ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

FIELD AND LABORATORY STUDIES ON THE PERFORMANCE PREDICTION OF RAISE BORING MACHINES

M.Sc. THESIS

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Department of Mining Engineering
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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

BAŞYUKARI KUYU AÇMA MAKİNALARIN PERFORMANS TAHMİNİ İÇİN SAHA VE LABORATUVAR ÇALIŞMALARI

YÜKSEK LİSANS TEZİ

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Aydin Shaterpour Mamaghani, a **M.Sc.** student of ITU **Graduate School of Science Engineering and Technology** student ID **505121001**, successfully defended the **thesis** entitled "**FIELD AND LABORATORY STUDIES ON THE PERFORMANCE PREDICTION OF RAISE BORING MACHINES**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Prof. Dr. Nuh BILGIN** Istanbul Technical University	....
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To my family,

FOREWORD

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January 2015 Aydin SHATERPOUR MAMAGHANI
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ABBREVIATIONS

RBM	**:** Raise Boring Machine
ASTM	**:** American Society for Testing and Materials
ISRM	**:** International Society for Rock Mechanics
UCS	**:** Uniaxial Compressive Strenght
BTS	**:** Brazilian Tensile Strength
PLCM	**:** Portable Linear Cutting Machine
SE	**:** Specific Energy
TBM	**:** Tunnel Boring Machine
FN	**:** Normal Force
FC	**:** Cutting Force

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FIELD AND LABORATORY STUDIES ON THE PERFORMANCE PREDICTION OF RAISE BORING MACHINES

SUMMARY

Excavation of shafts and other vertical structures in mining and civil engineering fields for material and human transportation and ventilation purposes is a difficult and dangerous job taking quite long time. Raise boring provides a safe means of excavating shafts between two levels of underground structures without using explosives. A raise boring machine (RBM) operates by the principle of first drilling a small diameter pilot hole and then, reaming the hole in one or more stages to the desired size.

Raise boring system is the most up-to-date, secure and fast way for boring large diameter shafts. RBM creates a hole with smooth walls which usually does not require lining. The hole is more stable than a drilled and blasted raise and has better air flow, making it ideal for ventilation raises. In addition RBM can safely be used in areas of geological sensitivity.

One of the applications of raise boring machines in Turkey was realized in Eti Copper Kure Asikoy underground mine located at Kastamonu to excavate a ventilation shaft between the levels 660 m and 630 m having a length of 22 m and excavation diameter of 2.6 m. This thesis describes an analysis of the raise boring performed, and gives suggestions on how to optimize the raise boring. The analysis is made in two parts, a laboratory analysis and an analysis of the excavation. The laboratory analysis investigates the physical, mechanical and petrographical property of sample which collected from mine. In addition linear cutting tests are performed to find out samples cuttability and relationships between cutting performances of cutters with different cutting depth, and maximum tool forces. The analysis of excavation concerns the achieved penetration rates, thrust force, and cutterhead torque and the factors influencing these parameters.

At the last section of the thesis, excavation performance parameters of RBM such as thrust, torque, and penetration rate theoretically estimated based on the experimental results. Then, the realized and predicted values compared to serve a useful guide for future applications.

The findings of the study showed that the two basic concepts of rock cutting mechanics could be used to estimate the performance of raise boring machines. Thrust force and torque values could be formulated using the parameters that are a function of the rock compressive strength, the number of inserts in contact with the face for a given time and the projectile area of each insert. Another important point emerging from this study is that field specific energy obtained for TBMs and RBMs is very closely related for a given penetration and in rocks having similar strength values. This interrelationship will permit to use immense accumulated data for TBM applications in different projects for predicting the performance of RBMs.

BAŞYUKARI KUYU AÇMA MAKİNALARIN PERFORMANS TAHMİNİ İÇİN SAHA VE LABORATUVAR ÇALIŞMALARI

ÖZET

Türkiye'de ve Dünya'da gerek maden gerekse de altyapılar için kuyu açma işleri son senelerde önemli ölçülerde artmıştır. Bu nedenle kuyu açma makineleri bir çok maden ve inşaat projelerinde tercih edilmektedir. Dünya'da bir çok ülkede ve özellikle maden sahalarında bu makinalar kullanılmaktadır. Örneğin İsveç'in Kiruna demir madeninde 17 adet bu makinalardan bulunuyor. Bu madende bu makinalarla kullanarak 3 yıl içinde 50 km'lik kuyu açmayı planlamışlar. Türkiye'de ise bu makinaların kullanımı gittikçe artmaktadır. Türkiye'de özellikle metalik madenlerinde başyukarı kuyu açma makinaları en güvenli ve en hızlı kuyu açma yöntemi olarak gözükmektedir. Maden ve inşaat projelerinde, cevher ve insan nakliyatı ve havalandırma amacı ile açılan dikey kuyular veya diğer dikey yapılar, çok zorlu ayrıca da tehlikeli ve zaman alıcı bir iştir. Başyukarı kuyu açma makinaları, madenlerde iki düzey arasında patlayıcı madde kullanmadan, çok sağlam kuyu açmasını sunmaktadır. Bu makinalar 1950 senesinden bu tarafa Dünya’da birçok maden de havalandırma ve cevher nakli kuyuları açmak için kullanılmıştır. Ayrıca geçen 20 yılda tünellerde de kullanılmaya başlamıştır. Bu makinaların 0-90º açısı arasında çalışabildiği için madenlerin havalandırma ve cevher nakil şaftları, hidroelektrik santrallerin denge bacaları, eğimli cebri boru hatları, metroların yeraltı geçişlerinde hatları arası geçiş tünelleri (yatay), havalandırma bacaları, merdiven tünelleri (eğimli), kara yolu tünellerinin havalandırması gibi farklı amaçlar için kullanılmaktadır. Kazı, yer altında bulunan galeri ya da boşluğa ulaşana kadar devam ediyor. Makine bu süreçte tijleri otomatik bir kol rod tutucu yardımıyla ekleyerek pilot delgiye devam ediyor. Aşağıda bulunan galeri boşluğuna ulaşıldığında ise trikon bitler sökülerek asıl kazıyı yapacak olan genişletici başlık (reamer) takılıyor ve başyukarı olarak tabir edilen şekilde, tersten kazı başlıyor.

Delme-patlatma yöntemlerine göre birçok avantaj sağlayan RBM'ler günümüzde en çok kullanılan kuyu açma ekipmanları arasındadır. Klasik yönteme göre daha hızlı ve güvenli delgi yapabilen makinenin dört farklı yöntemi ile kuyu açmasını sağlıyor. Klasik kuyu açma yönteminde, trikon bitlerin yardımı ile önce küçük çaplı bir kılavuz delgi açılıyor ve sonra bu açılan deliği bir veya daha fazla aşamada istenilen çapa kadar büyütür. Pilot delgi sırasında öğütülen malzeme flashing ile yüzeyde çökelme havuzunda toplanırken, kesici kafa ile yapılan tarama kazısı sırasında tarayıcı kafadaki kesici uçların her dönüşü sırasında keserek zeminden söktüğü 0-5 mm boyutlarındaki kazı malzemesi ise aşağıya dökülüyor ve belirli aralıklarla yükleyici yardımıyla toplanarak kamyonlarla pasa sahasına naklediliyor. Normalde bir 50 metre kuyunu delme-patlatma yöntemi ile bir kaç ayda açarken, bu makina aynı kuyunu 15 günde açmak kapasitesine sahiptir. Bu makinalar ayrıca büyük şehirlerde de su, elektrik, atıksu kuyu açmasını da daha kolay bir şekilde yapmaktadırlar. Şehirlerde delme-patlatma yöntemi yasak olduğu için bu yöntem en güvenilir ve en hızlı kuyu açma yöntemidir. Ayrıca madenlerde yukarı seviyeye erişim olmadığında bu makinalar alt seviyede kurulup ve yukarıya doğru kuyu açma özelliğine sahiptiler. Bu yöntem literatürde 'kör kuyu' açma yöntemi olarak geçmektedir. Dördünce yöntemde de

madenin alt seviyesi kesici kafanı takmaya müsait olmadığı için kullanılmaktadır. Burada da hem kılavuz delgi ile ve hem de kılavuz delgisiz genişletme operasyonu yapılmaktadır. Bu makinaların yatırım maliyetleri çok yüksek olduğundan dolayı, seçim aşamasında dikkatli olmak gerekiyor. Oldukça karmaşık ve pahalı olan RBM'lerin performansı kuyu çapı ve jeoloji gibi farklı ve çok sayıda parametreye bağlı olarak değişmektedir. Bu nedenle RBM seçimi özenle yapılmalı ve proje için uygun özelliklere sahip bir makine seçilmelidir.

Bir diğer önemli noktada da büyük çaplı kuyu açmakla ilgilidir. Büyük çaplı kuyuları açmak için, başyukarı kuyu açma sistemi en güncel, güvenilir ve hızlı yöntemdir. Bu makinalar örselenmemiş kuyular açıyor ki tahkimata bile gerek duyulmuyor. Bu sistem ile açılan kuyular, delme ve patlatma yöntemi ile açılan kuyulardan daha sağlamdılar ki bu avantajları havanın iyi dolaşmasına sebep oluyor ve bu yöntemi havalandırma kuyularının açmasında üstün konumda tutuyor. Bu kuyularda tahkimata ihtiyaç olduğu zaman püskürtme beton, bulon, ve çelik hasır kullanılabilmektedir. Ayrıca başyukarı kuyu açma makinaları, jeolojik duyarlılığı olan alanlarda da güvenli olarak kullanıla bilir.

Türkiye'de başyukarı kuyu açma makinaların uygulamalardan biri, Kastamonu ilinde bulunan Eti Bakır Küre'nin Aşıköy yeraltı maden işletmesinde yapılmıştır. Bu işletmede başyukarı kuyu açma makinası 2012 yılında Atlas Copco firmasından alınmıştır ve bu projeden önce iki havalandırma kuyusu açmıştır. Birinci havalandırma kuyunun uzunluğu 65 metreydi ve ikinci kuyunun da uzunluğu 100 metreydi. Yeni açılan havalandırma kuyusu 660 m ve 630 m düzeyler arasında açılmıştır. Bu kuyunun uzunluğu 22 m ve çapı da 2.6 metreydi. Burada ilk önce trikon bit kullanarak 30 cm çapında kılavuz delgi açılmıştır, sonra sabitleyiciler ilave edilmiştir. Sabitleyicilerin asıl kullanma amacı doğru yönde ve doğru açıda kuyunun ilerlemesidir. Sonra normal tijler ilave olarak delme işi devam etmiştir. Burada toplam 16 tij (kesici kafanın tiji dâhil) kullanılmıştır. Normal tijlerin ağırlığı 450 kg ve uzunlukları 1.52 metredir. Bu kuyunun kılavuz delgisi 3 iş günüde bitmiştir ve genişletme işlemi ise 4 iş gün içinde bitmiştir. Böylece 22 metre iç havalandırma kuyusu 7 iş gününde bitmiştir.

Bu tezde, kullanılan başyukarı kuyu açma makinanın performansı incelenmiş ve daha verimli kullanılması için öneriler sunulmuştur. Bu incelemeler, iki ayrı bölümde yanı laboratuvar ve sahada yapılmıştır. Laboratuvarda, sahadan alınan numunelerin fiziksel, mekanik ve petrografik incelemeleri yapılmıştır. Bu deneyler için Amerikan Standart ve Test Metotları (ASTM) ve Uluslararası Kaya Mekaniği Birliği (ISRM) tarafından önerilen standartlara göz önünde tutarak yapılmış. Fiziksel ve mekanik özellikleri belirlemeye yönelik olarak, tek eksenli basınç dayanımı, çekme dayanımı, statik elastisite modülü, akustik deneyler (dinamik elastisite modülü ve Poisson oranı), ve ince kesitlerin petrografik analizleri yapılmıştır. Bu deneylerin sonucu detaylı olarak 5. Bölüm ve Ekler Bölümünde açıklanmıştır.

İlaveten doğrusal kazı deneyi, numunelerin kazıla bilirliği ve kazı performansı ile kazı derinliği arasında ki ilişkileri belirtmek için yapılmıştır. Taşınabilir doğrusal kazı deney setinde kama ve konik uçlu keskiler kullanılabildiği gibi mini disk keskiler de kullanılabilmektedir. Yapılan bu çalışma kapsamında farklı özelliklere sahip 3 standart keski yani kama, konik ve disk kullanılmıştır. Kazı deneylerin yapılmasının asıl amacı laboratuvarda spesifik enerjinin hesaplanması ve bu hesaplan miktarların hangisinin sahadaki spesifik enerjiye daha yakın olmasının incelemektir. Bu incelemenin sonucunda disk keskilerin spesifik enerji miktarları özellikle 5 mm derinlikte ve yardımsız kazı biçiminde daha yakın değerler göstermektedir. Ayrıca Kazı incelemesinde, makinanın penetrasyon oranı, itme kuvvetleri ve kesici kafanın dönme momentinin etkileyen faktörleri de araştırılmıştır.

Bu tezin son bölümünde, makinanın performansı ile ilgili olan faktörler örneğin itme kuvvetleri, dönme momenti ve penetrasyon oranı teorik deneysel sonuçlarına göre tahmin edilmiştir. Sonra, tahmin edilen faktörler ile sahadan elde edilen gerçek veriler bir sonraki uygulamalara katkıda bulunmak amacı ile kıyaslanmıştır. Sahadan elde edilen sonuçlara göre makinanın penetrasyon değeri 1-11 tijleri için 2.12 mm/devir olmuştur. Disk kesiciler penetrasyon yöntemi ile hesaplanan miktar ise 2.49 mm/devir olmuştur. İtme kuvvetin gerçek değeri sahada 1376 kN hesaplanmıştır. Tahmin edilen miktarsa 1484 kN göstermektedir. Tork değerlerine baktığımız zaman da saha verileri 91 kNm ve tahmin edilen miktar ise 94 kNm gösteriyor.

Tünel açma makinaları ile ilgili bir çok literatür bulunmaktadır ama başyukarı kuyu açma makinaları ile ilgili ciddi bir eksiklik gözükmektedir. Bu tezin asıl amacı bu makinaların çalışma yöntemini ve uygulanan performans parametrelerinin, tünel açma makinaları gibi tahmin etmektir. Bu çalışmanın sonucunda bu karara varılmıştır ki kaya kesme mekaniğinin iki temel kavramı, başyukarı kuyu açma makinalarının performansını tahmin etmek için kullanılır olabilir. İtme kuvvetleri ve dönme momentleri, Kaya basınç dayanımı fonksiyonu ve belirli bir süre için kayanın yüzü ile temas eden insertlerin sayısıyla formüle edilebilir. Bu çalışma sonucunda bir diğer önemli konu da saptanmıştır. Sahadan elde edilen spesifik enerji değerleri, tünel açma makinalarda ve başyukarı kuyu açma makinalarda, belirli penetrasyon ve benzeri kayaç basınç dayanımında, biri-birine çok yakındılar. Bu karşılıklı ilişki, tünel açma makinalarından elde edilen verilerin, başyukarı kuyu açma makinalarının da performansları ile ilgili olan faktörlerin tahmininde kullanılabilmesine uygun bulunmuştur.

1. INTRODUCTION

Excavation of shafts and other vertical structures in mining and civil engineering fields for material and human transportation and ventilation purposes is a difficult and dangerous job taking quite long time. Raise boring provides a safe means of excavating shafts between two levels of underground structures without using explosives.

The RBM was developed to meet the demands of the underground mining industry but has also found wide range of applications in tunnelling or infrastructural projects. A raise boring machine operate on the principle of first drilling a small diameter pilot hole and the reaming the hole in one or more stages to the desired size. Raise boring machines are usually used for boring shafts and raises ranging from 0.7 to 9 m diameter and up to 2000 m length. Raise boring is a well-established full-face excavation method. In full-face excavation method, the entire cross section of the hole is bored to the final diameter without using explosive materials.

In RBM operation, workers are not needed to access the raise while it is under construction and this lead to safe work area for workers. However, capital cost of these machines are high and in most cases, companies specialized in shaft boring are preferred for short length of shafts.

1.1 Objective of the Thesis

This thesis aims to summarize a case study on raise boring machine performance used to excavate ventilation shafts in a copper mine located at the city of Kastamonu, Kure Province, on Northern Turkey. Later, compare the realized excavation performance with the results of previously developed a theoretical model and an experimental model by using concepts of rock cutting mechanics.

In this study firstly, petrographic, physical, and mechanical characteristics of the samples taken during pilot hole drilling operation were identified in the laboratory. Later, two prediction methods, by using the experimental results, were used to predict the excavation performance of the RBM used in Kure-Asikoy underground copper mine for excavating a ventilation shaft. One of the methods is based on the theoretical concept of disc cutting penetration (Roxborough and Phillips, 1979) and the other one is based on the experimental specific energy concept (Rostami et al. 1994). In addition, the linear cutting test is performed to find out samples cuttability and relationships between cutting performances of cutters with different cutting depth, and maximum tool forces, which is very important by machine manufacturers to design appropriate machine for different geological conditions. In order to validate (compare) the prediction results, the performance of the RBM was recorded in the field.

2. GENERAL INFORMATION ABOUT RAISE BORING MACHINES

2.1 History of RBMs

The raise boring technology was developed to meet the demands of the mining industry but has also found numerous applications in tunneling or infrastructural projects for ventilation purposes even in very hard rock formations or in opening deep shafts.

As Stack (1995) stated in his voluminous work, Bade in 1949 did the first major breakthrough in this area. He tried to eliminate the necessity of intensive workmanship for shaft excavations in difficult conditions. Robert E. Cannon during the late 1950s embodied in German mine operation basic principles initiated by Bade, i.e. he drilled a small pilot hole, which was then enlarged by back reaming. In 1962 Cannon, 31R raise drill was used to drill a 17 cm pilot hole, which was later back reamed with a 100 cm diameter reaming head, in Iron River Mine, Michigan. German Wirth Company in 1963 introduced an electro-hydraulic raise drill that the pilot hole was drilled from the lower level to the upper level and the hole was then reamed downwards. Calweld-Smith Company introduced the first blind hole or box-hole raise borer in about 1967. In this machine, rotational and thrust forces for the cutter head were provided via the drill string from the power unit located on the mine floor at the foot of raise (Stack, 1995). Robbins designed their 81R machine for using in Mt. Isa mines, Queensland, Australia in 1971-72. This mine required 2.4 m diameter holes of varying length up to 600 m. Ingersoll-Rand were producing large diameter raise drills in 1973 and installed at Copper Cliff North mine for trial purposes. Subsequently the drill was used to back-ream raises of 2.10 m to depth of 300 m. Raise boring operations were also used in coal mines in Europe to diameter up to 8 m (Bruemmer and Wollers, 1976, Grieves, 1981, Muirhead, 1982). Bruemmer (1979) stated some case studies in operation blind shaft borer with hydraulic muck removal system in the German coal mining industry. Todd and Facchinetti (1979) explained down reaming at San Giacomo Al Vomano Hydro-Electric project in Italy. Friant et al. (1985) illustrated combination blind or reaming drill for raise construction. They stated that raise boring could be conducted with a predrilled pilot hole or blind (without pilot hole) at advance rate between 1.22 and 1.83 meter per hour. Hendricks (1985) investigated development of a mechanical shaft excavation system. Worden (1985) provided a detailed, pragmatic description of activities in the reaming cycle. Pigott (1985) stated variety of techniques and equipment which when combined to permit faster and cheaper drilling of shafts in soft to medium strength formations. Pugsley (1989) explicated deep hole raise boring at Falconbridge operation, Sudbury Ontario. Stacey and Harte (1989) explained the problems when using of raise boring machine for excavation of deep level mines of South Africa. They described high cutter wear and jamming and oscillating of the head occurred in deep level mines. Oosthuizen (2004) contributed on large diameter vertical raise drilling and shaft boring techniques as an alternative to conventional shaft sinking techniques.

2.2 Working Concept and Classification

Raise boring machines are used for excavation of shafts and other vertical structures in mining and civil engineering fields for material and human transportation and ventilation purposes. RBM uses a small diameter drill rod, around 230-350 mm, to drill a pilot hole down to the required depth of the shaft, which can be drilled up to around 2000 m. Once the pilot hole has been drilled to the desired depth, a reamer of up to 9 m diameter is attached to the drill rod. The reamer is then pulled back up to the upper level, creating a round shape. Raise boring machine has been generally used in the underground mining and construction development for boring shafts ranging from 0.7 to 9 m in diameter and up to 2000 m in length. Raise boring is also a well-established full-face excavation method. In full-face excavation method, the entire cross section of the hole is bored to the final diameter without using explosive materials.

