ISTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

TBM PERFORMANCE IN TWO TUNNELS IN ISTANBUL AND THE EFFECT OF ROCK QUALITY DESIGNATION

M.Sc. Thesis by
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Department : Mining Engineering

Programme : Mining Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

İSTANBUL'DAKİ İKİ TÜNELDE TBM PERFORMANSLARI VE KAYA KÜTLE SINIFLANDIRMASININ ETKİSİ

YÜKSEK LİSANS TEZİ

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FOREWORD

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Mining Engineer

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ABBREVIATIONS

TBM	**:**	Tunnel Boring Machines
RQD	**:**	Rock Quality Designation
EPB	**:**	Earth Pressure Balance
RPM	**:**	Revolution Per Minute
MSV	**:**	Multi Service Vehicle

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TBM PERFORMANCE IN TWO TUNNELS IN ISTANBUL AND THE EFFECT OF ROCK QUALITY DESIGNATION

SUMMARY

Since the beginning of history, human beings have opened tunnels for several different reasons. Long time ago, the tunnels were used as a method for secret passages and for storage. Nowadays, with the increasing population tunnels are being opened for solving and facilitating transportation problems.

In the last 20–30 years, tunneling has a big tendency to be done by mechanized tunneling rather than conventional methods. Using tunnel boring machines is the most important mechanized tunneling method at the moment.

Tunnel excavation by tunnel boring machines is more safe and faster. Machine efficiency is very important since the initial investment is high. From the beginning of the project till the end, the most effective factor is mostly the actual geology excavated. This factor plays an important role, starting from the design period of the machine till the end of the project.

In this thesis, it is shown that TBM performance is highly dependent on geological conditions. The effects of the existing geological conditions can be clearly observed, eventhough the machines used in Anadoluray and Avrasya Metro Group have the same construction, same design and the same diameter.

The variation of the TBM’s advance rates and parameters are investigated with the varying RQD values; although the average compressive strength is similar. In addition the consumption of the consumables in these geologic conditions is also stated in this study.

A big variation in the machine parameters were seen obviously when the excavated geology has a tendency to change from rock conditions to soft formation. A decrease in the thrust force; while an increase in the torque values dependent to the stickiness property and the fine material content in the excavated medium, was established. The increase in the penetration rate while a decrease in the thrust force and either the increase in the penetration rates or the increase in the torque values, lead to an adjustment of lower cutterhead revolution by the operator is indicated. Moreover it is seen that the rise in the torque values are dependent to the stickiness of the excavated material and the tendency to block the cutterhead, rather than the reduce in the thrust force values. The importance of foam regulation for avoiding this situation is also mentioned.

When all the issues above are evaluated, the importance of the geological profile for the success of the project is clearly seen. It is obvious that big benefits on the projects can be obtained by giving more priority to drill boreholes and ground investigations when the investments for the projects are taken into consideration.

İSTANBUL'DAKİ İKİ TÜNELDE TBM PERFORMANSLARI VE KAYA KÜTLE SINIFLANDIRMASININ ETKİSİ

ÖZET

Tarih boyunca insanlar birçok farklı nedenlerden dolayı tünel açmıştır. Uzun yıllar öncesinde insanlar tünelleri gizli bir geçit veya ihtiyaç fazlalıklarını depolamak için başvurdukları bir yöntem olmuştur. Günümüzde ise, dünyada artan nüfus ile beraber ulaşım sorununu çözmek ve rahatlatmak için tüneller açılmaya devam edilmektedir.

Son 20–30 yılda ise tünel inşaatları geleneksel yöntemlerden, mekanize kazı ile açma yöntemlerine doğru büyük bir eğilim göstermektedir. Bu mekanize kazı yöntemlerinden en önemlisi ise tünel açma makineleri ile gerçekleştirilen projelerdir.

Tünel açma makinelerini kullanımıyla açılan tüneller daha güvenli ve daha hızlı bir şekilde açılabilmektedir. Ilk yatırım maliyetleri yüksek olduğundan, makine verimliliği oldukça önemlidir. Makine verimliliği, makinenin doğru seçiminden, zorlu jeolojik koşullara kadar birçok etkenlerden dolayı değişkenlik göstermektedir. Projenin en başından, bitimine kadar en önemli etkileyici faktör çoğu zaman mevcut jeolojik koşullar olmaktadır. TBM makinelerinin dizayn evresinden, projenin bitimine kadar bu faktör rahatlıkla görülebilmektedir.

Bu çalışmada, TBM makine parametrelerinin mevcut jeolojik parametrelerine ne kadar bağımlı olduğu gösterilmektedir. Anadoluray ve Avrasya Metro Grubun'da kullanılan makinelerin aynı yapıda, aynı dizaynda ve aynı çapta olmasına karşın mevcut jeolojik koşulların makinelerin üzerinde ne kadar farklı bir etkisi olduğu açıkça gözlenebilmektedir. Avrasya Metro Grubu projesinde kayaç ortalama basınç dayanımları birbirlerine çok yakın olmasına karşın, farklı RQD değerlerinde makinenin ilerleme koşullarının ve parametrelerinin nasıl değişkenlik gösterdiği incelenmiştir. Ayrıca jeolojik koşulların malzeme tüketimindeki etkisi de çalışmada belirtilmiştir.

Kazılan zemin, kaya koşullarından yumuşak zemin koşullarına doğru bir geçiş gösterdiği zaman makine parametrelerinde ciddi bir değişim olduğu açıkça görülmüştür. Itme kuvveti değerlerinde bir düşüş; fakat buna karşın kazılan malzemenin yapışkanlık özelliğine ve ince tane yüzdesine göre torkta bir artış olduğu tespit edilmiştir. Bununla beraber itme kuvveti düştüğünden, penetrasyon değerlerinde bir artış ve gerek penetrasyon değerinin yükselişiyle, gerekse tork değerlerindeki artışlardan dolayı operatörlerin kesici kafa dönüş hızını azalttığı belirlenmiştir. Bununla beraber torkun, itme kuvvetlerinin düşmesinden dolayı değil de, tamamen kazılan malzemenin yapışkanlık ve kesici kafayı bloke etme eğilimine göre esas bir artışının olduğu görülmüştür. Bu olumsuz durumu gidermekte, yapılan köpük regülasyonlarının önemine de değinilmiştir.

Bütün bahsedilen konular değerlendirildiğinde, bir projenin başarılı olmasında jeolojik profilin ne kadar önem taşıdığı açıkça görülmüştür. Bu projelere yapılan yatırımlar düşünüldüğünde, sondaj çalışmalarına ve zemin etüdü çalışmalarına daha büyük önem verilmesinde çok faydalı sonuçlar alınabileceği açıkça ortadadır.

1. INTRODUCTION

Tunnel boring machines have been very crucial in mechanized tunneling with the developments in the last twenty years. High investigations and having the latest techology with fast and safe tunneling, influenced the preference of excavating the tunnels with tunnel boring machines rather than conventional methods.

The increasing popularity of tunnel boring machines, also increased significantly the researches based on this subject. In addition to researches and plenty of articles; maybe the most important was the experiences gained from other projects. The experiences and the challegens faced on sites had played an important role in influencing the efficiency of tunnel boring machines in general.

In this thesis two identical tunnel boring machines from the same project was investigated in detail while it was as well compared with two other machines from another project having very similar specifications in general. The effect of geological conditions on tunnel boring machines were observed. The influence of geology on machine operational parameters were indicated. The effect of RQD variation on the tunnel boring machines were investigated as the average compressive strength of the excavated rock was very similar in the entire project. The machine parameters were observed with the varying RQD values and results were evaluated.

The consumable consumption overall the project were compared for both machines and in two tunnel boring machines from another project which had very similar specifications overall. The relation between the TBM performance and the consumable consumption was analyzed. In addition, the methods to improve the advancing conditions with the consumables were evaluated.

Moreover the operational differences between the operators were observed. The effect of operational differences in consumable consumption and in advance rates were indicated. The relation between all the machine parameters by each other were compared and evaluated as well.

The aim of this thesis was to detect the optimum advancing conditions for the tunnel boring machines under the specified geological conditions in the project. In addition, the relation between the consumable consumption and the influence of the advancing conditions, as well as improving efficiency of the TBM by evaluating the operational parameters and correlation between each other.

2. GENERAL INTRODUCTION TO MECHANIZED TUNNELING AND TBM TYPES

The human history has been linked to some development phases of the use of underground space since the beginning. For instance, its is possible to identify the Tomb Era in Egypt, which started 5000 years ago, then, the Mining Era 4000 years ago and the Channel Era in Europe, during the 1600s. During the 1800s, it was the Railway Era, when the tunneling engineering was enormously busted in Europe and North America. Examples of methods and technologies of this Era are the classical tunneling methods (Austrian, Belgian, English, German and Italian methods), the first shield (1843), hydraulic and pneumatic machines and tools (1857), the invention of dynamite (1864) and the use of compressed air (1869). During this period, the major challenges of the tunneling engineering were related to technical and safety aspects, leading to the development of the classical tunneling methods [1].

In recent years, tunnel construction work has become increasingly mechanized, and particularly the development and benefit of full-face tunnel boring machines has been fully recognized. Tunnel Boring Machines are classified in two types–soft ground and hard ground [2].

2.1 Hard Rock TBMs

Hard rock TBMs are divided into three groups which are:

- Hard rock gripper TBM
- Hard rock single shield TBM
- Hard rock double shield TBM [3].

The various mechanized mining techniques within hardrock depend on the quality of the rock, which is classified based on international systems. Two of the most well known classification systems are Barton and Bieniawski. The final decision for the machine type always depends on the maintenance of the rock stability and the unexpected amount of water ingress [4].

In any case all different kinds of hardrock TBM have to fulfill the high demands of the tools during mining. Thus the focus in hardrock tunneling is concentrated on tool technology and all related components which are faced to abrasion [4].
The mining process is based on the overcoming of the compressive and tensile strengths of the rock in order to get rock–chips falling to the bottom. The chips are then picked up by the openings of the buckets at the gauge area of the cutterhead. Due to the gravity and the rotation of the cutterhead they slide down along the bucket channels to the center of the machine in to a funnel which is called as muck ring and onto the machine conveyor belt. From there the muck is transported through the back up to muck skips, dumpers or the tunnel conveyor belt [4].

2.1.1 Hard rock gripper TBM

In stable rock conditions with low water ingress the gripper technique is applied whereas it has to be distinguished between single and the double gripper systems. Both techniques are based on the gripper shoes being tensed up onto the rock surface which offer an abutment to the thrust forces. Thus a certain limit of the rock strength is required for gripping the shoes against the rock surface [4].

After one stroke the machine stops and the rear support bars of the machine are extended in order to keep the machine supported while retracting the gripper shoes. Afterwards the moveable frame with the gripper shoes mounted on is driven forward and tensed up again in order to retract the support bars for the next mining stroke [4].

In contrast to the shielded TBM where the installation of segment lining is independent from rock quality, the performance rate of a gripper TBM seen in Figure 2.1 and in 2.2 is dependent on the extent of the necessary rock support and of the time required for installation. The installation of the essential rock support devices can be performed immediately behind the front shield which is illustrated in Figure 2.3. The devices are anchors, nets steel installation and shotcrete which originated from the conventional tunnel constructions [4].

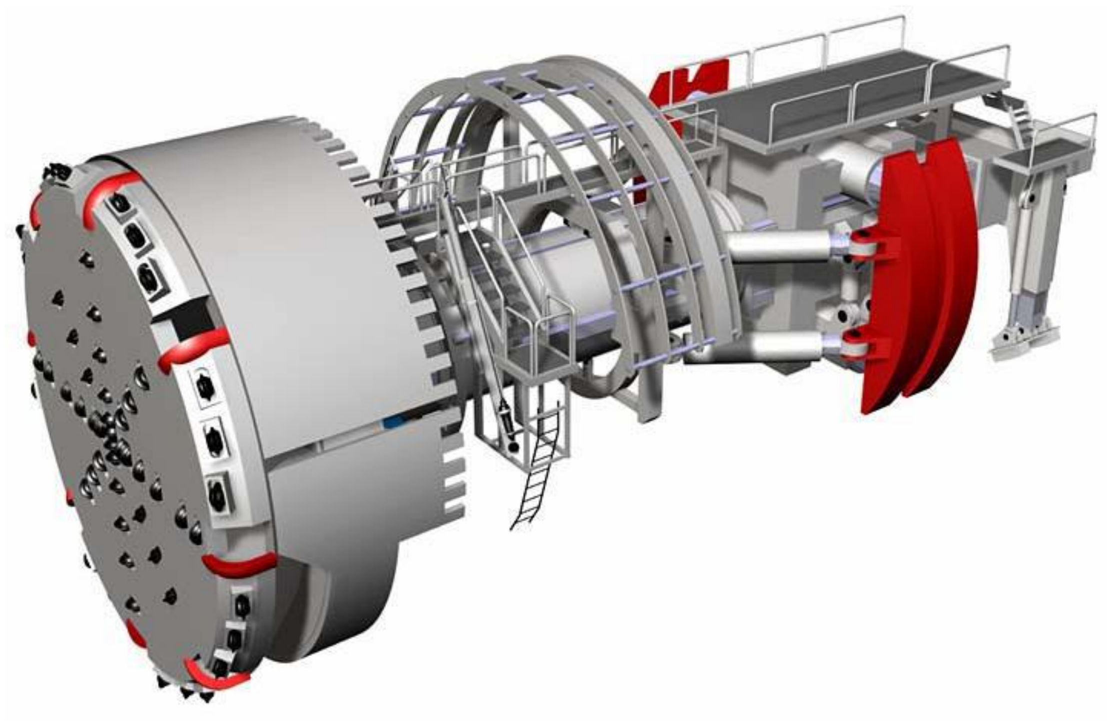

Figure 2.1 : A gripper TBM [3].

Figure 2.2 : A gripper TBM for Gotthard tunnel [5].

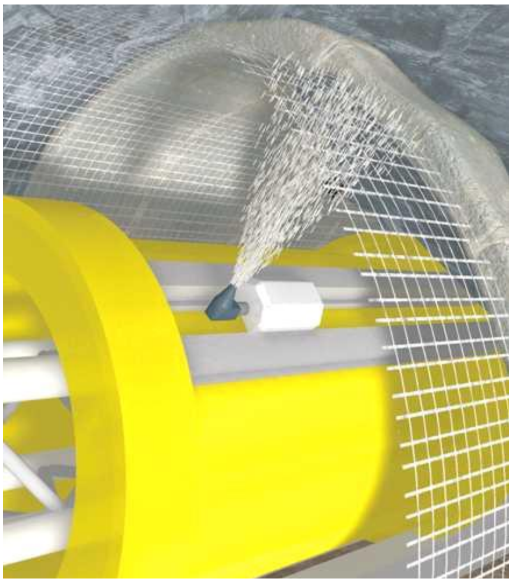

Figure 2.3 : Application of shotcrete in a gripper TBM [3].

2.1.2 Single shielded TBM

The shielded TBM is mainly applied in unstable hard rock conditions with the risk of ground collapse seen in Figure 2.4. The shield has the function to support the rock and to protect the personnel and the technical devices. The lining is made of pre-cast reinforced concrete segments which are put in place by the erectors and temporarily bolted together [4].

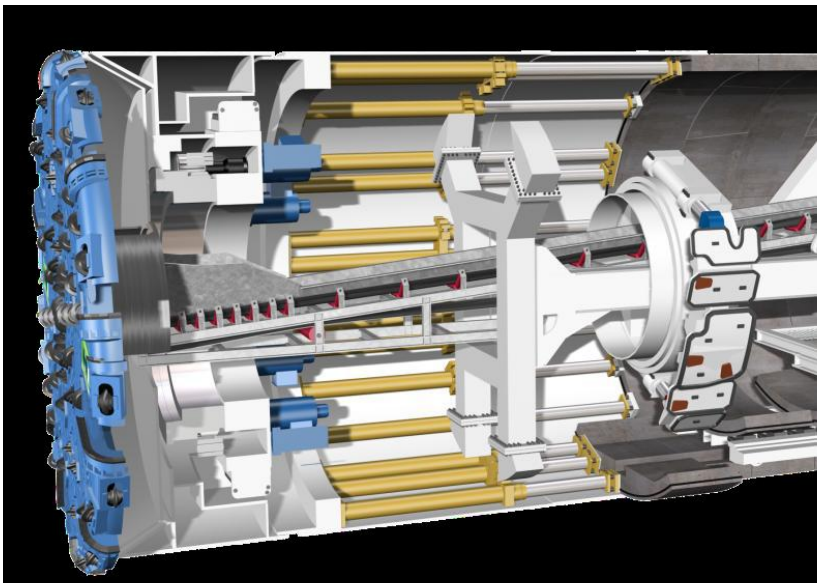

Figure 2.4 : A simple illustration of single shield TBM [3].

The pushing forces of the machine are maintained axial against the segments. The ring gap between the outer diameter of the segment and the tail skin of the machine plus the conicity of the shield skin has to be grouted continuously with mortar and or pea gravel. The geometry of the segments has an influence on the performance rate and the quality of the tunnel [4].

2.1.3 Double shield TBM

The double shield machine uses the techniques of gripper and shielded techniques which is seen in Figure 2.5 and thus can be applied in a wide range of geological conditions. The double shield TBM consists of a front shield with cutterhead, main bearing and drive as well as a gripper shield with gripper shoes, tail shield and auxiliary thrust cylinders. Both shield parts are connected by a section called telescopic shield where the telescopic thrust cylinders operating as the main thrust cylinders [4].

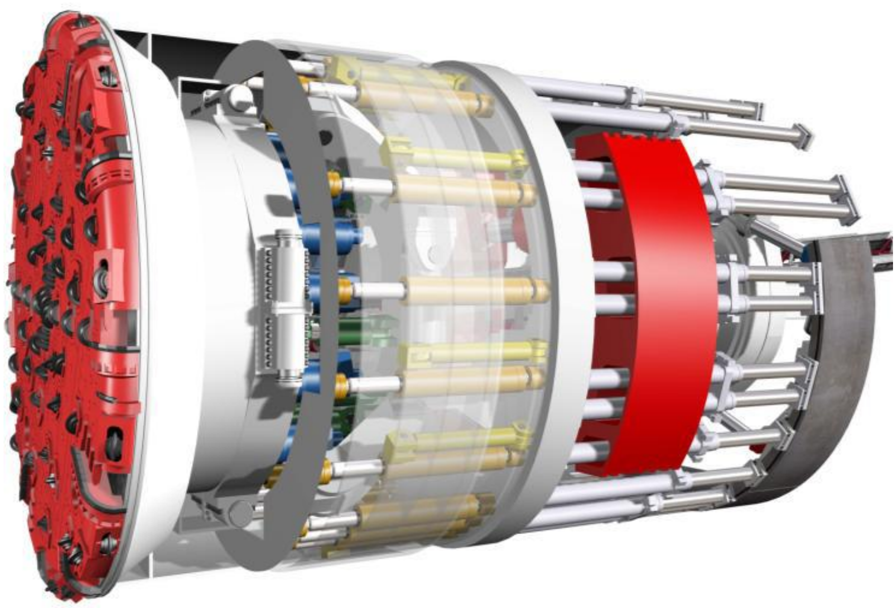

Figure 2.5 : An illustration of double shield TBM [3].

The principle is based on the gripping of the machine radial against the tunnel wall, while the excavation and segment installation are performed at the same time. Cutterhead and front shield are pushed forward by the telescopic cylinders. The auxiliary thrust cylinders in the tail shield serve only for the support of the segments. When the full stroke is reached for the telescopic cylinders, the tension of the gripper shoes is released and the gripper shield is pulled forward towards the front shield. The auxiliary thrust cylinders are extended accordingly, in order to maintain the positioning of the last set segment ring. The support during the re-gripping procedure of the gripper shield is accomplished by the vertical support shoes and the shield of the front shield and the auxiliary thrust cylinders [4].

The biggest advantage of the double shield which is seen in Figure 2.6 is, it can converted to single shield when necessary which is the second mode. In this second mode, also referred to as single shield mode, front and gripper shield form a rigid unit; the telescopic joint is completely closed and the cylinders are completely retracted. The auxiliary thrust cylinders do not produce the necessary thrust force; therefore, simultaneous tunneling and building of rings are no longer possible so the performance rate reduces accordingly [4].

Figure 2.6 : Double shield machine for Brisbane Australia with a diameter of 12.4 m [3].

2.2 Soft Rock TBMs

2.2.1 Slurry shield (mixshield) TBMs

The patent for liquid face supporting technology was already registered in the nineteen hundreds and has been successfully applied since the 1960s [6].

The original single chamber design of the traditional slurry shield was developed into a two chamber system (Mixshield) in Germany by the companies Wayss & Freytag and Herrenknecht in the 1980s. This way, the pressure conditions at the tunnel face can be controlled more precisely. Hence, the risk of the settlements in city areas was reduced immensely [6].

The mixshield TBM is mainly used in non-cohesive soil conditions, which require liquid face support (bentonite). Bentonite serves as a support and conveying medium which has a crucial influence on the function ability of the mixshield. An efficient operation of a mixshield TBM requires extensive separation technology to reduce the density of the bentonite. In addition an extra space for a separation plant is needed at the surface [6].

In solid clay soils, the use of bentonite is not necessary and water may be used as a muck transport and conveying medium [6].

An important advantage of a mixshield TBM in comparison to EPB shield is the use of a stone crusher at the invert area to crush the boulders. This characteristic qualifies the mixshield operation in mixed geologies of hard rock and glacial soil formations, which contain the entire grain distribution spectrum including big boulders [6].

The excavated soil flows with the support of a bentonite suspension through the opening of the submerged wall into the rear chamber and through a rake type classifier by the centrifugal pump out of the tunnel and into the separation plant. Various openings in the excavation and working chamber provide continuous mixing of the soil with fresh bentonite [6].

In principle, the pressure at the tunnel face is determined by the volume balance between the suspension supplying line and discharge line as well as the excavated material at the tunnel face. A crucial support pressure control is achieved by an air bubble in the upper part of the working chamber which is coupled to an automatic compressed air regulation. Thus, changes of the density of the suspension can be quickly compensated [6].

2.2.1.1 Double chamber

The slurry shield, originally developed by the Japanese, possesses of one working chamber, which is filled with the bentonite suspension. Density variations of the suspension by uncontrolled material break down at the tunnel face lead directly to instabilities, since the density correlates with the pressure at the face. Therefore, at the beginning of the 1980s, the double chamber system was developed. Via an air cushion in the rear working chamber, the pressure at the tunnel face is regulated by a compressible air. The rear chamber and the front excavation chamber area are connected by an opening in the submerged wall. In Figure 2.7 is a good illustration of a double chambered mixshield TBM with more detailed explanation [6].

