ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A COMPARATIVE STUDY ON THE RELATIONSHIPS BETWEEN DESIGN PARAMETERS OF TBMS WITH TWO CURRENT EXAMPLES OF LARGE SECTION TBMS

M.Sc. THESIS

Uğur ATEŞ

Department of Mining Engineering

Mining Engineering Programme

JANUARY 2013

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A COMPARATIVE STUDY ON THE RELATIONSHIPS BETWEEN DESIGN PARAMETERS OF TBMS WITH TWO CURRENT EXAMPLES OF LARGE SECTION TBMS

M.Sc. THESIS

Uğur ATEŞ
(505111009)

Department of Mining Engineering

Mining Engineering Programme

Thesis Advisor: Prof. Dr. Nuh BİLGİN

JANUARY 2013

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

TBM TASARIM PARAMETRELERİ ARASINDAKİ İLİŞKİLERİN ARAŞTIRILMASI VE BUNA BAĞLI OLARAK İKİ BÜYÜK ÇAPLI TBM PROJESİNİN İNCELENMESİ

YÜKSEK LİSANS TEZİ

Uğur ATEŞ
(505111009)

Maden Mühendisliği Anabilim Dalı

Maden Mühendisliği Programı

Tez Danışmanı: Prof. Dr. Nuh BİLGİN

OCAK 2013

Uğur Ateş, a **M.Sc.** student of ITU **Graduate School of Science Engineering and Technolgy** student ID **505111009**, successfully defended the **thesis** entitled "**A COMPARATIVE STUDY ON THE RELATIONSHIPS BETWEEN DESIGN PARAMETERS OF TBMS WITH TWO CURRENT EXAMPLES OF LARGE SECTION TBMS**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Prof. Dr. Nuh BİLGİN** ....
Istanbul Technical University

Jury Members : **Prof. Dr. Hanifi ÇOPUR** ....
Istanbul Technical University

Assoc. Prof. Dr. İbrahim OCAK ....
Istanbul University

Date of Submission : 10 December 2012
Date of Defense : 22 January 2013

FOREWORD

I would like to express my most sincere gratitude to my supervisor, Prof. Dr. Nuh BİLGİN, for his support and generous guidance throughout my study.

I am also grateful to my lecturer Prof. Dr. Hanifi ÇOPUR for his valuable comments on this thesis.

I would like to thank Cengiz-İçtaş-Belen Joint Venture for providing TBM data and permitting job-site visits for the thesis. Moreover, I also want to thank Statkraft and Gülermak companies for providing TBM data.

Last but not least, I want to thank my family and S. Berra GÜRGÜÇ for their continuous support and encouragement throughout my study.

January 2013

Uğur ATEŞ
(Geophysics Engineer)

TABLE OF CONTENTS

Page

ABBREVIATIONS

CCS **:** Constant Cross Section
EPB **:** Earth Pressure Balance
RQD **:** Rock Quality Designation
TBM **:** Tunnel Boring Machine
UCS **:** Uniaxial Compressive Strength

LIST OF TABLES

Page

LIST OF FIGURES

Page

A COMPARATIVE STUDY ON THE RELATIONSHIPS BETWEEN DESIGN PARAMETERS OF TBMS WITH TWO CURRENT EXAMPLES OF LARGE SECTION TBMS

SUMMARY

After invention of modern tunnel boring machines in 1950s, the technology improved significantly. Parallel to technology TBMs are also improved and new TBM types were invented.

Especially in the recent years, because of the rapidly increasing world population, the demand for underground structures was increased. Since the area above the ground, especially in cities, is limited, building underground structures is the only way to cope with demand.

With lots of advantages over the conventional methods tunnel boring machines are one of the most used machinery for underground constructions. Nowadays tunnels up to 16 meters can be excavated with TBMs and the size of TBMs have been increasing day by day. However, TBMs are expensive machines and their performance is related with lots of parameters. Thus, they should be selected with a great care.

In this thesis, TBM design parameters suggested by different sources were reviewed, new TBM design parameter calculation models were created and their accuracy was analyzed. The results of the theoretical TBM design parameter calculations were compared with TBM project data.

For comparison, a TBM database was created which includes a total number of 329 TBMs. The TBMs were separated into three groups, namely large diameter TBMs, which includes TBMs larger than or equal to 9.5 meters, small diameter TBMs, which includes machines smaller than 9.5 meters and TBMs manufactured before 1985. By using this database, the relationships between the design parameters for different types of TBMs were analyzed and design differences between the TBM types were covered.

At the latest section of the thesis, two large diameter TBM projects, namely, Ankara-İstanbul High Speed Railway Project Tunnel No. 26 and Kargı Dam and Hydropower Project, were examined. The reasons and results of the problems faced during the excavation were analyzed.

The findings of the study showed that the theoretical models give the accurate results for the TBM design and they are consistent with manufactured TBMs properties. Moreover, geology and diameter are the most effective parameters for calculations. Because of the geology, same sized two TBMs could have very different parameters. Especially squeezing, swelling and fractured ground conditions needs special designed TBMs, which have high thrust and torque forces.

The case studies also showed that an insufficient geological exploration could cause big delays on the projects. In some cases, TBM can be modified in the underground but it is extremely hard to change all properties of the TBM. Furthermore, these modifications could cost a lot of money and time. Moreover, TBM performance prediction method that used for performance prediction should be consistent for the project. Using wrong performance prediction method could cause overestimated or underestimated performance predictions.

TBM TASARIM PARAMETRELERİ ARASINDAKİ İLİŞKİLERİN ARAŞTIRILMASI VE BUNA BAĞLI OLARAK İKİ BÜYÜK ÇAPLI TBM PROJESİNİN İNCELENMESİ

ÖZET

Gelişen teknolojiye paralel olarak modern tünel açma makinaları da 1950'li yıllardaki bulunuşlarının ardından büyük gelişmeler göstermiş ve zaman içinde yeni TBM modelleri geliştirilmiştir.

Son yıllarda, dünya nüfusundaki hızlı artışa paralel olarak ihtiyaç duyulan yer altı yapılarının sayısında ve boyutlarında da artış gözlemlenmektedir. Yer üzerindeki alan kısıtlı olduğundan demiryolu, otoyol gibi bazı yapıların yer altına alınması kaçınılmaz olmaktadır.

Klasik tünel açma yöntemlerine göre birçok avantaj sağlayan TBM'ler günümüzde en çok kullanılan tünel açma ekipmanları arasındadır. Gelişen teknoloji ile birlikte, TBM kullanarak 16 metre çapa kadar tünel açmak mümkün olmakta ve TBM'lerin boyutu her geçen gün büyümektedir. Oldukça karmaşık ve pahalı olan TBM'lerin performansı tünel çapı ve jeoloji gibi farklı ve çok sayıda parametreye bağlı olarak değişmektedir. Bu nedenle TBM seçimi özenle yapılmalı ve proje için uygun özelliklere sahip bir makine seçilmelidir.

Bu çalışmada farklı kaynaklar tarafından önerilen TBM tasarım parametre hesaplamaları incelenmiş, yeni hesaplama modelleri geliştirilmiştir. Çeşitli araştırmacılar tarafından önerilen değişik hesaplama yöntemlerinin temelde birbirine benzer olduğu ve genellikle aynı parametreleri kullandığı görülmüştür. Ayrıca hesaplamalar sonucunda elde edilen tasarım parametrelerinin doğruluğu daha önce üretilen TBM'lerin verileri ile karşılaştırılmıştır.

Karşılaştırma için 329 adet TBM içeren bir veri tabanı oluşturulmuştur. Veri tabanında bulunan TBM'lerin 70 tanesi 1985 öncesi üretilmiş, geri kalan 259 tanesi ise bu yıldan sonra üretilmiştir. 1985 sonrası üretilen TBM'ler, 24 tek kalkanlı, 38 çift kalkanlı, 72 pabuçlu, 86 pasa basınçlı ve 39 çamur basınçlı modeli içermektedir.

Oluşturulan veri tabanında TBM'ler, 9,5 metreye eşit ve daha büyük olan büyük çaplı TBM'ler, 9,5 metreden küçük olan küçük çaplı TBM'ler ve 1985 öncesinde üretilen eski TBM'ler olarak gruplandırılmıştır. Veri tabanı kullanılarak farklı boyuttaki ve türdeki TBM'lerin çap, itme kuvveti, döndürme kuvveti, ağırlık ve disk sayısı gibi parametreleri ve bu parametrelerin birbirleri ile olan ilişkileri de incelenmiştir. 1985 öncesinde üretilen TBM'ler günümüzdeki TBM'lerden daha farklı özelliklere sahip olduğundan bu TBM'ler ayrıca incelenmiştir.

Veri tabanı kullanılarak ayrıca büyük ve küçük çaplı TBM karşılaştırması yapılmıştır. Büyük çaplı TBM'lerin daha çok otoyol (2 veya 3 şeritli otoyol tünelleri) ve demiryolu (çift hatta sahip demiryolu tünelleri) projelerinde kullanıldığı görülmüştür. Küçük çaplı TBM'lerin ise yoğun olarak metro, su transferi ve kanalizasyon projelerinde kullanıldığı belirlenmiştir. Küçük çaplı TBM'ler ayrıca tek

hatta sahip demiryolu veya 1-2 şeritli otoyolların inşasında kullanılmaktadır. Su transferi için açılan tünellerin genellikle çok büyük çapa sahip olması gerekmediğinden küçük çaplı TBM'ler bu tarz tüneller için tercih edilmektedir. Bu tip TBM'ler bazı projelerde ise büyük çaplı bir TBM kullanılmadan önce pilot tünel açılmasında kullanılabilmektedirler.

Yapılan analizlerde farklı TBM modellerinin farklı özelliklere sahip olduğu, hesaplamalarda TBM tipine uygun parametrelerin kullanılması gerektiği gözlenmiştir. EPB TBM'ler diğer TBM tipleri ile karşılaştırıldığında en yüksek torka sahip TBM'lerdir. Bu TBM'leri çamur basınçlı TBM'ler izlemektedir. Bunun nedeni EPB TBM'lerin ayna basıncını dengelemek için kazılan malzemeyi basınç odasında döndürmesidir. Pasanın birim hacim ağırlığı yüksek olduğundan EPB TBM'ler, çamur basınçlı TBM'lere göre daha yüksek tork değerlerine ihtiyaç duymaktadır. Ayrıca zemin TBM'lerin torku ile çapı arasında oldukça yüksek bir korelasyon vardır.

Zemin TBM'lerinin aksine, kaya TBM'lerinde tork çaptan çok formasyonun özelliklerine bağlı olarak değişmektedir. TBM grupları içinde en düşük torka sahip olan TBM'ler pabuçlu TBM'lerdir. Tek ve çift kalkanlı TBM'lerde ise tork formasyonun kırık çatlak miktarına ve sıkışma özelliğine sahip olup olmamasına bağlıdır. Kırık çatlak miktarı yüksek olup kendini tutamayan ve sıkışan formasyonlarda kopan parçalar kesici kafanın çevresinden ve önünden baskı uygulayıp, açıklıklardan içeri girdiğinden bu tip formasyonların olduğu yerlerde yüksek torka sahip olan TBM'lerin kullanılması gerekmektedir.

Analizlerde zemin TBM'lerinin en yüksek itme kuvveti değerlerine sahip olduğu görülmüştür. Bunun nedeni ayna basıncı arttıkça, TBM'lerin bu basıncı yenmek için daha fazla itme kuvveti uygulaması gerekmesidir. Pabuçlu TBM'ler, en düşük itme kuvveti değerlerine sahiptirler. Torka benzer olarak itme kuvveti de kaya dayanımı arttıkça, kesikleri bastırmak için gereken kuvvet artacağından, artmaktadır.

Tek kalkanlı TBM'lerin itme kuvveti pabuçlu TBM'lere göre yüksek, zemin TBM'lerine göre düşüktür. Bu tip TBM'lerin kazı yaptığı ortamlarda ayna basıncı olmaması, ihtiyaç duyulan itme kuvvetinin zemin TBM'lerine göre daha düşük olmasına neden olmaktadır. Çift kalkanlı TBM'lerin ana itme kuvveti pabuçlu ve tek kalkanlı TBM'lerin arasında kalmaktadır. Bu durumu, çift kalkanlı TBM'lerin uzun ve ağır bir kalkana sahip olmasıyla açıklamak mümkündür. Kalkanın ağır olması ve uzun olması kalkan ile kaya arasındaki sürtünme kuvvetini arttırmakta ve TBM ilerlemek için yüksek itme kuvvetine ihtiyaç duymaktadır. Bu tip TBM'lerin ikincil itme kuvveti değerleri ise genellikle diğer pabuçlu ve tek kalkanlı TBM'lerden yüksek, zemin TBM'lerine ise oldukça yakın olmaktadır. Ana itme kuvvetine benzer olarak bu durumu kalkanın daha uzun ve daha ağır olması ile açıklamak mümkündür.

Yeni TBM'ler ile eski TBM'ler arasında özellikle kesici disk teknolojisindeki ilerlemelere ve disk tipindeki değişime bağlı olarak çeşitli farklılıklar olduğu, aynı çaptaki bir TBM'in günümüzde, eskiye oranla daha fazla itme ve döndürme kuvvetine sahip olduğu belirlenmiştir.

Yapılan karşılaştırmalarda ampirik TBM tasarım parametresi hesaplamalarının doğru sonuçlar verdiği ve sonuçların üretilen TBM'lerin özellikleri ile uyumlu olduğu gözlenmiştir. Bununla beraber TBM çapının ve jeolojinin, hesaplamalardaki en önemli parametreler olduğu görülmüştür. Doğru TBM seçimi ve segman tasarımı yapılabilmesi için bölgedeki jeolojik koşulların çok iyi belirlenmesi gerektiği, aksi takdirde TBM özelliklerinin yanlış hesaplanabileceği ve proje için yanlış TBM'in seçilebileceği görülmüştür. İki TBM aynı çapta olsa bile farklı jeolojik koşullar nedeniyle birbirlerinden çok farklı özelliklere sahip olabileceği gözlemlenmiştir. Özellikle sıkıştırma, şişme özelliğine sahip olan formasyonlar ile çok fazla kırık çatlak içeren formasyonlarda yüksek itme ve tork kuvvetine sahip olan TBM'lerin kullanılması gerekmektedir. Ayrıca pabuçlu, tek kalkanlı ve çift kalkanlı TBM'lerin tasarım parametrelerinin belirlenmesi için önerilen ampirik hesaplamaların da doğru sonuçlar verdiği gözlenmiştir.

Tezin son bölümünde ise ülkemizde büyük çaplı TBM kullanılan iki proje, Ankara-İstanbul Hızlı Tren Projesi 26 Numaralı Tünel ve Kargı Barajı - Hidroelektrik Santrali Projesi, incelenmiştir. Bu projelerde kullanılan TBM'lerin performans analizi yapılmış, kazı sırasında karşılaşılan problemlerin nedenleri ve çözümleri üzerinde durulmuştur. Kazıların daha sorunsuz devam edebilmesi için yapılabilecek olan değişiklikler tartışılmıştır. Ayrıca hızlı tren projesinde kullanılan TBM'de kazıya başladıktan sonra farklı zamanlarda yapılan değişiklikler ve bu değişikliklerin sonuçları irdelenmiştir.

Ankara-İstanbul Hızlı Tren Projesi 26 Numaralı Tünel'de kullanılan TBM'de kazı başlangıcından itibaren farklı tarihlerde birçok değişiklik yapılmış ve TBM tek kalkanlı TBM'den EPB TBM'e dönüştürülmüştür. Ayrıca TBM'in tork ve itme kuvveti arttırılmıştır. Torkun arttırılması için motorların dönüş hızı düşürülmüş, itme kuvvetinin arttırılması için ise TBM'e ek piston montajı yapılmıştır. Ayrıca yüksek itme kuvvetinin segmanlara zarar vermemesi için belli bir itme kuvvetinin üzerindeki değerlerin kullanılacağı bölgelerde itme silindirleri ile segmanlar arasında çelik segman koyularak kazı yapılmasına karar verilmiştir.

İncelenen iki proje de jeolojinin TBM seçiminde ne kadar önemli olduğunu ve yanlış yapılacak TBM seçiminin projede büyük aksamalara sebep olabileceğini göstermiştir. Ayrıca bazı durumlarda kazıya başladıktan sonra TBM'in özellikleri değişebilse de tüm istenilen özelliklerin değişmesinin her zaman mümkün olmayacağı ve yapılan bu değişikliklerin oldukça zaman alıcı ve maliyetli olduğu görülmüştür. Projeye başlanmadan önce yapılacak performans tahminlerinde kullanılacak performans tahmin yönteminin proje şartları için uygun olması gerektiği ve uygun olmayan yöntem kullanımının gerçeği yansıtmayan sonuçlar verebileceği görülmüştür.

Kazı sırasında TBM'in itme kuvveti, döndürme kuvveti gibi özellikleri ile kazılan malzemenin miktarının sürekli olarak takibinin yapılmasının jeoloji ve kazı ile ilgili çok önemli bilgiler sağlayabileceği gözlenmiştir. Özellikle sıkışan zeminlerde kazıya uzun süre ara verilmesinin sıkışma riskini arttırdığı bu nedenle duraklamaların olabildiğince kısa tutulmasının gerekli olduğu belirlenmiştir. Ayrıca hem hesaplamalarda hem de TBM'de yapılan gözlemler sonucunda TBM'in kalkanın etrafına kayganlaştırıcı malzeme enjeksiyonu yapılmasının ihtiyaç duyulan itme kuvvetinde düşüşe neden olduğu belirlenmiştir. Kırık çatlak miktarı çok fazla olan jeolojilerde, bir tane büyük çaplı TBM kullanmak yerine iki adet küçük çaplı TBM kullanmanın da jeoloji ile ilgili yaşanabilecek sorunların azaltacağı belirlenmiştir.

1. INTRODUCTION

World’s population and urbanization are increasing tremendously which requires bigger infrastructures. Because of limited space above the ground, only way to build these infrastructures is building them underground. Drill and blast method have been used for constructing these underground structures widely, however, because of the urbanization, it is very hard to use this method in the cities

Tunnel boring machines (TBMs) provide a safe working area for crew with high advance rates. Moreover, they cause minimal ground disturbance, which is very convenient for the buildings above the ground and creates uniform muck, which helps to the transportation of excavated material. Thus, use of tunnel boring machines for underground construction has been increasing steadily.

After first modern TBMs in 1950s, TBM technology improved steadily. Today it is possible to manufacture and use TBMs up to 16 meters.

Capital cost of these machines, for not only large diameter also for medium and small diameter machines, is very high and machines must be selected carefully. Otherwise, contractor could face very low advance rates and damage on the ground structures, which could cost a lot of money and time

To select a proper TBM for a specific project, geological conditions and structures build above the tunnel line should be inspected carefully. Then, TBM’s type and machine specifications, like thrust, torque, cutterhead power, number of cutters, cutter spacing etc. could be determined according to the these properties.

Kahraman (2007) was also analyzed some of TBMs design parameters statistically for the TBMs manufactured from 1953 to 1994 and found some relationships between the parameters. He classified TBMs in four groups, namely manufactured before 1970, 1970-1979, 1980-1989 and after 1989. However he did not group TBMs according to their type or diameter, but it should be mentioned that TBMs built before 1980’s were generally gripper type machines. Different from his analyses, in this thesis TBMs were grouped according to manufacturing date, type and diameter.

1.1 Objective of the Thesis

This thesis' aim is to review the relationships between TBM design parameters and compare them with large section TBM project data.

To make a statistical analysis of the TBMs properties, a database is created which includes TBMs manufacturing date, diameter, cutterhead power, thrust, torque, TBM weight, cutter number and size, manufacturer, project name, project type, tunnel length, geology on the tunnel alignment and advance speeds. The TBMs without diameter, thrust, torque and manufacturer values are also included into the database but not used for analysis.

TBMs then were grouped in three namely large diameter TBMs, which includes TBMs larger than or equal to 9.5 meters, small diameter TBMs, which includes machines smaller than 9.5 meters and TBMs manufactured before 1985.

The database created for the comparison includes total number of 329 TBMs. The relationships between the design parameters, especially between diameter, torque and thrust, were investigated in detail and some statistical evaluations were made. The accuracy of the theoretical and empirical calculations were investigated by using the TBM project data.

Moreover, design parameters and performance of two large diameter TBMs from Turkey, which were used in Ankara-İstanbul High Speed Railway Project Tunnel No. 26 and Kargı Dam and Hydropower Project, were analyzed. The TBMs design parameters and statistical evaluations were compared, the relationship between the problems, faced during projects, and TBM selection were investigated.

2. GENERAL INFORMATION ABOUT TUNNEL BORING MACHINES

2.1 TBM Types

Tunnel boring machines consist of cutterhead, thrust cylinders, articulation cylinders, grippers, cutterhead engines and erector. They also have back-up trailers, which carries hydraulic and electrical equipment, conveyors and ventilation fans.

TBM manufacturing is strongly related with geological conditions of the project. Manufacturers give different names to TBM models, however, it is possible to classify TBMs into two main groups, which are hard rock TBMs and soft ground TBMs.

Open, single shield and double shield TBMs are used to excavate rock formations while soft ground TBMs are used to excavate in soil or mixed face conditions (Figure 2.1).

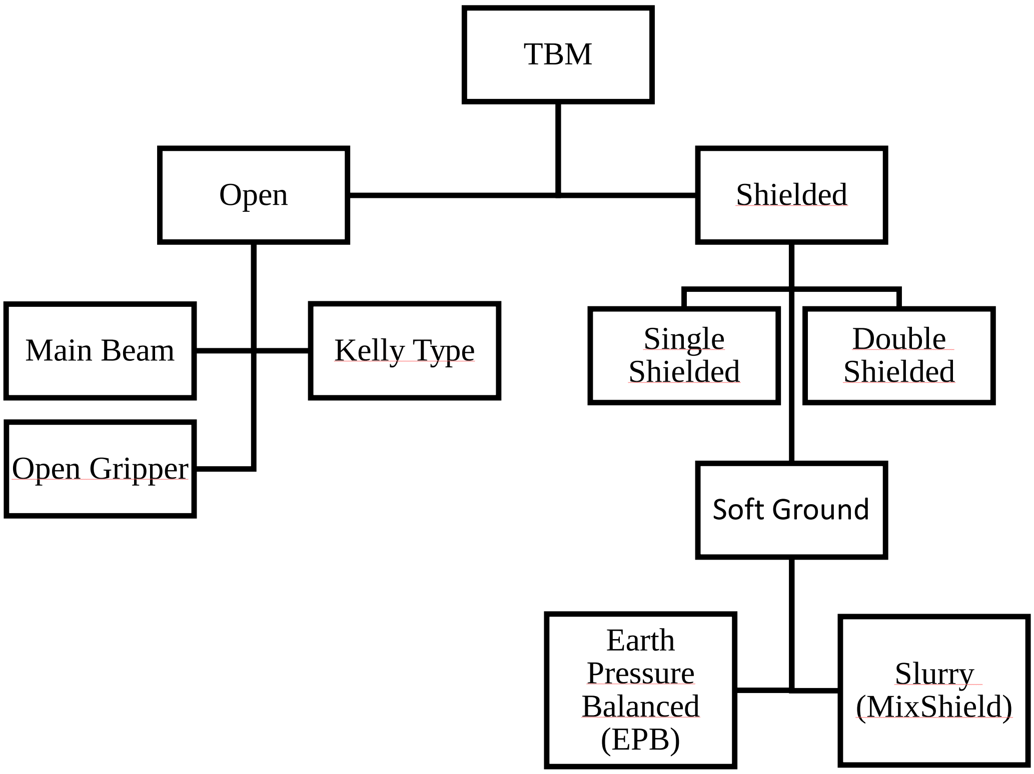


Figure 2.1 : TBM types (Einstein and Bobet, 1997).

There are some recommendations made for TBM selection for soft ground by German Committee for Underground Construction (DAUB) (2005) and Japanese Society of Civil Engineers (JSCE) (2007).

In this thesis, main beam type TBMs will be included into the gripper TBM group, while polyshield, hydroshield and mixshield TBMs will be included into the slurry TBM group.

2.1.1 Gripper TBMs

The gripper TBM (Figure 2.2) is also described as open TBM. The area of application is mostly in hard rock with medium to high stand-up time. It can be most economically used if the rock does not need constant support with rock anchors, steel arches or even shotcrete. In order to produce the thrust behind the cutter head, the machine is braced radially against the tunnel wall by hydraulically moved clamping shoes, the called grippers (Maidl et al., 2008).

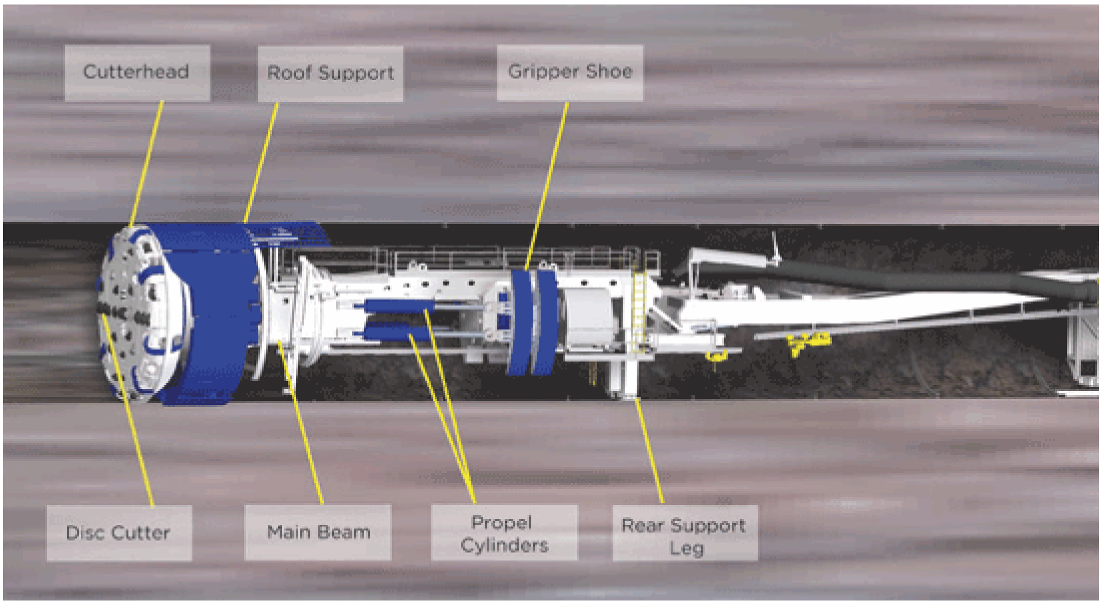


Figure 2.2 : Gripper TBM (Url-1).

2.1.2 Single shield TBMs

Single shield TBMs are primarily used in hard rock with short stand-up time and in fractured rock. The cutter head is not essentially different from that of a gripper TBM in relation to excavation tools and muck transport. To support the tunnel temporarily and to protect the machine and the crew, this type of TBM is equipped with a shield. (Figure 2.3) The shield extends from the cutter head over the entire machine. The tunnel lining is installed under the protection of the shield tail. Support with reinforced concrete segments has become the most commonly used system nowadays. In contrast to the gripper TBM, the machine is thrust forwards with thrust jacks directly against the existing tunnel support (Maidl et al., 2008).

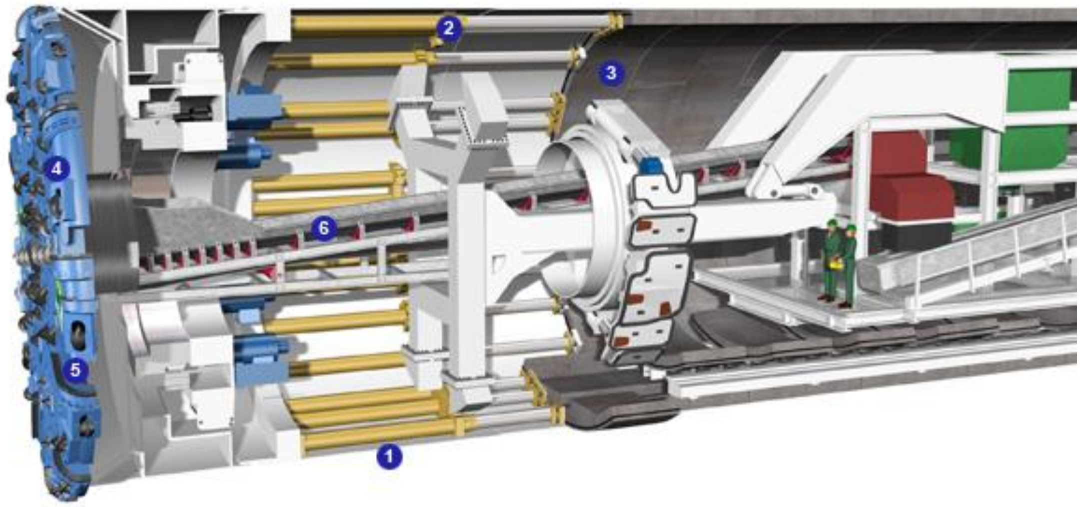


Figure 2.3 : Single shield TBM (Url-2).

2.1.3 Double shield TBMs

The double shield or telescopic shield TBM (Figure 2.4) is a combination of a single shield TBM and a gripper TBM.

The Double Shield TBM owes its name to its special design, whose main feature is an extendable front shield in the front part of the machine, which allows the cutterhead to be extended. The reaction forces (torque and axial and longitudinal forces) arising during drilling are conducted into the rock by the extended gripper shoes, which are located in the middle section of the tunnel boring machine. The lining segments can be installed during tunneling, ensuring high tunneling performance. On completion of a thrust stroke, the gripper shoes are retracted and the rear section of the machine is pushed against the front shield. This changeover phase only lasts a few minutes and then the next section of tunnel can be excavated (Url-1).

However, continuous excavation can be carried out only in undisturbed sections of rock because the gripper shoes need the surrounding rock as an anchorage. When the TBM reaches a section of rock containing fault zones, the telescopic front shield is retracted. The entire boring machine is then driven forward for drilling only by the auxiliary thrust cylinders, which are supported on the tunnel lining. This type of tunneling is referred to as "discontinuous" since in this process tunneling with the thrust cylinders is not possible until a segment ring has been installed (Url-1).

The double shield TBM has, however, essential disadvantages compared to the single shield TBM. When used in fractured rock in gripper mode, the rear shield can be blocked due to the material getting into the telescopic joint, which requires cleaning operation and causes time loses. (Maidl et al., 2008). Moreover, because of the long shield design, it has a high potential of jamming in squeezing ground.

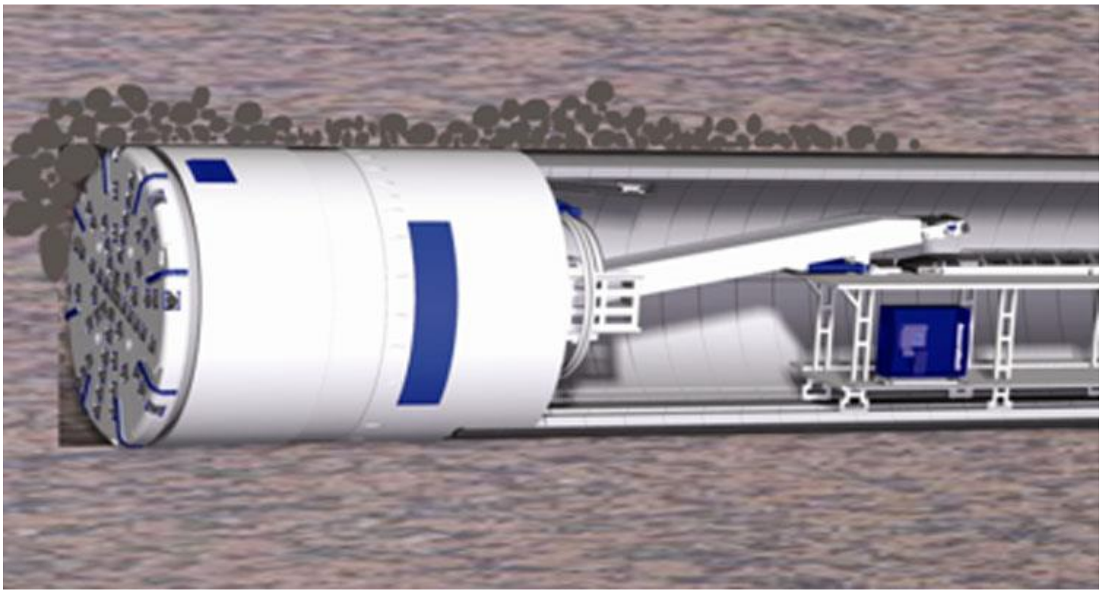


Figure 2.4 : Double shield TBM (Url-1).

2.1.4 Slurry (MixShield) TBMs

The Slurry TBM is a machine that is able to support the excavation face by pressurized, bentonite slurry pumped into the excavation chamber. The slurry is substantially composed of a bentonite suspension in water, with some additives if necessary. The excavation chamber, is a space between the excavation face and a steel bulkhead (separating the chamber from the remaining part of the TBM), where the excavated material is collected and mixed with the slurry. A pumping system performs the functions of feeding the fresh slurry to, and removing the muck from, the chamber through a pipeline. The balance between inflow and outflow involved in this cycle allows the slurry to be maintained under pressure in the chamber. By the variation of the inflow and/or outflow of the slurry, it is possible to control the face-support pressure value (Guglielmetti, 2008).

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 (Figure 2.5). 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 (Herrenknecht and Rehm, 2003).

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 (Herrenknecht and Rehm, 2003).

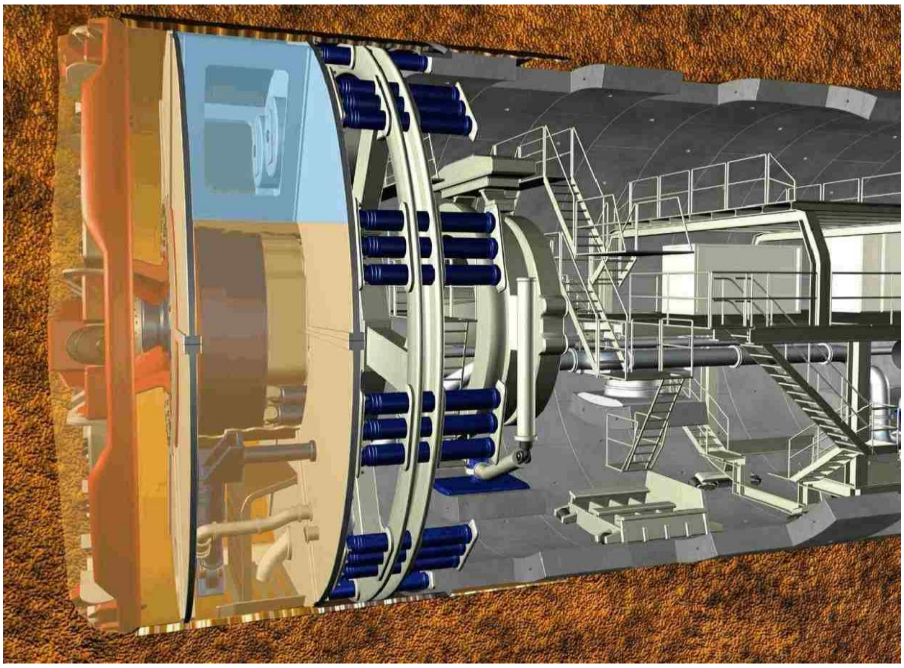


Figure 2.5 : Mixshield TBM (Url-2).

2.1.5 Earth pressure balanced (EPB) TBMs

EPB TBM is based on the principle of using the thrust and forward movements of the TBM to maintain a pressure on the face. The face support pressure is applied by utilizing the ground just excavated, collected, and pressurized in the chamber (Guglielmetti, 2008) (Figure 2.6).

The openings in the TBM cutterhead, which is equipped with cutting tools such as discs or picks, permit collection and accumulation of the excavated ground in the chamber (which is very similar to the slurry shield chamber). The muck extraction from the chamber is done through a rotating screw conveyor (Figure 2.7). The extracted quantity is proportional to the screw rotation speed, whereas the excavated quantity is proportional to the TBM's penetration rate. A dynamic equilibrium based on the balance of excavated and extracted volume (volume balance) is created inside the chamber. Adjustment of this balance, through variation of the screw rotation speed, makes it possible to create accumulation and consequent pressurization of material into the chamber (Guglielmetti, 2008).

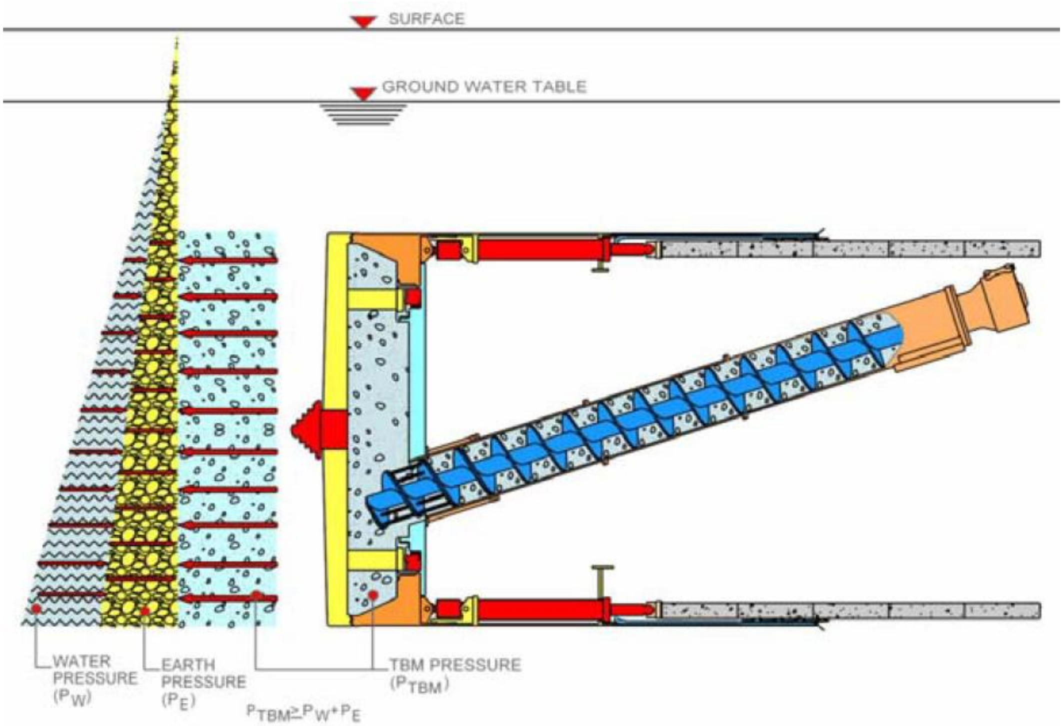


Figure 2.6 : Work principle of an EPB TBM (Slinchenko, 2010).

The face support pressure is controlled by varying the screw rotation speed, as a function of the TBM penetration rate. The longitudinal thrust cylinders acting on the already positioned lining segments inside the rear shield exert a pushing force on the shield and bulkhead, which then transfers to the ground a pressure that must be adequate for excavating and counteracting the friction forces on the shield and for supplying the needed face-support pressure (Guglielmetti, 2008).

Figure 2.8 shows usage areas of EPB and slurry TBMs in relation with the grain size. In silt and clay formations EPB TBMs are used, while in sand and gravel formations slurry TBMs are used.