Raise boring site preparation begins with a comprehensive plan. Rock formations having several geological discontinuities are risk factors prolonging the termination of shaft boring process (Visser, 2009). In such cases, a detailed geotechnical evaluation or ‘raise bore rock quality assessment’ based on the McCracken and Stacey method is recommended in the case of deep and / or large diameter shafts (Peck and Lee, 2008). Excavating shafts with raise boring machine divided in four ways as explained below:

2.2.1 Horizontal

Standard raise boring machines are capable of boring raises at angles from vertical to 45 degrees from horizontal. Raise drilling can be used to drill horizontal holes, such as holes for water, electricity or gas pipes. As seen in Figure 2.1, by addition of only a few accessories and minor adjustment in standard raise boring machine, the raises have been completed from 45^{o} degrees to horizontal. In horizontal raise boring, cutting removal is the most important subject, and special attention has to be taken for efficient operation. In pilot drilling the water flow has to be adequate to prevent the cuttings from settling along the bottom of the hole. In addition, during reaming the cut face must be cleaned.

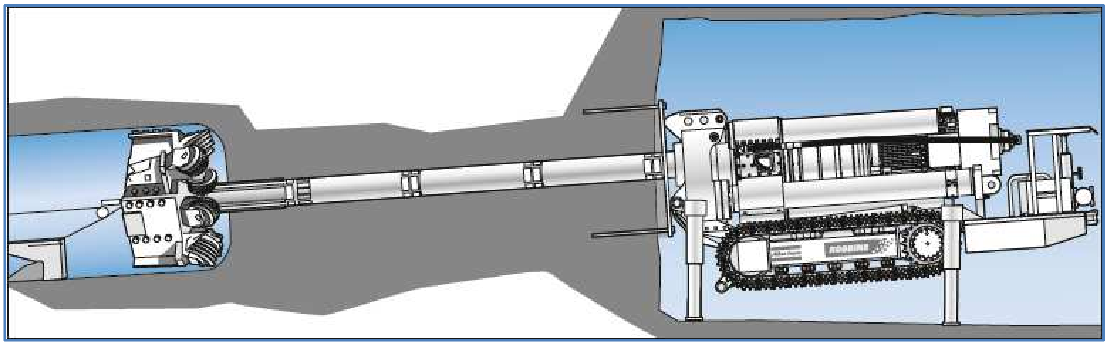

Figure 2.1: Overview of horizontal (or low angled) raise boring machine (After courtesy of Atlas Copco).

2.2.2 Down Reaming

In this way, the pilot hole is drilled down to a lower level of elevation in the mine or civil project. The drill string is then retrieved; reamer is attached, and then is pushed down towards the lower level of elevation below (Figure 2.2). This method uses drill string in compression and usually stabilizers must be installed to eliminate the potential of the drill string buckling. This method is used, when space at the lower level does not permit the connection of a reamer. Safety is the significant advantage of down reaming over back reaming. Men and equipment are at no time exposed to the hazards associated with working under an open raise. Safety is a significant advantage of down reaming over conventional back reaming. Men and equipment are at no time exposed to the hazards associated with working under an open raise. Secondly, cost associated with conditioning, supporting the ground at the break through area are no longer required, as access to the break through site for reamer installation, and maintenance has been eliminated.

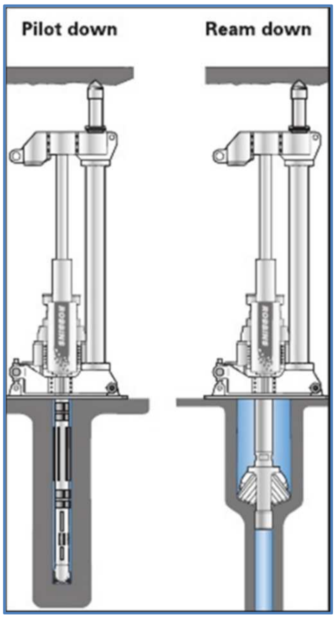

Figure 2.2: Overview of down reaming (After courtesy of Atlas Copco).

2.2.3 Up Reaming

In this way, the pilot hole is drilled down to a lower level, once the pilot drilling operation is finished the drill bit is removed and a reamer is attached to drill rod. The broken rock or cuttings will fall to the lower level by gravity where they can be transported away. However, in this way, the drill string will remain in constant tension whilst being rotated in order for it to drill at optimum stability and safety. Figure 2.3 show the conventional raise boring with pilot drilling and back reaming. In this way, the entire shaft is extended upwards from the bottom with the diameter of the reamer.

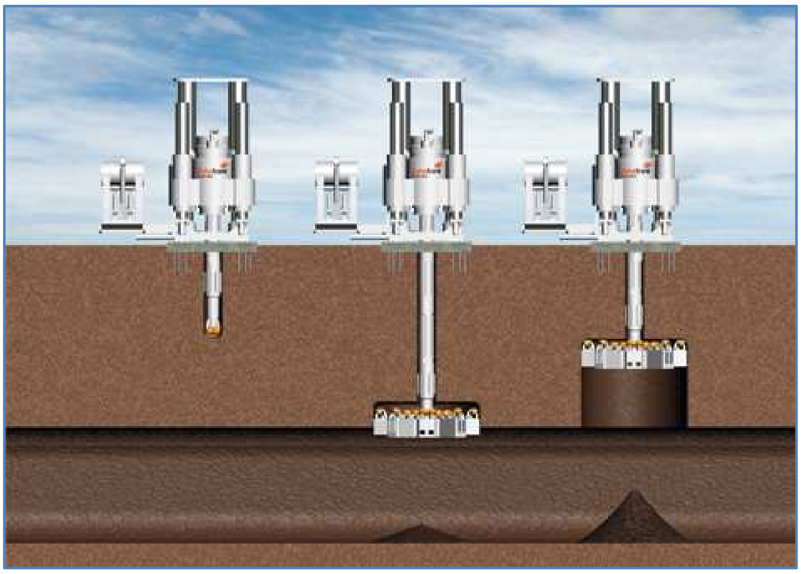

Figure 2.3: Conventional raise boring (After courtesy of Raisebore Australia).

2.2.4 Boxhole

In this method, a hole is drilled vertically, from the bottom upward. Boxhole boring is used to excavate raises where there is limited or no access to the upper level. It should be noted that, for reduce oscillation and bending stresses, stabilizers are periodically added to the drill string. The crushed rock falls downwards and is collected in a special device attached to the raise drill. Figure 2.4 show the boxhole boring with pilot hole and without pilot hole drill operation.

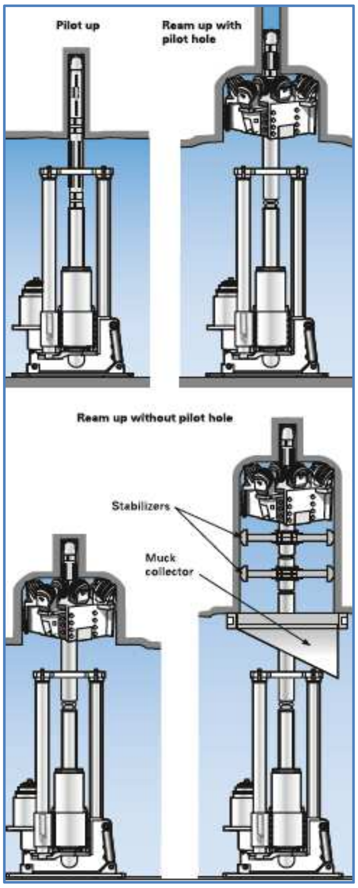

Figure 2.4: Boxhole boring with and without pilot hole drill (After courtesy of Atlas Copco).

2.3 Technical Features of RBMs

There are two main systems of powering the cutterhead on raise boring machines.

1. Electric drive through gear reducers: In this system, electric motors of 0 to 125 hp are directly geared to the cutterhead main bearing.
2. Electric-hydraulic combination: Hydraulic motors are used in combination with electric and turn the cutterhead.

There are at least four types of cutter geometry used for raise boring applications (Brooke, 2008). These are disc cutters, kerfed carbide insert cutters, rowed cutters and randomly placed carbide insert cutters. Disc cutter provides higher boring rates. Tungsten carbide insert rings have been used widely on disc cutters. Compared to randomly placed carbide insert cutters, kerf cutters tend to require higher thrust and torque to spall out chips, but are more efficient if sufficient load and torque are available. The rowed cutter design has multiple rows of inserts, but no steel kerfs. These cutters are preferred in most cases since they have much longer life although their penetration is comparatively low giving small chips and smooth shaft walls. As stated by Brooke (2008), the random insert cutters show significant increases in drilling rates, while reducing drilling torque. Figure 2.5 show the four cutters, which used in raise boring machine.

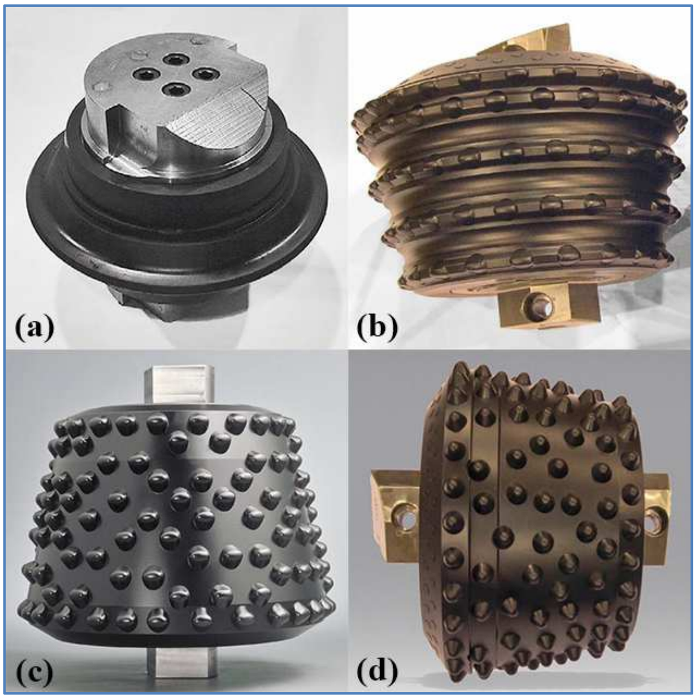

Figure 2.5: The cutters used in raise bore machine; a) Disc, b) Kerf, c) Carbide rowed, d) Random insert cutters (After courtesy of Atlas Copco).

Removal of cutting from a down-excavated shaft is done by compressed air, water or high viscosity water (mud). During back reaming, the cutting fall by gravity to the lower level where they can be picked up with a mechanical loader.

2.4 The Advantages and Disadvantages of Raise Boring

There are many advantages inherent with use of raise boring machines. The main advantages are:

- Speed: Continues operation (pilot, reaming and removing muck) provides a faster advance rate than other methods.
- Safety: The operators sitting in an operator cabin without any risk for air pollution or rock fall from weak rock zones.
- Rock support: This machine creates a shaft with smooth walls, which usually does not requires roof and side support.
- Labor requirements: Labor requirements are generally less for RBM, reducing labor costs as well as less construction time provide less cost.

The main limitations are:

- High capital cost: Capital cost is high and in most cases, contractor and companies prefer this machine when be certain that the machine is suitable for use over a sufficient length of shaft due to amortize the cost.
- Geological discontinuities: Several problems are faced in geological formations where geological discontinuities are dominant. In such case, boring time extended due to supporting shaft walls with rock bolts, wire mesh or steel lining.
- Assembly and disassembly time: These times could be 1 to 2 weeks in some cases.

3. ONE RAISE BORING MACHINE CASE STUDY FROM TURKEY

3.1 Description of the Project and RBM

Kure Mine has an ore body having about 600 m length, 50 m width and 800 m depth. The ore body contains a reserve of around 25 million tons, which is planned to last for up to 20 years. Around 754 miners work on different levels, and the mine is in operation 24 hours a day, seven days a week. The Kure Copper Mine is located at the 60 km north of Kastamonu and 25 km away from the Black Sea coast (Figure 3.1). Bakibaba open pit mine operations finished in June 2009, then the underground mine operations have been started in Bakibaba and Asikoy regions in Kure.

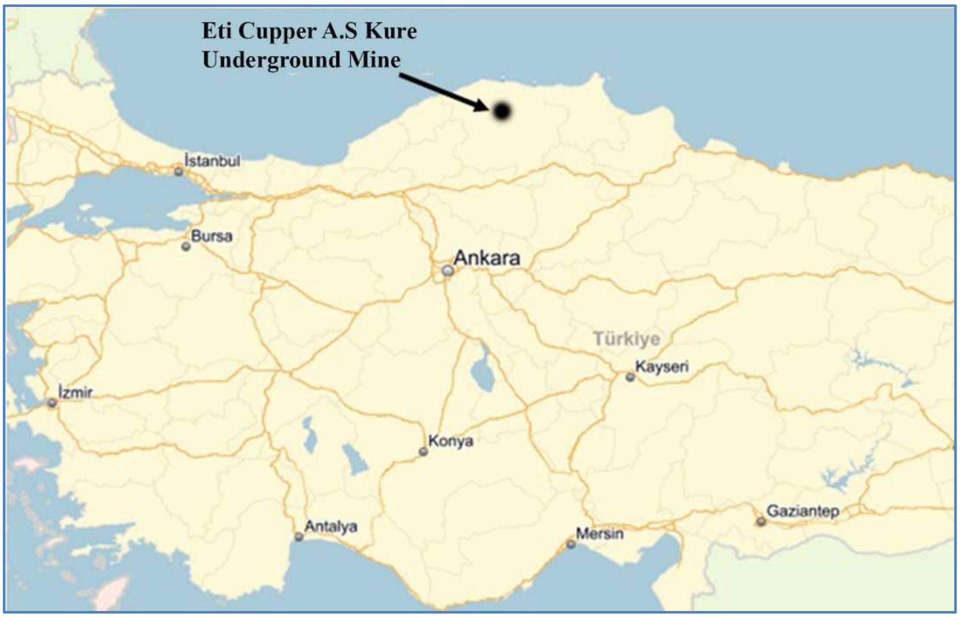

Figure 3.1: Location of the Eti Copper A.S. underground mine.

One of the applications of raise boring machines in Turkey was realized in Eti Copper Kure Asikoy underground mine located at Kastamonu. An Atlas Copco Robbins 73RH C Raise Boring Machine with specifications summarized in Table 3.1 was selected for excavation of the ventilation shaft between the levels 660 m and 630 m. Length and diameter of the ventilation shaft are 22 m and 2.6 m, respectively. Daily working schedule was one shift of 8 hours for pilot drilling and two shifts (16 hours) for reaming operations.

Table 3.1: Main characteristics of 73RH C Raise Bore.

Parameters	Value
Diameter (range)	1.5-2.4 m
Derrick Length	5.19 m
Thrust Capacity	4,159 kN
Reaming Torque	173 kNm
Break out Torque	210 kNm
Rotational Speed of Pilot Drill	0-52 rpm
Rotational Speed of Reamer Head	0-17 rpm
Drive System Power	200-250 kW
Derrick Mass	13,150 kg

RPM is the revolution per minute.

Roller cutters with tungsten carbide inserts are installed into gauge saddles on the cutterhead. The machine was originally designed to drill diameters up to 1.8 m; however, it was modified by adding 6 further roller cutters the cutterhead to drill a shaft with 2.6 m diameter. Figures. 3.2 and 3.3, show the raise boring machine and one of the roller cutter used in reamer head, respectively.

Figure 3.2: Atlas Copco 73RH C Raise Boring Machine (After courtesy of Atlas Copco).

Figure 3.3: One of the roller cutters used on the reamer head.

3.2 Geology of the Project Site

The area mentioned in this study is located at Kastamonu Province, Kure County in Northern Turkey. Asikoy and Bakibaba underground mines are in operation. The copper deposits in this region are known as Kure Copper Deposits. Kovenko (1944) stated that, MTA institute in 1938 was explored the geology vicinity of deposits in Asikoy and Kizilsu. As a result of this research, gossans zone were revealed in these places. Kure Copper Deposits are located at the western part of medium Pundits tectonic. Koc et al. (1995) stated that copper deposits, despite having quiet different geological properties of southeastern Anatolia ophiolite belt, might be included in Kuroko and Cyprus of Kieslager. The general geological map of Kure is given in Figure 3.4. The Kure area is chiefly made up of eugeosynclinal accumulations comprising subgraywacke and black shale and a Submarine basalt complex. Kure ore mass is part of ophiolitic series. This ore had occurred in series of altered basalt and covered with black shale. Hanging wall rocks consist of black shale and coarse-grained gravel. Stockwork pyrite and chalcopyrite veins are found in footwall rocks. The massive sulfide ores consist of pyrite, chalcopyrite, bornite, covellite, sphalerite, digenite, marcasite, tennantite, and carrollite. Major tectonic movements occurred within the Kure Formation. The units of Kure Formation are cut by north-south faults. Mineralization accordingly to the effect of this fault zone has emerged in the tholeiitic basalts, near the borders of pelagic sediments. These ores have average copper contents of 6% in the Bakibaba Mine and 2-2.5% in the Asikoy Mine.

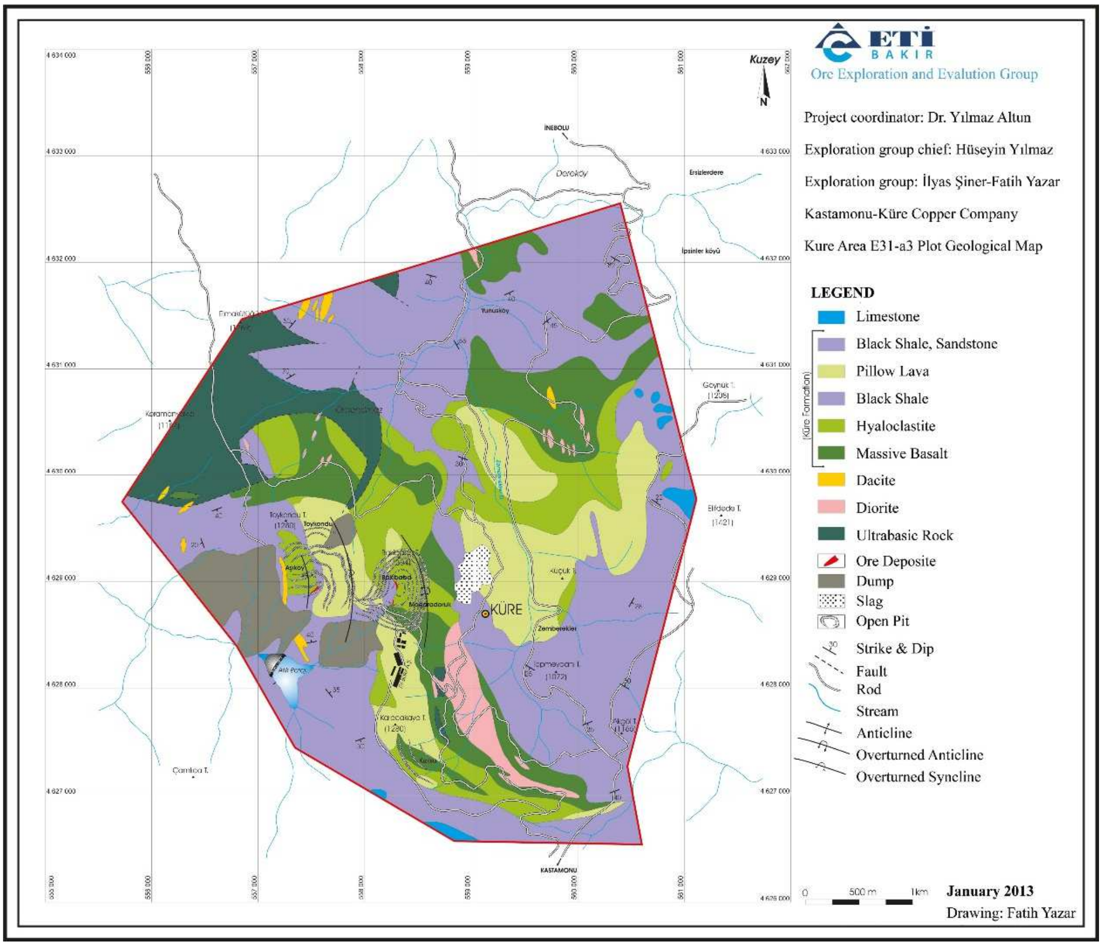

Figure 3.4: General geological map of Kure (Revised and modified from Japan international Cooperation Agency, The Mineral Exploration of Kure Area Consolidated Report [March 1995]).