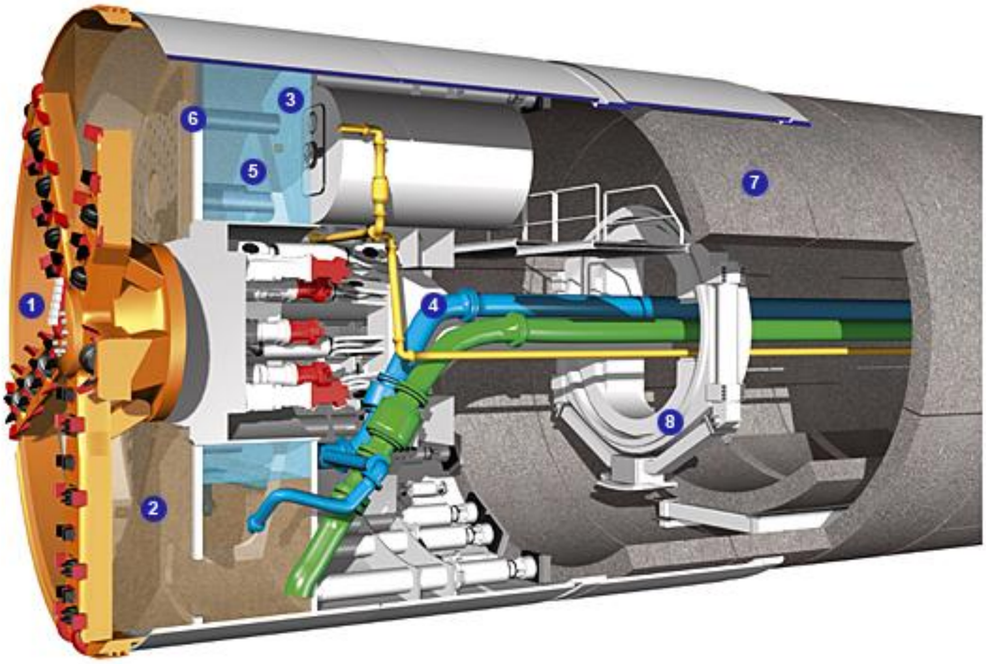

Figure 2.7 : An illustration of a double chambered mixshield TBM [5].

The machine is used as a mixshield where gravelly geological conditions indicate an unstable tunnel face or mixed geological conditions. At the tunnel face the soil is loosened all over by the cutting wheel (1) rotating in the bentonite suspension. The soil then mixes with the bentonite suspension.The area of the shield in which the cutting wheel rotates is known as the excavation chamber (2) and is separated by the pressure bulkhead (3) from the section of the shield under atmospheric pressure.

The bentonite suspension supplied by the feed line (4) is applied in the excavation chamber via an air bubble (5) at a pressure equaling the native soil and water pressure, thus preventing an uncontrolled penetration of the soil or a loss of stability at the tunnel face.The support pressure in the excavation chamber is not controlled directly by the suspension pressure but by a compressible air cushion (5). For this reason the excavation chamber behind the cutting wheel is separated from the pressure bulkhead by a so-called submerged wall (6). The area of the submerged wall and pressure bulkhead is known as the pressure/working chamber [5].

Whereas the front area of the tunnel face is completely filled with suspension, the suspension behind the submerged wall barely covers the machine's axles and is kept at the exact target pressure value by the compressed air cushion, which is precisely controlled by a compressed-air control system. Irregularities in the bentonite feeding circuit can thus be compensated considerably more effectively [5].

The loosened soil mixed with the suspension is pumped through the feeding circuit to the separation plant outside the tunnel. In order to prevent blockages to the feeding circuit and to ensure trouble-free operation of the discharge pumps, a sieve of largish stones and clumps of soil is placed in front of the suction pipe to block the access to the suction channel [5].

The tunnels are normally lined with steel reinforced lining segments (7), which are positioned under atmospheric pressure conditions by means of erectors (8) in the area of the shield behind the pressure bulkhead and then bolted in place. Mortar is continuously forced into the remaining gap between the lining segments' outer side and the excavation diameter through injection openings in the tailskin or openings directly in the segments [5].

Two types of mixshield tunnel boring machine is existing which one is a mixshield with a higher aperture ration on the cutterhead that is seen in Figure 2.8 while the other type has a closed cutterhead. In Figure 2.9 the world largest TBM is seen with a diameter of 15.600 mm and having a closed cutterhead.

2.2.1.2 Bentonite and seperation technology

The efficiency of the mixshield is dependent to a considerable degree on the bentonite technology. Bentonite, as a rule, is a three–layer silicate, which can store water in between the individual mineral layers which causes swelling. An efficient swelling process takes several hours and requires a high frequency mixer, in order to solve the clay minerals homogeneously in water. The fresh bentonite suspension has a density, depending on the mixing recipe, slightly above the water, to support the hydrostatic groundwater pressure within the soil [6].

Figure 2.8 : An example of mixshield with open type cutterhead [3].

The dissolved bentonite suspension seals the tunnel face with a mud cake, which can only result from a pressure gradient between the excavation chamber area and tunnel face. With a slight positive over pressure in the suspension compared to the existing groundwater pressure, bentonite displaces the pore water and activates shearing stresses between the soil particles, which stabilizes the face [6].

Figure 2.9 : Mixshield with closed type cutterhead [3].

An additional mechanical support of the tunnel face are the hydraulically extendable support plates which are perforated in order to supply the tunnel face with fresh bentonite in case of personnel enter into the working chamber [6].

2.2.2 Earth pressure balanced (EPB) TBM

Earth pressure balance technology (EPB) has undergone crucial development in the last ten years. The classical application range of the EPB shields could be broadened by the addition of additives in cohesive soil conditions up to less cohesive grainy soils and in mixed geology such as soft ground and rock [7].

EPB technology is fundamentally based on the use of the excavated ground as supporting medium in the excavation chamber. Under normal conditions, this requires a cohesive soil with stiff to soft consistency (IC=0.5–0.75), which extrudes through the openings of the cutterhead towards the screw conveyor during machine stroke and closes the connection between pressurized excavation chamber, conveyor and atmospheric conveyor during stand still of the machine [7].

The existing soil is a full face excavation with the rotating cutterhead of the earth pressure balance shield. The rotating speed and direction of the cutterhead is in most cases changed during the excavation to accomplish the best mixing and conditioning of the ground and to counter a rolling of the shield. Inside the excavation chamber, between the cutterhead rear and the stators of the pressure wall, the excavated material is kneaded into a plastic mash with the support of agitators [7].

In contrast to the slurry TBM, this type of machine has the technical advantage that a separation plant is not required, hence space and cost for these systems are unnecessary [7].

Due to the balancing of the thrust speed of the machine and rotation of the screw conveyor it is possible to establish a controlled volume balance and/or controlled support pressure. This provides control of the pressure ratios at the tunnel [7].

The increase of thrust cylinder speed and/or the reduction of the revolutions of the screw conveyor cause an increase of ground pressure which is illustrated in Figure 2.10. The reduction of the thrust cylinder speed and/or the increase of the conveyor screw revolutions leads to a reduction [7].

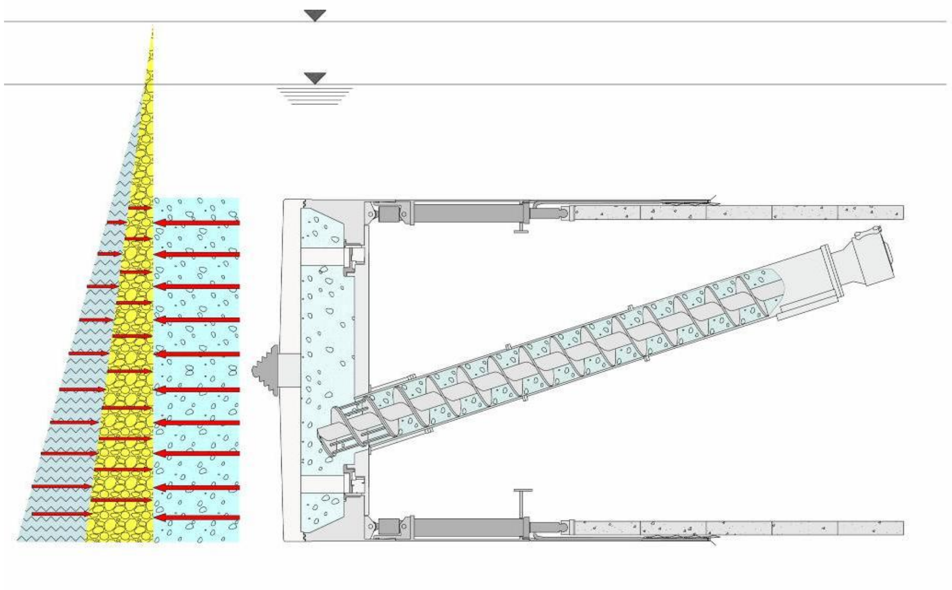

Figure 2.10 : Control of ground settlement in EPB tunneling [8].

In order to maintain a stable chamber pressure, excavated material should be a homogeneous mix of coarse and fine particles, improving overall plasticity of the material. Required physical properties of an excavated material are achieved through conditioning it with foam, polymer, bentonite or simply water, creating a material of paste-like consistency [8].

The support effect of the soil mash is accomplished by the transmission of thrust forces by pressure wall onto the mash. Respectively, depending on the existing ground and water pressure, the soil mash is strengthened, until it reaches a balance with the applied pressure of the thrust cylinders. A balance is reached, if the soil mash in the excavation chamber can not be conditioned any further by ground and water pressure. If the support pressure of the soil mash is increased beyond the equilibrium, the compression of the mash in the excavation chamber as well as the existing ground may cause displacements of the area in front of the shield. During a reduction of the earth pressure, the existing ground can penetrate into the earth mash and produce settlements on the surface [7].

Figure 2.11 is a good illustration of the pressure distribution in EPB TBM. The highest pressure is seen in the invert area of the cutterhead. The most important thing is that the screw conveyor has a property to reduce the pressure as the material passes through the helix structure inside the screw conveyor. Every full rotation of the helix inside corresponds approximately between 0.1–0.2 bar which reduces the pressure nearly to 0 when the material reaches to the screw conveyor rear gate. One of the most important criteria in screw conveyor design is the maximum expected pressure from the geology. According to the expected maximum pressure, the design of the screw conveyor is done to have the minimum pressure possible at the rear gate.

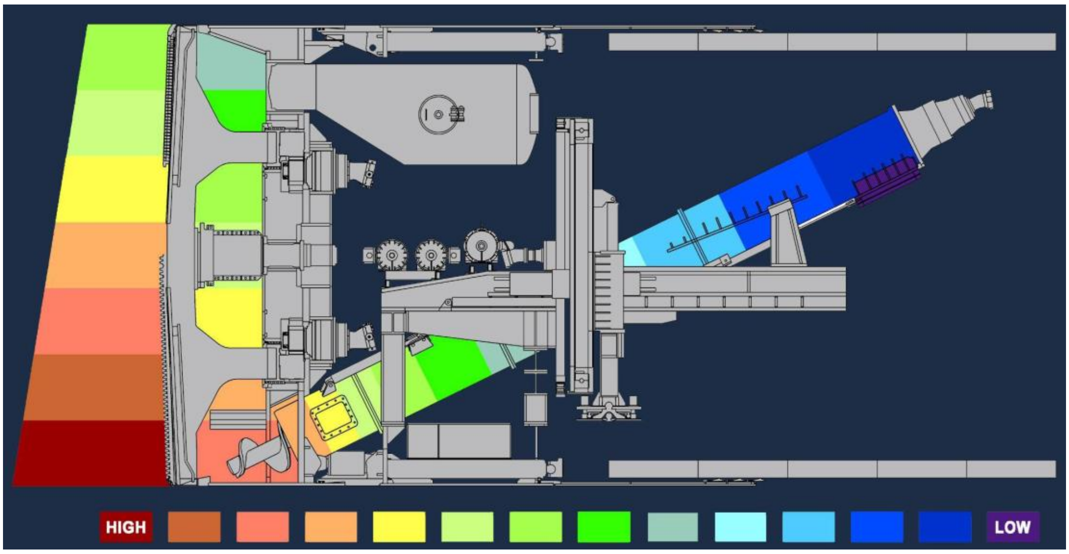

Figure 2.11 : Pressure reduction in EPB machines through the transport system [9].

Innovative solutions by application of special additives further enable expansion of application of EPB technology in the non binding soft ground and/or hard rock area. Foam supported EPB technology has continued its development in the last years and fulfills highest ecological as well as structural requirements.

Soil treatment is very essential for efficient excavation conditions in EPB machines. There are several different methods for treating the soil especially with the latest technology in earth pressure balance machines in the last 10 years. A wide range of application is possible from low cohesive, to a certain limit of grain conditions with the improved opportunities.

Soil can be conditioned with

- Water
- Bentonite, clay or polymer suspension
- Foam (surfactant foam)
- Foam–polymer mixture (surfactant–polymer–foam)

- Polymer (polymer foam)

Due to the application of light foam, the material received a reduction in density in the EPB mode, which can also be in the range of bentonite suspension. The limit of the density decrease may result for example a blow out risk underneath the water. In case of an over foaming o the ground in the excavation chamber, the rising air bubbles may cause a structural collapse due to instant reduction of the internal ground friction. Therefore, pressure control in the excavation chamber is necessary, which gives a conclusion to the specific weight of the excavated material [7].

$$Foam = \frac{Q_{foam}}{Q_{soil}} \times 100\% \qquad \textbf{(2.1)}$$

The quality of the foam is significantly influenced by the foam expansion rate (FER), which is depending on the machine and technology as well as the utilized foam product. The expansion rate reflects the increase in volume of the starting liquid (water plus additive) by mixing it in the foam generator [7].

The differences in the types of the TBMs are explained above. The TBMs that will be mentioned in this paper are EPB–hard rock convertible TBMs. With this opportunity it is possible to advance in open and in closed mode. In the open mode it is possible to install the muck ring as well as the machine belt while in closed mode the rotary coupling is installed which is used in most case for application through the cutterhead and screw conveyor for the transportation of the excavated material to the TBM band [7].

3. SOME INFORMATION ON MECHANIZED TUNNELING IN ISTANBUL

Istanbul is a really big metropol having a population more than 15 million which has big traffic jams all around the city. In the recent years investments in subway projects has increased significantly. There are still a couple of projects in progress in European side as well as in Anatolian side.

In Anatolian side there are two projects on going which are constructed by Anadoluray and Avrasya Metro Group.

In Figure 3.1 the planned subway line is shown which will be completed by Anadoluray and Avrasya Metro Group joint ventures that has already started and still is under construction. From Kozyatagı station to Kadıköy station two hard rock - EPB convertible TBMs are used for excavating a tunnel length of approximately 8.5 km each tube. Avrasya Metro Group excavates from Kartal station to direction Kaynarca with two hard rock–EPB TBMs having approximately 4.5 km each tube; meanwhile the track between Kozyatagı and Kartal is continuing with drill and blast.

Figure 3.1 : The excavated tunnel track for subway in Anatolian side of Istanbul.

The aim of this project in the future is to connect Gebze with this subway line. This subway line that is still in construction will be connected with Marmaray project that will make the public transportation possible between the European and the Anatolian side of Istanbul by underground subways. The line beyond Kaynarca to Gebze direction has not been organized and started yet; however it would be a great success as it would reduce the traffic significantly if the planned project could be accomplished in the end. The area around Gebze is a really big industrial place for Istanbul that most of the people have to travel everyday from the city centre to the industrial area and with the help of this subway line, this industrial zone will develop much faster and a significant decrease in traffic population will be seen.

In this chapter a general comparison between both projects will be mentioned. The effect of the geological conditions over the TBMs can be investigated more accurate as the machines are nearly the same; however the geological formations are varying. The advance rates of both projects are mentioned and the experiences of challenging geological conditions in one of the projects is also stated. The consumption of the consumables are compared and the differences in electric and hydraulic drives, which is one of the biggest difference in these machines, are also taken into consideration.

3.1 Description of the Projects and TBM

In Anadoluray (Yapı Merkezi–Dogus–Yüksel–Belen–Yenigün) Joint Venture two identical hard rock–EPB convertible TBMs are being used with an excavation diameter of 6.57 m to complete a tunnel with approximately having 8500 meters each tube with a total of two tubes. The total power of the machine is 1260 kW which is supplied by four hydraulic pumps at the pump station in gantry 1. The excavated material is transported by locomotives from the TBM to the shaft bottom at where which the vertical band conveyor lifts up the dumped material from the shaft to the surface.

In the beginning of the project, the excavated material was transported by machine belt to the TBM conveyor belt. The geology is mainly consisted of weathered and fractured limestone with some short dyke intrusions on the tunnel path. This chipped limestone was lifted up by the buckets in the cutterhead to reach the necessary height so that the excavated material can roll over the muck ring by gravity forces, to where the excavated material from the cutterhead can be transported to the bridge area which the TBM conveyor belt exists. However, the machine band was replaced with screw conveyor when the TBM had a breakthrough to the first station (Yeni Sahra). As softer geological formations were foreseen, this modification was necessary to avoid collapses as much as possible. With the geologic formation getting softer and fine particle amount in the excavated ground increasing, it was necessary to use foam to convey the material with the necessary consistency. In such ground conditions using screw conveyor will increase the efficiency in the advance rates. However, the operator skills become more important when operating an EPB machine. Basically the foam parameters should be adjusted by the operator according to the actual excavated material which is quite critical and sensitive. In some cases when wrong ratios are applied on the foam parameters, the advance rates will also be affected because of the decreasing efficiency of the foam.

In this project locomotives are used to transfer the material to the dump area under the shaft where the vertical band is installed. After a length of excavation, California switches were installed to avoid the time loss for train trips. Meanwhile when the advance is done on the TBM with the muck cars, the other locomotive with the muck cars can be sent from the shaft with the next ring set to the California switch area which made it possible for the locomotive inside the TBM to pass the other locomotive ready waiting for the next advance at this switch point. Normally when the ring building time is assumed to be half an hour this California switch becomes effective after 1–1.5 km of tunnel and this switch system should be repeated when the tunnel length increases.

In project from Kartal to Kaynarca two EPB TBMs are used with the same excavation diameter. The contractor is Avrasya Metro Group joint venture consisting of Astaldi, Gülermak and Makyol companies. The project length is approximately 4500 meters each tube with a total of two tubes. The machines used in this project are very alike on the ones used in Anadoluray joint venture. The main difference is tunnel belt which is used to convey the excavated material and multi service vehicles shortly called as MSVs to supply the segments and as well as grout which is used to fill the annular void between the tunnel perimeter and the pre-cast ring outer circumference.

The material excavated is harder and has less geologic discontinuities when compared with Anadoluray project. Because of this Avrasya Metro Group joint venture had better advancing condition while Anadoluray joint venture had a lot of difficulties because of challenging geological conditions.

3.2 TBM Specification of Both Projects

As it is seen in Table 3.1 the machines in both jobsites are nearly the same and have only small differences. The main difference is that Anadoluray have TBMs with hydraulic motors to rotate the cutterhead while the TBMs in Avrasya Metro Group have electric motors. Due to this difference the hydraulic station opposite to the control cabin is bigger and a little bit more elaborated. The design and the opening ratio of the cutterhead is the same while the numbers of cutters have a slight difference.

In S-360 and S-363 which were manufactured for Anadoluray were later modified and additional stone limiters were welded on the cutterhead to reduce the size of the boulders. Photographs of the TBMs for Anadoluray and Avrasya Metro Group joint venture is seen below which were taken at Herrenknecht AG company in Schwanau, during the acceptance of the TBMs which is seen in Figure 3.2 and 3.3.

Figure 3.2 : S-360 machine at factory acceptance [5].

Table 3.1 : Comparison of machine parameters for both projects.

	Avrasya Metro Group TBMs	Anadoluray TBMs
Type	2 x EPB - hard rock convertible TBMs	2 x EPB - hard rock convertible TBMs
Cutterhead diameter	6570mm	6570mm
Front shield diameter	6540mm	6540mm
Middle shield diameter	6530mm	6530mm
Tail shield diameter	6520mm	6520mm
Number of segments in one ring	5+1	5+1
Outside / inside diameter of segments	6300mm / 5700mm	6300mm / 5700mm
Cutterhead power	8 x 160 = 1280 KW electric motors	4 x 315 = 1260 KW hydraulic motors
Total power	2046 KW	
Max. thrust force	16 double cyl. with max 42575 kN at 350 bar	16 double cyl. with max 42575 kN at 350 bar
Max. articulation / steering force	14 cyl. with max 41563 kN at 420 bar	12 cyl. with max 33778 kN at 350 bar
Max revolution per minute	5.33 rpm	5.5 rpm
Nominal torque	3663 kNm	2912.3 kNm
Max. torque	5018 kNm	5200 kNm
Breakthrough torque	5384 kNm	6356 kNm
Stabilizer max force	538 kN at 350 bar	1540 kN at 500 bar
Gripper max force	1060 kN at 150 bar	-
Number of discs	4 center twin cutters, 31 single 17 inch single disc and 1 multiple disc overcutter	26 single + 6 x 2 double discs
Number of scrapers	64	64
Number of buckets	8	8
Erector longitudinal travel	2000mm	1800mm
Erector rotation angle	200˚	200˚

Figure 3.3 : S-506 machine at factory acceptance [5].

3.2.1 Comparison of the cutterhead drives in the projects

In Figure 3.4 and 3.5 the graphics for the cutterhead drives for both projects can be seen. The installed power is very similar in both projects where 1260kW is installed in S-360 and S-363 TBM while 1280kW is installed in S-505 and S-506. The main differences in the drives are Anadoluray machines have hydraulic drives where Avrasya Metro Group machines have electric drives.

3.2.2 Advantages and disadvantages of the hydraulic and electric drives

In general hydraulic drives are preferred in TBMs which will advance in soft formations and electric drives in hard rock formations. From this result mostly hydraulic drives are used in EPB TBMs while electric drives are used in hard rock TBMs. Both of the drives have advantages and disadvantages when compared to each other which can be listed as below.

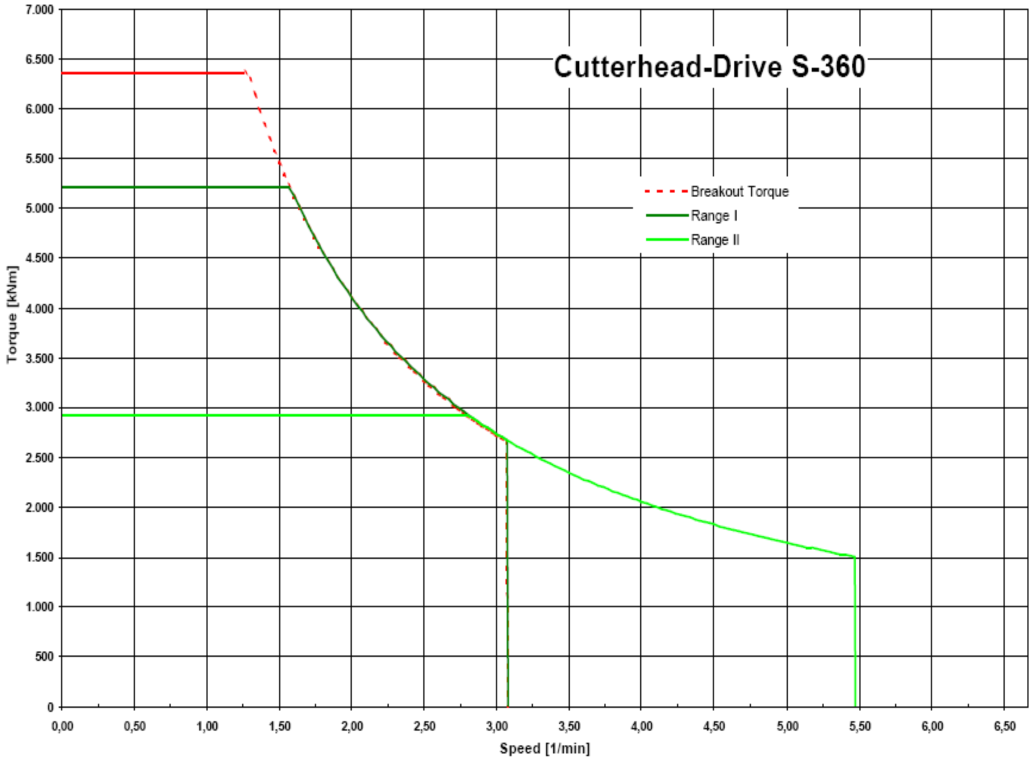

Figure 3.4 : Main drive power for S-360/S-363 TBMs [5].

