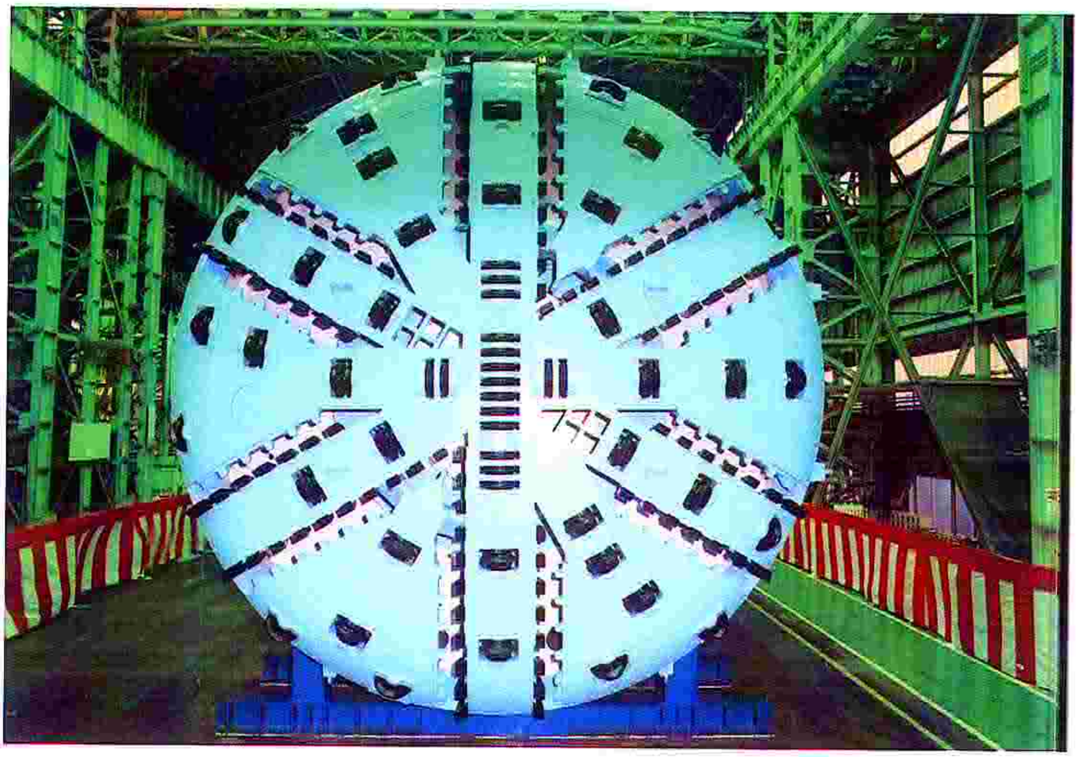

Figure 7.1 : Slurry TBM Cutter Face

As TBM dimension, cutter face diameter is 7.85m and machine shield length is 11m. In figure 7.1 you can see the cutter face of the TBM. To excavate a tunnel curve portion, this machine equips articulation system at the middle of body.

Equipped trust force power is 75000 kN, and cutter face rotating speed can run up 4 times per minutes.

Main expected excavated soil is soft rock for this TBM.

Compression strength of excavated rock is about 80Mpa.

Maximum compressive strength of hard rock we expect in our tunnel line is 200Mpa.

To excavate these conditions of rock, 55 pieces disc cutter bits are attached in cutter face. Disc cutter diameter is 17 inches and tip-insert type is applied. [2]

Table 7.1 : Data analyses of machine according to the rock types. [3]

		From the soft to moderate hard	From moderate hard to hard
Confined compressive strength		5 ~ 50 MPa	60 ~ 100 MPa
Excavation mode		Priority to cutter torque	Priority to cutter revolution
Cutter revolution	Max. Revolution	0.5 ~ 1.8 rpm	2.5 ~ 4 rpm
	Circumferential speed	12.4 ~ 44.8 m/min	62.2 ~ 99.6 m/min
Cutter torque	Instand Max.	15873 kNm	11428 ~ 7150 kNm
	Continuous Max.	10582 kNm	7619 ~ 4767 kNm
	Torque ratio of continuous torque	21.8	15.7 ~ 9.8

For excavation of soft rock low rotation and high torque is required but for hard rock high rotation and low torque is required as seen in tables 7.1 and 7.2.

Table 7.2 : Data analyses of machine according to the rock types. [3]

Description	From the soft moderate hard	From the moderate hard to hard
Resistance torque due to fracturing rock	5517 kNm	4388 kNm
Resistance torque due to friction between face and front surface of cutter head	1698 kNm	0
Resistance torque due to friction between outer surface of cutter head and surrounding earth	2003 kNm	0
Resistance torque due to agitating spoils	0	
Resistance torque due to friction bye bearing and seals	260 kNm	
Total required torque	9478 kNm	4648 kNm
Equipped continuous torque	10582 kNm	7619 ~ 4767 kNm
Safety factor	1.1	1.6 ~ 1.0

Example of penetration according to the rock typies.

- Penetration: P=11mm/min at 80MPa

  (thrust force = 250kN/disc)

- Advance speed: Max. 44mm/min at 80MPa

  (V=11mm/min×4.0rpm=44mm/min)

- Estimated frequency of changing disc cutter:

  →350m (hard tip inserted type) at 80MPa

  →230m (non hard tip inserted type) at 80MPa

Penetration: P=17mm/min at 50MPa

(upper limit of penetration)

(thrust force = 250kN/disc)

Advance speed: Max. 30mm/min at 50MPa

(V=17mm/min×1.8rpm=30mm/min)

Estimated frequency of changing disc cutter:

- 430m (hard tip inserted type) at 50MPa
- 660m (non hard tip inserted type) at 50MPa [3]

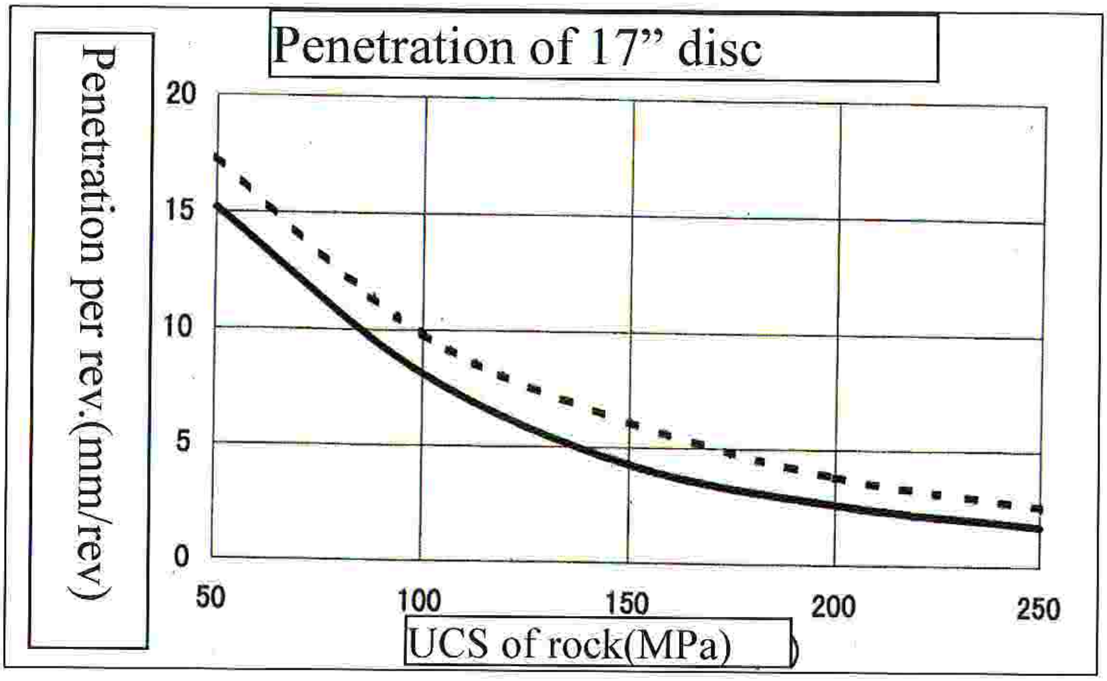

Figure 7.2 : Penetration of Disc Cutters. [3]

7.1 Disc Cutter Change Procedure

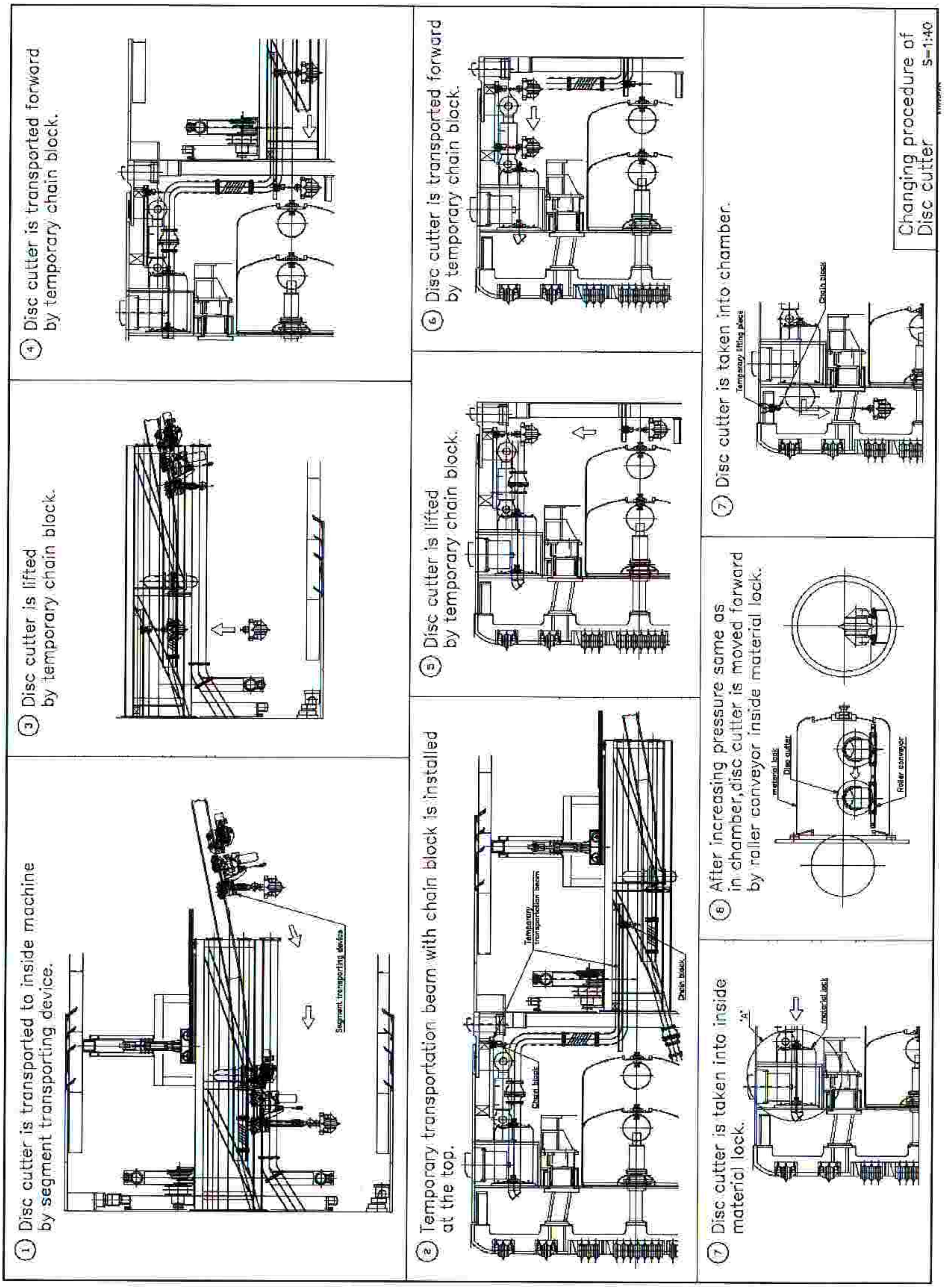

Figure 7.3 : Procedure of Changing Disc Cutters [3]

Changing procedure of Disk Cutter as seen in figure 7.3

1. Disc cutter transported inside machine by segment transporting device.
2. Temporary transportation beam with chain block is installed at the top.
3. Disc cutter lifted by temporary chain block.
4. Disc cutter is transported forward by temporary chain block.
5. Disc cutter is lifted by temporary chain block.
6. Disc cutter transported forward by temporary chain block.
7. Disc cutter is taken into inside material lock.
8. After increasing pressure same as in chamber disc cutter is moved forward by roller conveyor inside material lock.
9. Disc cutter is taken into chamber.