3.3 Underground Production Method

Sublevel caving method is used for ore production and filling process is followed this operation. The main reason for using this method is to obtain full recovery of the ore. At first, both a raise and a network of tunnels are made. At different sublevels, jumbos are used for long hole drilling, drilling directly upwards into the roof. Then these holes are charged with explosives and blasted (Figure 3.5). Drilling and blasting takes place at different underground levels of the mine at the same time. After each blasting operation, broken ore is mucked out with remote control scoop trams vehicle (Figure 3.6). Moreover, the waste rock above the ore body caves gradually upwards as the ore is extracted. The blasting, caving and transportation operations are repeated until depletes the entire ore body. After the blasting and removing muck from panel, the filling operation carried out between excavated levels. In Asikoy underground mine, between 945-792 m levels, the ramps incline is %10, the waste panel size is 5×5 m^2

(wide × height) and the ore panel size is 5×5 m^2 (wide × height). However, between 792-610 m levels, the ramps incline is %12, the waste panel size is 5×5 m^2 (wide × height) and the ore panel size is 7×5 m^2 (wide × height). In sublevel caving method, continuous excavation activity on going at one sublevel without interfering with another.

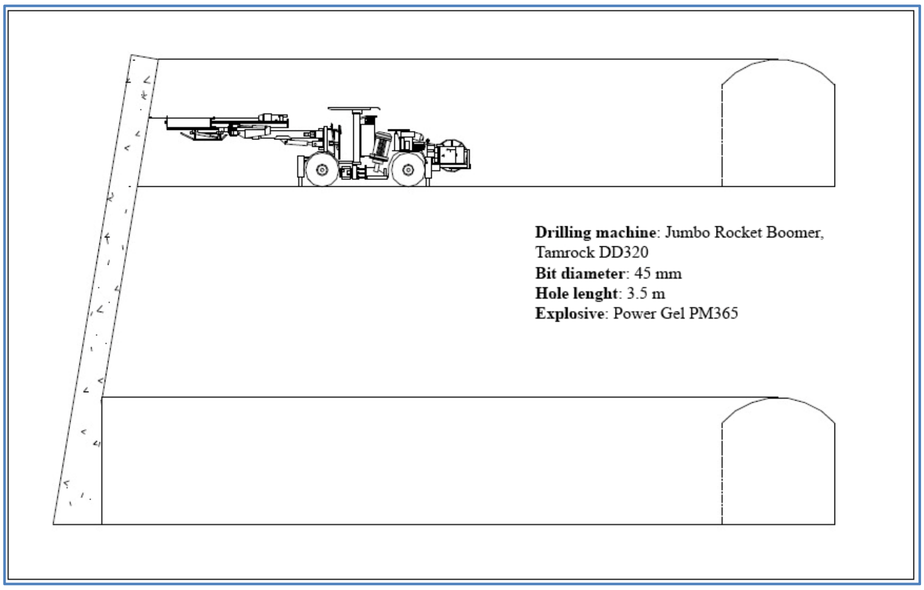

Figure 3.5: Ore and waste gallery.

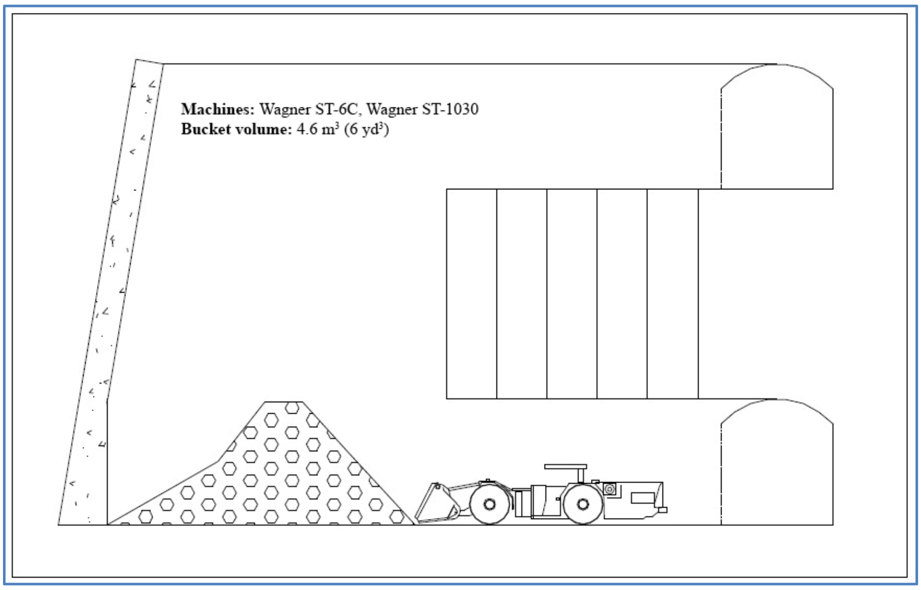

Figure 3.6: Ore transport operation.

4. EXPERIMENTAL STUDIES OF SAMPLES AND RESULTS

4.1 Physical and Mechanical Properties

Physical and mechanical property tests including uniaxial compressive strength, Brazilian tensile strength, and static elasticity modulus were performed based on ISRM suggestions (Ulusay and Hudson, 2007). Acoustic velocity test (dynamic elasticity modulus and Poisson's ratio) are performed based on ASTM (2005). In addition, petrographical characteristics of three rock samples were analyzed by using a microscope with plane polarized light. Applied testing methodologies are summarized in the sections below.

4.1.1 Uniaxial compressive strength test

Uniaxial compressive strength (UCS) is an important mechanical parameter required for the design of geotechnical, mining, and tunnelling projects. The compressive strength, is used to identify and classify the resistance of rocks. UCS tests were accomplished on grinded core samples with a length to diameter ratio of around 2.5. The stress rate applied to core samples was 0.5 kN/s. The uniaxial compressive strength values are calculated by using equation 4.1:

$$\sigma_c = \frac{F}{A} \tag{4.1}$$

Where;

σ_c: Uniaxial compressive strength, MPa

F: Failure Load, N

A: Core sample section area, mm^2

4.1.2 Brazilian tensile strength test

Brazilian (indirect) tensile testing of rock cores is an easy and common method for determining the tensile strength of rock. In the Brazilian test, a cylindrical specimen is loaded in compression (indirect tensile) until failure over a short strip along the specimen length at each end of the vertical diameter. Brazilian tensile tests were performed on core samples with 0.25 kN/s stress rate and the ratio of a length to diameter of around 0.7. Tensile strength of the core samples values are calculated by using equation 4.2:

$$\sigma_t = \frac{2F}{\pi LD} \tag{4.2}$$

Where;

σ_t: Brazilian tensile strength, MPa

F: Failure load, N

L: Core sample length, mm

D: Core sample diameter, mm

4.1.3 Static elasticity modulus and poisson's ratio

The samples prepared for uniaxial compressive sterngth test were used for determining static elasticity and poission's ratio. The elastic modulus of rock sample is defined as the slope of its stress-strain curve in the elastic deformation region.

For measuring the deformation of rock samples, both diagonal and axial deformation are mesured in stiff machine has exist in Mining Engineering Department of Istanbul Technical University. Equation 4.3 and 4.4 are used to calculate the diagonal and axial displacements in rock samples (ISRM, 1981).

$$\varepsilon_a = \frac{\Delta l}{l_0} \tag{4.3}$$

Where;

ε_a : Axial displacement, mm

Δl : Change in length of sample, mm

l_0 : Sample length, mm

$$\varepsilon_d = \frac{\Delta D}{D_0} \qquad \textbf{(4.4)}$$

Where;

ε_d : Diagonal displacement, mm

ΔD : Change in diameter of sample, mm

D_0 : Sample diameter, mm

The stress-versus-strain curves for the axial and diagonal direction are plotted. Average slope of the more-or-less straight line portion of the stress-strain curve is used to calculate the average static elastic modulus. And the Poission's ratio is calculated by Equation 4.5:

$$\nu = -\frac{\varepsilon_d}{\varepsilon_a} \qquad \textbf{(4.5)}$$

4.1.4 Acoustic P and S wave velocity test

Acoustic velocity test are performed based on ASTM (2005). P-wave velocities (V_P) and S-wave velocities (Vs) were measured on the samples having a diameter of 48 mm and a length of 120 mm. These tests involve propagating an ultrasonic compression wave and two orthogonal shear waves along the longitudinal axis of the sample, then measuring the velocity of the waves as they travel through the specimen to calculate dynamic elastic properties, including Young’s modulus, bulk modulus and Poisson’s ratio. In the tests, the PUNDIT 6 instrument and two transducers (a transmitter and a receiver) having a frequency of 1 MHz were used. A good acoustic coupling between transducer faces and sample surface is necessary for the accuracy of transit time measurement.

4.1.5 Petrographic analysis

Petrographical characteristics of three rock samples were analyzed by using a microscope with plane polarized light. A petrographic analysis is an in depth investigation of the chemical and physical features of a particular rock sample. A complete analysis should include macroscopic to microscopic investigations of the rock sample.

4.2 Portable Linear Cutting Machine Test

Full-scale cutting machine is a laboratory test apparatus designed to provide data for the evaluation of rock cuttability selection and designing of mechanical miners, and predicting their excavation performance. Average tool forces are used for machine design and performance optimization. Normal force is used to determine the machine thrust requirements to achieve a given rate of advance. Cutting force is used for calculating machine torque and power requirements. The ratio of cutting to normal force, also known as the cutter coefficient, increases with tool depth of cut.

One of the disadvantages of large scale linear cutting machine is related to block size. When blocks have small size, it is not possible to carry out the cutting test. In order to solve this problem, the small scale (portable) linear cutting machine was developed. The new small scale linear cutting machine was designed in 'Excavation Technology and Mining Machinery Laboratory' of Istanbul Technical University, which is able to carry cutting test with chisel, conical and disc cutters. The new designed machines working principle is the same large scale machine, but it needs less manpower and instead of large blocks, small blocks can be used to perform linear cutting test.

Three borehole samples were used in linear cutting test. The data sampling rate was 1,000 Hz and the cutting speed of the linear cutting machine was around 3 cm/s. A chisel tool having a rake angle of -5^0, clearance angle of 5^0, and 12.7 mm tip width, a disc tool having 2 mm tip width, and a conical tool having a tip angle of 60^0, attack angle of 45^0 and clearance angle of 15^0, were used to cut borehole samples at two different depths of cut in unrelieved cutting mode. Bilgin et al. (2014) stated that tool forces alone are not enough to evaluate the efficiency of cutting systems. Specific energy is defined as the energy used to drill or cut a unit volume of rock which is one of the most important factors in determining the efficiency of a cutting system. Specific energy is estimated as shown in equation 4.6 (Pomeroy, 1963; Roxborough, 1973).

$$SE = FC / Q \qquad \textbf{(4.6)}$$

Where SE is specific energy (MJ/m^3), FC is cutting force acting on the tool (kN), and Q is yield or rock volume cut in unit cutting length (m^3/km). Specific energy might be used to estimate the net cutting rate of tunnel boring machines, roadheaders, and other mechanized excavation machines. Equation 4.7 can be used for estimation of net cutting rate (Rostami et al., 1994):

$$NCR = k.P_{cutting} / SE_{opt} \tag{4.7}$$

Where NCR is the net instantaneous cutting rate (m^3/h), k is the coefficient related to transference of cutting power to the rock, $P_{cutting}$ is the cutting power of the excavation machine (kW), and SE_{opt} is optimum specific energy (kWh/m^3) obtained from linear cutting experiments.

4.3 Sieve Analysis of Muck Samples From RBM

The size distribution of muck samples are used in determining the efficiency of cutting. Coarseness index (CI) is a comparative size distribution of the cut rocks using sieve analysis of the cut materials (Roxborough and Rispin, 1973a). Roxborough and Rispin (1973b), stated that CI is a nondimensional number used for comparison of muck size. CI is the sum of cumulative weight percentages retained in each sieve. Literature survey on the CI studies were executed by Tuncdemir et al., (2008) .The sieve set used in calculating CI values have the apertures of 5.6, 4, 2, 1, 0.5, 0.25 and 0.125 mm in this study for pilot and reaming operation as well as LCM tests..

4.4 Experimental Results

4.4.1 Physical and mechanical properties

Summary results of physical and mechanical properties of borehole samples are given in Table 4.1 and the detailed results are given in Appendix A1.

Table 4.1: Physical and mechanical properties of the rock samples tested (Ulusay and Hudson, 2007 and ASTM, 2005 standards).

Properties	**Value**
Uniaxial compressive strength (MPa)	81.6 ± 29.3
Brazilian tensile strength (MPa)	10.96 ± 2.7
Static Young’s modulus (GPa)	11.28 ± 2.5
Static Poisson’s ratio	0.14 ± 0.07
p-Wave velocity (m/s)	5994 ± 560
s-Wave velocity (m/s)	3083 ± 329
Dynamic Young’s modulus (GPa)	71 ± 14
Dynamic Poisson’s ratio	0.32 ± 0.03
Density (g/cm^3)	2.81

Examples of the borehole samples before and after UCS, BTS and elasticity tests are presented in Figures 4.1-4.3.

Figure 4.1: Sample 3. a) Before UCS test b) After UCS test.

Figure 4.2: Sample 23. a) Before BTS test b) After BTS tes.

Figure 4.3: Sample 4. a) Before elasticity b) After elasticity.

Photographs of the thin-sections of three rock samples are shown in Figures. 4.4, 4.5 and 4.6. The sample 1 is generally composed of albitization plagioclase and abundant calcite; brecciated texture dominated the sample. The sample 2 consists of calcite vein and plagioclase; the void space of the sample was filled with the calcite. The sample 3 is characterized as an iron oxide and plagioclase; all of the crushed material is filled with oxide iron.

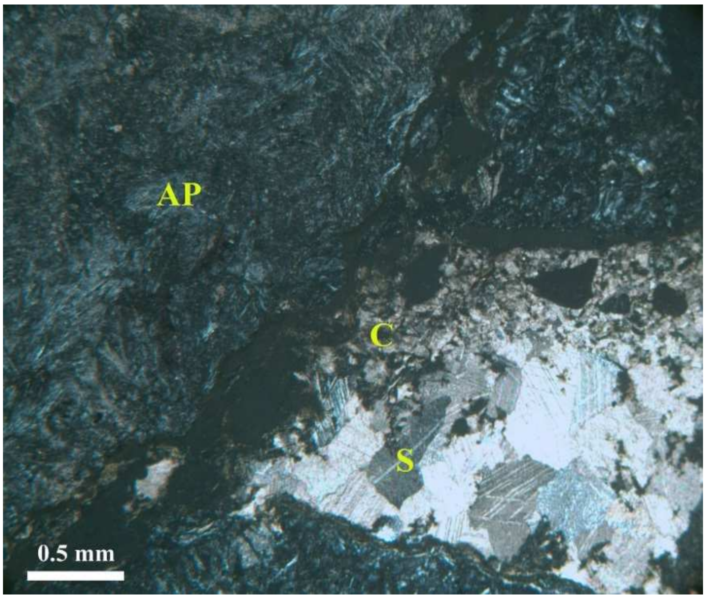

Figure 4.4: Photograph of thin section of the Sample 1: Albitization Plagioclase (AP), Calcite (C), Spilite (S) [plane polarized light].

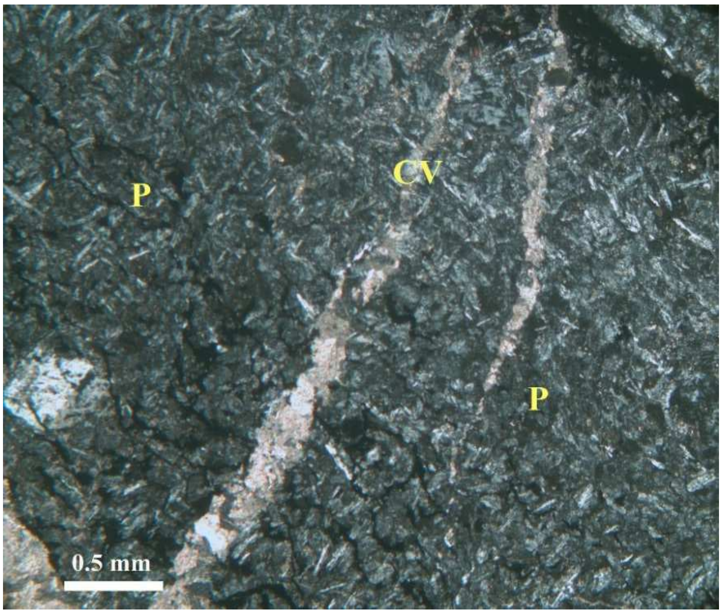

Figure 4.5: Photograph of thin section of the Sample 2: Calcite Vein (CV), Plagioclase (P) [plane polarized light].

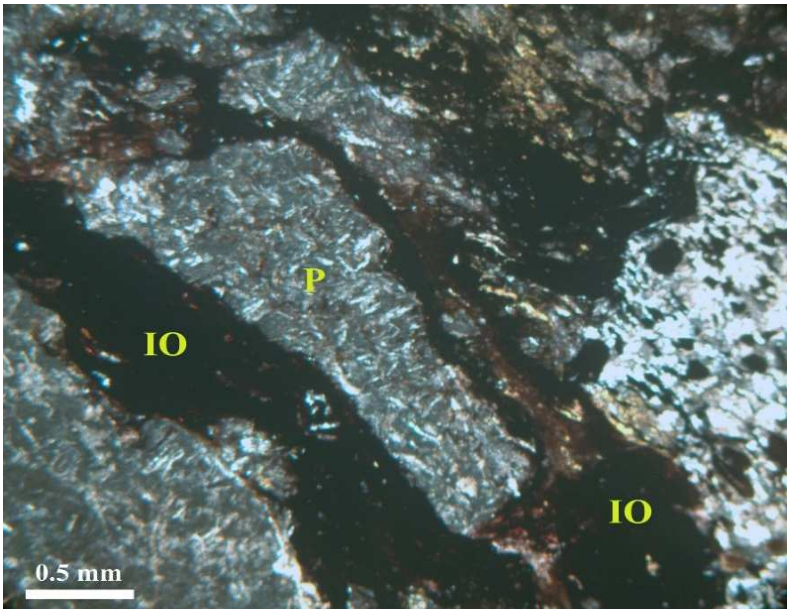

Figure 4.6: Photograph of thin section of the Sample 3: Iron Oxide (IO), Plagioclase (P) [plane polarized light].

4.4.2 Linear cutting test

Before taking a cut, the borehole samples were trimmed to produce smooth flat surface by using a chisel tool. Average normal and cutting forces (FN, FC), and Specific Energy (SE) obtained from linear cutting tests carried out by three different types of standard cutter tools at two different depths of cut (3 and 5 mm) in unrelieved cutting mode are summarized in Table 4.2 and detailed results are given in Appendix A2. As seen, the average normal forces from the highest to the lowest are obtained as sample three (disc cutter), sample one (chisel), and sample two (conical). The average cutting force values from the highest to lowest are obtained as sample one, sample three, and sample two. However the average specific energy values are obtained 26.18, 21.69, and 18.69 kwh/m^3 for samples, respectively. Coarseness Index (CI) is used for the comparison of muck size.

Table 4.2: Summary of the linear cutting test results.

Cutting Tool Type	Depth of Cut (mm)	Average Normal Force (kN)	Average Cutting Force (kN)	Specific Energy (kWh/m^3)	CI %
Chisel	3	10.54	5.40	34.19	626
	5	13.13	6.94	18.17	646
Conical	3	2.89	1.67	24.65	607
	5	5.19	3.01	18.74	683
Disc	3	8.67	1.49	20.00	610
	5	22.13	5.41	17.38	627

Maximum normal and cutting forces obtained from linear cutting tests in unrelieved cutting mode are summarized in Table 4.3 for three samples. As seen in Table 4.3, the maximum normal forces follow similar trends as average normal forces. However the maximum cutting forces don't follow similar trends as average cutting forces and sample two have much forces than sample three.

Table 4.3: Maximum normal and cutting forces obtained from linear cutting tests.