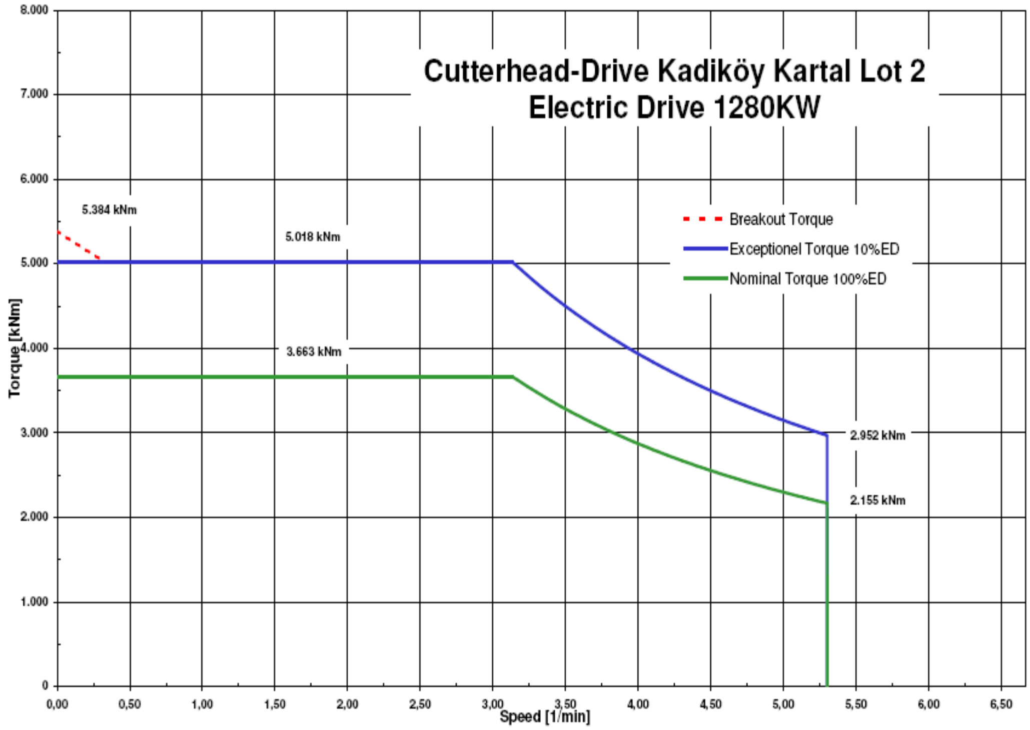

Figure 3.5 : Cutterhead drive power for S-505/S-506 TBMs [5].

3.2.2.1 Advantages of electric drives

- One of the biggest advantage is the efficiency of the power. Energy losses are much lower in electric drive when compared with hydraulic which as well can be seen from the comparison graphics in figures 3.4 and 3.5. Eventhough the maximum and the breakthrough torque is lower in electric drives, the torque values achieved in high rotations are higher which as well indicates the low energy losses compared with hydraulic drives.
- A wide range in constant torque is possible with the electric drives while in hydraulic it is much more limited.
- As a general rule in hydraulics, the lost energy will appear as a temperature increase in the system. Because of this reason, energy necessary to cool the motor and the gearboxes are lower compared with hydraulic.
- Less amount of hoses is necessary in the system.
- Cleaner working area and no environmental hazards.

3.2.2.2 Disadvantages of electric drives

- More space is necessary.
- More sensitive and complicated systems compared with hydraulic drives. Safe set part of the motor is to protect the motor which the safe set shear valves get damaged when overloaded, to secure the motor from any further damage. During operation these safe set shear valves have to be replaced plenty of times especially in challenging geological conditions.
- Instant high torques are not possible and electric drives can not be forced as much compared with hydraulic drives.
- The maximum torque values are always lower then hydraulic drives.

3.2.2.3 Advantages of hydraulic drives

- Higher torque values can be achieved with the same power installation compared to electric drives.
- Instant high torque values can be supplied which is very important when a cutterhead is blocked.

- Less space is necessary.

3.2.2.4 Disadvantages of hydraulic drives

- Energy loses are quite high compared with electric drives.
- The working area and conditions are not so clean.
- Environmental hazards are higher.
- More hoses and connections are necessary so at the beginning it looks more complicated.
- Energy consumption is higher because of high energy loses and for cooling the overheated system.

3.3. Geotechnical Information of The Projects

3.3.1 Geological conditions of Anadoluray project

The geological formation which is excavated by two TBMs consists of Trakya and Kartal formation. Trakya and Kartal formations are seen from Kozyatagı station in the direction of Kadıköy station. Only the chainage from 0+000km to 8+500 will be mentioned in this thesis as the rest of the route is constructed by conventional tunneling methods.

Greywake consisting of claystone, siltstone and sandstone is seen in Trakya formation from chainage 0+000km to 3+500km. Claystone and siltstone are observed abundantly in this formation. The interbedding of claystone and siltstone which prevail poor to fair rock conditions are very fractured. Random zones of fractures are very prevalent. Sandstones found in Greywacke as midlayers contain fair to good rock conditions. Thickness of the sandstone layers vary between 10 cm to 2.5 m.

From chainage 3+500km to 8+500km shales of Kartal formation are observed. Shales are heavily jointed, densely fractured and relatively strong.

At the beginning of the project, very big blocks were excavated. In some areas the problem was, before the discs can achieve a good chipping of the rock; big blocks were completely ripped off from the tunnel face because of the high torque on the cutterhead. Examples from this situation can be seen in Figure 3.6. Figure 3.6(a) which normally shows the general grain distribution without any problems and the other two photographs Fig 3.6(b) and indicating big boulders.

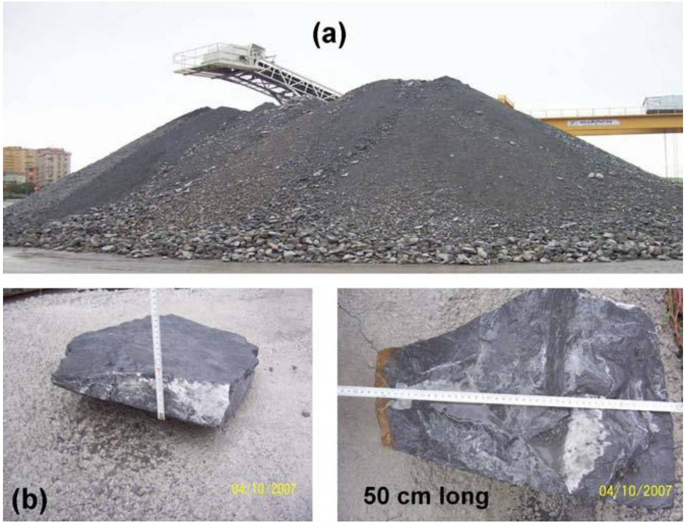

Figure 3.6 : General distribution of grain size and the size of the big boulders.

After the stone limiter modification on the cutterhead, better advancing conditions were obtained by limiting the boulder size which can easily enter inside the excavation chamber.

3.3.2 Geological conditions of Avrasya project

Kartal–Kaynarca alignment consists of old Paleozoic sedimentary rock formation with shallow magmatic and volcanic intrusions. There are two main formations in this line which are Dolayaba and Kartal formation [10]. The geological map of the tunnel route is seen in Figure 3.7 and a more detailed one is presented in Appendix 1.

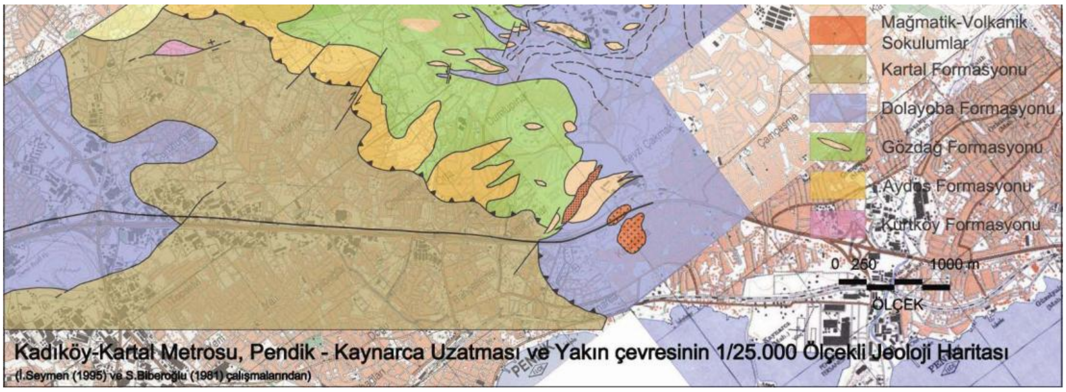

Figure 3.7 : Geological map of the tunnel route [10].

If shortly defined; Dolayaba formation have grayish–black limestone with varying thicknesses and Kartal formation have yellowish–bright brown colored siltstone–sandstone layered laminated mudstone; however in some areas grayish–black colored fossiliferous carbonated–laminated mudstone (carbonated shale) can also be seen [10].

4. CONSUMPTION OF CONSUMABLES DURING THE PROJECTS

It can be expected that the consumables should be nearly same when the two projects are compared. However it should be kept in mind that all the consumables on the TBM are very closely related to the challenging geologies. During the complete duration of the project there would be areas where some of the consumables are consumed more compared to the other areas where the other consumables are maybe even less used. For example when the excavated formation gets stronger there would be an increase in the disc consumption while the foam consumption will be less which can be said as it will be the opposite when the formation gets softer.

However there are some consumables such as the greases which remain mostly unchanged unless advanced under earth pressure or face some difficult conditions such as collapses that can occur on the face of the cutterhead.

4.1 Consumable Consumption

The theoretical excavations of both projects are the same as the diameter of the cutterhead and the length of a ring is the same. However the average material consumptions are different which are seen in the Table 4.1 for Anadoluray Joint Venture and Table 4.2 Avrasya Metro Group as the machines advanced in different geological conditions.

Table 4.1 : Average consumption of S-360 and S-363 TBM together.

Anadoluray	
Electricity	28kWh/m^3
Water	500liter/m^3
Foam	1,5 liter/m^3
HBW grease	0,18liter/m^3
Tailskin grease	0,43liter/m^3
EP2 grease	0,033liter/m^3
Disc	0,0010piece/m^3

Table 4.2 : Average consumption given for S-505 and S-506 seperately.

Avrasya Metro Group		
	S-505	S-506
Electricity		34kWh/m^3
Water		275litre/m^3
Foam	1.29l/m^3	0.90l/m^3
HBW grease	0.140l/m^3	0.123l/m^3
Tailskin grease	0.287l/m^3	0.270l/m^3
EP2 grease	0.049l/m^3	0.044l/m^3
Disc	0.0011piece/m^3	0.0013piece/m^3

4.2 Comparison of Consumables of Anadoluray and Avrasya Metro Group TBMs

As mentioned before the geological conditions of Anadoluray project was tougher compared with Avrasya Metro Group project. Although all the TBMs were very similar to each other, the real EPB application was done in S-360 and S-363 machine because the geology was much softer compared with the project in S-505 and S-506. As expected S-360 and S-363 TBMs consumed more foam which also means more water consumption compared to Avrasya Metro Group TBMs. When the water consumption is observed, the value is nearly doubled in Anadoluray jobsite. The most important reason was that, more water was necessary to produce more foam and the other reason was in some areas, the ground was so dry that additional water had to be applied through the excavation chamber for a better reaction of the foam. The excavated material should have the necessary water content for the foam to be applicable. In addition more water was used to clean the blocked cutterhead frequently because of the high ratio of the fine material.

High grease consumptions also indicates that S-360 and S-363 TBMs advanced more in EPB mode. In fact both machines had to counter balance the existing earth and water pressure in a long length of tunnel track. When the earth pressure is higher, more main drive grease (EP2 grease) and more labyrinth grease (HBW grease) should be pumped and the necessary pressure should be exceeded so that the water or the material does not integrate from the sealing area of the main drive. There should be always the labyrinth grease coming out from the sealing area when it is looked from the front part of TBM. This HBW grease avoids the material intrusion inside the main drive. The tailskin or tail shield grease also have the same property. Tail shield grease is pumped between aligned brushes to avoid any grout, water or material, to penetrate back inside the TBM. Normally the grout pressure, which is pumped through the tail shield to fill up the annular gap between the segments and the excavated ground, should always be minimum 1 to 1.5 bar higher then the expected earth pressure on the screen panel. Otherwise the gap between excavated ground and the segments will never be properly grouted.

To balance the earth and water pressure, the excavated medium in the excavation chamber should have a good consistency which means more foam application, more material inside the excavation chamber to balance the pressure, more necessary to mix the material good which results in high consumption of foam and water; however more torque values on the cutterhead even if the mixture is very good. Because of the high torque values the rotation of the cutterhead has to be reduced but because of soft geological conditions, the penetration rate can be increased.

In contrast to the high consumption of foam, grease and water; the disc consumption is lower in S-360 and S-363 compared with S-505 and S-506. As the geologic formations are softer in Anadoluray project and when lubrication property of foam is taken into consideration, it is an expected result that the disc consumption is lower compared with the other project.

The consumption of electricity is lower in Anadoluray jobsite where electric motors and additional tunnel band conveyor were used on the other jobsite. The electric consumption increases when the cutterhead drive uses electric motors instead of hydraulic.

4.3 Comparison of S-505 and S-506 TBM

The first TBM which started advancing was S-506 in the Avrasya Metro Group project. So the geology was first disturbed by this machine which faced higher thrust force values compared with the second machine S-505. Because that the thrust forces were slightly higher in S-506 and the operator drove the TBM with lower cutterhead revolution and higher penertration rates, the disc consumption was higher. TBM advance, related to machine parameters will be explained in next section in more detail.

S-505 advanced in a more loosened geology compared to S-506. It was more necessary to fill up the excavation chamber and applying pressure to the tunnel face. The mixture of the material was more important so foam application and water consumption increased. When advancing with a partially filled excavation chamber in some areas, the foam consumption increased due to a good EPB application.

Because of EPB application and water flow in some areas, the grease consumption had to be increased as well.

The disc consumption was lower as the thrust forces were lower compared with S-506 and more foam consumption increased the lubrication and reduced the wear on the discs. Having the benefits from the foam decreased the average disc consumption in total.

5. ADVANCE RATES OF ANADOLURAY AND AVRASYA METRO GROUP TBMS

Advance rates of S-360 and S-363 TBMs are seen in Figure 5.1 and 5.2 respectively. At the beginning of the project the advance rates were very low in both S-360 and S-363 projects. One of the reasons was the warming up period of the site and on the other hand, many collapses were faced because of the difficult geological conditions and the site request to start in open mode with the conveyor belt. After a couple of months the stone limiters were welded on the cutterhead to reduce the opening ratio of the cutterhead against the big boulders encountered during excavation.

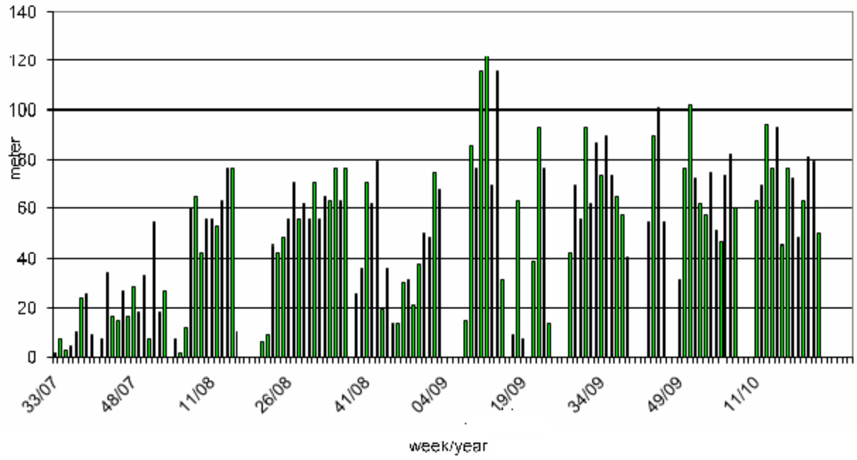

Figure 5.1 : Weekly advance rate of S-360 TBM in Istanbul Kadikoy.

In the first station which is called as Yeni Sahra, the machine belt was replaced with the screw conveyor which increased the advance rates after making it possible to excavate in EPB conditions. In Figure 5.3 the change in the advance rates are shown when additional bars on the cutterhead were welded and the advance rates when the TBM was operated in closed (EPB) mode.

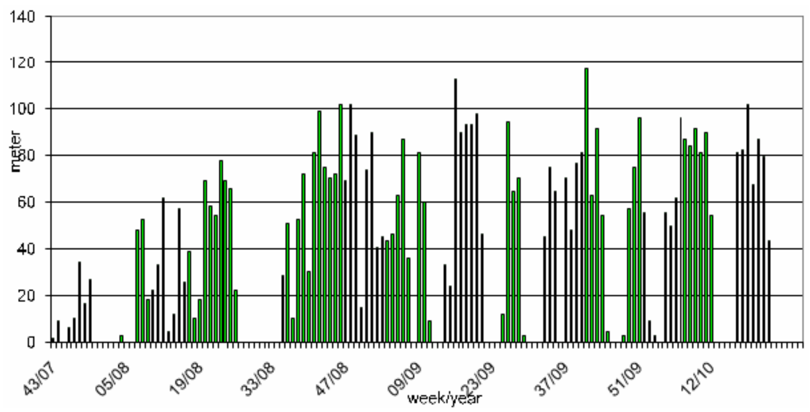

Figure 5.2 : Weekly advance rate of S-363 TBM in Istanbul Kadikoy.

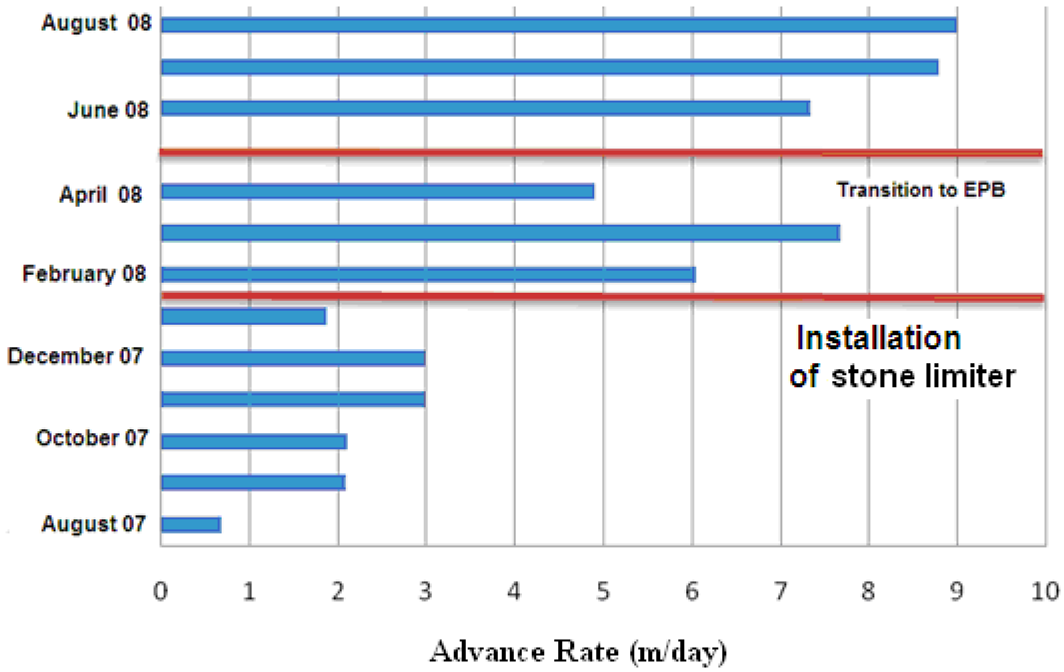

Figure 5.3 : Average daily advance rate (m/day) of S-360 TBM.

The same was done in S-363 and very similar improvements in the advance rates were observed.

Both S-505 and S-506 machine's advance rates are quite good which can be seen from Figure 5.4 and 5.5. One of the biggest reason for high advance rate was that both of these machines advanced with tunnel belt conveyor which meant continiuos excavation if the grout and the segments could be delivered on time to the TBM. The other reason was that there were not much difficulties as compared with Anadoluray jobsite related to geology.

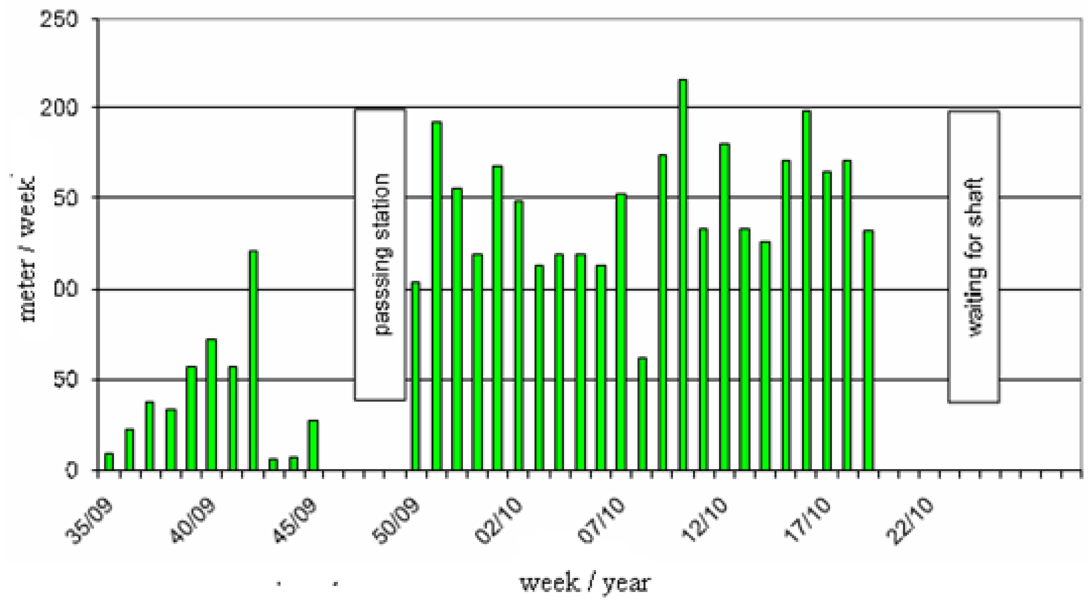

Figure 5.4 : Weekly advance rate of S-505 in Istanbul Kadikoy.