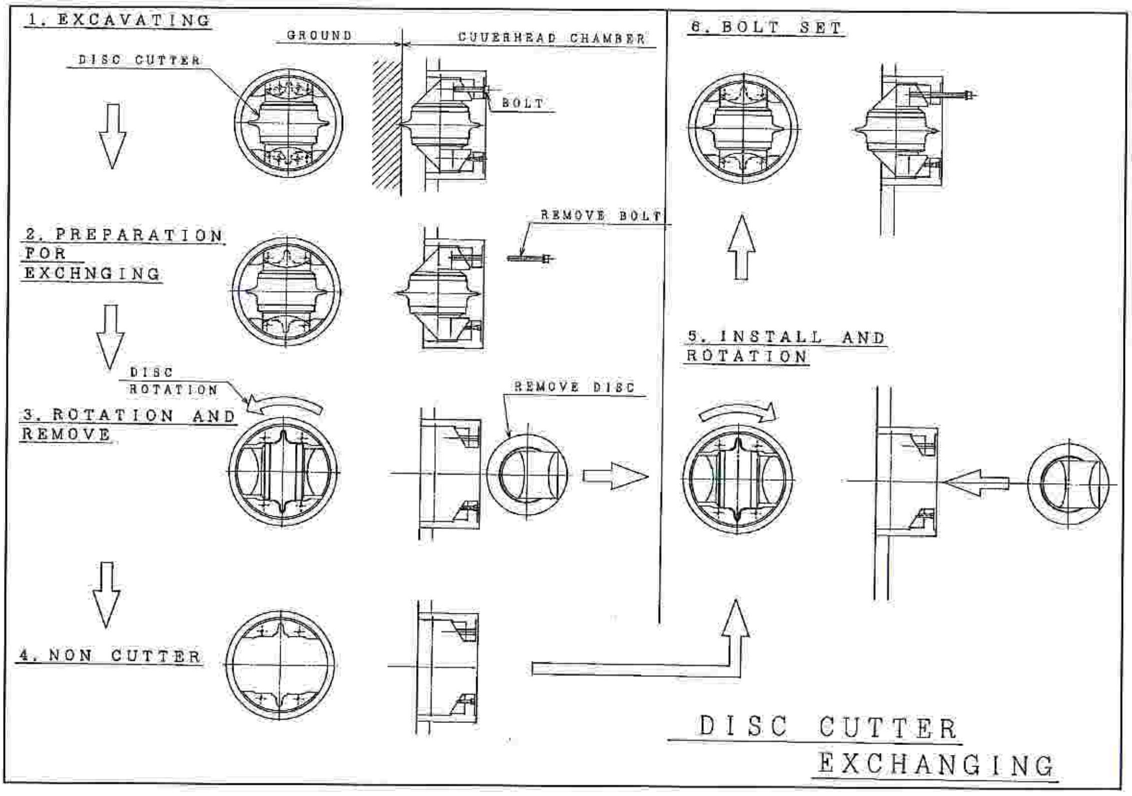

Figure 7.4: Easy Changing of Disc Cutter [3]

8. INFORMATION ABOUT IMMERSED TUNNEL

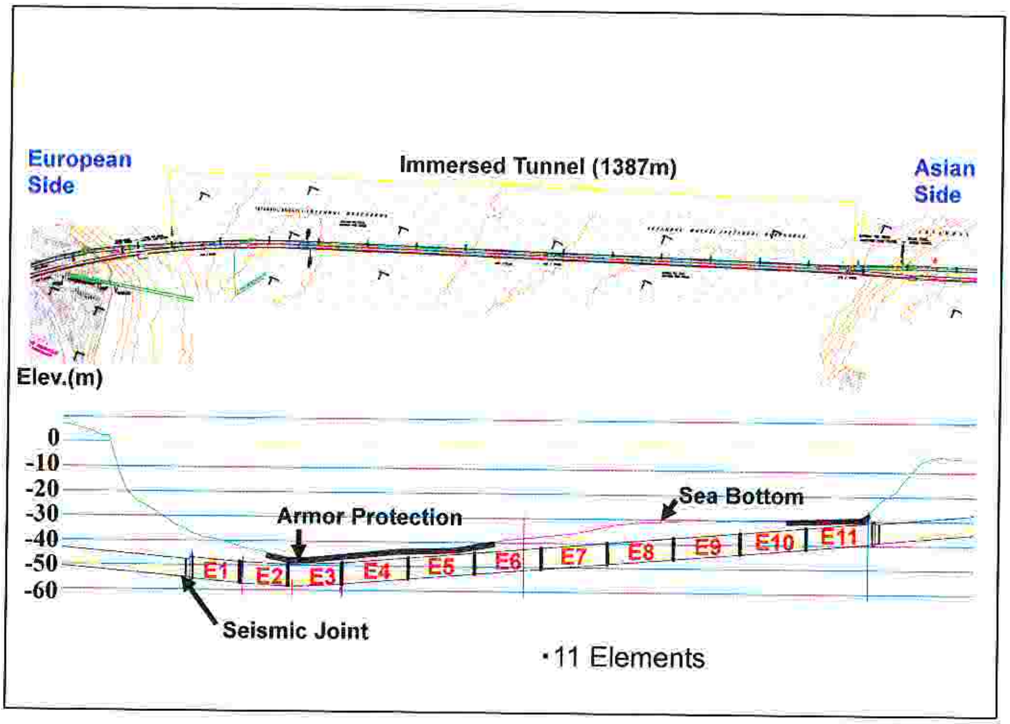

Figure 8.1: Plan of Immersed Tunnel

For immersed tunnel total length is 1,387 km as seen in figure 8.1. 11 elements of tunnel shall precasted on the job site and will be joined under the sea one by one. This drawing is showing us a typical cross-section of a immersed tunnel.

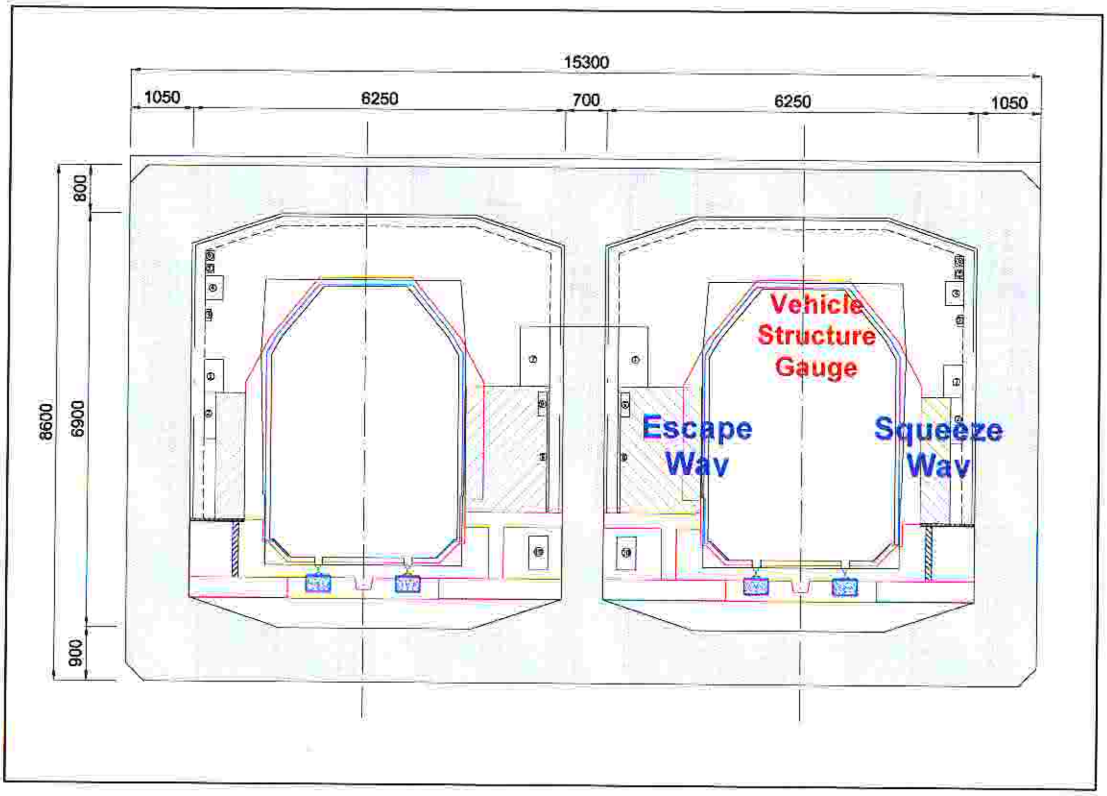

Figure 8.2: Profile of Immersed tunnel

Figure 8.2 shows the plan of tunnel. These elements are casted on Tuzla Job Site and will be carried to bosphorus by Catamaran type ship as mentioned in figure 8.3.

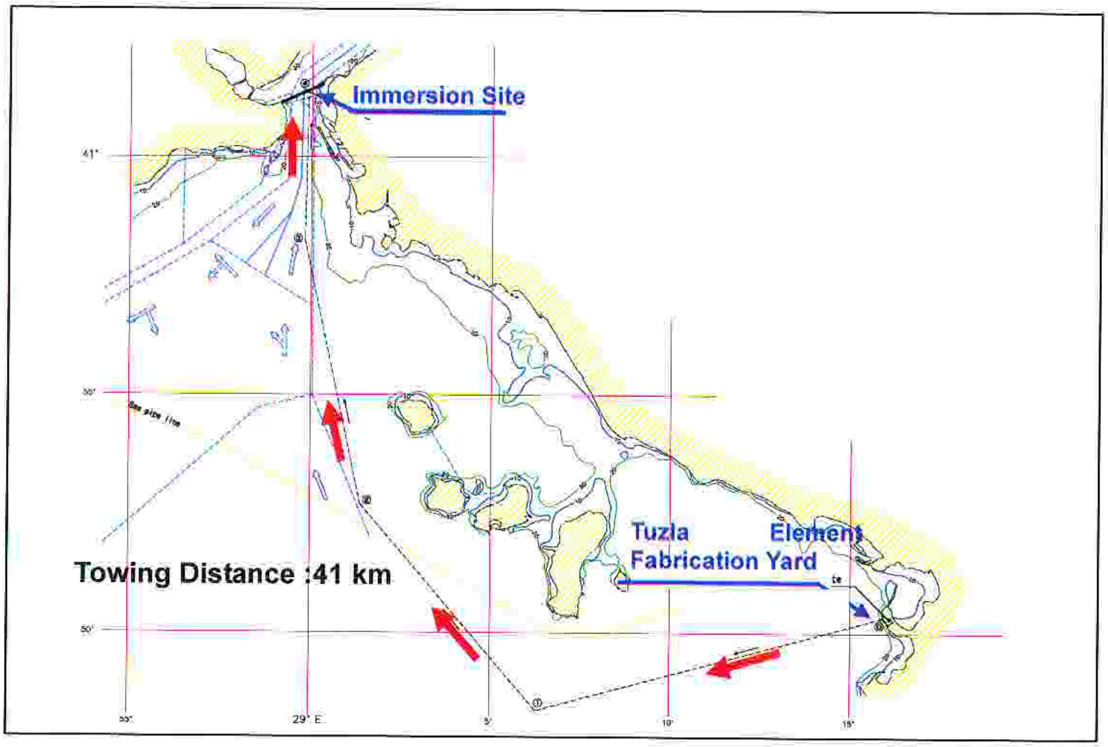

Figure 8.3 : Route of Immersed Tunnels

9. GENERAL INFORMATION OF R/C SEGMENT LINING

9.1 DESIGN OF R/C SEGMENT LINING

For the design of the r/c segment lining there are parameters to be considered. Also it is essential to state that there is no unique design for a segmental lining.

Very often its design is based on the experience and skill acquired by consulting engineers and contractors on past projects.

For the basic data required to design a tunnel lining we shall consider ....

- Its function
- Its operating life
- The operating constraints
- Environmental constraints
- Structural sizing criteria resulting especially from the above-mentioned constraints

For these requirements we should consider lots of parameters. For instance reinforcement details, constituent materials, loads etc...For this part we shall focus on loads which are important for the segment design.

9.1.1 Ground Load

A-)The vertical ground load

The vertical ground load acting on the tunnel crown is calculated as a uniformly distributed load. Its magnitude is determined by considering such factors as the overburden, cross sectional shape ,and outer diameter of the tunnel, as well as the ground conditions.

i)Soil

The ground load is calculated as follows using Terzaghi's formula in accordance

accordance

$$Pv = \frac{B(\gamma - 2C/B)}{2\tan\phi}.(1 - e^{\frac{-2H}{\beta}\tan\phi}) \qquad \textbf{(9.1)}$$

Where

Pv: loosening ground load acting on the top a ring

B: width of loosened soil at the top a ring

g: weight of soil per unit volume

C: cohesion of soil

ø: internal friction angle of soil

H: overburden depth

R: mean tunnel radius

ii)Rock

The load shall be calculated by Protodiakonov's equation in accordance

$$Pv = \frac{B}{0.10\partial} \qquad \textbf{(9.2)}$$

Where

B: width of ground between slip planes, level with crown

∂: unaxial compressive strength

B)The horizontal ground load is calculated as uniformly distributed load acting on the tunnel lining from the crown to the bottom. Its magnitude is shall calculated by multiplying the vertical ground load by the coefficient of the lateral ground load.

i)The ground load shall calculated by the following equations, in accordance [10]

$$P_{h0} = \partial P_{v0} \qquad \textbf{(9.3)}$$

where

Ph0 : horizontal ground load

PV0 : vertical ground load

∂ : coefficient of lateral ground load ii)The ground load shall calculated by the following equations in accordance [10]

$$P_{h0} = \partial P_{v0} \tag{9.4}$$

where

Ph0 : horizontal ground load

PV0 : vertical ground load

∂ : coefficient of lateral ground load

9.1.2 Water Pressure

The water pressure is calculated taking into consideration the possible changes in the ground water level during and after construction to ensure the safety of the tunnel.

The calculation of the water pressure due to ground water, does not consider the decrease in pressure due to water penetration. The water pressure is calculated for the following two cases.

- Normal condition: maximum value obtained from measurements
- Unusual condition:200-year return-period groundwater level+1.0 m

9.1.3 Dead Weight of Segments

The dead weight of the segments per unit length is calculated as a vertical load distiributed along the centroid of the lining.