Cutting Tool Type	Depth of Cut (mm)	Maximum Normal Force (kN)	Maximum Cutting Force (kN)
Chisel	3	27.32	15.74
	5	35.25	22.83
Conical	3	9.54	5.56
	5	20.77	12.67
Disc	3	22.77	4.42
	5	41.94	12.29

5. FIELD STUDIES ON PERFORMANCE OF THE RAISE BORING MACHINE

The raise boring machine passed 22 m of underwater basalt rocks between the depth of 660 and 630 m. Figure 5.1 show rod assembly and disassembly in the pilot drilling and reaming. The RBM started running on the 1 February 2014 and its advance rates until 11 February 2014 are summarized in Table 5.1 for pilot drilling and reaming operations. Operational parameters of the RBM such as machine rotational speed, thrust, torque and penetration were recorded by the author during this period, which were used for further analysis of the excavation performance.

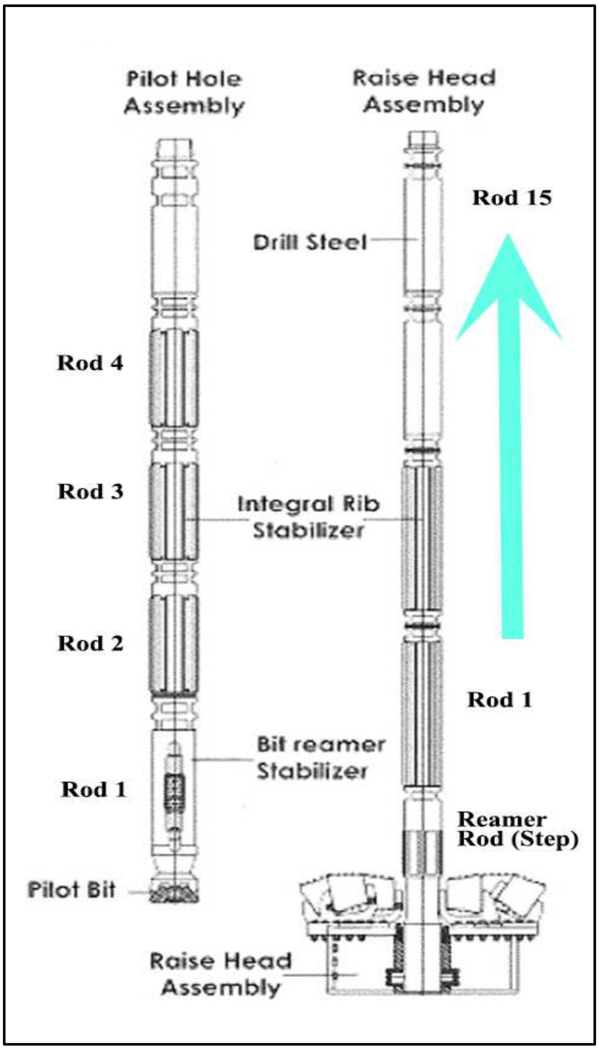

Figure 5.1: Rod assembly and disassembly in the pilot drilling and reaming.

Table 5.1: Mean advance rates of the RBM for pilot drilling and reaming between the upper and lower levels (the depth between 660 and 630 m).

Parameter	Pilot Drilling	Reaming
Best advance rate, (m/h)	6.185	1.433
Mean advance rate (all stoppages included), (m/h)	2.541	1.247

Performance parameter analysis of the RBM equipped with tungsten carbide inserts in reaming, such as penetration rate, thrust and torque values are presented in Table 5.2. A detailed calculation for 15 rods is shown in Table 5.3.

Table 5.2: Mean measured values of the RBM operational parameters.

Operation	Penetration (mm/rev)	Net Thrust (kN)	Torque (kNm)
Reaming	2.12	1376	91

Table 5.3: Performance analysis of the RBM penetration rate, thrust, and torque values for 15 roads in reaming.

Rod No.	RPM (Rev/min)	Net Thrust (kN)	Torque (kNm)	Penetration (mm/rev)
15	4	176	37	4.00
14	6	757	54	2.12
13	7	988	63	2.09
12	7	608	66	2.72
11	9	1221	86	1.82
10	9	1270	85	2.61
9	9	1245	91	2.28
8	8	1349	93	2.20
7	10	1382	94	2.39
6	10	1498	94	1.91
5	10	1472	96	1.96
4	9	1493	94	2.11
3	9	1436	94	2.15
2	9	1323	84	1.65
1	9	1444	94	2.19
Reamer Rod	7	354	38	8.12

All analyzed data are summarized in Figures 5.2-5.7. As seen in Figures 5.2 and 5.3, the mean penetration rate for pilot drilling and reaming operations were 10.63 and 5 m/h, respectively. However, it is also worth noting that mean penetration rate increased up to 23.6 m/h in 5 February 2014 for pilot drilling and increased up to 7.11 m/h in 10 February 2014 for reaming. It should be noted that performance of RBM for the first and the last three rods is exceptional, since in the first rod operator increases gradually rpm, torque and thrust until stable values are obtained and in the last three rods operator decreases gradually the operational parameters of RBM in order to stop the sudden collapse of the shaft collar. These facts are clearly demonstrated in Figures 5.4 and 5.5. As can be seen in Figure 5.4 the rotational speed values in reaming operation varied between 4 and 10 rpm. As it is shown in Figure 5.5, the mean and maximum thrust values for reaming were 1126 and 1498 kN, respectively. RBM torque value varied between 37 and 94 kNm (Figure 5.6), and net advance rate varied between 0.89 and 1.43 m/h for reaming operation (Figure 5.7). It should be noted that maximum penetration rate should be controlled by predetermined bit force using the rotational speed. Increases in penetration rate due to increases in rotational speed are not as dramatic as penetration rate increases due to increased cutter load. Load per cutter, reamed diameter, geological formation and angle of the raise are some factors influencing the torque requirements. Geological formation might be more complex subject in higher torque requirements. However, in general, due to deeper penetrations in the softer formation, higher torque may be experienced in RBM. At the beginning and end of the reaming operation, the operational parameters of RBM show lower values. At the beginning of reaming (rod 15) when the cutters contacted with the roof rocks of bottom level due to concern over wear of drill string and drill string failure, rotational speed should be lower than the other rods. Whereas at the ending of reaming (rod 1), when the cutters are near to floor of upper level, rotational speed should be lower than other rods. Otherwise, rock blocks could fall in the reamer and cause damage to cutters.

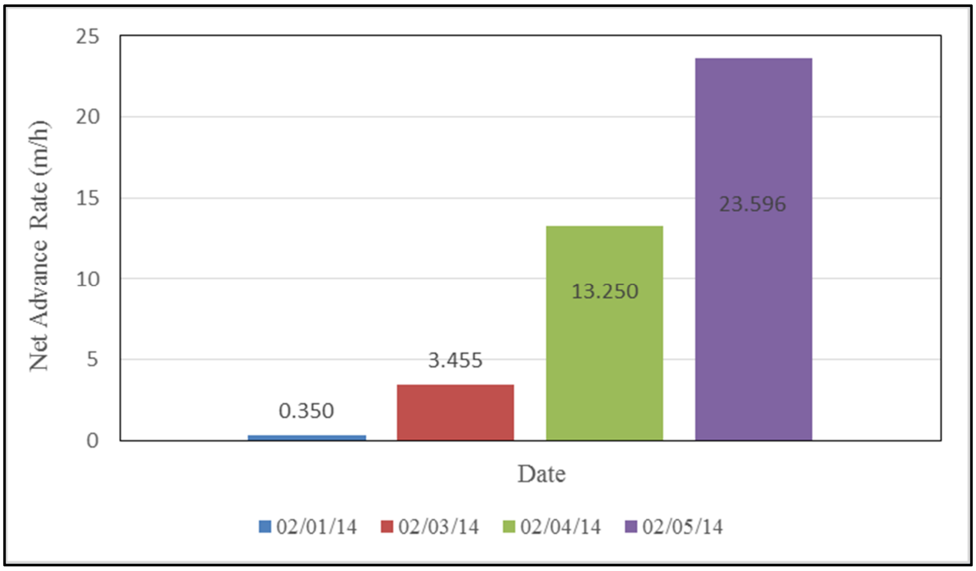

Figure 5.2: Net advance rate values for pilot drilling.

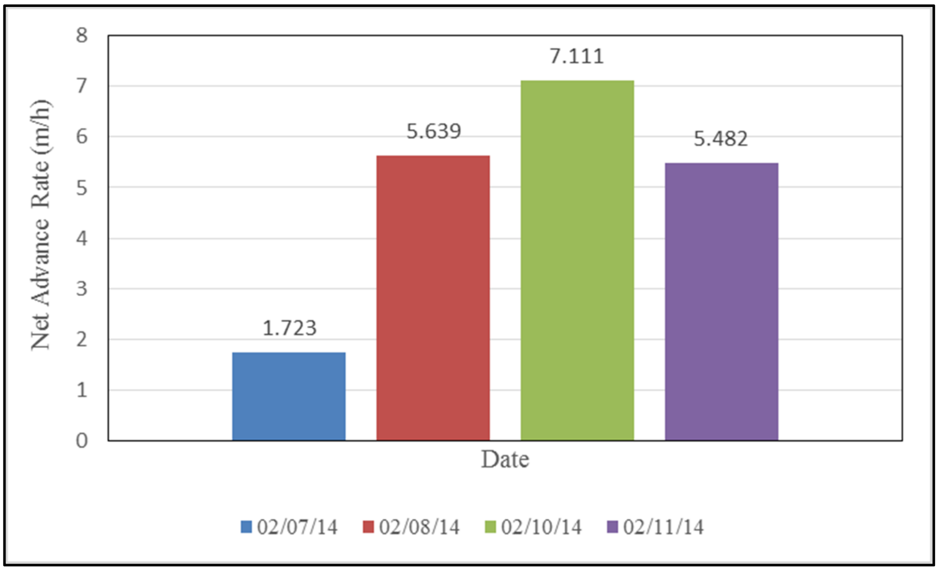

Figure 5.3: Net advance rate values for reaming.

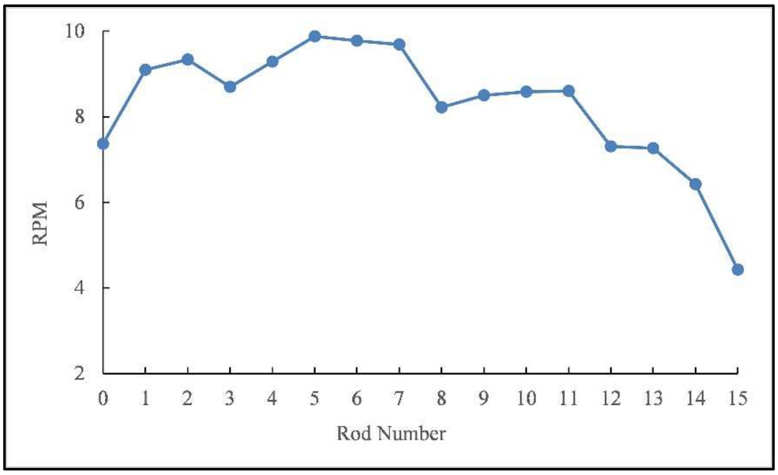

Figure 5.4: Rotational speed values in reaming operation (rod 0 refer to reamer rod).

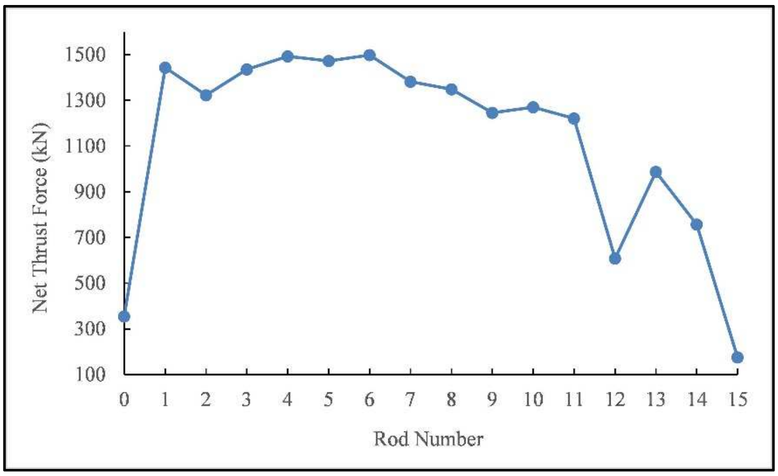

Figure 5.5: Net thrust force values applied to reamer head (rod 0 refer to reamer rod).

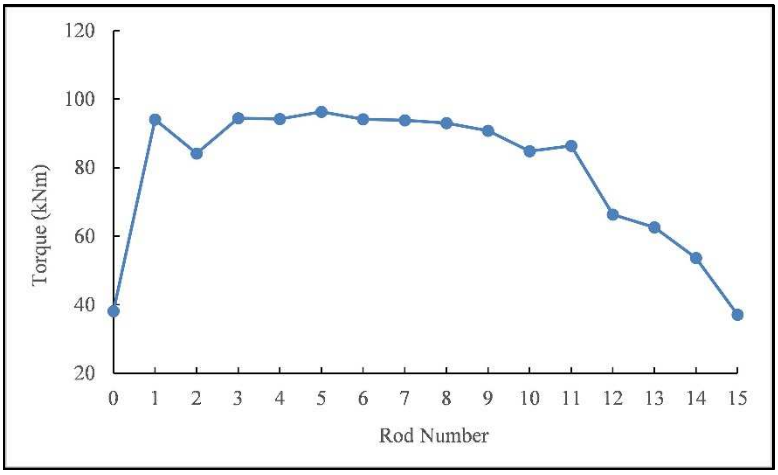

Figure 5.6: Torque values in reaming operation (rod 0 refer to reamer rod).

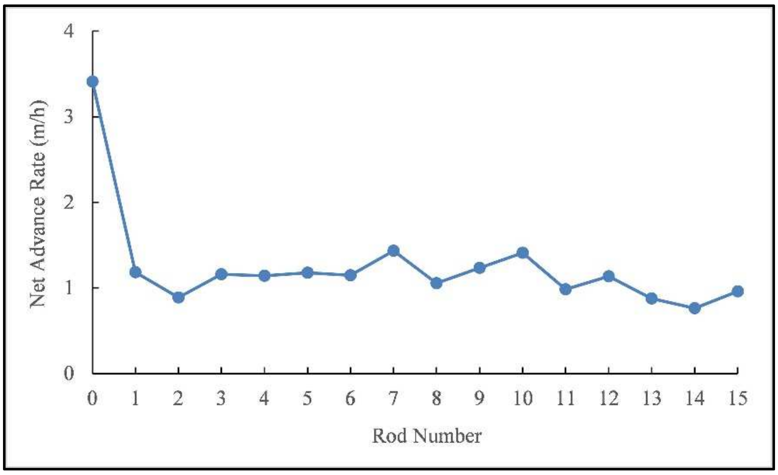

Figure 5.7: Net advance rate values in reaming operation (rod 0 refer to reamer rod).

Specific energy is the another important factor, which indicates the performance of RBMs. Table 5.4 summarizes the net penetration rate, power spent to excavate the rock and field specific energy. As seen from this table the average field specific energy for 1-11 rods, is around 15 kwh/m^3.

Table 5.4: The net penetration rate, power and field specific energy values in reaming operation.

Rod No.	Net Penetration Rate m^3/h	Power kW	Field Specific Energy kWh/m^3
15	4.00	15.50	3.08
14	2.12	33.92	8.48
13	2.09	46.18	10.06
12	2.72	48.38	8.13
11	5.16	81.05	15.71
10	7.38	80.11	10.85

Rod No.	Net Penetration Rate m^3/h	Power kW	Field Specific Energy kWh/m^3
9	6.46	85.76	13.27
8	5.52	77.91	14.11
7	7.51	98.44	13.11
6	6.00	98.44	16.39
5	6.17	100.53	16.29
4	5.98	88.59	14.82
3	6.07	88.59	14.59
2	4.65	79.17	17.01
1	6.20	88.59	14.28
Reamer Rod	8.12	27.85	1.56

Caner (2010) analyzed the performance of Tunnel Boring Machine (TBM) for Uluabat power tunnel. In Uluabat (Bursa) project tunnel route consisted of Akçakoyun limestone between chainage 7+750 and 6+000 m and Karakaya meta sandstone, mudstone; graphitic schist within chainages 11+465m-7+750m and 6+000m-1+792 m. Tunnel excavation started in 2002 using conventional excavation methods. However the excavation stopped in November 2003 due to extreme roof deformations and floor heaves up to 1m. However a private investor took over the project and decided to continue the project with 5.05 m diameter EPB-TBM. In this project due to consequence of squeezing ground squeezing, disc consumption was 0.034 discs/m^3 (Caner, 2010). As seen from Figure 5.8, he founded the correlation between field specific energy and advance per revolution parameter for limestone.

Bilgin et al. (2012) investigated the effect of replacing disc cutters with chisel cutters in Beykoz Tunnel, Turkey. The formations in Beykoz tunnel varied from alluvium, sludge, mudstone, shale and limestone to quartzite with strengths from soft to very hard. The dykes frequently intruded the sedimentary rocks resulting in different degrees of weathering causing tremendous delays in progress rate of the single shield hard rock TBM. The disc cutters started cutting inefficiently in clayey medium strength ground with extreme water income, at where also excessive disc consumptions started due to insufficient friction between the disc cutters and very soft formation, and it was decided to replace all disc cutters with chisel tools (Bilgin et al., 2012). As seen from Figure 5.9, they founded the relationship between field specific energy and advance per revolution parameter for limestone, sandstone and carbonate shale.

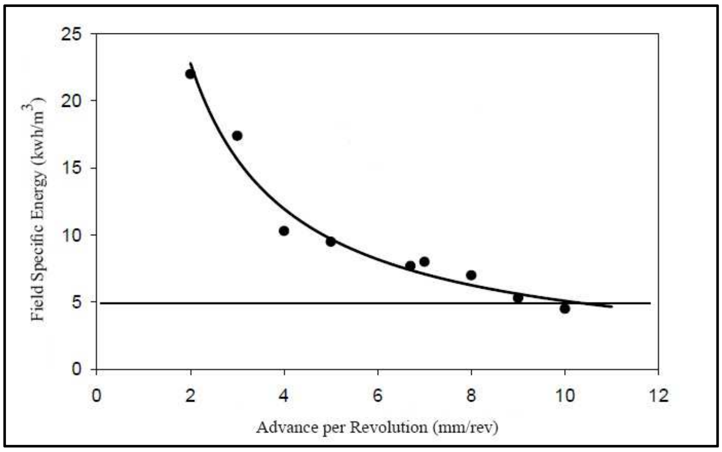

Figure 5.8: The relationship between advance per revolution and field specific energy in Uluabat (Bursa) water tunnel for Akcakoyun Limestone, uniaxial compressive strength = 52 MPa (Caner, 2010).

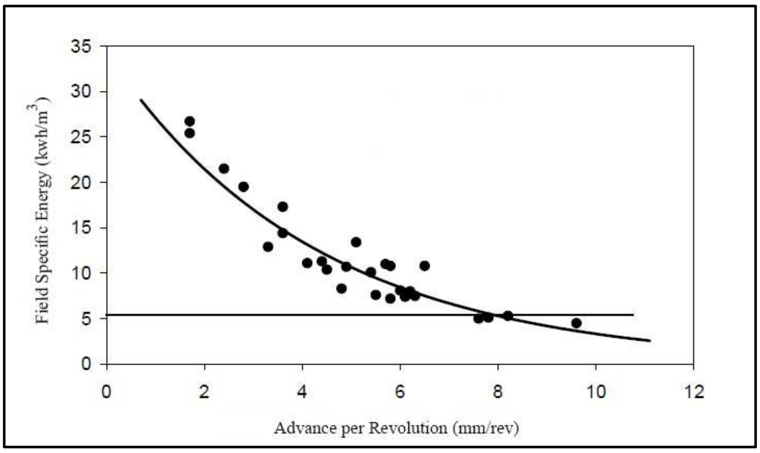

Figure 5.9: The relationship between advance per revolution and field specific energy in Beykoz Tunnel for limestone, sandstone, carbonated shale, Uniaxial compressive strength = 96.3 MPa (Bilgin et al., 2012).

As stated in Chapter 4, the laboratory mechanical tests indicated that the samples taken from RBM area had 81.6 MPa uniaxial compressive strength. As seen in Chapter 5, the average measured penetration in the field is 2.12 mm/rev. Figures. 5.8 and 5.9 show that specific energy is around 20 kWh/m^3 for TBM's working in rock formations having 52 MPa and 96.3 MPa of compressive strength and for a penetration value of 2 mm/rev. As seen from Table 5.4, the average field specific energy for 1-11 rods is around 15 kwh/m^3. The similarity between specific energy values for TBM's and RBM's is worth nothing, showing that tremendous data collected for TBM's may also be used to estimate the performance of RBM's.