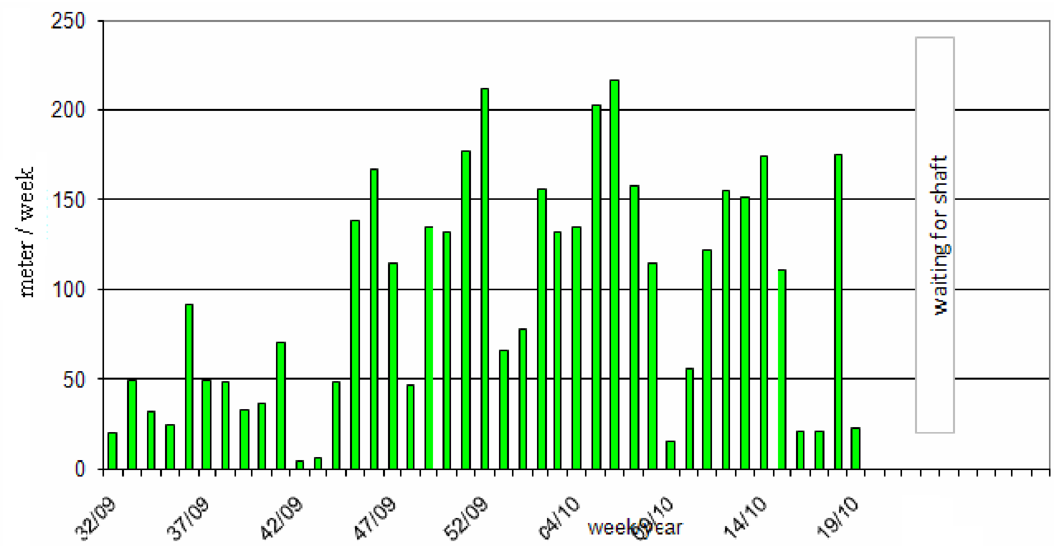

Figure 5.5 : Weekly advance rate of S-506 in Istanbul Kadikoy.

In addition, multi service vehicles (MSV) are faster compared to locomotives. The biggest advantage of these vehicles is that the maximum slope the locomotive can work is %4 while these vehicles can work with much higher slopes without any problem. Tunnel belt is necessary if MSV will be used in a project as it is not possible to convey excavated material with these vehicles.

5.1 Best Advance Rates of Avrasya Metro Group TBMs

In the Tables 5.1–5.3 below the best and the average advance rates of S-505 and S-506 can be seen.

Table 5.1 : S-505 and S-506 TBMs best advance rates.

TBM Best Advances		
	S-505	S-506
Best daily advance	39m	36m
Best weekly advance	216m	216m
Best montly advance	786m	706.5m

Table 5.2 : S-505 and S-506 TBMs average advance rates without stoppages.

TBM Average Advances without Stoppages		
	S-505	S-506
Average daily advance	21.7m	21.2
Average weekly advance	141m	138m
Average monthly advance	607m	593m

Table 5.3 : S-505 and S-506 TBMs average advance rates with stoppages.

TBM Average Advances with Stoppages		
	S-505	S-506
Average daily advance	12.5m	13.5m
Average weekly advance	88m	95m
Average monthly advance	375m	407m

6. THE PERFORMANCE OF S-505/S-506 TBMs RELATED TO GEOLOGICAL CONDITIONS

6.1 The Compressive Strength of Rock in the Tunnel Route

The performances of both TBMs are analyzed using the data received from the machines. The important thing which should be kept in mind is the average value of the rock's compressive strength (UCS) is almost the same for both tubes. In the boreholes which have been made through the tunnel profile, values vary between 34 MPa to 36 MPa which can be assumed to be the same. The graphics which will be seen below is mostly to figure out the relationship of the RQD (rock quality designation) with the TBM parameters and to have an overview of the project advancing conditions.

The geological characteristics of the tunnel profile is given in more detail in the previous sections. In this section both TBMs will be taken into consideration separately.

6.2 The Effect of RQD on TBMs Performance

6.2.1 Definition of RQD

Rock-quality designation (RQD) a rough measure of the degree of jointing or fracture in a rock mass and is measured as a percentage of the drill core in lengths of 10 cm or more. High-quality rock has an RQD of more than 75%, low quality of less than 50%. Rock quality designation (RQD) has several definitions. The most widely used definition was developed in 1964 by D. U. Deere. It is the borehole core recovery percentage incorporating only pieces of solid core that are longer than 100 mm in length measured along the centerline of the core. In this respect pieces of core that are not hard and sound should not be counted though they are 100 mm in length. RQD was originally introduced for use with core diameters of 54.7 mm (NX-size core). RQD has considerable value in estimating support of rock tunnels [11].

RQD is defined as the quotient:

$$RQD = \frac{l_{sum.of.100}}{l_{tot.core.run}} \times 100\% \qquad \textbf{(6.1)}$$

From the RQD index the rock mass can be classified as follows:

Table 6.1 : RQD classification table [11].

RQD	Rock mass quality
<25%	very poor
25-50%	Poor
50-75%	Fair
75-90%	Good
90-100%	Excellent

6.2.2 General distribution of RQD

Unfortunately, it is not possible to evaluate and compare the machine parameters according to the varying geology in details as the average compressive strength is nearly the same which can be assumed as one of the most important geological parameter. Indeed, big changes in the machine parameters can not be seen often, when the data from 2000 rings are observed. However there are some areas where the machine parameters vary. The RQD values obtained from 17 boreholes are classified as in Figure 6.1 and the machine parameters are checked with the variation of these RQD values.

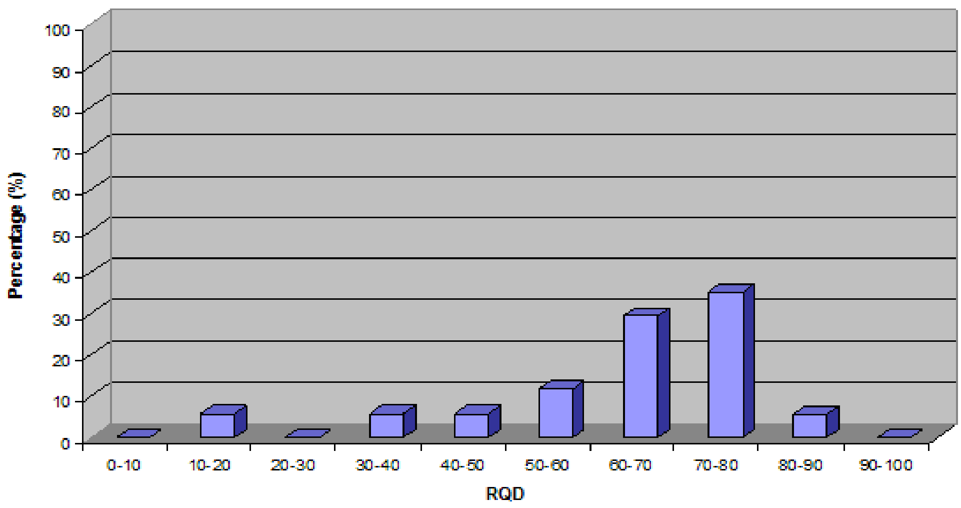

Figure 6.1 : RQD distribution overall the excavated tunnel profile.

The rock mass quality of the geology is fair in general. The distribution of the rock mass quality (RQD) is given above as well in Figure 6.1 from the 17 boreholes that were investigated.

Investigations have been made through out the tunnel profile before starting excavation for the best design of the TBM in the expected geology. In a total of 17 boreholes were drilled for the observation of the rock conditions.

The tables and the graphics in the sections below indicate the RQD distribution in all over the excavated tunnel profile. The machine parameters were taken 5 rings before and after the boreholes to show the characteristic property of the geology as accurately as possible. The values seen in the tables are the average values of these rings in total; where the average of the machine parameters were calculated from 10 rings in some of them while the quantity included in the average was higher on the others according to the distributions. Most of the samples taken from the boreholes is observed to be between 60–80 in RQD values indicating a rock mass quality of fair. Only the samples taken from one borehole was in a good quality.

6.2.3 Distribution curve and histogram related to RQD for thrust force of TBM

As it can be see in Figure 6.2, most of the thrust force values are between 7000kN to 9000kN. From the analyzed 2000 data, which means 2000 rings and that a single ring corresponds to 1.5 meter which is one advance cycle of the TBM, 394 of them are between 7000–8000kN and 362 are between 8000 – 9000kN. It is only seen 43 ring advances over 12000kN. This graphic illustrates that the machine has advanced in relatively soft geological formations. However it will not be always correct to estimate the geological formation or strength of the rock by only observing the thrust forces seen during excavation of rings; because high forces on the thrust cylinders can be observed in several different conditions, independent from the strength of the rock.

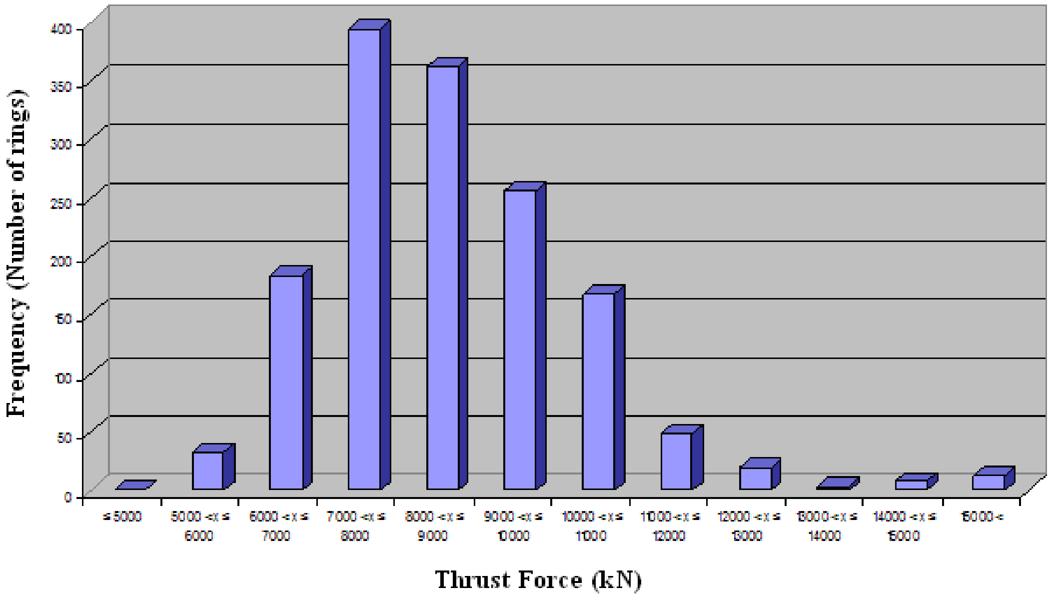

Figure 6.2: Distribution of thrust force for S-505 TBM.

If we would like to list the possible reasons for high thrust forces then it can be listed as seen below :

- The forces will increase if there is ground pressure in the zone which is being excavated and the operator is advancing in EPB mode to balance the pressure foreseen from the geotechnical engineers to avoid any collapses. Or it can only even be water pressure which is also increasing the thrust forces seen in the control cabin.
- Filling up the excavation chamber also changes the thrust forces but not in big percentages.
- Squeezing ground can change the thrust force parameters significantly sometimes even more than three or four times compared to the expected values. There are some projects which have experienced very tough geologies where in one project the over excavation in diameter was above 90mm, which was indeed a very high value, but still it was not possible to pull the rear part of the shield through the opened section because of the squeezing effect of the ground. This example can be assumed extreme; however usually what happens is, the ground settles on the TBM in unstable geologies which increases the thrust forces significantly when there is a big standstill inside the tunnel. The existing voids, small or big, are always tried to be closed by

soft formations. If a long standstill is foreseen in similar geologies then the best solution will be to make the last advances with injecting bentonite through the shield to have a good lubrication around the shield before stopping the advance.

- The next reason for high thrust forces can arise due to the wrong ring installations. If these wrong ring installations continue consecutively then after a while the tail shield clearance will be zero and the ring will start to touch the shield. This also increases the thrust forces whereas damage on the installed rings and even the tail shield is possible if not realized.
- Worn disc cutters also have a significant effect on high thrust forces. In operation the cutter tools should be checked as much as possible to avoid the raise in the thrust force.

It can be seen in Figure 6.2 that the thrust forces observed are normal for a geology consisting of mostly soft rock conditions with a homogenous distribution.

In S-506 the maximum frequency in thrust force is seen between 8000–9000kN which is observed nearly 350 times as shown in Figure 6.3; while in S-505 the maximum frequency in thrust force is seen between the values 7000–8000kN which is around 400 times. Furthermore, the average thrust forces over 12.000kN are observed in 133 data in S-506; however in S-505 it is only 43. In addition to these results, when it is also taken into consideration that S-506 machine was the first machine which started advancing and always was in front of S-505 TBM then an important fact can be realized. As a result, S-506 was the first TBM which started excavation and faced tougher geological conditions as compared to S-505; since S-506 disturbed the formation.

This can be assumed as an advantage of S-505 advancing behind S-506 but it can always not be an advantage. In this project the second tunnel boring machine did not face so much difficulties as the excavated material was consisting mostly of weathered, fractured limestone and mudstone. However when the same situation happens in a soft and unstable geology, then the machine which is advancing from behind can experience more collapses and harder geological conditions compared with the machine ahead.

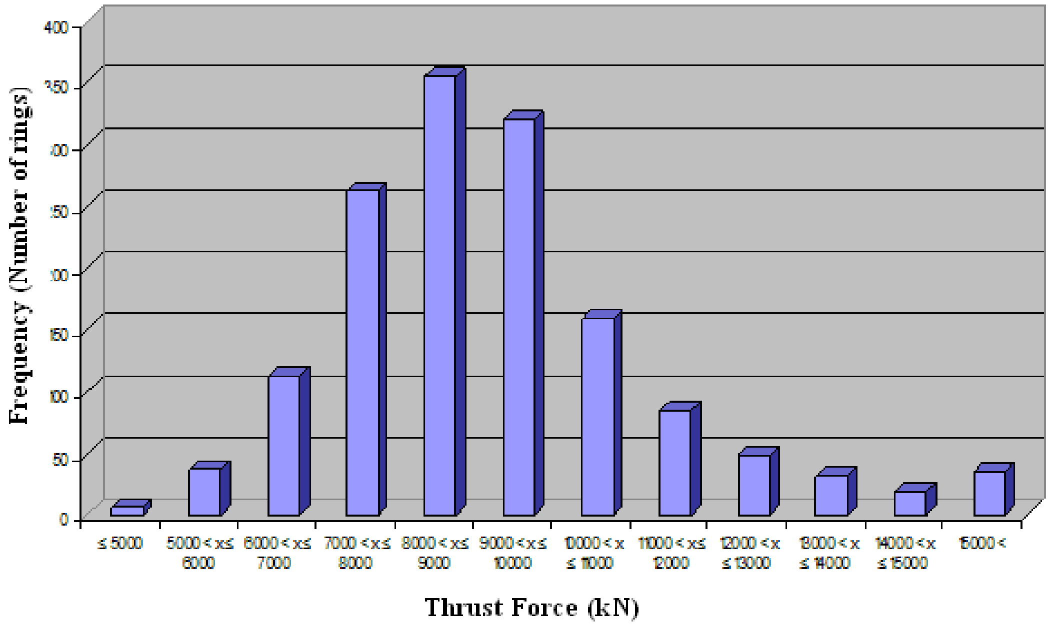

Figure 6.3 : Distribution of thrust force for S-506 TBM.

Below are Tables 6.2 and 6.3 separately for S-505 and S-506 TBMs and the histograms for observing the relationship between RQD and thrust force for both machines.

Table 6.2 : Machine operational parameters related to RQD values in S-505.

RQD	RPM (rev/min)	Torque (MNm)	Thrust Force (kN)	Speed (mm/min)	Penetration (mm/rev)	Specific Energy (kWh/m³)
0-10	-	-	-	-	-	-
10-20	4.32	1.50	7268.00	51.73	11.91	6.42
20-30	-	-	-	-	-	-
30-40	4.77	1.52	7066.27	49.36	10.36	7.57
40-50	5.09	1.57	11886.27	36.45	7.18	11.60
50-60	4.29	1.68	8652.68	42.64	10.00	8.98
60-70	4.38	1.77	7375.58	42.18	9.76	10.00
70-80	4.59	1.63	8888.88	40.53	8.91	9.68
80-90	3.75	1.66	9373.36	50.00	13.36	6.39
90-100	-	-	-	-	-	-

Table 6.3 : Machine operational paramaters related to RQD values in S-506.

RQD	RPM (mm/rev)	Torque (MNm)	Thrust Force (kN)	Speed (mm/min)	Penetration (mm/rev)	Specific Energy (kWh/m³)
0-10	-	-	-	-	-	-
10-20	3.70	1.90	6490.09	51.45	13.91	6.97
20-30	-	-	-	-	-	-
30-40	3.94	2.27	8936.55	45.64	11.55	10.22
40-50	4.33	1.88	11225.45	42.00	9.55	10.04
50-60	3.98	1.67	8983.27	45.59	11.45	7.80
60-70	3.89	1.74	8092.74	44.89	11.71	8.2
70-80	4.02	1.81	8975.64	46.33	11.71	8.13
80-90	3.72	1.96	10198.55	49.91	13.45	7.49
90-100	-	-	-	-	-	-

Figure 6.4 is the graphic for thrust force related with varying RQD. It is clearly seen that there is a peak value when the RQD is between 40 and 50. Between these rings which represent the area that the borehole was done, geological intrusion was observed where the thrust forces were relatively higher. When this area was observed in a longer chainage, the big change in thrust forces can be seen accurately. Figure 6.5 is the graphic of thrust force variation from that area for better illustration.

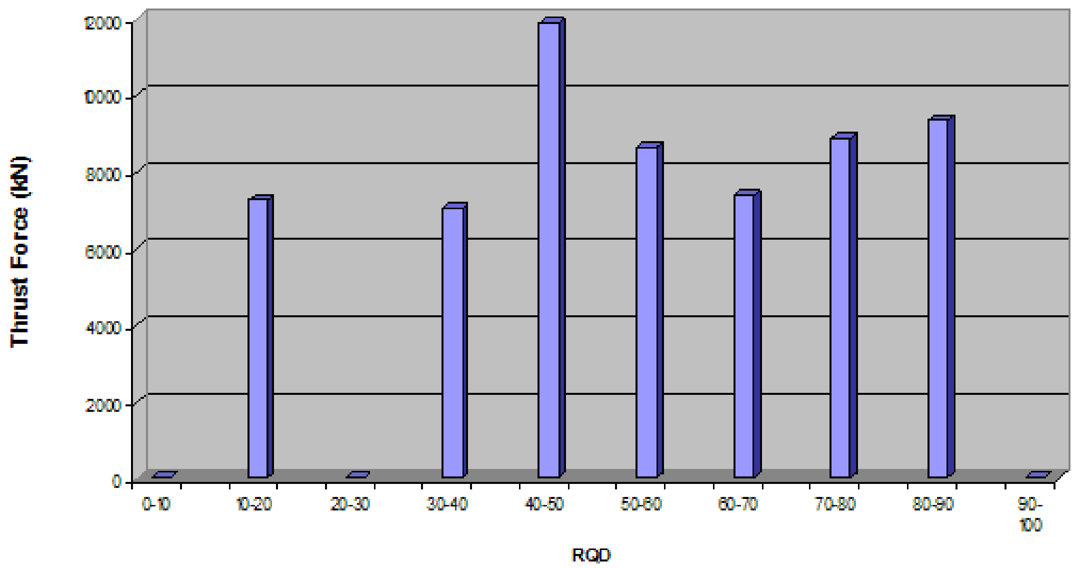

Figure 6.4 : The graphic for thrust force related to RQD values for S-505.

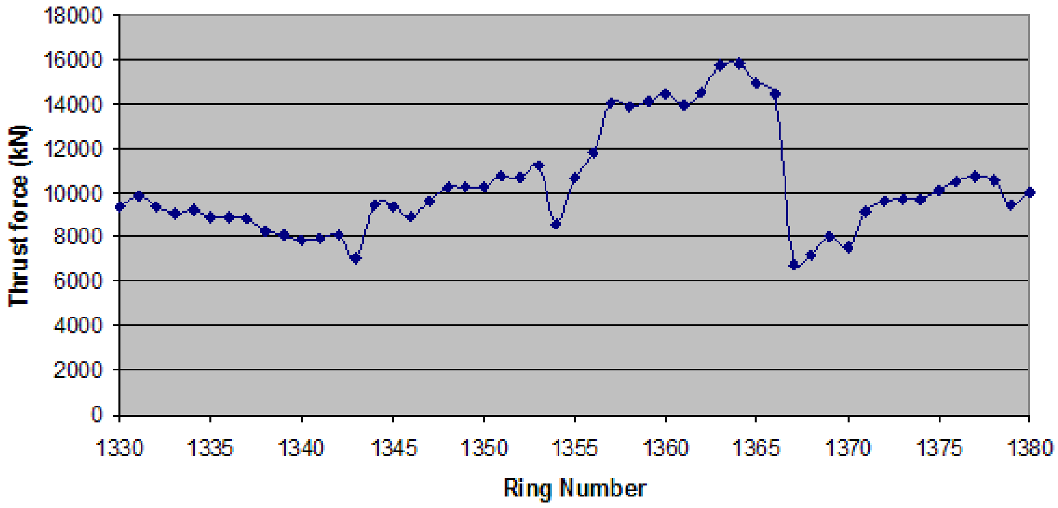

Figure 6.5 : Variation of thrust force between the ring numbers from 1330 to 1380 for S-505.

The borehole for RQD 40–50 corresponds to the rings between 1350 and 1360. In figure 6.5, there is a significant increase from ring 1354 which the thrust force is around 8000kN and reaches up to 16000kN in 10 rings. In general the thrust force is over 8000kN when the graphic is observed. From this graphic, we can evaluate that the RQD was low; however the compressive strength of the rock which was excavated here was higher from the other areas. The reason of the sudden decrease of the thrust force from approximately 14.000kN to 6.000kN is because there was a disc change at the end of that excavation. There was a sudden relief in thrust force values; however it again climbed up to 10.000kN in a short distance. The peak value which is seen between rings 1358 to 1367 indicates the importance of the cutter tools which has a high effect in thrust force as well. In normal conditions it seems that an average of 10.000kN is sufficient in this geology; however when the condition of the cutter tools get worse this force can climb up easily in a short distance which is as well seen in the graphic above. Furthermore, not including the sudden relief of the thrust force after the disc change but a rough overview of the next 15 rings, it is obviously seen that the thrust force reduces to 10.000kN again.

In conclusion it can be said that the thrust force has a general tendency of increasing in thrust force–RQD distribution graphic when the exceptional case in RQD from 40 to 50 is ignored.

In Figure 6.6, there is a peak value seen at RQD between 40 and 50. In addition, the thrust force values observed in RQD between 60 and 70 is even lower from the thrust forces observed when the RQD is in the limits from 30 to 40. For analyzing these differences in both cases mentioned above, two separate thrust force graphics for RQD values between 40 to 50 and 60 to 70 are shown in Figures 6.7 and 6.8.

