APPLICATION OF PUNCH PENETRATION TESTS INTO ROCK CUTTABILITY DETERMINATION FOR ISTANBUL METRO PROJECT

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Gürcan Dursun, B. sc.
(594Y003)

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Examination Commitee
Thesis Supervisor  : Prof. Dr. Nuh Bilgin
Member            : Prof. Dr. Şinasi Eskikaya
Member            : Assoc. Prof. Dr. Ali Kahrinan

FEBRUARY 1999
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And all the others that have not been mentioned here.

Gürhan DURSUN

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SUMMARY

In this study, Punch Penetration laboratory tests and their possible practical applications have been investigated. Research has been carried out both in situ and laboratory.

Site investigation has been done at Mecidiyeköy and Ayazaga Tunnels which are the construction part of Istanbul Metro Project.

Laboratory tests have been realized in the Rock Mechanics Laboratories of Istanbul Technical University.

The main objective of the study was to specify the standard testing conditions of Punch Penetration Tests and to apply them to rock cutting mechanics science.

Consequently, the samples, which have been taken from Istanbul Metro Construction tunnels, have been subjected to Punch Penetration, Schmidt and Point Load tests respectively. The results were evaluated later for predicting the performance of impact hammer in tunnel drivages.
ÖZET

Bu çalışmada, Punch Penetration testler ile ilgili laboratuvar bulguları ve pratikte elde edilen sonuçlar birlikte incelemiştir. Araştırma gerek laboratuvar gerekse arazi çalışmaları olarak yürütülmüştür.

Arazi çalışmalarını İstanbul Metro şantiyesinin bir bölümünü oluşturan Mecidiyeköy ve Ayazağa tünelerinde gerçekleştirilmiştir.

Laboratuvar testleri ise İstanbul Teknik Üniversitesi’nde bulunan Arazi Kontrolü ve Kaya Mekanıği laboratuvarlarında gerçekleştirilmiştir.

Bu çalışmanın ana konusu Punch Penetration Test standartlarının tesbit edilmesi ve bu standartların kazı kesme mekaniği bilimine uygulanmasıdır.

Bu nedenle, İstanbul Metrosu kazı çalışmalarından elde edilen numuneler sırası ile Punch Penetration, Schmidt ve Nokta Yük deneylerine tabi tutulmuştur. Elde edilen sonuçlar daha sonra söz konusu metro çalışmasında kullanılan gagali kazıçılara elde edilen makine ilerleme hızları ile karşılaştırılmıştır.
CHAPTER 1.

1.1. Introduction and Objectives

Today's global understanding brings the idea of rapid construction of underground structures in mining and civil industry. The decrease of mine reserves that could be exploited by surface mining methods, caused an increase in the underground mining operations. Also, the most valuable reserves near to the surface have already been exploited and deep underground mining, which has technical limits, became a necessity. In such case, unstable market prices have also affected the concept of mining which necessitates effective production by mechanical mining systems.

In the meantime, substructure problems of big cities have increased with the augmentation of population and technological improvements. These problems have also to be solved at very short time period and this necessity also brings again the concept of rapid mechanical systems.

Latest experiences have clarified that a wrong selection of mechanical system could cause an inverse effect on excavation efficiency. Consequently, rock cutting mechanics have been studied by many research people for many years for the design of cutting systems.

Punch Penetration tests, which carried out at Istanbul Technical University Mining Faculty - Rock Mechanics and Rock Excavation Laboratories had the main objectives of establishing the tests conditions and finding a basic application in rock cutting mechanics for more efficient excavation systems.
1.2. Previous Researches on Punch Penetration Tests

Numerous authors have studied the static penetration of a wedge into rock and the theoretical studies of hit penetration into brittle materials have been published which have their common origin in the wedge-penetration model established by Paul and Sikarskie. Thus, Benjumea and Sikarskie extended the model to include non-isotropic materials, while Miller and Sikarkie, and Lundberg independently considered penetration of conical indenters. In these investigations it was assumed that the way of the force acting on the indenter is transmitted to the solid rock depending on two parameters, namely the geometry of the indenter and the angle of friction which describes the interaction between the surface of the indenter with the crushed and solid rock. This assumption was modified by Dutta who postulated that the way that the force is transmitted depends on the rock material only.