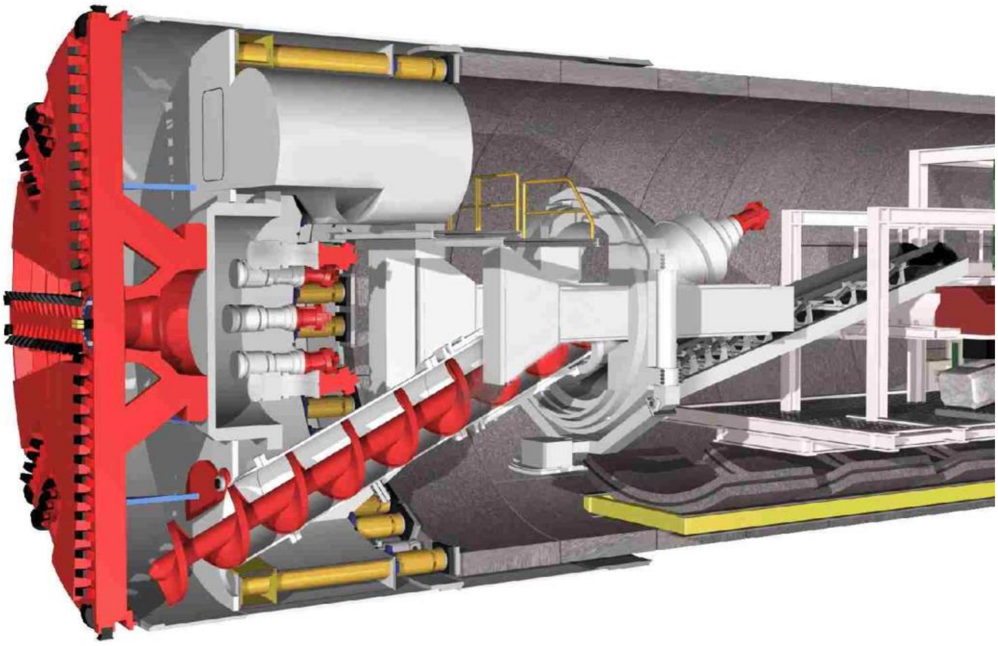


Figure 2.7 : EPB TBM (Url-2).

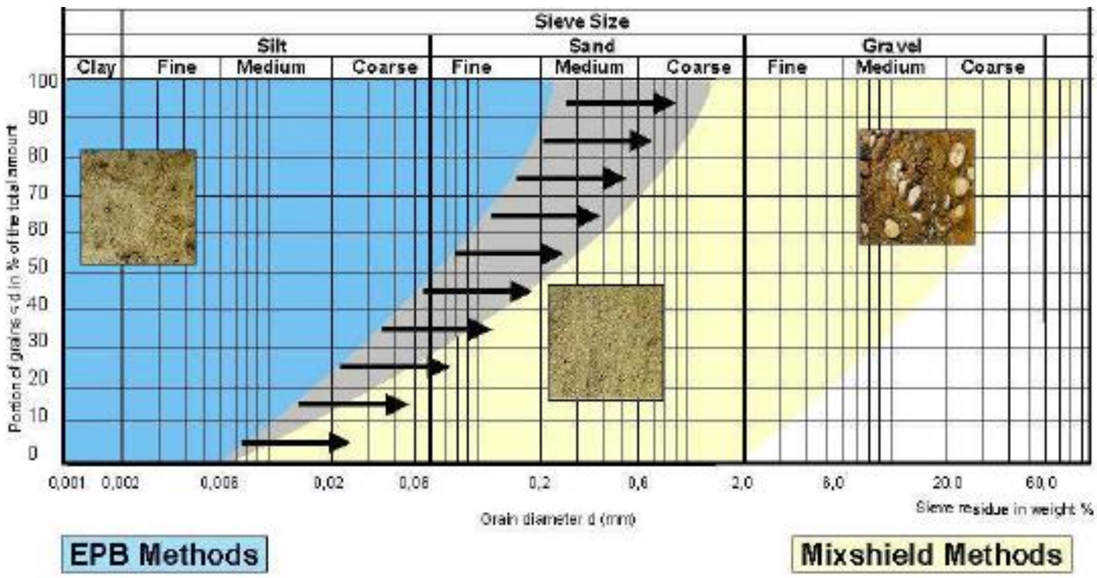


Figure 2.8 : Usage areas of EPB and Mixshield TBMs (Bappler, 2006).

2.2 History of TBMs

Tunneling developed rapidly during the industrialization at the start of the 19th century with the building of the railway network. In hard rock, this was by drilling and blasting. The first stage of the developing mechanization of tunneling therefore was the development of efficient drills for drilling holes for the explosive. There were also attempts to excavate the rock completely by machine (Maidl et al., 2008).

The history of the TBMs dates back to 1800's. During the period 1846-1930 more than 100 rock, hard-ground and soft ground tunneling machines of various types were designed and patented. (Stack, 1995).

The American Charles Wilson developed and manufacture a tunnel boring machine as early as 1851, which he first patented in 1856 (Figure 2.9). The machine had all the characteristics of a modem TBM and can thus be classified as the first machine, which worked by boring the tunnel (Maidl et al., 2008).

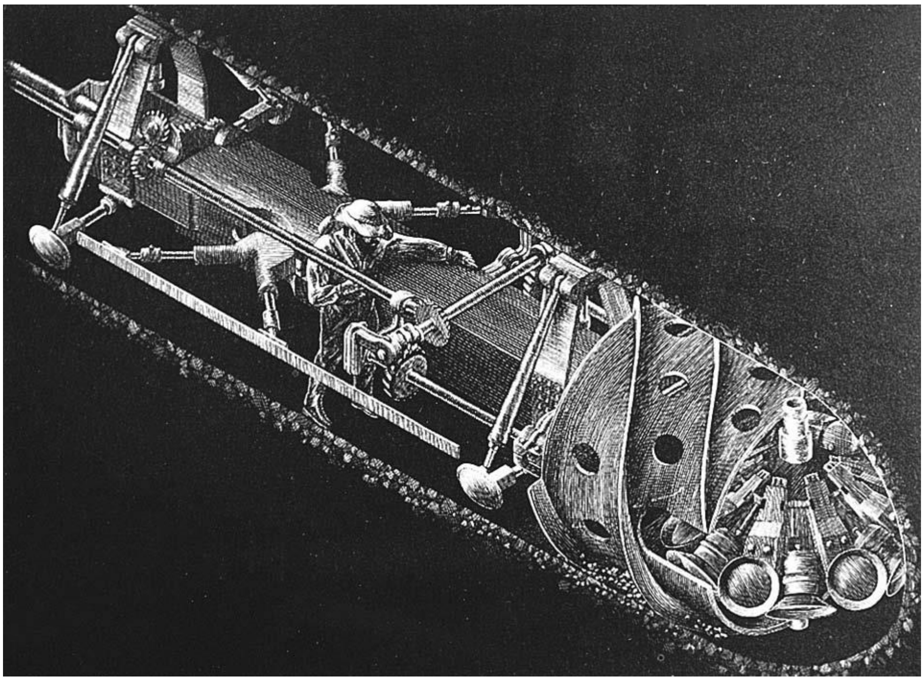


Figure 2.9 : First tunnel boring machine by C. Wilson (Maidl et al., 2008).

The Price shield, named after its inventor and patented in 1896, was the first machine to combine a shield with a rotating cutter head. The cutting wheel consisted of four spoke-type arms on which the cutting or scraping tools were affixed. Further, the cutting wheel was equipped with tub-shaped spoons, which collected the excavated ground, lifting it up and hauling it into a chute. Thus the material passed into readily placed trolleys and was then transported to the surface. The cutting wheel was driven electrically via a long axle. This machine was successfully employed in London clay from 1897 onwards (Maidl et al., 1996).

In this thesis, TBMs which dates back to 1950s, were covered. Because of this reason and the long history of the TBMs, hereafter this part will only cover TBMs that were manufactured in and after 1950s.

The breakthroughs to the development of today's TBMs did not occur until the 1950s, when the first open gripper TBM with disc cutters as its only tools was developed by the mining engineer James S. Robbins (Figure 2.10). Preliminary tests driving the Humber sewer tunnel in Toronto showed that, with only disc cutters and with considerably greater working life, the same advance performance could be achieved as with the intended combination of hard metal cutters and discs of the former TBM (Maidl et al., 2008).

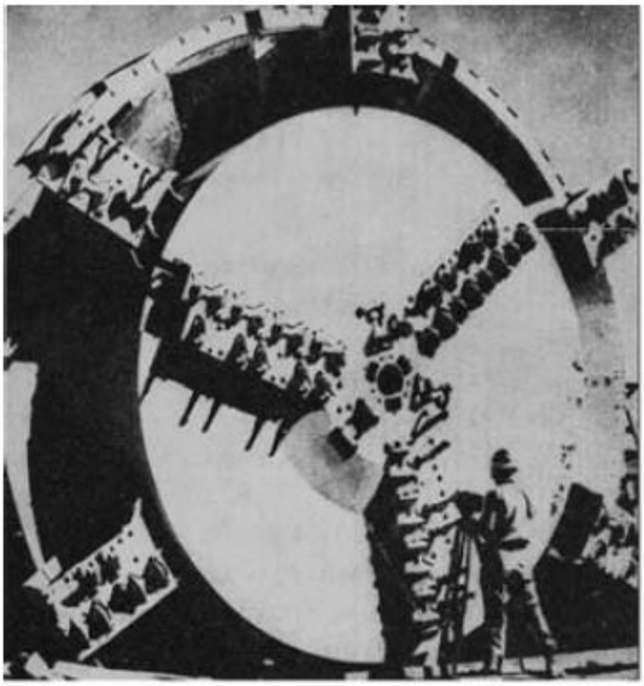


Figure 2.10 : The first Robbins TBM (Stack, 1995).

Using this TBM in the Humber sewer tunnel, advances of up to 30 m/d were achieved in sandstone, limestone and clay. Mechanical tunneling at this time was primarily concentrated on stable and relatively soft rock. With the growing success of Robbins, further American manufacturers like Hughes, Falkirk-Lawrence, Jarva and Williams began manufacturing tunnel boring machines. Machine types still current today like the main beam TBM or the kelly TBM had their origins at this time (Maidl et al., 2008).

In the 1960s, German manufacturers like Demag and Wirth began manufacturing tunnel boring machines like North American type. These machines were mainly intended to bore hard rock. The developing technology for hardening the disc cutters enabled the use of this type of tool in really hard rock. At the end of the 1960s, inclined headings and large tunnel sections were driven for the first time using the reaming method, the development of reamer boring being closely associated with the Murer Company (Maidl et al., 2008).

As late as 1959, the idea of a fluid-supported tunnel face was successfully tested by Elmer C. Gardner for a sewer tunnel with a diameter of 3.35 m. In 1960 Schneidereit introduced the term active face support through a bentonite suspension. In 1967 the first slurry shield with a cutting wheel and hydraulic mucking was used in Japan. It had a diameter of 3.1 m. In Germany, the first shield with a bentonite-supported tunnel face was developed and used by Wayss & Freytag (Maidl et al., 1996).

The development of earth-pressure balance shields started much later. This technique was first developed by the Japanese company Sato Kogyo Company Ltd. in 1963, after considerable research both in the laboratory and in the field, a unit was finally manufactured by Ishikawajima-Harima Heavy Industries (IHI) in 1966 (Stack, 1995). The development of earth-pressure balance shields was due to the strict environmental regulations and laws already in force in many major cities in Japan. These concerned air and ground water pollution, the dumping of excavated material and also health and safety precautions pertaining to compressed air (Maidl et al., 1996).

Progress in the 1970s and 1980s was directed towards driving in brittle rock and the enlargement of tunnel sections, with the consideration of the stand-up time of the soil/rock becoming particularly important. Encouraged by the successful implementation of a gripper TBM for the Mangla dam project in 1963 with a diameter of 11.17 m, a gripper TBM was also used for the construction of the Heitersberg tunnel (Ø10.65 m) in Switzerland in 1971. The work necessary to secure the rock with steel installation, anchors and mesh-reinforced shotcrete however made the hoped for advance impossible. The required adaptation to the large cross-section was first achieved in 1980 by the modification of the Robbins gripper machine from the Heitersberg tunnel by the Locher und Prader Company to a shielded TBM with segmental lining for the advance of the Gubrist tunnel (Ø11.50 m). Robbins and Herrenknecht have continued to made shield machines of this type in diameters ranging between 11 and 16 m (Maidl et al., 2008).

At the same time, Carlo Grandori developed the concept of the double shield TBM and, in collaboration with Robbins, put it into practice for the building of the Sila pressure tunnel (Ø 4.32 m) in Italy (Figure 2.11). The main intention of the development of this machine was to make the gripper TBM, which had then already proved very effective in appropriate geological conditions, more flexible for use in heterogeneous rock conditions. Since their first use in 1972 and the successful modification of this type of machine, double shield TBMs with customized segmental lining designs have achieved high advance rates under favorable rock conditions and have been made by all the well-known manufacturers, mainly in the medium diameter range. The capability of the double shield TBM design was demonstrated impressively at the end of the 80s in the chalk of the Channel Tunnel, which is favorable for tunneling (Maidl et al., 2008)

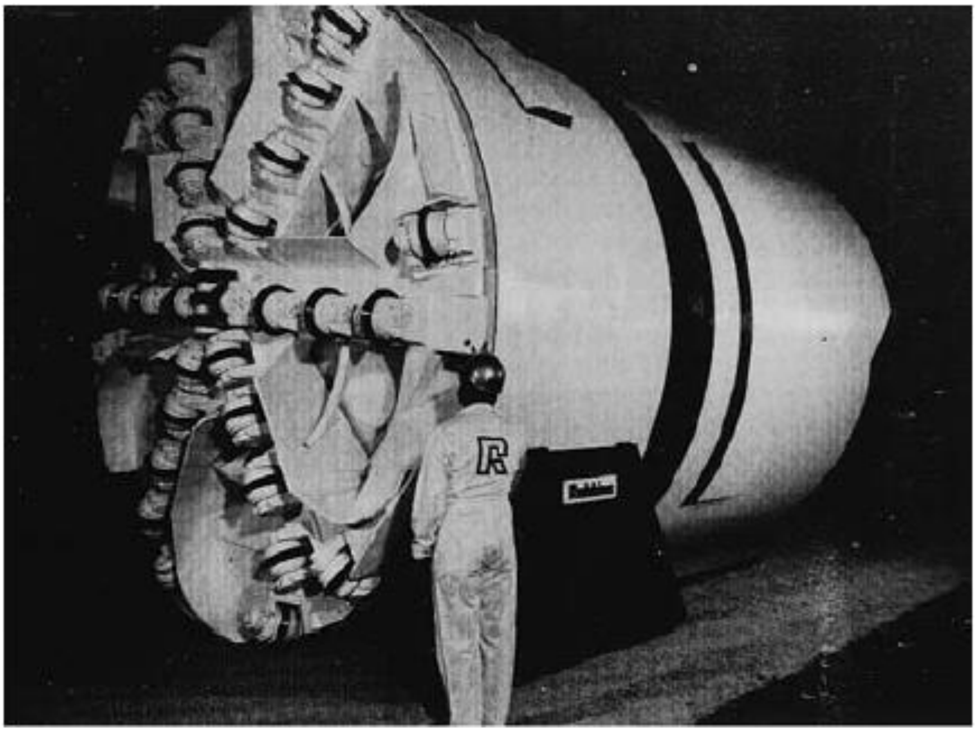


Figure 2.11 : Double shield TBM 144-151, Sila pressure tunnel, Ø4.32 m, 1972.

Alongside the development of the TBM with shield, the manufacturers of open gripper TBMs began to investigate possibilities of improving their machines to enable any necessary lining to be installed earlier. The state of progress with large diameter TBMs today is the installation of lining elements immediately behind the boring shield or partial areas of the shield and the systematic installation of rock anchors (Maidl et al., 2008).

Today’s TBMs have advanced computer systems to control and record the excavation parameters. Moreover, they also have advanced guidance systems to minimize deviation from the route.

3. THEORETICAL CONCEPTS USED FOR THE DESIGN OF TBMS

3.1 Cutterhead Torque Calculation

3.1.1 Hard rock TBMs

3.1.1.1 Gripper TBMs

Gripper TBMs are used in hard and stable rock conditions. For this type of TBMs, compressive strength of the rock is the main factor that affects the torque. Torque requirement of a gripper TBM can be calculated as (Bilgin et al., 2008);

$$T = \sum_{i=1}^{Nc} r_i \cdot Fc \cdot f_L \approx Nc \cdot F_R \cdot \frac{D}{4} \cdot f_L \qquad \textbf{(3.1)}$$

Where T is cutter torque (kNm), r_i cutter distance to the cutterhead center, Nc is number of cutters, F_R is mean rolling force of cutting discs, D is excavation diameter, f_L a constant for friction loses (it can be taken as 1.2),.

3.1.1.2 Single shield and double shield TBMs

Single and double shield TBMs are used in hard but unstable rock conditions. In addition to cutting torque, friction forces are also important for these types of TBMs especially in squeezing and fractured geologic formations. To calculate torque requirements of these types of TBMs, properties of geologic formations must be examined properly.

If the rock is stable TBMs torque can be calculated as given in Equation **3.1**. However if the rock is fractured and/or squeezing, friction torque on frontal surface of the cutterhead (T_1) (Equation **3.2**) and friction forces around the circular surface (Equation **3.3**) (T_2) of the cutterhead must be added to the cutting torque (Shi et al., 2011). Adding these friction forces to the cutting torque will help to determine the required torque after stops. The calculation method is similar to soft ground TBMs and it will be covered in detail in the following section.

$$T_1 = \frac{\pi D^3}{12} K_0 \mu_1 \gamma H (1-\eta) \quad \textbf{(3.2)}$$

$$T_2 = \frac{\pi D^2}{4} (1+K_0) \mu_1 \gamma H t \quad \textbf{(3.3)}$$

where D is excavation diameter, K_0 is coefficient of lateral earth pressure at rest, H is overburden depth, μ_1 is coefficient of friction (Table 3.1), γ is unit weight of the rock, η is opening ratio of the cutterhead, t is the thickness of cutterhead.

3.1.2 Soft ground TBMs

Torque requirement of a soft ground TBM can be calculated by using the Equation **3.4** (Japan Society Of Civil Engineers (JSCE), 2007) ;

$$T = \alpha \cdot D^3 \quad \textbf{(3.4)}$$

Where T is cutter torque (kNm), D is excavation diameter of the TBM (m) and α is torque factor.

The torque factor depends on machine properties and soil conditions. It is generally taken between 10-23 for EPB TBMs and 8-20 for slurry TBMs (Figure 3.1).

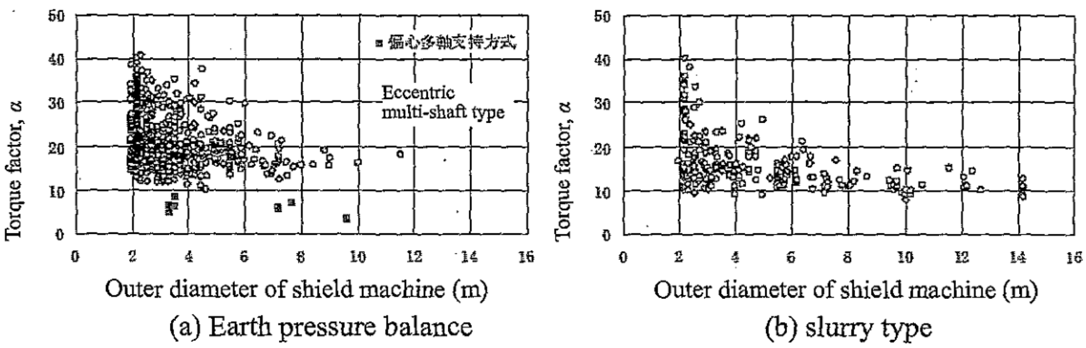


Figure 3.1 : Torque factors for different diameters and TBM types (JSCE, 2007).

To illustrate the relations between torque and diameter, upper and lower limits of torque values derived from the Equation **3.4** is also shown in Figure 3.2. As can be clearly seen, especially for large diameter TBMs, the empirical equation can only be used for making a rough estimate.

To calculate the required torque for a TBM several factors, e.g. dynamic friction coefficient, overburden depth, additives, excavation diameter, geology, machine properties and other aspects should be taken into consideration.

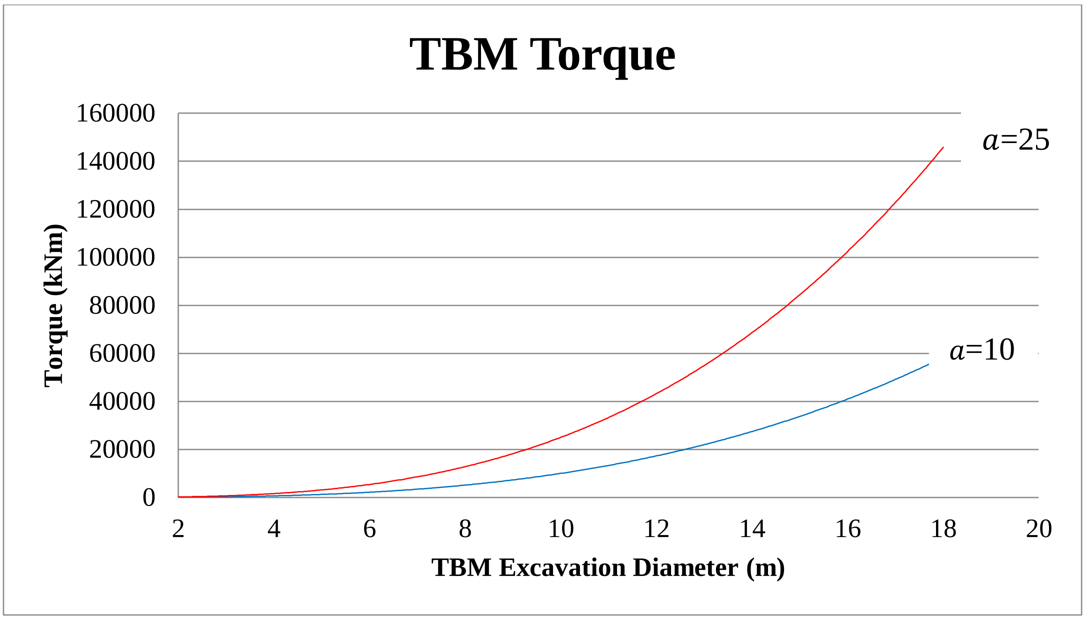


Figure 3.2 : Upper and lower torque limits according to Equation 3.4.

Total torque requirement of the soft ground TBMs can be calculated by sum of 8 torque components (Japan Society Of Civil Engineers (JSCE), 2007, Shi et al., 2011, Song et al., 2010)

$$\sum T = T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7 + T_8 \qquad \textbf{(3.5)}$$

Where;

T_1: Friction torque on cutterhead's frontal surface

T_2: Friction torque on cutterhead's circular surface

T_3: Friction torque on cutterhead's back surface

T_4: Torque needed to overcome the cutting resistance of the soil

T_5: Shearing torque on cutterhead openings

T_6: Torque required to overcome the resistance of the soil mixing and stirring (Agitating torque)

T_7: Torque of rotation of main bearing

T_8: Torque of cutterhead sealing

3.1.2.1 Friction torque on frontal surface (T_1)

When a shielded TBM is advancing, the frontal face of the cutterhead resists the earth pressure from the soils against it (Shi et al., 2011). It can be calculated as;

$$T_1 = \int_0^{2\pi} \int_0^{D} K_0 \mu_1 \gamma (H - rSin\theta) r^2 dr d\theta$$

$$= \frac{\pi D^3}{12} K_0 \mu_1 \gamma H (1 - \eta) \quad \textbf{(3.6)}$$

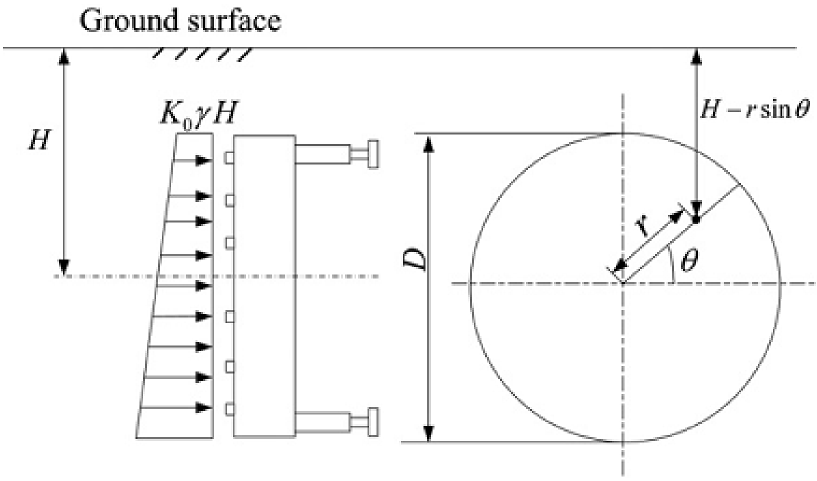


Figure 3.3 : Forces acting on frontal surface of the cutterhead (Shi et al., 2011).

Coefficient of dynamic friction is related with soil properties and lubrication. Lubrication can reduce friction up to 50% (Gehring, 1996). Friction coefficients for different rocks with and without lubrication are given in Table 3.1 (Ramoni, 2010).

Table 3.1 : Friction coefficients for dynamic friction with and without lubrication.

	Dynamic Friction		**Static Friction**	
	Not lubricated	**Lubricated**	**Not lubricated**	**Lubricated**
Rock	0.25-0.30	0.10-0.15	0.40-0.45	0.15-0.25
Gravel	0.25-0.30	0.15	0.40-0.55	0.20-0.30
Sand	0.35-0.40	0.15	0.45-0.55	0.20-0.30
Silt	0.35-0.40	0.10	0.30-0.50	0.15-0.20
Clay	0.30-0.35	0.10	0.20-0.55	0.15-0.20

Like friction coefficient, lateral earth pressure coefficient (K_0) is also related with soil properties. Lateral earth pressure coefficients for different soil types are given by DAUB (2007) in Table 3.2.

Table 3.2 : Lateral earth pressure coefficients.

Consistency	**Undrained shear strength (Cu) (kN/m^2)**	**Lateral earth pressure coefficient (K_0)**
Pulpy	<25	0.7-1.0
Soft	25-60	0.5-0.8
Stiff	60-150	0.4-0.6
Semi-Solid	150-300	0.3-0.5
Solid	>300	0.2-0.4

3.1.2.2 Friction torque on circular surface (T_2)

The friction torque on circular surface is caused by the earth pressure composed of two parts; vertical component P_1 and lateral component P_2 (Figure 3.4) (Shi et al., 2011). It can be calculated as;

$$T_2 = \frac{\pi D^2}{4}(1 + K_0)\mu_1 \gamma H t \tag{3.7}$$

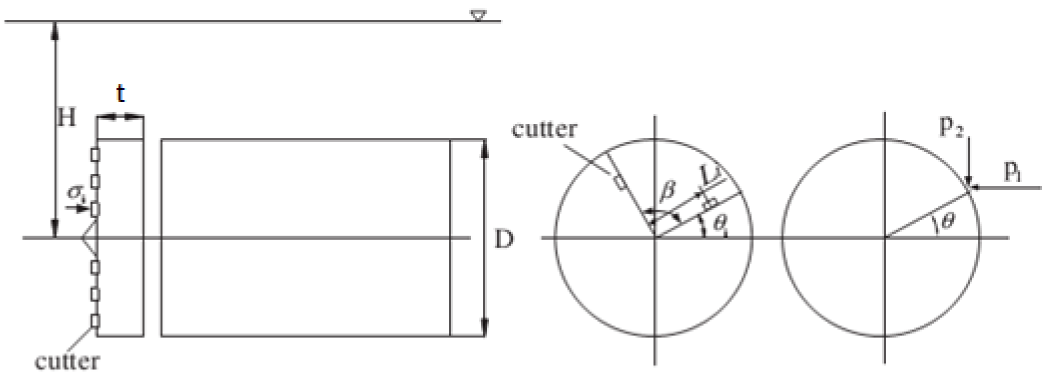


Figure 3.4 : Vertical and lateral earth pressure acting on circular surface (Shi et al., 2011).

3.1.2.3 Friction torque on back surface (T_3)

Similar to torque on frontal surface (T_1), friction torque on back surface is related with soil pressure in the pressure chamber. According to Shi et al. (2011) it can be calculated as;

$$T_3 = \frac{\pi D^3}{12} K_0 \mu_1 \gamma H (1 - \eta) f_{\Delta p} \tag{3.8}$$

Where $f_{\Delta p}$ is coefficient related to the difference between inner and outer pressures (it can be taken as 1 in good conditions where pressure inside the chamber is equal to the face pressure).

3.1.2.4 Cutting torque (T_4)

The cutting torque is the sum of torque forces applied on each cutter to cut the soil. Cutting force estimation models suggested for different types of cutters by Potts and Shuttleworth (1958), Evans (1962) and Nishimatsu (1972). Lobanov and Joanknecht (1980) suggested calculating cutting force as (modified by Çopur (2012a));

$$Fc = 2.5 \cdot (1 + \cot(90 - a) \cdot \tan(\delta)) \cdot d \cdot w \cdot \frac{1 - \sin(\emptyset)\cos(2\xi)}{1 + \sin(\emptyset)\cos(2\xi)} \cdot \sigma_s \cdot \cos(\emptyset) \tag{3.9}$$

$$\xi = 2\pi - 2a - \delta - \arcsin(\sin(\emptyset) \cdot \sin(\delta)) \tag{3.10}$$

where Fc is mean cutting force, σ_s is shear strength of ground, α is rake angle, δ is angle of friction between ground and cutter, d is depth of cut, w is width of cutter, Ø is angle of internal friction of ground.

After calculating cutting force, cutting torque can be calculated as;

$$T_4 = \sum_{i=1}^{Nc} r_i \cdot Fc \cdot F_L \approx Nc \cdot Fc \cdot \frac{D}{4} \cdot F_L \tag{3.11}$$

3.1.2.5 Shearing torque on cutterhead openings (T_5)

Shearing resistance is generated by the rotating cutterhead when the excavated soils falling into the working chamber through the opening of cutterhead (Shi et al., 2011). It can be calculated as;

$$T_5 = \frac{\pi D^3}{12} \cdot k_q \cdot \eta \cdot \tau \quad \textbf{(3.12)}$$

Where τ is shear modulus of soil and k_q is a coefficient related to shear area.

3.1.2.6 Agitating torque (T_6)

The soil in the pressure chamber is rotated and stirred by the agitating bars, which are mounted on the back surface of the cutterhead. This action generates a resistance and it is related with unit weight of the muck and agitating bar properties. Since the unit weight of the muck in EPB TBMs pressure chamber is higher than slurry TBMs agitating torque on EPB TBMs is higher than slurry TBMs. Shi et al. (2011) suggested to calculating agitating torque as;

$$T_6 = \sum_{i=1}^{n_b} \gamma \cdot (H - R_b Sin\theta_i) \cdot D_b \cdot L_b \cdot f_c \cdot n_b \cdot R_b \quad \textbf{(3.13)}$$

where n_b is number of bars, R_b is distance between the bar and the centerline of shield, θ_i is angle of the plane through the axes of the bar and the shield with respect to the horizontal plane, D_b is diameter of the bar, L_b is length of the bar, f_c friction factor between the earth and the steel bar.

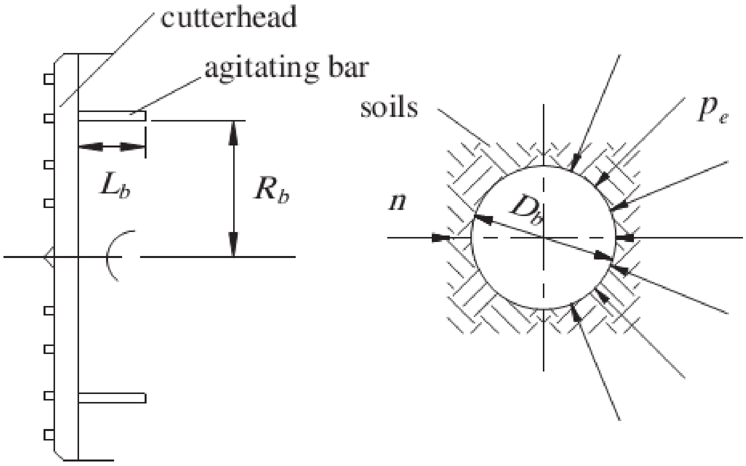


Figure 3.5 : Diagram of parameter related with agitating bars (Shi et al., 2011).

3.1.2.7 Torque of rotation of main bearing (T_7)

There is a large bearing in the TBMs to support the heavy cutterhead to rotate. The bearing bears both axial force because of thrust and radial force resulting from the cutterhead weight (Shi et al., 2011). This force can be calculated as;

$$T_7 = F \cdot \mu_r \cdot R_t + W_c \cdot R_r \cdot \mu_r \quad \textbf{(3.14)}$$

Where F is thrust force of TBM, R_t is distance from the thrust acting point to the centerline of shield, μ_r is coefficient of rolling resistance, W_c is weight of cutterhead, Rr is radius of radial roller bearing.

3.1.2.8 Torque of cutterhead sealing (T_8)

Soft ground TBMs have sealing rings on the bearing to separate excavation chamber from the driving mechanisms and non-pressurized environment. Generally, TBM manufacturers use several sealing rings. Torque caused by these sealing rings can be calculated as (Shi et al., 2011);

$$T_8 = 2\pi \cdot R_s^2 \cdot F_s \cdot n_s \cdot \mu_s \quad \textbf{(3.15)}$$

where F_s is positive pressure applied on the sealing rings, R_s is radius of the sealing ring, n_s is number of the sealing rings, μ_s is frictional coefficient between sealing material and steel.

3.1.2.9 Total torque requirement

As mentioned before total torque requirement of a soft ground TBM can be calculated by summing up 8 torque components. However some of these components require parameters, which are kept as marketing secret by manufacturers. Thus calculating the exact torque requirement is very hard.

According to various studies, the most important torque factors are T_1, T_2 and T_3 components (Shi et al., 2011, Song, Liu, & Guo, 2010). These three factors consist between 57% and 89% of total torque.

Moreover agitating torque (T_6) is also an important factor for EPB TBMs and it consists around 10% of total torque. Theorically, because of unit weight of the muck, it is not affective in slurry TBMs as much as EPB TBMs, however, there is not enough data to support this idea.

It is also seen that shearing torque (T_5) increases with increasing opening ratio. On TBMs which have large opening ratios it could consists up to 20% of the total torque. Moreover, large opening ratio reduces the T_1 and T_3 components of the torque.

It is found that by calculating T_1, T_2 and T_3 and increasing the sum of these three components by 25-30% gives closer results to the required total torque of the TBMs. Furthermore, lubrication has a very important role in reducing torque requirement.

3.2 Thrust Calculation

3.2.1 Hard rock TBMs

3.2.1.1 Gripper TBMs

Gripper TBMs have no shield thus the main component of total thrust is normal force, which applied to cutters to cut the rock. This force can be calculated as (Bilgin et al., 2008);

$$F = N_c \cdot F_N \cdot f_L \qquad \textbf{(3.16)}$$

Where F is TBM thrust (kN), Nc is number of cutters, F_N is normal force, f_L a constant for friction loses (it can be taken as 1.2),

Moreover thrust force required to pull the backup is also should be taken into consideration.

3.2.1.2 Single Shield and Double Shield TBMs

Single and double shield TBMs have shield and they are used in fractured/squeezing rock conditions which the rock applies a friction force around the shield. Since the conditions are similar to the soft ground, equations given to calculate soft ground TBMs thrust requirements in the following section, except F_2 equation which gives thrust force required to overcome the chamber pressure acting on bulkhead, can be used for single and double shield TBMs. It should be noted that there is no face pressure on hard rocks thus there is no need to calculate F_2 (Equation **3.24**).

Moreover, thrust required to cut the rock on hard rock TBMs have bigger proportion of the total thrust in comparison with soft ground TBMs.

3.2.2 Soft ground TBMs

Total thrust requirement of the soft ground TBMs is suggested as sum of 5 thrust components (From F1 to F5) by Japan Society of Civil Engineers (JSCE, 2007), however, thrust force to overcome the penetration force of the cutting tools (F_6) should be added to the Equation **3.17** as suggested by Çopur (2012a);

$$\sum F = F_1 + F_2 + F_3 + F_4 + F_5 + F_6 \tag{3.17}$$

Where;

ΣF is total thrust force requirement of the soft ground TBMs,

F_1: Thrust force required to overcome friction (adhesion) between shield and ground due to earth pressure,

F_2: Thrust force required to overcome the chamber pressure acting on bulkhead,

F_3: Thrust force required to overcome the drive force caused by direction changes (in curved alignments),

F_4: Thrust force required to overcome the frictional force acting between the segments and the tail seals,

F_5: Thrust force required to overcome the hauling force of trailing (backup) units,

F_6: Thrust force required to overcome the penetration (normal) force of cutting tools into the ground.

3.2.2.1 Thrust force required to overcome friction between shield and ground due to earth pressure (F_1)

F_1 is estimated by Equation **3.18** or Equation **3.19** (JSCE, 2007):

$$F_1 = \mu_1 \cdot \left[\pi \cdot D_s \cdot L_s \cdot P_m + W_e\right] \quad \text{for sandy soils} \tag{3.18}$$

$$F_1 = C_a \cdot \pi \cdot D_s \cdot L_s \quad \text{for clayey soils} \tag{3.19}$$

Where, μ_1 is coefficient of friction between steel (shield) and soil, D_s is shield (or excavation) diameter, L_s is shield length, P_m is average earth pressures acting on shield, W_e is weight of shield machine, and C_a is adhesion force (between shield and cohesive soil). The suggested values of μ_1 are presented in Table 3.1.

Shield length L_s can be assigned as a function of D_s by assuming that (L_s/D_s) ratio varies linearly between 2 (for D_s of 3 m) and 1 (for $D_s \geq 12$ m) (Japan Society Of Civil Engineers (JSCE), 2007).

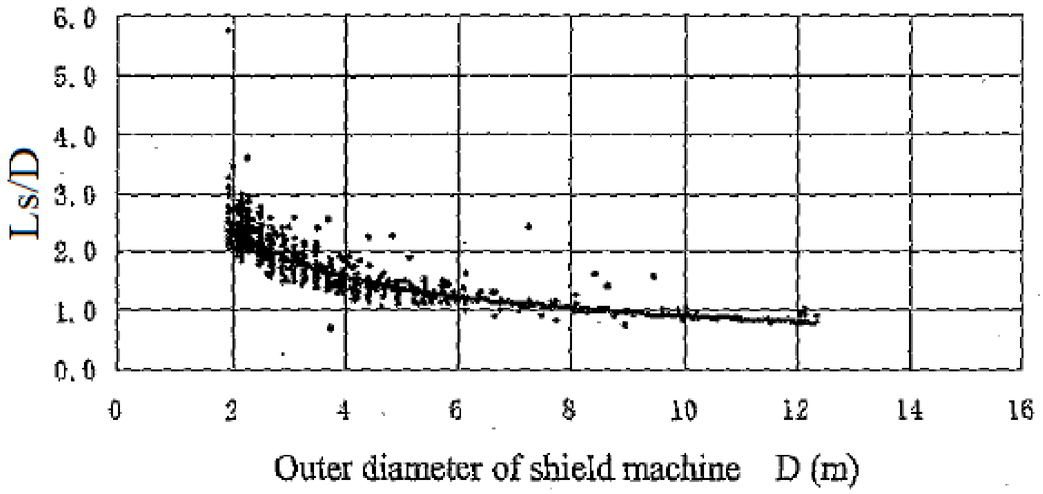


Figure 3.6 : Shield length – diameter ratio for soft ground machines with articulation (Japan Society Of Civil Engineers (JSCE), 2007).