The dead weight of the primary lining is calculated using the following equation

$$g_1 = \frac{W_1}{2\pi . R_c} \tag{9.5}$$

q1=dead weight of segments per unit length(kN/m)

W1=weight of one ring of segments(kN)

Rc=radius of a circle of the centroidal line of segments(m)

9.1.4 Effect of Surcharge

The effect of the surcharge on the tunnel is determined taking into consideration the distribution of the stress in the ground.

The effect on the soil due to the surcharge (loads of vehicles and trains on the ground surface) decreases with depth . Therefore, the earth pressure acting on the tunnel lining decreases with the distance from the surcharge.

The following are considered for the design

- Loads of exiting structures
- Loads of structures expected to be constructed in the future
- All future expected loads

9.1.5 Soil Reaction

The soil at the tunnel bottom is equal to the vertical earth pressure acting on the tunnel crown plus the load that counter balances the dead weight of segments.

9.1.6 Railway Live Load

The tunnel should designed under the railway live load in the disadvantageous case. For the design of the transverse section because of the large load ,the locomative load of the most safe side should taken into account.

9.1.7 Loads Applied During Construction

The design of the segments into consideration conditions and the following loads.

9.1.7.1-Thrust force of jacks

The trust force of jacks is a temporary load is applied to the segments rings when advancing the shield machine .It is the most influential force among the loads acting on the segments during construction as seen in figure 9.1

Figure 9.1: Jacks of TBM.

9.1.7.2 Backfill Grouting Pressure

Where backfill grout is injected in a well-controlled manner, the exterior surface of the segment ring is subject to a force similar to fluid pressure. In such cases, the effect of the pressure due to backfill grouting can be neglected in the design of the segments, except when the segments are thin box-type segments composed of skin plates (in locations under special load conditions) or when the design in corporates radially inserted K segments. In actual construction, the backfill grout pressure acting on the segments varies depending on the grouting method and the ground conditions, and the segments could be subject to locally large pressures so it is necessary to consider these pressures in the design. For normal cases, it is acceptable to use the value in which 100 kN/m^2 should added to hydraulic pressure. Figure 9.2 shows the backfilling process. [4]

Figure 9.2: Backfill process.

9.1.7.3 Load from Erector Operation

The load from erector operation is considered one of the segments. The load from erector operation is taken into consideration when designing the segment hangers and when evaluating the effect of the load on the segments during their erection. Figure 9.3 shows the segments during erection.

Figure 9.3: Erector operation

9.1.7.4 Superimposing

The superimposing load is one under the condition where segments are superimposed during their storage and transportation. The impact during storage and transportation is taken into consideration by multiplying the load by the impact coefficient. Figure 9.4 shows the segments while loading on truck.

Figure 9.4: Transportation of the segments

9.1.7.5 Dead Weight During Assembling Segments

Although segments are assembled within the skin plate of TBM, the assembly is unstable because the surrounding ground still supports the segments. Thus, the impact of the dead weight of the segments thereon must be evaluated.

Figure 9.5: After assembling the segments

9.1.7.6 Effects of Earthquakes

The effects of earthquakes on a tunnel are considered in the design if it is determined that they cannot be ignored. This determination is based on such factors as the ground conditions and the tunnel alignment and location.

If the tunnel is driven through relatively uniform soils and has a large overburden, the effects of earthquakes are considered to be small since the tunnel behaves in a way similar to that of the surroundings soils. However, if the tunnel is subjected to any of the following conditions, it could be greatly affected by the behavior of the surrounding soils and the effects of earthquakes are determined by taking into consideration the dynamic interaction between the tunnel and the surrounding soil.

- The cross sectional area and the stiffness of the tunnel sharply change(an opening ,station and a joint with a tunnel element and others)
- The ground conditions suddenly change.(in a strait and others)
- The tunnel has sharp curves.
- The tunnel passes through soft soils.

It is also desirable that the following factors be considered when evaluating effects of earthquakes.

- Ground deformation during earthquakes
- Effects of overburden soils
- Inertia force of tunnel and shaft

9.1.7.7 Effects of a Adjoining Tunnel

Where two or more tunnels are constructed near each other as shown in figure 9.6 , the preceding tunnel could be affected by the succeeding tunnel and their interaction creates earth pressures and soil reactions different from those cases where only one tunnel is driven. Furthermore, such an interaction could cause long-term adverse effects on the tunnels.

Figure 9.6: Job site.

9.1.7.8 Explosions

The tunnel design is based on the assumption that an explosion could occur at any location in the tunnel. A static pressure of 100kN/m2 shall used as the explosion pressure.

9.1.7.9-Temperature Effects

This tunnel, unlike special tunnels such as energy conveyance tunnels, is a little subjected to temperature variations and temperature gradients, so the impact of thermal stress is minimal. Therefore we shall not consider temperature effects in the design.

9.2 REINFORCED SEGMENTS

Tunnel lining with segments may have a single or a double layer lining design consist of a cast in place lining on the interior wall of the segment lining.

In a single layer lining construction, the segments form the final lining. They must fulfill all requirements, resulting from construction conditions, rocks, groundwater conditions and utilization. Generally the segments are reinforced pre-cast components. Only in smaller tunnel diameters and with lower quality requirements segments without reinforcement are used.

Figure 9.7 and 9.8 shows preparation of reinforcement for segments.

Figure 9.7: Preparation of R/C Segment reinforcement

Figure 9.8 : After preparation of R/C Segment reinforcement.

9.3 REQUIREMENTS FOR UTILIZATION

The requirements of the utilization of segment lining result from rock and water pressure, along with the use and the construction conditions.

High concrete strength is compelling regarding load transfers in the joints ,thrust forces and the backup loads(construction conditions).Usually reinforced concrete segments are produced in concrete strength class B45, sometimes also in B55 or higher. For Marmaray Project Contract BC1 the concrete class is B50.

It should be mentioned , that the concrete of the segments in the tunnel portal area must have a high frost resistance ;a high frost and de-icing salt resistance is necessary for road tunnels. With chemical attack due to sulfate containing water (>600 mg SO4/l) or sulfate containing soil(>3000 mg SO4/kg) [5] cement with a high sulfate resistance has to be used for the segments.

9.4 SEGMENT CONSTRUCTION

9.4.1 Ring Geometry

A segment ring consist 6 segments plus one key segment ; totally seven segment. For The ring division and the segment dimension have to be optimized according to the project specific requirements. The ring division is among other things influenced by:

- Tunnel diameter
- Max. Permissible size of the segments for the intended transport
- Mechanical engineering mechanisms for installing the segments in the tunnel (erector),
- Number of thrust jacks and their distribution over the range of the ring.

Figure 9.9 : Checking of Ring geometry at the site.

9.4.2 Ring Joints

The ring joints are stressed by normal and transverse forces. The normal forces result from the thrust cylinder forces during construction and in the final state from water pressure. Transverse forces in the ring joints result from different deformations of neighboring rings.

To avoid damage due to stress peaks and to improve the load transfers, load transfer plates inserted in the ring joints have proven to be satisfactory. Also, for installation of cam and pocket system, the use of kaubit strips or equivalent is recommended. In figure 9.10 shows an example segments ready for assembling.

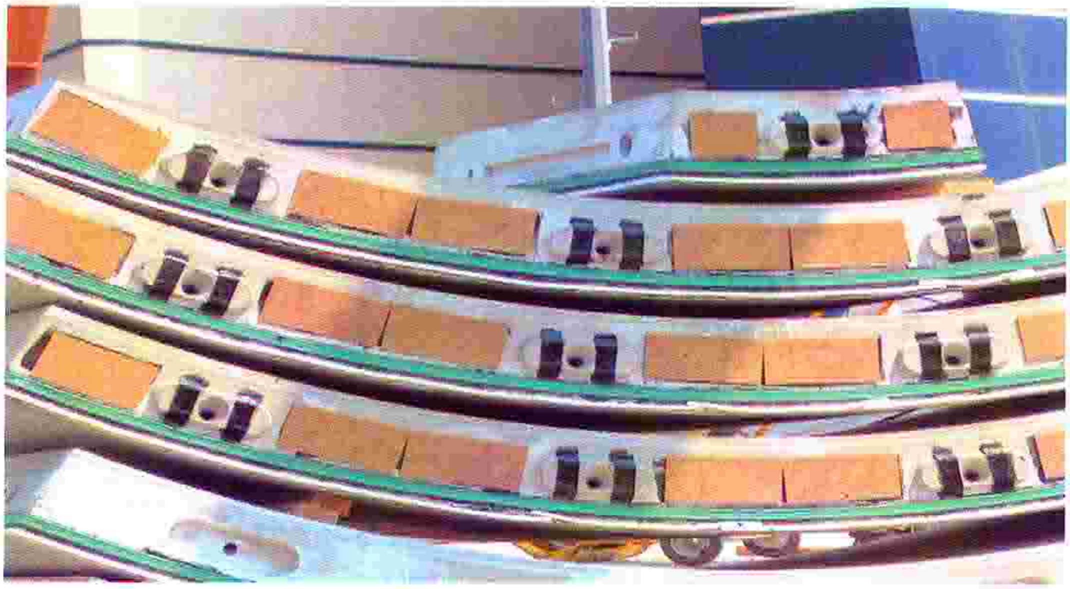

Figure 9.10: Ready segments for assembling.

9.4.3 Segment Bolting and Segment Dowelling

For the installation of the segment ring and to secure the geometry, it is useful to bolt the segment connections along, the longitudinal grooves and ring joints. Generally the screw connections can be taken out again after imbedding the ring in the grout .Then a bolted connection is no longer necessary since the longitudinal joints are pressed into place by the ground pressure and water pressure and pre loads are present in the ring joints created by resetting forces of the sealing section.

Figure 9.11: TBM Tunnel.

9.4.4 Segment Production

Generally, segments are manufactured in an existing pre casting plant or in special job-site plants developed for the project.

Following dimensions/tolerances are recommended:

- Segment width -/+ 0,6 mm
- Segment thickness -/+ 3,0 mm
- Segment floor length -/+ 0,8 mm
- Longitudinal joints evenness -/+ 0,5 mm
- Ring joint evenness -/+ 0,5 mm
- Cross-setting angle in longitudinal joints -/+ 0,04°
- Angles of the longitudinal joint taper -/+ 0,01° [5]

The dimensional tolerances can be defined project specific.

Figure 9.12: Casting of R/C Segment Concrete for TBM.

Figure 9.13: Curing period of R/C Segment Concrete for TBM.

Figure 9.14: Storage of segments prepared for TBM

9.4.5 Segment Installation

During the excavation, segments shall be brought to the tunnel face by the battery locomotive. Before segment will bring into the tunnel, Gasket, Share Strip, Transmission Strip, Protection Strip and Guidance Rod shall be attached to the segment at Site.

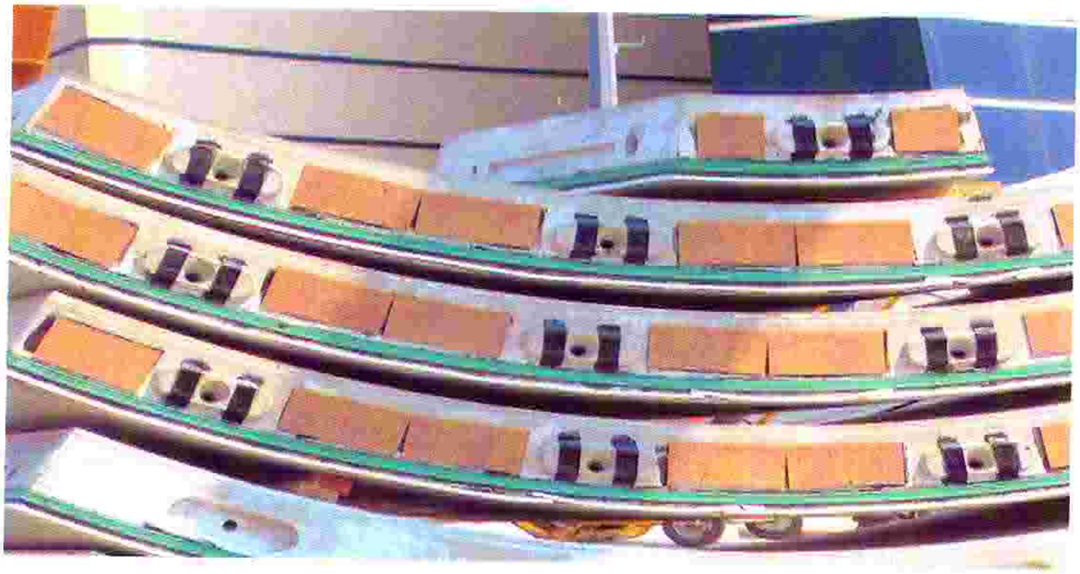

Figure 9.15: Ready segments for assemble.

In Marmaray Contract BC1 there are 7 kinds of segmental ring. In accordance with the design alignment and the survey data, the suitable type and suitable installation position of the segment shall be decided by engineers or managers.

During installation and/or after installation, engineers are checking whether installation work is performed correctly by in accordance with instructions.

10. GEOLOGY OF ROUTE

For Marmaray project BC1 according to drilling datas and other researches, project design engineers divided the route geology into the 6 main formation.

These are Bakirkoy, Gungoren, Cukurcesme, Tuzla, Baltalimanı and Trakya formations.