Cheatham has assumed the rock to behave plastically and has obtained force-penetration equations for both Coulomb-Mohr and parabolic criteria. Evans and Murrell have studied the penetration of two types of wedge and found equations relating the penetration characteristics (force / displacement) to wedge angle for the various-strength coals tested. Brace attempted to find a correlation between hardness as determined by intending the material and other mechanical properties and concluded that the results of such a test are generally inclusive. His paper, however, contains a very extensive bibliography of indenting of many different materials. Gnirk also has a fairly complete literature review on the static penetration of rock, of which he makes use in his indexing studies. Due to studies that have been done, a wide range of behavior is found in the wedge penetration of different rocks under different external conditions.

Although comparisons of theoretical force penetration relationships with experimental data have been published, the extent of the comparisons made is quite limited. Paul and Sikarskie compared their theoretical results with Reichmuth’s data
for wedges with apex-angles of 60, 75, 90, 105 and 120°, while Miller and Sikarkie used cones with apex-angles of 45 and 60°. Apex-angles of 90° and 120° for wedges and cones were used in experiments reported by Dutta.

1.2.1 Theory of the Penetration of Rock by Conical Indenters

Three material parameters of the rock must be specified in the present theory:

- The angle of internal friction of the rock ($\phi$)
- The compressive strength of the rock ($\delta_c$)
- The slope of the force penetration curve during the crushing ($k$)

for a given wedge geometry. The indenter is assumed to be rigid and perfectly cone-shaped with an apex-angle $2\theta$, and the rock surface is assumed to be plane. The effective friction between the indenter and the solid rock, which depends primarily on the intermediate layer of crushed rock, it is characterized by the angle of friction $\phi_f$. Only the part $x_d$ of the penetration due to destruction is considered. Elastic and dynamic effects are not taken into account.

When the indenter is forced towards the rock surface, it is assumed that radial cracks are formed as a result of the tensile tangential stress. Chip failure then occurs on a conical surface, which extends from the tip of the indenter to the free surface at an angle of inclination $\psi$ (the failure angle). The idealized geometry of chip failure is illustrated in Figure 1.1.

The stress acting on a chip before failure are assumed to be such that equilibrium prevails. Failure occurs when the average normal and shear stress $\delta$ and $\tau$ acting on the most critical potential failure surface satisfy the Coulomb-Mohr failure criterion. This criterion is illustrated in Figure 1.2., where $\delta_c$ is the compressive strength and $\phi$ is the internal angle of friction of the rock material.
The failure angle $\psi$, corresponding to the most critical failure surface, is found to be

$$\psi = \arctan \left\{ \left[ \cot(\alpha) \right]^{1/3} - \left[ \tan(\alpha/2) \right]^{1/3} \right\}$$  \hspace{1cm} (1)

where

$$\alpha = \theta + \phi_f + \phi$$  \hspace{1cm} (4)
Figure 1.3. Failure angle $\psi$ versus $\alpha = \theta + \phi_f + \phi$ [4]

Since chipping is impossible unless $\psi > 0$, a necessary condition for chip formation is obtained from equation (1) as

$$\alpha < \pi/2$$

(2)

Furthermore, the relationship between the force at chip failure $F^*$ and the penetration $X_d$ is found to be parabolic, i.e.

$$F^* = kX_d^2$$

(3)

where $k$ is given by

$$k/\sigma_c = \pi(1-\sin\phi) \sin(\theta+\phi_f) \cos\psi + 2 \sin^2\psi \cos(\alpha + \psi)$$

(4)
Using the fact that the force acting on the indenter $F$ is always smaller than or equal to $F^*$, we also obtain a lower value $K$ for the ratio $V/W$ of chip volume to work done, i.e.

$$V/W > K$$  

where $K$ is given by

$$K_0 = 2\cos \psi \cos (\alpha + \psi) / (1 - \sin \phi) \sin (\theta + \phi f)$$  

Numerical results for $K_0$ and $K_0$ versus $(\theta + \phi f)$ for different values of $\phi$ are given in Figure 1.4. and 1.5, respectively.