Weight of shield machine W_e (kN) can be estimated as a function of D_s by Equation **3.20** for both EPB and SPB TBMs. This equation was derived from the TBM database and it will be covered in the next sections of the thesis.

$$W_e = 883.65 \cdot e^{0.2207 \cdot D_s} \quad \textbf{(3.20)}$$

Average earth pressures acting on shield P_m is as the averages of 4 components of vertical and horizontal earth pressures at rest (soil and water pressures) on crown and invert levels by JSCE (2007). To derived make calculations simpler, P_m can be assumed to be averages of uniformly distributed vertical earth pressure acting on crown and horizontal earth pressure acting on tunnel springline as suggested by (PJA, 1995);

$$P_m = \frac{\sigma_v + \sigma_h}{2} \quad \textbf{(3.21)}$$

Where, σ_v is vertical earth pressure acting on crown and σ_h is horizontal earth pressure at rest acting on tunnel springline. It is assumed that Equation **3.21** can be implemented to Equation **3.18** (Çopur, 2012a). The earth pressures can be estimated based on AITES-ITA (2000) by selecting the maximum of arcing height h_0 or $2D_s$. It is also assumed that total pressure approach (groundwater pressure being included with the soil pressure) is valid and estimated by using bulk unit weight instead of using buoyant unit weight of the soil. Therefore, vertical earth pressure σ_v on crown and horizontal earth pressure σ_h on tunnel springline can be estimated by using Equation **3.22** and Equation **3.23** as a function of $2D_s$ as suggested by Çopur (2012b).

$$\sigma_v = 2 \cdot D_s \cdot \gamma_b \tag{3.22}$$

$$\sigma_h = K_0 \cdot \left(\sigma_v + \gamma_b \cdot D_s / 2\right) \tag{3.23}$$

Where, γ_b is bulk unit weight of soil Coefficient of lateral earth pressure at rest K_0 is usually suggested to be either 1 or 0.5.

3.2.2.2 Thrust force required to overcome the chamber pressure acting on bulkhead (F_2)

EPB and slurry TBMs have a pressure chamber to apply pressure to the ground for avoiding collapses. Thus a force (F_2) is required against this pressure force. It can be calculated as (JSCE, 2007);

$$F_2 = \sigma_T \cdot \frac{\pi \cdot D_s^2}{4} \tag{3.24}$$

Where, σ_T is face pressure acting on excavation chamber if the face is not stable and can be estimated by adding 20 kPa to σ_h (Kanayasu et al., 1995) for both EPB and SPB TBMs.

3.2.2.3 Thrust force required to overcome the drive force caused by direction changes (F_3)

A shield machine is subject to reaction forces from the surrounding ground when a curved section is excavated or when the direction of the shield machine is corrected. The maximum value of this load is usually estimated based on an assumption that one side of the machine is subjected to a reaction force equal to the passive earth pressure, or that the machine is subjected to the ground reaction force when half of the shield jacks, i.e., only one side of the machine, are operated (Figure 3.7) (Japan Society Of Civil Engineers (JSCE), 2007) (Equation. **3.25**).

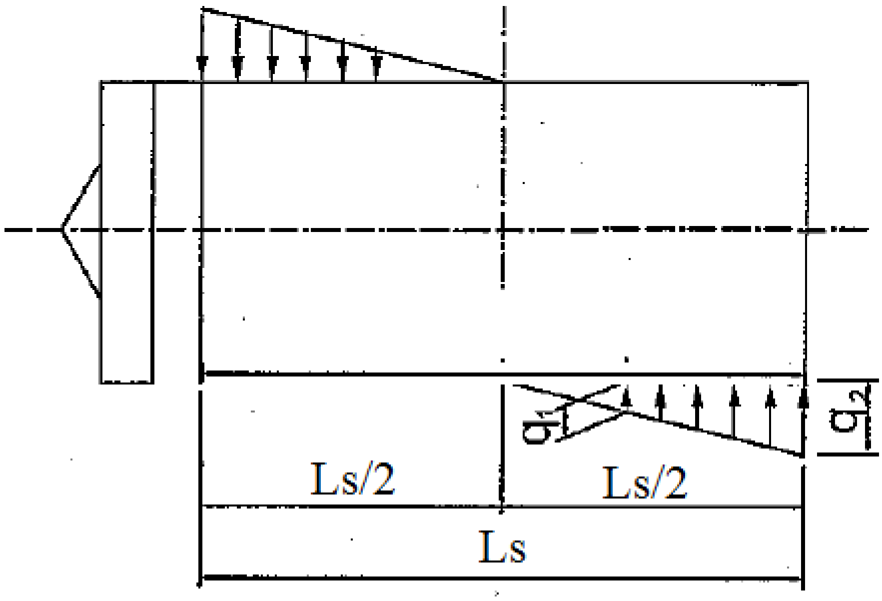


Figure 3.7 : Load imposed by direction changes (Japan Society Of Civil Engineers (JSCE), 2007).

$$F_3 = \mu_1 \cdot D_s \cdot \frac{L_s}{2} \cdot \frac{q}{2} \qquad \textbf{(3.25)}$$

Where, q is pressure imposed by shielded TBM direction change and it can be assumed to be equal to σ_h (Çopur, 2012a).

If the tunnel is straight, F_3 can be taken to be 0.

3.2.2.4 Thrust force required to overcome the frictional force acting between the segments and the tail seals (F_4)

Soft ground TBMs use advanced sealing systems on the shield to prevent ingress of the materials and grout from the tail shield. This sealing system creates a friction force between the shield and the segments. This force can be calculated by (Japan Society Of Civil Engineers (JSCE), 2007);

$$F_4 = \mu_2 \cdot \pi \cdot D_o \cdot L_{sc} \cdot P_m \qquad \textbf{(3.26)}$$

Where, μ_2 is coefficient of friction between seals and segments (usually between 0.2 and 0.3), D_0 is outer diameter of segments, L_{sc} is length of contact between segment and tail.

3.2.2.5 Thrust force required to overcome the hauling force of trailing (backup) units (F_5)

As the TBM advances it pulls backup unites, thus the force for pulling backup unites should be calculated. It can be estimated by (Japan Society Of Civil Engineers (JSCE), 2007);

$$F_5 = \mu_3 \cdot G \tag{3.27}$$

Where, μ_3 is coefficient of friction between wheel and rail (in fact, it can be considered as rolling resistance of wheels which can be assumed maximum 0.15), and G is weight of trailing gears (backup).

If the backup is self-propelled, F_5 is taken to be 0.

Weight of trailing gears G can be estimated as a function of D_s by using Equation **3.28** for both EPB and SPB TBMs. Like weight of the TBMs (Equation **3.20**) this equation was also derived by using the TBM database and it will be explained in the following chapters.

$$G = 868.82 \cdot e^{0.1713 \cdot D_s} \tag{3.28}$$

3.2.2.6 Thrust force required to overcome the penetration (normal) force of cutting tools into the ground (F_6)

A thrust force is required for the penetration of the cutters to the soil and Çopur (2012a) suggested that it can be estimated by using Equation **3.29** (Bilgin et al., 2008);

$$F_6 = N_c \cdot F_n \cdot F_L \tag{3.29}$$

Where, N_c is number of cutters on TBM cutterhead, F_n is mean normal force acting on a cutter and F_L is a constant for frictional loses (usually assumed to be 1.2). F_n can be obtained by experimentally or estimated by theoretical or empirical approaches.

3.2.2.7 Total thrust requirement

Installed thrust requirement FN_{inst} can be estimated by Equation. **3.30**:

$$F_{\text{inst}} = \sum F \cdot \text{Safety Factor} \quad \textbf{(3.30)}$$

Safety factor varies depending on machine manufacturer, it can be taken up to 2.

4. LARGE DIAMETER TBMS

For observation and understanding, the differences between large and medium size cross section TBMs will be treated in separately in the following chapter.

4.1 Large Diameter TBMs

World's population and urbanization are increasing rapidly and there is an enormous demand for high-capacity infrastructures. Large diameter TBMs are allowing to build this kind of infrastructures safely in a tight schedule.

The large diameter TBMs are not restricted to special geological applications (Herrenknecht and Bappler, 2011). They can be used in soft rock, hard rock and mixed face conditions. Using a large diameter TBM allows building larger infrastructures. They also have all the advantages of TBMs, e.g. improved safety and rapid construction. With large diameter tunnels, innovative configurations of corridors within the tunnels have been developed to optimize the usage of this underground space.

Kuala Lumpur's Stormwater Management and Road Tunnel (SMART) is a very good example of the innovative designs (Figure 4.1). The 13.2 m diameter tunnel consists of a 9.7 km storm water bypass tunnel, with a 4 km double-deck motorway in the storm water tunnel. The double-deck road tunnel located at the center stretch of the tunnel will serve as traffic dispersal to alleviate the chronic congestion of the southern road arteries of the city. For majority of the time, the 2x2 lane road tunnel is opened for traffic when flood diversion is not in operation. During normal storms, the tunnel will serve its dual purpose in channeling storm water, and concurrently the road tunnel portion will still be opened to traffic flow. In event of major storms, which is anticipated to occur once a year, road tunnel will be shut to traffic and flood gates at the end of the road tunnel opened to accommodate the increase water flow (Kok and Klados, 2006).

Because of the limitations of old times and without a demand for high-capacity infrastructures, there was only a few large diameter TBMs until 1990s. However, by improved technology and demand for large section underground openings, more than 100 large diameter TBMs have been manufactured up to now (Figure 4.2). Moreover, the diameters of TBMs continue to increase. For example, Hitachi Zosen Company started to manufacture a 17.6 meter diameter TBM for Alaskan Way Highway Tunnel, and Herrenknecht Company has a 19.25 meter diameter TBM in the pipeline for Orlovsky Tunnel, which will be the largest TBM ever manufactured.

Figure 4.1 : Cross section of Stormwater Management and Road Tunnel.

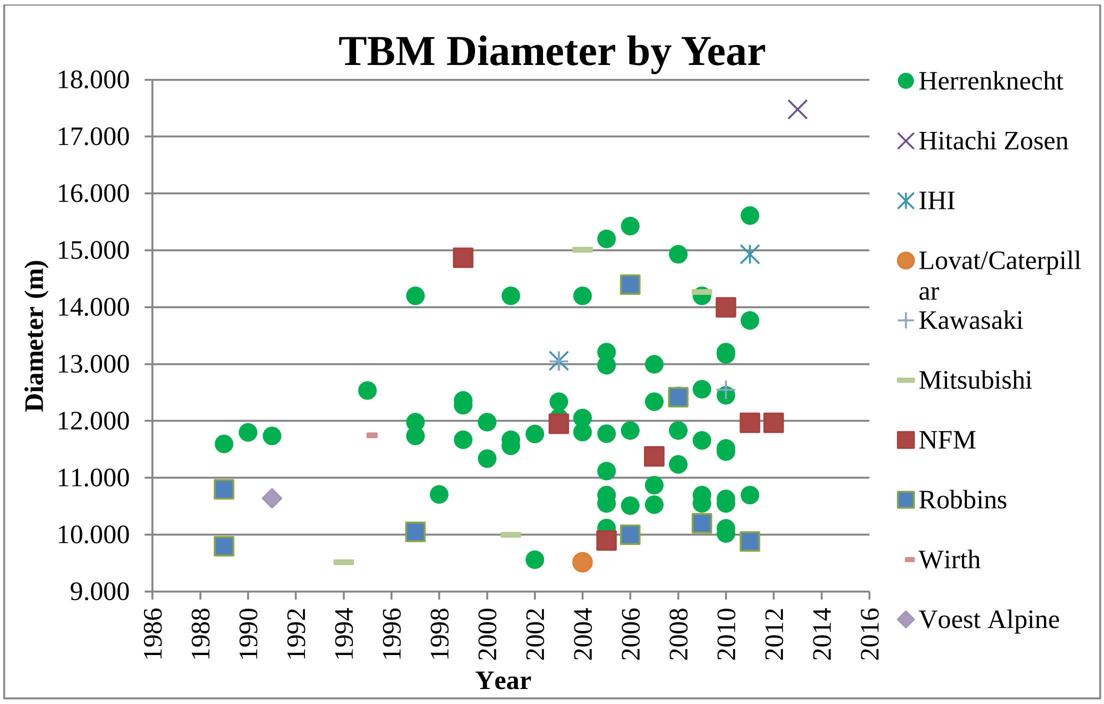


Figure 4.2 : Large diameter TBMs manufactured after 1985.

As can be seen from the Figure 4.3, 42% of the large diameters TBMs were used in road construction projects while another 40% were used for railway projects.

Especially three lane roads, double track railways and metros requires a TBM which is larger than 10 meters.

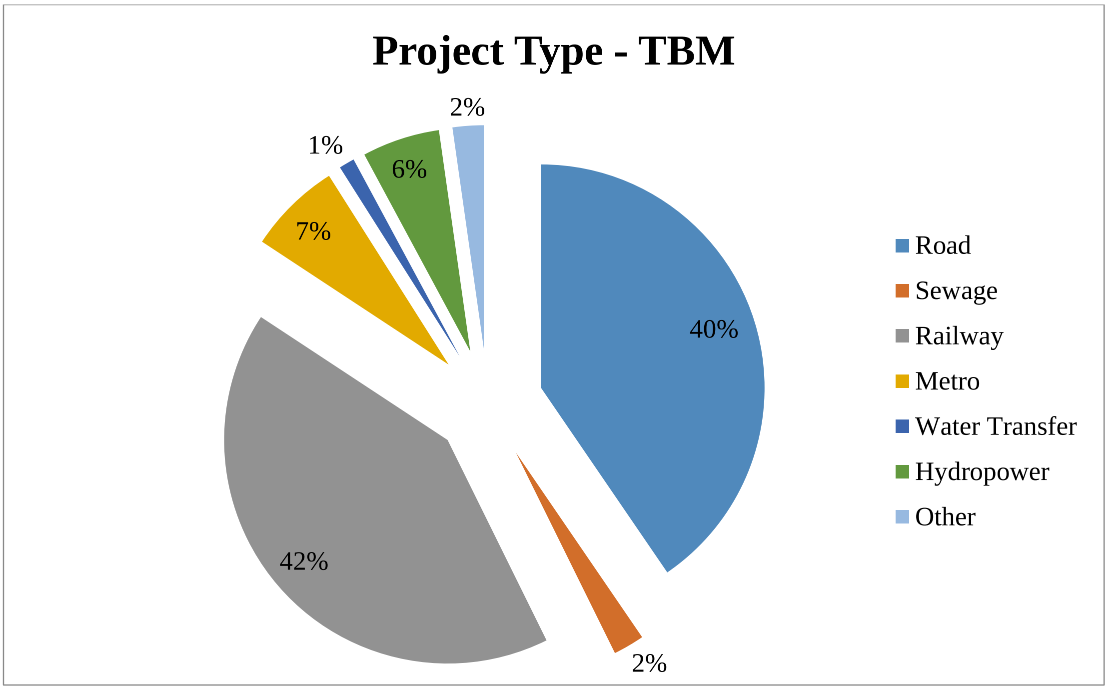


Figure 4.3 : Project types where large diameter TBMs were used.

4.2 Disadvantages of Large Diameter TBMs

Large diameter TBMs have some advantages as mentioned before as well as disadvantages. These disadvantages are;

- High capital cost.
- As the diameter increases, the increase in face collapses goes up exponentially (Figure 4.4). Because the cutterhead crosses more fractured zones than small diameter TBMs.
- Removal of excavated material could slow down the excavation if it is not planned properly (Figure 4.5).
- Since large diameter TBMs have more cutters than smaller ones maintenance of the cutters takes a lot of time in comparison with small diameter TBMs.
- High potential of jamming because of low advance rates and long maintenance hours.

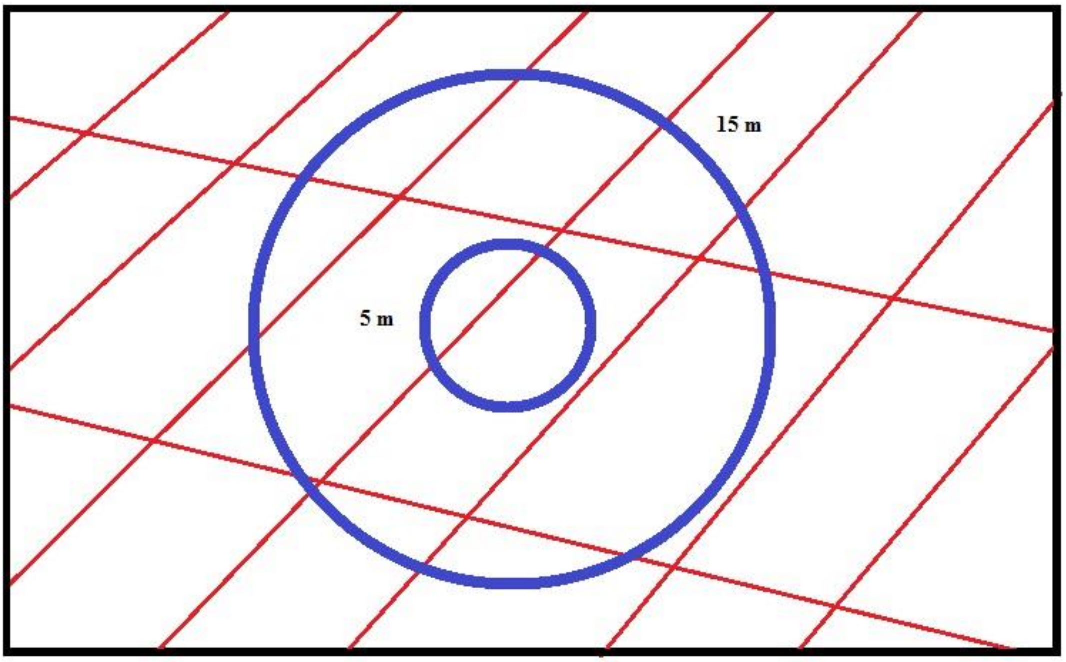


Figure 4.4 : Crossed fractures according to diameter.

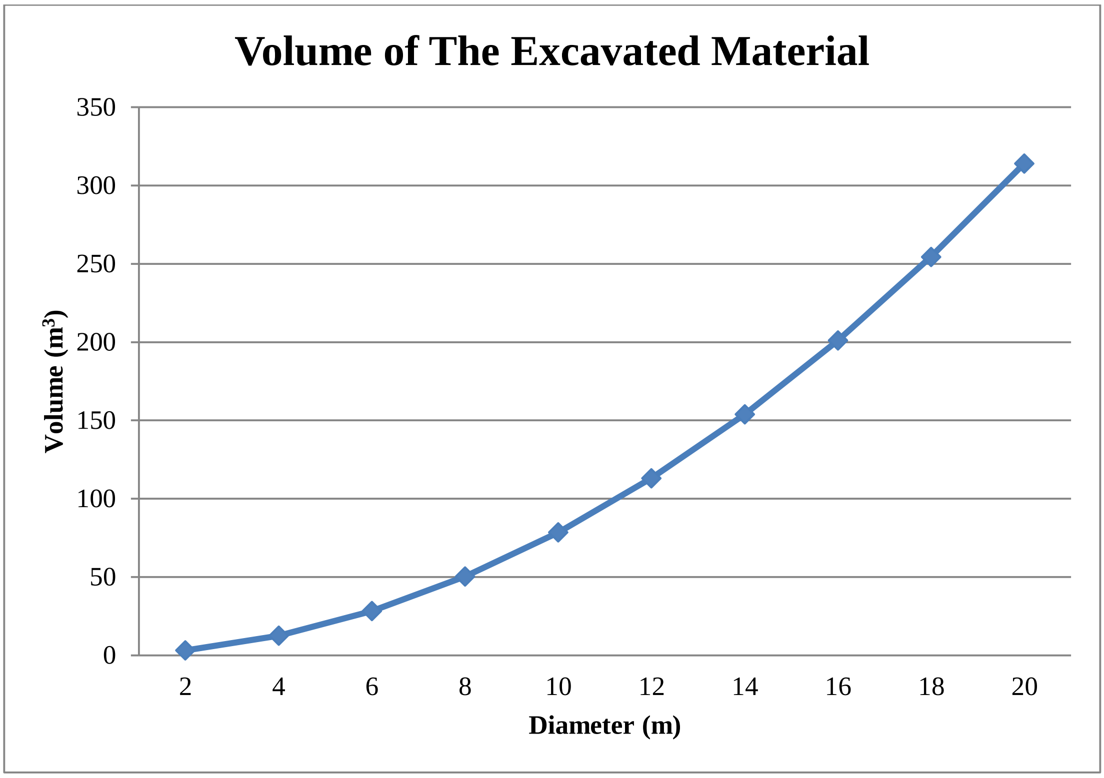


Figure 4.5 : The change of volume of the excavated material with TBM diameter.

- Large diameter TBMs have to excavate at deeper depth than small diameter TBMs to avoid surface collapses.

- Large diameter TBMs are heavy machines (Figure 4.10), which causes misalignment of tunnel. Thus, alignment should be monitored constantly.

4.3 Design Parameters of Large Diameter TBMs

In this section, the data of 20 single shield, 9 double shield, 7 gripper, 24 EPB and 28 slurry TBMs properties, which were manufactured between 1985 and 2012, were analyzed. The TBMs in this section have a minimum diameter of 9.5 meters, and the TBMs were built before 1985 will not be covered.

It should be mentioned that some TBMs used in more than one project without a change in the design, especially before 1990's, these TBMs are taken into consideration only once, for their first project.

4.3.1 Torque and thrust requirements for large cross section TBMs

According to the analyses (Figure 4.6) it has been found that for EPB, slurry and gripper TBMs, torque is strongly related to the TBM's diameter, while for single shield and double shield TBM's torque depends on also formation or rock properties. It should be mentioned that single shield, double shield and gripper TBMs are hard rock TBMs, however, gripper TBMs are chosen for intact rock conditions while others are used in fractured/unstable conditions. This could be the explanation of different torque – diameter relationships.

Furthermore for larger diameters, torque requirement of an EPB TBM is far more than other types. For example, the required torque force for a TBM which has 13 meters excavation diameter is approximately 15,000 kN.m for a single shield TBM, 20,000 kN.m for a double shield TBM and 10,000 kN.m for a gripper TBM, while the figures for an EPBM and a slurry machine is nearly 45,000 kN.m and 20,000 kN.m, respectively. This can be explained by soft ground TBMs working principles. EPB machine rotates excavated earth material in the chamber and slurry TBMs rotates earth-slurry mixture in the chamber, which has a low density, thus EPB machines need more torque force than others.

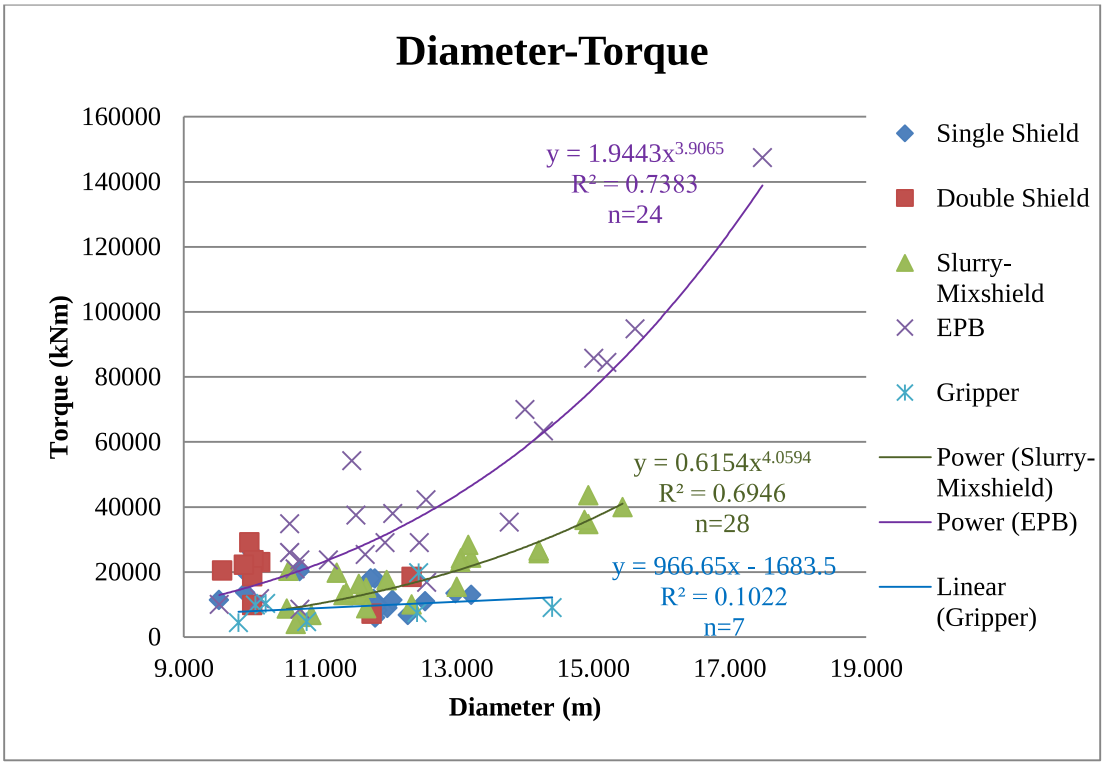


Figure 4.6 : Torque - Diameter relationship for large diameter TBMs.

Like torque requirement, thrust requirement (Figure 4.7) is also related with formation properties for single shield and double shield TBMs, and it is connected with diameter for EPB and slurry TBMs. It should be mentioned that gripper TBMs' thrust – diameter relationship is not strong and it is related with formation properties, especially uniaxial compressive strength of the rock. Moreover single shield and double shield TBMs could have propelling force figures as much as, or, even more than soft ground machines, however, there is not enough data to support this idea after 12 meters. This could be related to high friction coefficients of the rocks as explained in the previous section. The gripper TBMs have the lowest thrust figures.

The high thrust rates of the soft ground TBMs, especially for larger diameters, can be explained by squeezing conditions in these types of grounds. Moreover because of the very large surface area of the shielded TBMs, the friction between the shield and the ground is very high. Thus, soft ground TBMs need tremendous forces to compete with the friction.

It is also found that double shield TBMs auxiliary thrust is nearly 2 times higher than their normal thrust, which can also be explained by high friction forces between the shield and ground.

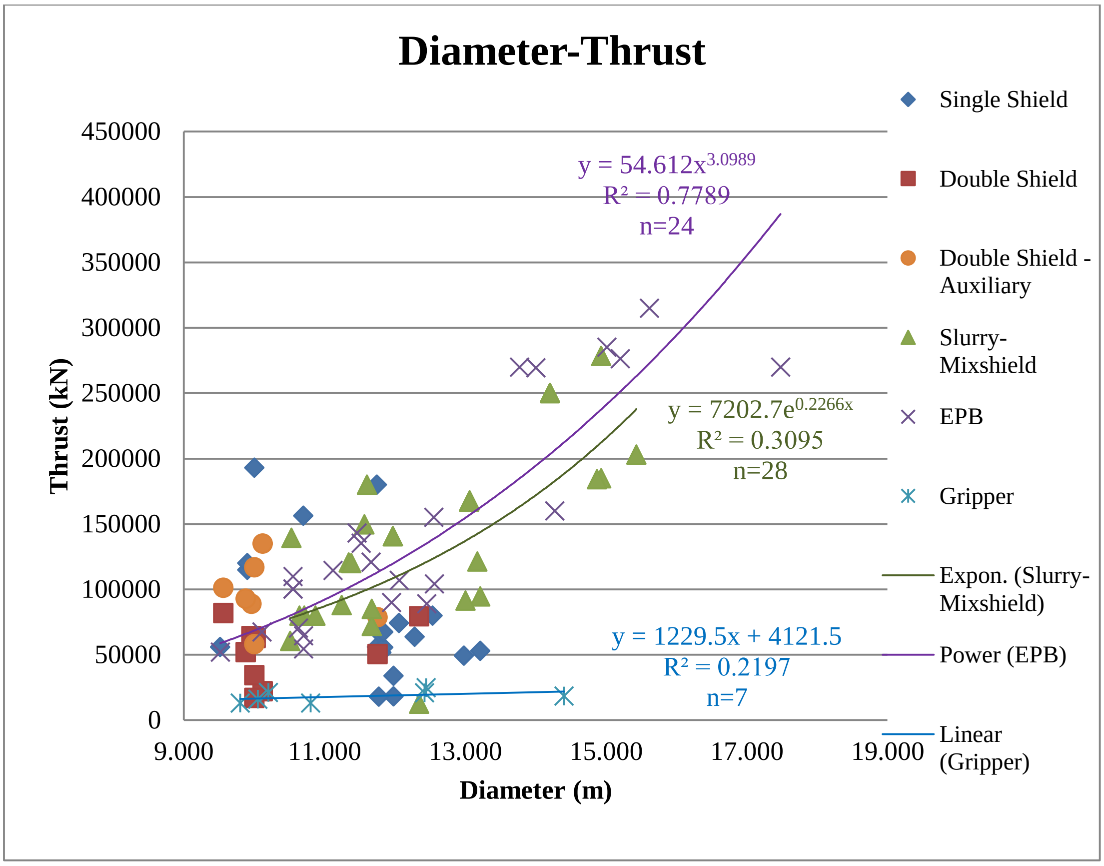


Figure 4.7 : Thrust - Diameter charts for large diameter TBMs.

There are linear relationships between thrust and torque for all types of TBMs except double shielded and EPB machines (Figure 4.8). Moreover it should be noted that EPB TBMs have a power trendline between thrust and torque forces but it is very close to a linear relationship. The correlation is significant for EPB and gripper TBMs. However it should be mentioned that the gripper TBM number is very low to make a good analysis.

Furthermore, thrust – torque ratio is decreases with increasing diameter (Figure 4.9). However the relationship between thrust-torque ratio and diameter has a very high standard deviation and it is not strong to make a good prediction.

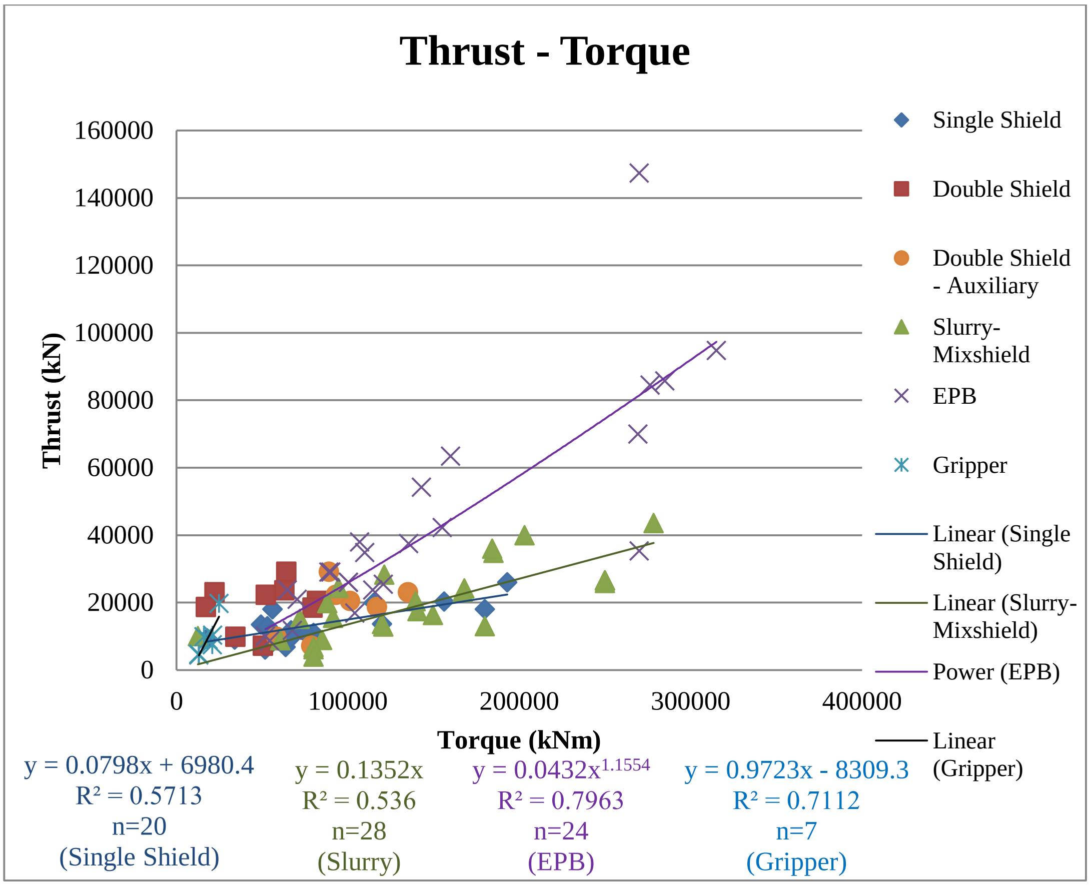


Figure 4.8 : Thrust - Torque relationships for large diameter TBMs.

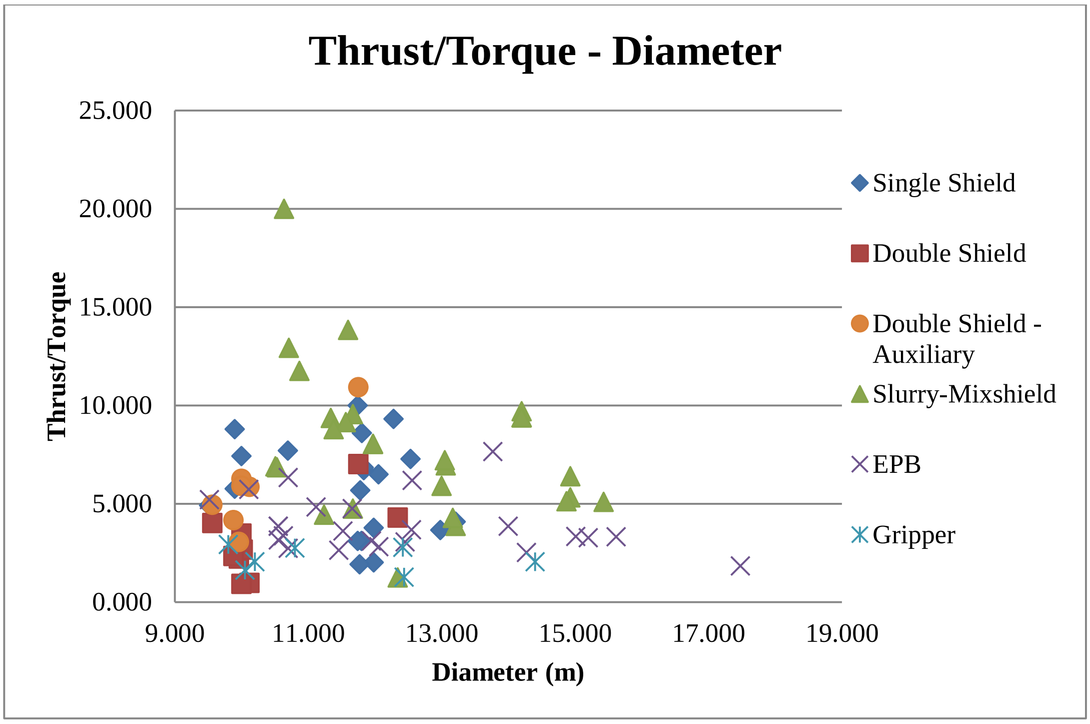


Figure 4.9 : Thrust/Torque - Diameter relationship for large diameter TBMs.

4.3.2 TBM weight and number of cutters

Figure 4.10 shows TBM weights as a function of diameter. It should be mentioned that these figure includes both TBMs weight and backup trailers weight. Because of the TBM's shield design, the heaviest TBMs are double shielded ones, where the lightest ones are gripper TBMs, which have no shield. Moreover, EPB TBMs weight has a strong relationship with diameter. 13-meter diameter TBMs approximate weights are 2000 tons for single shield, more than 4000 tons for double shield, 1500 tons for gripper, 3000 for EPB and 2000 tons for slurry machines. While the backup unites were included the weight figures, backup facilities also should be taken into consideration for analysis, however, there is not enough data about the backup units weight which used in these 88 projects.

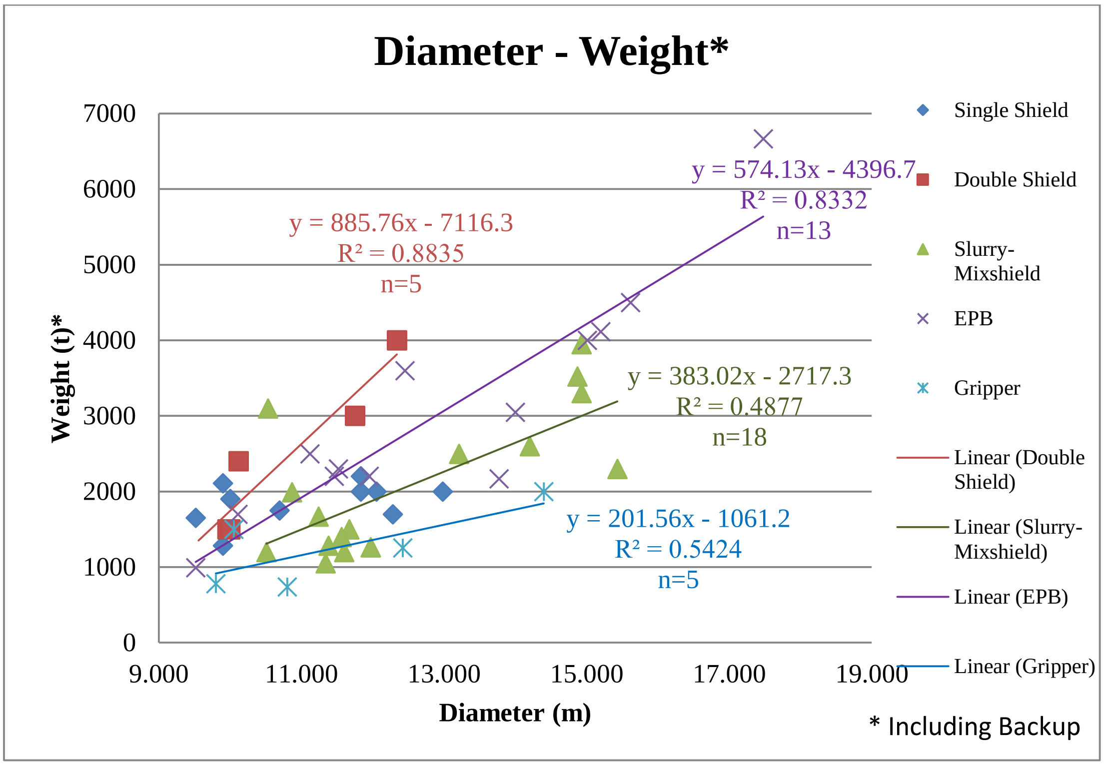


Figure 4.10 : Weight - Diameter relationships for large diameter TBMs.

Gripper, single shield and double shield TBMs are hard rock TBMs. They used to excavate hard rock formations and they have similar cutterhead designs. Thus, these types of TBMs' cutter numbers can be analyzed together (Figure 4.11).

Optimal spacing to depth ratio for cutters is extremely important for designing the cutterhead and these variables depends on the formation properties, which will be excavated. Therefore, the number of cutters is strongly related with formation, diameter and cutter size.

It should also be mentioned that the some manufacturers use disc cutters on soft ground TBMs for mixed formations, however, there is not enough data investigate the relationship between diameter and number of cutters for these types of machines. With a limited number of data, it is possible to say that EPB TBMs have more cutters than hard rock TBMs for the diameters larger than 12 meters.