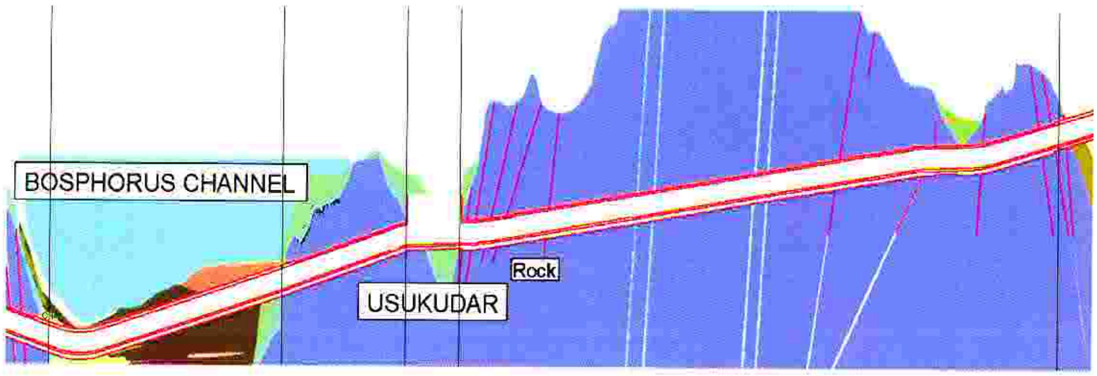

Figure 10.1: Geology map of route of Kazlıcesme to Bosphorus Channel

Trakya formation contains Sandstone, Mudstone, Diabase rock types. Their unconfined compressive strength results are between 2,8~ 178,3 MPa. Also ground water pressure is between 0,3~0,8 MPa. You can divided in to three parts according to the rock types.

First one is fault zones; In these part's unconfined compressive strength results are between 2~20 MPa. The second one is moderate rock type ; These part's unconfined compressive strength results are nearly 70 MPa. The third one is the stiff rock type ; These part's unconfined compressive strength results are more than 180 MPa.

Table 10.1 :Formations of the route between 0+000 and 9+824 [6]

KM	CONSTURUCTION TYPE	FORMATION
0+000~0+960	CUT & FILL	BACKFILL
0+960~1+200	CUT & COVER	BACKFILL
		BAKIRKOY
1+200~1+800	TBM TUNNEL	BAKIRKOY
1+800~3+685	TBM TUNNEL	GUNGOREN
3+685~4+080	YENIKAPI STATION	BACKFILL
		MARINE DEPOSIT
	CUT & COVER	GUNGOREN
		CUKURCESME
4+080~4+140	TBM TUNNEL	GUNGOREN
4+140~4+420	TBM TUNNEL	TRAKYA
4+420~4+560	TBM TUNNEL	GUNGOREN
4+560~6+225	TBM TUNNEL	TRAKYA
6+225~6+460	SIRKECI STATION	TRAKYA
6+460~7+427	TBM TUNNEL	TRAKYA
7+427~8+814	IMMERSED TUNNEL	
8+814~9+599	TBM TUNNEL	TRAKYA
9+599~9+824	USKUDAR STATION	BACKFILL
	CUT & COVER	MARINE DEPOSIT
		TRAKYA

Table 10.2 :Formations of the route between 9+824 and 13+860 [6]

9+824~12+745	TBM TUNNEL	TRAKYA
12+745~12+950	TBM TUNNEL	ALLUVION
		TRAKYA
12+950~13+410	TBM TUNNEL	TUZLA
		BALTALIMANI
		TRAKYA
13+410~13+860	CUT & COVER	BACKFILL
		ALLUVION
		TRAKYA

11. PREPARATION WORKS OF TBM EXCAVATION

For the preparation works items as below.

11-1 Setting of Entrance

11-1-1 Survey and Setting Out

For the tunnel construction alignment is very important. For every step of the project you should monitor the alignment.

At the beginning of the project topographic measuring team made the topographic measurements and marked the tunnel center line and corners of the construction.

11-1-2 Setting of Entrance Hardware

Figure **11.1** Setting of Entrance Hardware

The entrance hardware was made in the factory. The entrance hardware consist of five parts. This entrance hardware was assembled with the welding in job site. After assembling, it was set by Rough terrain crane.

11-1-3 Formwork and Casting Concrete

Figure 11.2: Formwork and Casting Concrete

After setting of entrance hardware a formwork should be constructed around it. This concrete is called entrance concrete. Concrete was casted by concrete pumping vehicle.

11-1-4 Assembly packing , hold down frame and hold down plate (Flapper)

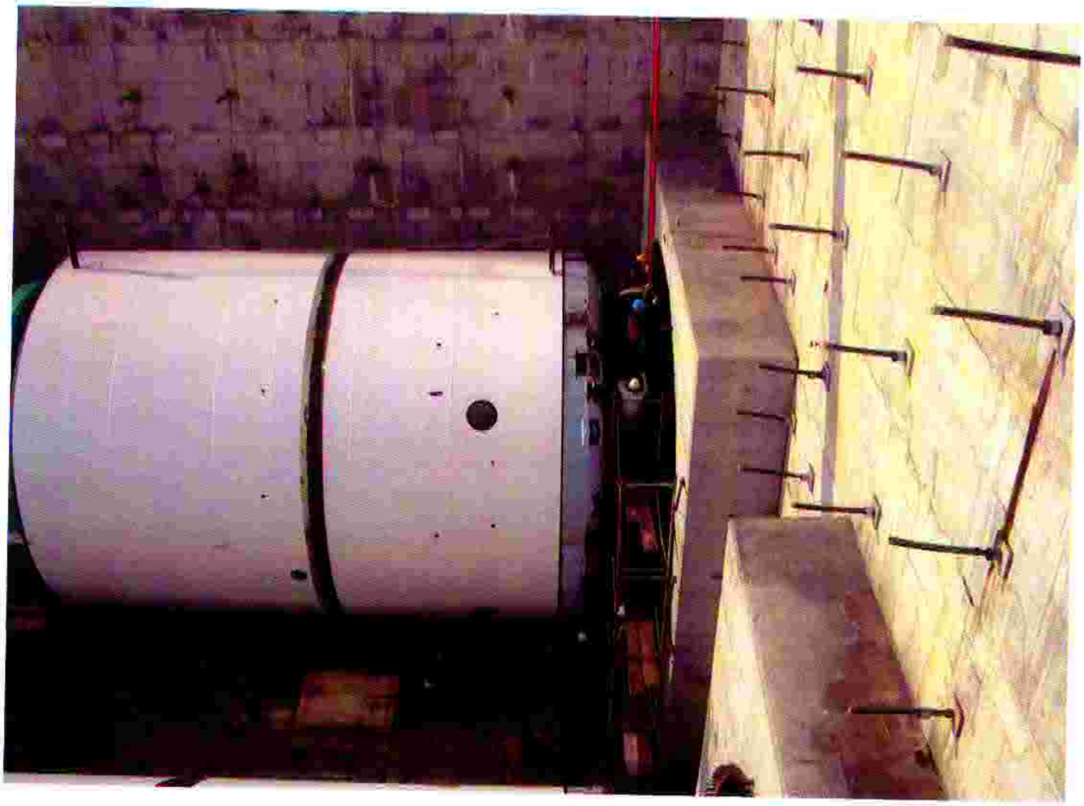

Figure 11.3: Assembly packing , hold down frame and hold down plate (Flapper)

Packing was installed by rough terrain crane and vehicle for high lift work. Afterwards, hold down frame and flapper is installed.

11-2 Work for TBM Saddle

11-2-1 Survey and Setting out

Like setting of entrance the topographic measuring team makes the topographic measurements and mark the tunnel center line and corners of the construction.

11-2-2 Setting of TBM Saddle

The TBM saddle is a base that serves as a reference level and bearing for the machine to advance. The saddle is of rigid structure to sufficiently bear the dead load of the machine. Steel structures for the saddle was assembled on the base plate concrete and firmly secured with the bolts and by welding to prevent slippage.

11-2-3 Fixing of TBM Saddle

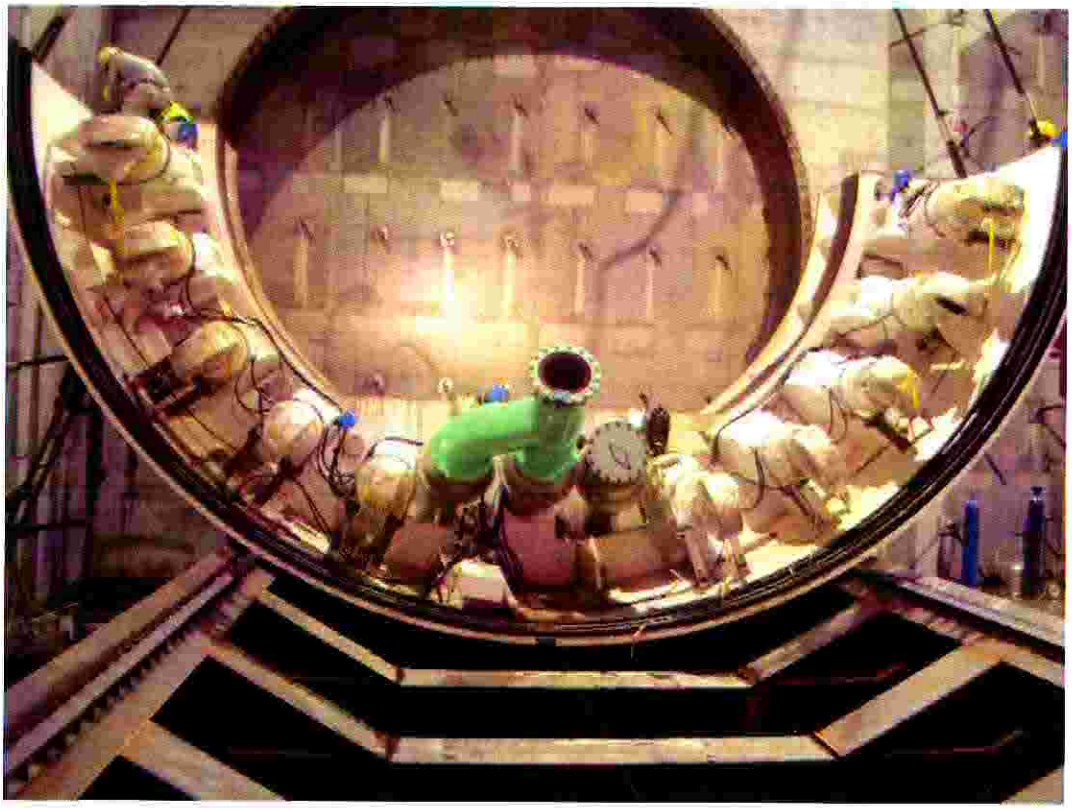

Figure 11.4: Fixing of TBM Saddle

The saddle was fixed by anchor to the bottom to prevent movement by impactive forces when the TBM departs . Shrinkage-compensating mortar was poured between base plate concrete and steel to prevent movement.

11-3 Work for Reaction Beam

11-3-1 Survey and Setting Out

Topographic survey was done before setting of reaction beam.

11-3-2 Setting of reaction beam

Figure 11.5: Setting of reaction beam

Reaction beam was built with help of Rough terrain crane. Each parts was joined with bolts and welding. This assembly was divided in two parts (upper part and lower part) for TBM assembly. When TBM assembly finish ,reaction beam of upper side was build immediately.

Reaction beam was required to have such structure that withstands the thrust of the TBM during initial advancement,prevents flexural stresses from acting on temporarily erected segments. Reaction beam was fixed an anchor on base plate concrete.

11-4 Demolition of Existing Wall

The existing wall was removed just before moving of TBM. Scaffolding for the removal of existing wall was erected on front of the entrance. The existing wall was chipped from the top to bottom in five or four stages of scaffolding. Waste generated from the chipping was loaded man power and carried out of the entrance using a crane.

12 UTILIZATION OF TBM

For TBM excavation time is important. If we analyses the shift reports there are 6 main parts. These are;

- Maintanance of TBM
- Preparation for TBM Excavation
- TBM Excavation
- Segment Installation
- Surveying
- Service Extensions

12-1 Preparation for TBM Excavation

Engineers and operators are supposed to use time effectively. Well planned excavation makes the TBM performance higher and poor planned can bring a lot of problem with it. Therefore, some parameters required to be fixed for excavation before starting the work for each shift such as ;

- Slurry Pressure
- Slurry Flow Volume
- Excavation Speed
- Jack Stroke
- Thrust, Cutter Torque
- Slurry Property

The information is provided by TBM managers or engineers with excavation instruction sheet to TBM operators. Also before excavation if there are water inside the shield before assembling of segments, it should be discharged.

This time duration is defined as preparation for excavation.

12-2 TBM Excavation

First, the slurry treatment plant is started, and after the confirmation of its starting, the slurry transportation system is activated.

After activation of slurry transportation system, the excavation is started.

During the excavation, necessary parameters of excavation is monitored with the control panel in the TBM operation room and the slurry transportation system operation room. TBM operator and slurry transportation system operator monitor and adjust parameters which is directed in the excavation instruction sheet.

These parameters are recorded by the slurry transportation system timely and TBM engineers and/or supervisors are check whether excavation work is performed correctly in accordance with instruction sheets.

The excavated material is carried to the slurry treatment plant by slurry. In this plant, at first, gravel and sand are separated from slurry by the primary treatment equipment. And then, silt and clay are separated from slurry by the secondary treatment equipment. The separated material is stored in disposal pits.

These excavated materials are loaded to trucks by the excavator and brought out from the site to suitable places according to the purpose.

After 1500 mm excavation, the slurry transportation system and the slurry treatment plant are stopped for erection of precast reinforced concrete segment installation.