![Diagram](image.png)

Figure 1.4. $K/\sigma_C$ vs. $(\theta + \phi f)$ for different values of $\phi$ and $K_0\epsilon$ versus $(\theta + \phi f)$ for different values of $\phi$
CHAPTER II.

2.2. Test Apparatus

The first nine test were done with the following test apparatus.

DESCRIPTION OF THE TEST EQUIPMENT AND TEST PROCEDURE

2.1. Laboratory Experiments

Several sets of experiments were carried out in order to clarify the Punch Penetration Test conditions and to see the relationship between the test results and the performance of rapid excavation systems. The mentioned laboratory experiments were done at Istanbul Technical University Mining Faculty - Rock Mechanics and Rock Excavation Laboratories.

Punch Penetration Experiments and other related tests were done in two groups of samples and experimental conditions. The first experimental group (i.e. Anhydrite, Gypsum, Trakya Formation), which have been carrying the various different physical specifications, were tested without confining pressure. The samples having the cubic size of 10-15 cm were tested with the punch penetration experiment set shown in figure 2.1. Also the same group of samples were tested with Schmidt Hammer. Finally, both Punch Penetration and Schmidt Test results were evaluated at the same graph on the conclusion chapter. (Graph 4.23.)

After testing of different physical and mechanical characteristics of different rock samples, obtained from Istanbul Subway - Experimental Tunnels construction, a second group of punch penetration test was realised. Different from the first punch penetration experiments, these tests were carried out with confining pressure obtained by white cement cure in steel moulds. Also the same samples from these group, were subjected to the point load tests. Finally, all the data obtained from the experiments and from the Istanbul Subway Construction investigation drilling
logs were evaluated together.

2.2. Test Apparatus

The first nine test were done with the following test apparatus:

2.2.1. Hydraulic Press

The punch penetration test were realised using a hydraulic press in 3000 kN capacity which has been designed for consistent, reliable testing. General view drawing of the machine is given by Figure 2.1. The automatic cycle enables high throughput of samples making this range of machines particularly suitable for central or commercial testing organisations. The compression machine has a automatic console providing the control for the compression frame (and flexural frame when fitted). The fascia comprises a Dot Matrix, Vacuum Fluorescent Display (VFD) which has an exceptionally long operating life. All parameters such as sample sizing, pacing rate, date etc., are entered using the touch sensitive QWERTY keyboard and function keys.

The microprocessor software provides a series of self test routines for checking the correct functioning of the machine; simple menu driven data entry facilities and functions for calibration, verification, data storage and optional print routines.

Up to 500 sets of tests data may be stored in a temporary memory for later access via PC. Stored test data may also be viewed on the console display screen. A Y/t facility to connect to a suitable chart recorder is fitted as standard. The test parameters can be displayed in kN, lbf or kgf and associated mm or inch units.

The hydraulic power which situated in the base of the Automatic Console is the hydraulic power pack which provides the hydraulic power to the compression frame (and flexural frame when fitted) by way of a variable output pump controlled by a stepper motor.
Figure 2.1.  

a - Arrangement of Compression Tubes  
b - Autotest 3000 Compression Machine
The high pressure oil pump only delivers the flow of oil as required by the rate of loading, which results in efficient operation over periods of extended use. The compression frames of the machine have a single acting stroking ram with over travel protection to shut the machine down should maximum platen travel be reached.

The AutoTest 3000 kN compression machine has the following specifications:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall dimensions (compression frame)</td>
<td>590 x 510 x 1215 mm</td>
</tr>
<tr>
<td>Console</td>
<td>520 x 430 x 1215 mm</td>
</tr>
<tr>
<td>Max. vertical clearance</td>
<td>340 mm</td>
</tr>
<tr>
<td>Max. vertical clearance (Block tester)</td>
<td>260 mm</td>
</tr>
<tr>
<td>Max. horizontal clearance</td>
<td>310 mm</td>
</tr>
<tr>
<td>Upper platen dimensions</td>
<td>220 x 220 x 38 mm</td>
</tr>
<tr>
<td>Lower platen dimensions</td>
<td>445 x 250 x 75</td>
</tr>
<tr>
<td>Max. ram travel</td>
<td>50 mm</td>
</tr>
<tr>
<td>Rated power</td>
<td>1600 W</td>
</tr>
<tr>
<td>Approx. weight of console</td>
<td>145 kg</td>
</tr>
<tr>
<td>Approx. weight of compression frame</td>
<td>1270 kg</td>
</tr>
<tr>
<td>Approx. weight of comp. frame and block tester</td>
<td>1370 kg</td>
</tr>
<tr>
<td>Hydraulic oil capacity</td>
<td>12 liters</td>
</tr>
<tr>
<td>Hydraulic oil type</td>
<td>Shell Tellus T46</td>
</tr>
<tr>
<td></td>
<td>(or equivalent oil to viscosity ISO HV 46)</td>
</tr>
</tbody>
</table>