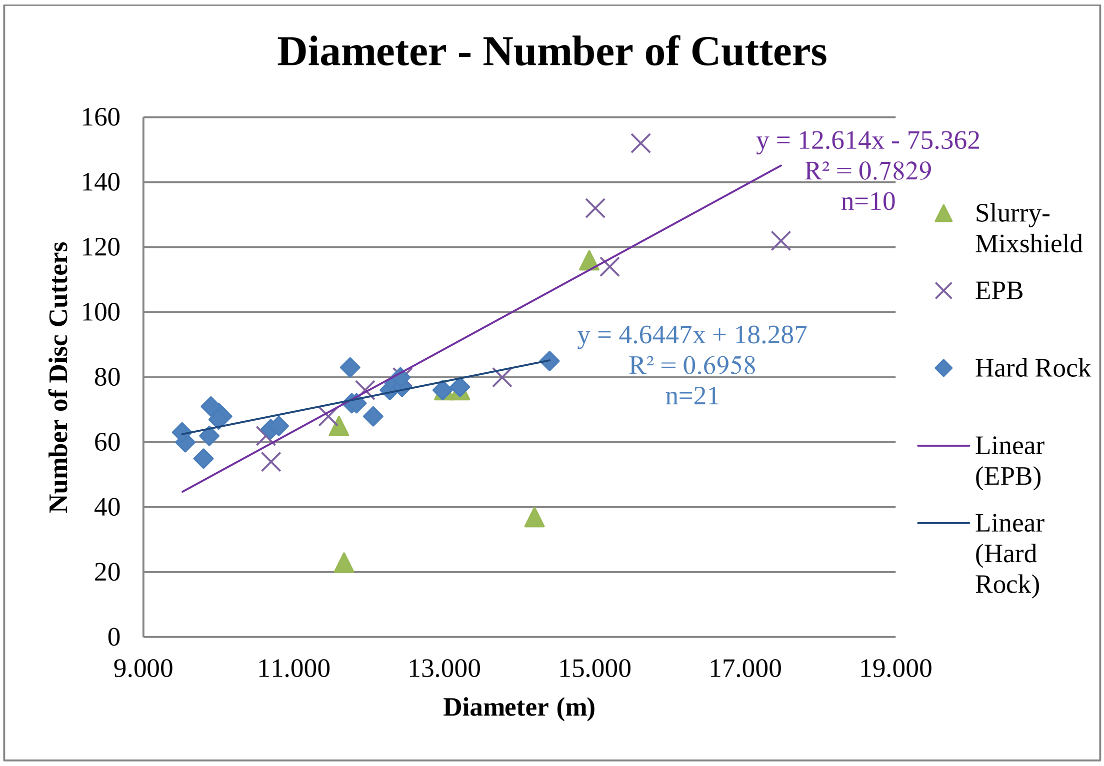


Figure 4.11 : Number of Cutters - Diameter relationships for large diameter TBMs.

Moreover, it should be noted that because of limited space for the cutter disc housing, on the center of the cutterhead manufacturers generally use 3 to 6 double cutters on this area.

4.4 Small Diameter TBMs

Unlike the larger ones small diameter TBMs have been manufactured and heavily used in different projects since 1950's (Figure 4.12). However, because of the differences between the design parameters, this section covers TBMs that were manufactured after 1985.

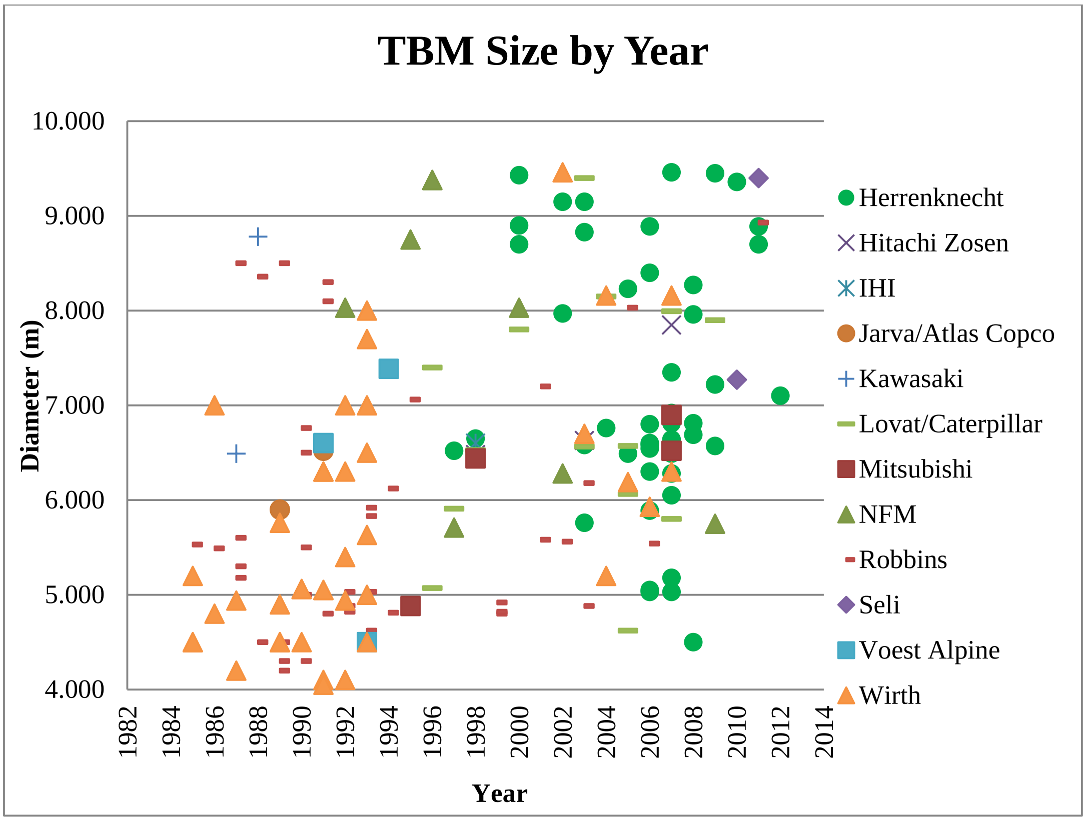


Figure 4.12 : Small diameter TBMs manufactured after 1985.

This section covers and compares, 4 single shield, 29 double shield, 65 gripper, 62 EPB and 11 slurry TBMs' design properties with each type and large diameter TBMs.

Small diameter TBMs main usage areas are different than large diameter TBMs. Every 1 in 3 small diameter TBM is used in mainly for metro projects. In contrast to the large diameter TBMs, road and railway projects together consists less than one fourth of the total projects which small diameter TBMs were used (Figure 4.13). Using a small diameter allows to build a single track metro or railway and double lane road. For fractured formations using two small diameter TBMs is generally more advantageous than using a one large diameter TBM, because, as mentioned before large diameter TBMs are more sensitive to the fractured formations. Small diameter TBMs have also been widely used for cable or other utility tunnels.

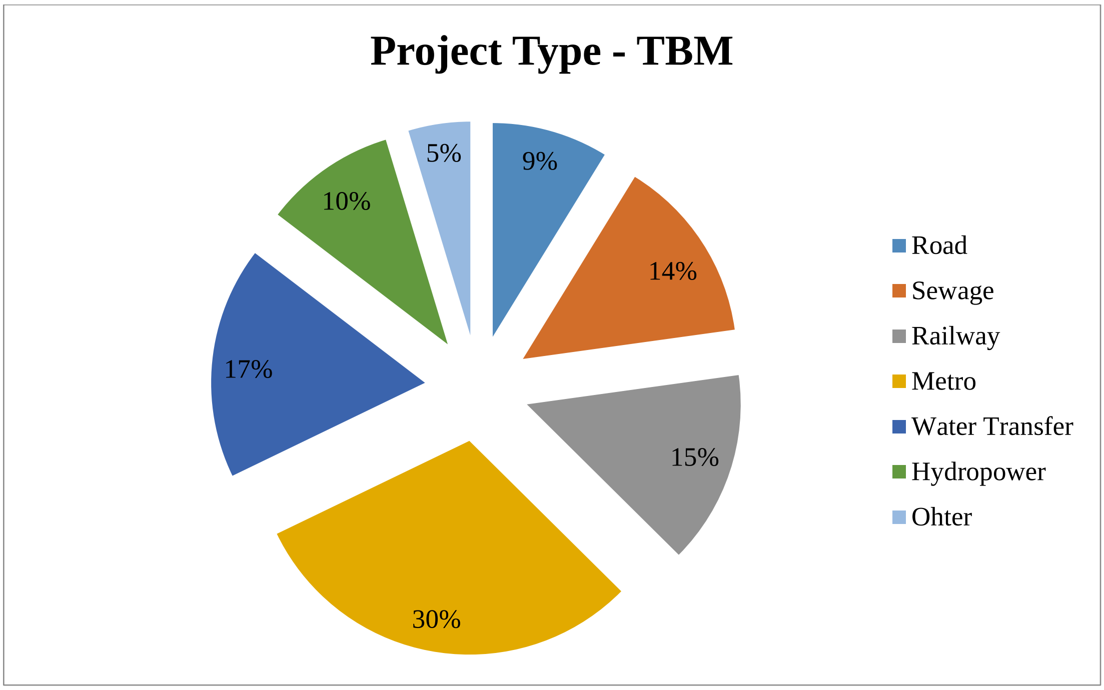


Figure 4.13 : Project types where small diameter TBMs were used.

4.4.1 Torque and thrust requirements for small diameter TBMs

Single shield and double shield TBMs torque requirements is different from larger ones. It is found that for these models torque is related to diameter more strongly, which is related to the formation in large section TBMs. On small diameter TBMs arching height of the rock is lower than large diameter TBMs (approximately 2 times of the diameter). This difference cause low earth pressure on and towards the cutterhead. Therefore number of cutters and rolling force required to cut the rock is more effective than large diameter TBMs. However it should be noted that only 4 single shield TBMs were analyzed. Thus the relationship could change as the TBM number increases.

Similar to single and double shield TBMs, gripper TBMs torque force is related with rock cutting and therefore the number of cutters, which is directly related with diameter.

EPB and slurry TBMs have exponential relationship between their torque and diameter which is similar to large diameter ones. It should also be mentioned that the EPB TBMs torque is generally higher than other types, which, again, can be explained with its working principles. Moreover small cross section slurry TBMs have close figures to gripper TBMs.

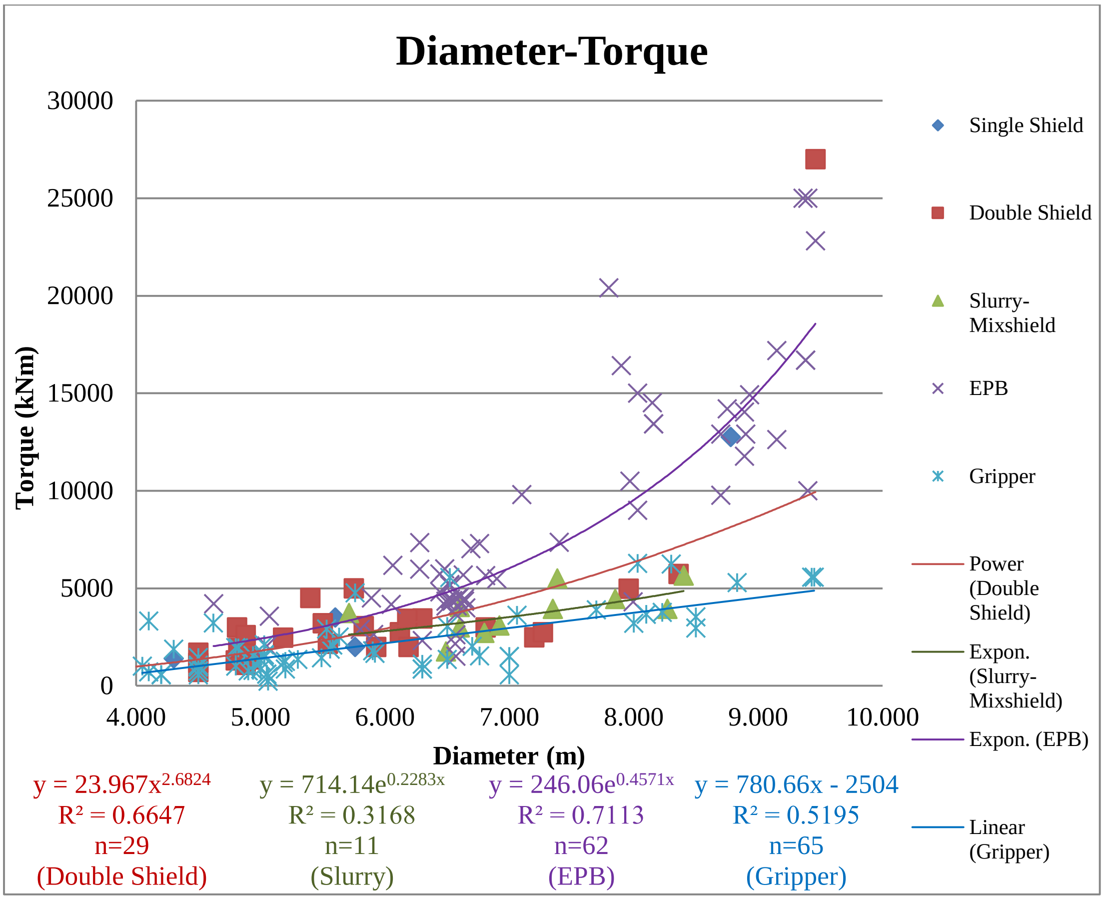


Figure 4.14 : Torque - Diameter relationship for small diameter TBMs.

In general terms small diameter TBMs thrust – diameter relationship is similar to large diameter TBMs (Figure 4.15).

Slurry and EPB machines thrust force is nearly equal to each other and it is related with diameter like large diameter ones.

There is a slight relationship between double shield (gripper mode) and gripper TBMs diameter and thrust figures. As mentioned before double shield TBMs working principle on the gripper mode is same as gripper TBMs. Therefore, they have similar trend between their thrust and diameter and it is related with number of cutters and rock strength. Their thrust is generally higher than gripper TBMs because they have a long shield, and, for this reason their weight is higher than gripper TBMs which requires more thrust force to advance.

On auxiliary mode, a double shield TBM works as a single shield TBM and friction forces on the shield is important like soft ground TBMs. Thus, the trend is similar to soft ground TBMs.

Moreover, generally, gripper TBMs have the lowest thrust figures for a given diameter like large diameter TBMs

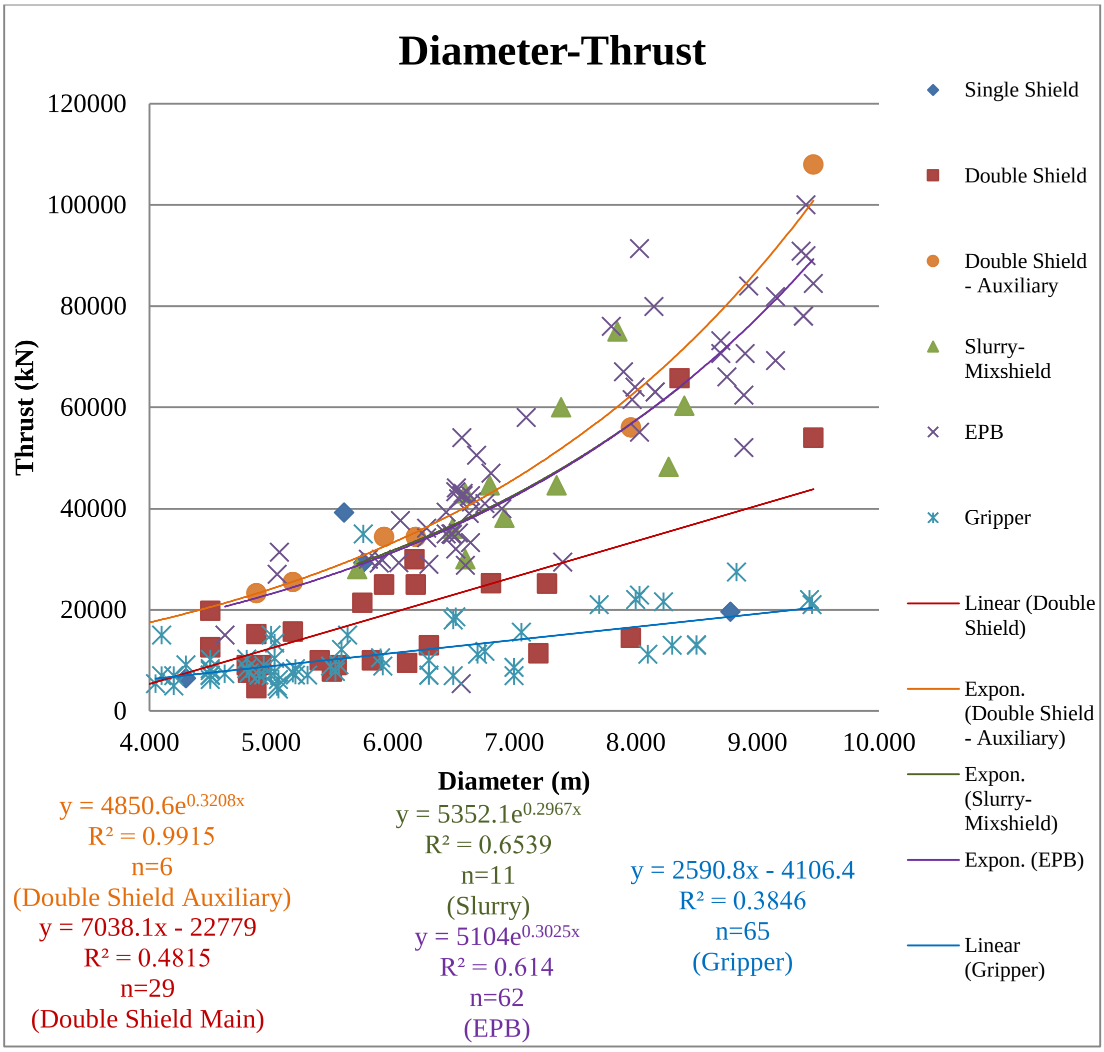


Figure 4.15 : Thrust - Diameter charts for small diameter TBMs.

By analyzing thrust – torque figures it is found that gripper TBMs and double shield TBMs (gripper mode) thrust torque relationship is similar and very close to each other (Figure 4.16). Like these, double shield TBMs auxiliary mode and EPB TBMs thrust – torque figures are also similar to each other.

For all types of TBMs (except single shield TBMs which has not enough data to analyze) thrust increases linearly with the increasing torque figures. Moreover gripper and EPB TBMs have stronger thrust-torque relationship than other types.

It should be mentioned again, that there is very limited data about the double shield TBMs auxiliary thrust.

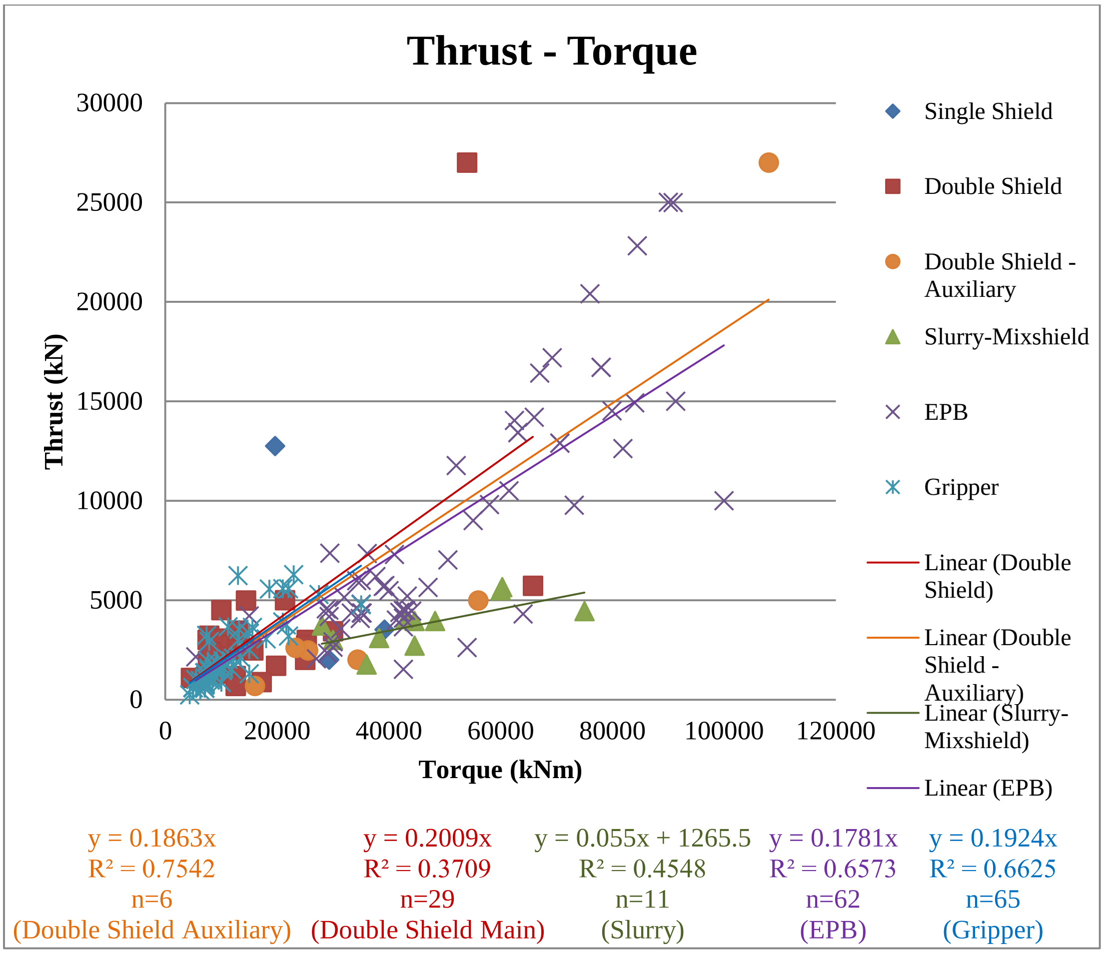


Figure 4.16 : Thrust - Torque relationships for small diameter TBMs.

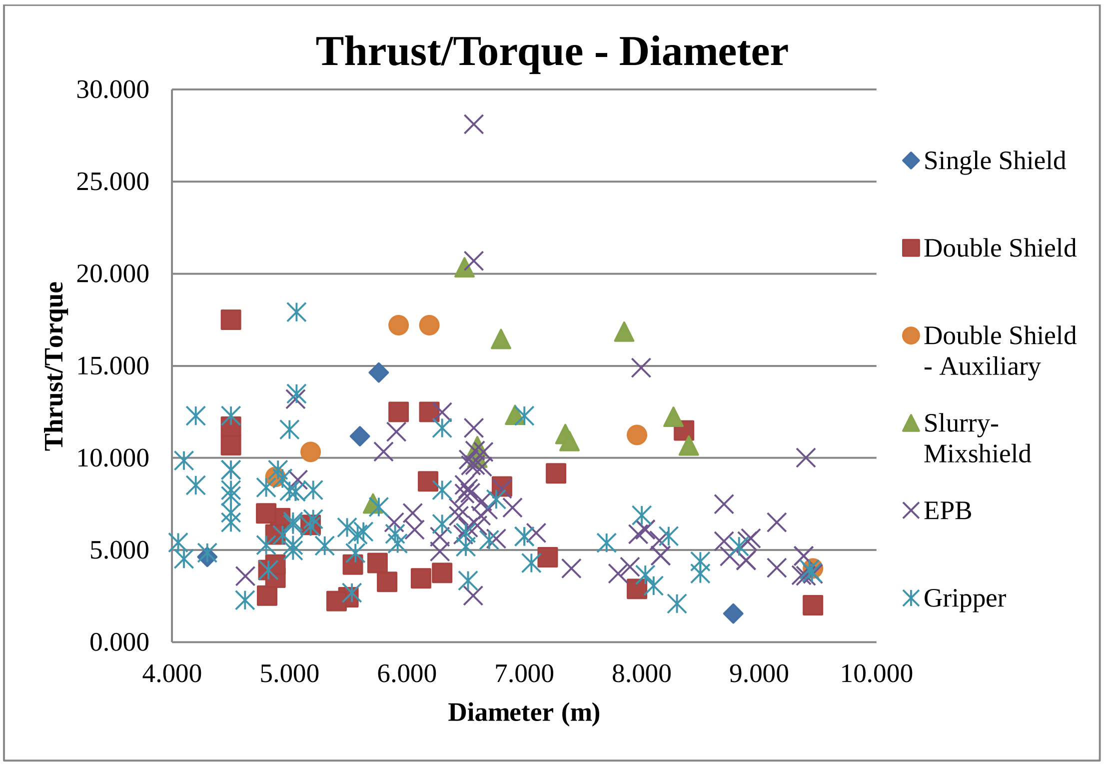


Figure 4.17 : Thrust/Torque - Diameter relationship for small diameter TBMs.

As the diameter increases thrust – torque ratio decreases in small diameter TBMs like large ones (Figure 4.17). It is also found that the large diameter TBMs thrust – torque ratio is less than small diameter ones.

4.4.2 TBM weight and number of cutters

Figure 4.18 shows TBM weights, including backup weight, as a function of the diameter. Like large diameter TBMs, weight is related with the diameter and TBM type.

Generally gripper TBMs are the lightest TBMs for a given diameter. Moreover it also should be noted that, like large diameter TBMs, there is not enough data about the backup unites which used with these TBMs. It is found that the weight trends for all types of TBMs, except double shield ones which a trend could not be found, are very close to each other.

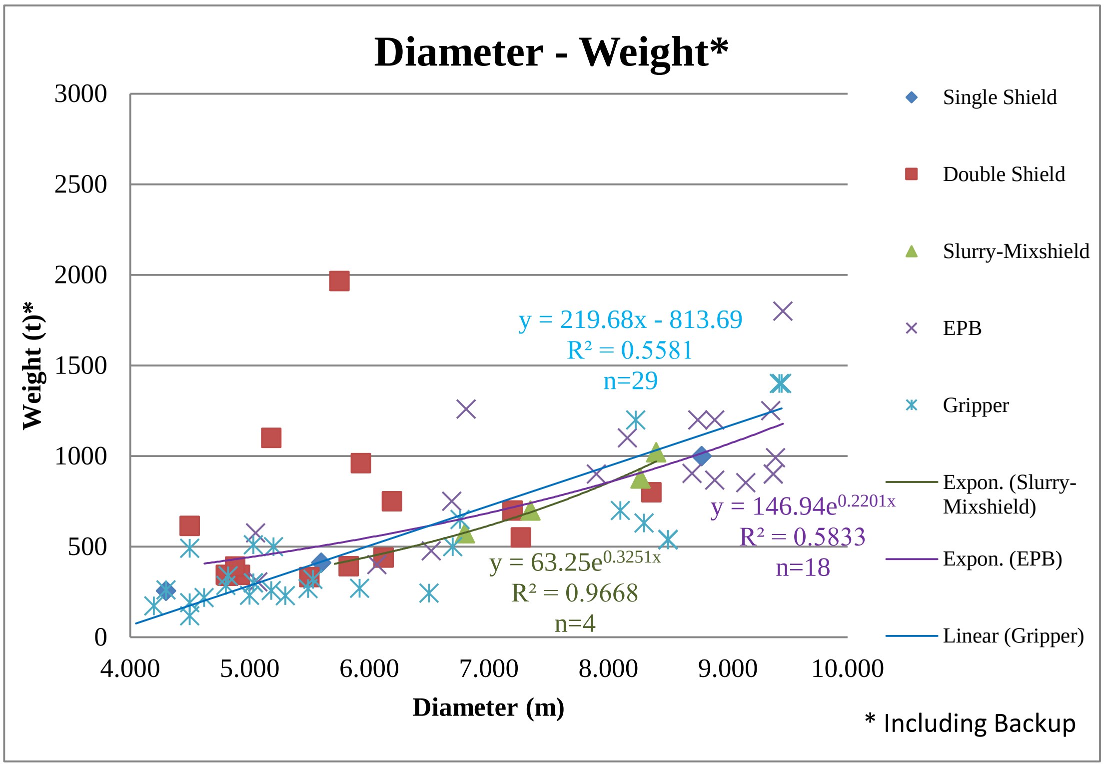


Figure 4.18 : Weight - Diameter relationships for small diameter TBMs.

To make a good comparison between large and small cross section TBMs, single shield, double shield and gripper shield TBMs are combined in hard rock TBM group for the cutter number data, like large diameter TBMs (Figure 4.19). The relationship between the number of cutters and diameter on small diameter TBMs is stronger than large ones for hard rock TBMs. However, it should be noted that the strong relationship could be related to the large number of data.

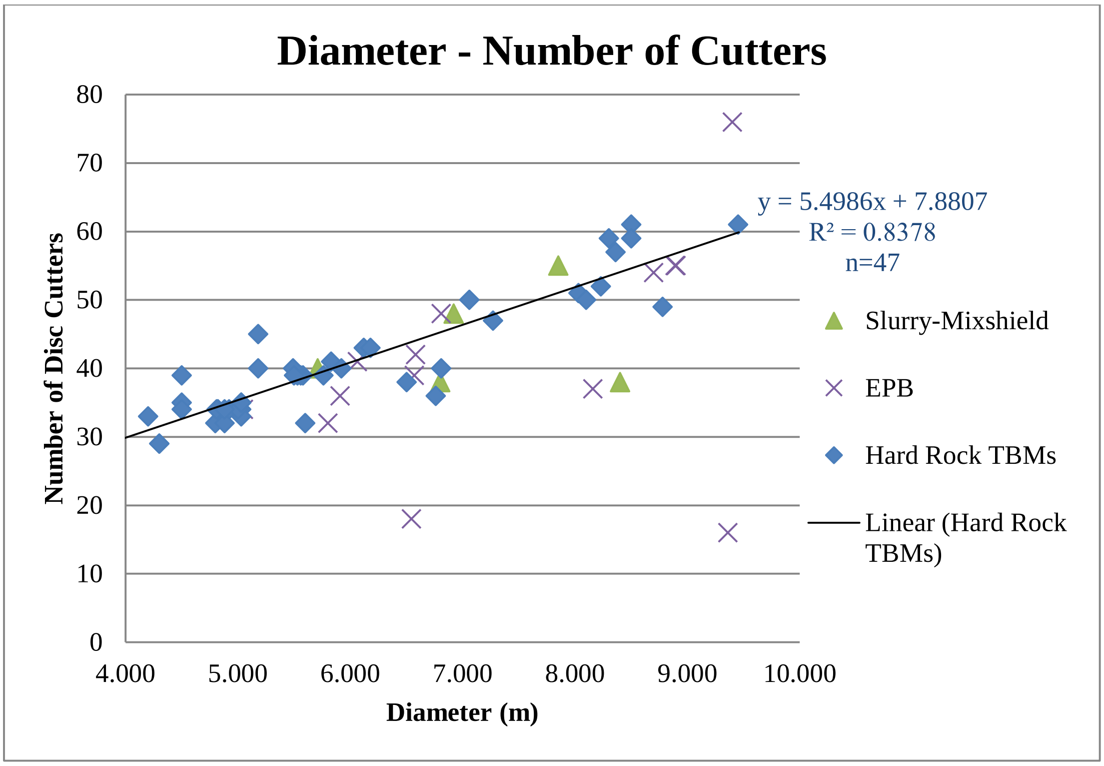


Figure 4.19 : Number of Cutters - Diameter relationships for small diameter TBMs.

4.5 TBMs Manufactured Before 1985

A brief history of TBMs is given in the first section of the thesis. Because of very different design parameters and technology, TBMs which manufactured before 1985 were grouped according to their type and their properties, and analyzed separately. It should also be noted that in this section TBMs were not grouped according to their diameter, because there was not enough TBMs larger than 9.5 meters before 1985 to make a good analyze. Moreover there is only enough data about the gripper TBMs, thus this section mainly covers the gripper TBMs, but other types properties were also given as a reference where it is possible.

In this section total number of 71 TBMs, which includes 3 single shield, 2 double shield, 64 gripper and a slurry type, properties were studied.

According to analyses (Figure 4.20) the first noticeable difference between modern and old TBMs is project types where the TBMs were used. For modern TBMs, road and railway tunnels consist nearly 45% of the total usage, where before 1985 these projects consist only 15%. The main usage areas of the old TBMs were water transfer tunnel and hydropower plant tunnel projects.

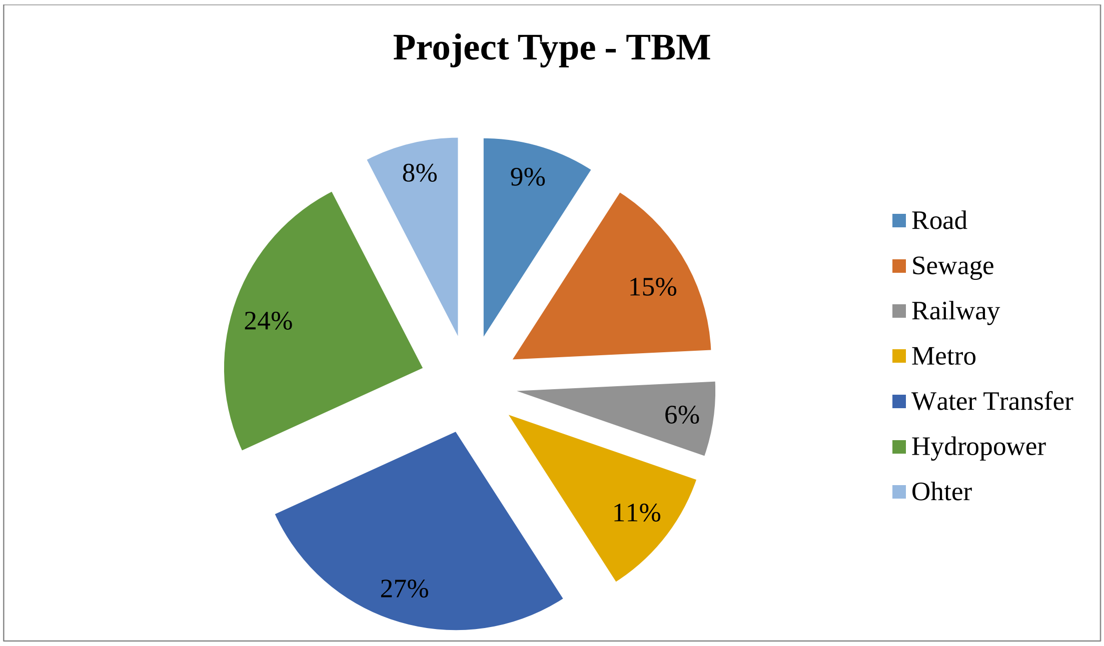


Figure 4.20 : Project type proportions which the TBMs were used before 1985.

It should be mentioned that in the past, using the same TBM for more than one project was common. Some TBMs were refurbished and used for more than 10 projects. For example a Robbins TBM, model number 123-133, manufactured in 1970 and used until 1992 without any major change in the design. Moreover, some companies, like Jarva, standardized their TBM design.

4.5.1 Torque and thrust requirements of old TBMs

As explained above this section will only cover gripper TBMs. Like modern ones, old gripper TBMs torque is related with its diameter and formation. As the diameter and formations uniaxial compressive strength (UCS) increase, TBM's torque is also increase (Figure 4.21).

Unlike to the torque requirements, thrust is related with formation's properties more than diameter (Figure 4.22). With increasing UCS, TBMs thrust force is increases. For example 8 meter diameter Ohae Dam TBM has 444 kN thrust force (UCS along the route 1-3 MPa) where 8.1 meter diameter Bramefarine Tunnel TBM's thrust force is 7060 kN (UCS along the route 14-42 MPa) and 7.8 meter diameter Bergen Roadway Tunnel TBM's thrust force is 11420 kN (UCS along the route 140-246 MPa).

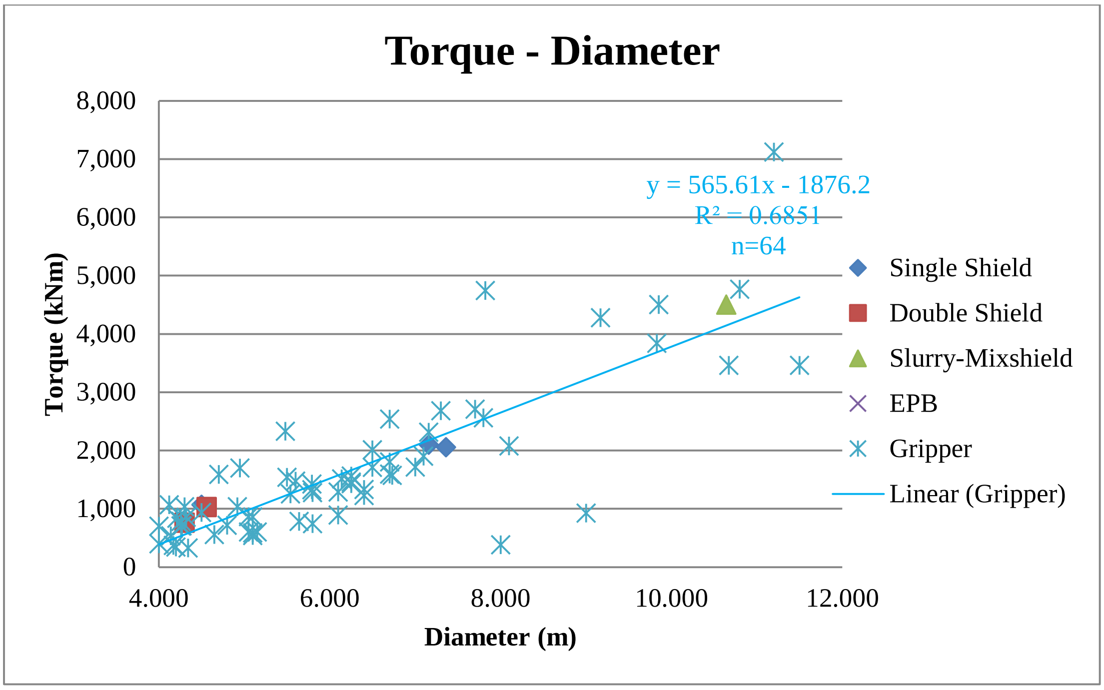


Figure 4.21 : Torque - Diameter relationships for old TBMs.

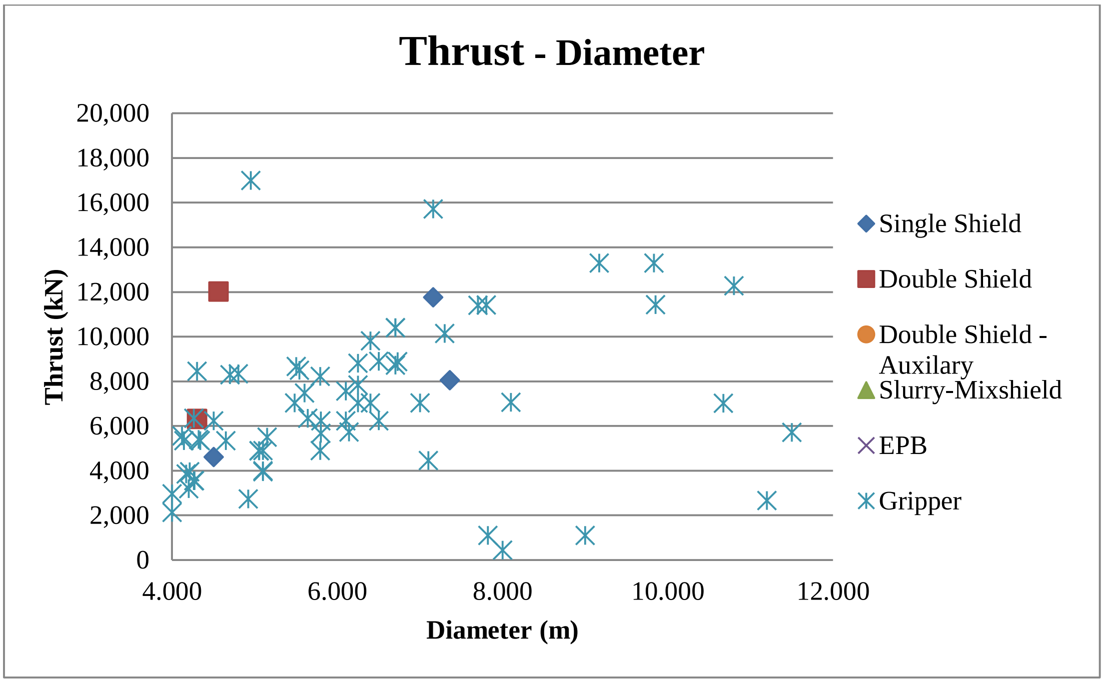


Figure 4.22 : Thrust - Diameter relationships for old TBMs.