During excavation, back-fill grouting process continues. In figures 12.3 , 12.4 and 12.5, back fill grouting time is not calculated because this activity is independent from TBM excavation. Therefore the duration does not effect directly the performance of TBM. [9]

12-3 Precast Reinforced Concrete Segment Installation

Before segments are brought into the tunnel for assembly, all accessories like gasket , share strip , transmission strip , protection strip and guidance rod are installed on the segment and then the segments are brought to the tunnel face by the battery locomotive in accordance with the installation instruction sheet in which type of segment and installation position are directed, provided by TBM engineers or managers.

In this project, there are 7 kinds of segmental ring. In accordance with the design alignment and the survey data, the suitable type and suitable installation position of the segment shall be decided by TBM engineer or manager.

After completion of 1500 mm excavation, segment assembly work starts accordingly. During assembly of segments excavation is stopped and the segments are installed in accordance with instruction sheets.

During installation and/or after installation, TBM engineer is checked whether installation work is performed correctly in accordance with instruction sheets. [9]

12-4 TBM Survey

The bench marks associated with the network points which are set by "topographic land survey" are installed with the TBM advance by TBM survey team. The coordinates of bench marks must be managed by the TBM survey team and the survey for checking must be carried out periodically by them.

TBM is guided by the automatic survey system which will be used these bench marks and the reflectors installed on TBM back up car. TBM position can be monitored by this system in the operation room. The survey equipments of this system has to move ahead with TBM advance. In addition, segment positions are surveyed by using the total station and the level each shift. Site engineers prepare excavation instruction report in accordance with this information for each shift. [9]

12-5 Backfill Grouting

In order to prevent the ground movement (settlement), it is necessary that the backfill grouting is done sufficiently, properly and early by pumping into the annular void between the segment and the ground from the grout hole of the segments.

Besides, in order to control the direction of TBM with high accuracy, it is necessary that the segments are fixed as early as possible by the backfill grouting. For these reasons, the backfill grouting has to be performed continuously and sufficiently by the material which shall harden quickly.

About the facilities of this work, mainly they consist of the mixing plant and the injection unit. The mixing plant is installed on the ground, and the injection unit shall be installed in the backup car inside tunnel.

Flow chart of this work is as follows.

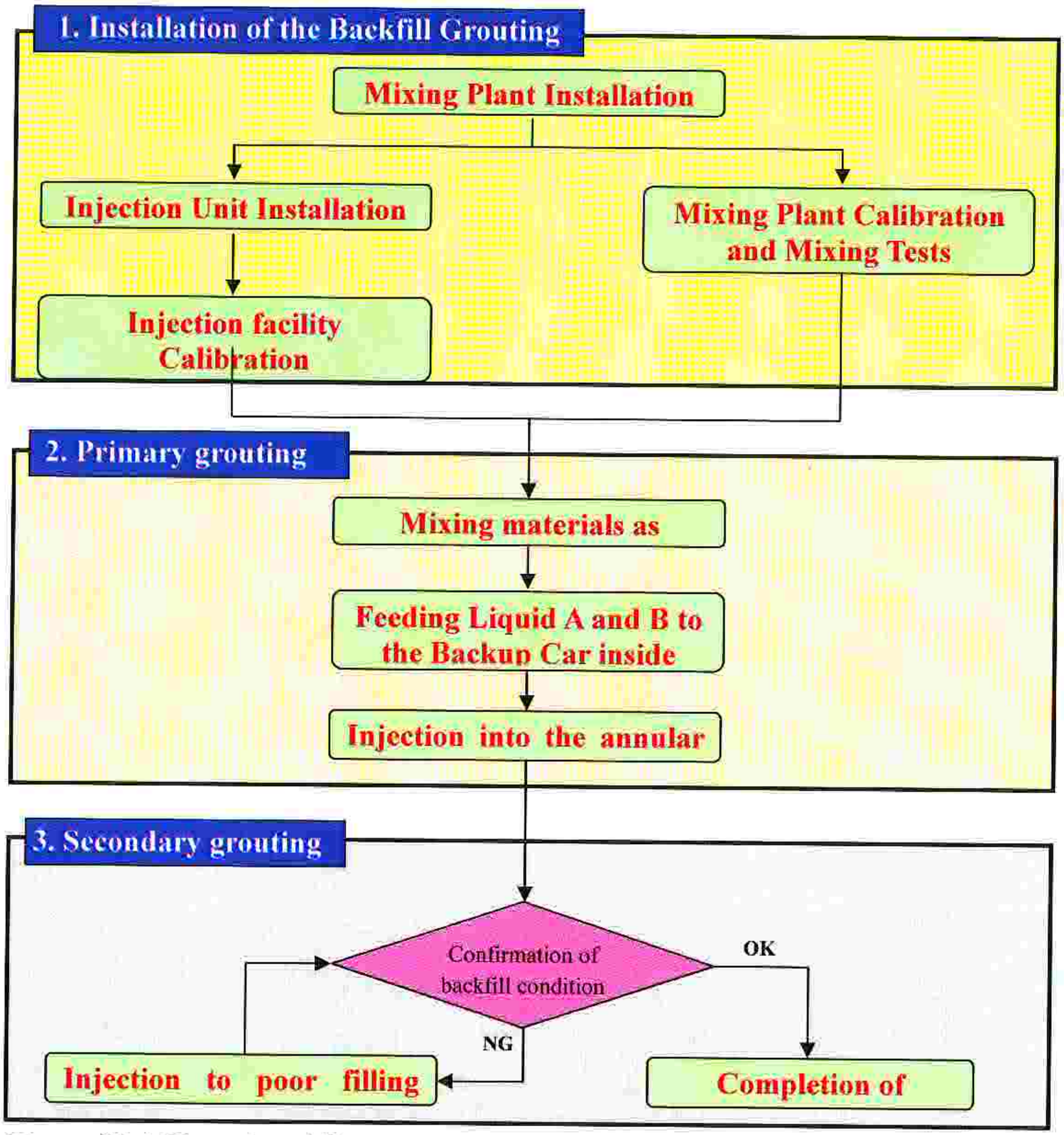

Figure 12-1 Flow chart [4]

As shown at figure 12-1 above, there is two types of backfill grouting considered. These are primary grouting, secondary grouting

- **Primary Grouting**

Grouting consist of two types of liquid.

- Liquid A; which is the mix of Cement, Bentonite and Water
- Liquid B; sodium silicate

Liquid A is mixed at the mixing plant. Then it is pumped to the agitator in the TBM Backup car by the feeding pump.

Liquid B which is the sodium silicate is also pumped to the storage tank in TBM backup car.

When the TBM commences the excavation and advances, liquid A and B will be fed from the backup car up to the special dual pipe separately by each injection pump, and then these liquid will be mixed by the special dual pipe and be fed into the annular void between the segment and the ground from the grout hole of the segment in accordance with the excavation speed of TBM.

After tail of TBM passes through 1st permanent ring, backfill grouting process shall be started. Backfill grouting is illustrated in figure 12.2.

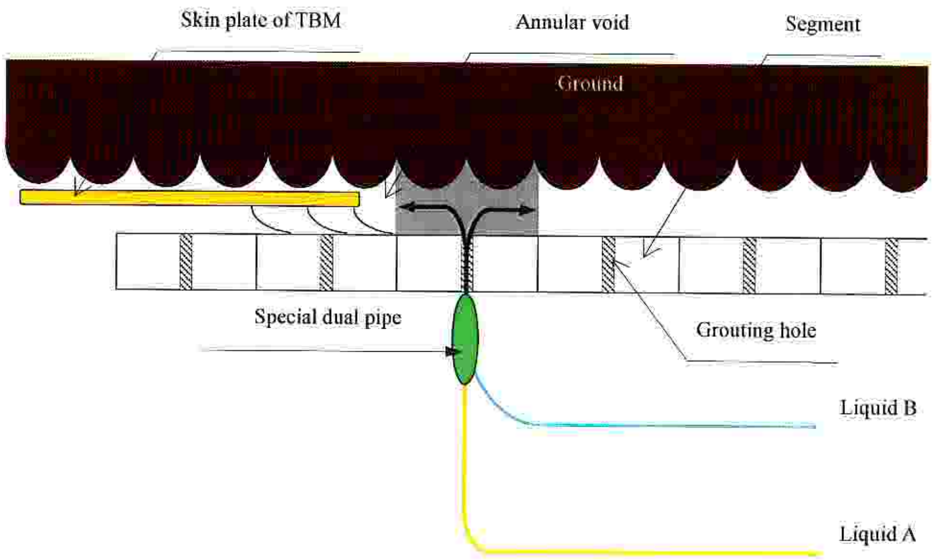

Figure 12-2 : Backfill Grouting [4]

These operations is automatically controlled by the backfill grouting system.

- **Secondary grouting**

Since this material becomes gel momentarily, the poor grouting by a material separation or a material outflow will not occur easily. For this reason, generally this backfill grouting method does not need the secondary grouting.

However, the situation of the primary grouting is checked every day with the backfill grouting record. If there is the section where the amount of primary grouting is less than 100% on the average, the reason is identified, and if necessary, the secondary grouting is realized. The ingredients and properties and procedure of secondary backfill grouting is same as primary grouting.

As mentioned before, this activity is independent from TBM excavation. Therefore the duration is not effected directly the performance of TBM.

12-6 Service Extensions

- **Temporary railway extention**

The steel sleepers and rails for materials carrying in; are extended during excavation. These are brought in the tunnel face together with segments by battery locomotive. This work is carried out during excavation.

This activity is also independent from TBM excavation. Therefore the duration does not effect directly the performance of TBM. However these information is given to outlined the all picture of TBM activities.

- **Pipes extention**

Slurry TBM carries out the disposal material by pipes so that pipes extension is neccesery for this operation. Due to the pipe length (6m), each pipe for slurry feeding, slurry discharging, water supply, drainage backfill grouting are extended for every 6m excavation. The pipes are brought in the tunnel by battery locomotive. This work will be carried out during segment installation.

This activity is also independent from TBM excavation. Therefore the duration is not effect directly the performance of TBM. However these informations are given to outlined the all picture of TBM activities.

- **Cable extention**

High voltage cable for 500 m was built into the cable drum in the back up car, this cable are reeled again to the cable drum after TBM goes ahead every 500 m and then a new high voltage cable is installed and connected to the cable reeled to the drum.

12.7 Preparation Work for Entering into the TBM Chamber

In order to change cutter bits and disc cutters or other reasons, entering into TBM chamber is necessary. At that time, preparation works are carried out and checking with opening man lock and material lock as follows.

1. Discharging slurry from chamber
2. Checking the tunnel face ground condition
3. Setting the ladder and the lifting equipment

- **Check and exchange of the cutter bits and disk cutters**

The cutter bits and the disk cutters are worn away as usual by rock excavation. For this reason, the cutter bits and the disc cutter are checked regularly and exchange if the attrition of them are more than predetermined value.

Maintanence duration occurs generally for pipe blockage. the entering of some big size rock from chamber of TBM makes this blockages.

As it is seen from figure 12.3 , 12.4 , 12.5 every beginning of the project there is a duration that every body get used to understand their job. By time passed everybody understand their job and find solutions to do their job fast and better than before.

For TBM, man power is not the only parameter which effect the machine performance. Also geological parameters and the mechanical parameters of the machine is important. For instance for Slurry TBM pipe diameter of discharge pipes is important. Especially when TBM was passing from the fault zone in Trakya Formation some blockage of discharge pipes is observed. At that time the excavation is stopped and blockage problem is solved.

Job analyses for July 2007, November 2007 and the mean values are given in figure 12.3 , 12.4 , 12.5.

As seen from these figures the machine excavation time increased from 26 % to 32% from July to November. Maintanence of the machine decreased from 31% to 26% and segment lining decreased from 20% to 12%. These figures shows that there is a learning time for each project.