All the operations of the machine are controlled from the front panel which consists of a Vacuum Fluorescent Display (VFD), a keyboard, a numeric keypad and 8 function keys which is used to control the operation of the system.
2.2.2. Load Cell

It is a force transducer used to measure the force applied on the sample. Figure 2.3. is a drawing of the complete load cell, while Figure 2.4. is a technical drawing showing the construction of a typical model in this range. Force-sensing element is used either a ring type or a column-type element (Figure 2.4.).

The type of element supplied depends upon the force range for which the transducer is supplied, with the ring-type element used for lower forces. By using different types of element the same full-range output can be obtained for different ranges.
Figure 2.3. Strain-gauge load cell

Figure 2.5. shows circuit diagram for a typical load cell which has six strain gauges mounted on it. Four of the straining gauges form the arms of the bridge. The other two are the resistors marked ‘span temperature effect adjust’. On the ring-type element the bridge resistors are arranged on the top, bottom and two sides of the inside of the ring. The ‘span temperature effect adjust’ strain gauges are mounted on the outside of the ring-type element. They are mounted so that they are not subjected to any strain (i.e. they are dummy gauges), but are at the same temperature as four active straining gauges.
Figure 2.4. Construction of a typical load cell
2.2.3. Linear Variable Differential Transformer (LVDT)

Linear variable differential transformer (LVDT) is a proof ring transformer, which measures deflection resulting from an applied force (This deflection simply refers to the fact that displacement in a straight line is measured). When a load is applied to the top and bottom of the proof ring, their separation changes and the plunger is moved along the main axis of the differential transformer.

The LVDT of Figure 2.6. has a primary winding and two secondary windings. The primary is usually fed with AC of constant amplitude and frequency. AC voltages are induced in the secondary windings by transformer action.
When no load is applied to the proof ring, the plunger is commonly adjusted so that the ferromagnetic armature which it carries is centered in the windings. Because of the resultant symmetrical arrangements, the secondary voltages are then equal.

The series-opposition connection shown in the figure gives an output which is the difference between these voltages. More specifically, $V_0 = V_1 - V_2$. This is zero with the armature centred, because $V_1 = V_2$. When a tensile load is applied to the proof ring, the armature is displaced from its central position and towards the upper secondary winding. Because the armature is made of a ferromagnetic material, the coupling between the primary and the upper secondary coil is increased while the coupling with the lower secondary coil is decreased. Consequently, the voltage induced in the upper secondary is greater in magnitude than the voltage induced in the lower secondary.
The difference between the secondary voltages is now no longer zero and an output voltage appears which, over a certain range, is linearly related to the displacement.

2.2.4. X-Y Recorder

In mentioned punch penetration tests the signal obtained from LVDT and load cell have been recorded by this apparatus. The PL3 XY/t recorder has been designed for observing the various applications. The recorder may be operated in the horizontal or vertical mode, providing the moving carriage is not made to move against the gravity.

2.2.5. Spherical Indenter

All the Punch Penetration tests were carried out with a spherical indenter having a diameter of 11 mm.

2.3. Test Samples

The first nine samples, which have been already been existed from the Istanbul Technical University - Mining Faculty Laboratories, are named as “Group I. - Samples”. Samples obtained from Istanbul Subway construction are named as “Group II. - Samples”. These two different groups are tested by means of different experimental conditions. The formation names and the dimensions of the samples are given on the Table 2.2.