Figure 4.23 shows both old TBMs and modern TBMs torque – diameter relationship. As it can be clearly seen from the graph old TBMs torque force is lower than modern TBMs for the same diameter. Moreover modern TBMs torque increases more rapidly with the diameter.

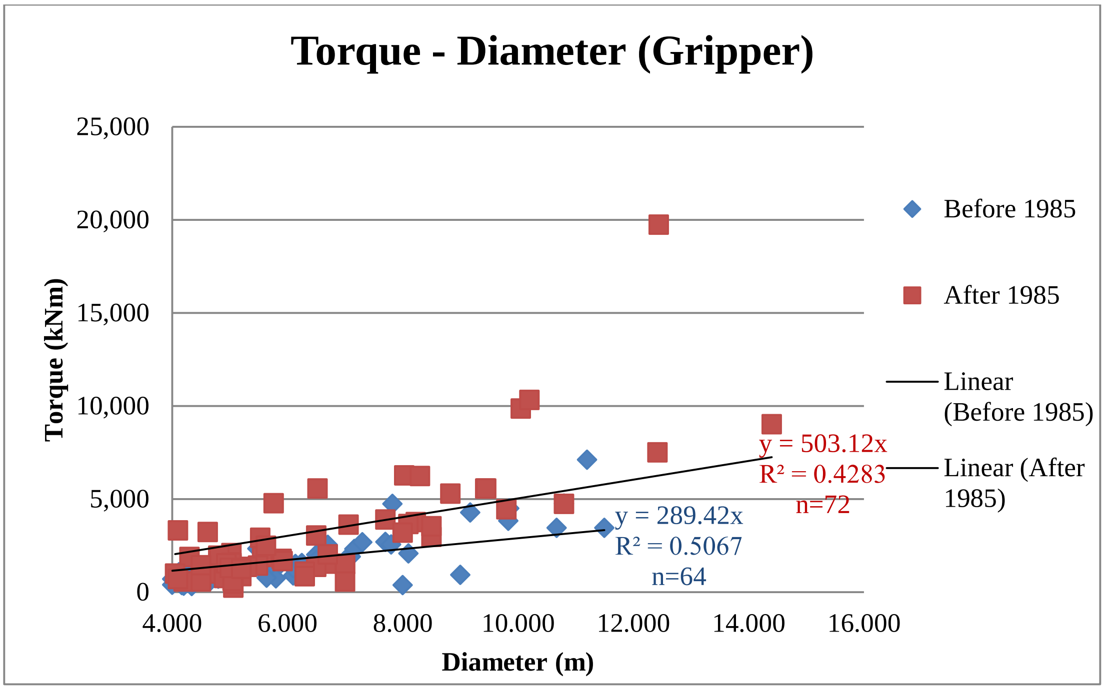


Figure 4.23 : Torque – Diameter relationship comparison between old and modern TBMs.

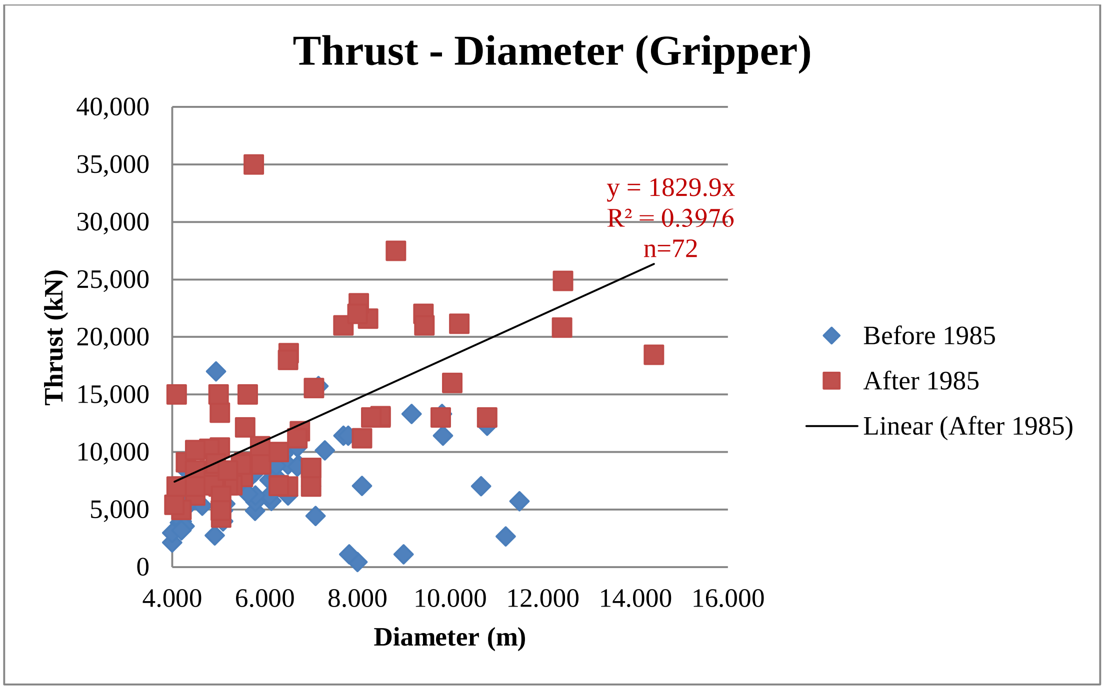


Figure 4.24 : Thrust – Diameter relationship comparison between old and modern TBMs.

By comparing the modern and old TBMs thrust force, it is found that the modern TBMs' propelling force is generally more than old TBMs (Figure 4.24). This could be explained by technological possibilities and disc cutters size. Modern disc cutters, 17 and 19 inches, can compete with loads more than 300 kN, which is far more than small size cutters. Moreover, TBMs and backup unites were less complicated and lighter in old times, thus, the required thrust force to propel the TBM was less than today.

According to Kahraman (2007) the new TBMs are more powerful and heavier than the old TBMs, which is consistent with this thesis. Modern TBMs thrust and torque forces are higher than old TBMs.

4.5.2 TBM Weight and number of cutters

As mentioned before TBMs manufactured before 1985 were lighter than modern TBMs. This could be explained by design parameters of the TBM, as well as the backup unites functions. Modern TBMs are far more complicated than older ones and they have more facilities. Thus TBMs weight increased by time. Figure 4.25 shows gripper TBMs manufactured before 1985 as well as manufactured after 1985.

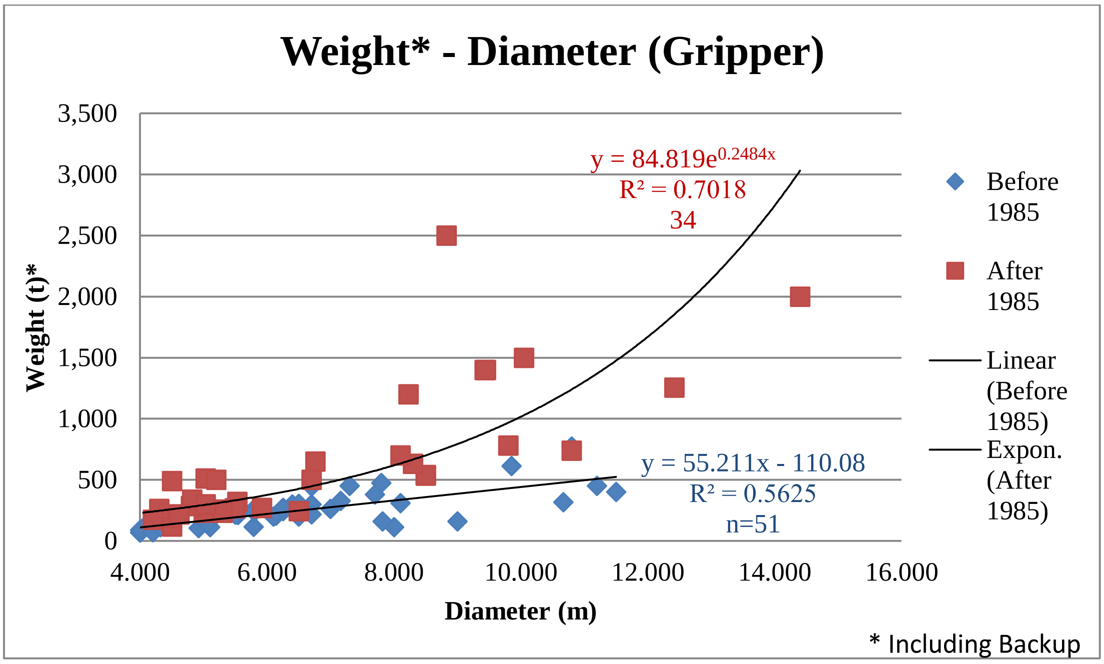


Figure 4.25 : Weight - Diameter relationship comparison between old and modern TBMs.

Cutter numbers for old and modern hard rock TBMs as a function of the diameter are given in Figure 4.26. Similar to the modern TBMs, old TBMs' cutter numbers increases with increasing diameter. As mentioned above cutter diameter was less than now at old times. Moreover, disc cutters had a V-shape (V-profile), which caused a rapid loss of efficiency as the tip wear occurred. Beginning in the late 1970s, V-shape ring profiles were replaced by constant cross-section (CCS) profiles to maintain cutting efficiency as tip wore out.

Cutters with V cross sections are no more used except in special cases due to uneven wear on the cutter tips which progressively changes the contact area with the rock (Bilgin et al., 2012).

The optimum S/P ratio is between 10 and 20 for CCS discs (Bilgin et al., 2012), which is more than V-Type disc cutters. This allows increasing the cutter spacing without any change in penetration rate and specific energy. Because of this reasons modern TBMs utilize less cutters than old TBMs.

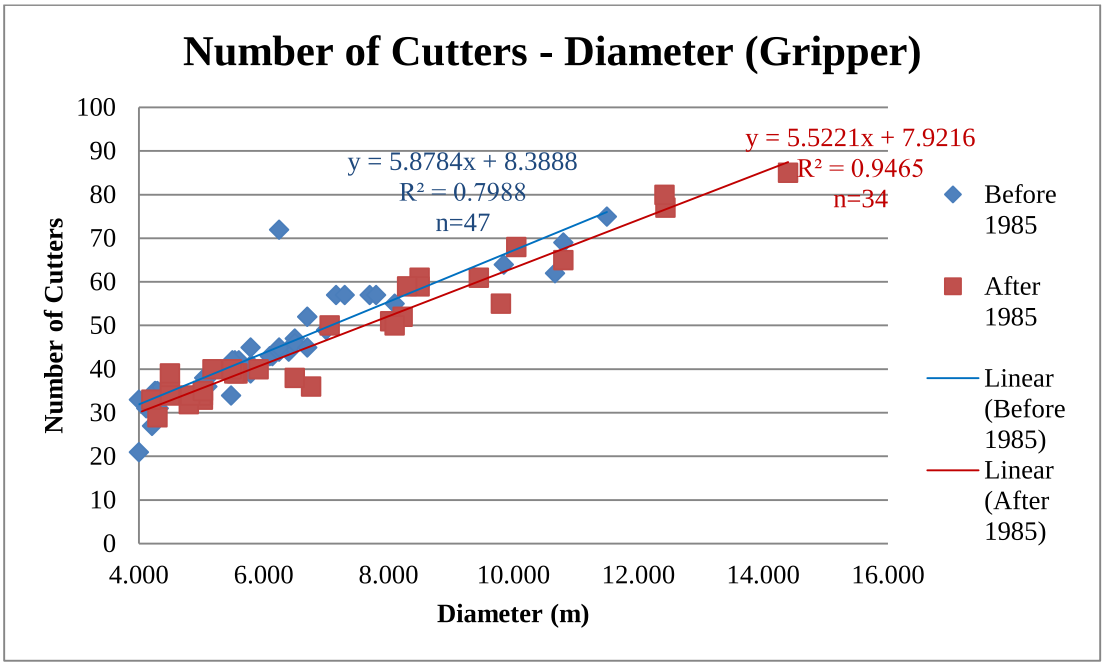


Figure 4.26 : Cutter Number - Diameter relationship comparison between old and modern TBMs.

5. REVIEW OF STATISTICAL EVALUTIONS AND COMPARISON WITH THEORIES

In this part of the thesis, small diameter and large diameter TBM data are combined and analyzed together. Total number of 259 TBMs' properties, which includes 24 single shield TBMs, 38 double shield TBMs, 72 gripper TBMs, 86 EPBMs and 39 slurry TBMs, were studied.

The combined data gives information about the usage areas of the TBMs. According to Figure 5.1, the main usage areas of the TBMs are road, railway and metro tunnel constructions. These three project types consists nearly two thirds of the TBM usage.

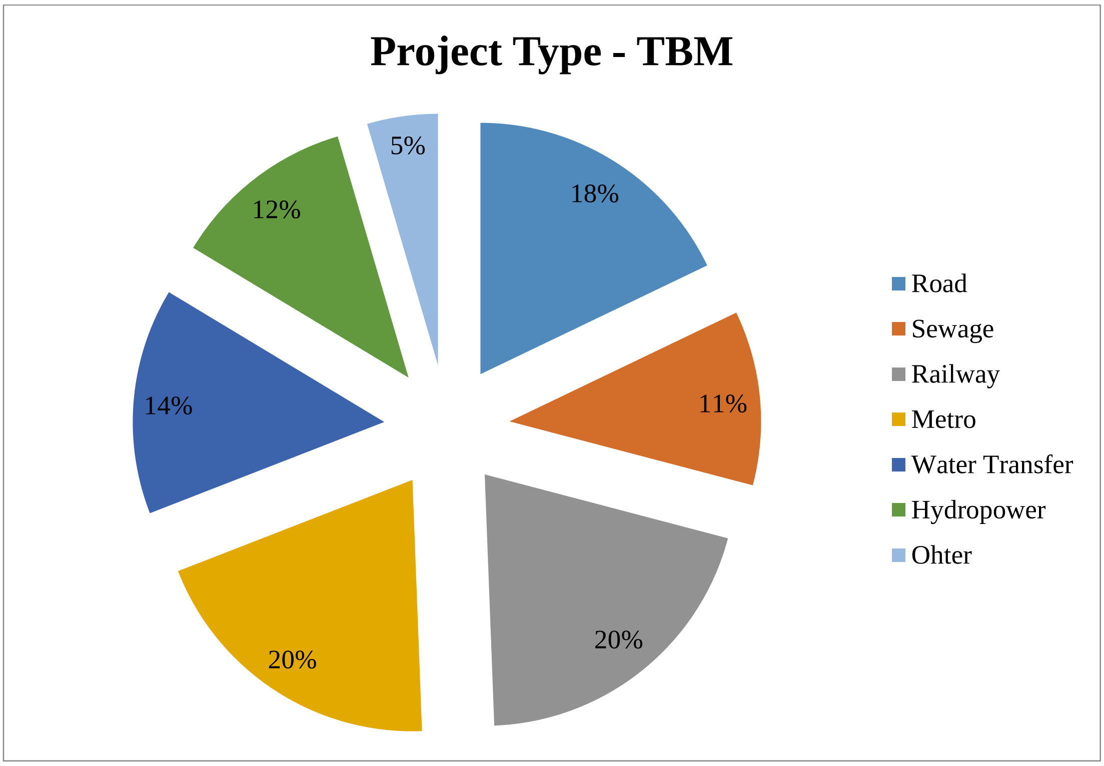


Figure 5.1 : Project types where TBMs were used.

With the help of new technological developments, TBM diameter has been increasing constantly (Figure 5.2). Today it is possible to manufacture and use a 16 m TBM without any problem. Also as mentioned before state of the art 17 and 19 meter TBMs are on the pipeline and manufacturing by Hitachi Zosen and Herrenknecht companies.

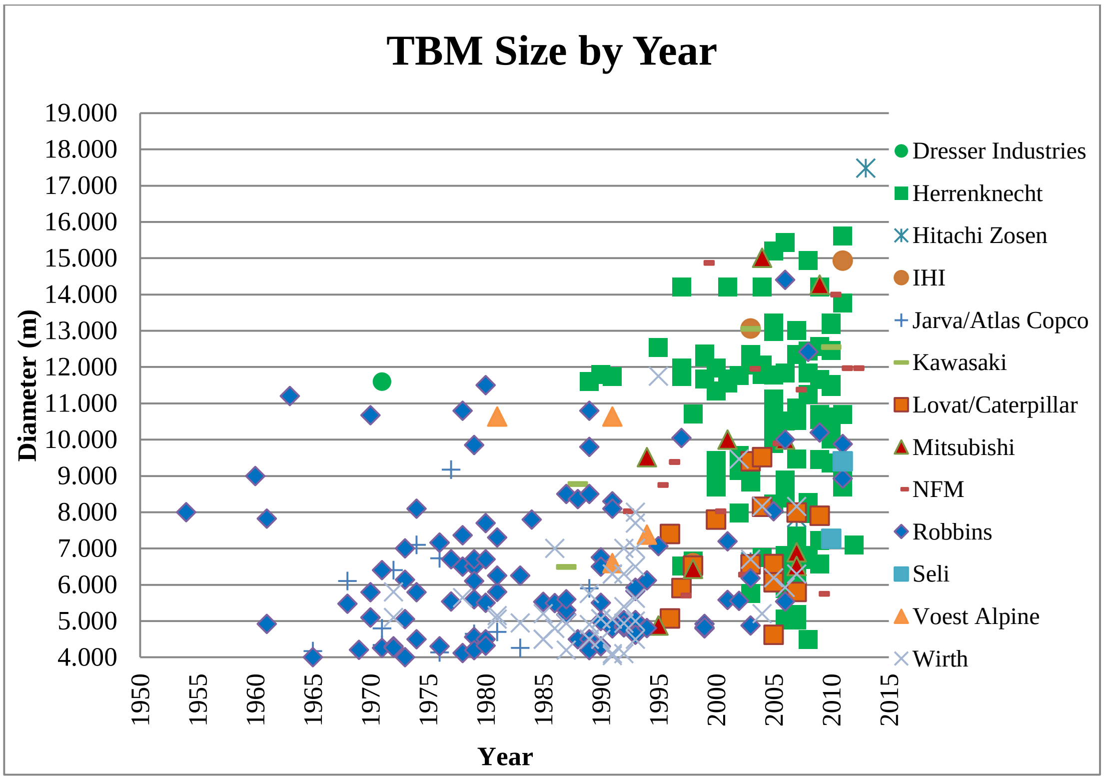


Figure 5.2 : TBM diameter by year.

5.1 Torque Requirements of TBMs

5.1.1 Combination of small and large diameter TBM data

By examining the data in large scale, it is found that the diameter could help to predict the TBMs torque. For all TBM types, torque increases with diameter. However, formation properties are very important to make a good prediction, especially for hard rock TBMs. It should be remembered that some geological conditions need special TBM designs for reasonable advance rates, and diameter is not enough to predict a TBMs properties, formation must be taken into consideration.

Torque – Diameter relationships are shown in Figure 5.3. It is noticeable that the EPB TBMs torque, especially for large diameters, is far more than other types.

Increased TBM numbers are also allow understanding the torque – diameter relationships for single shield and double shield TBMs, which could not be found for larger diameters because of lack of data.

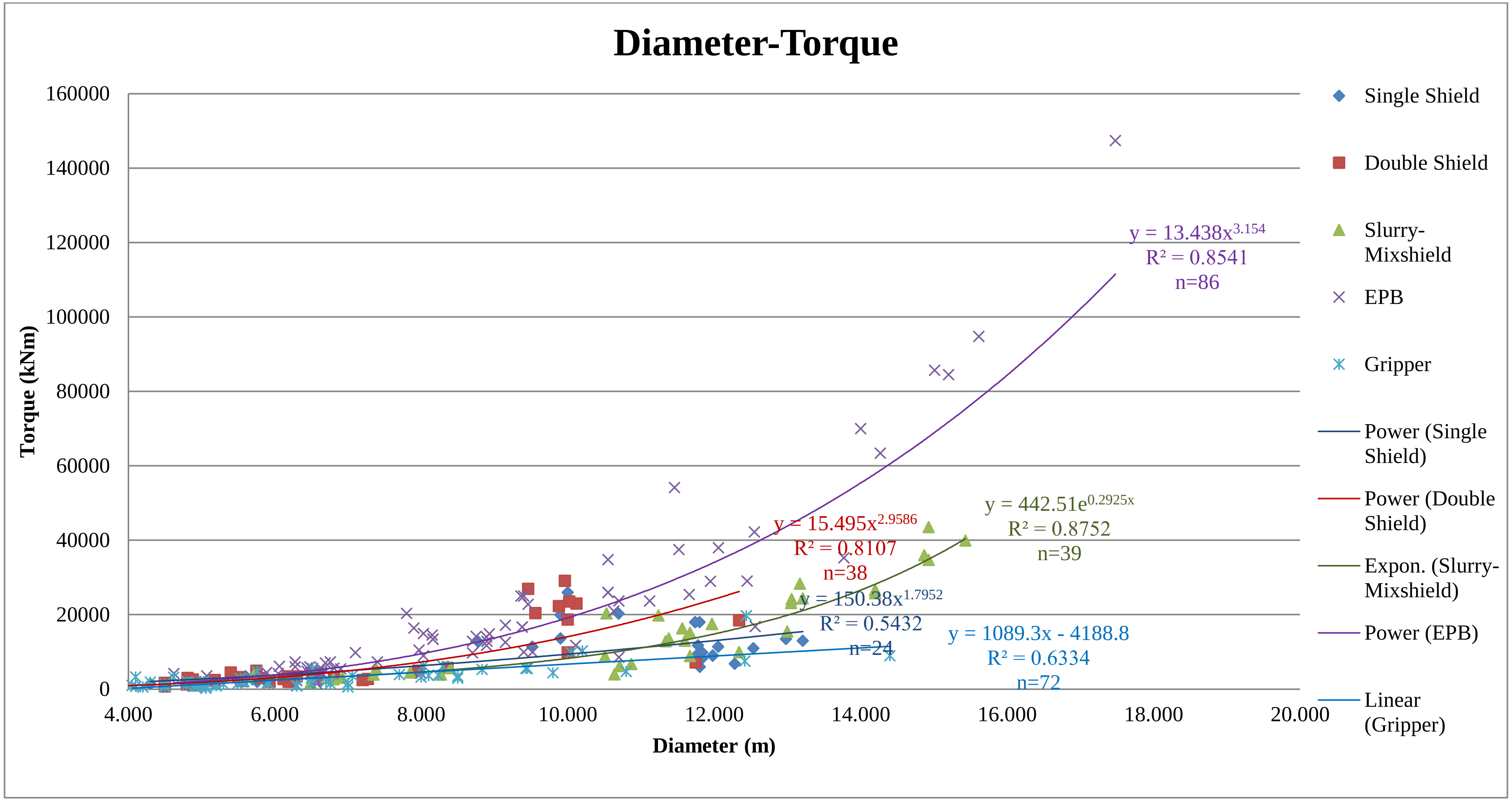


Figure 5.3 : Installed torque for different TBM types and diameters.

5.1.2 Comparison between calculated and installed TBM torque for hard rock TBMs

In this part theoretically calculated torque forces compared with installed torque forces of 72 gripper TBMs, 24 single shield TBMs and 38 double shield TBMs.

To make calculations simpler overburden depth is calculated as 1.5 times of the diameter and unit weight of the rock at face is taken as 2.6 t/m^3. Cutterhead opening ratios are taken as 20%. Coefficient of lateral earth pressure is taken as 1, and cutterhead thickness is taken as 0.7 m. Uniaxial compressive strength of the rocks are taken between 50 and 250 MPa. To calculate rolling force (F_R) of the discs the model developed by Rostami and Ozdemir (1993) is used.

It should be noted that nominal torque values of the TBMs are for comparison, thus friction coefficient is taken 0.25 which is dynamic friction coefficient for rocks. To calculate required torque for starting the cutterhead (breakout torque) after a standstill static friction coefficient should be used, which is around 0.45 (Ramoni, 2010). Moreover lubrication could reduce the required torque as much as 50%.

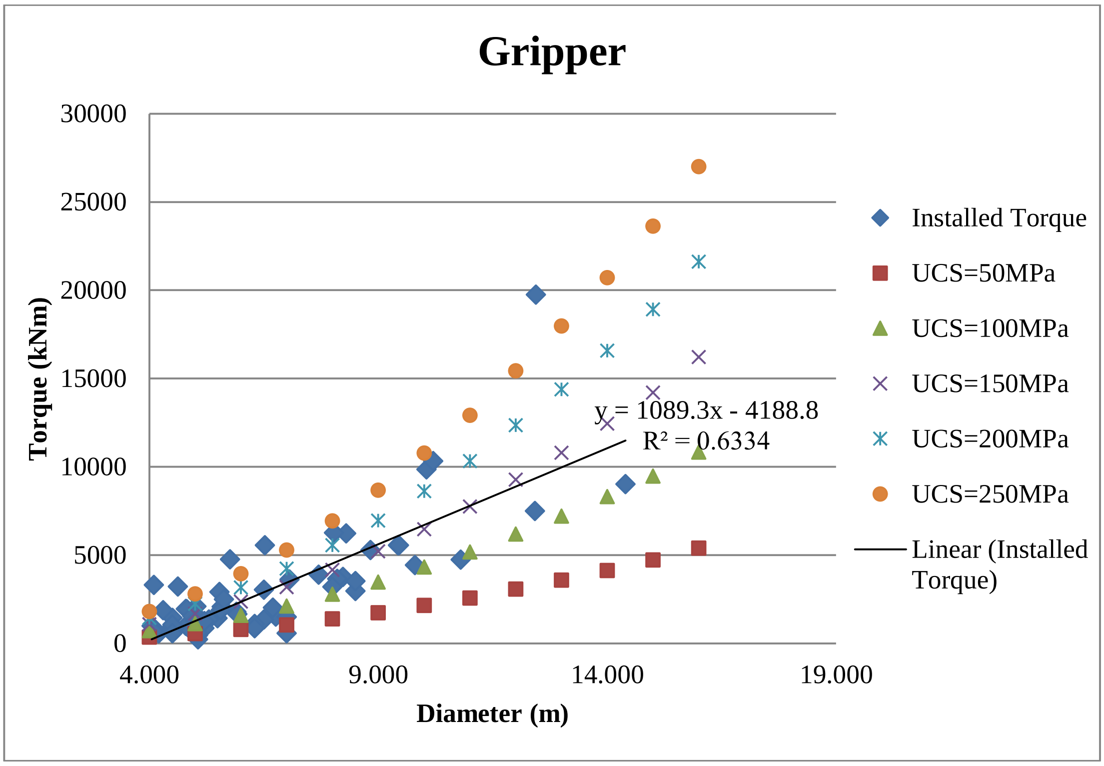


Figure 5.4 : Comparison of installed and calculated torque for gripper TBMs.

For gripper TBMs it is possible to say that calculation method given in this report gives closer values to installed torque.

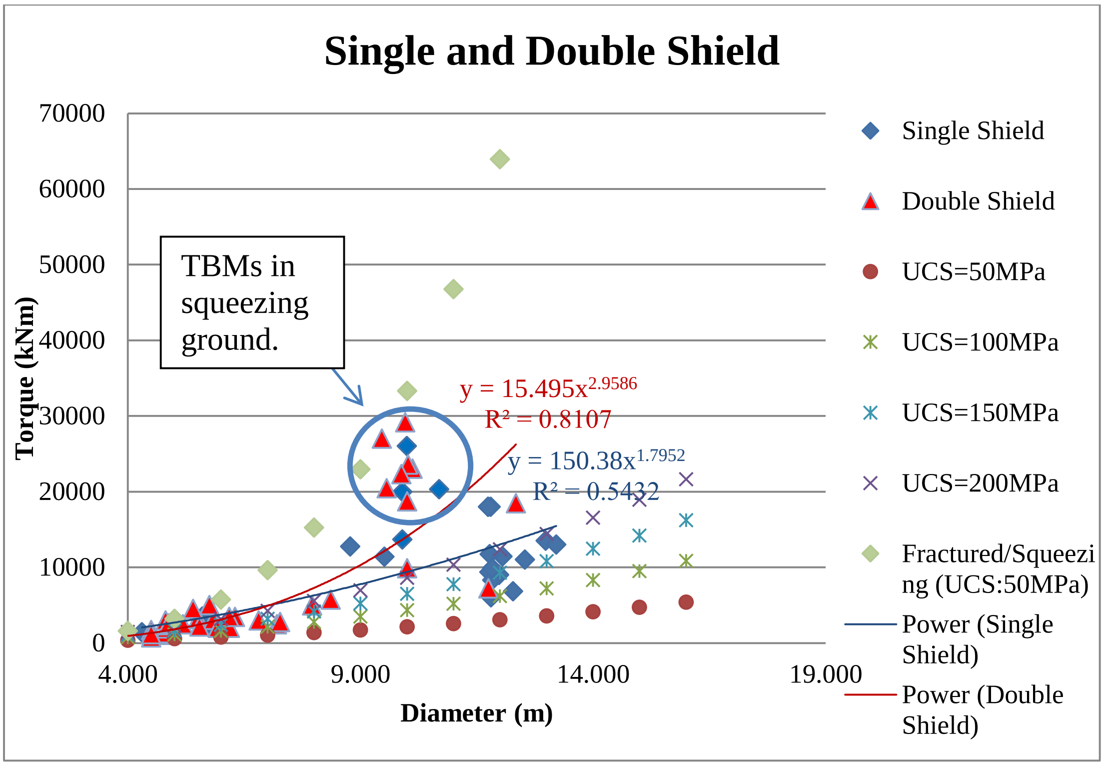


Figure 5.5 : Comparison of installed and calculated torque for single and double shield TBMs.

Figure 5.5 shows torque calculations and installed TBM data for single and double shield TBMs. Figure has two calculation types. The first one is for stable rock conditions (UCS=50-200MPa) and the second one is for fractured rock conditions with UCS 50MPa.

As can be seen from the figure, some of the TBMs are in between UCS 50MPa and UCS 200 MPa lines. These TBMs are used for excavating stable or stable but fractured rock conditions. It is very hard to calculate the exact ground pressures on the cutterhead, thus to make calculations simpler increasing the calculated torque with a safety factor should be enough to select the required torque.

In other cases, which are marked with squeezing ground label, using rock strength is not enough to calculate the required torque. As mentioned before friction torque on frontal surface of the cutterhead (T_2) and friction forces around the circular surface (T_3) of the cutterhead must be added to the cutting torque.

5.1.3 Comparison between calculated and installed TBM torque for soft ground TBMs

In this part of the report calculated torque forces compared with installed torque forces. Torque values are calculated for 39 slurry and 86 EPB TBMs.

Because of insufficient data about the geology and TBM design parameters, overburden depth is calculated as 2 times of the diameter and unit weight of the soil at face is taken as 1.7 t/m^3 and 2.2 t/m^3 for slurry and EPB TBMs respectively. For calculation of T_3, unit weight of the soil in pressure chamber is taken as 1.3 t/m^3 for slurry TBMs and 2.0 t/m^3 for EPB TBMs. Cutterhead opening ratios are taken as 40% for slurry TBMs and 30% for EPB TBMs. To see the effect of different geological conditions, friction coefficients were changed between 0.1 and 0.2. As the slurry and EPB TBMs use slurry/foam/polymer, the cutterhead is always lubricated for these types of TBMs. Thus, frictions coefficients for lubricated conditions were used (Table 3.1).

Coefficient of lateral earth pressure is taken as 0.5, and cutterhead thickness is taken as 0.7 m. To calculate values on the figures T_1, T_2 and T_3 is calculated and increased 30%.

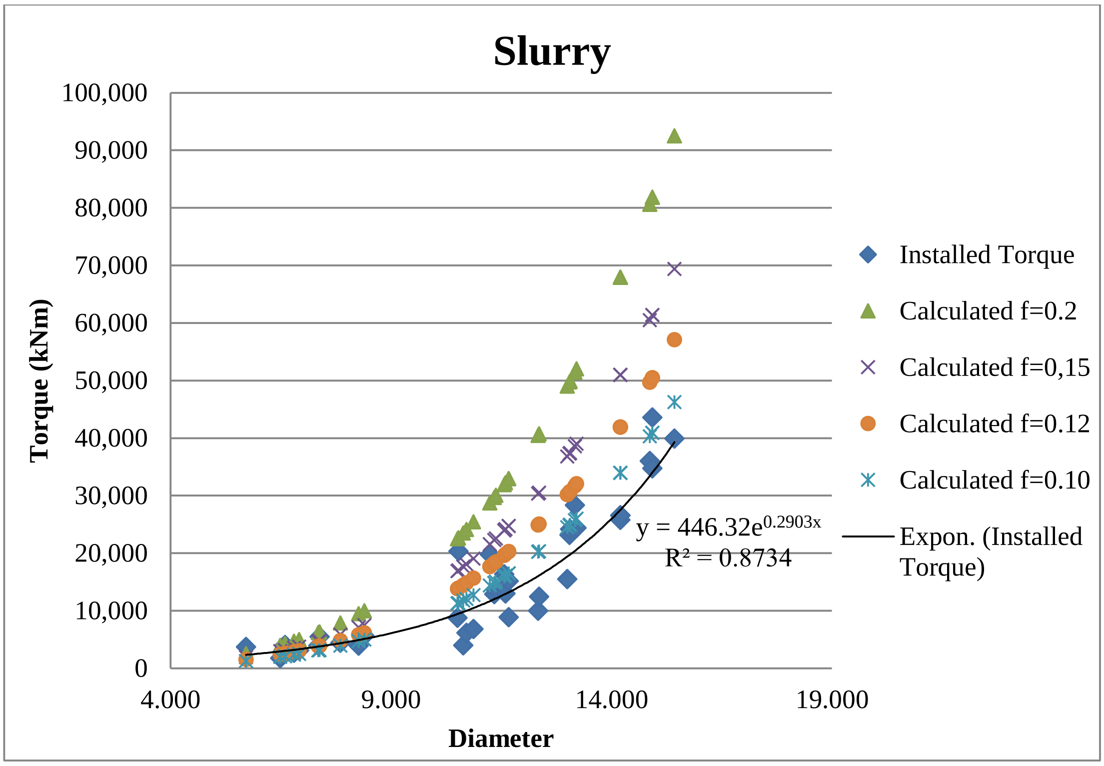


Figure 5.6 : Comparison of installed and calculated torque for slurry TBMs.

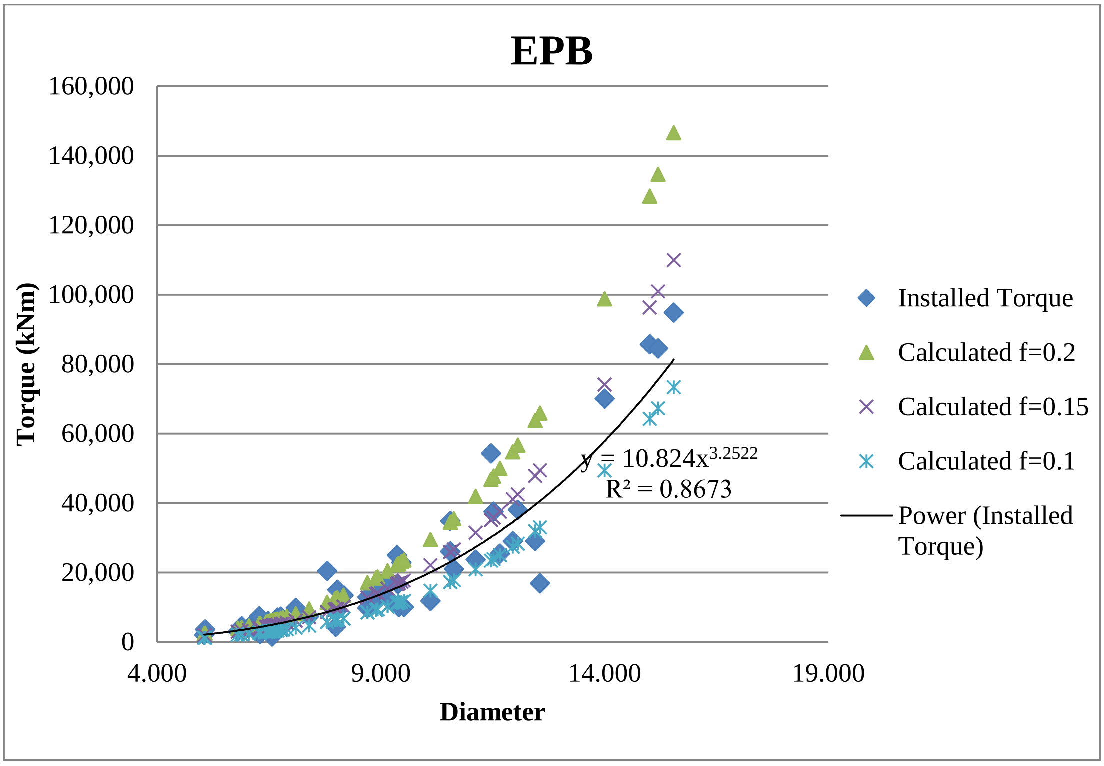


Figure 5.7 : Comparison of installed and calculated torque for EPB TBMs.

The soils friction coefficient is changes between 0.1-0.15 thus the installed TBM torques are closer to these values. As can be seen from the Figure 5.6 and Figure 5.7 calculations give closer results to the real installed torque values. Moreover trendlines for both slurry and EPB TBMs can be used to make a quick prediction of the torque requirement.

5.2 Thrust Requirements of TBMs

5.2.1 Combination of small and large diameter TBM data

Like torque – diameter relationships, thrust - diameter relationships (Figure 5.8) are also affected by the geological conditions and diameter is not enough to predict TBMs properties correctly, especially for hard rock TBMs. Different projects requires to consider different design parameters (thrust, torque, cutterhead power etc.) which is suitable to cope with the projects special needs.

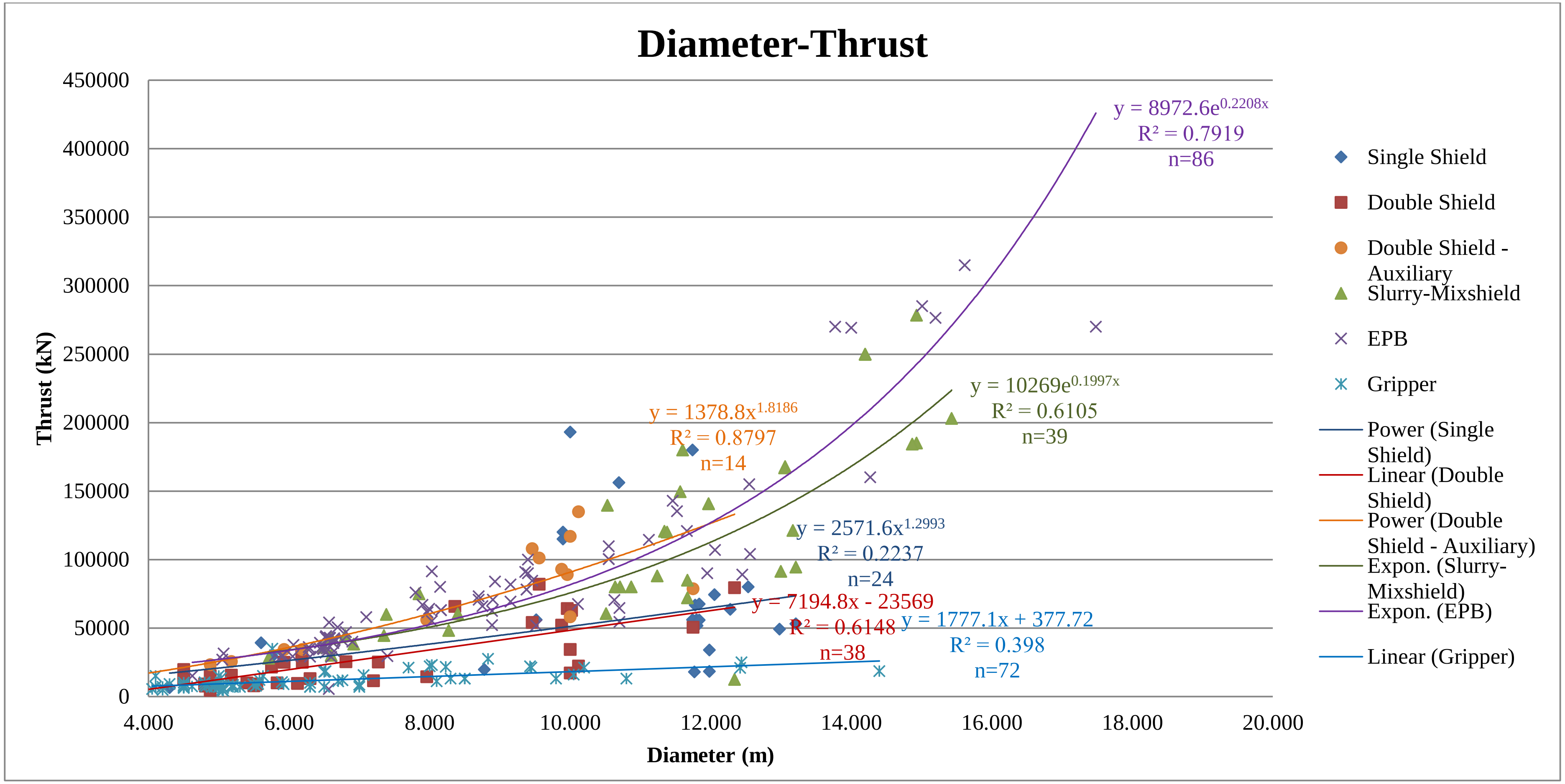


Figure 5.8 : Installed thrust for different TBM types and diameters.