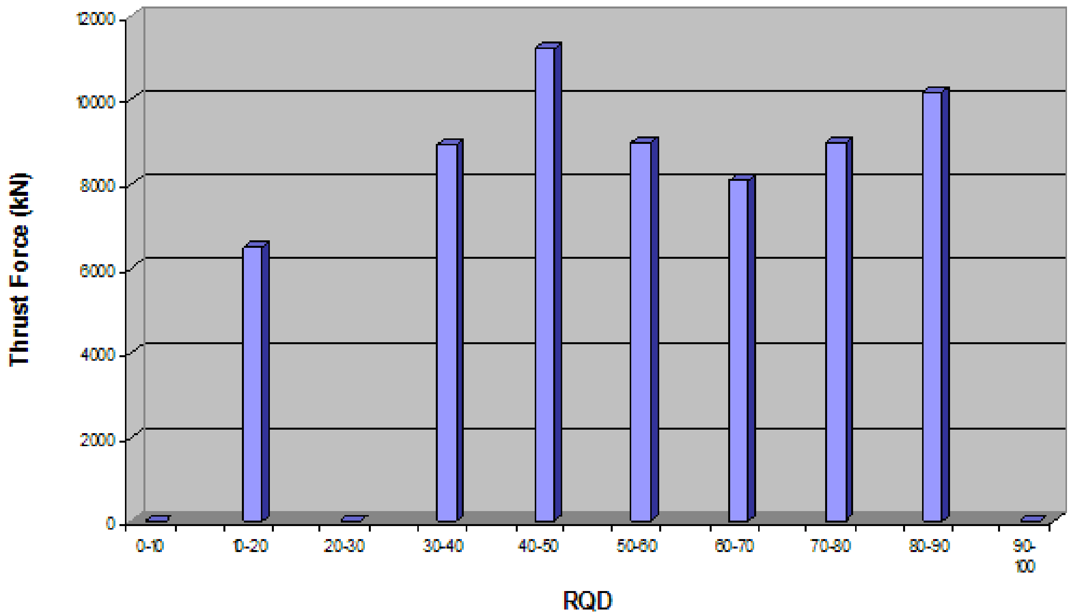

Figure 6.6 : The graphic for thrust force related to RQD values for S-506.

Figure 6.7 for the rings between 1310 and 1350 is to understand the high thrust forces seen in RQD between 40 and 50. The thrust force 11225 kN is the average value between the rings 1325 and 1335 representing the borehole area where the average RQD was found between 40 and 50. When the overall distribution is analyzed for the 40 rings around this borehole it can be seen that the thrust forces are relatively high when compared with other chainages. The thrust force never gets below 8000kN and the average is over 10000kN. This case is very similar case to the one mentioned in S-505 where the RQD might be low; but the compressive strength of the rock around this area looks a little bit higher then most of the chainages in overall project.

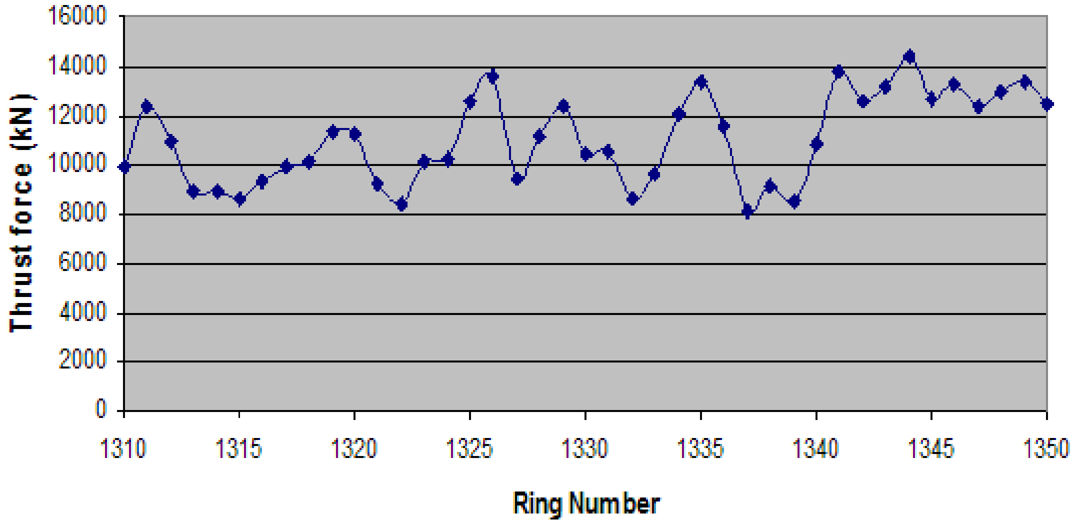

Figure 6.7 : Variation of thrust force between the ring numbers from 1310 to 1350 for S-506.

When thrust force values between RQD 60–70 is observed it is relatively lower than it should be. In Figure 6.8, the average thrust force for the mentioned RQD is represented between the rings 2085 and 2095. It is seen that after ring 2078 the geologically weak formation is observed because of the fault zone, which is frequently seen in the geological profile as well, where the thrust forces reduce significantly till a value of 4224kN which is very low indeed. Eventhough the RQD is between 60 and 70, the geology consists of very weak rock conditions. The sudden peak value from 4224kN to 9001kN is because of a standstill where the tunnel band was extended that lasted for approximately 16 hours. From this result it can be easily said that the geology is very unstable, which the excavated ground settled on the machine that increased the forces suddenly. The thrust force reduces to the average value around 6000kN after two advances from the standstill. This weak zone ends when the machine reaches ring 2110 and continues the next advances with an average above 8000kN. The reason of the decrease in thrust force - RQD distribution graphic can be explained under these circumstances which in conclusion shows us again that higher rock quality designation values can only end up in higher thrust forces in the same compressive strength of the rock.

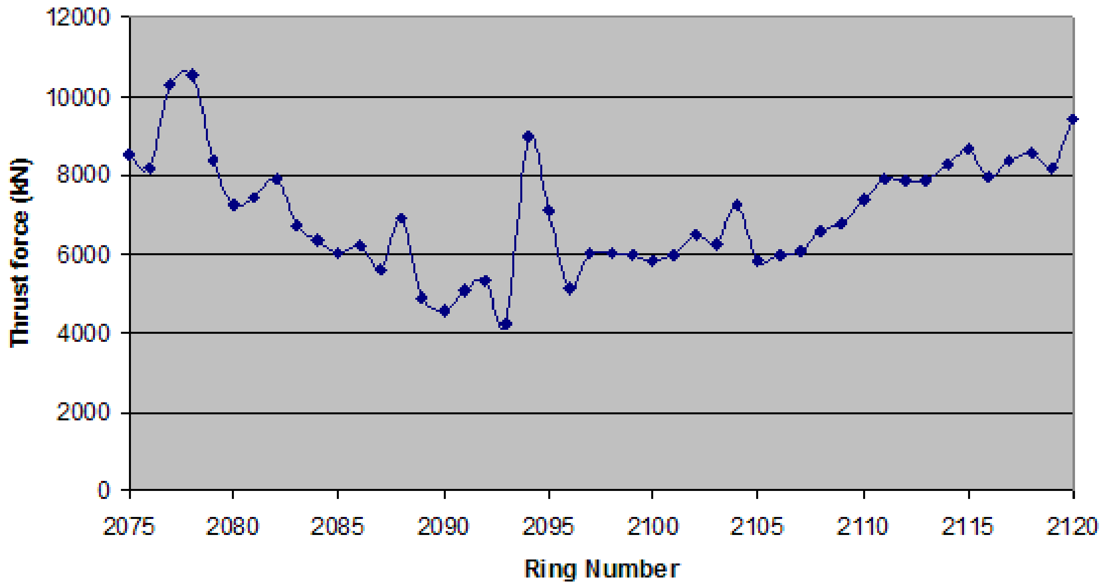

Figure 6.8 : Variation of thrust force between the ring numbers from 2075 to 2120 for S-506.

6.2.4 Distribution curve and histogram related to RQD for penetration per revolution

Penetration is one of the most important machine parameter which mostly is dependent to the operator. Adjustment in penetration should be done accurately according to the existing geological conditions to protect the cutterhead and cutter tools from any damage or reducing the wear as much as possible while achieving the best advance rates. In Figure 6.9 and 6.10 the penetration distribution graphics for both machines are shown.

Penetration and thrust force are really dependent to each other except for the cases which the thrust forces can arise because of different reasons that are listed above as well. In laboratory conditions when all the parameters are exactly the same, the penetration will increase when the thrust force is increased. However practically it is the opposite as the geological parameters can always change when the machine is advancing. To understand it better, it will be the best to give the normal process which the operators are applying during the advance.

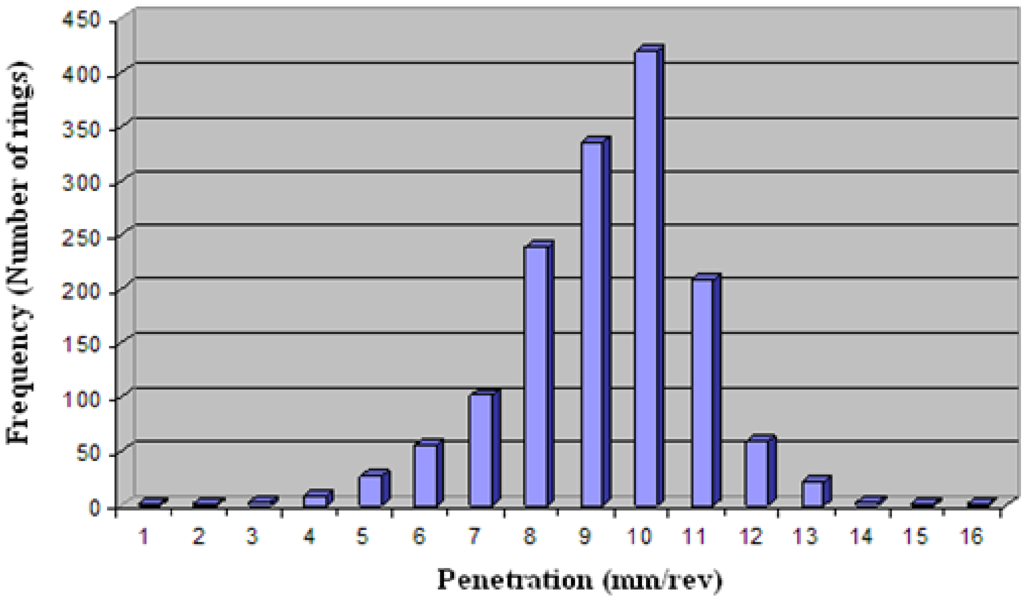

Figure 6.9 : Distribution of penetration for S-505 TBM.

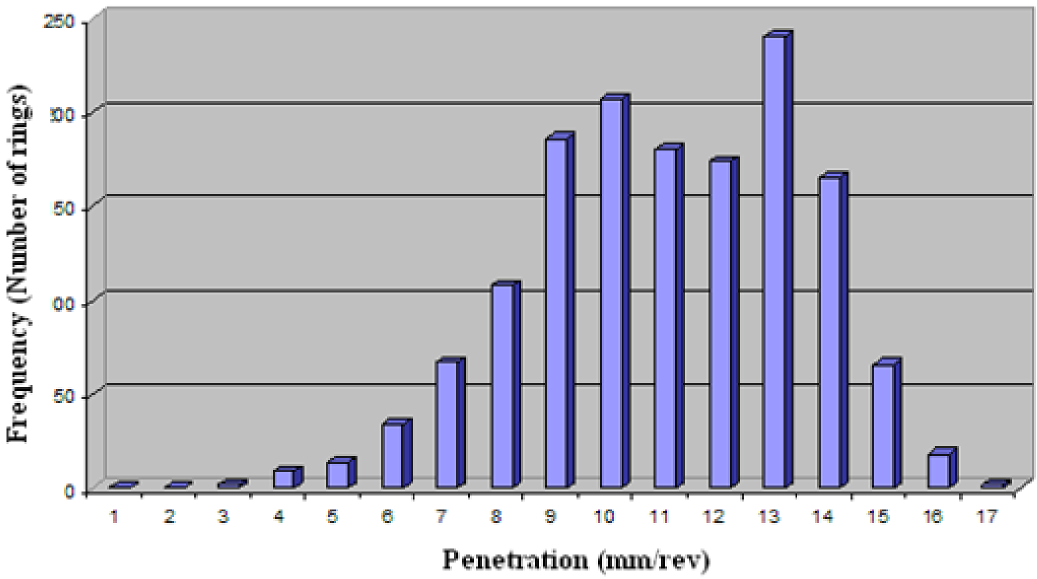

Figure 6.10 : Distribution of penetration for S-506 TBM.

Normally an operator tries to set the machine parameters just after starting an advance which are adjusting the revolution of the cutterhead, adjusting the pressures in thrust jacks which gives us the total thrust force of the machine and the expected advance speed experienced from the recent advances. When he adjusts his thrust force in a specific value such as lets say 10.000kN and with this force let us assume that the machine achieves a penetration rate of 10mm/rev with 4 revolutions per minute (RPM) which will correspond to an advance speed of 40mm/min. When everything remains constant in the geology the operator can advance in these conditions till the complete cycle of advance is finished. However let us assume that the rock strength is rising from 50 MPa to 100 MPa. Then the first thing what the operator will see will be the reduction in the machines advance speed which will effect in the same ratio the penetration rate as the RPM will not change. This example shows easily that the thrust force applied by the machine will not be sufficient to achieve the target values which in that case the operator has to increase the oil flow in the thrust cylinders to obtain higher pressures on the each group of cylinder that at the end will show higher total thrust forces which is possible to be seen on the display screen inside the control cabin. It is all the same in our daily life as well. When driving a car with a constant speed on a straight road, the velocity will start to decrease when the road will get inclined and the driver will have to increase the throttle to keep the speed in the same value.

The "Penetration Distribution" graphics shown in Figures 6.9 and 6.10 are nearly the same with "Thrust Force Distribution" graphics; however mirror inverted. When the thrust force is increasing, the penetration is decreasing on the TBM. It is possible to keep the penetration of the machine constant even though when the thrust force is increasing. However in this condition, the possibility to damage the discs and the cutterhead structure is increasing. In all of the projects the aim should be always efficient advancing. In this case the experience of the operator is very important. The operator should evaluate the parameters which are seen in the control cabin as well as observing from time to time the excavated material and adjust the machine parameters with the optimum advancing conditions without damaging any structure on the cutterhead.

In S-506, the highest frequency in the penetration value is in 13mm/rev while in S-505 it is 10mm/rev. In addition in S-505 there are nearly no advances done where the penetration is over 14mm/rev while in S-506 the frequency is nearly 250 rings. Furthermore when the TBMs positions are also taken into consideration which S-506 was always advancing ahead and having higher thrust forces, then it can easily stated that the operators in S-506 forced the machine little bit more with high penetration rates, while S-505 TBM operator were taking more care of the cutterhead and the discs. Indeed when the disc consumptions are analyzed in Tables 4.1 and 4.2, it is seen that the disc consumption of S-506 is higher then the value seen in S-505.

In Figure 6.11, it is seen that the lowest penetration is in RQD within the range of 40 to 50, which has the highest thrust force seen in table. This is an expected result which has been mentioned above and the highest penetration is seen in RQD between 80 and 90. This highest penetration can be assumed as the operator's preference with achieving the highest advance rate with the lowest revolution on the cutterhead and meanwhile having the highest penetration. When the graphic is analyzed, a general tendency of penetration decreasing can be seen while the RQD is increasing except for the two cases experienced in RQD values 40 to 50 and 80 to 90.

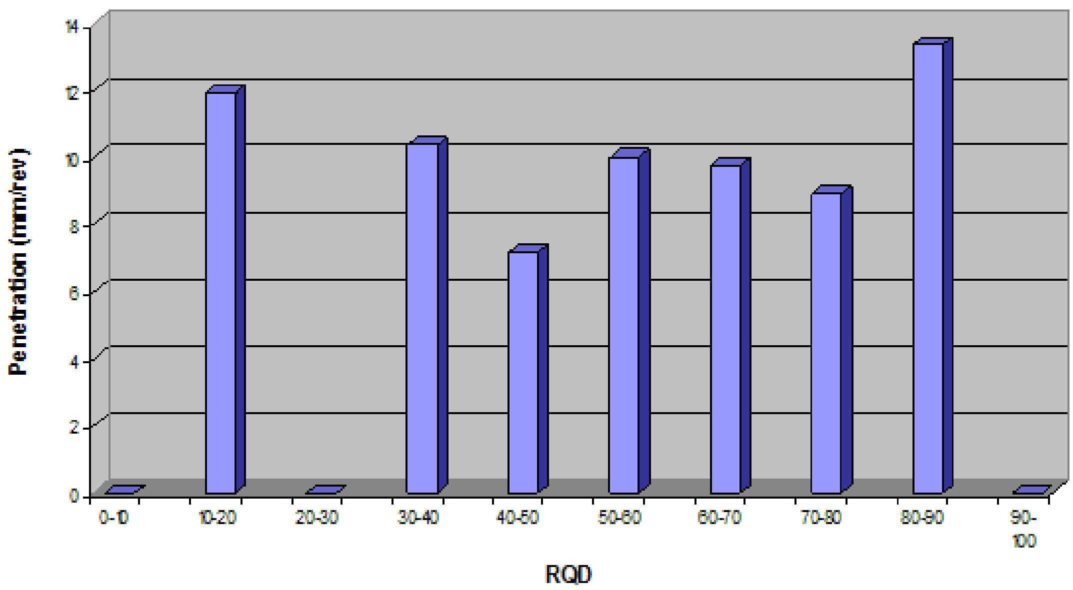

Figure 6.11 : Penetration distribution related to RQD values for S-505.

In Figure 6.12 the lowest penetration is seen where the highest thrust force was experienced which is RQD between 40 and 50. Meanwhile the highest penetration arises in the graphic where the thrust force was the lowest that was in RQD 10 to 20. In S–506 TBM's graphic the average penetration rates are seen very close to each other which also indicates that there was not a very big difference in the geological conditions at where these values are observed.

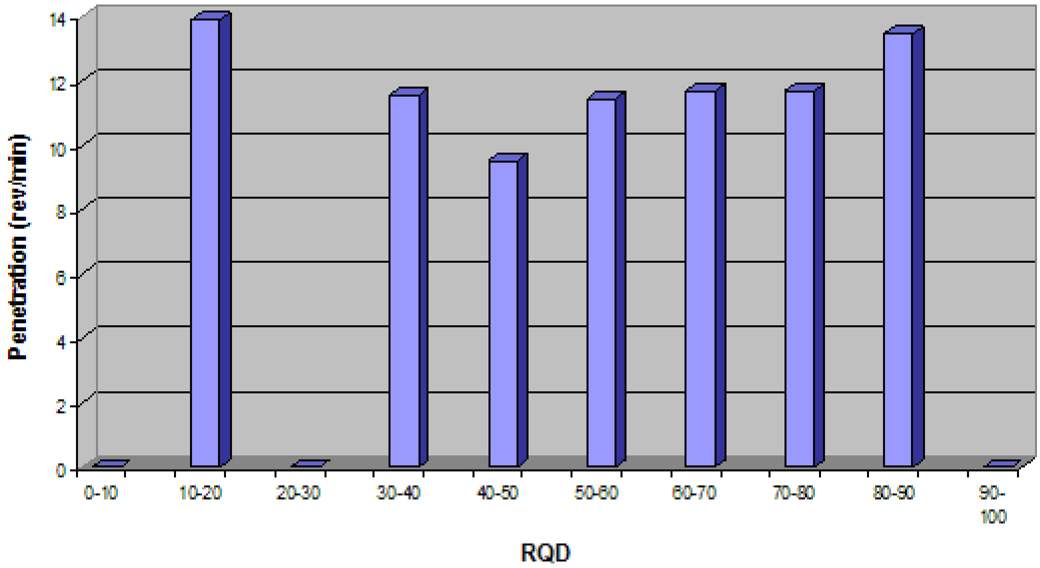

Figure 6.12 : Penetration distribution related to RQD values for S-506.

6.2.5 Distribution curve and histogram related to RQD for torque

Torque of the machine is a little bit more independent from the thrust force and can vary a lot with the small changes in the geology. It can be observed as well when the graphic from thrust force and penetration are checked that torque graphic is more homogeneously distributed. Rather than the compressive strength of the rock, which effects the thrust force values, the characteristic properties of the geology is rather more effective on torque values. The ratio of the fine materials in the excavated material, the stickiness of the material and the clogging characteristic of the material is very important. The TBM can advance with the same thrust force values; however the torque values can vary with the changes of the different material content.

Most likely high changes in the torque values are observed in soft geological formations which usually consist of clay, silt and similar formations. In rock formations, mostly problems based on torque values are not really much observed unless an unstable rock formation is excavated and possible small or big collapses are experienced.

When the machine is advancing in soft ground formation or very fractured rock formation, then the torque values can increase significantly if precautions are not taken. Fine materials can sometimes be sticky and create additional torque by starting to close the openings between the spokes of the cutterhead. In addition in soft ground formation, materials such as clay can also cause clogging the cutterhead first by starting to surround the spokes of the cutterhead and closing slowly the openings between them. For such cases foam ratios should be adjusted according to the excavated geology, sometimes additional water must be applied for the foam to better react on the cutterhead face or inside the excavation chamber. Some additional steel structures which are stators and rotors are also installed in the backside of the cutterhead and inside the excavation chamber to have a better mixture of the foam and the excavated material to transport the material easier and reducing the torque values for convenient advance.

Torque values also increase when compensating the actual calculated earth pressures. The first set will be to increase the excavated material inside the excavation chamber for starting to apply pressure on the unstable ground. The more the excavation chamber is full the more material the cutterhead has to rotate and mix which has a direct effect on the increasing torque values. In such conditions foam ratios should be adjusted accurately to achieve the best mixture and with minimum clogging effect of the material to reduce the torque as much as possible especially when the excavation is planned to be continued with a full chamber.

In Figure 6.13, the torque values are nearly perfect with a very good distribution and none of the values can be assumed as high torque in such a diameter. Most of the values are between 1.4–2.0MNm which absolutely represents very good advancing conditions. In these diameters torques over 3.0–3.5MNm can be assumed as limit torque values which should be careful about. Because this limit value, mostly indicates that the clogging of the cutterhead can occur suddenly, especially at the time when the torque values increases in the recent advances. It can be said that in figure 6.13 the geological formation was not so complicated to create a problem for the TBM and it will appropriate to say that the operator also advanced good.

In S-506 torque distribution given in Figure 6.14 it is seen that the values are mostly between 1.8MNm to 2.2MNm. The torque distribution for this tunnel boring machine is also very good as high torque values which are over 3.5MNm is not faced. However when both machines are compared S-506 torque values are relatively a little bit higher then the values seen in S-505 machine. This difference can be explained again as S-506 was the first TBM which was excavating as well the drive of the operator was also an effect in this relatively high values when compared.

Penetration distribution of S-506 TBM was as well higher then S-505 which can be accepted as another fact to increase the torque value.

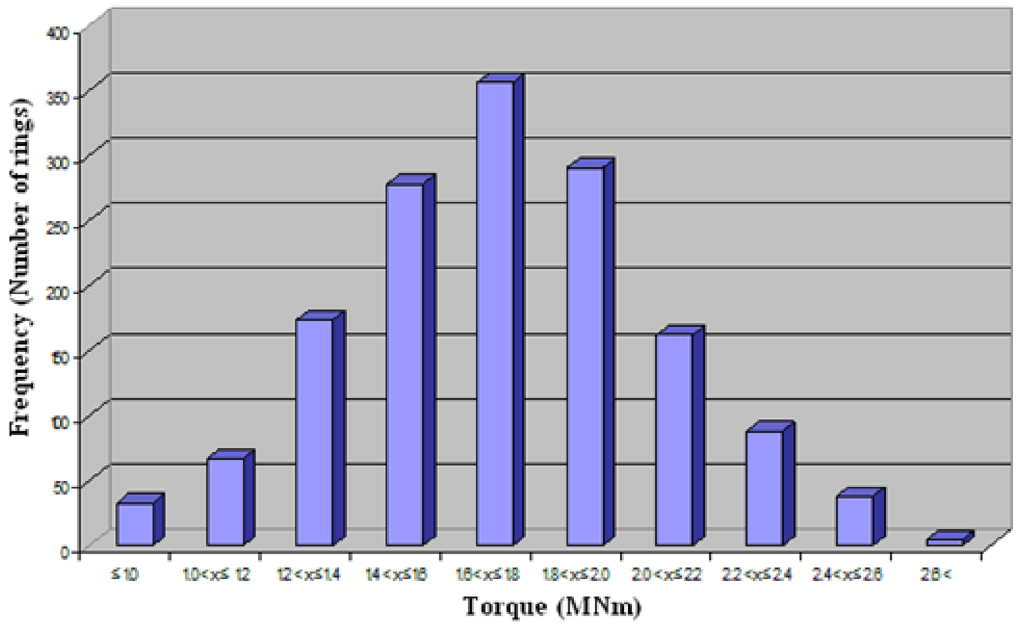

Figure 6.13 : Distribution of torque for S-505 TBM.