2.4. Calibration of the Test Apparatus

The first five tests were carried out with 0.5 kN/sec loading rate with the Hydraulic Press, 1/2,5 LVDT and 1/1 load cell scale. During these tests it is observed that the chipping formation could not be seen on the recorder graph in detail.

Consequently, next four tests were carried out with lower (0.25 kN/sec) loading rate, 1/2,5 LVDT and ½ load cell recording rate scale. By these calibrations, it is
<table>
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<tr>
<th><strong>Table 2.1. PL3 XY/t recorder specifications</strong></th>
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</thead>
<tbody>
<tr>
<td><strong>Writing Format</strong></td>
</tr>
<tr>
<td><strong>Writing Area (full scale)</strong></td>
</tr>
<tr>
<td><strong>Pen lift</strong></td>
</tr>
<tr>
<td><strong>Writing System</strong></td>
</tr>
<tr>
<td><strong>Operating Position</strong></td>
</tr>
<tr>
<td><strong>Writing Speed ‘X’</strong></td>
</tr>
<tr>
<td><strong>Writing Speed ‘Y’</strong></td>
</tr>
<tr>
<td><strong>X Sweep Time Base</strong></td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
</tr>
<tr>
<td><strong>Damping</strong></td>
</tr>
<tr>
<td><strong>Linearity</strong></td>
</tr>
<tr>
<td><strong>Repeatability</strong></td>
</tr>
<tr>
<td><strong>Dead Band</strong></td>
</tr>
<tr>
<td><strong>Input Mode</strong></td>
</tr>
<tr>
<td><strong>Circuit System</strong></td>
</tr>
<tr>
<td><strong>Servo Protection</strong></td>
</tr>
<tr>
<td><strong>Voltage Reference</strong></td>
</tr>
</tbody>
</table>
Figure 2.7. X-Y Recorder

Figure 2.8. Tests-Set X/Y Recorder, LVDT and Load Cell
### Table 2.2. Group I and II Test Samples

<table>
<thead>
<tr>
<th>Sample Test Number</th>
<th>Sample Dimensions(cm)</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group I. Sample I.</td>
<td>8-10-14</td>
<td>Anhydrite</td>
</tr>
<tr>
<td>Group I. Sample II.</td>
<td>8-8-12</td>
<td>Gypsum</td>
</tr>
<tr>
<td>Group I. Sample III.</td>
<td>10-12-18</td>
<td>Trakya Formation</td>
</tr>
<tr>
<td>Group I. Sample IV.</td>
<td>9-10-14</td>
<td>Trakya Formation</td>
</tr>
<tr>
<td>Group I. Sample V.</td>
<td>6-8-12</td>
<td>Cellesite</td>
</tr>
<tr>
<td>Group I. Sample VI.</td>
<td>6-6-10</td>
<td>Gypsum</td>
</tr>
<tr>
<td>Group I. Sample VII.</td>
<td>8-10-14</td>
<td>Cellesite</td>
</tr>
<tr>
<td>Group I. Sample IIX.</td>
<td>7-8-16</td>
<td>Trakya Formation</td>
</tr>
<tr>
<td>Group I. Sample IX.</td>
<td>7-10-19</td>
<td>Trakya Formation</td>
</tr>
<tr>
<td>Group II. Sample I.</td>
<td>Ø 4.5 - 4.7</td>
<td>Lam. Mudstone</td>
</tr>
<tr>
<td>Group II. Sample II.</td>
<td>Ø 4.5 - 5.8</td>
<td>Lam. Mudstone</td>
</tr>
<tr>
<td>Group II. Sample III.</td>
<td>Ø 4.5 - 7.3</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Group II. Sample IV.</td>
<td>8-6-9</td>
<td>Trakya Formation</td>
</tr>
<tr>
<td>Group II. Sample V.</td>
<td>7-8-10</td>
<td>Trakya Formation</td>
</tr>
</tbody>
</table>
Figure 2.9. Group I. Test Sample - 5 (Cellestite)

Figure 2.10. Test Sample 2.5. Group I. Test Sample - 6 (Gypsum)
Figure 2.11. Group I. Test Sample - 7 (Cellestite)

Figure 2.12. Group I. Test Sample - 8 (Trakya Formation)
Figure 2.13. Group I. Test Sample - 9 (Trakya Formation)

Figure 2.15. Group II. Test Samples (Samples from Istanbul Metro Shaft)
Figure 2.14. Group II. Test Samples (1-2).