The muck samples obtained from pilot and reaming operation are given in Figure 5.10, which shows that the muck size is a good indicator of the main characteristics of the geologic formation excavated and the efficiency of drilling and reaming operations. The CI values are calculated for pilot and reaming operation as 559% and 764%, respectively, indicating that reaming operations are more efficient than pilot drilling due to difference operation and tool (bit) sizes. Size distribution curves are seen in Figure 5.11. As seen from these figures the muck obtained from the reaming operations is coarser than the muck obtained from the pilot drilling operation emphasizing on the efficiency of reaming operations since specific energy which is indicator of efficiency of cutting and drilling operations, decreases with coarseness index (Tuncdemir et al., 2008). Specific energy is the energy used to drill or cut a unit volume of rock and it is always preferred as small as possible.

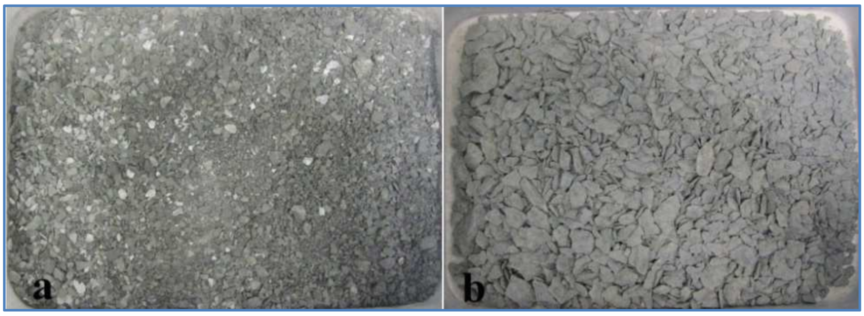

Figure 5.10: Sample obtained from. a) Pilot drilling b) Reaming.

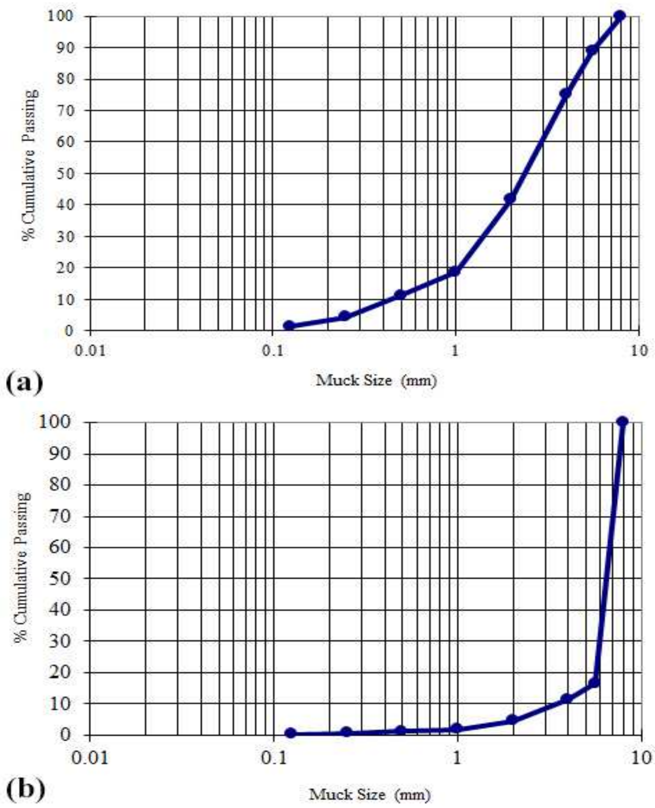

Figure 5.11: Muck Size distribution curves. a) Pilot drilling b) Reaming.

Machine utilization is one of the most important factors in determining the excavation efficiency and economy, since daily advance rates are directly related to these factors. Machine utilization time is defined as the ratio of the net cutting time of the machine to the total working time. Advance rate is average machin advance rate per day, including all delays, calculated from instantaneous cutting rate and utilization, and expressed in m/h. Figure 5.12 shows the time distribution of different activities in the shaft from 1 February to 11 February 2014. As shown, advance time for drilling, involved 40% of all activities (pilot drilling and reaming). However, the main downtime in RBM advance was the delays due to water, electric and shift change 26%, delays due to site preparation 11%, delays related to pull and tear down rods 10%. Besides for starting the excavation operation, site preparation should be done and the delays related to this operation was 11% of all activities.

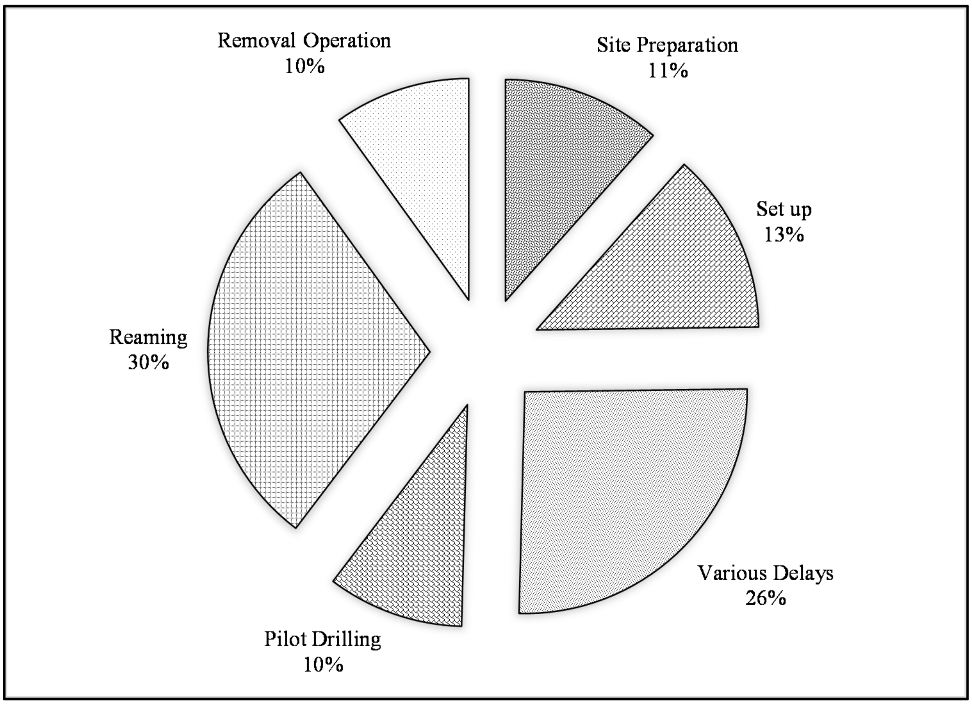

Figure 5.12: Time distribution of different activities in the shaft excavation.

6. PREDICTION PERFORMANCE OF THE RAISE BORING MACHINE

Performance of the raise boring machine used for excavation of the ventilation shaft in Kure-Asikoy Copper Mine is predicted by using a theoretical model based on disc cutting penetration concept developed by Roxborough and Phillips (1975) and, an experimental method based on specific energy concept suggested by Rostami et al. (1994).

6.1 Performance prediction based on disc cutting penetration theory

Roxborough and Phillips (1975) investigated the rock excavation by disc cutters. They used a simple mathematical model to describe the variation of thrust and rolling forces depending on diameter, edge angle, and penetration of disc cutter. They assumed that the normal force equals the value of compressive strength of the rock multiplied by the projected area of disc contact area in the thrust direction (Equation 6.1) as illustrated in Figure 6.1.

$$F_T = \sigma_c \times A \quad \textbf{(6.1)}$$

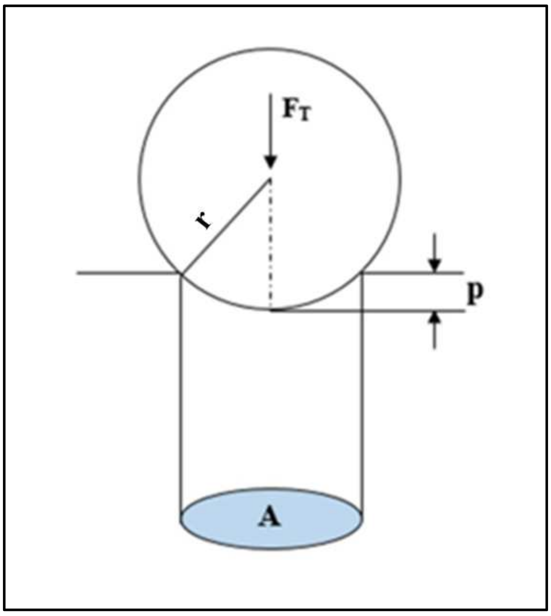

Figure 6.1: A typical disc cutter: F_T is applied thrust force, A is projected area, p is penetration, and r is disc diameter.

The concept described by Roxborough and Phillips (1975) was also used below to formulate thrust force of roller cutters used in Atlas Copco Raise Boring Machine. First, the contact area of one tungsten carbide bit is formulated; then, the number of bits, which are in contact with the rock, are found six by using site observations. At the end, thrust force is estimated by multiplying the compressive strength of rock by total contact areas of the bits contacting the rock.

The disc contact area of a bit (see Figures 6.2 and 6.3) can be estimated approximately as in equation 6.2:

$$A = W \times (L + 2x) \tag{6.2}$$

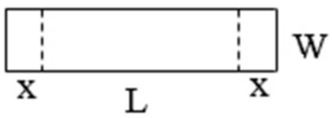

Figure 6.2: Disc contact area (L is the length of the bit, x is extended length of bit, W is the width of bit).

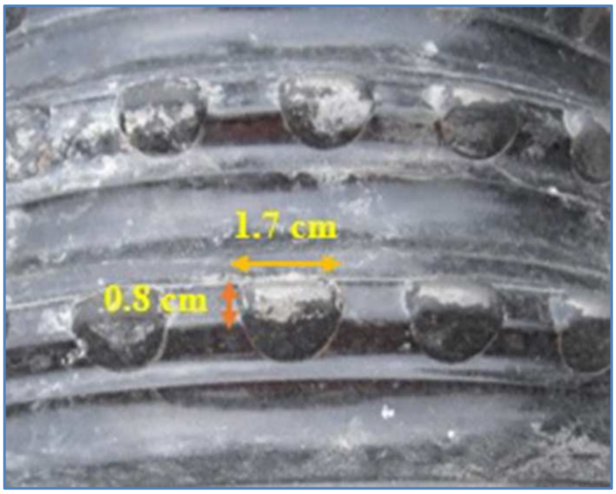

Figure 6.3: Dimension of an insert bit used in reamer roller cutter.

where, W is the width of bit (in this case 0.8 cm) and L is the length of bit (1.7 cm in this case), x is the extended length of the bit due to inclination (in this case, the bit is inclined sideways with an angle of 60°). The parameter x, which is related to bit penetration, can be calculated estimated as shown in Figure 6.4. According to the given input parameters, the parameter x is founded to be $2p/\sqrt{3}$.

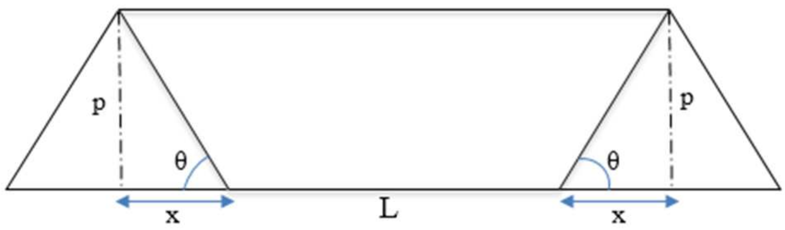

Figure 6.4: Extended length of the bit.

For estimating penetration, daily advance rate, total thrust force and torque of the raise boring machine; total number of effective bits (N) in contact with the rock should be estimated by using equation 6.3:

$$N = N' \times 0.05 \quad \textbf{(6.3)}$$

Where, N' is total number of carbide inserts in reaming head (Bilgin et al., 2014). N depends on design of cutter and may be taken as 5% the number of all inserts in contact with the rock for a given time t; this value can be obtained from the in situ observations during operation of machine. In this application, N is estimated for 16 cutters having 129 inserts in each roller cutter as in equation 6.4:

$$\text{N}' = \text{Total number of bits} \times \text{Number of roller cutters} \quad \textbf{(6.4)}$$

$$\text{N} = 129 \times 16 \times 0.05 = 104$$

The total thrust force can be estimated by multiplying the total number of areas of effective bits (N) by the compressive strength of the rock. However, it should be noted that net thrust applied to the reamer might be estimated after subtracting the weight of drill string and reamer head from total thrust force recorded in data acquisition system.

Home (1978) stated that, equation 6.5 could be used to estimate torque value of a RBM:

$$\text{Torque} = 0.66 \times \text{r} \times \text{n} \times \text{f} \times \text{T} \quad \textbf{(6.5)}$$

Where, r, is the RBM radius, n is the number of cutters, f is the ratio of rolling force to thrust force, and T is the total thrust force. The ratio of rolling force to thrust force is usually taken 0.08 for roller cutters with inserts (button or strawberry cutters) and 0.15 for single disc cutters (Bilgin et al., 2014).

6.2 Performance prediction based on specific energy concept

Specific energy is one of the most important factors in determining the efficiency of rock excavation. Bilgin et al. (2012) stated that specific energy might be used to estimate the net production rate of TBMs, roadheaders, and other mechanized excavation machines. Rostami et al. (1994) and Copur et al. (2001) expressed that equation 6.6 could be used to estimate net production rate of any mechanical excavator:

$$NPR = k \times P / SE_{opt} \qquad \textbf{(6.6)}$$

Where NPR is net production rate in (m^3/h), k is energy transfer ratio from the cutting head to the tunnel face. It is usually 0.8 for TBMs and 0.45-0.55 for roadheaders (Bilgin et al., 2014). P is power spent to excavate the rock, and SE_{opt} is optimum specific energy obtained from full-scale laboratory linear cutting tests in (kWh/m^3).

Operational (field) specific energy (SE, in kWh/m^3) of a raise boring machine can be estimated by equation 6.7 assuming it works in optimum cutting conditions:

$$SE = 2 \times \pi \times RPM \times T / NPR \qquad \textbf{(6.7)}$$

Where, RPM is rotational speed in (rpm) of the reamer head and T is RBM torque in (kNm). The part ($2\times\pi\times RPM\times T$) of the above equation is the net power spent during excavation rock.

7. COMPARISON BETWEEN FIELD AND PREDICTED PERFORMANCE PARAMETERS

A comparison is made between the results of both field and peredicted performance parameters for this project. Performance analysis of the RBM in reaming operation, and comparison of the measured and predicted RBM penetration rate, thrust and torque values are presented in Table 7.1. A detailed calculation for 15 rods is shown in Table 7.2.

Table 7.1: Mean measured and predicted (based on disc cutting penetration concept) values of the RBM operational parameters for rods 1-11.

Operation	Measured Penetration (mm/rev)	Predicted Penetration (mm/rev)	Measured Net Thrust (kN)	Predicted Thrust (kN)	Measured Torque (kNm)	Predicted Torque (kNm)
Reaming	2.12	2.49	1376	1484	91	94

Table 7.2: Performance of the RBM for 15 roads in reaming and comparison of the measured (in situ) and predicted (based on disc cutting penetration concept) penetration rate, thrust and torque values.

Rod No.	RPM (Rev/min)	Measured Net Thrust (kN)	Predicted Thrust (kN)	Measured Torque (kNm)	Predicted Torque (kNm)	Measured Penetration (mm/rev)	Predicted Penetration (mm/rev)
15	4	176	1782	37	12	4.00	4.45
14	6	757	1483	54	52	2.12	2.48
13	7	988	1483	63	68	2.09	2.48
12	7	608	1578	66	42	2.72	3.10
11	9	1221	1436	86	84	1.82	2.17
10	9	1270	1561	85	87	2.61	2.99
9	9	1245	1514	91	85	2.28	2.68
8	8	1349	1499	93	93	2.20	2.58
7	10	1382	1530	94	95	2.39	2.79
6	10	1498	1452	94	103	1.91	2.27
5	10	1472	1467	96	101	1.96	2.37
4	9	1493	1483	94	102	2.11	2.48
3	9	1436	1483	94	99	2.15	2.48
2	9	1323	1404	84	91	1.65	1.95
1	9	1444	1499	94	99	2.19	2.58

As seen from the tables the field and predicted values are close together. However, it should be noted that in the first and the last three rods is exceptional especially in thrust force. The main reason for this difference is related to operator in order to stop the sudden collapse of the shaft collar. In the first rod operator increases gradually rpm, torque and thrust until stable values are obtained and in the last three rods operator decreases gradually the operational parameters of RBM. Figures 7.1-7.2 show relationship between measured and predicted values of RBM performance parameters. As seen, a significant concurrence are identified between the measured and predicted torque, and penetration values, with a coefficient of determination (R^2) of 0.91, and 0.99, respectively.

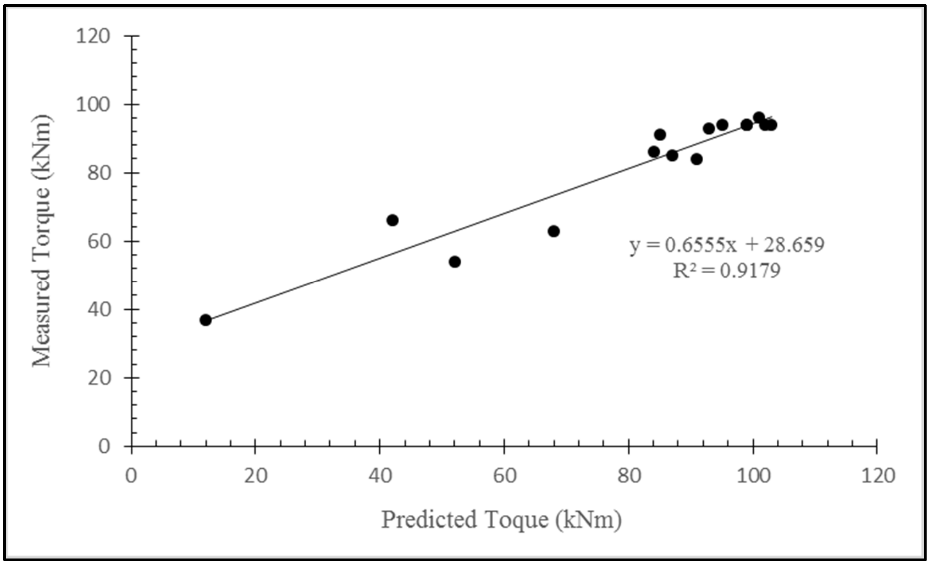

Figure 7.1: Relationship between measured and predicted torque values.

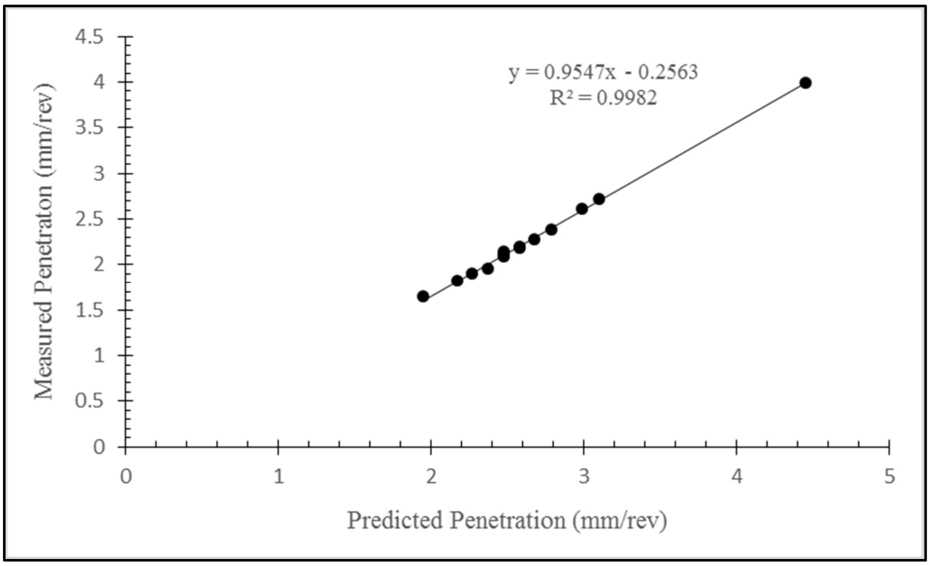

Figure 7.2: Relationship between measured and predicted penetration values.