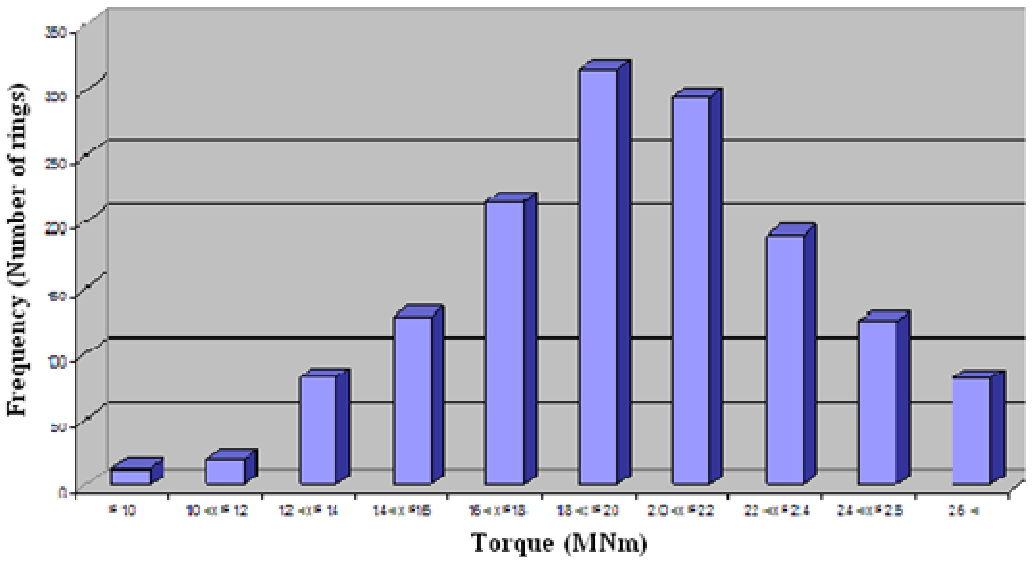

Figure 6.14 : Distribution of torque for S-506 TBM.

When both machines torque distributions are analyzed it can be seen that both TBMs did not have a very difficult geology concerning especially the values figured in torque values. Indeed throughout the tunnel profile neither S-505 nor S-506 machines faced high torque values which resulted with a collapse or a blockage of the cutterhead because of sticky and cloggy material.

When the torque distribution related with the RQD values is observed for S-505 which is seen in Figure 6.15; eventhough the highest torque value is seen in between RQD 60 to 70, it can be assumed that all torque values are the same. The 0.2–0.3 MNm difference in the torque value can arise even from the small operational differences in advance conditions. Any small change in penetration, thrust force value, the ratio of the material in the excavation chamber and even the variation of the wear on the discs can cause this difference.

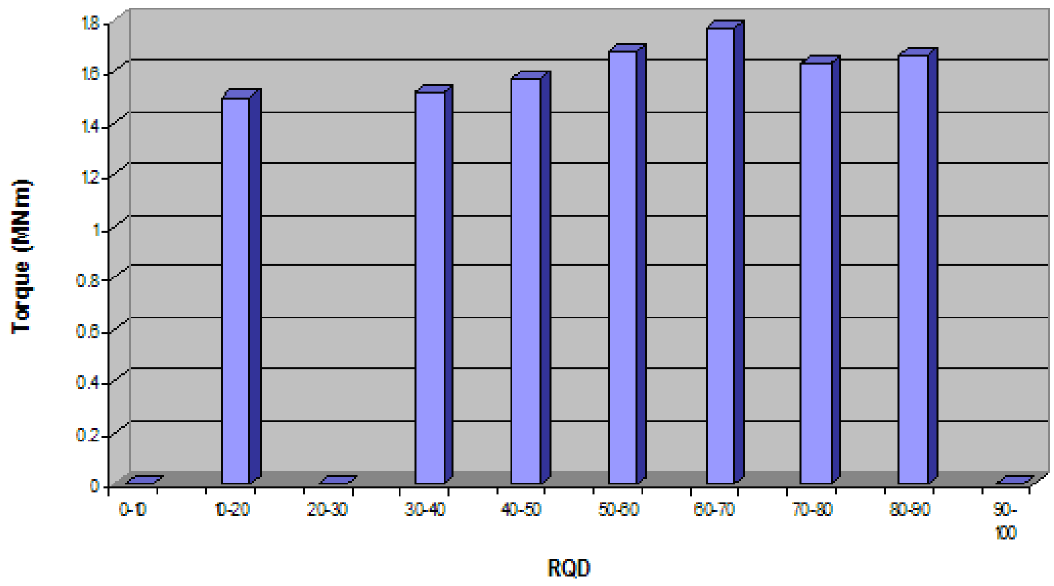

Figure 6.15 : Torque distribution related to RQD values for S-505.

From the Figures 6.15 and 6.16, the difference in the torque values from both machines can be seen easily. In S-505 the torque of the machine changes from 1.4MNm to 1.8MNm with an average not even 1.6MNm while in Figure 6.16, S-506 machine have the lowest value of 1.6MNm in one RQD range while the other torque values are higher. The average torque value in S-506 is still a little bit above the maximum torque value seen in S-505. This difference between the both machines can be explained as higher penetration rates seen in S-506 while less foam was consumed as well when compared with S-505. However both machines torque distribution is good and there are no high values observed which can create difficulties to the TBM.

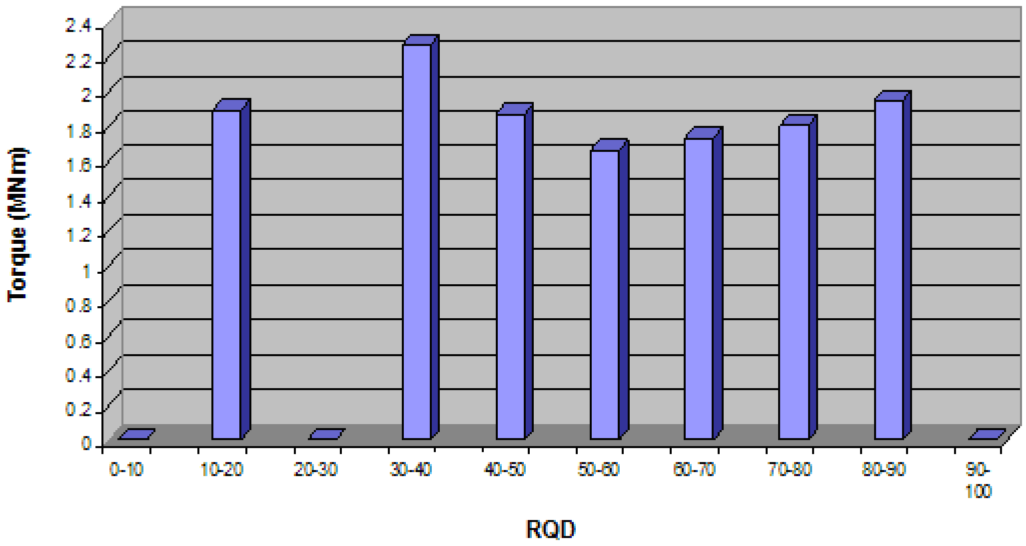

Figure 6.16 : Torque distribution related to RQD values for S-506.

6.2.6 Distribution curve and histogram related to RQD for rate of advance

In every jobsite, for sure the most important machine parameter is the advance rate of the TBM for the jobsite management for finishing the project in the shortest time possible. Although the advance speed somehow represents how fast the project can be finished, it should not be assumed as the only criteria. Most of the time looses are arising because of logistics. Besides the TBM can be capable of advancing faster; however the results should be estimated and foreseen when the advance speed is increased. That is why the operator should suspect the best and efficient advance speeds without causing any standstills only because of this reason.

When the advance speed of the machine is analyzed in Figure 6.17, it can be easily seen that the machine did not have difficult geology where the advance rates were low. It is clear that the average speed is over 40mm/min which can be accepted as a really good advance rate. From this speed distribution we can come to a conclusion that the TBM type was correctly selected and geology was not so tough. The graphic can be also evaluated as the thrust forces were very low when the machine was advancing with a speed of over 50mm/min and thrust forces were rather high where the TBM was not advancing over 30mm/min.

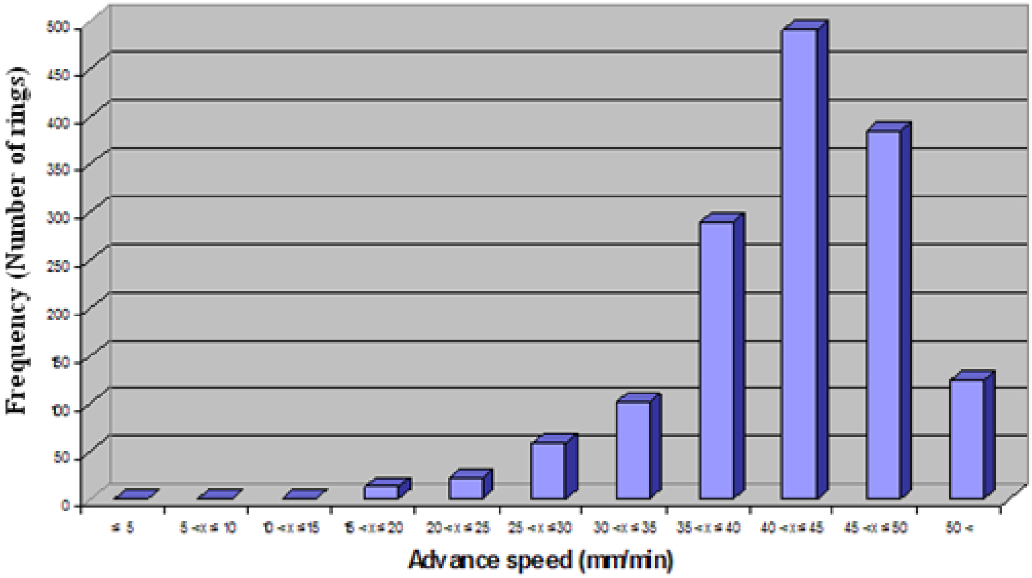

Figure 6.17 : Distribution of advance speed for S-505 TBM.

Compared with S-505, it can be seen that S-506's advance speed distribution in Figure 6.18 are higher. As mentioned above in other graphics as well, the difference is arising from operator difference. The most important fact is, the effiency of the TBMs. It is of course better to advance faster as long as the efficiency of the TBM is the same, which means that there are no standstills occurring or occurred because of advancing in higher speeds.

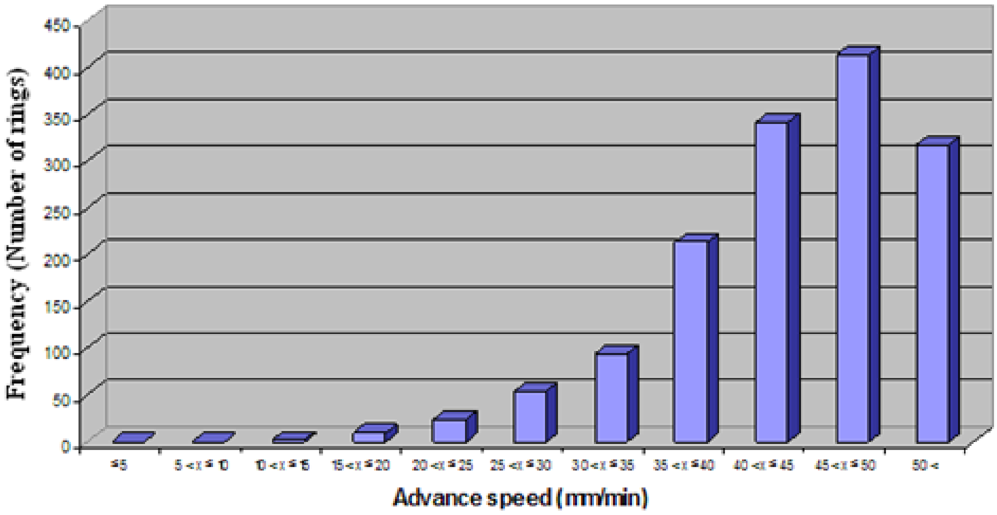

Figure 6.18 : Distribution of advance speed for S-506 TBM.

The advance speed distribution of both TBMs dependent to RQD values are very similar which are seen in Figures 6.19 and 6.20. In S-505 a small amount of decrease in advance speed can be seen in RQD values between 40 and 50 where the thrust force was the highest.

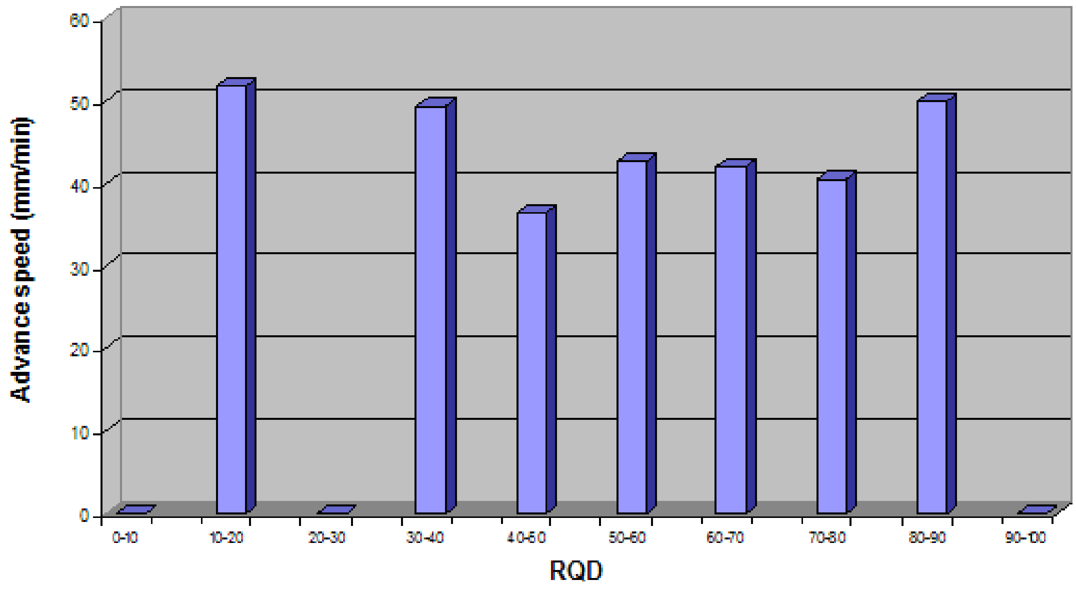

Figure 6.19 : Advance rate distribution related to RQD values for S-505.

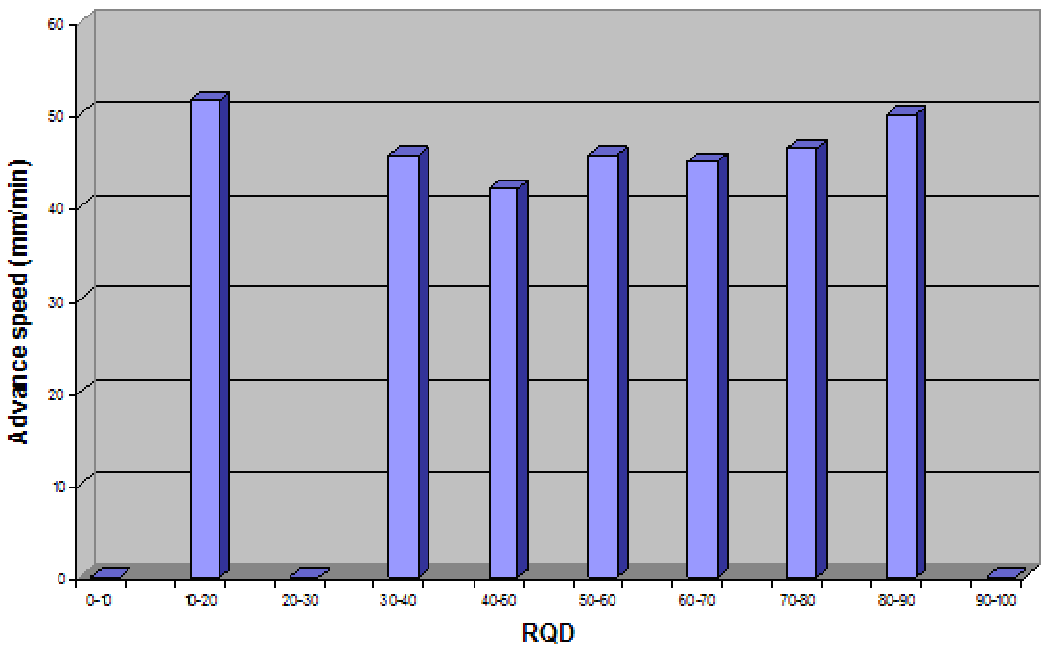

Figure 6.20 : Advance rate distribution related to RQD values for S-506.

6.2.7 Distribution curve and histogram related to RQD for RPM

In Figure 6.21 the cutterhead revolution per minute (RPM) distribution can be seen which can be assumed as always rotated in high speeds. This actually indicates that the formation excavated was rock. In soft formation it is usually advised to rotate the cutterhead around 3.0–3.2 rpm maximum in this diameter range. If the cutterhead is rotated faster in soft formation the more possible and easier the cutterhead will be blocked. In soft formation because of low thrust forces, there are no risks to damage the discs or damaging the structure of the cutterhead because of high loads. As mentioned, in order not to block the cutterhead the revolution is reduced while the penetration can be increased by given more thrust force which will be again in the accepted limit. However in rock conditions and especially in hard rock, the revolution of the cutterhead is tried to kept as high as possible because it is not possible to achieve the necessary penetration values due to the results of high thrust forces arised from the strength of the rock.

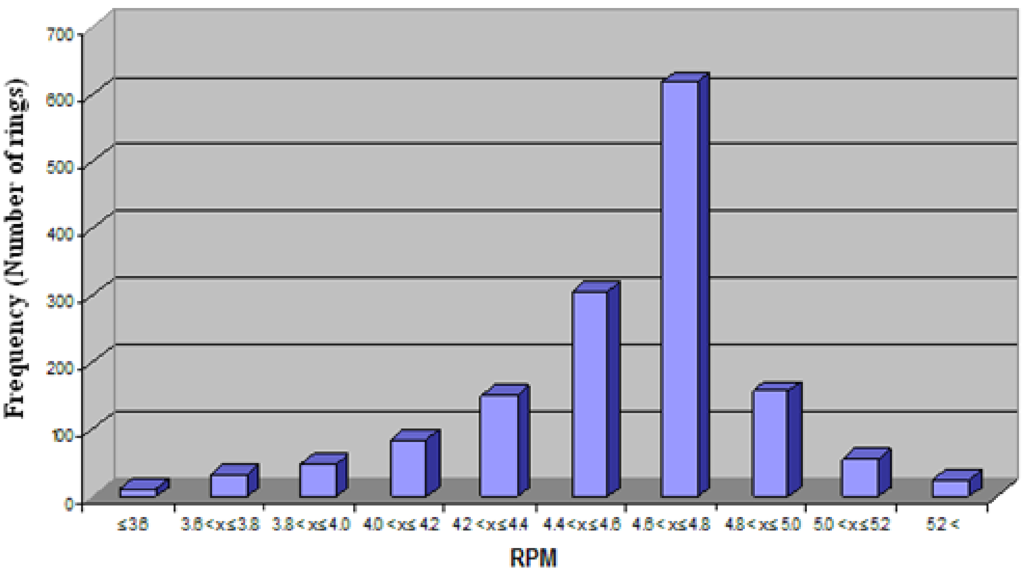

Figure 6.21 : Distribution of RPM for S-505 TBM.

In S-506 TBM the cutterhead was mostly rotated between 4.2 to 4.4 revolutions per minute which is shown in Figure 6.22. However when both TBMs are compared, the highest distribution is seen with 600 data between 4.6 and 4.8 revolutions per minute; while in S-506 there are only four data recorded. In addition the overall distribution is more homogeneous in S-505 then compared with S-506. In S-506 it looks like there are two different cases that are applied for two different geologies. It can be assumed that rotation between 4.2 to 4.4 was applied to rock conditions; whereas the rotation between 3.6 and 3.8 was applied when the TBM was advancing in EPB mode with partially full cutterhead.

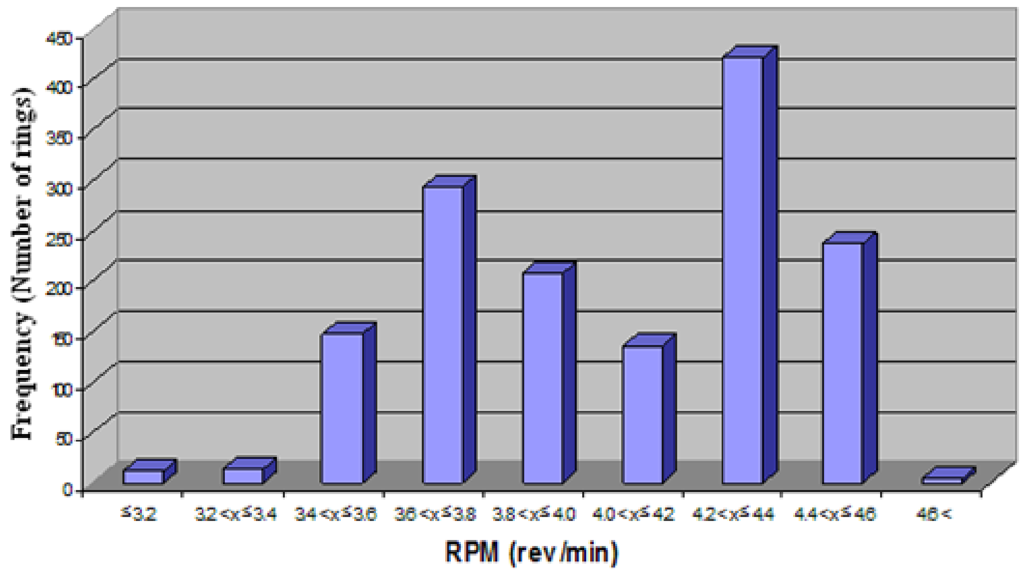

Figure 6.22 : Distribution of RPM for S-506 TBM.

Cutterhead revolution is also dependent to operator preference. However it does not mean that the operator can turn the cutterhead in every revolution no matter what the geology is. In every kind of geology, the operator experiences the best cutterhead revolution, the best penetration by observing the machine parameters during advancing. It is not possible to say the exact value in any machine parameter eventhough the conditions can be exactly the same. However it is possible to define a range in all the machine parameters to achieve the optimum advancing conditions.