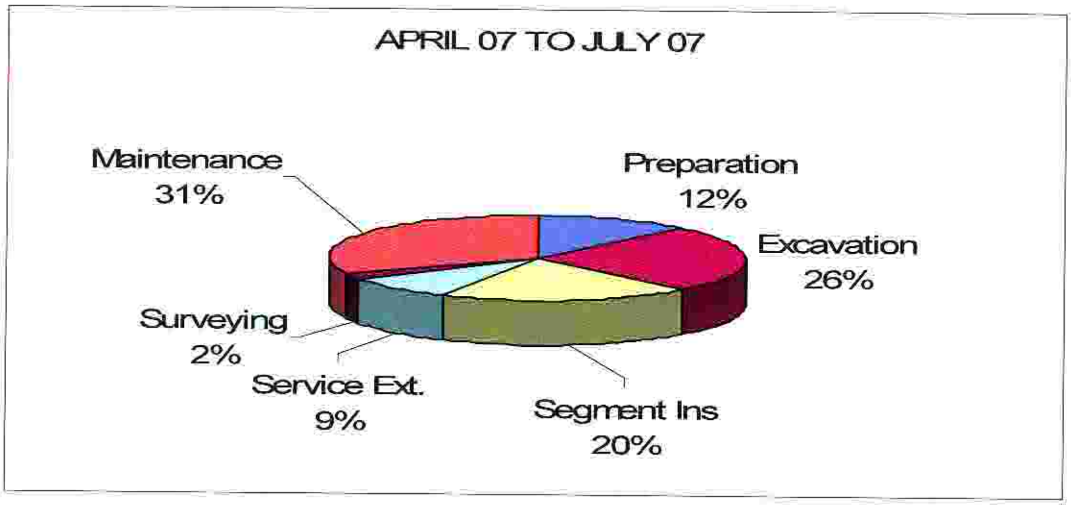

Figure 12.3 : Job analyses in July 2007

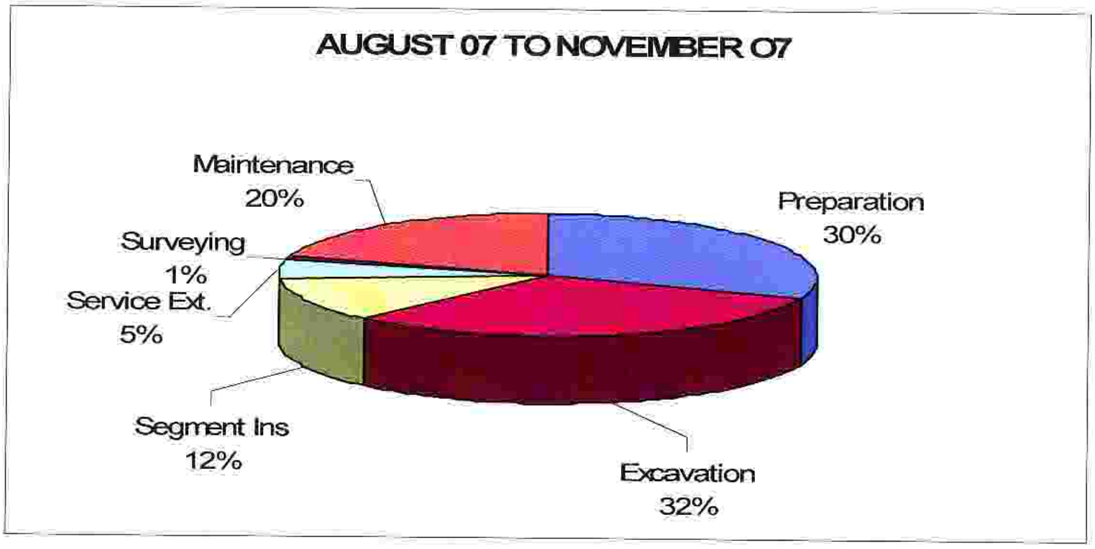

Figure 12.4 : Job analyses in November 2007

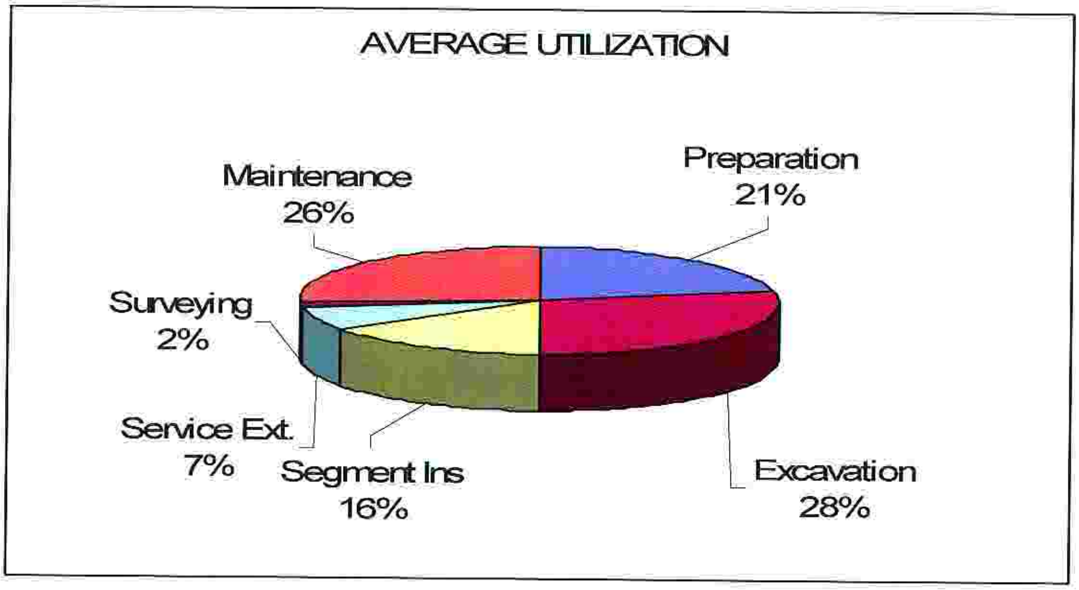

Figure 12.5 : Mean values of job analyses between April 07 to November 07

13 DAILY PROGRESS

As it is seen from 13.1 that the table excavation speed is not constant at Trakya formation. There are some reasons of it. The main problem is the blockage of discharge pipes and pumps of slurry. At the trakya formation the rock types Mudstone and Sandstone make this blockage. The pipes should be cleaned. Opening this blockage makes lose the time and this time directly effects your performance.

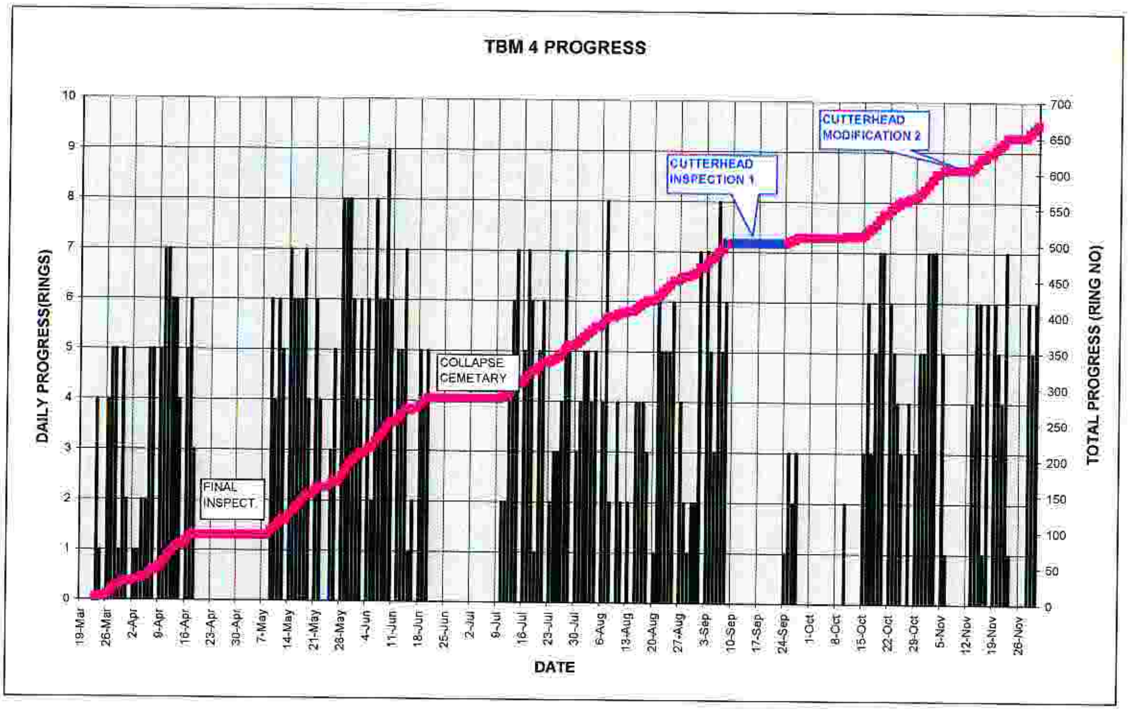

Figure 13-1 : The charge of Daily progress

Table 13-1 Details of excavations

The best excavation advance per day	13,5 m/day
The average excavation advance per day	3,94 m/day
The best excavation advance per week	57 m/week
The average excavation advance per week	27,6 m/week
The best excavation advance per month	157 m/month
The average excavation advance per month	112,33 m/month

TBM daily progress evaluated from 19-03-2007 to end of November 2007 are reported in Table 13-1. The geology in this period is Trakya formation.

As we know the Trakya formation is not homogeneous so that there is not a constant speed of excavation.

Also when we analyse the figure 13-1 we can see some durations which TBM did not excavate.

The other waiting duration was because of a collapse on a cementary area on the other TBM route. As it is mentioned before two TBM are working at the same time but some distance must be kept for safety between two TBMs. There are technical reasons of this safety distance but main purpose is to control settlements on the ground. The tunnelling at urban area makes the settlement prior issue. For this reason TBM 4 waits the other TBM to pass collapsed area so that time passed without excavation on end of July 2007.

There was cutter disk inspection on September 2007 .While this inspection carried on there was no excavation. Also after inspection TBM manufacturer supervisor made some modification to improve the progress of TBM. The main purpose of this modification was to minimize the blockage due to passing big size rock samples which passed from the chamber easily.

After this modification on November 2007 supervisors stopped the TBM excavation to check the effectiveness of modifications.

During this four waiting periods mentioned above TBM 4 did not excavate.

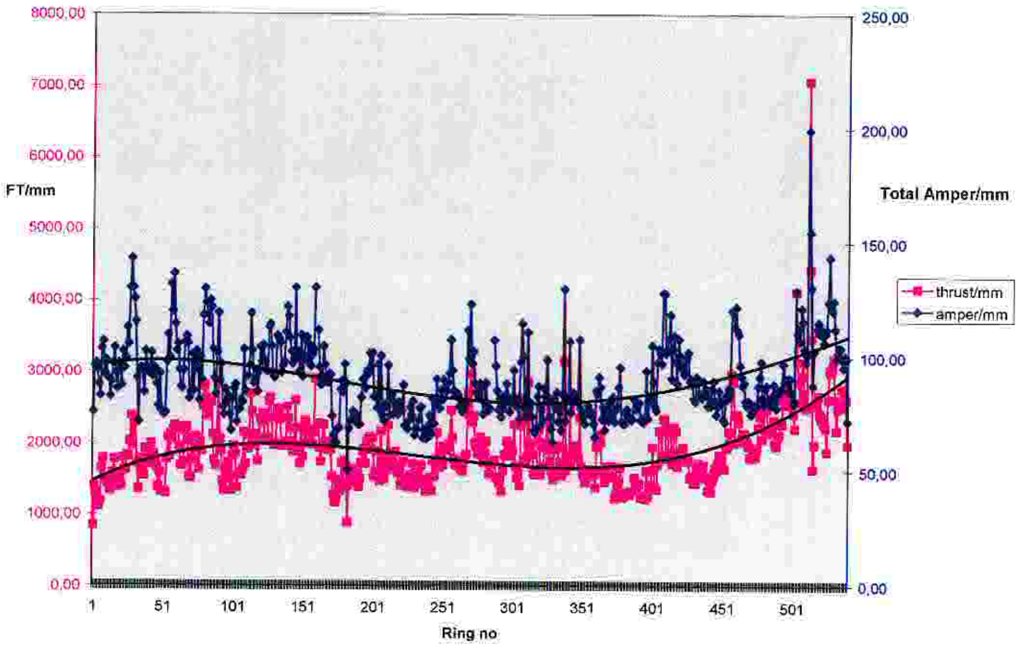

Figure 13-2 : The variation of penetration index (FT/mm) and total ampers of 8 cutting motors, during the tunnel route.

In figure 13-2 the datas are taken from operation data recorder of TBM 4. From excavation of first ring to 540 th ring all datas are noted in figure 13-2. Cutter Motor Current of total 8 motor's amper calculated per mm. RPM and the excavation time datas also are taken from operation data recorded.

$$Amper = \frac{\sum 8\ \text{motors}}{\left(1500 / rpm \times excavationtime\right)} \tag{13.1}$$

Also same calculation is done for the thrust forces. Every ring excavation average thrust forces taken from the operation room and penetration index on (FT/mm) is calculated as below

$$FT/mm = \frac{Thrustforce}{\left(1500 / rpm \times excavationtime\right)} \tag{13.2}$$

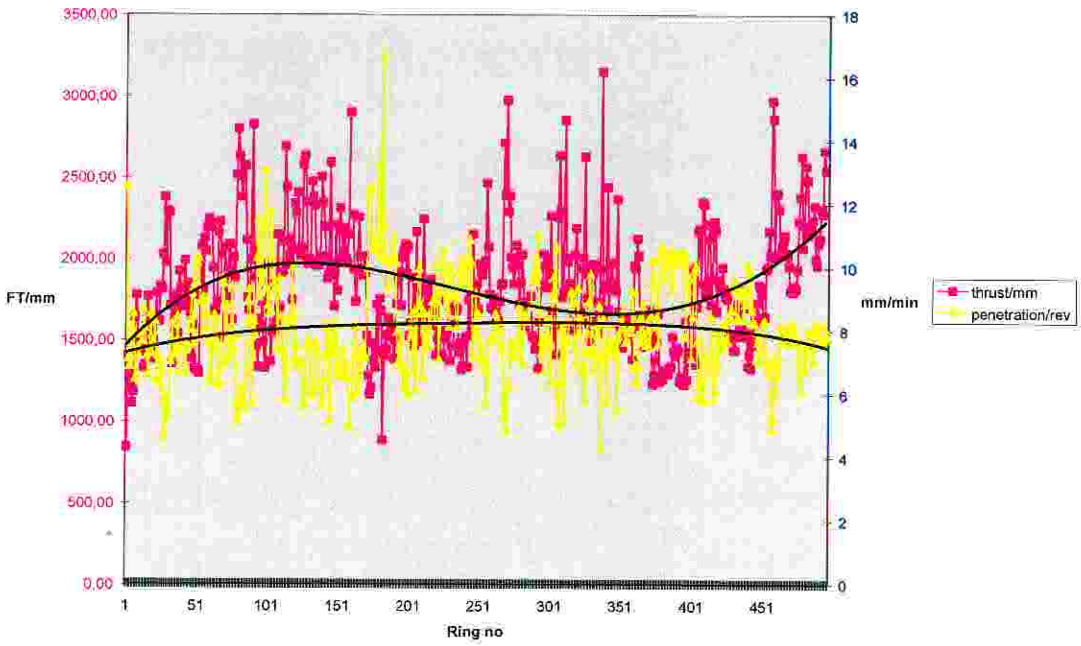

Figure 13-3 : The variation of penetration index (FT/mm) and penetration per revolution of TBM, during the tunnel route.