Figure 2.15. Group II. Test Samples (Samples from Istanbul Metro Shaft)
Figure 2.16. Group II. Test Samples from KS.01.08. investigation drill cores

Figure 2.17. Group II. Test Samples from KS.01.01. investigation drill cores
Figure 2.18. Group II. Test Samples with steel molds

Figure 2.19. Group II. Test Samples with white cement surround
achieved to observe better chipping records. Apparatus calibration, which have been
done for achieving meaningful test results on the X-Y recorder, LVDT and hydraulic
press are given below:

Calibration of the Hydraulic Press

The punch penetration tests have been done at two different loading rates. The first
five tests have been done with the calibration of the hydraulic press to loading rate of
0.50 kN/sec and the rest have been done with a loading rate of 0.25 kN/sec.

Calibration of the LVDT

LVDT calibration has done by means of ruler with the scale 1/25 on the recorder
paper. In other words, every 1 mm real displacement equals to 2.5 cm recording on
the paper.

Calibration of the X-Y Recorder

The calibration of the X-Y recorder has been done by means of voltage adjusting
switches of the recorder. With the arrangement of these switches it is achieved to
record page-fit graphs on the A3 recording paper.

2.4. Point Load Index and Schmidt Hammer Test

Point Load Strength Index is basically found out by means of loading samples with
conical intender and recording the loading value when the rock has failed. This
index usually is used for rock classifications.

Index value is an empirical value related with the rock uniaxial compressive
strength. Therefore,
Point Load Index, $I_p$, is equals to:

$$I_p = (P/D^2) \cdot (P_d)$$

$P$: Load applied on the sample during the failure
$D$: Diameter of the sample
$P_d$: Diameter of the loading piston

There exists an empirical relationship between point load strength index and uniaxial compressive strength as:

$$\delta_c = C \cdot I_p$$

$C$ value is changing between 12 - 24 and usually accepted 24 for practical calculations.

Index tests were also carried out by means of Schmidt Hammer and Schmidt Values have been recorded to evaluate with $\alpha$ (kN/mm) rate later. Schmidt hammer developed in 1948 by Swiss engineer Ernest Schimdt, it is a portable, cost effective instrument capable of estimating intact rock strength with distinct advantages over traditional testing. Laboratory tests are time consuming, expensive, and nearly always subject to bias due to platen effects, integrity loss during coring and preparation, and sample alteration from environmental conditions. Conversely, a large number of nondestructive Schimdt hammer tests can be performed quickly and efficiently in either laboratory or the field. Significant ranges of scatter are typically produced when many hammer tests are performed.

Studies also show that a variety of additional factors may affect laboratory and field-determined index values, including following [10]:

28
- Varying degrees of surface irregularity
- Impact surface moisture content
- Inhomogeneities in the rock fabric
- Presence of cleavage slips, bedding planes, porous cavities, and other local anomalies
- Orientation and size of tests surface
- Duration and degree of test surface weathering
- Rock mass confinement; in place versus confined laboratory setting

Numerous empirical equations have been proposed for calculating uniaxial compressive strength ($\sigma_a$) and modulus of elasticity ($E_t$) of rock and coal from Schmidt hammer index values ($H_s$) [9-10].
CHAPTER III.

IN-SITU STUDIES IN ISTANBUL METRO TUNNELS

3.1. Istanbul Metro Project

The construction of Istanbul metro tunnels were started in 1993, the project is divided into two sections due to construction restrictions. Section one covers the construction area between Taksim and 4. Levent. Total length of the tunnels on this line is 7045 meters. This section has 6 stations. The length of the section two, which is planned between Taksim and Topkapı, is 9845 meters. It has 7 stations planned. So far all the excavation (except the new extra tunnels between 4. Levent and Maslak) has been concluded successfully.