In Figure 6.23 the highest cutterhead revolution (RPM) is seen where the RQD is between 40 and 50. The reason is quite obvious as the thrust force in that area was the highest. The rest of thrust forces were very similar to each other but the lowest revolution of the cutterhead is seen in the RQD values between 80 and 90 although the second highest thrust force has been experienced in that chainage. In addition when the Table 6.2 is observed, it is seen that the highest advance rate is achieved with the lowest revolution on the cutterhead. Normally the operator could have increased the RPM and achieved the same advance speed with lower penetration which also would have affected the thrust force to reduce in a small amount. This example indicates that the machine parameters are dependent to the operators in similar geologies.

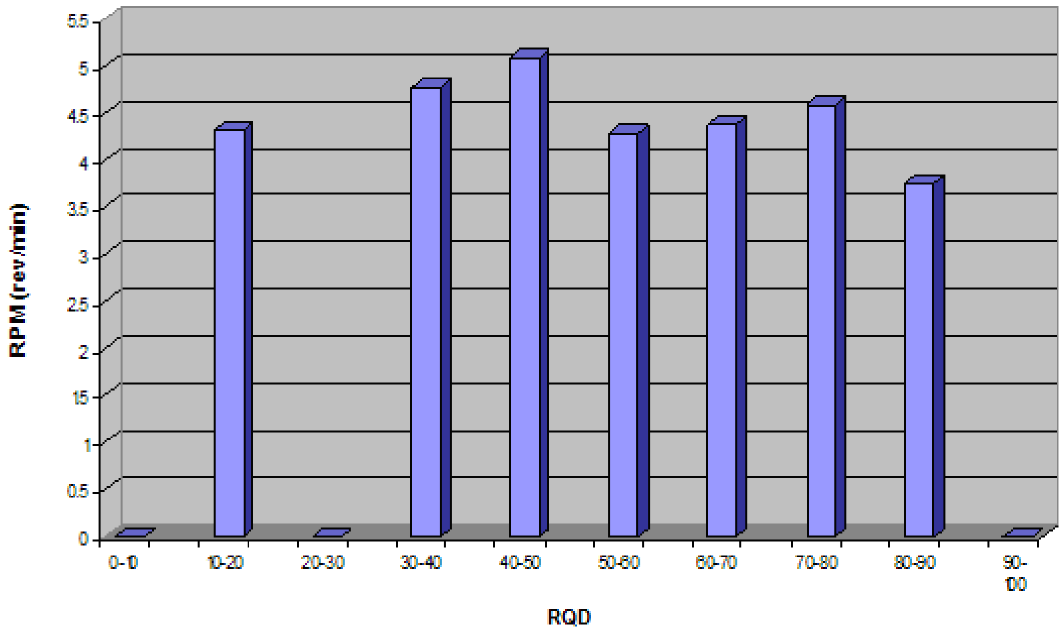

Figure 6.23 : RPM distribution related to RQD values for S-505.

In S-505 all of the cutterhead revolutions are over 4 rev/min except for the RQD value between 80 and 90 while in S-506 the revolution is over 4 rev/min in only one specified RQD range which is seen in Figure 6.24.

6.2.8 Distribution curve and histogram related to RQD for specific energy

Both machines specific energy distribution is seen in Figures 6.25 and 6.26. The specific energy distribution is mostly seen between 9 and 10kWh/m^3 in S-505, while the distribution is nearly the same between the values 7 to 11kWh/m^3 in S-506. However the average specific energy values of the both TBMs are very close to each other.

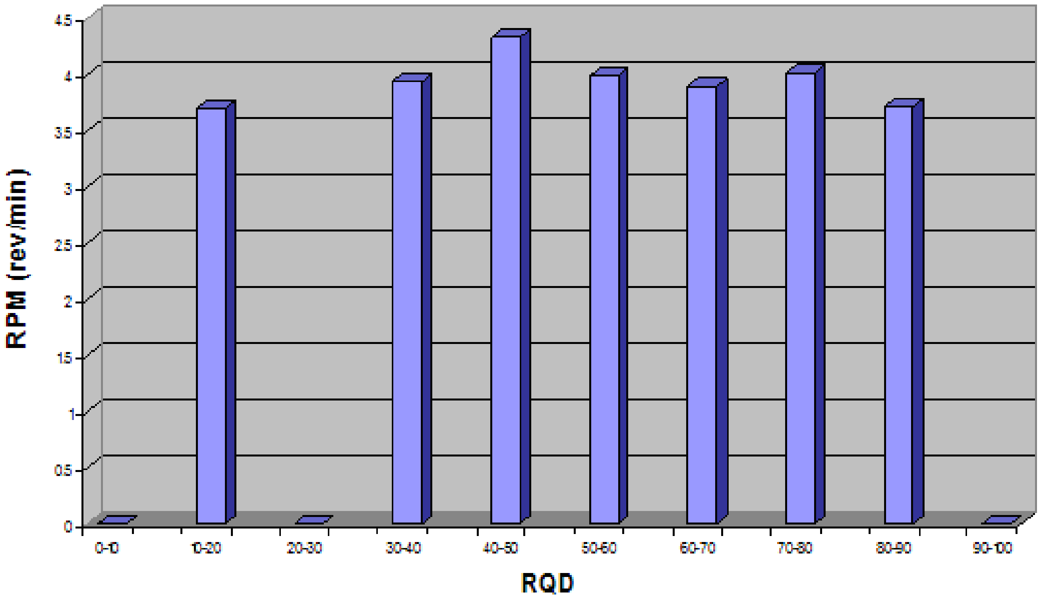

Figure 6.24 : RPM distribution related to RQD values for S-506.

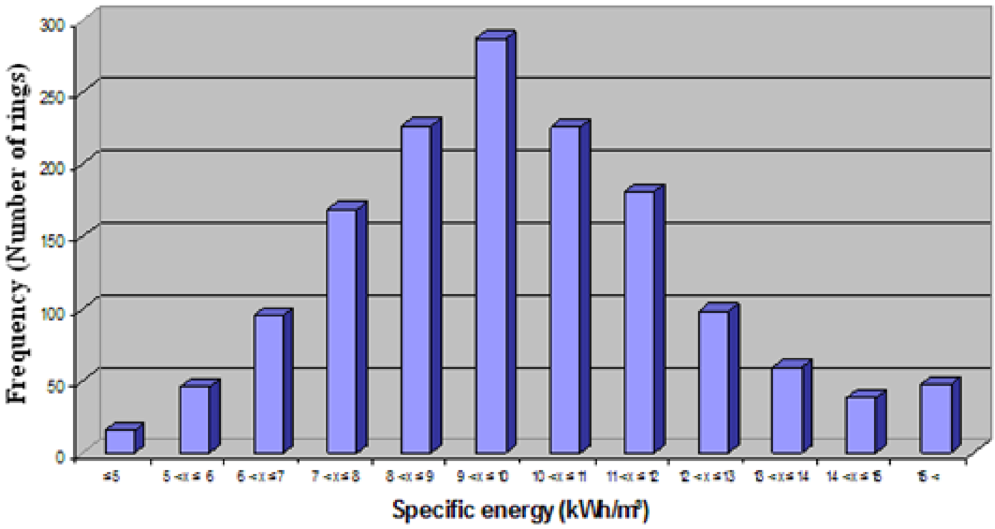

Figure 6.25 : Distribution of specific energy for S-505 TBM.

The highest specific energy was obtained where the highest thrust force was seen in Figure 6.27. The minimum specific energies were seen in RQD values 10 to 20 as well as 80 to 90. Furthermore the graphic can be evaluated to have a tendency to increase till RQD 60 to 70, whereas after that level it starts decreasing.

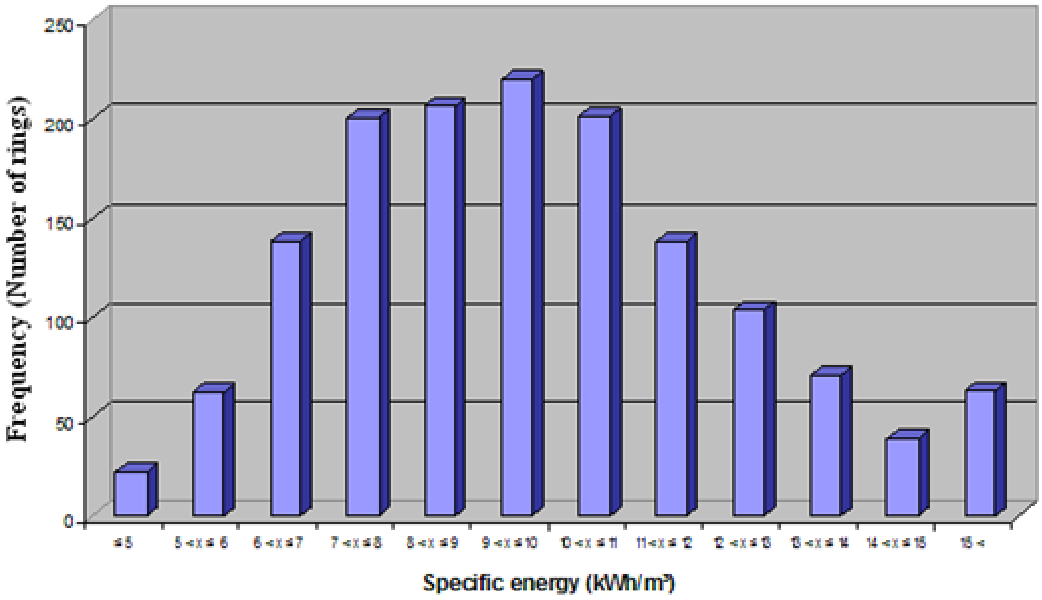

Figure 6.26 : Distribution of specific energy for S-506 TBM.

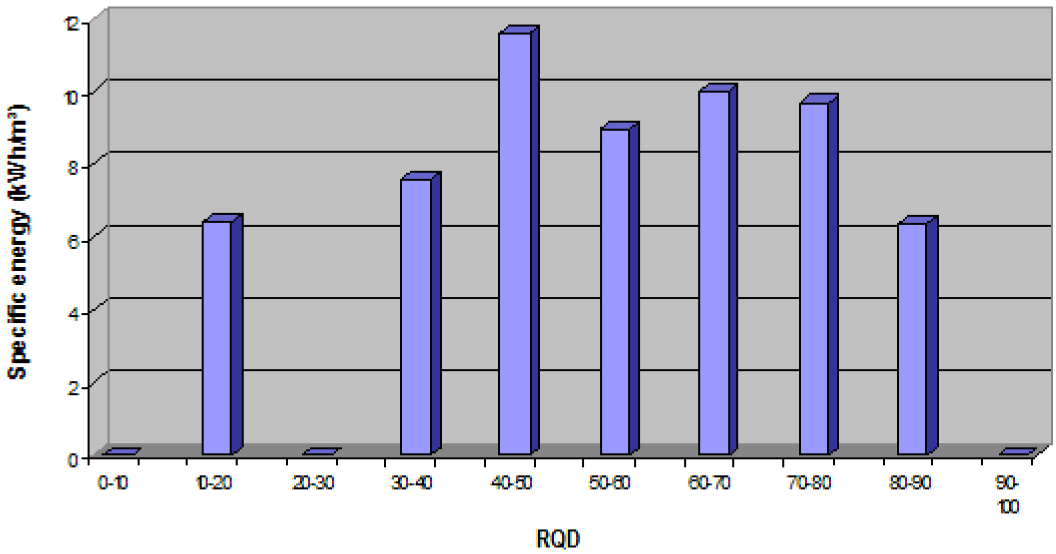

Figure 6.27 : Specific energy distribution related to RQD values for S-505.

The specific energy distribution related to RQD values for S-506 can be seen in Figure 6.28. In this graphic it can be seen that especially the specific energy distribution seen between RQD values between 50–90 is very similar.

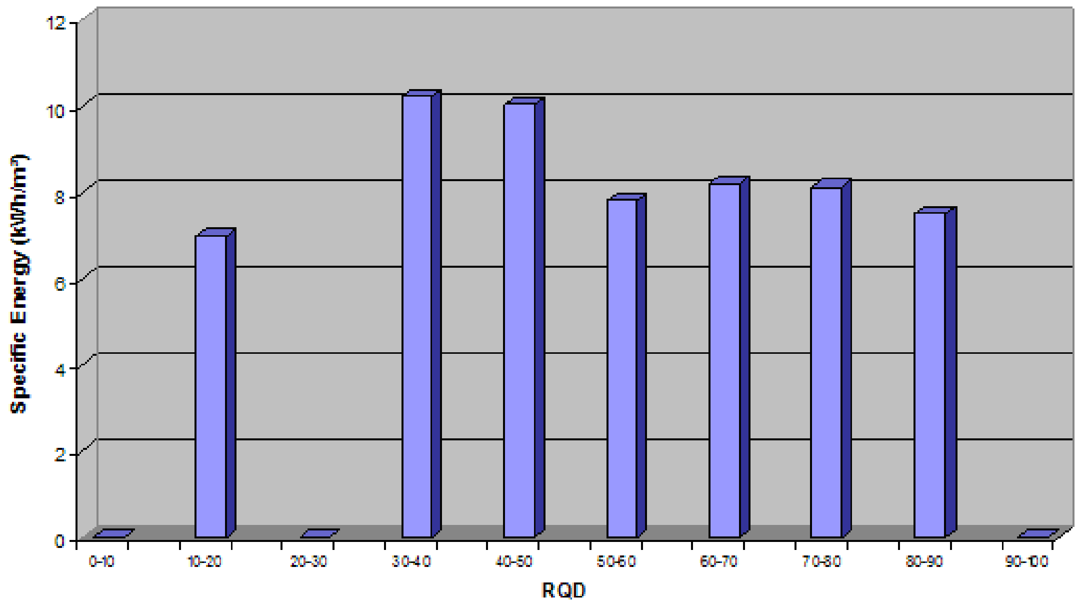

Figure 6.28 : Specific energy distribution related to RQD values for S-506.

Two good examples can be given from the specific energy distribution related to RQD value which are :

- **For RQD 40–50 :** Eventhough the torque value of S-506 is higher then S-505 and the thrust force values are close to each other, the specific energy of S-506 is nearly %15 lower then S-505 because the penetration rate is higher. Although the torque value of S-505 is lower, the specific energy is higher compared with S-506 because of higher revolution on the cutterhead and lower penetration rate adjustment.
- **For RQD 60–70:** In this example S-505 and S-506 TBMs torque values are the same; however the thrust force value in S-506 is nearly %10 higher then in S-505. In normal circumstances the specific energy of S-506 should be higher; but because that the revolution of the cutterhead is lower and the penetration rate of the TBM is higher then in S-505, the specific energy is nearly %20 less compared with the other machine.

From the results above it can be thought that increasing the penetration also have a good effect in excavation with making the same job with lower power consumption. However as mentioned in the texts above, the machine parameters should be adjusted according to all possibilities which can occur during the advance. If we generalize the subject, achieving low specific energy is always a benefit for the jobsite which means low consumption of power on the site; however if the TBM standstills are longer for maintenance, cutter tool change, welding grill bars on the cutterhead because of wear… etc compared with another machine just because high penetration rates to achieve low specific energy values then it can be said easily that it has a lot more disadvantages then the advantages succeeded.

Best adjustment of the machine parameters are always in the hands of the operators. The operators should not only drive the TBM but lead the team in the tunnel as well as normally they should have the best sense on the machine. From the instant changes in the machine parameter values, from the change of the noise from the hydraulic pumps and even from the vibrations of the TBM; the operators should be capable of sensing the possible next step.

7. THE RELATIONSHIP BETWEEN OPERATIONAL PARAMETERS OF THE TBMs

Each of the machine operational parameters is dependent to other machine parameters in general. The Tables 7.1 and 7.2 seen below are classified according to the penetration values obtained from both TBMs.

7.1 The Relationship Between Penetration and Thrust Force

When thrust force–penetration graphic is observed in Figure 7.1, as mentioned above as well, penetration increases when the thrust force decreases. There is a slight increase in thrust forces when the penetration is 15 and 16mm/rev; however it is better not to include in this evaluation as there are only one sample from each when a data of 2000 rings are checked. Meanwhile in some cases it can be seen from the data that there is a big difference in the thrust force even though the penetrations are the same. Basically the reason would be that the operator wanted to have the same advance speed in different rock strengths.

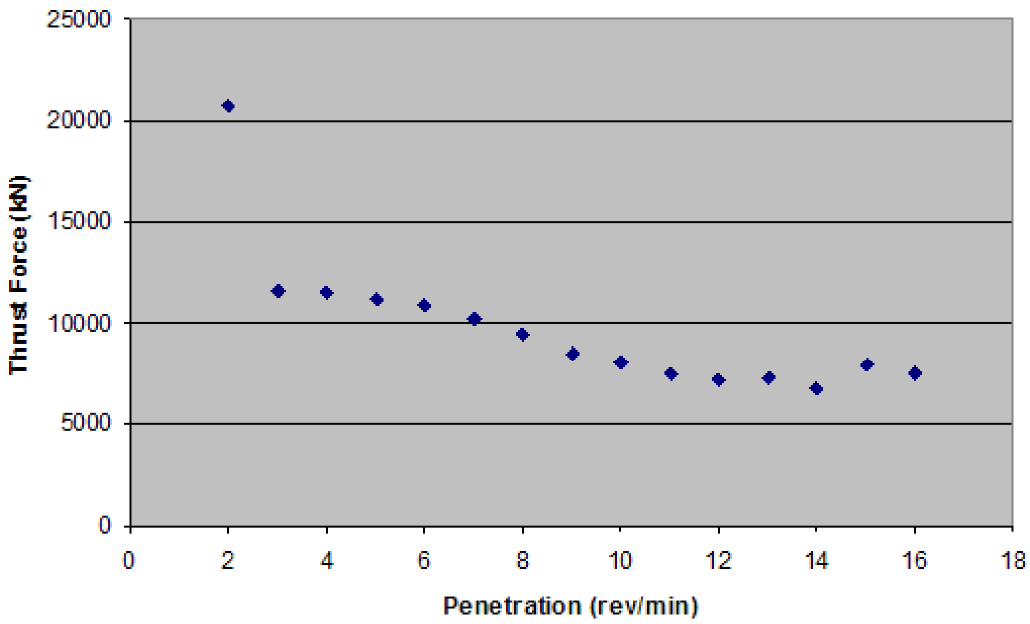

Figure 7.1 : Relationship with thrust force and penetration for S-505.

Table 7.1 : Table for machine paramaters related to penetration values in S-505.

Data	Penetration (mm)	RPM (rev/min)		Torque (MNm)		Thrust Force (kN)		Speed (mm/min)		Specific Energy (kWh/m³)	
		Average	Std Deviation	Average	Std Deviation	Average	Std Deviation	Average	Std Deviation	Average	Std Deviation
1	2	4.30	0.00	0.66	0.00	20668	0.00	8.00	0.00	18.25	0.00
4	3	5.15	0.15	1.08	0.35	11605	1186.60	16.75	0.83	16.87	4.87
9	4	4.70	0.26	1.14	0.27	11530	1144.64	19.11	1.52	14.36	3.26
27	5	4.86	0.30	1.33	0.37	11145	1820.06	24.11	2.11	13.82	3.81
56	6	4.88	0.22	1.53	0.32	10790	2307.39	29.39	2.00	13.13	2.90
102	7	4.79	0.29	1.64	0.29	10149	1415.25	33.81	2.66	11.95	2.08
239	8	4.78	0.24	1.72	0.29	9440	1438.53	38.50	2.27	10.97	1.92
336	9	4.67	0.23	1.72	0.31	8477	1140.96	42.27	2.26	9.81	1.78
420	10	4.58	0.26	1.79	0.35	8029	1393.51	45.61	2.92	9.25	1.88
208	11	4.49	0.31	1.78	0.34	7534	1182.84	48.90	3.25	8.39	1.63
59	12	4.28	0.37	1.71	0.41	7156	1048.77	50.80	4.30	7.43	1.82
22	13	3.92	0.33	1.58	0.33	7319	846.16	50.41	4.56	6.33	1.34
4	14	3.88	0.55	1.70	0.24	6792	572.30	53.75	7.29	6.31	0.90
1	15	3.50	0.00	1.83	0.00	7932	0.00	51.00	0.00	6.46	0.00
1	16	3.80	0.00	2.20	0.00	7519	0.00	60.00	0.00	7.17	0.00

Table 7.2 : Table for machine paramaters related to penetration values in S-506.

Data	Penetration (mm)	RPM (rev/min)		Torque (MNm)		Thrust Force (kN)		Speed (mm/min)		Specific Energy (kWh/m³)	
		Average	Std Deviation	Average	Std Deviation	Average	Std Deviation	Average	Std Deviation	Average	Std Deviation
2	3	4.4	0.1	0.92	0.12	20753.5	1443.5	12.5	0.5	16.55	1.8
9	4	4.34	0.13	1.47	0.55	14675.78	5038.9	18.11	0.99	18.16	7.01
14	5	4.42	0.09	1.73	0.33	13449.71	3297.1	22.71	1.22	17.37	3.51
34	6	4.39	0.17	1.72	0.35	12198.85	2697.2	26.32	1.62	14.82	2.98
67	7	4.39	0.15	1.77	0.29	11691.51	2698.8	30.69	1.49	13.04	2.19
108	8	4.39	0.16	1.86	0.31	10373.52	1905.37	35.42	1.68	11.9	2.01
186	9	4.36	0.17	1.95	0.33	10168.84	2035.63	39.53	1.78	11.06	1.93
207	10	4.32	0.18	2.01	0.35	9607.67	1745.18	42.88	2.02	10.42	1.83
180	11	4.18	0.26	2.06	0.39	8891.02	1498.40	45.86	2.97	9.66	1.87
174	12	3.97	0.28	2.06	0.42	8341.40	1582.76	47.67.	3.28	8.82	1.82
240	13	3.8	0.23	1.97	0.41	8087.61	1225.27	49.33	2.93	7.83	1.62
165	14	3.75	0.23	2.07	0.41	8045.8	1308.5	52.27	3.1	7.63	1.49
66	15	3.68	0.21	2.03	0.42	7845.83	1284.17	54.62	3.17	7.06	1.47
16	16	3.59	0.25	2.07	0.42	7664.69	1114.06	56.81	4.45	6.72	1.35
2	17	3.7	0	1.61	0.64	6220	725	63	1	4.9	2.01

In S-506 TBM in Figure 7.2, it is clearly seen as well the penetration increases when the thrust force decreases. Between the penetrations from 12 to 16 mm/rev the thrust forces are very similar. When the penetration was increased from 12 to 16 mm/rev the cutterhead revolution was slightly decreased; however still the average advance speed raised from 48 mm/min to 57 mm/min approximately. As the torque values are very similar and the biggest difference is in the penetration rate, the lowest energy consumption which is the lowest specific energy was seen when the penetration was 16mm/rev between these values.