The analysis of field data indicates that, average specific energy value for 1-11 rods is 15 kWh/m^3. In addition, as describe in Chapter 5, the average measured penetration in field is 2.12 mm/rev. The linear cutting test with disc cutter at 3 mm depth of cut in unrelieved cutting mode show closely value (20 kwh/m^3) to the field value (15 kwh/m^3). However, specific energy value (17.38 kwh/m^3) obtained in laboratory experiment is very close at 5 mm depth of cut in unrelieved cutting mode. The laboratory analysis indicate that linear cutting tests could be used to predict specific energy.

8. CONCLUSIONS AND RECOMMENDATIONS

Raise boring system is the most up-to-date, secure and fast way for boring large diameter shafts. RBM creates a hole with smooth walls, which usually does not require lining. The hole is more stable than a drilled and blasted raise and has better airflow, making it ideal for ventilation raises.

The raise boring machine was developed to meet the demands of the underground mining industry but has also found wide range of applications in tunnelling or infrastructural projects. The selection of appropriate RBM is very important for the success of the shaft excavation and it must be done with a great care.

Eti Copper A.S Underground Mine raise boring operation was visited to recording operational conditions and performance parameters of RBM. In addition, borehole samples were collected for performing physical and mechanical tests in the laboratory. Then the samples were tested with a linear cutting test using three different cutters (chisel, conical, and disc) to determine the cuttability of the samples.

This research study showed that two basic concepts of rock cutting mechanics might be used to estimate the performance of raise boring machines.

1. Thrust force and torque values may be formulated using these parameters, which are a function of the rock compressive strength, the number of bits, which are in contact for a given time, and the projectile area of each bit.
2. Another important point emerging from this study is that field specific energy obtained for TBMs and RBMs are very closely related for a given penetration and in rocks having similar strength values. This interrelationship will permit to use immense accumulated data for TBM application in different projects for predicting the performance of RBMs.

The obtained result from field measurements and predicted values are summarized as follows:

- The mean daily advance rate for pilot drilling and reaming were measured as 2.54 and 1.25 m/h, respectively. The penetration rate was measured 2.12

mm/rev and predicted penetration rate for reaming is very close values as 2.49 mm/rev.

- The RBM torque value for reaming changes between 84 kNm and 96 kNm. The thrust force value of reaming changes between 1221-1498 kN. The estimated value for torque is 94 kNm and for thrust force is 1484 kN. As seen, the estimated values for RBM performance parameter are close the real measurement values in the field.
- The field data indicate that average specific energy value for 11 rods is 15 kWh/m^3. In addition, the average measured penetration in field is 2.12 mm/rev. The linear cutting test with disc cutter at 3 mm depth of cut in unrelieved cutting mode show closely value (20 kwh/m^3) to the field value (15 kwh/m^3). However, specific energy value (17.38 kwh/m^3) very closely at 5 mm depth of cut in unrelieved cutting mode. This result indicate that linear cutting tests could be used to predict specific energy.

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APPENDICES

APPENDIX A1: Detailed results of UCS and static elasticity modulus test.

İTÜ Maden Fakültesi / *ITU Faculty of Mines*

Maden Mühendisliği Bölümü / *Mining Engineering Department*

Tek Eksenli Basınç Dayanımı ve Statik Elastisite Modülü Deneyi / *Uniaxial Compressive Strength and Static Elasticity Modulus Test*

Proje / *Project*: *Master Thesis*

Firma / *Company*: *İTÜ*

Yer / *Location*: *Küre - KASTAMONU*

Sondaj No / *Borehole No*: *AS 10*

Numune No / *Sample No*: *36*

Derinlik / *Sample Depth*: *42.35 - 42.53*

Yapan / *Performed by*: *Emre Avunduk*
Aydin Shaterpour

Analiz / *Reduced by*: *Aydin Shaterpour*

Deney Tarihi / *Test Date*: *24 Nisan 2014*

Standart / *Standard*: E.T. Brown, (ed.), "ISRM Commission on Testing Methods, Rock Characterization Testing and Monitoring, ISRM Suggested Methods", Pergamon Press, 1981.

Kırılma Öncesi

Before Failure

Kırılma Sonrası

After Failure

Sondaj / Derinlik / Numune No.	Numune Boyu (L)	Numune Çapı (D)	Numune Ağırlığı	L/D Oranı	Yoğunluk (ρ)	Yenilme Yükü (P)	Basınç Dayanımı (σ_c)	Statik Elastisite Modülü (E_{sta})	Statik Poisson Oranı (ν)	Yenilme Tipi
Borehole / Depth / Sample ID	*Sample Length (L)*	*Sample Diameter (D)*	*Sample Weight*	*L/D Ratio*	*Density (ρ)*	*Failure Load (P)*	*Compressive Strength (σ_c)*	*Static Elasticity Modulus (E_{sta})*	*Static Posisson's Ratio (ν)*	*Failure Type*
	(cm)	(cm)	(g)		(g/cm^3)	(kN)	(MPa)	(GPa)		
AS 10	11.400	4.760	568.61	2.39	2.80	86.1	48.4	7.7	-0.08	Normal Yenilme / *Normal Failure*

NOT: Yükleme Hızı 0.5 kN/s tutulmuştur. Deneyler doğal nem içeriğindeki numuneler üzerinde yapılmıştır.

NOTE: Loading rate is kept 0.5 kN/s. These tests are performed in the samples with natural water content (air dried).

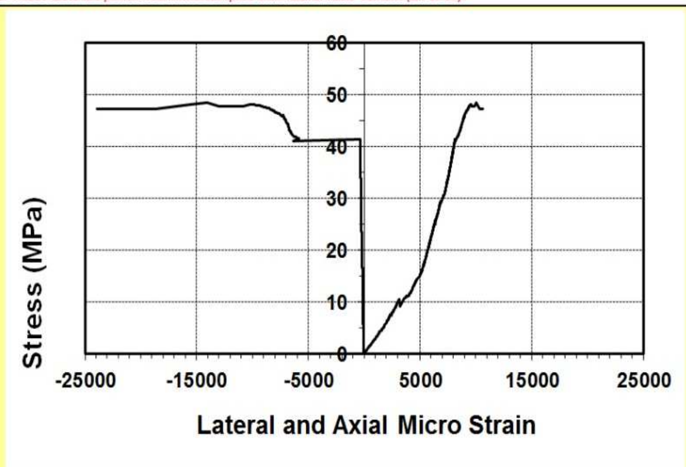

Figure A.1 : Sample one (altered basalt) UCS and static elasticity modulus test details.

İTÜ Maden Fakültesi / *ITU Faculty of Mines*

Maden Mühendisliği Bölümü / *Mining Engineering Department*

Tek Eksenli Basınç Dayanımı ve Statik Elastisite Modülü Deneyi / ***Uniaxial Compressive Strength and Static Elasticity Modulus Test***

Proje / *Project*: *Master Thesis*

Firma / *Company*: *İTÜ*

Yer / *Location*: *Küre - KASTAMONU*

Sondaj No / *Borehole No*: *AS 4*

Numune No / *Sample No*: *21*

Derinlik / *Sample Depth*: *39.00 - 39.23*

Yapan / *Performed by*: *Emre Avunduk*, *Aydin Shaterpour*

Analiz / *Reduced by*: *Aydin Shaterpour*

Deney Tarihi / *Test Date*: *2 Nisan 2014*

Standart / *Standard*: E.T. Brown, (ed.), "ISRM Commission on Testing Methods, Rock Characterization Testing and Monitoring, ISRM Suggested .Methods", Pergamon Press, 1981

Kırılma Öncesi

Before Failure

Kırılma Sonrası

After Failure

Sondaj / Derinlik / Numune No.	Numune Boyu (L)	Numune Çapı (D)	Numune Ağırlığı	L/D Oranı	Yoğunluk (ρ)	Yenilme Yükü (P)	Basınç Dayanımı (σ_c)	Statik Elastisite Modülü (E_{sta})	Statik Poisson Oranı (ν)	Yenilme Tipi
Borehole / Depth / Sample ID	*Sample Length (L)*	*Sample Diameter (D)*	*Sample Weight*	*L/D Ratio*	*Density (ρ)*	*Failure Load (P)*	*Compressive Strength (σ_c)*	*Static Elasticity Modulus (E_{sta})*	*Static Posisson's Ratio (ν)*	*Failure Type*
	(cm)	(cm)	(g)		(g/cm^3)	(kN)	(MPa)	(GPa)		
AS 4	11.800	4.750	579.73	2.48	2.77	100.7	56.8	22.5	-2.78	Yapısal Yenilme / Structural Failure

NOT: Yükleme Hızı 0.5 kN/s tutulmuştur. Deneyler doğal nem içeriğindeki numuneler üzerinde yapılmıştır.

NOTE: Loading rate is kept 0.5 kN/s. These tests are performed in the samples with natural water content (air dried).

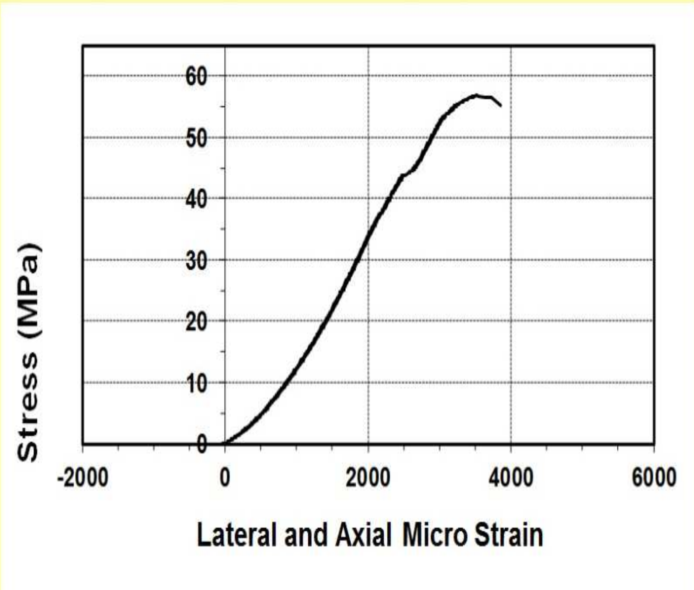

Figure A.2 : Sample two (altered basalt) UCS and static elasticity modulus test details.

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Maden Mühendisliği Bölümü / *Mining Engineering Department*

Tek Eksenli Basınç Dayanımı ve Statik Elastisite Modülü Deneyi / *Uniaxial Compressive Strength and Static Elasticity Modulus Test*

Proje / *Project*: *Master Thesis*

Firma / *Company*: *İTÜ*

Yer / *Location*: *Küre - KASTAMONU*

Sondaj No / *Borehole No*: *AS 4*

Numune No / *Sample No*: *21*

Derinlik / *Sample Depth*: *39.00 - 39.23*

Yapan / *Performed by*: *Emre Avunduk*
Aydin Shaterpour

Analiz / *Reduced by*: *Aydin Shaterpour*

Deney Tarihi / *Test Date*: *2 Nisan 2014*

Standart / *Standard*: E.T. Brown, (ed.), "ISRM Commission on Testing Methods, Rock Characterization Testing and Monitoring, ISRM Suggested Methods", Pergamon Press, 1981

Kırılma Öncesi
Before Failure

Kırılma Sonrası
After Failure

Sondaj / Derinlik / Numune No.	Numune Boyu (L)	Numune Çapı (D)	Numune Ağırlığı	L/D Oranı	Yoğunluk (ρ)	Yenilme Yükü (P)	Basınç Dayanımı (σ_c)	Statik Elastisite Modülü (E_{sta})	Statik Poisson Oranı (ν)	Yenilme Tipi
Borehole / Depth / Sample ID	*Sample Length (L)*	*Sample Diameter (D)*	*Sample Weight*	*L/D Ratio*	*Density (ρ)*	*Failure Load (P)*	*Compressive Strength (σ_c)*	*Static Elasticity Modulus (E_{sta})*	*Static Posisson's Ratio (ν)*	*Failure Type*
	(cm)	(cm)	(g)		(g/cm^3)	(kN)	(MPa)	(GPa)		
AS 4	11.800	4.750	579.73	2.48	2.77	100.7	56.8	22.5	-2.78	Yapısal Yenilme / Structural Failure

NOT: Yükleme Hızı 0.5 kN/s tutulmuştur. Deneyler doğal nem içeriğindeki numuneler üzerinde yapılmıştır.

NOTE: Loading rate is kept 0.5 kN/s. These tests are performed in the samples with natural water content (air dried).

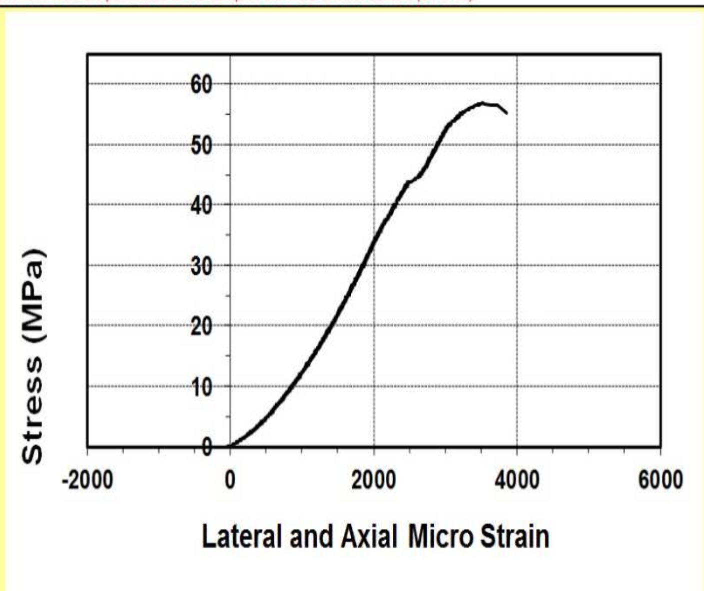

Figure A.3 : Sample three (altered basalt) UCS and static elasticity modulus test details.

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Maden Mühendisliği Bölümü / *Mining Engineering Department*

Tek Eksenli Basınç Dayanımı ve Statik Elastisite Modülü Deneyi / *Uniaxial Compressive Strength and Static Elasticity Modulus Test*

Proje / *Project*:	*Master Thesis*
Firma / *Company*:	*İTÜ*
Yer / *Location*:	*Küre - KASTAMONU*
Sondaj No / *Borehole No*:	*AS 5*
Numune No / *Sample No*:	*32*
Derinlik / *Sample Depth*:	*41.42 - 41.59*
Yapan / *Performed by*:	*Emre Avunduk* *Aydin Shaterpour*
Analiz / *Reduced by*:	*Aydin Shaterpour*
Deney Tarihi / *Test Date*:	*2 Nisan 2014*
Standart / *Standard*:	E.T. Brown, (ed.), "ISRM Commission on Testing Methods, Rock Characterization Testing and Monitoring, ISRM Suggested .Methods", Pergamon Press, 1981

Kırılma Öncesi

Before Failure

Kırılma Sonrası

After Failure

Sondaj / Derinlik / Numune No.	Numune Boyu (L)	Numune Çapı (D)	Numune Ağırlığı	L/D Oranı	Yoğunluk (ρ)	Yenilme Yükü (P)	Basınç Dayanımı (σ_c)	Statik Elastisite Modülü (E_{sta})	Statik Poisson Oranı (ν)	Yenilme Tipi
Borehole / Depth / Sample ID	*Sample Length (L)*	*Sample Diameter (D)*	*Sample Weight*	*L/D Ratio*	*Density (ρ)*	*Failure Load (P)*	*Compressive Strength (σ_c)*	*Static Elasticity Modulus (E_{sta})*	*Static Posisson's Ratio (ν)*	*Failure Type*
	(cm)	(cm)	(g)		(g/cm^3)	(kN)	(MPa)	(GPa)		
AS 5	11.600	4.760	606.02	2.44	2.94	153.5	86.2	19.3	-4.59	Normal Yenilme / *Normal Failure*

NOT: Yükleme Hızı 0.5 kN/s tutulmuştur. Deneyler doğal nem içeriğindeki numuneler üzerinde yapılmıştır.

NOTE: Loading rate is kept 0.5 kN/s. These tests are performed in the samples with natural water content (air dried).

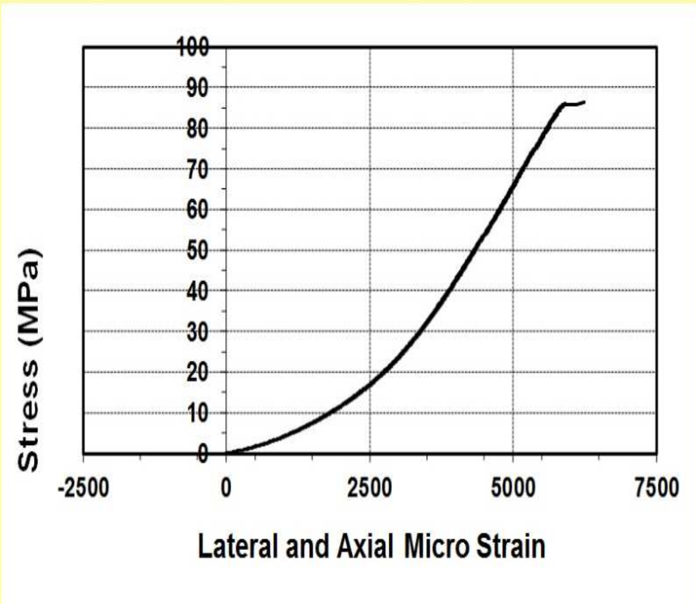

Figure A.4 : Sample four (basalt) UCS and static elasticity modulus test details.

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Maden Mühendisliği Bölümü / *Mining Engineering Department*

Tek Eksenli Basınç Dayanımı ve Statik Elastisite Modülü Deneyi / *Uniaxial Compressive Strength and Static Elasticity Modulus Test*

Proje / *Project:* *Master Thesis*

Firma / *Company:* *İTÜ*

Yer / *Location:* *Küre - KASTAMONU*

Sondaj No / *Borehole No:* *AS 9*

Numune No / *Sample No:* *30*

Derinlik / *Sample Depth:* *41.05 - 41.25*

Yapan / *Performed by:* *Emre Avunduk*
Aydin Shaterpour

Analiz / *Reduced by:* *Aydin Shaterpour*

Deney Tarihi / *Test Date:* *24 Nisan 2014*

Standart / *Standard:* E.T. Brown, (ed.), "ISRM Commission on Testing Methods, Rock Characterization Testing and Monitoring, ISRM Suggested Methods", Pergamon Press, 1981.

Kırılma Öncesi
Before Failure

Kırılma Sonrası
After Failure

Sondaj / Derinlik / Numune No.	Numune Boyu (L)	Numune Çapı (D)	Numune Ağırlığı	L/D Oranı	Yoğunluk (ρ)	Yenilme Yükü (P)	Basınç Dayanımı (σ_c)	Statik Elastisite Modülü (E_{sta})	Statik Poisson Oranı (ν)	Yenilme Tipi
Borehole / Depth / Sample ID	*Sample Length (L)*	*Sample Diameter (D)*	*Sample Weight*	*L/D Ratio*	*Density (ρ)*	*Failure Load (P)*	*Compressive Strength (σ_c)*	*Static Elasticity Modulus (E_{sta})*	*Static Posisson's Ratio (ν)*	*Failure Type*
	(cm)	(cm)	(g)		(g/cm^3)	(kN)	(MPa)	(GPa)		
AS 3	11.900	4.760	611.75	2.50	2.89	181.1	101.8	26.6	-0.24	Normal Yenilme / *Normal Failure*

NOT: Yükleme Hızı 0.5 kN/s tutulmuştur. Deneyler doğal nem içeriğindeki numuneler üzerinde yapılmıştır.

NOTE: Loading rate is kept 0.5 kN/s. These tests are performed in the samples with natural water content (air dried).

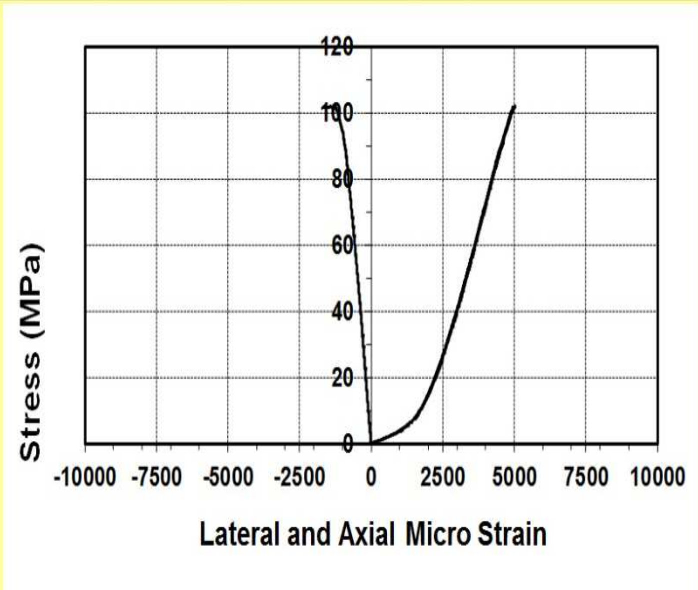


Figure A.5 : Sample five (basalt) UCS and static elasticity modulus test details.