EPB and slurry TBMs propelling force is more than other types and this can be explained by geological conditions. Because of the squeezing ground around the soft ground TBMs these machines require more thrust force than others. It is also noticeable that double shield TBMs auxiliary thrust force has a very similar trend to EBM TBMs thrust force. This could be related to TBMs weight which is generally more than other types and longer shield designs which increases friction forces in fractured geological conditions. Thus double shield TBMs requires high thrust forces to advance.

Moreover double shield TBMs gripper mode has a very similar trend with gripper TBMs, however because of the long and heavy shield their thrust force is higher than gripper TBMs.

5.2.2 Comparison between calculated and installed TBM thrust for hard rock TBMs

In this part same TBM data and variables from the torque calculation section which includes 72 gripper TBMs, 24 single shield TBMs and 38 double shield TBMs is used.

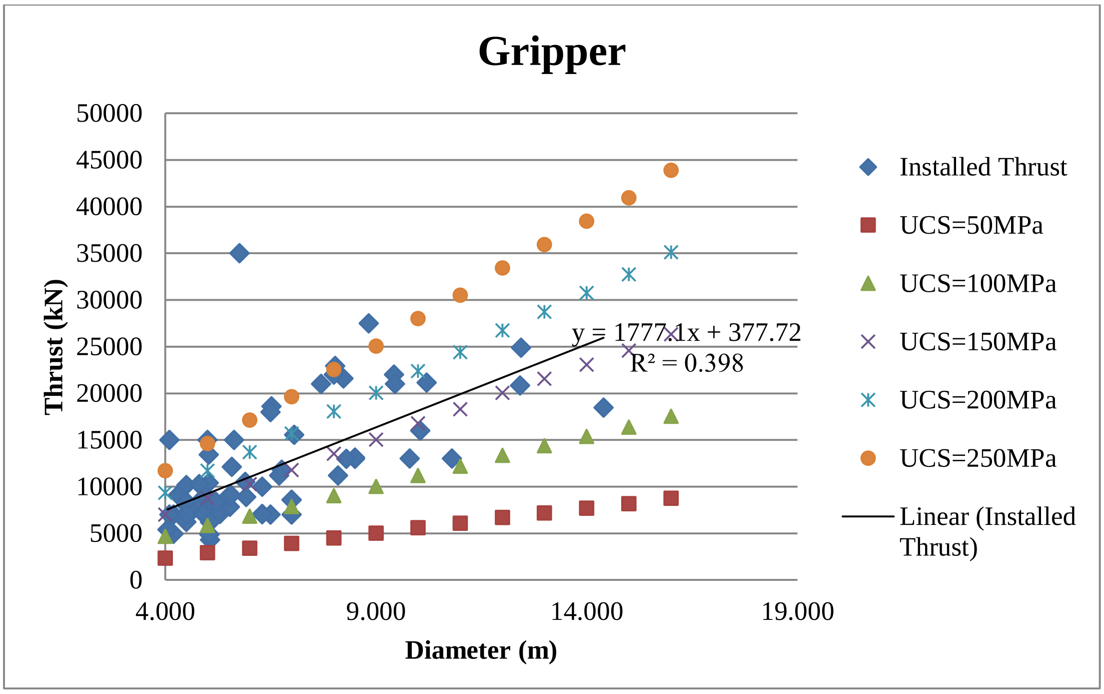


Figure 5.9 : Comparison of installed and calculated thrust for gripper TBMs.

Figure 5.9 shows installed and calculated thrust forces for gripper TBMs. As it can be seen clearly from the figure it is possible to predict required thrust force by using uniaxial compressive strength. To calculate normal force of the discs (F_N) the model developed by To calculate rolling force (F_R) of the discs the model developed by Rostami and Ozdemir (1993) is used.

It should be mentioned that the trendline for the statistical data gives very close values to the 150MPa compressive strength calculation.

Figure 5.10 shows installed and calculated thrust values for single and double shield TBMs. For all calculations unit weight of the rock at face is taken as 2.6 t/m^3. To show the effect of arching height, uniaxial compressive strength and lubrication on thrust force, different parameters are used for calculation. These parameters are shown on the figure. It should be noted that some of the design parameters have very limited effect on thrust, thus, only friction between the shield and thrust required for cutting is calculated.

It is possible to say that lubrication and arching height have a great influence on thrust values. While changing the arching height is very hard and expensive, it can be changed by grout injection from the TBM or surface before the TBM arrives, using lubrication to reduce the thrust is very reasonable. Furthermore it can reduce thrust by 25-50% (Ramoni, 2010).

Moreover, it is also possible to say that thrust force required to cut the rock has also very limited effect on total thrust, which can clearly be seen from the figure.

It should be kept in mind that it is nearly impossible to make a TBM selection only using statistical data, because of too many effecting parameters.

5.2.3 Comparison between calculated and installed TBM thrust for soft ground TBMs

While slurry and EPB TBMs shield designs are very similar it is possible to calculate their thrust together. This section covers total number of 125 TBMs, which includes 39 slurry and 86 EPB TBMs.

To make calculations simpler overburden depth is calculated as 2 times of the diameter, shield length is calculated as a function of Ds by assuming that (Ls/Ds) ratio varies linearly between 2 (for Ds of 3 m) and 1 (for Ds > 12 m), friction coefficient between the shield and the TBM is taken by 0.25 (the value is between lubricated and not lubricated values), and unit weight of the soil at face is taken as 2.2 t/m^3 and safety factor is taken by 1.2.

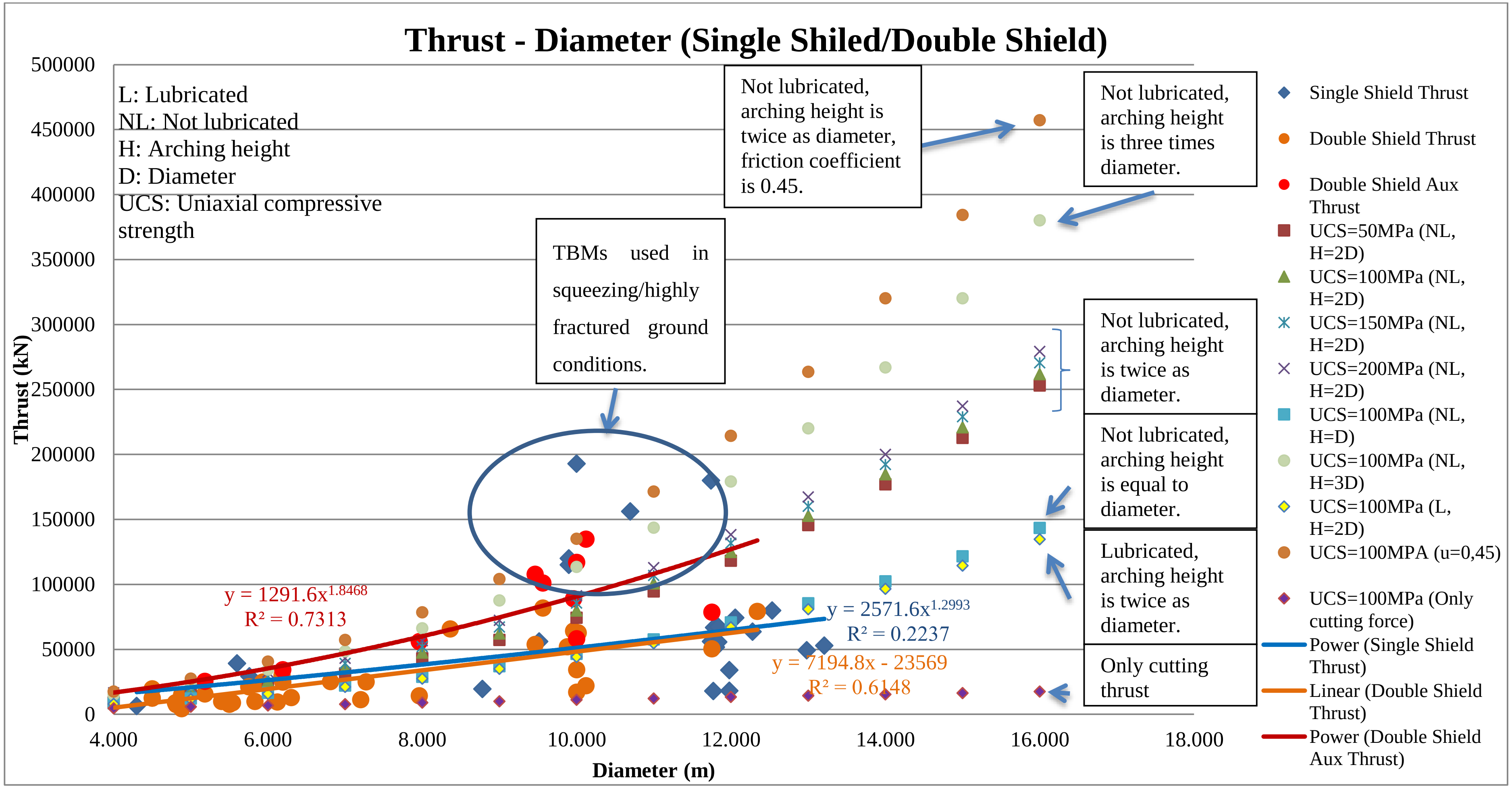


Figure 5.10 : Installed and calculated thrust values for single shield and double shield TBMs for different conditions.

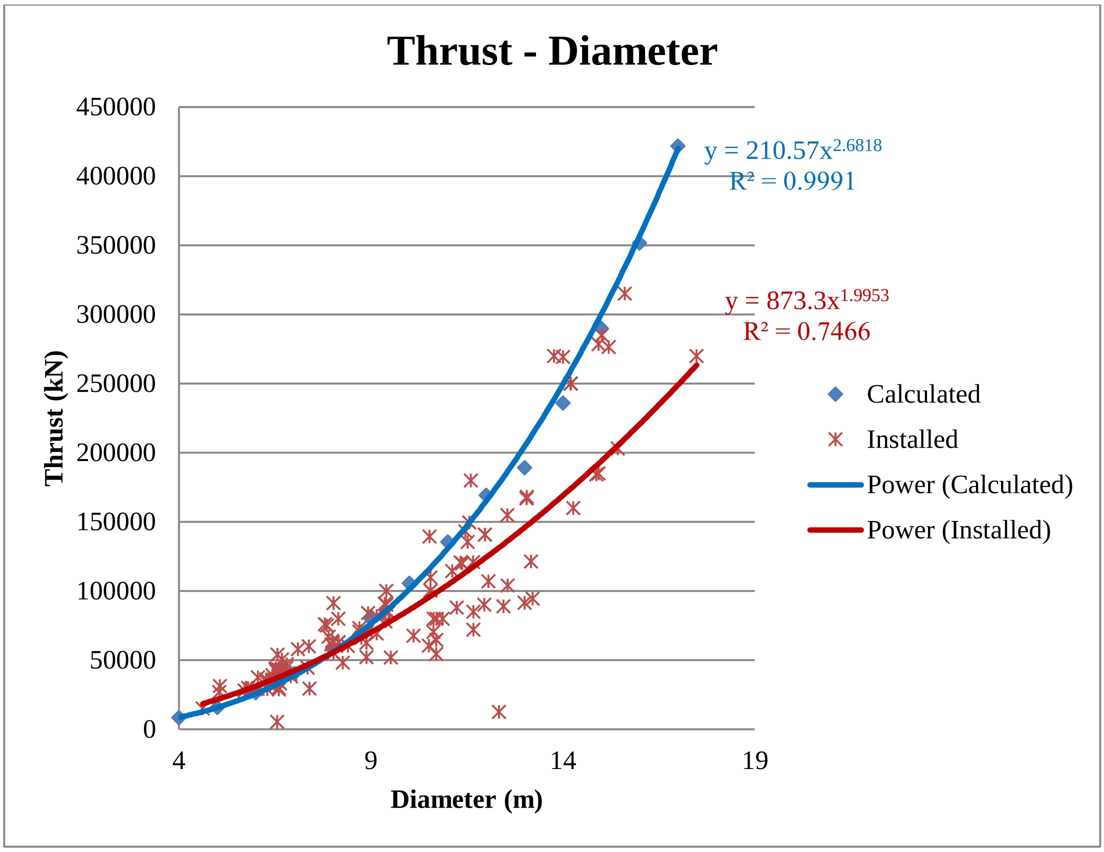


Figure 5.11 : Installed and calculated thrust values for soft ground TBMs.

Figure 5.11 shows calculated and installed thrust values for soft ground TBMs. It is possible to say that calculation gives closer results to the real values. However, it should be kept in mind that the diameter is not the only factor affecting thrust and geology is important. Thus, there are some differences between the thrust values for the same diameter. Moreover lubrication and face pressure are also important.

5.3 Thrust-Torque Ratios

There is a strong relationship between torque and thrust forces (Figure 5.12) for slurry, EPB and double shield TBMs auxiliary thrust. In other TBMs this relationship is not strong as soft ground TBMs, because, in this TBMs formation properties are affect TBM design and thrust and torque forces could be very different for two TBMs which have the exact same diameter.

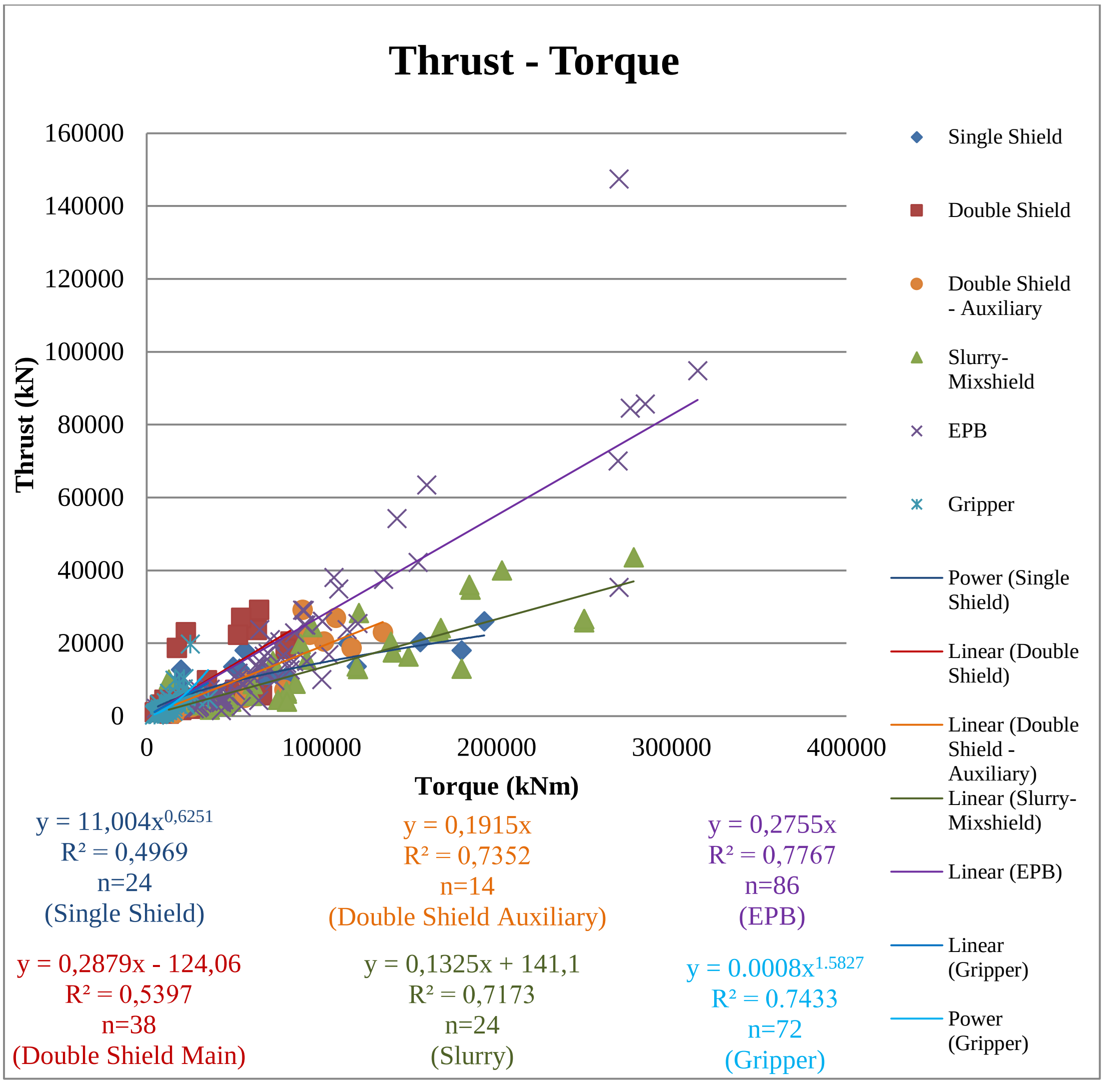


Figure 5.12 : Thrust - torque relationships.

Thrust/torque ratio decreases with increasing diameter for all types except for single shield machines, which a relationship could not be found with the data used in this thesis, (Figure 5.13). This means required force to rotate the cutterhead is increases more than thrust force as the diameter increases. It should be noted that the correlation coefficients are very low to predict the thrust/torque ratio as a function of the diameter for all types of TBMs.

Kahraman (2007) was found that thrust and torque increase linearly with increasing machine diameter. However, in this project it is found that the thrust and torque have an exponential or a power function with the diameter for all types of TBMs manufactured after 1985, with some exceptions. This difference is probably related with the increasing diameter of the TBMs. Today, there are some TBMs which have more than 15 meter cross section. These large section machines needs tremendous thrust and torque forces for an acceptable excavation rate. Thus these large diameter TBMs changed the correlation types between the machine diameter and design parameters from linear to power or exponential.

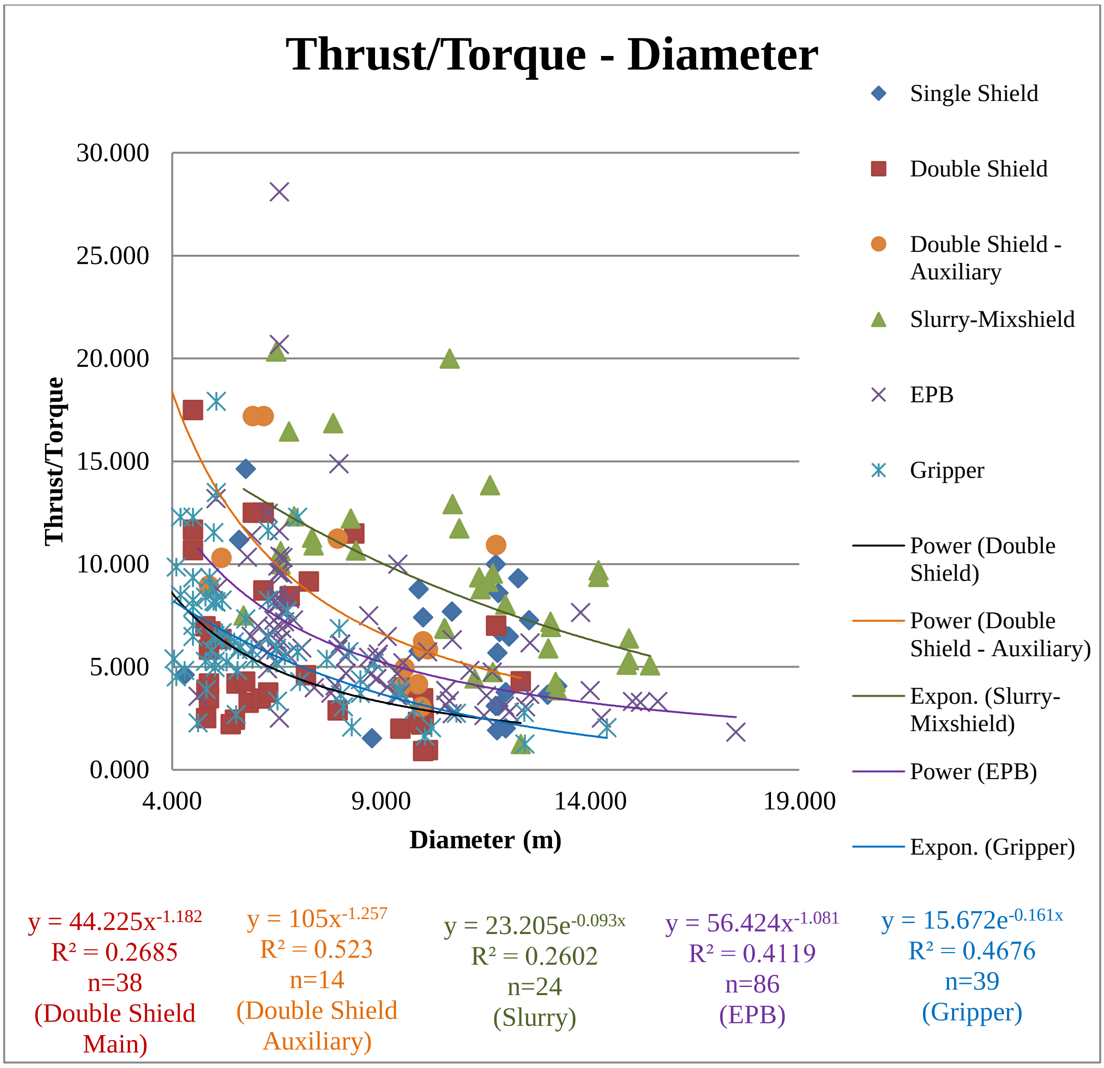


Figure 5.13 : Thrust/torque ratios for different TBM types and diameters.

5.4 TBM Weight

As mentioned before in the small diameter and large diameter sections, TBMs weight increases with diameter. Generally, gripper TBMs are the lightest ones in any size because of their design and double shield TBMs are the heaviest TBMs (Figure 5.14). Single shield, EBP and slurry shield TBMs mostly have similar weights, which is less than double shield TBMs. All TBMs have power or exponential relationship with the diameter. It is found that there is not too much weight difference for small diameters between TBMs however, as the diameter increases weight difference between models increases for a given diameter.

Like thrust and torque, number of cutters and diameters relationship is also different from Kahraman (2007)'s correlations which is related to increased diameter and complexity of the TBMs and backup trailers.

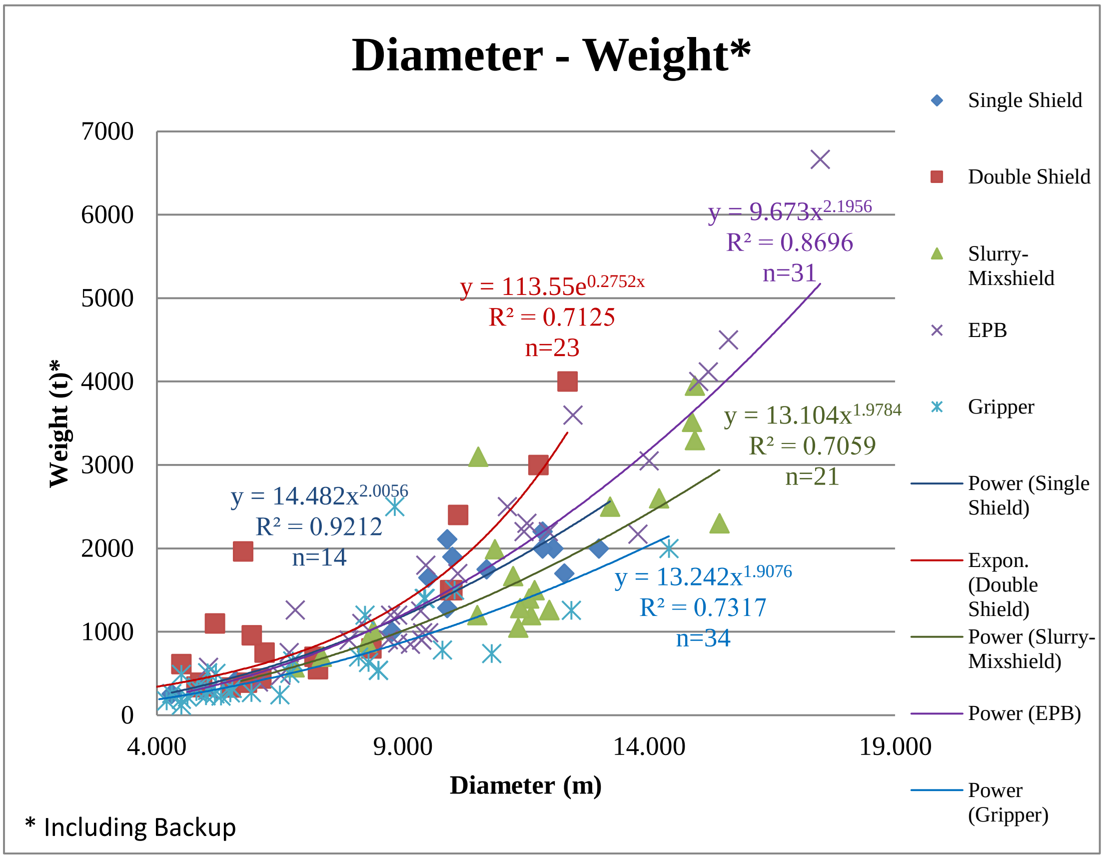


Figure 5.14 : TBM weights for different TBM types and diameters.

By combining EPB and slurry machines there is enough data to analyze shield weight and backup weight of the soft ground machines separately which should be used on thrust calculations. The data can be used for calculating weight of the shield (W_e) and weight of the backup trailers (G) parameters. Figure 5.15 and Figure 5.16 shows diameter-weight (ton/m) relationships. Since single shield TBMs weight is very close to the EPB and slurry TBMs, figures can also be used for calculating single shield TBMs and their backup trailers weight.

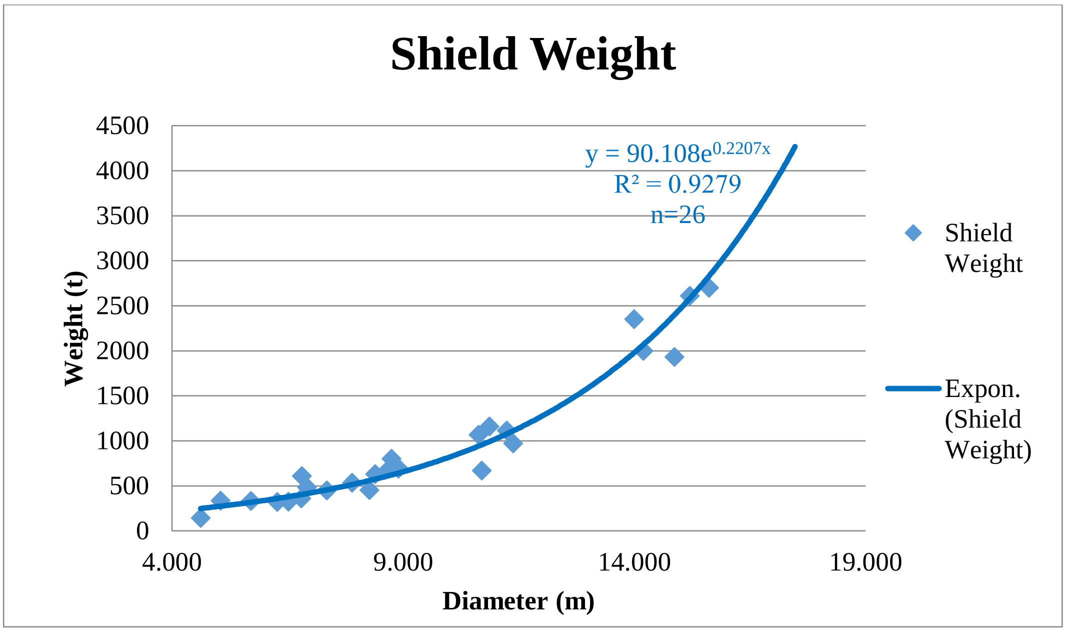


Figure 5.15 : Soft ground TBM shield weights.

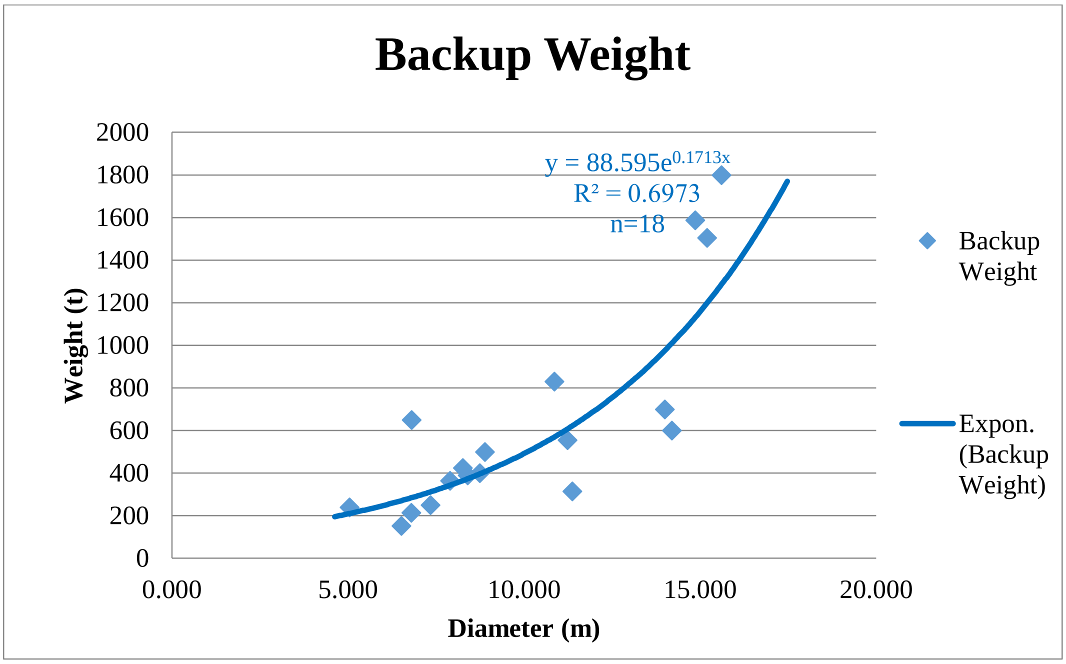


Figure 5.16 : Soft ground TBM backup weights.

5.5 Number of Cutters

In this part, again, hard rock TBMs are analyzed together while EPB and slurry TBM analyzed separately. It is possible to say that for hard rock TBMs, cutter numbers are generally same for a given diameter. However, for EPB and slurry TBMs the numbers changes in a wide range (Figure 5.17).

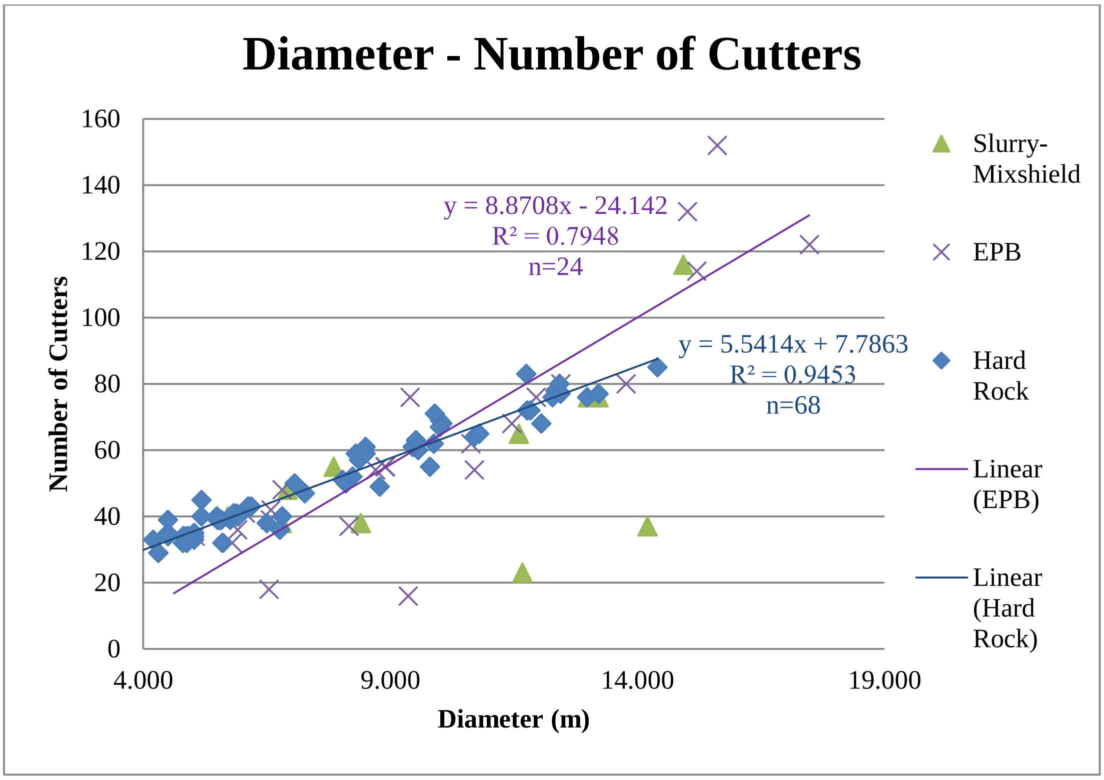


Figure 5.17 : Number of cutters for different TBM types.

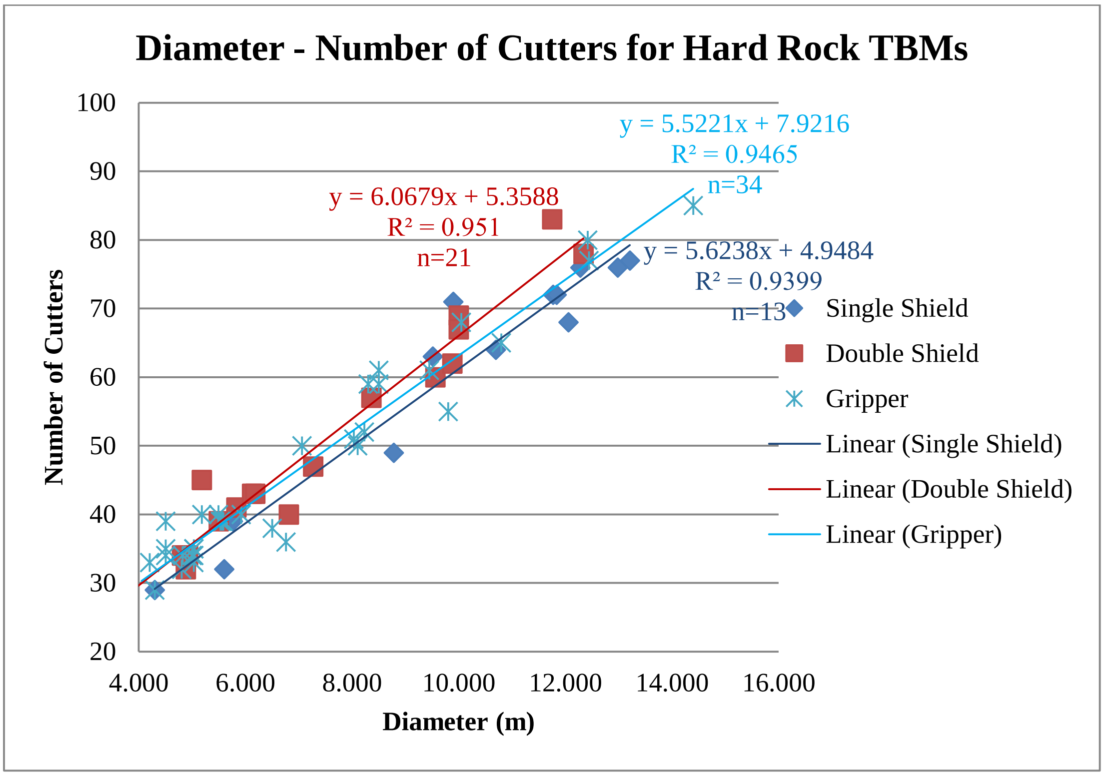


Figure 5.18 : Number of cutters for hard rock TBMs.

In Figure 5.18 hard rock TBMs cutter numbers shown separately. As can be seen from the figure, double shield TBMs have more cutters than other types, while single shield

TBMs have the least cutter number. The gripper TBMs are stand between double and single shield TBMs.

6. TWO LARGE DIAMETER TBM CASE STUDIES FROM TURKEY

6.1 Ankara-İstanbul High Speed Railway Project Tunnel No. 26

Tunnel No. 26 is one of the longest tunnels at phase 2 of Ankara – Istanbul High Speed Railway Project. It has a length of 6.1 km, and lies between chainage 216+260 and 221+750 of the project. Phase 2 consists of 33 tunnels, which have total length of 55 km. All tunnels were planned to excavate by using NATM method. As planned excavation of Tunnel No. 26 by NATM method started on October 2009. However, the first 297 meters of the tunnel were completed with a rate of 2m/day in mica and graphite schists (Poşuk et al., 2011). In the light of additional geological information, it was decided to continue excavation by using a TBM.

The TBMs performance calculated by using Q_{TBM} method and 8.35 m/h advance rate is predicted which makes breakthrough date 1 year after starting the excavation (Poşuk et al., 2011).

6.1.1 Geology of the tunnel alignment

The T26 tunnel takes place between Ankara-Istanbul High-speed Railway Project's 216+260 km and 221+750 km. The tunnel alignment passes from the 200 meter east of Ahmetpinar Village of Bilecik province. Moreover, on 1 km west side of the alignment and parallel to the highway, there is Karasu Brook. The tunnel's alignment topography presents various relieves, and the tunnel overburden thickness varies between 30-236 meters (Ertin et al., 2012).

Along the tunnel alignment Palaeozoic aged Pazarcık Karmaşığı has been observed. The Unit outcrops between Bilecik and Bozüyük, and various rock structures of overlapping were presented. The unit presents erosional contact relation with its Triyas aged Karakaya Group on top, and eroded, as well as partly faulty Bayırköy Formation. The unit on the whole, has gone through metamorphism under green schist facieses conditions and made up of structurally embedded rock of various thicknesses. Within the widespread outcropping schists, sandstones, marbles, migmatite-gneiss and granodiorite were found in the form of megablocks. The unit is cut by the quartz and aplite dykes of the Bozüyük granitoide. The main unit which was observed between km: 216+260 and km: 220+300 is graphite schist. Graphite schists are black - dark grey - greenish dark grey colored, with apparent schistosity, fragmented, medium to highly weathered, and weak to medium strong (Ertin et al., 2012).