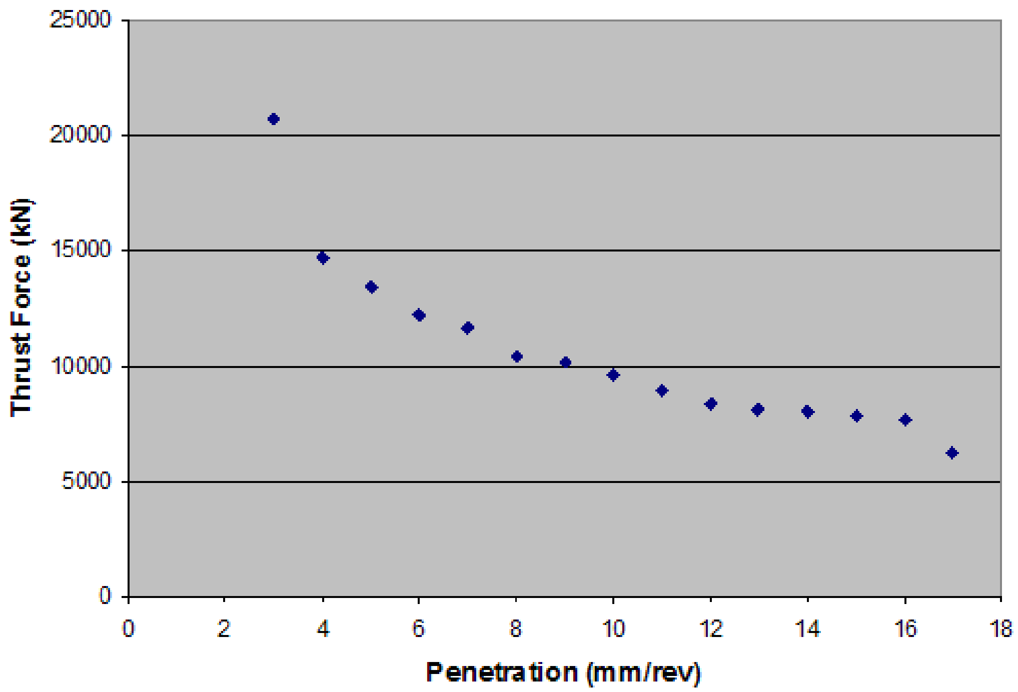

Figure 7.2 : Relationship with thrust force and penetration for S-506.

7.2 The Relationship Between Penetration and Torque

It is seen from Figure 7.3 below that when penetration increases the torque as well is increasing. As the discs penetrate deeper, the necessity of the torque increases for rotating the cutterhead as the discs will be in contact with bigger surface area and will need higher power to manage which results as an increase in the torque value. In the graphic the optimum area for torque values is seen when the penetration is over 10mm/rev until 16mm/rev where there is a jump in the torque value suddenly.

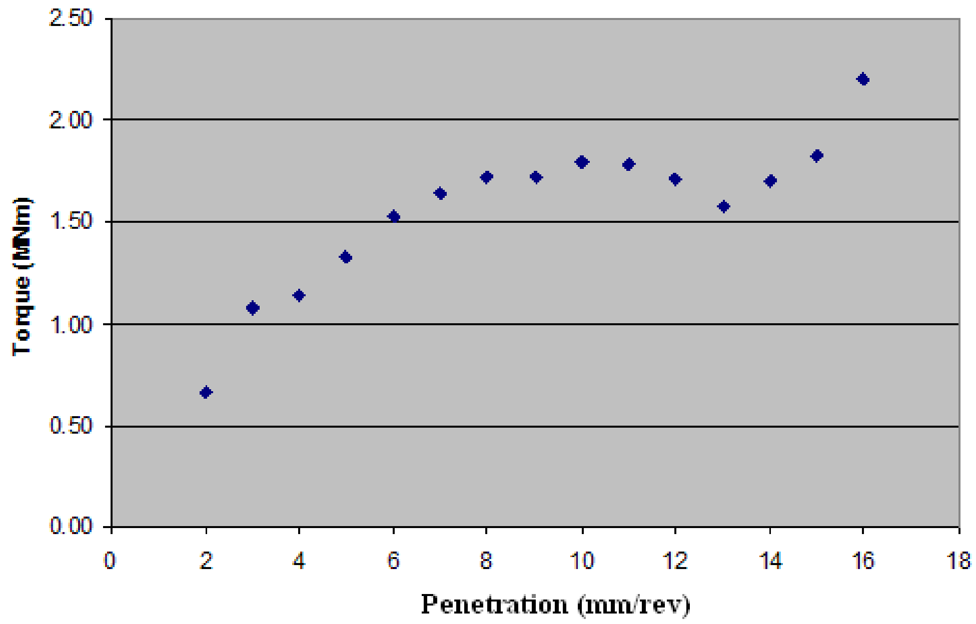

Figure 7.3 : Relationship with torque and penetration for S-505.

A more homogeneous distribution is seen in the Figure 7.4 in S-506, where the optimum value for the machine seems to start when the penetration is over 8mm/rev As the torque is nearly the same until the penetration rate of 17mm/rev it can be assumed that the best advancing conditions are achieved when the cutter tools penetrates with 15 to 16mm/rev by only evaluating the results from this graphic.

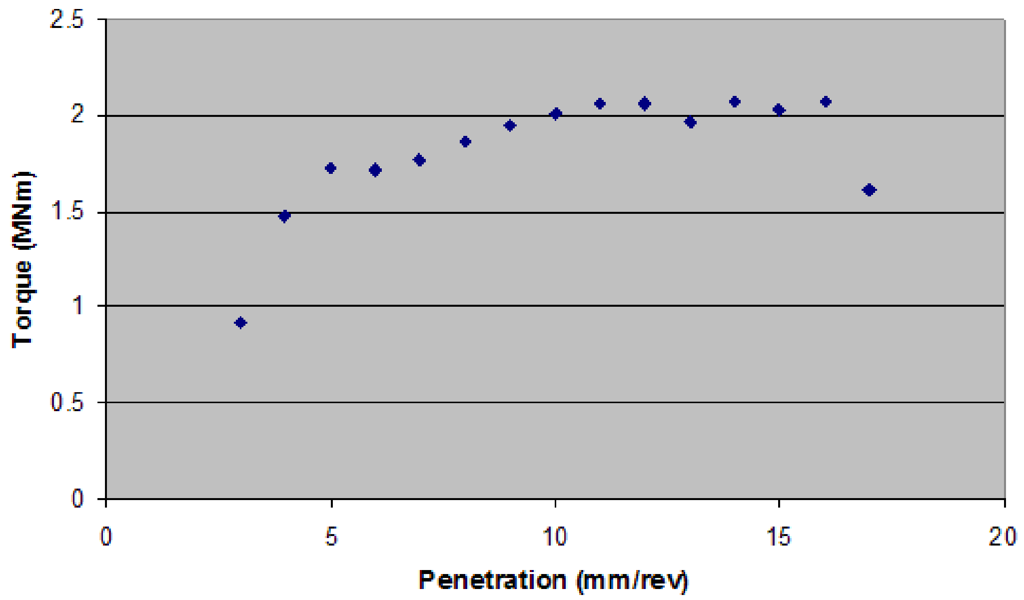

Figure 7.4 : Relationship with torque and penetration for S-506.

When the penetration rate reaches to 17 mm/rev the torque value is observed to decrease suddenly. First of all there is only two data with this penetration rate which might not be indicating results which can be evaluated. Secondly when the Table 7.2 is checked the average torque and the thrust forces are lower from other advances which also can be the reason that the geology is soft that can be seen from the low thrust forces, weathered and a possible of water flow in these two advances when the low torque values are taken into consideration.

7.3 The Relationship Between Penetration and Specific Energy

The optimum area for specific energy is when the penetration is over 12mm/rev which is seen in Figure 7.5. This value will surely change from project to project from formation to formation. When the Table 7.1 is analyzed it can be seen that only 87 rings have advanced with minimum 12 mm/rev, which indicates the optimum area from the graphic. Under these conditions the operator could have increased the machines penetration rate to advance more in the optimum area for specific energy when only the graphic below is evaluated.

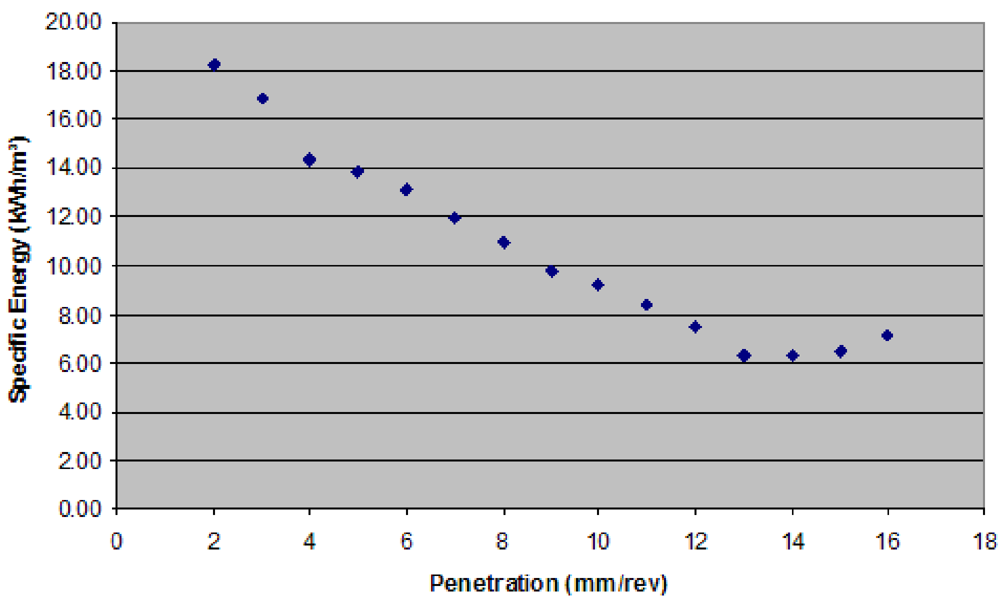

Figure 7.5: Relationship with specific energy and penetration for S-505.

From the Figure 7.6, it is clearly seen that when penetration increases the specific energy reduces significantly. Because that there are no big changes in torque value and cutterhead revolution, the only effect that decreases the specific energy is the penetration rate in this graphic. To increase the penetration rate has a real big benefit on decreasing the specific energy but while increasing the penetration rate attention should always be given on the existing thrust force and the force as well in the steering cylinders.

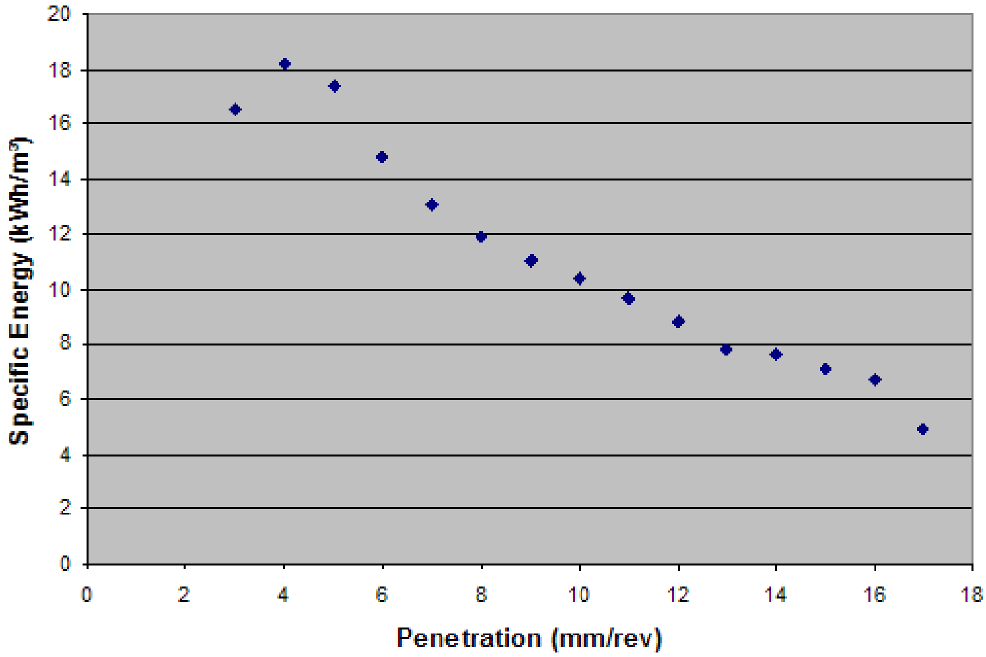

Figure 7.6 : Relationship with specific energy and penetration for S-506.

7.4 The Relationship Between Torque and Thrust Force

In Figure 7.7 the relationship between torque and thrust force is seen. The torque value is relatively low compared with the other values when the thrust force is over 20.000kN. The torque in general has a tendency to increase when the thrust force is decreasing. However, when the thrust forces are around 10.000kN, a variation of more than 0.5MNm in the torque difference can be seen which actually can be evaluated as the torque and thrust force can be assumed as relatively more independent from each other compared with the other machine parameters. In addition the torque values between approximately 7.000kN to 9.000kN the torque values are nearly the same. Moreover a peak value in the torque is seen where the value is 2.20MNm but a good evaluation can't be done as there is only one data in this torque value.

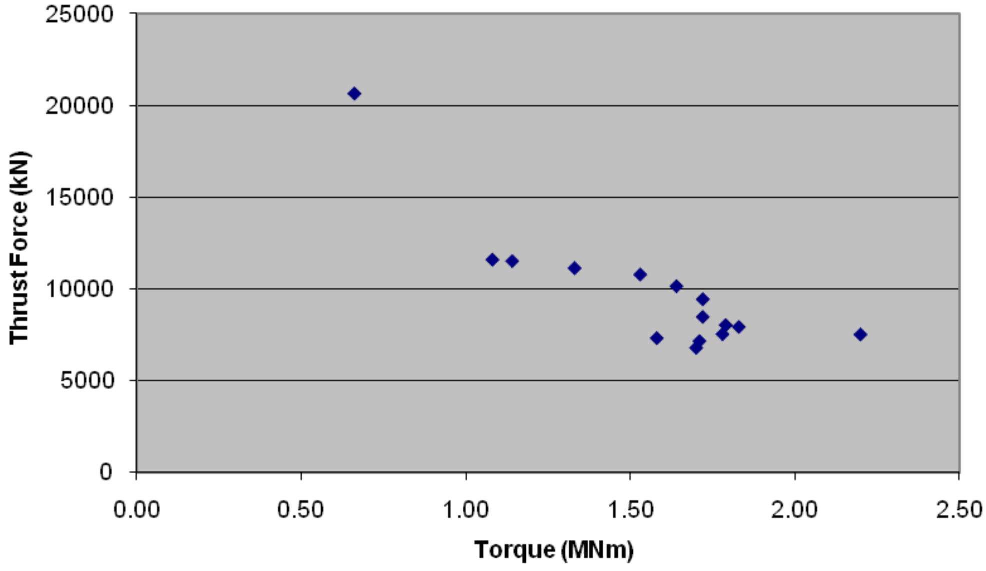

Figure 7.7 : Relationship between torque and thrust force for S-505.

In Figure 7.8 the relationship between the thrust force and the torque is seen. In this graphic as well we have an extreme case of thrust force where it is over 20.000kN which the lowest torque value is seen. As mentioned in Figure 7.7 as well the torque value has a tendency to increase when the thrust force is decreasing. The torque values are around 2MNm as the thrust force values are below 10.000kN. The formation excavated was always rock eventhough in some areas the thrust force value was quite low. As the excavation was always in rock either relatively strong or weak with fractures the torque value was never so high. However if the formation got softer and changed to a geology consisting of clay, silt or similar formations then the torque values would have a significant increase.

Because of the reason mentioned above the variation of the torque values are more dependent to the geological conditions, rather than directly observing the thrust forces, which are consisting of fine material distribution, stickiness property of the geology and etc. Although the decrease of the thrust force indicates that the formation is getting softer it is important to distinguish if the rock strength is getting lower or if the geological formation is totally changing before evaluating the reason of the torque change.

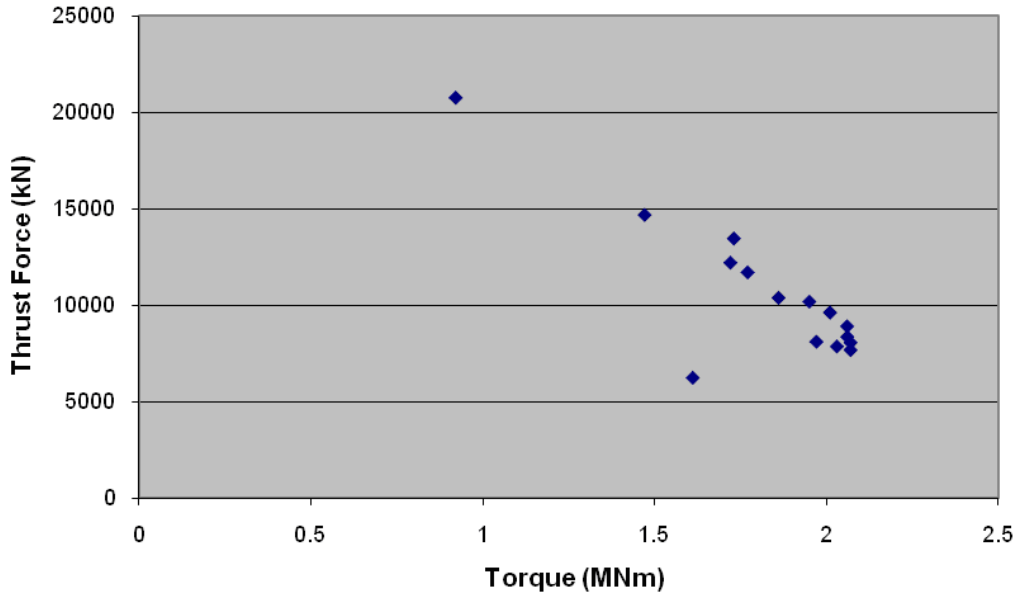

Figure 7.8 : Relationship between torque and thrust force for S-506.

8. CONCLUSIONS AND RECOMMENDATIONS

In conclusion the machine performance parameters are very dependent on the actual excavated geological formations. In today's technology, it is possible nearly to excavate in all formations; however a big variation in advancing conditions can be seen depending on the geology.

Basically penetration rate varies with the thrust force. When the thrust force values are over 15.000 kN, the penetration value is lower than 10 mm/rev. Eventhough it is possible to achieve the penetration rate in the mentioned thrust forces, it is mostly not efficient according to the experiences from the projects. Indeed; in the project from Avrasya Metro Group, it is seen that the penetration rates over 10 mm/rev was always seen where the thrust forces were lower than 10.000 kN. Such as when the forces are in an acceptable range which can be assumed to be lower than 10.000 kN, it is the operators preference to adjust the penetration rates between 10 – 15 mm/rev which is seen as well in "thrust force – penetration" graphics. It must be kept in mind that the mentioned values are valid only when the TBM is operating in open mode. In closed mode, the expected ground pressure and the ratio of the excavated material inside the excavation chamber must be taken into consideration.

Torque values are not very dependent on the machine parameters. In some cases torque parameters can show variation when the thrust forces changes; however in some cases the recorded values can be very similar. For example in table 7.1 the thrust forces reduce from 11600kN to values around 9500kN which the difference is around %20 while the change in torque is from 1.08MNm to 1.72MNm is nearly %60. Moreover in table 7.2 it is seen that the thrust force value decreases from 13500kN to 7600kN but the torque variation is from 1.73MNm to 2.07MNm. From these two examples it can be seen that surely there is a relation between thrust force and torque however very slightly, which these differences can be influenced from other changes in the machine parameters as well. Change in the torque value is very dependent on geological conditions. Eventhough the TBM can advance with very similar machine parameters a big variation can be seen in the torque values due to the change in the geological properties. The increase in the value depends on the stickiness, fine material content and the clogging property in the excavated medium. However this raise in the torque parameters can be decreased significantly by the proper use of the foam and always adjusting the foam parameters according to the existing geology.

When specific energy values are observed, it is seen that when torque and cutterhead revolution is constant; the specific energy shows variation as the advance speed of the machine changes. A decrease in energy consumption is seen when the advance speed increases while torque and rpm remains the same which means this decrease in specific energy will be seen as the penetration rate increases. However when torque and cutterhead revolution increases the specific energy will also increase. The thrust force does not have an effect on specific energy directly; however an effect is seen indirectly as the variation of thrust force will change the other machine parameters.

When all the graphics above are considered together, then the formation excavated can be defined as mostly rock conditions because the cutterhead revolution is observed to be high without a problem; meanwhile soft rock conditions due to the relatively high penetration rates with acceptable thrust forces. In addition the torque values observed also indicates that the excavated profile does not involve soft and sticky formation.

There is a significant relation of RQD values with the machine parameters as long as the compressive strength of the rock is remaining unchanged. When the compressive strength remains the same, a tendency of thrust force increase can be seen. However the effect of RQD variation to the machine is much lower than the variation of the compressive strength of the rock or a change in the property of the soil.

From all these results, it can be easily said that all the machine parameters have a relation with each other either high or low. These variations of the machine parameters are mostly because of the changes in the geological conditions if the extreme cases are ignored. This indicates us the importance of the geology over the mechanized tunneling. In addition, the geological formation is the most specific item that has an effect to the complete project starting from the design phase of the tunnel boring machine. During excavation, the geological parameters and variations have a significant effect on advance rates of the machine. When the tunnel boring machine is wrongly selected, the project can have a big delay which the contractor can pay penalties because of contractual reasons.

The geological effect, over the TBM continues till the project is finished as it is possible normally to advance in easy conditions; while there can be lots of difficulties that can decrease the target advance rates. In addition the consumption of the consumables is also effected significantly from the actual conditions.

As TBM investment is quite high, it is really important to make investigations as much as necessary to evaluate the existing geological conditions in detail and in a reliable manner. In addition when a good evaluation is done, it is possible to avoid the difficulties in tunneling as well as reducing the additional costs.

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APPENDICES

APPENDIX A.1 : Geologic Profile of Avrasya Metro Group Project

APPENDIX A.1

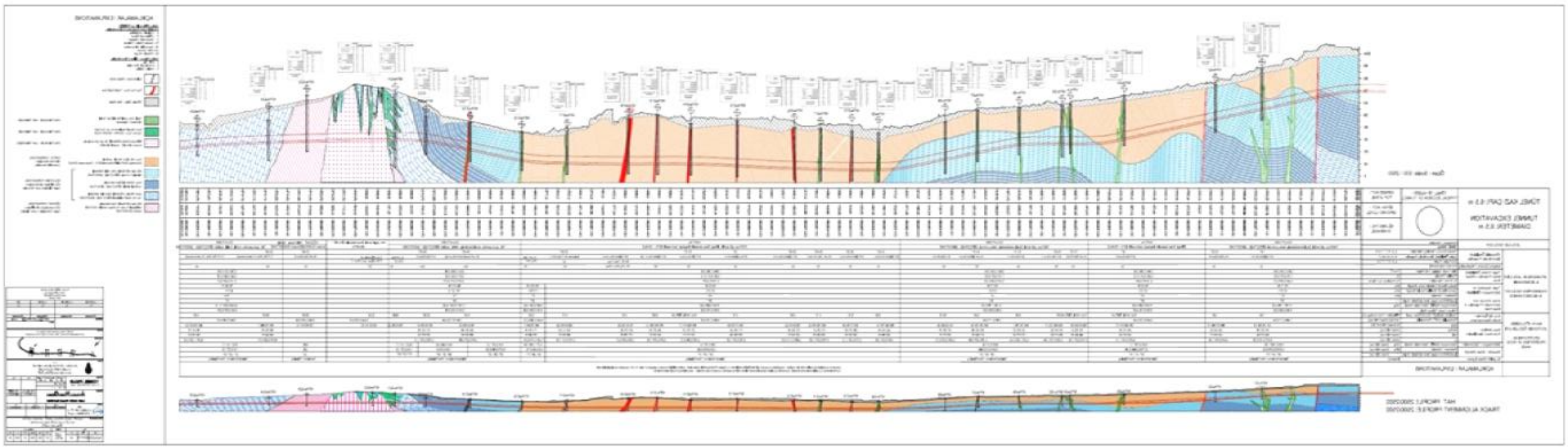

Figure A.1: Geologic profile of Avrasya metro group project.

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