APPENDIX A2: Detailed results of small-scale linear cutting test.

I.T.U. MINING ENGINEERING DEPARTMENT

SMALL-SCALE LINEAR CUTTING TEST (V. 1.2)

Company :	ITU	Test Date :	6/2/2014
Project :	Master Thesis	Analysis Date :	6/2/2014
Location:	Küre-Kastamonu	Tested by:	A. Shaterpour

Test No :	1			
File Name :	msc_d3_t1	Tool Holder :	ITU	
Sample :	Basalt	Cutting Speed :	3	cm/sn
Sample Type :	Igneous	Depth of Cut :	3	mm
Cutter :	Standard Chisel			

				FN Normal	FR Cutting	FS Side	
Cutting Length :	12.5	*cm*					
Muck Weight :	15.25	*g*	Average:	1227.9	608.4	1.8	*kgf*
Sample Density :	2.82	*g/cm3*	Std. Dev.:	515.9	281.6	18.7	*kgf*
Q:	0.04	*m3/km*	Min:	-517.9	-120.0	-122.9	*kgf*
Specific Energy :	137.96	*mJ/m3*	Max:	2936.6	1498.3	63.7	*kgf*
Specific Energy :	38.32	*kwh/m3*					

Explanation:

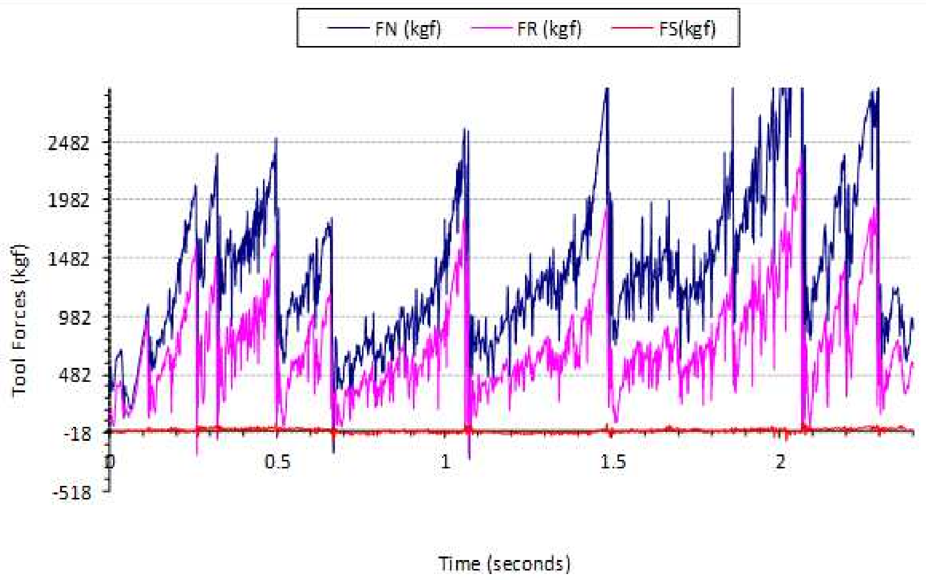


Figure A.6 : Chisel cutter; depth of cut 3 mm in unrelieved cutting mode (line 1).

I.T.U. MINING ENGINEERING DEPARTMENT

SMALL-SCALE LINEAR CUTTING TEST (V. 1.2)

Company :	ITU	Test Date :	6/2/2014
Project :	Master Thesis	Analysis Date :	6/2/2014
Location:	Küre-Kastamonu	Tested by:	A. Shaterpour

Test No :	2			
File Name :	msc_d3_t2	Tool Holder :	ITU	
Sample :	Basalt	Cutting Speed :	3	cm/sn
Sample Type :	Igneous	Depth of Cut :	3	mm
Cutter :	Standard Chisel			

				FN Normal	FR Cutting	FS Side	
Cutting Length :	12.0	cm					
Muck Weight :	14.45	g	Average:	879.7	471.0	-0.9	kgf
Sample Density :	2.82	g/cm3	Std. Dev.:	511.2	300.7	19.3	kgf
Q:	0.04	m3/km	Min:	-561.3	-182.1	-76.2	kgf
Specific Energy :	108.21	mJ/m3	Max:	2527.9	1649.6	45.2	kgf
Specific Energy :	30.06	kwh/m3					

Explanation:

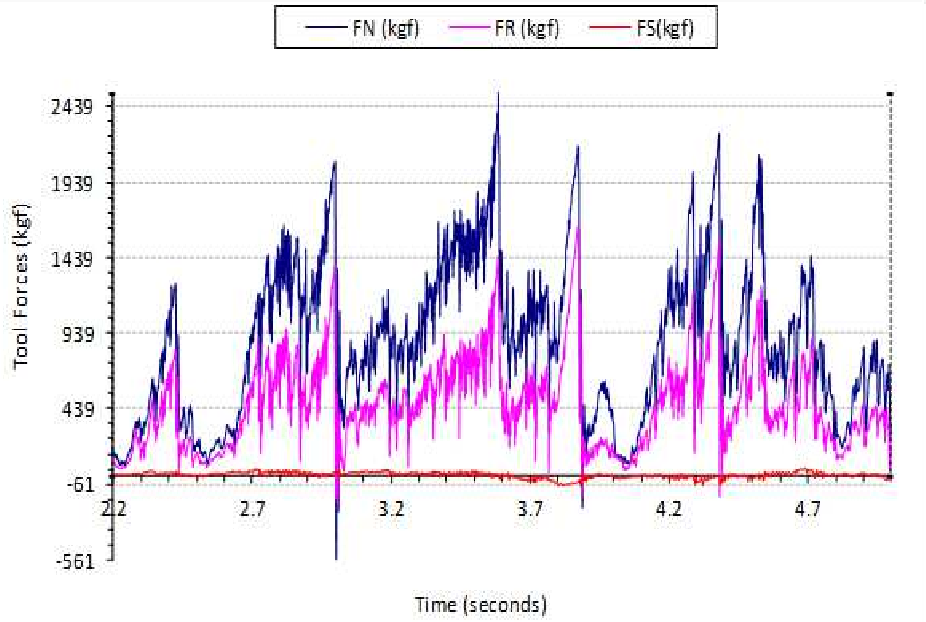
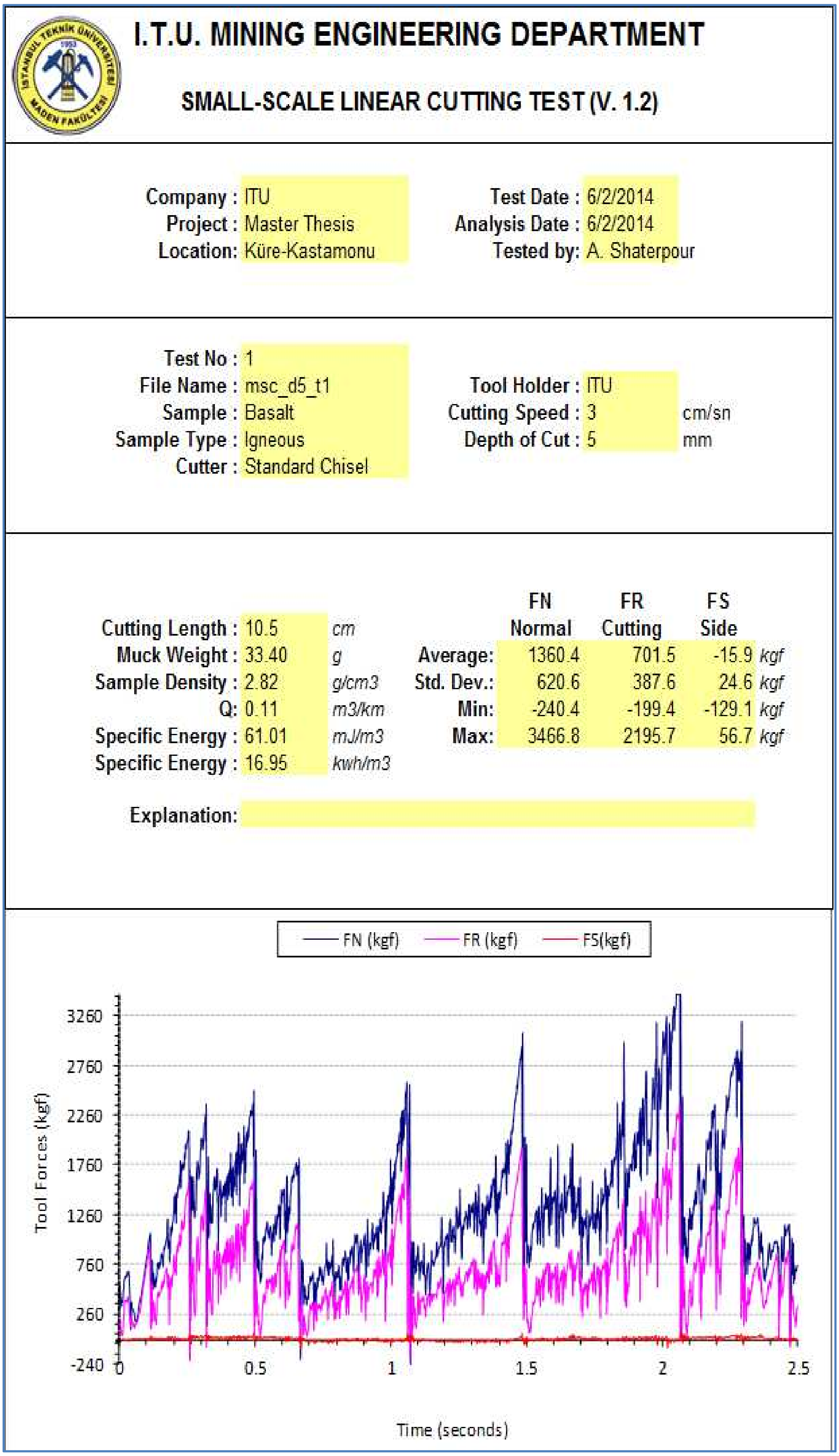


Figure A.7 : Chisel cutter; depth of cut 3 mm in unrelieved cutting mode (line 2).



I.T.U. MINING ENGINEERING DEPARTMENT

SMALL-SCALE LINEAR CUTTING TEST (V. 1.2)

Company :	ITU	Test Date :	6/2/2014
Project :	Master Thesis	Analysis Date :	6/2/2014
Location:	Küre-Kastamonu	Tested by:	A. Shaterpour

Test No :	1		
File Name :	msc_d5_t1	Tool Holder :	ITU
Sample :	Basalt	Cutting Speed :	3 cm/sn
Sample Type :	Igneous	Depth of Cut :	5 mm
Cutter :	Standard Chisel		

					FN	FR	FS
Cutting Length :	10.5	cm			Normal	Cutting	Side
Muck Weight :	33.40	g	Average:		1360.4	701.5	-15.9 kgf
Sample Density :	2.82	g/cm3	Std. Dev.:		620.6	387.6	24.6 kgf
Q:	0.11	m3/km	Min:		-240.4	-199.4	-129.1 kgf
Specific Energy :	61.01	mJ/m3	Max:		3466.8	2195.7	56.7 kgf
Specific Energy :	16.95	kwh/m3					

Explanation:

Figure A.8 : Chisel cutter; depth of cut 5 mm in unrelieved cutting mode (line 1).

I.T.U. MINING ENGINEERING DEPARTMENT

SMALL-SCALE LINEAR CUTTING TEST (V. 1.2)

Company :	ITU	Test Date :	6/2/2014
Project :	Master Thesis	Analysis Date :	6/2/2014
Location:	Küre-Kastamonu	Tested by:	A. Shaterpour

Test No :	2			
File Name :	msc_d5_t2	Tool Holder :	ITU	
Sample :	Basalt	Cutting Speed :	3	cm/sn
Sample Type :	Igneous	Depth of Cut :	5	mm
Cutter :	Standard Chisel			

				FN Normal	FR Cutting	FS Side	
Cutting Length :	10.5	cm					
Muck Weight :	27.76	g	Average:	1266.7	686.8	-2.1	kgf
Sample Density :	2.82	g/cm3	Std. Dev.:	628.1	394.8	18.0	kgf
Q:	0.09	m3/km	Min:	-239.2	-213.2	-96.4	kgf
Specific Energy :	71.87	mJ/m3	Max:	3582.8	2371.4	83.5	kgf
Specific Energy :	19.96	kwh/m3					

Explanation:

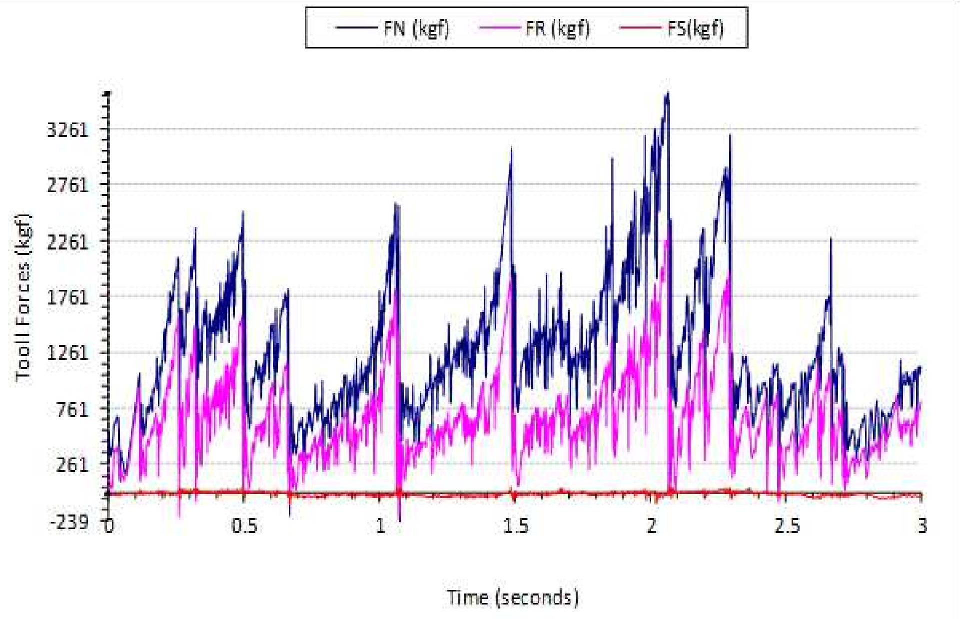


Figure A.9 : Chisel cutter; depth of cut 5 mm in unrelieved cutting mode (line 2).

I.T.U. MINING ENGINEERING DEPARTMENT

SMALL-SCALE LINEAR CUTTING TEST (V. 1.2)

Company :	ITU	Test Date :	6/2/2014
Project :	Master Thesis	Analysis Date :	6/2/2014
Location:	Küre-Kastamonu	Tested by:	A. Shaterpour

Test No :	1			
File Name :	msc_konik_d3_t1	Tool Holder :	ITU	
Sample :	Basalt	Cutting Speed :	3	cm/sn
Sample Type :	Igneous	Depth of Cut :	3	mm
Cutter :	Standard Conical 1			

				FN Normal	FR Cutting	FS Side	
Cutting Length :	12.0	*cm*					
Muck Weight :	7.02	*g*	Average:	296.1	163.8	22.1	*kgf*
Sample Density :	2.82	*g/cm3*	Std. Dev.:	157.3	86.1	27.5	*kgf*
Q:	0.02	*m3/km*	Min:	-78.6	-28.1	-44.8	*kgf*
Specific Energy :	77.44	*mJ/m3*	Max:	944.6	507.4	132.2	*kgf*
Specific Energy :	21.51	*kwh/m3*					

Explanation:

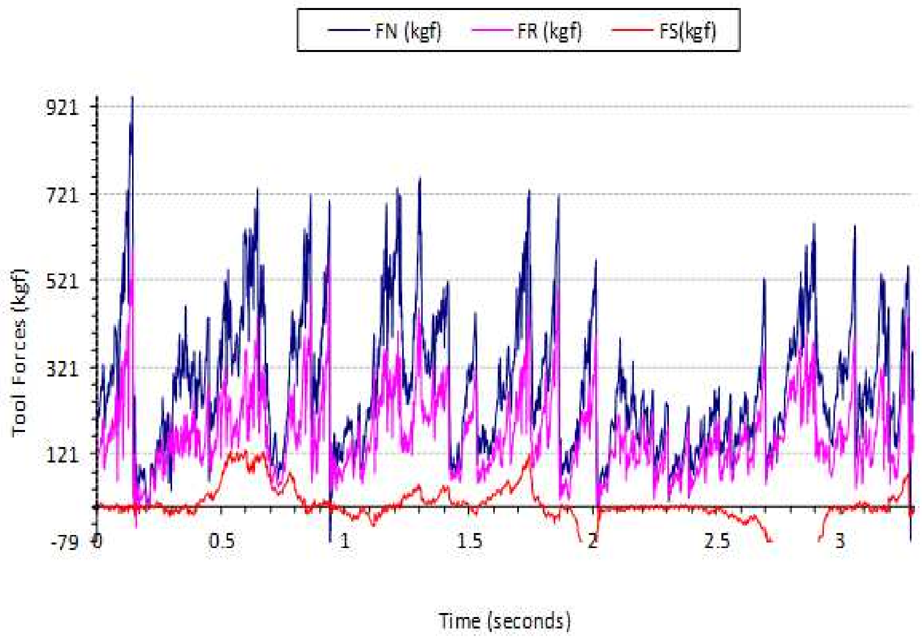


Figure A.10 : Conical cutter; depth of cut 3 mm in unrelieved cutting mode (line 1).

I.T.U. MINING ENGINEERING DEPARTMENT

SMALL-SCALE LINEAR CUTTING TEST (V. 1.2)

Company :	ITU	Test Date :	6/2/2014
Project :	Master Thesis	Analysis Date :	6/2/2014
Location:	Küre-Kastamonu	Tested by:	A. Shaterpour

Test No :	2			
File Name :	msc_konik_d3_t2	Tool Holder :	ITU	
Sample :	Basalt	Cutting Speed :	3	cm/sn
Sample Type :	Igneous	Depth of Cut :	3	mm
Cutter :	Standard Conical 1			

				FN Normal	FR Cutting	FS Side	
Cutting Length :	13.0	*cm*					
Muck Weight :	6.09	*g*	Average:	282.8	169.5	-2.1	*kgf*
Sample Density :	2.82	*g/cm3*	Std. Dev.:	158.9	92.1	54.2	*kgf*
Q:	0.02	*m3/km*	Min:	-158.5	-46.0	-200.3	*kgf*
Specific Energy :	100.07	*mJ/m3*	Max:	963.6	603.8	134.1	*kgf*
Specific Energy :	27.80	*kwh/m3*					

Explanation:

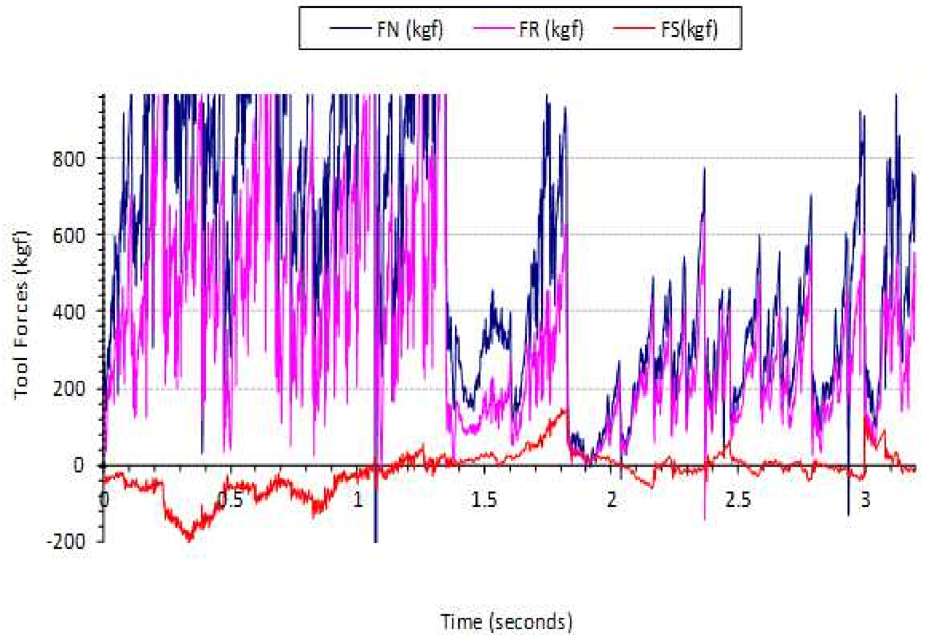


Figure A.11 : Conical cutter; depth of cut 3 mm in unrelieved cutting mode (line 2).