Within the graphite schists which can easily be separated along the schistosety planes, a few marble block with diameters of 10.00 meters, quartz seams of up to 2.00 meter thickness, as well as mica schists in the form of mega blocks were observed (Ertin et al., 2012).

Within Km: 220+300 and Km: 221+750 chlorite schists were found. Chlorite schists are light green- greyish colored. Their schistosity planes are relatively less apparent when compared with graphite schists. And medium strong to strong, moderately - slightly weathered and fractured with quartz fillings (Ertin et al., 2012).

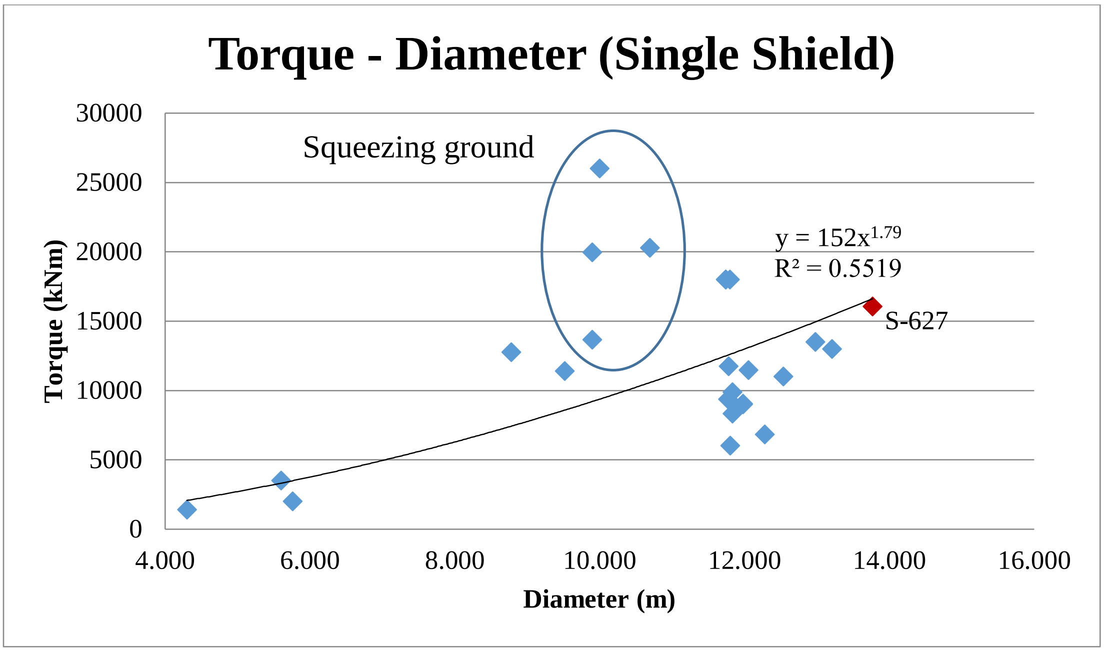
6.1.2 TBMs technical details

A single shield (S-627) TBM was manufactured by Herrenknecht for the project. Technical details of the TBM are given in Table 6.1.

Table 6.1 : S-627 technical details.

Machine Type	Single Shield
Machine Diameter	13770mm
Installed Power	9700kVa
TBM Length (inc. backup)	80m
Shield Length	10.45m
Weight (inc. backup)	2170t
Number of Thrust Cylinders	2x15
Stroke	2800mm
Installed Thrust Force	84464 kN at 350 bars
Muck Removal	by Screw Conveyor and Belt Conveyor
Cutterhead Power	16x350kW (5600kW)
Rotation Speed	0-4 /min
Nominal Torque	16056kNm
Breakaway Torque	24083kNm
Overload Torque	25689kNm

By comparing with 24 single shield TBMs it is possible to say that the S-627's thrust and torque values are close to the average for its' diameter (Figure 6.1). However, it should be mentioned that TBMs used in squeezing ground conditions have higher thrust and torque values from the average.



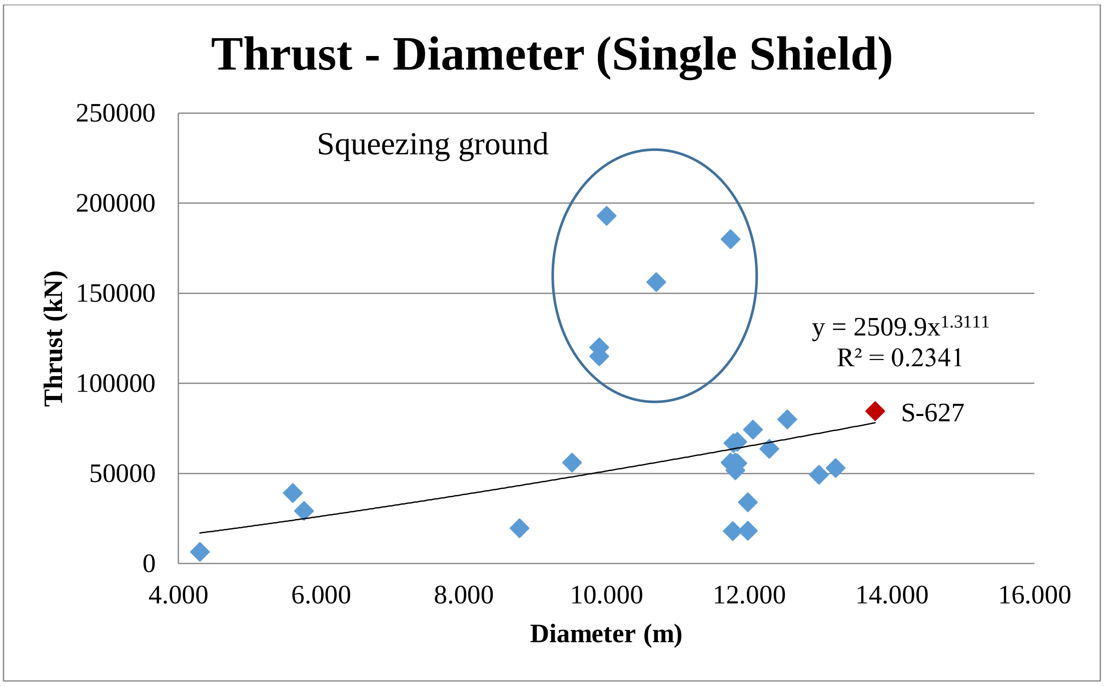


Figure 6.1 : Torque (upper) and thrust (below) values for 24 single shield TBMs.

6.1.3 Excavation

S-627 arrived jobsite in April 2011 for assembly. The TBM was assembled approximately in two months, which is shorter than average for its size, and started to excavate in 20 June 2011.

Figure 6.2 : TBM assembly at the portal.

6.1.3.1 Advancing in the half opened tunnel

The TBM advanced half-opened tunnel until ring 147.

On 12.07.2011, it is realized that the TBM was submerged and excavation stopped. A special steel rope system ordered to pull the TBM from the top to reduce the vertical displacement. Until the rope system is ready water pillows used to lift the TBM, however, because of the weight of the shield and soft ground the system could not lift the TBM enough.

The parts of the rope system arrived to the jobsite on 31.07.2011 and installation was completed on 12.08.2011.

Excavation of half opened tunnel completed on 20.09.2011 (Ring No. 147). After starting to excavate full face cutterhead blocked several times on the next 5 ring but TBM continued to excavation. However, on ring no. 151 cutterhead blocked again and attempts to free the cutterhead was not conclude.

6.1.3.2 Cutterhead modification

To reduce the blockages it was decided to reduce the opening rate of the cutterhead. Figure 6.3 shows the closed and half-closed openings on the cutterhead.

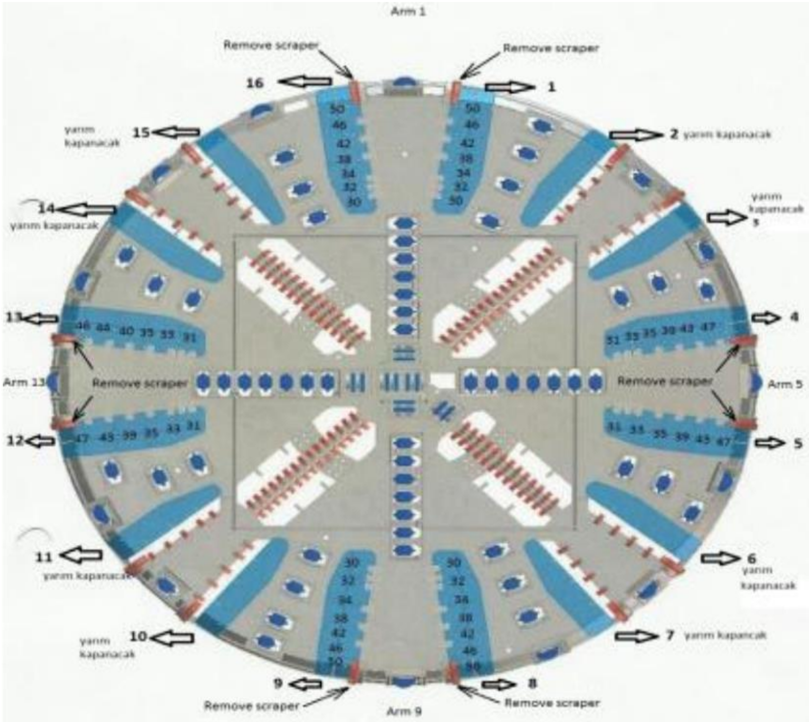


Figure 6.3 : Cutterhead modification.

In addition the cutterhead modification, new bentonite lines to the chamber were added to threat the ground and reduce the blockages. On 30.10.2011, TBM started to advance again.

6.1.3.3 Increasing thrust and torque of TBM

After advancing 281 m, from ring no. 151 to 293, cutterhead blocked again on 06.12.2011. TBM's advance rate on this period was 7.3 m/day including stoppages. Because of the high ground pressure and insufficient torque and thrust of the machine, the shield jammed and cutterhead blocked. Injecting bentonite to the chamber and around the shield did not help to starting advance again. After numerous tries, it was decided to increase thrust and torque of the machine.

On 19.12.2011 dismantling of the cutterhead motors and thrust cylinders was started. After 30 days, on 17.01.2012 maintenance was completed. During the maintenance TBM's gearbox and tail seals ware changed and thrust capacity of cylinders was increased. Changing the gearbox lowered the cutterhead's rotation speed and increased the torque.

After the maintenance S-627's torque increased to 35200 kNm and breakout torque increased to 40132 kNm.

TBM started to advance on 18.01.2012 and advanced 57.9 meters in 24 days until the next cutterhead maintenance. The TBM's advance rate was 2.63 m/day for this period including stoppages.

On 09.02.2012 TBM stopped for maintenance and until 09.03.2012 maintenance continued. During the maintenance some welding operations done on the cutterhead and some of the discs changed with ripper cutters.

After advancing 3 days cutterhead blocked by a big rock block in front of the TBM. Numerous attempts to rotate the cutterhead failed and it was decided to use explosives. Moreover during the stoppage the rippers which were attached in last maintenance were changed with disc cutters. TBM continued excavation on 18.03.2012.

6.1.3.4 Additional thrust cylinder installation

S-627 continued the excavation without any problem until 31.03.2012 and stopped for planned disc change. However after the disc change TBM jammed again because of the squeezing ground. A Power Pack hydraulic system installed to the TBM to increase the thrust, which was not enough to start advance again. To protect the segments from the high thrust force a steel ring was build. On 18th April 587 bar pressure, which is approximately 145000 kN, was tried but TBM did not moved.

Then, it was decided to install 10 additional thrust cylinders, which have thrust force around 100000kN and open drifts around the shield to reduce the earth pressure.

On this stop, a probe drill was also installed to the TBM. Moreover the angle of belt conveyors were reduced to carry conditioned muck, wear plates on the cutterhead were changed, agitating bars installed to the cutterhead and new bentonite lines were added.

TBM stopped for 82 days which is the longest stop from the beginning of excavation. On 20th June TBM started to advance again. Until 21.07.2012 TBM didn't stopped for a long time and continued to excavation except planned cutter changes. The average daily advance of the TBM is approximately 4.38 m/day for this period.

From the beginning of excavation S-627 advanced 891 meters in 398 days, which makes daily advance rate around 2.23 meter.

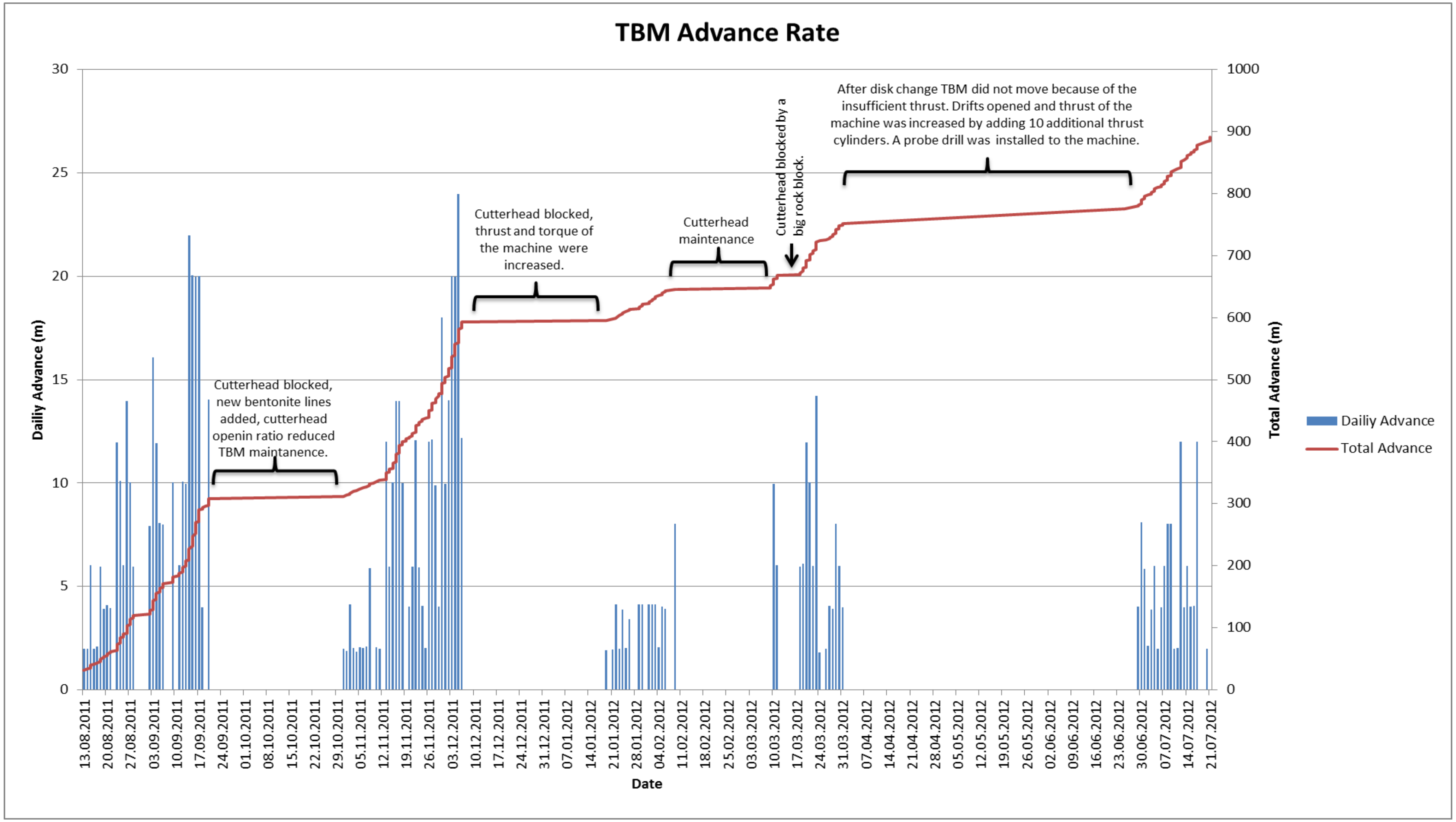
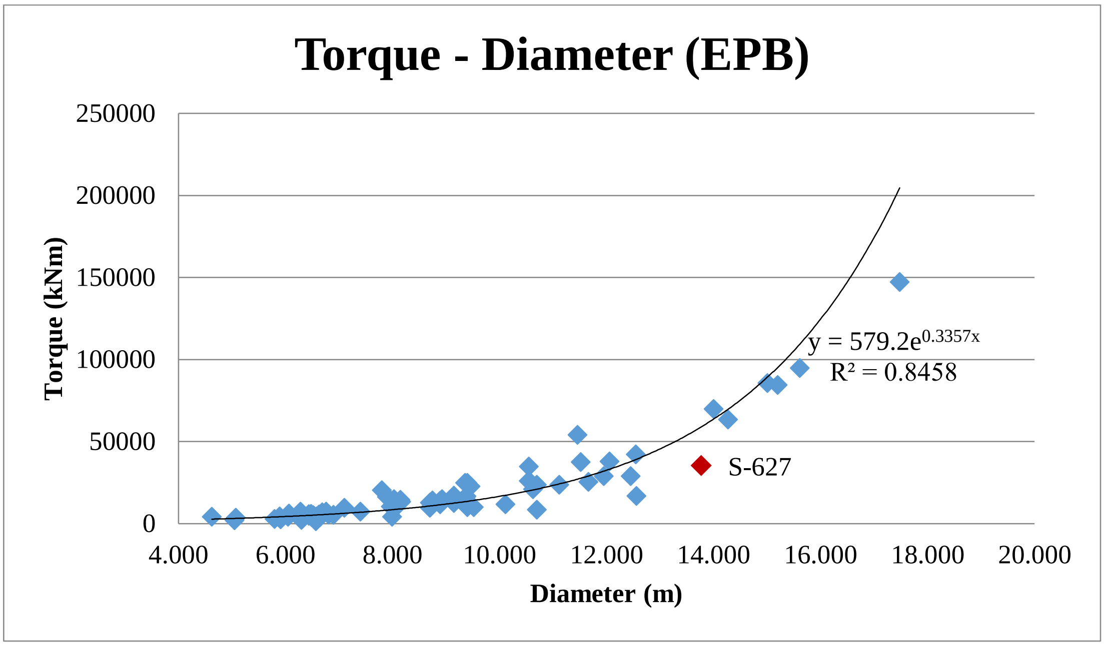


Figure 6.4 : TBM advance rates.

6.1.4 Review of modifications and current problems

6.1.4.1 TBM modifications

After modifications, S-627 was converted to an EPB TBM. Figure 6.5 shows torque values of EPB TBMs and S-627. As it can be clearly seen from the graph S-627's torque values are well below than the average. Moreover it should be mentioned that because the TBM was a single shield machine originally, some of EPB functions are missing.



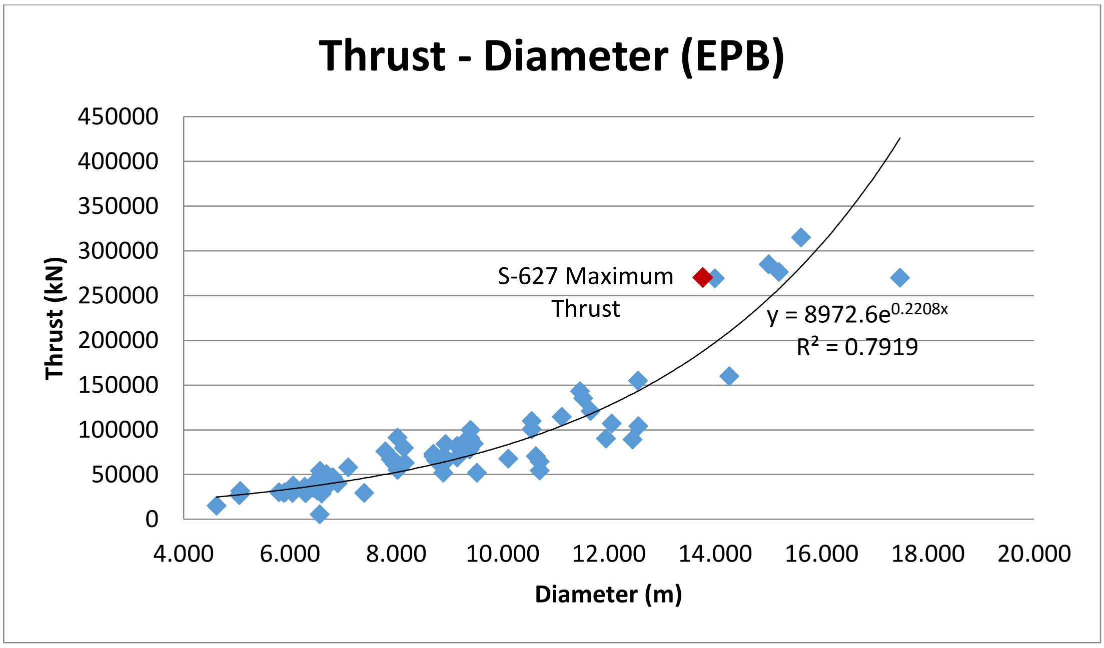


Figure 6.5 : Torque (upper) and thrust (below) values of EPB TBMs.

S-627's maximum thrust force, especially after installing additional thrust cylinders, exceeds the average thrust force of EPB machines (Figure 6.5). TBM specifications before and after modifications can be seen on Table 6.2.

Table 6.2 : TBM specifications before and after modification.

	Before	**After**
Machine Type	Single Shield	EPB
Machine Diameter	13770 mm	13770mm
Number of Thrust Cylinders	2x15	2x15 + 10
Installed Thrust Force	84464 kN at 350 bars	Approximately 170000 kN + 100000kN (by additional cylinders) (219% increased)
Muck Removal	by Screw Conveyor and Belt Conveyor	by Screw Conveyor and Belt Conveyor (incline of the belt conveyor is reduced to cope with conditioned muck)
Nominal Torque	16056 kNm	35328 kNm (119% increased)
Breakaway Torque	24083 kNm	40132 kNm (66% increased)

6.1.4.2 Using the steel ring

It should be kept in mind that the segment design on the project limits the thrust force. To protect segments, which were designed for a lower thrust force, a steel ring must be installed after the latest ring before using additional cylinders. The steel ring spreads the force equally around the surface and protect the segments from cracking due to high thrust pressure.

If the TBM squeezes, segments on the feeder sent outside of the tunnel, steel ring send to the TBM and build after the latest ring (Figure 6.6). After advancing by using steel ring, the ring removed and sent outside, and then the segments send to the TBM and build. This process takes between 7 to 12 hours, which is nearly equals to a shift. The steel ring used for 5 times until 21.07.2012, which means the TBM waited approximately 2 days for the steel ring installation and de-installation.

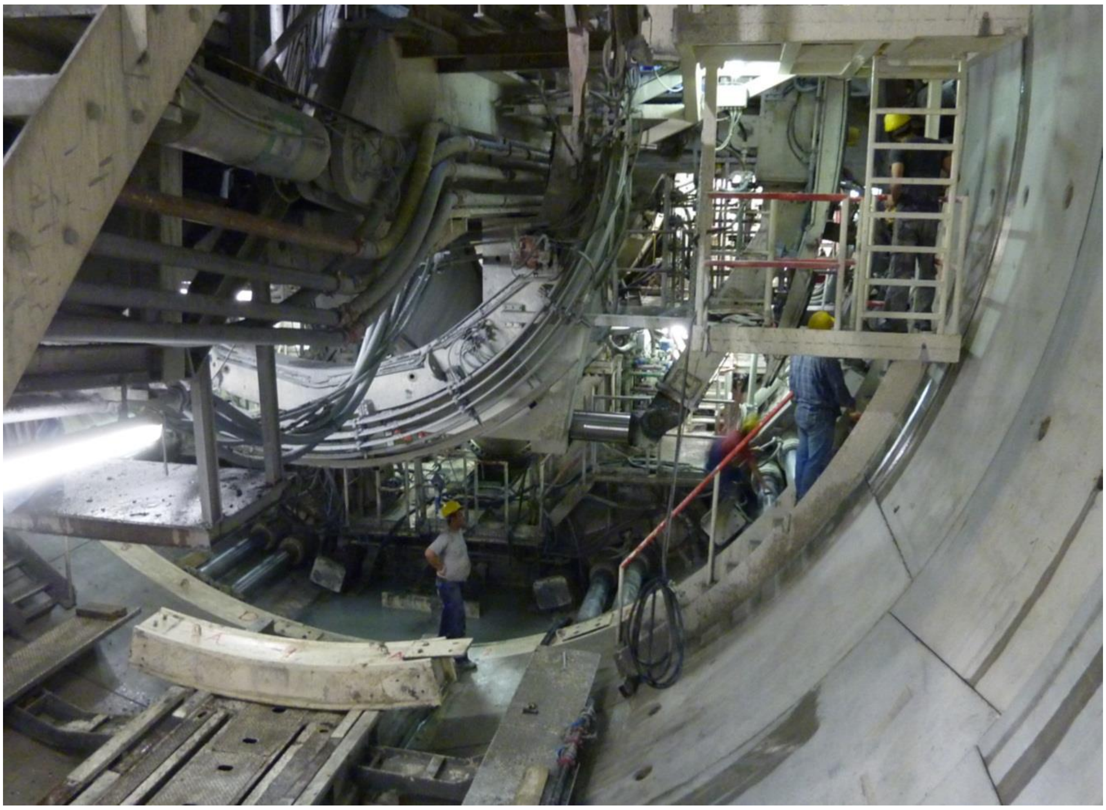


Figure 6.6 : Building of steel ring.

6.1.4.3 Tail sealing system

Another problem of the TBM is related with tail seals. At the moment TBM has 2 rows of seal consisting of 1 row of wire brush seals, 1 row of spring plates. To fill the gap between segments and formation high pressure grout injection is used. However because of the insufficient sealing capability of the tail seals, when the grout pressures exceed 3 bars, it starts to enter the shield (Figure 6.7).

The inadequate sealing system causes two problems. Firstly, workers spend too much time for clearing the shield before ring build. Depending on the how much grout entered the shield, cleaning process takes between 5 to 30 minutes.

Secondly, the gap between the segments and rock formation cause collapses on the top of the segments, which increases segment load and causes cracks on the segments (Figure 6.8).

Figure 6.7 : High pressure grout entering the shield.

Figure 6.8 : Cracks on the segments.

6.1.4.4 Disc wear

Another problem of the TBM is very high disc wear rates, which causes constant maintenance stops. According to tests Cerchar Abrasivity Index value of the rocks along the tunnel changes between 0.5 and 3 (Çopur and Balcı, 2010) which means the rock is medium abrasive. At the moment disc consumption is 386 m^3/disc. In every 10-15 rings TBM stops for disc inspection and in every 15-20 rings TBM stops for disc change which takes up to 48 hours.

Disc changing process deeply affects TBM utilization rate and sometimes long waiting times results squeezing of the TBM which will be covered later in the report.

6.1.5 Thrust and torque of the machine

Firstly, it should be noted that because of the TBM's computer problems there is no data recorded for some of the rings. Moreover additional thrust cylinders which were installed on the last maintenance are not connected to TBM's PLC and controlled manually, thus additional approximate thrust force of these cylinders added to the data manually.

Maximum and average thrust force and torque can be seen on Figure 6.9 and Figure 6.10. As expected when the machine advancing in half opened tunnel maximum thrust and torque is low but on some rings maximum applied torque force reached to machines maximum values. This could give clues about the insufficient torque of the machine. Furthermore 4 rings after half opened tunnel, on ring 151, cutterhead of the machine was blocked.

Reducing the opening rate from %39 to %19 helped machine to advance. Low opening rate reduced collapses and prevented big blocks to enter the cutterhead.

By increasing overburden, which is around 70 m on ring 286 and earth pressure, applied torque and thrust of the machine was started to increase. According to geotechnical report average RQD value on this area is below 50%, and uniaxial compressive strength of the rock is changes between 20 to 29 MPa. Moreover on some points after ring 250, torque is reached the maximum values of the machine and cutterhead was blocked again on 293 which was resulted a big TBM maintenance and increasing thrust and torque of the machine.

Average torque values after the first maintenance is close to machines maximum design torque and maximum torque values are close to 40MNm which is the maximum torque of the machine after gearbox change (Figure 6.10). Average thrust values are close and on some points higher and maximum thrust values are well above than machines design thrust.

These indicate without any torque and thrust increase, excavation would be impossible or would be extremely hard and time consuming. On some points drifts would be needed to reduce earth pressure around the shield to advance.

After planned cutter change on ring 373, because of the squeezing ground, attempts to start the excavation failed. Opening a drift around the shield and reducing the earth pressure also did not help the TBM to advance. Then it was decided to install additional thrust cylinders. As mentioned before these cylinders have 100000 kN thrust capacity. With help of these cylinders TBM started to advance again.

As can be seen from the Figure 6.9, maximum applied thrust force is constantly increasing from the beginning of the excavation, by increasing overburden. Especially when excavating weak zones with high overburden, additional precautions would needed to be taken like ground treatment before the TBM reaches these points.

6.1.6 Thrust force after stops

When advancing in squeezing ground, constant advance of the TBM and keeping planned stoppages as much as short is very important. Long waiting times result jamming of the shield and requires very high thrust forces or sometimes opening drifts to advance again.

Figure 6.11 shows waiting times between stops and stars of S-627 from ring 360 to 442 and thrust differences between them. The figure also shows the reasons for waiting times. As can be clearly seen from the graph when the waiting time increases, thrust difference between stop and start of the machine is increases. Moreover after the last modifications TBM make long stops only for cutter changes which is unavoidable except one stop for an electrical problem.

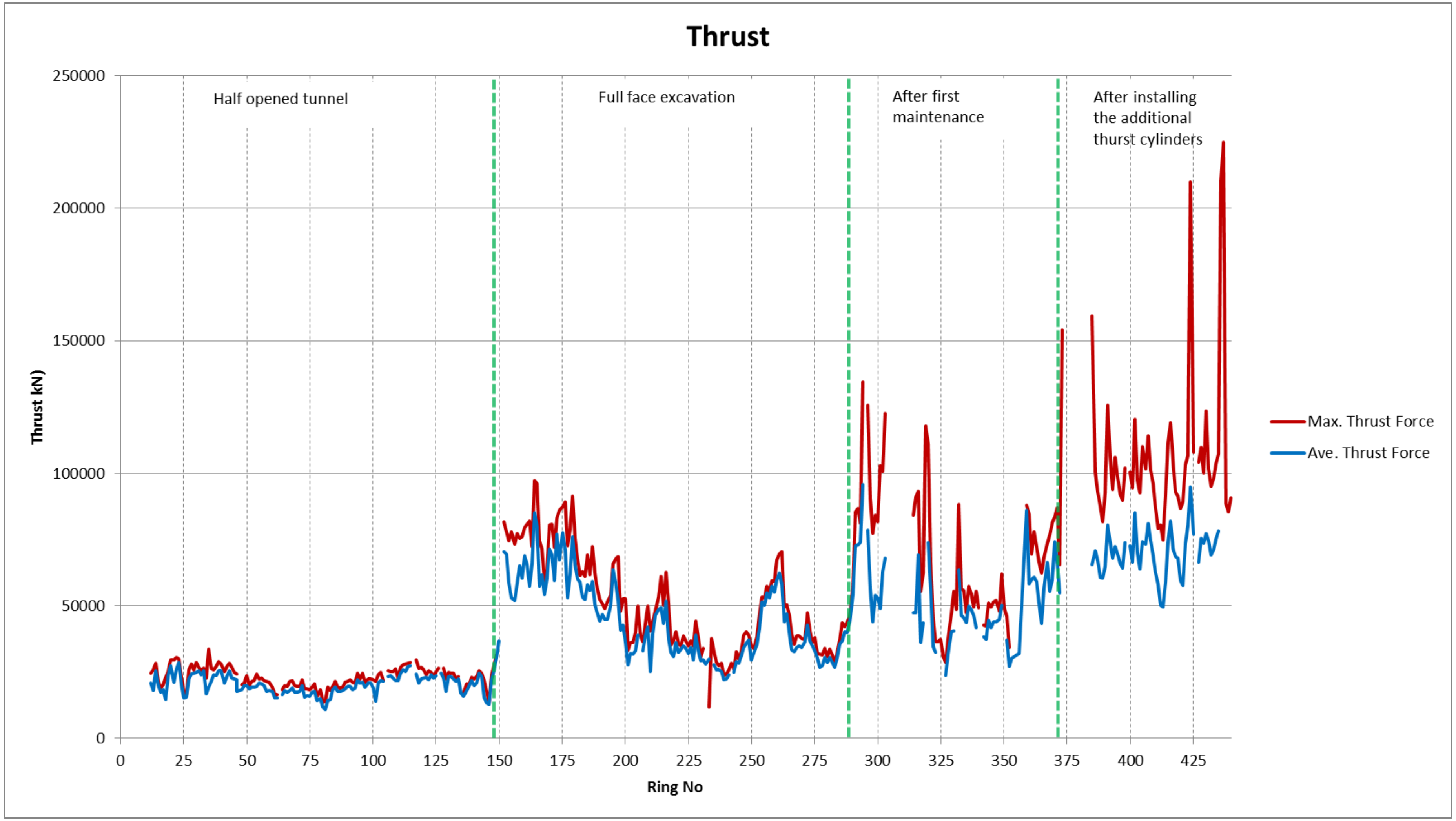


Figure 6.9 : Maximum and average thrust force.

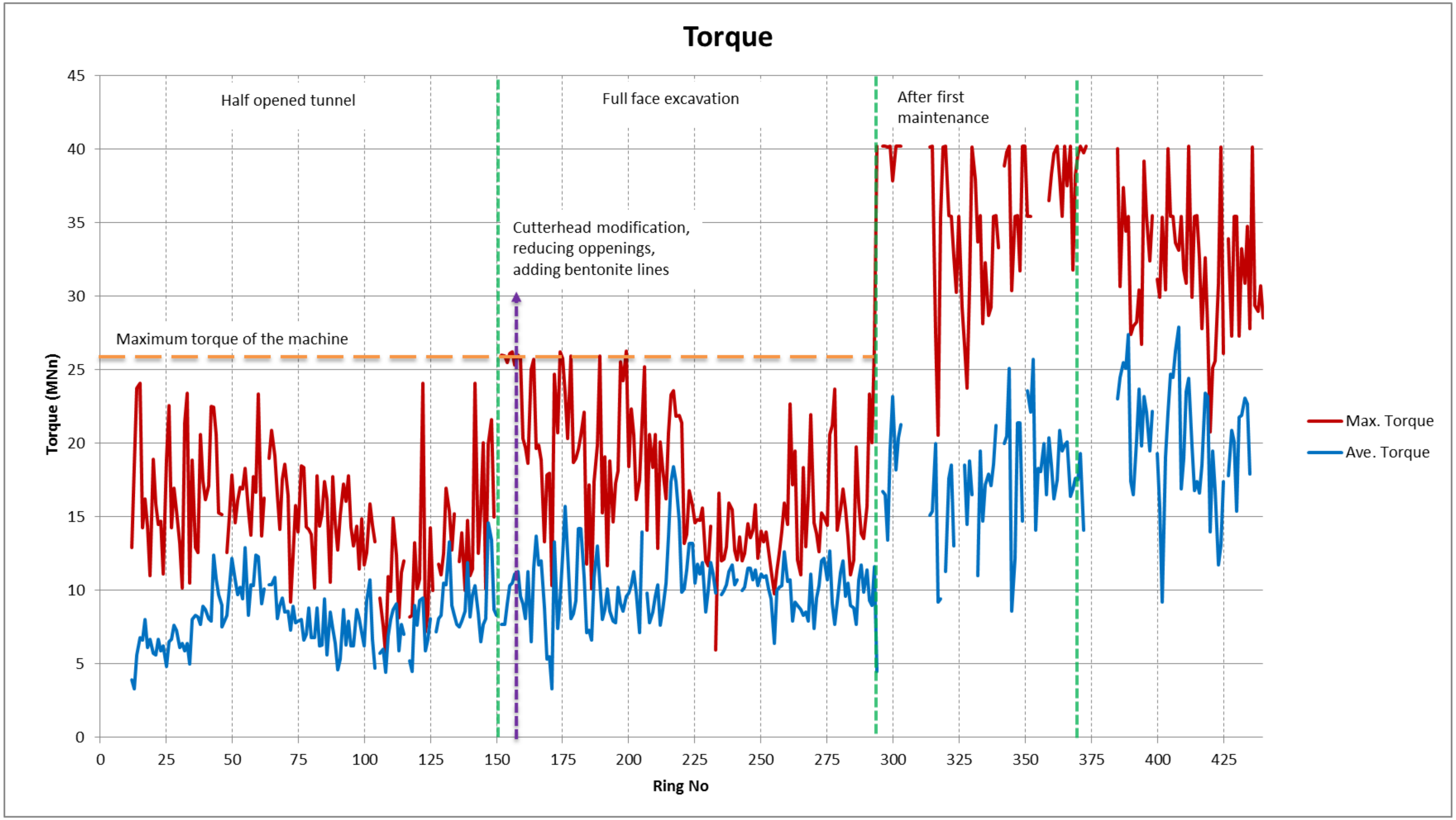


Figure 6.10 : Maximum and average torque.

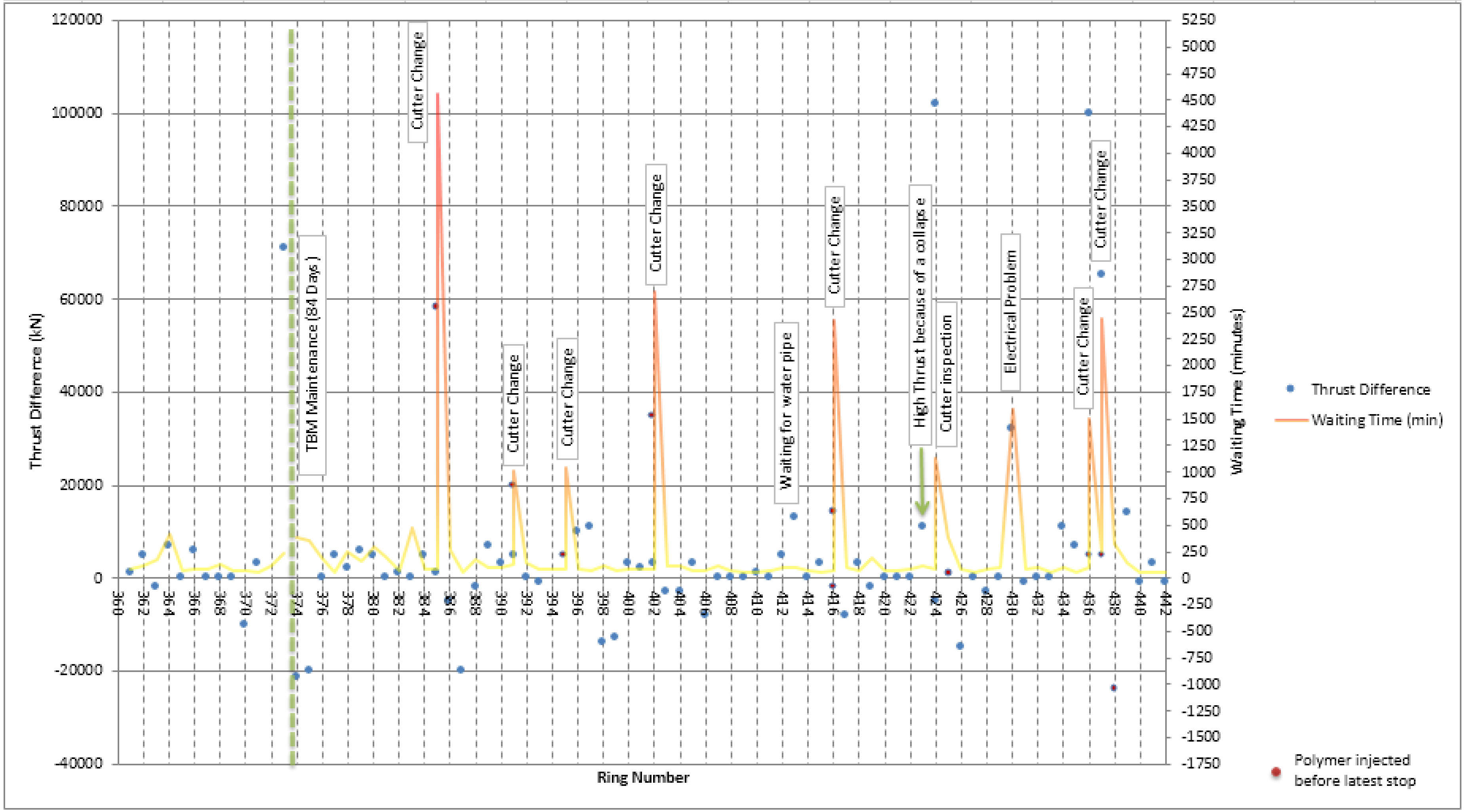


Figure 6.11 : Thrust difference between stops and starts of the TBM.