If we evaluate the thrust per mm and the amper per mm of cutter motors from the beginning of the excavation, we can say that for Trakya Formation the thrust force per mm and total cutter motor amper are not constant. As we know Trakya formation is not homogeneous for rock properties. Main rock types of this formation is mudstone and sandstone. Also If we analyse the figure the thrust force was decreased while passing from the sandly lean clay. Especially on figure 13-3 thrust force per mm is decreasing between 201th to 350th rings but penetration per revolution is increasing. This mean that machine can penetrate the ground with less torque.

14. SAMPLING FROM EXCAVATION MATERIALS

Some muck samples taken from rings 545, 552, 663, 670, 677 to investigate the effects of rock properties on the machine performance. The size of muck when using slurry TBM is usually small, that is way cone indenter and shore hardness were choosen for mechanical tests. The material collected for rock testing is seen in figures 14-2. The main reason of collecting muck samples and doing tests were to evaluate some TBM performance data in different strength rock formation.

Figure 14-1 Excavated materials in disposal pit

Figure 14-2 Samples from excavation of ring no 552

14-1 Cone Indenter

Cone indenter is portable instrument capable of giving a measure of rock strength without requiring the preparation of accurately shaped and finished specimens. Since a description of it was first published in March 1969. Step of test is defined as :

- Inspect the cone for damage or wear . It must not be chipped or worn to a radius greater tahan 0,076mm and should be free to rotate in its mounting
- Set the dial gauge to zero.
- Push the steel strip several times and check that it returns to zero each time.
- Select a chip of rock not larger than 12 mm x 12 mm x 6mm ensuring that the surface to be tested is sound and clean.
- Set the specimen on the steel strip and turn the micrometer screw until the specimen is just held in position by the cone.
- Reset the dial gauge to zero.

- Read the micrometer (reading M_1)
- Turn the micrometer screw slowly clockwise until the dial gauge reads 0,635 mm

The penetration of the cone into the specimen

$$Ps = (M_1 - M_0) - D_1 \tag{14.1}$$

Then the standard cone indenter number

$$I_s = \frac{D_1}{P_s} \tag{14.2}$$

- If Ps is less than 0,2 mm proceedas follows:
- Turn the micrometer screw clockwise until the dial gauge reads 1,27 mm(reading D_2)
- Read the micrometer (reading M_2)

The penetration of the cone into the specimen

$$Pm = (M_2 - M_0) - D_2 \tag{14.3}$$

Then the standard cone indenter number

$$\mathrm{Im} = \frac{D_2}{P_m} \tag{14.4}$$

If we want to calculate Fc

$$Fc = 24,8 \; Is \tag{14.5}$$

$$Fc = 35,8 \; Im \; [7] \tag{14.6}$$

14-2 Determinig Shore Hardness

The purpose of this test to identify and discuss the need for a method to determine standardized SH values , considering the specimen size effect so that the SH as an essentially nondestructive hardness measuring method can be used as a reliable predictor of other mechanical properties of rocks especially the UCS.

For the test procedure ; the specimen in the apparatus horizontally with the ground test surface facing upwards allowing 2,44 g diamond-tipped hammer to drop freely on the test surface and carefully measuring and logging the rebounding height on the scale which ranges from 0 to 140. [8]

After testing the specimens the average shall taken.

If the specimen volume can not be obtained as equal to or greater than 80 cm^3 in volume

$Vs < Vc = 80\ cm^3$, size corrected values of SH can be estimated SH_e for the critical volume by using the arithmetical means of the measured SH values SH_m in the following equation :

$SH_e = 0{,}248\ (80 - Vs) + SH_m$ for $Vs < Vc$ [8]

Where Vs is the volume of the tested specimen.

If the volume can be obtained as equal to or greate than 80 cm^3 in volume ($Vs > Vc = 80\ cm^3$) [8]

the arithmetical means of the measured SH values are directly taken as the SH values.

These two method were applied on the specimens taken from excavation as seen in figure 14-3 and table 14-1 and table14-2 is prepared.

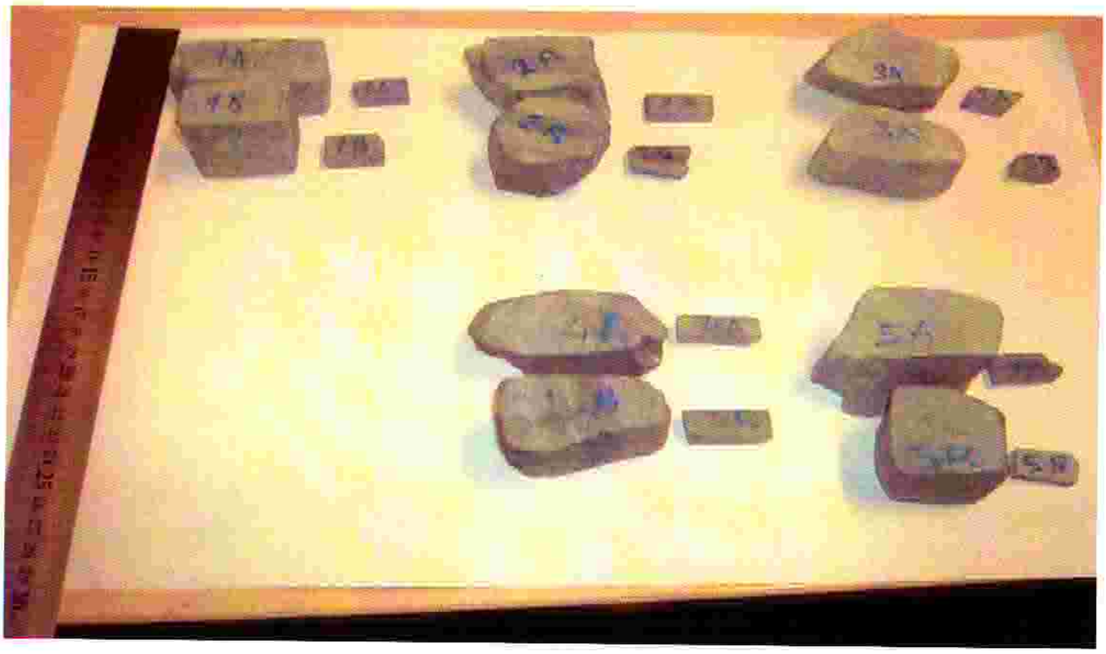

Figure 14-3 Sample prepared for lab. test.

Figure 14-4 Combination of sandstone and mudstone.

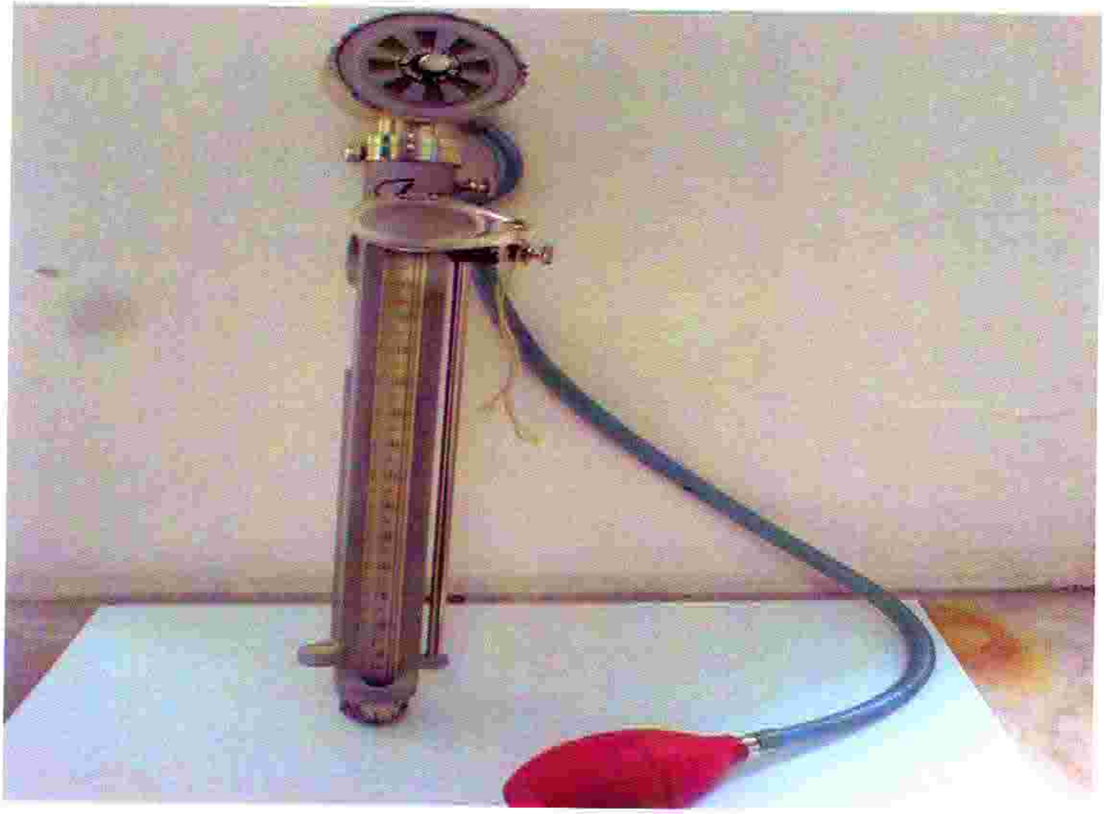

Figure 14-5 Model C-2 Shore sclerosccope

Figure 14-6 Cone indenter

Table 14-1 Calculations according the cone indenter

	Specimen	M0	M1	Ps	Is	MPa	M2	Pm	Im	MPa
677	mudstone	5,500	6,350	0,215	2,953	73,2				
677	mudstone	3,400	4,325	0,290	2,190	54,3				
670	mudstone	4,500	5,600	0,465	1,366	33,9				
670	sandstone	6,400	7,125	0,090			7,975	0,305	4,164	149,1
663	sandstone	4,000	4,825	0,190			5,950	0,680	1,868	66,9
663	mudstone	5,300	6,250	0,315	2,016	50,0				
552	mudstone	2,825	3,660	0,200	3,175	78,7				
552	mudstone	2,900	3,775	0,240	2,646	65,6				
545	sandstone	4,000	4,775	0,140			5,850	0,580	2,190	78,4
545	sandstone	3,300	4,075	0,140			5,100	0,530	2,396	85,8

Table 14-2 Calculations according to Shore Hardness

Specimen	677 Sand stone	677 Sand stone	670 Sand stone	670 Mud stone	663 Sand stone	663 Mud stone	552 Mud stone	552 Mud stone	545 Sand stone	545 Sand stone
SH 1	55	61	47	32	41	21	35	42	56	61
SH 2	46	66	46	28	32	51	33	29	59	58
SH 3	51	71	50	25	31	49	32	28	60	57
SH 4	51	64	51	24	37	43	37	26	51	59
SH 5	44	72	52	27	34	36	34	22	55	55
SH 6	45	68	50	32	35	34	33	31	61	57
SH 7	54	69	52	31	50	28	32	30	55	54
SH 8	50	74	50	28	32	27	32	34	54	61
SH 9	46	68	52	28	39	67	32	36	54	65
SH 10	49	71	53	30	29	48	32	36	55	61
∑ SH	49,10	68,40	50,30	28,50	36,00	40,40	33,20	31,40	56	58,8
SHsd	3,78	3,92	2,26	2,76	6,16	13,86	1,69	5,76	3,09	3,29
x	6,0	4,0	3,9	4,0	3,4	3,1	3,3	5,4	3,2	3,0
y	2,7	4,1	4,9	4,0	4,0	4,0	6,0	3,0	4,5	5,2
z	2,8	2,4	4,1	3,5	4,4	3,6	3,5	4,0	3,8	3,1
Vs	45,36	39,36	78,351	56	59,84	44,64	69,3	64,8	54,7	48,3
MPa	57,69	78,48	50,71	34,45	41,00	49,17	35,85	35,17	62,2	66,6

On table 14-2 , SH1 ,SH2, SH3, SH4, SH5, SH6, SH7, SH8, SH9, SH10 means the readings of the test. SHsd means the standart deviation between readings. Vs is the volume of the specimen. Vs is calculating the multiply of length of x, y, z coordinates of specimen. As we see from the tables rock types of formation is not homogeneous so that some datas are closed to each other but some of them not. From the observations during excavation we see lots of sandstone and mudstone types. Also we see that sandstone gives higher values than mudstone as expected.