I.T.U. MINING ENGINEERING DEPARTMENT

SMALL-SCALE LINEAR CUTTING TEST (V. 1.2)

Company :	ITU	Test Date :	6/2/2014
Project :	Master Thesis	Analysis Date :	6/2/2014
Location:	Küre-Kastamonu	Tested by:	A. Shaterpour

Test No :	1			
File Name :	msc_konik_d5_t1	Tool Holder :	ITU	
Sample :	Basalt	Cutting Speed :	3	cm/sn
Sample Type :	Igneous	Depth of Cut :	5	mm
Cutter :	Standard Conical 1			

				FN Normal	FR Cutting	FS Side	
Cutting Length :	11.0	*cm*					
Muck Weight :	12.85	*g*	Average:	443.1	264.1	-22.6	*kgf*
Sample Density :	2.82	*g/cm3*	Std. Dev.:	330.5	205.4	98.3	*kgf*
Q:	0.04	*m3/km*	Min:	-178.0	-61.3	-454.8	*kgf*
Specific Energy :	62.54	*mJ/m3*	Max:	1907.2	1111.0	248.9	*kgf*
Specific Energy :	17.37	*kwh/m3*					

Explanation:

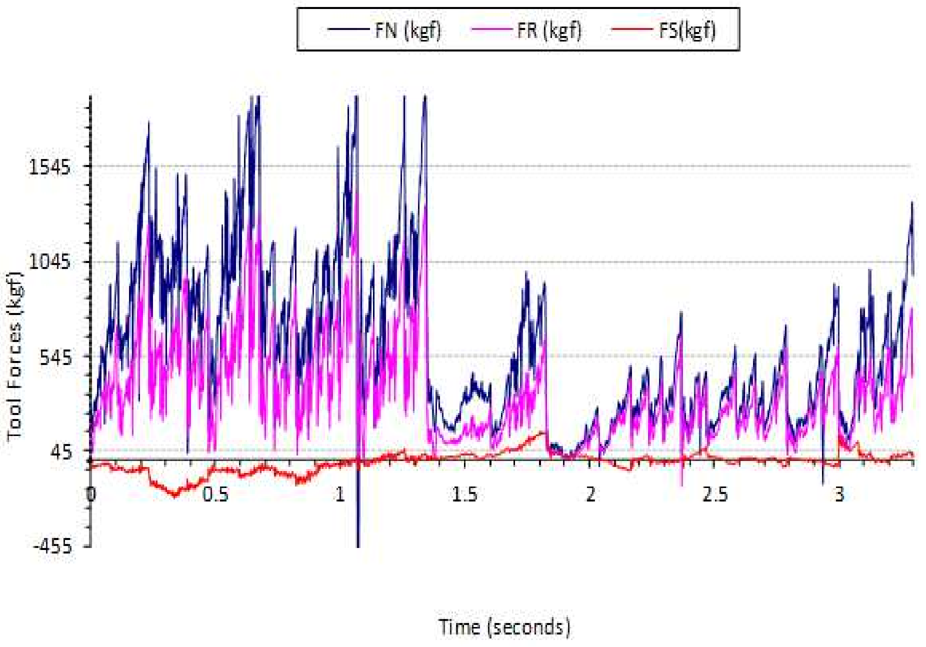


Figure A.12 : Conical cutter; depth of cut 5 mm in unrelieved cutting mode (line 1).

I.T.U. MINING ENGINEERING DEPARTMENT

SMALL-SCALE LINEAR CUTTING TEST (V. 1.2)

Company : ITU
Project : Master Thesis
Location: Küre-Kastamonu

Test Date : 6/2/2014
Analysis Date : 6/2/2014
Tested by: A. Shaterpour

Test No : 2
File Name : msc_konik_d5_t2
Sample : Basalt
Sample Type : Igneous
Cutter : Standard Conical 1

Tool Holder : ITU
Cutting Speed : 3 cm/sn
Depth of Cut : 5 mm

Cutting Length : 11.0 cm
Muck Weight : 14.86 g
Sample Density : 2.82 g/cm3
Q: 0.05 m3/km
Specific Energy : 72.40 mJ/m3
Specific Energy : 20.11 kwh/m3

	FN Normal	FR Cutting	FS Side	
Average:	595.9	353.5	-21.3	kgf
Std. Dev.:	439.8	266.5	55.3	kgf
Min:	-723.8	-128.2	-205.5	kgf
Max:	2246.6	1423.0	147.4	kgf

Explanation:

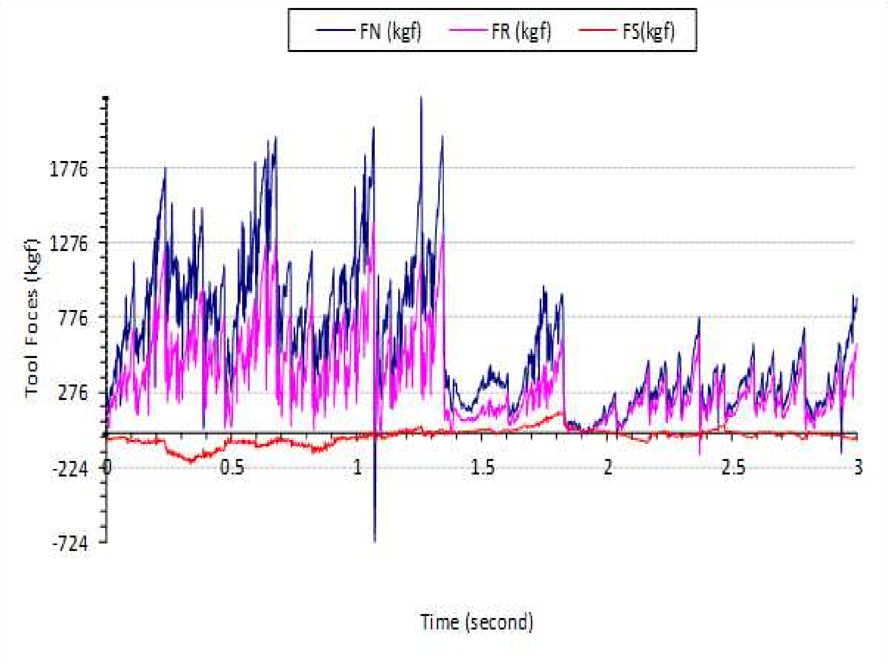


Figure A.13 : Conical cutter; depth of cut 5 mm in unrelieved cutting mode (line 2).

I.T.U. MINING ENGINEERING DEPARTMENT

SMALL-SCALE LINEAR CUTTING TEST (V. 1.2)

Company :	ITU	Test Date :	6/4/2014
Project :	Master Thesis	Analysis Date :	6/4/2014
Location:	Küre-Kastamonu	Tested by:	A. Shaterpour

Test No :	1			
File Name :	msc_disk_d3_t1	Tool Holder :	ITU	
Sample :	Basalt	Cutting Speed :	3	cm/sn
Sample Type :	Igneous	Depth of Cut :	3	mm
Cutter :	Standard Disc			

				FN Normal	FR Cutting	FS Side	
Cutting Length :	10.0	*cm*					
Muck Weight :	3.64	*g*	Average:	746.1	119.3	255.4	*kgf*
Sample Density :	2.82	*g/cm3*	Std. Dev.:	478.2	86.0	210.3	*kgf*
Q:	0.01	*m3/km*	Min:	10.1	-4.9	-49.1	*kgf*
Specific Energy :	90.66	*mJ/m3*	Max:	2303.3	433.7	803.7	*kgf*
Specific Energy :	25.18	*kwh/m3*					

Explanation: 1. Hat

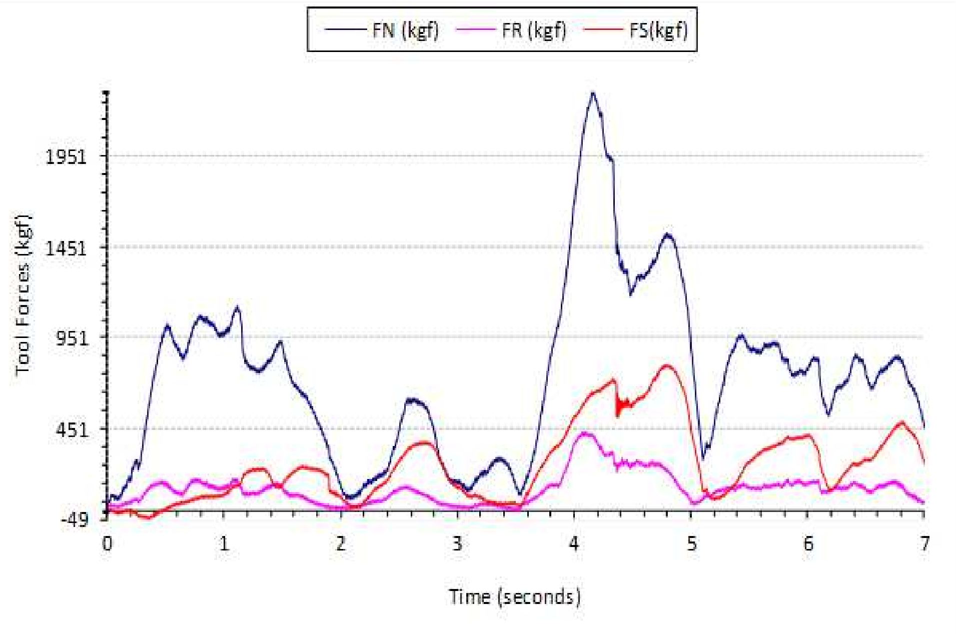


Figure A.14 : Disc cutter; depth of cut 3 mm in unrelieved cutting mode (line 1).

I.T.U. MINING ENGINEERING DEPARTMENT

SMALL-SCALE LINEAR CUTTING TEST (V. 1.2)

Company :	ITU	Test Date :	6/4/2014
Project :	Master Thesis	Analysis Date :	6/4/2014
Location:	Küre-Kastamonu	Tested by:	A. Shaterpour

Test No :	2			
File Name :	msc_disk_d3_t2	Tool Holder :	ITU	
Sample :	Basalt	Cutting Speed :	3	cm/sn
Sample Type :	Igneous	Depth of Cut :	3	mm
Cutter :	Standard Disc			

				FN Normal	FR Cutting	FS Side	
Cutting Length :	11.5	cm	Average:	988.1	179.6	35.1	kgf
Muck Weight :	10.65	g	Std. Dev.:	533.7	104.9	202.6	kgf
Sample Density :	2.82	g/cm3	Min:	39.7	-5.7	-384.8	kgf
Q:	0.03	m3/km	Max:	2250.1	449.9	469.2	kgf
Specific Energy :	53.66	mJ/m3					
Specific Energy :	14.91	kwh/m3					

Explanation: 2. Hat

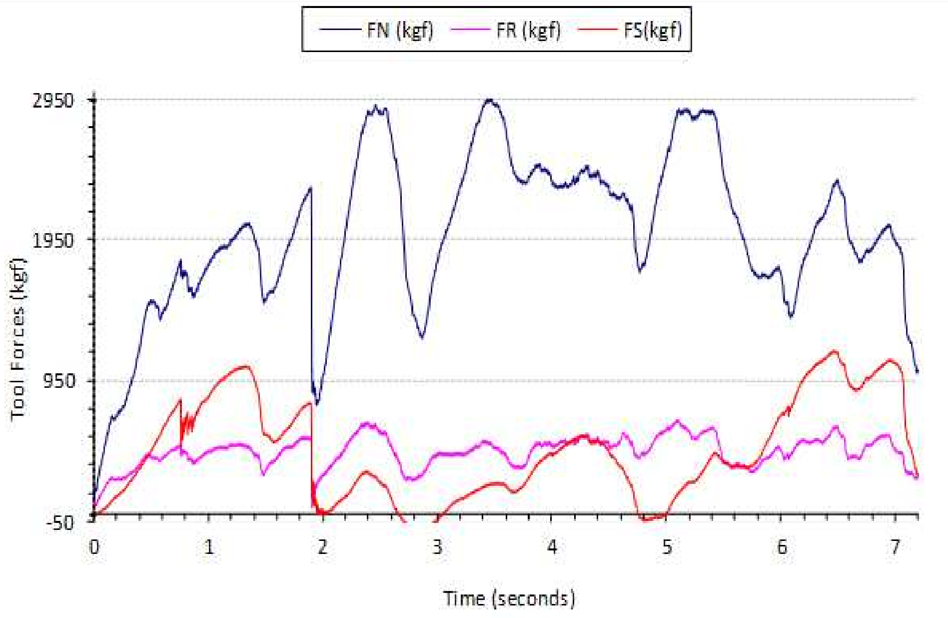


Figure A.15 : Disc cutter; depth of cut 3 mm in unrelieved cutting mode (line 2).

I.T.U. MINING ENGINEERING DEPARTMENT

SMALL-SCALE LINEAR CUTTING TEST (V. 1.2)

Company :	ITU	Test Date :	6/4/2014
Project :	Master Thesis	Analysis Date :	6/4/2014
Location:	Küre-Kastamonu	Tested by:	A. Shaterpour

Test No :	1			
File Name :	msc_disk_d5_t1	Tool Holder :	ITU	
Sample :	Basalt	Cutting Speed :	3	cm/sn
Sample Type :	Igneous	Depth of Cut :	5	mm
Cutter :	Standard Disc			

Cutting Length :	12.0	*cm*
Muck Weight :	29.07	*g*
Sample Density :	2.82	*g/cm3*
Q:	0.09	*m3/km*
Specific Energy :	74.56	*mJ/m3*
Specific Energy :	20.71	*kwh/m3*

	FN Normal	FR Cutting	FS Side	
Average:	2495.6	652.9	-53.4	*kgf*
Std. Dev.:	1195.3	397.4	298.9	*kgf*
Min:	19.5	-147.3	-736.9	*kgf*
Max:	5433.8	1789.3	518.3	*kgf*

Explanation: 1. Hat

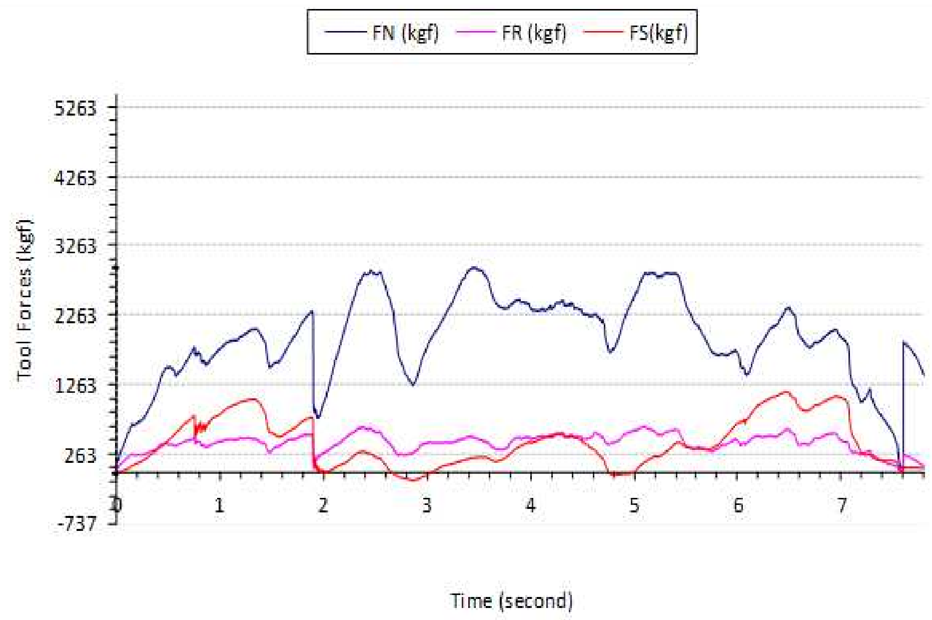


Figure A.16 : Disc cutter; depth of cut 5 mm in unrelieved cutting mode (line 1).

I.T.U. MINING ENGINEERING DEPARTMENT

SMALL-SCALE LINEAR CUTTING TEST (V. 1.2)

Company :	ITU	Test Date :	6/4/2014
Project :	Master Thesis	Analysis Date :	6/4/2014
Location:	Küre-Kastamonu	Tested by:	A. Shaterpour

Test No :	2			
File Name :	msc_disk_d5_t3	Tool Holder :	ITU	
Sample :	Basalt	Cutting Speed :	3	cm/sn
Sample Type :	Igneous	Depth of Cut :	5	mm
Cutter :	Standard Disc			

				FN Normal	FR Cutting	FS Side	
Cutting Length :	11.0	*cm*					
Muck Weight :	25.83	*g*	Average:	1931.2	429.6	429.6	*kgf*
Sample Density :	2.82	*g/cm3*	Std. Dev.:	625.7	122.9	349.5	*kgf*
Q:	0.08	*m3/km*	Min:	57.4	2.0	-125.0	*kgf*
Specific Energy :	50.61	*mJ/m3*	Max:	2954.7	669.1	1162.9	*kgf*
Specific Energy :	14.06	*kwh/m3*					

Explanation: 2. Hat

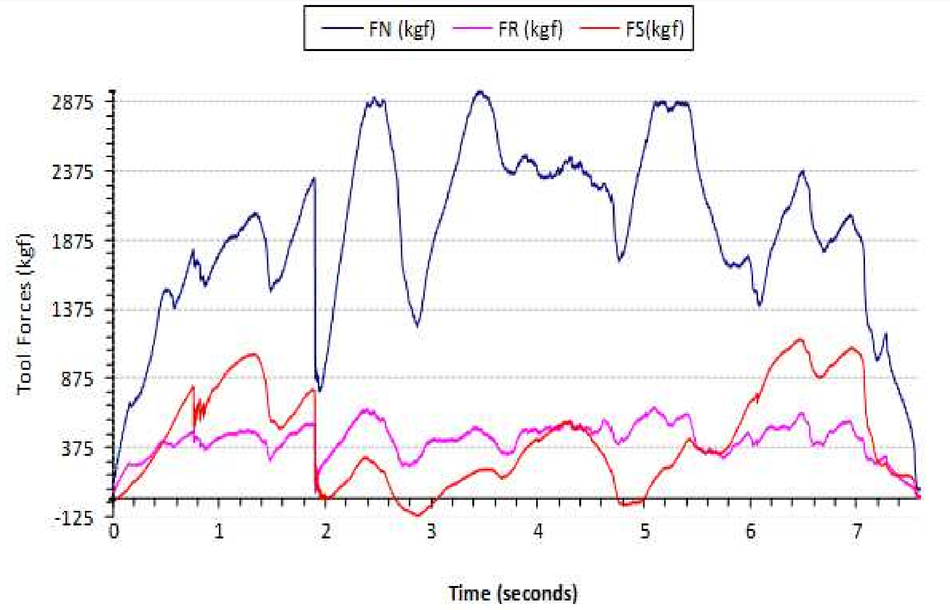


Figure A.17 : Disc cutter; depth of cut 5 mm in unrelieved cutting mode (line 2).

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PUBLICATIONS/PRESENTATIONS ON THE THESIS

- **Shaterpour Mamaghani, A.,** Bilgin, N., 2014. Some Contributions on the Performance Estimation of Raise Borers-A case Study in Kure Copper Mine, Turkey. *Tunnelling and Underground Space Technology* (under review).
- **Shaterpour Mamaghani, A.,** Bilgin, N., 2014. The Raise Boring Operation in Kure, Kastamonu Copper Mine. In: *World Tunnel Congress,* May 22-28, 2015 Dubrovnik, Croatia (accepted abstract).
- **Shaterpour Mamaghani, A.,** Avunduk, E., Bilgin, N., 2014. Rock Mechanical Aspects of Excavation Related to Raise Boring Machine. A Typical Example from Asikoy Underground Mine, Kastamonu, Turkey. *In: Eurock*, Oct 7-10, 2015 Salzburg, Austria (abstract submitted).