It should be noted that if the thrust is higher than 100000kN or if there will be a long stop, generally before stopping the TBM for the maintenance or ring build, in addition the bentonite, which is always injected, polymer with high lubricating capability is injected between the shield and ground to reduce the starting thrust. These points were presented with red dots in Figure 6.11.

By analyzing the data, it is possible to say that generally starting thrust of the TBM is not increase too much after waiting 750 minutes or less, which is enough for ring build or short maintenances. On these cases, thrust increase is generally lower than 20000kN. However, it should be kept in mind that if the thrust force before the stop is higher than 130000-140000kN longer stops should be avoided. Because a 20000 kN increase on these thrust values reaches the thrust limits of segments and to protect the segments steel ring should be build which takes too much time. If a long stop is necessary after high stop thrust, keeping the steel ring ready on TBM is a good idea for saving time.

6.1.7 Conclusions for Ankara-İstanbul High Speed Railway Project

The geotechnical data provided for the project was not good enough to make proper TBM selection. Moreover, TBM's performance prediction was made by using insufficient geotechnical data by using unsuitable performance prediction method for the project. The prediction of machine utilization time and determination of machine performance plays an important role in scheduling and planning tunnel excavation (Ocak and Bilgin, 2009).

S-627 was designed as a single shield TBM with average thrust and torque forces for its diameter. After constant blockages, cutterhead design was changed, torque and thrust of the machine were increased. And TBM was converted to an EPB machine. However having less torque and thrust capabilities for similar sized TBMs, S-627 jammed again. Then because of the high thrust demand, additional thrust cylinders were added to the machine which makes S-627's maximum thrust capacity slightly higher than average thrust capacity of similar sized EPB machines. TBM stopped for these modifications for nearly 7 months, which was more than half of the total excavation time. Until 22.07.2012, TBM's average daily advance rate was approximately 2.23 meter including stops, which is extremely low for a TBM.

Moreover, highly abrasive formation increases disc wear and frequent disc change is required which also lowers the utilization rate.

Insufficient geological data was also leaded to unsuitable ring design. Furthermore because of the increased thrust of the machine a steel ring must be used to protect the segments, which also slows down the excavation process.

6.2 Kargı Dam and Hydropower Project

The project is excavating an 11.8km long headrace tunnel for the Kargı Kızılırmak Hydropower Project and a double shield Robbins TBM of 9.84 m diameter is being currently working in the Western Tunnel.

The jobsite located in Corum Province about three hours from Ankara and after completion it will direct water from the Kızılırmak River to generate up to 470 GWh annually (Willis, 2012).

The project is set to be finished in 36 months which requires approximately 11 m daily advance rate. It is planned to bore and install the pre-cast segments for the first 3 km and use ring beams, rock bolts, and a final lining of shotcrete for the remaining 8 km of the tunnel (Willis, 2012).

6.2.1 Geology of the tunnel alignment

The geology along the tunnel route consists of 80% of Eocen aged Beynamaz Volcanics, which includes agglomerate, andesite, basalt and tuff. The uniaxial compressive strength changes between 40-100 MPa for the agglomerate, 70-120 MPa for andesite and basalt, and 30-80 MPa for tuff. The RQD for the volcanics generally changes between 75% and 100%.

The other 20% of the project, eastern part, consists of Kunduz Methamorphites, which includes marble, schist, metabasits, and Kargı Ophiolites which includes conglomerate, sandstone, schist, marble and phylites. The uniaxial compressive strength is between 10 and 120 MPa for these formations and RQD is generally 50%.

RMR classification for the Beyanmaz Volcanics is good rock, in contrast, for the other 20% it is mainly very poor rock.

There are also several faults and dykes on the tunnel line. The TBM started from the 3km long weak section.

It should be noted that there are only 6 drillings were made to observe the geology of the tunnel alignment.

6.2.2 TBMs technical details

A double shield TBM was manufactured by The Robbins Company for the project. Technical details of the TBM are presented in Table 6.3.

Table 6.3 : Robbins Double Shield TBM's technical details.

Machine Type	Double Shielded
Machine Diameter	9880mm
Shield Length	11.40
Shield Weight	1400t
Number of Main Thrust Cylinders	12
Number of Aux. Thrust Cylinders	18
Stroke	1700 mm
Installed Main Thrust Force	52040 kN (at 345 bar)
Installed Maximum Main Thrust Force	67879 kN (at 450 bar)
Installed Auxiliary Thrust Force	93,000 kN (at 345 bar)
Installed Max. Auxiliary Thrust Force	121,300 kN (at 450 bar)
Muck Removal	by Screw Conveyor and Belt Conveyor
Cutterhead Power	12x350kW (4440 kW) (expandable to 14 units, 5180 kW)
Rotation Speed	0-5 /min
Nominal Torque	22300kNm
Breakaway Torque	33450kNm

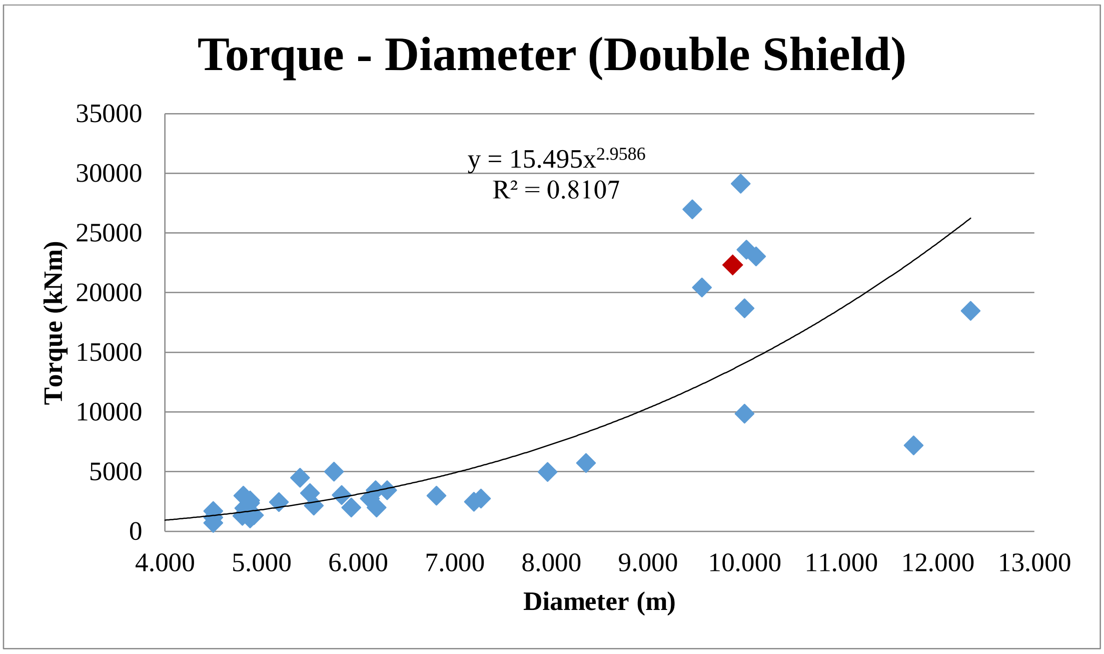
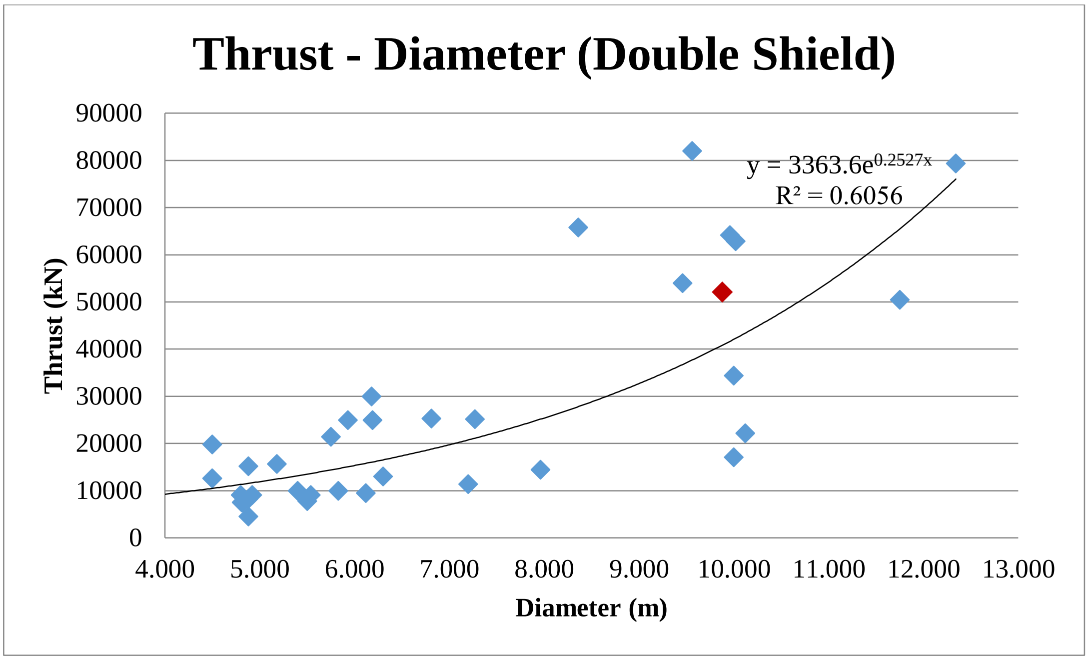


Figure 6.12 : Torque values for double shield TBMs.

The TBM has more than average torque capacity of double shielded TBMs (Figure 6.11), however its thrust and auxiliary thrust capacity (Figure 6.12) is similar to other double shields.



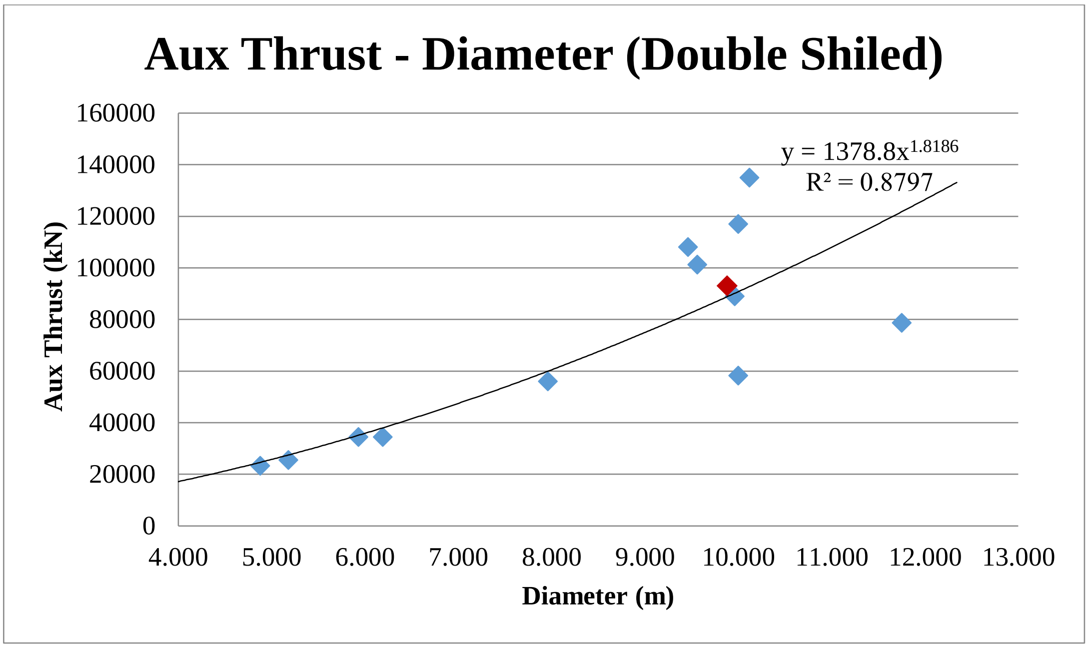


Figure 6.13 : Thrust (upper) and auxiliary thrust (lower) values for double shield TBMs.

6.2.3 Excavation

TBM parts assembled by using Onsite First Time Assembly (OFTA) method (Willis, 2012) which developed by The Robbins Company. OFTA allows TBMs to be initially assembled onsite, rather than in a manufacturing facility. The process eliminates all pre-assembly and disassembly in workshops and requires fewer total man-hours as a result. The reductions in man-power and shipping of large components generally add up to significant cost savings (David and Willis, 2009).

Figure 6.14 : Assembly on the jobsite (Willis, 2012).

After assembly excavation started on March 2012. Approximately one month after starting excavation the shield is jammed and a rescue drift along the shield was opened which took more than one month. On 9th September 2012 TBM was jammed again.

In total TBM was stopped for 79 days which is nearly 40% of the total boring time. Figure 6.15 shows TBM's advance rates until 24.09.2012. From the beginning of excavation, TBM advanced 949.5 meters in 194 days, which makes daily advance rate around 4.89 meter. This advance rate is nearly one third of the planned advance rate.

To compensate the delay it is decided to open another tunnel from Eastern part of the tunnel line with drill and blast method.

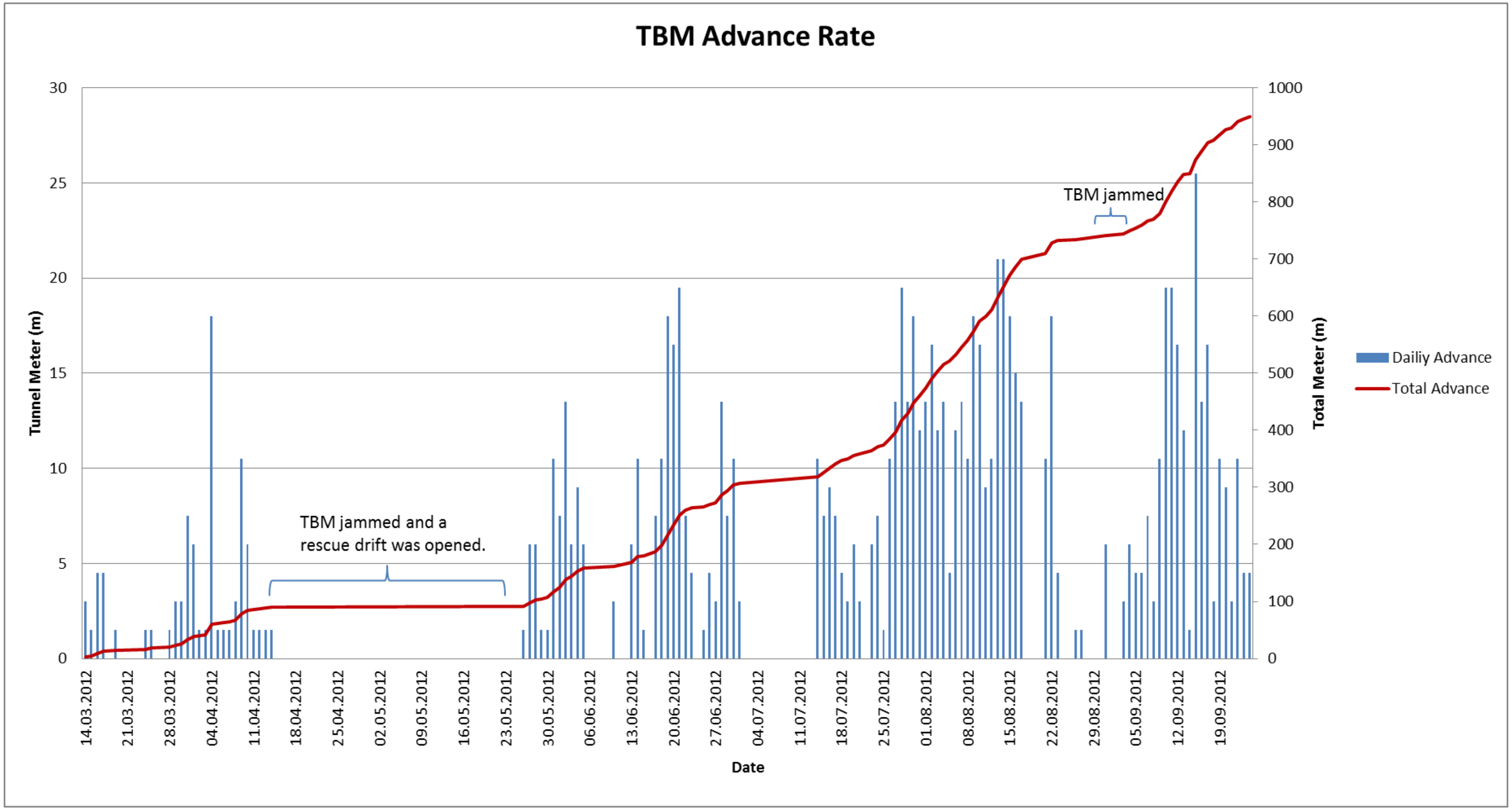


Figure 6.15 : TBM advance rates.

6.2.4 Thrust and torque of the machine

Average thrust and torque force per ring of the TBM showed on Figure 6.16 and Figure 6.17 respectively. Firstly, it should be mentioned that in contrast with the S-627 there is no maximum thrust and torque data is available for the Robbins TBM. Thus, the figures show only average thrust and torque. The red arrows on the figures show the locations where TBM was jammed.

It can be clearly seen from the Figure 6.16 that the thrust force of the TBM starts to increase before the jamming. By using this data risky areas can be spotted and waiting time in these areas could be minimized to reduce the jamming risk. Moreover, the TBM does not have shield lubrication system. If the shield jammings continued to occur, installing lubrication system to the shield could help TBM to advance, especially after long stops in squeezing ground. A similar system have been using on S-627 which was explained in detail in the previous sections and used on Uluabat project successfully (Caner, 2010)

Like average thrust also average torque of the TBM is increased steadily before the jammings (Figure 6.17). Sudden increase on the torque could indicate poor zones ahead of the TBM. On these zones earth material flows through the cutterhead and extracted material volume is increased. Using the torque and excavated material volume, prediction can be made about the formation.

Moreover, it should be mentioned that both thrust and torque have an increasing trend for the TBM. As the overburden increases both thrust and torque is also increases. Between the chainage 7+000.00 and 9+000.00 the overburden reaches to its maximum value. Both thrust and torque must be followed carefully for this 2 km and long waiting times should be avoided.

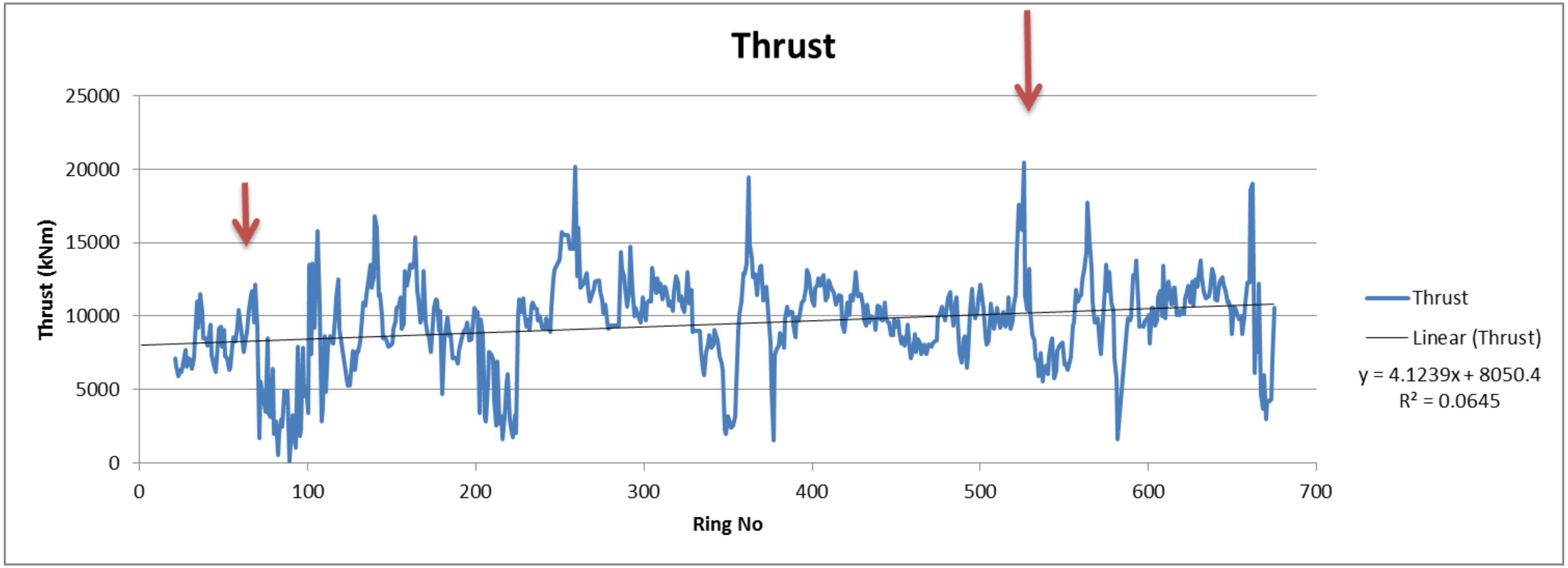


Figure 6.16 : Average thrust force of the TBM.

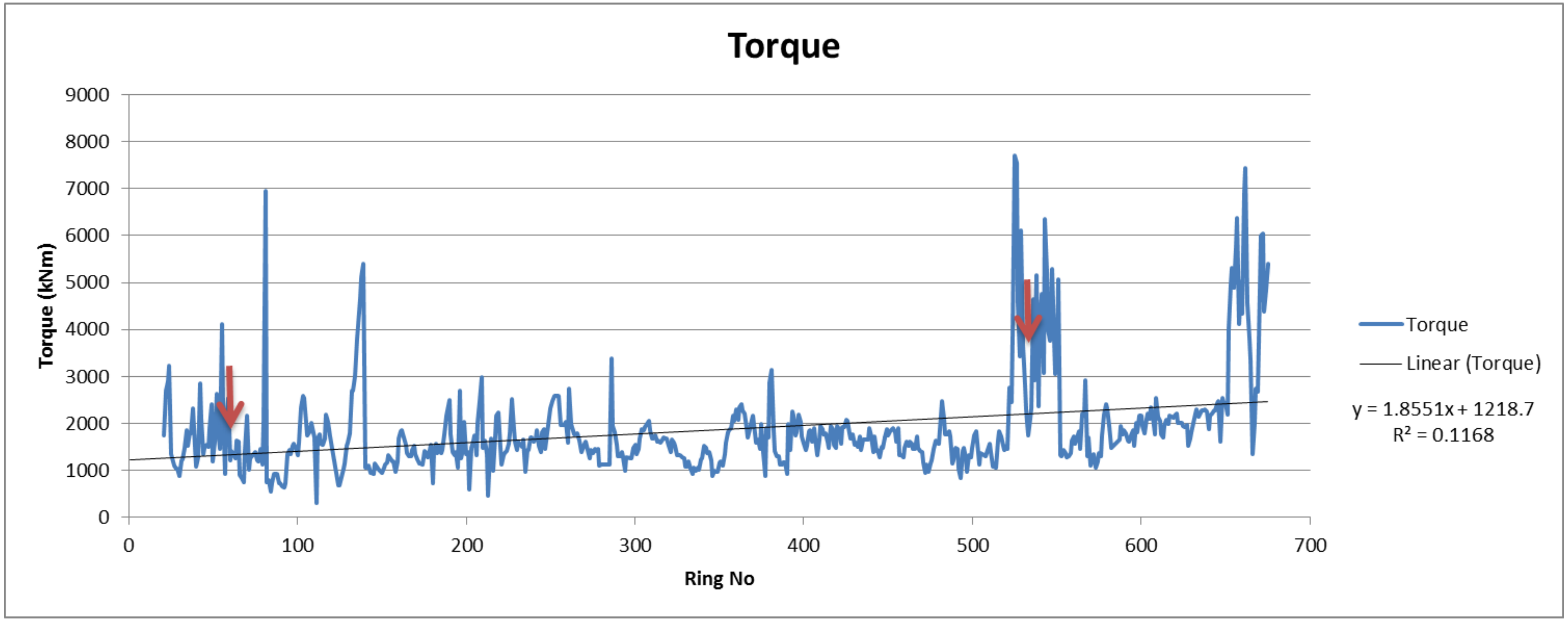


Figure 6.17 : Average torque of the TBM.

6.2.5 Conclusions for the Kargı Dam and Hydropower Project

Using an insufficient geological data lead to a wrong TBM design. The formation is very poor and causes shield jamming. The TBM has average thrust force for its size however, for squeezing/fractured geological formations the thrust force must be higher than the average. Moreover, when this thesis was written the overburden was around 200 m, however it will reach 475 m and will cause increased ground pressure. TBMs thrust, torque and segment design should be checked for high ground pressure effects before entering this zone.

Furthermore, both thrust and torque values of the TBM should be watched carefully as they can give clues about the geology. As the TBM has probe drills, they should be used constantly for understanding the geology ahead of the TBM.

Until 24.09.2012, TBM’s average daily advance rate is approximately 4.89 meter including stops, which is nearly one third of the expected rate.

7. CONCLUSIONS AND RECOMMENDATIONS

The TBM technology has been advancing day by day and today it is possible to excavate large cross section tunnels by using TBMs.

TBM selection is very important for the success of the project and it must be done with a great care. Machine performance is dependent on the geological formations and TBM model, thus TBMs properties should be chosen according to geology.

It is found that the suggested theoretical TBM design parameter calculations give proper results for TBM design and the results are consistent with the real TBM data. However, correct and sufficient geological information must be used for the calculations. The calculations are very dependent on the geological properties, especially, formation type, unit weight of the ground, compressive strength, shear strength, shear modulus of soil, angle of internal friction, overburden depth, coefficient of lateral earth pressure and coefficient of dynamic friction, must be determined carefully. Moreover, some theoretical calculation parameters need information about the TBM, like, cutterhead width and friction coefficients about the cutterhead sealings, which are kept confidential by the TBM manufacturers. Thus, it is very hard to calculate the exact parameters but by using a safety factor the correct TBM for the geology can be chosen.

329 TBM data were analyzed and some statistical evaluations were made. The biggest finding is that the TBMs design parameters are strongly connected with the geology and TBM diameter, which justifies the theoretical calculations. Two same type and same diameter TBMs could have different design parameters because of different geological conditions. It is also found that EPB TBMs generally have the highest torque and thrust values for a given diameter, while gripper TBMs have the lowest figures. Slurry TBMs generally have less, but close, thrust values to the EPB TBMs since they both excavate in the soil. However, EPB TBMs torque values are nearly two times higher than slurry TBMs. Since their shields are generally longer than other types double shield TBMs requires higher thrust forces to advance, thus their auxiliary

thrust is higher than other hard rock TBMs. Double shield TBMs main thrust force is close to single shield TBMs that are stands between the gripper and single shield TBMs. All of these findings can be explained by TBMs working principles and shield designs.

As the diameter increases thrust and torque differences between the TBM types become clear. It is also found that the ratio between thrust and torque values are different for all TBM types.

All types of hard rock TBMs have similar cutter numbers while some soft ground TBMs can also utilize disc cutters for mixed face conditions.

TBM weights are different for TBM types but it is possible to say that because of the shield design, double shield TBMs are the heaviest TBMs and gripper TBMs are the lightest ones for a given diameter. Single shield, slurry and EPB TBMs have similar weights.

TBMs thrust and torque values had increased as the TBM technology advances. Today's modern TBMs have more thrust and torque forces in comparison with TBMs manufactured in the past. While one of the biggest factor of these increase is related with cutter technology. Today's large diameter cutters can compete with high thrust forces. Moreover shifting from V-Type disc cutters to CCS type cutters helped to reduce cutter consumption and cutter number for a given diameter is also decreased.

There are also findings about the two case studies which confirms the theoretical assumptions.

Herrenknecht S-627 TBM, working in Ankara-İstanbul High Speed Railway Project, faced many problems and TBM was converted to an EPB machine from a single shield machine. TBMs thrust was increased from 84464 kN to 270000 kN and torque was increased from 16056 kNm to 35328 kNm, cuttherhead openings were reduced and new foam lines were added. Nearly 7 months were lost for repairs and modifications, which kept its daily advance rate approximately 2.23 meter. Since it was designed as a single shield TBM, it has not got EPB TBMs some key functions, like tail shield seal, which continuously causes problems and slows down the excavation. However, the case is a very good example for modifying the TBM in the underground after starting the excavation.

Moreover the TBM was not the only problem for the high speed railway project. The contractor also faced with problems about the segments.

The Robbins Double Shield TBM, which excavates Kargı Dam Tunnel, have also been faced some problems and as the overburden increases it is expected to face with more problems. The TBMs advance rate is 4.89 meters per day, which is one third of the expected advance rate.

The main problem for these two projects was insufficient geological exploration data. For given projects only 6 drill holes were used for geological exploration, while approximate tunnel lengths are 6 km and 11 km, respectively. Moreover wrong performance prediction system, Q-System, which was designed for the intact and stable rock conditions, is used to calculate S-627's advance rate.

For both projects, squeezing and fractured geological formations available on the tunnel alignment and overburdens are quite high, which caused constant stops and problems.

If the squeezing ground exists on the route, long stops must be avoided and the TBMs thrust force should be higher than the average for its size. Both theoretical calculations and in-situ observations confirms that using shield lubrication is a very effective way to cope with high thrust demand, since it could reduce required thrust up to 30-40%. TBMs thrust and torque forces should be monitored constantly while they can give information about the geology and it could be used to avoid jamming.

It may conclude that, TBMs are complicated and expensive machineries, thus wrong TBM selection could cost a lot for the companies and it could cause major delays on the project. Lots of parameters should be examined to select the proper TBM for the project and since the geology is the key parameter, geological conditions must be determined correctly.

REFERENCES

AITES-ITA, Working Group No 2. (2000). Guidelines for the design of shield tunnel lining. *Tunnelling and Underground Space Technology, 15*(3), 303-331

Bappler, K. (2006). *Full face tunnel boring machines, Herrenknecht AG.* ITA/AITES – Training Course Tunnel Engineering, Seoul.

Bilgin, N., Copur, H., and Balci, C. (2012). Effect of replacing disc cutters with chisel tools on performance of a TBM in difficult ground conditions. *Tunnelling and Underground Space Technology, 27*(1), 41-51

Bilgin, N., Copur, H., Balci, C., Tumac, D., Akgul, M., and Yuksel, A. (2008). *The selection of a TBM using full scale laboratory tests and comparison of measured and predicted performance values in Istanbul Kozyatagi-Kadikoy metro tunnels.* World Tunnel Congress 2008 – Underground Facilities for Better Environment and Safety, Agra, India, Sept. 22-24

Caner, E. (2010). *Sıkışan Zeminlerde Tam Cepheli Tünel Açma Makinelerinin Performans Analizi ve Uluabat Kuvvet Tüneli Örneği* (Master thesis), Istanbul Technical University, Istanbul, Turkey, p.155.

Çopur, H. (2012a). "MAD 513E Mechanical Excavation and Mechanisation in Soft Ground" Class Notes. ITU Mining Engieering Department.

Çopur, H. (2012b). Personal Communication.

Çopur, H., and Balcı, C. (2010). Ankara-İstanbul Hızlı Tren Projesi (2. Etap) Köseköy-Vezirhan (Kesim-1) İşi Kapsamındaki Karot Numunelerin Aşındırıcılıkları. Döner sermaye projesi.

David, S., and Willis, D. (2009). *Tunnel Boring Machines For The Srisailam Canal Tunnels, Andhra Pradesh, India*. World Tunnel Congress, Budapest, Hungary.

Einstein, H., and Bobet, A. (1997). *Mechanized tunnelling in squeezing rock–From basic thoughts to continuous tunnelling.* Tunnels for people, ITA World Tunnel Congress '97, Vienna

Ertin, A., Gicir, A., Yazici, I. F., Sahin, T., Posluk, E., and Babal, M. (2012). *Performance Evaluation of TBM Excavation for Tunnel No. 26 of Ankara-Istanbul High Speed Railway Project Using Qtbm Method.* EUROCK 2012, Stockholm, Sweeden

Evans, I. (1962). A Theory of the Basic Mechanics of Coal Ploughing *Mineral Resources* Vol. 2, pp. 761-799. pp. 761-799.

Gehring, K. H. (1996). Design criteria for TBM's with respect to real rock pressure. In H. Wagner & A. Schulter (Eds.), *Tunnel Boring Machines: Trends in Design and Construction of Mechanical Tunnelling Proceedings of the International Lecture Series* 1st ed., pp. 43-53: Taylor & Francis. pp. 43-53.

German Committee for Underground Construction (DAUB). (2005). Recommendations for static Analysis of Shield Tunnelling Machines.

Guglielmetti, V. (2008). *Mechanized tunnelling in urban areas: design methodology and construction control*: Taylor & Francis.

Herrenknecht, M., and Bappler, K. (2011). *Large-Diameter TBM Development*. Rapid Excavation and Tunneling Conference Proceedings, San Francisco, California, USA.

Herrenknecht, M., and Rehm, U. (2003). *Mixshield Technology*. Soft Ground and Hard Rock Mechanical Tunneling Technology Seminar, Colorado School of Mines Campus.

Japan Society Of Civil Engineers (JSCE). (2007). *Standard Specifications For Tunneling - Shield Tunnels*.

Kahraman, S. (2007). Historical Review of Tunnel Boring Machine (TBM) Data. *CIM Bulletin, 100, No. 1099*

Kanayasu, S., Kubota, I., and Shikubu, N. (1995). Stability of face during shield tunneling – a survey on Japanese shield tunneling. In F. a. Kusakabe (Ed.), *Underground Construction in Soft Ground* pp. 337–343. Rotterdam: Balkema. pp. 337–343.

Kok, Y. H., and Klados, G. (2006). *Uniqueness of SMART Project in the Logistic and Construction Challenges Encountered During TBM North and South Drive.* International Conference And Exhibition on Trenchless Technology and Tunnelling, Malaysia

Lobanov, V. A., and Joanknecht, L. W. F. (1980). *The Cutting of Soil Under Hydrostatic Pressure.* WODCON IX, Vancouver, Canada

Maidl, B., Herrenknecht, M., and Anheuser, L. (1996). *Mechanised shield tunnelling*: Ernst & Sohn.

Maidl, B., Schmid, L., Ritz, W., and Herrenknecht, M. (2008). *Hardrock tunnel boring machines*: Ernst & Sohn.

Nishimatsu, Y. (1972). The Mechanics of Rock Cutting. *International Journal of Rock Mechanics and Mining Science & Geomechanical Abstracts*, pp. 261–270

Ocak, İ., and Bilgin, N. (2009). *The Performance of Two EPB Machines in Istanbul Metro Tunnel Drivages in Soft and Shallow Ground*. ITA-AITES World Tunnel Congress, Budapest, Hungary.

PJA, Pipe Jacking Association. (1995). *Guide to Best Practice for the Installation of Pipe Jacks and Microtunnels*. London: Pipe Jacking Association.

Poşuk, E., Ertin, A., Korkanç, M., Pilatin, R. Y., Poşluk, E. A., and Arıca, E. (2011). *Performance evaluation of TBM excavation for tunnel no.26 at phase 2 of Ankara İstanbul high speed railway Project using QTBM method.* ROCMEC'2011-Xth Regional Rock Mechanics Symposium, Ankara, Turkey

Potts, E. L. J., and Shuttleworth, P. (1958). *A study of ploughability of coal, with special reference to the effects of blade shape, direction of planing to* *the clear, planing speed and the influence of water infusion.* Transactions Institution of Mining Engineers, London

Ramoni, M. (2010). *On The Feasibility Of Tbm Drives In Squeezing Ground And The Risk Of Shield Jamming* (Doctoral dissertation), ETH, Zürich, Switzerland, p.212.

Ramoni, M., and Anagnostou, G. (2010a). The Interaction Between Shield, Ground and Tunnel Support in TBM Tunnelling Through Squeezing Ground. *Rock Mechanics and Rock Engineering, 44*, 37-61

Ramoni, M., and Anagnostou, G. (2010b). Thrust force requirements for TBMs in squeezing ground. *Tunnelling and Underground Space Technology, 25*, 433-455

Ramoni, M., and Anagnostou, G. (2010c). Tunnel boring machines under squeezing conditions. *Tunnelling and Underground Space Technology, 25*, 139-157

Ramoni, M., and Anagnostou, G. (2011). *Tbm Tunnelling In Squeezing Ground - Basic Considerations And Decision Aids*. Rapid Excavation and Tunneling Conference Proceedings, San Francisco, California, USA.

Rostami, J., and Ozdemir, L. (1993). *A New Model For Performance Prediction of Hard Rock TBMs.* Rapid Excavation and Tunneling Conference, Boston, USA, June 13-17

Shi, H., Yang, H., Gong, G., and Wang, L. (2011). Determination of the cutterhead torque for EPB shield tunneling machine. *Automation in Construction, 20*(8), 1087-1095

Sial Yerbilimleri Müşavirlik Ve Mühendislik Ltd Şti. (2010). Ankara-İstanbul Hızlı Tren Projesi Vezirhan-İnönü (Kesim 2) 26 No'lu Tünel Jeolojik - Jeoteknik Raporu Ve Tünel Proje Raporu (pp. 72).

Song, X., Liu, J., and Guo, W. (2010). *A Cutter Head Torque Forecast Model Based on Multivariate Nonlinear Regression for EPB Shield Tunneling.* 2010 International Conference on Artificial Intelligence and Computational Intelligence

Stack, B. (1995). *Encyclopaedia of tunnelling, mining and drilling equipment*. Hobart, Tasmania: Muden Pub. Co.

Slinchenko, D. (2010). Control of ground settlement in EPB tunneling Retrieved 01.10.2012, from http://www.lovat.com/pdfs_powerpoints/Articles-&-Papers/CONTROL_OF_GROUND_SETTLEMENT_IN_EPB_TUNNELLING.pdf

Url-1 *<http://www.robbinstbm.com/ >, date retrived 01.10.2012*

Url-2 *<http://www.herrenknecht.com/ >, date retrived 01.10.2012*

Willis, D. (2012). Double shield taking on tough work in Turkey Retrieved 30.10.2012, from http://tunneltalk.com/TBM-Recorder-Aug12-Robbins-double-shield-takes-on-tough-ground-in-Turkey.php

CURRICULUM VITAE

Name Surname: Uğur ATEŞ

Place and Date of Birth: İstanbul – 19.09.1987

E-Mail: ates_ugur@hotmail.com

B.Sc.: Istanbul University, Department of Geophysics Engineering

PUBLICATIONS/PRESENTATIONS ON THE THESIS

Ateş, U., Bilgin, N., Çopur, H., 2013: Geniş Çaplı Tünel Açma Makinelerinin (TBM) Seçim Kriterlerine Genel Bir Bakış. *4. Maden Makinaları Sempozyumu*, May 23-24, 2013 İzmir, Turkey.