Table 14-3 Calculations of Cutter torque

Ring No	cutter torque %	cutter torque kN.m	RPM
545	12	931	2,5
552	13	1009,2	2,5
663	17	1321,54	2,5
670	15	1165,37	2,5
677	17	1645,61	2,0

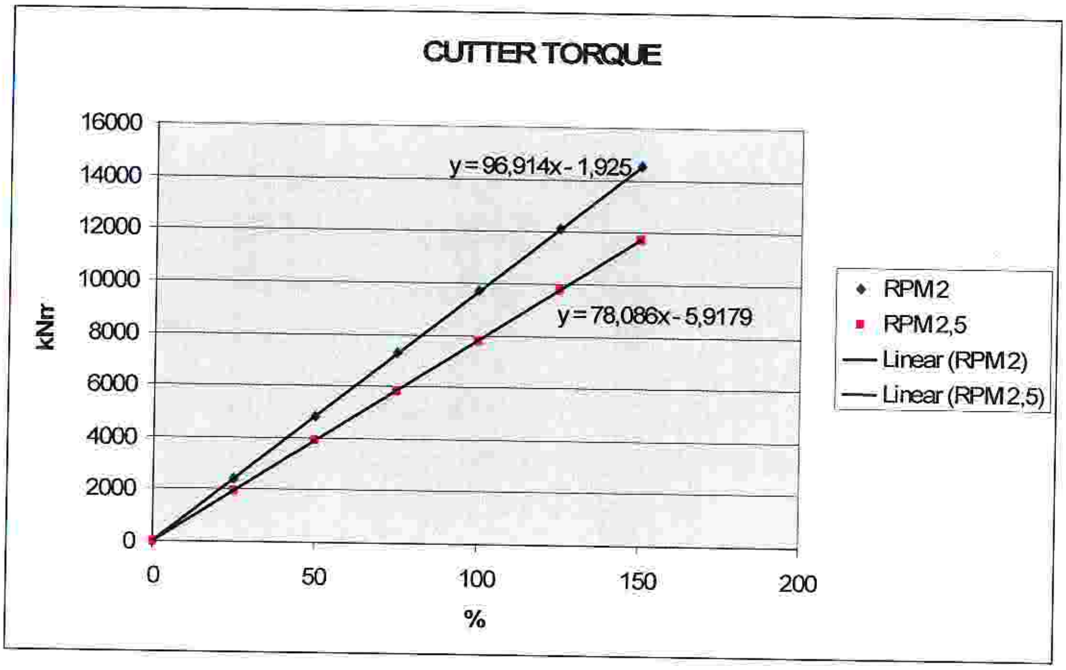

Figure 14-7 Chart of Cutter torque

The torque of TBM is recommended to be calculated from the chart as given in figure 14-7.

Figures 14-8, 14-9, 14-10 and 14-11 shows the variation of penetration index (FT/mm) and cutter torque/mm with shore hardness and cone indenter.

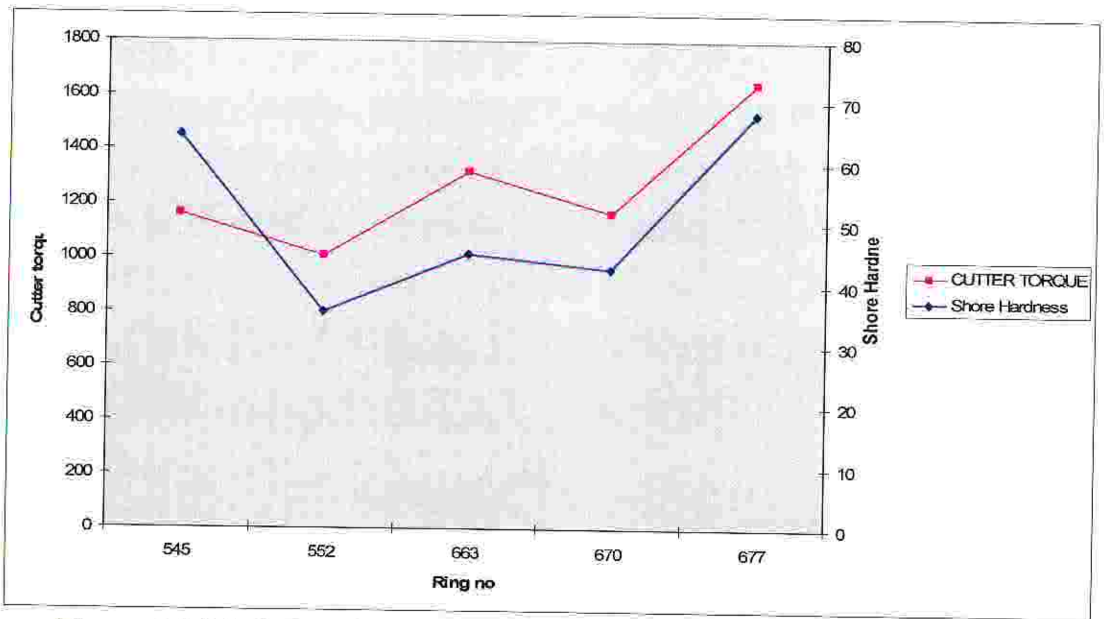

Figure 14-8 Relations between cutter torque and shore hardness of the rock.

When the rock hardness getting harder the torque is increasing also. By this chart we see a close relation between torque and rock hardness.

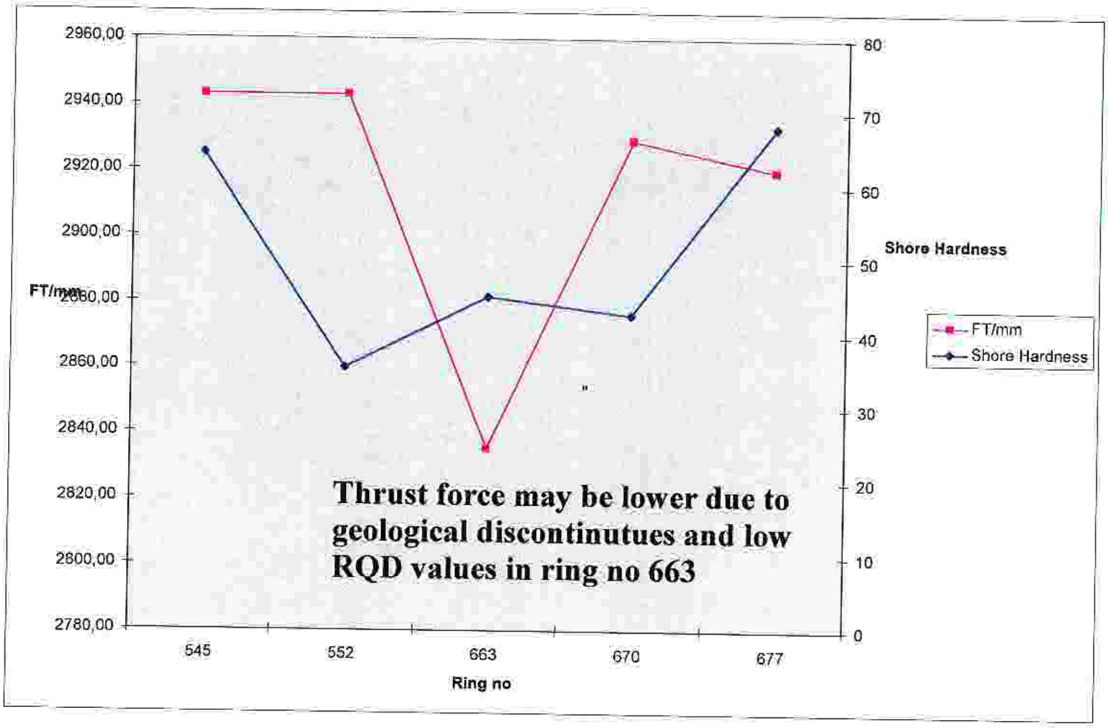

Figure 14-9 Relations between Penetration Index and shore hardness of the rock.

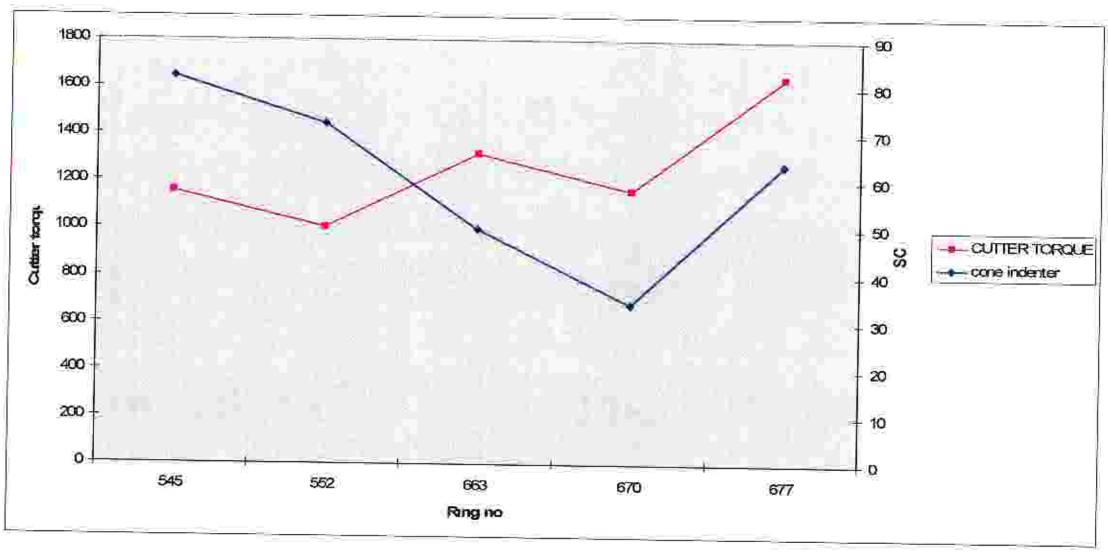

Figure 14-10 Relations between cutter torque and cone indenter of the rock.

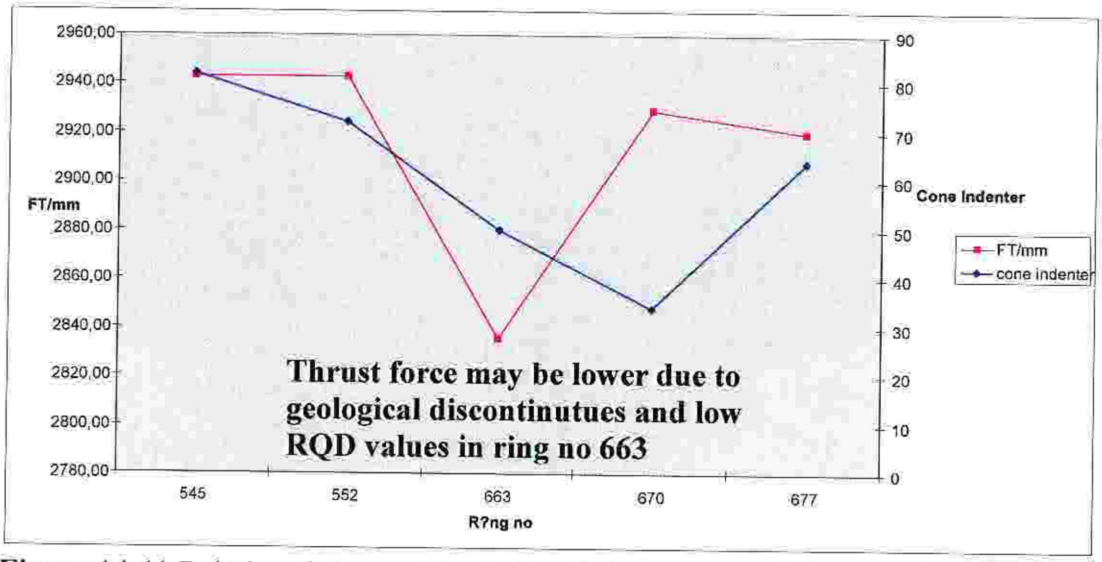

Figure 14-11 Relations between Penetration Index and cone indenter of the rock.

Figures 14-8, 14-9, 14-10 and 14-11 are pioneering in understanding the change of machine performance with rock properties.

15. CONCLUSION

Marmaray Project Contract BC1 is very important project for Istanbul. Passing crossing from the Istanbul Strait with the immersed tube tunnel technique and connection of these tubes with Slurry Type TBM under 55 m of Istanbul strait make the project important.

The major purpose of this research was to analyse the Slurry type TBM performance when Trakya formation.

The following results emerge after the performance analyse,

- Average advance excavation is daily 3,94 m/day, weekly 27,6 m/day, monthly 112,33m/day.
- Average revolution is 2,5 RPM during excavation.
- TBM average penetration per revolution is nearly 7,7mm/minute which is lower than manufacturer estimation mentioned on figure 7.2.
- Machine torque and FT/mm is not constant during excavation. The main reason, Trakya formation is not homogeneous. Formation contents Mudstone, Sandstone and Diabase and the hardness of these formations are different. In accordance with the actual cone indenter test result, Mudstone average hardness is 59 $^{\pm}$ MPa but Sandstone average hardness is 95,05 $^{\pm}$ MPa and shore hardness test results Mudstone average hardness is 38,66 $^{\pm}$ MPa but Sandstone average hardness is 59 $^{\pm}$ MPa. Therefore, these differences explain the inconsistency of machine torque and FT/mm very well.
- When the hardness of formation decreases, torque and the penetration index also decrease accordingly in accordance with the test and analysis results of relation between machine data and geology.
- Pie chart of job analysis figures that there was a learning time at the beginning and for time passing for construction rate of the machine increases its excavation time and decreasing other items such as surveying, service

extension, segment installation and maintenance as mentioned on figures 12-3, 12-4, 12-5. According to figure 12-5 average duration for maintenance % 26, for preparation %21, for surveying %2, for service extension %7, for segment installation %16 and for excavation is %28.

- Regarding the pie chart, the preparation works increased. The main reason is the entering of big size rocks from cutter face to slurry line. This big size rocks makes blockage at that time pipes needs to be cleaned. During this cleaning operation water and slurry inside the pipes discharged inside the tunnel. Before assembling the segments you should drain this water out. This two items are the main reasons effecting negatively the perfonmance of TBM. If this blockage can be stopped by TBM supervisors in the future, we can expect that the maintanence and preparation works percentage will decrease and excavation time will be increased.

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