Istanbul metro project has the following major goals:

- To increase the transport safety and comfort
- To decrease the transport time and to bring the flexibility to the current traffic
- To minimise the negative effects of transport by means of pollution
- To protect the natural and historical values of the city
- To establish an effective transport system by means of cost

Tunnel excavations have been realised by the operation of road-header and jackhammer tunnelling machines. These excavations are made by the New Australian Tunnelling Method, which means the application of shotcrete, wire-mesh lattice girder and column system. Total excavation was done in a formation changing from claystone to sandstone and mudstone laminations. This formation, which has a
common name as Trakya Formation, is extremely tectonized, there are several geological discontinuities within this formation. The strength of the formation increases with increasing depth of excavation.

The New Australian Tunneling Method was chosen due to its simplicity which does not need any specific, expensive machine. There are two tubes in each line. Consequently, excavation of many tunnel faces could be possible in the same time with better safety precautions.

According to the concept of New Australian Tunnelling Method, Istanbul Metro construction tunnels were divided into three types of supporting systems.

- **A_3 Type**: Tunnels passing under the buildings
- **A_2 Type**: Tunnels passing under the city roads
- **A_3 Type**: Tunnels passing under empty fields

The characteristics of different types of supporting systems are as follows:

**A_1 Type**: Maximum unit excavation length is 100 - 150 cm, shotcrete thickness is 10-15 cm, wire mesh must be used but steel coated assembly is not needed.

**A_2 Type**: Maximum unit excavation length is 100 - 120 cm, shotcrete thickness is 20 cm, one line wire mesh must be used, steel coated assembly on every 100-120 cm is necessary.

**A_3 Type**: Maximum unit excavation length is 80 - 100 cm, shotcrete thickness is 20 cm, double line wire mesh must be used, steel coated assembly on every 80-100 cm is needed.
Figure 3.1. P-Type Tunnel Profiles
Figure 3.2. B2 and B3 Type Tunnel Profiles

Figure 3.3. A-Type Tunnel Profile
Figure 3.4. Cut and Cover Type Tunnel Profile

Figure 3.5. B3 Type Tunnel Profile
Cut and Cover Type Tunnel

Retaining Wall

Figure 3.6. Cut and cover, retaining wall tunnel dimensions
Metro facility should carry the following operational figures while working with full capacity:

- 236 Wagons should be operated
- 75,720 passengers per hour should be transported
- Transportation capacity of the wagon should be 6 persons per meter square
- Train stop frequency should be 2 trains per minute
- Average speed of the trains should be 80 Km per hour
- Trains should consist of 8 wagons
- Average transportation time from Taksim to 4. Levent should be 14 minutes

Total length of the tunnels should be 12,933 m. according to the project. There are 6 different types of tunnel cross-sections used. These sections are stated as follows:

- Type A - Horseshoe - major line tunnels
- Type P - Station - platform tunnels
- Type T - Point tunnels
- Type B1 - Station platform connection tunnels
- Type B2 - Stair tunnels
- Type B3 - Emergency entrance and exit tunnels

Specifications of the project tunnels are given on the Table 3.1. according to their cross-section types.
Table 3.1. Specifications of the project tunnels

<table>
<thead>
<tr>
<th>Tunnel Type</th>
<th>Cross Section ((m^2))</th>
<th>N. Exc. Length ((m))</th>
<th>Volume ((m^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>36</td>
<td>10,176</td>
<td>366,170</td>
</tr>
<tr>
<td>P</td>
<td>64</td>
<td>1,096</td>
<td>70,200</td>
</tr>
<tr>
<td>B</td>
<td>42</td>
<td>360</td>
<td>15,120</td>
</tr>
<tr>
<td>B</td>
<td>22</td>
<td>327</td>
<td>7,194</td>
</tr>
<tr>
<td>B</td>
<td>44</td>
<td>320</td>
<td>14,080</td>
</tr>
<tr>
<td>T</td>
<td>100</td>
<td>654</td>
<td>65,400</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>12,933</strong></td>
<td></td>
<td><strong>538,164</strong></td>
</tr>
</tbody>
</table>

3.2. Experimental Tunnels

The specific tunnels chosen within the scope of this project are named as experimental tunnels. These tunnels are between 10+400 and 10+630 Km of the tunnel excavation named Mecidiyeköy tunnels. More detailed information could be obtained from the Appendix 1 regarding the experimental tunnels. The geological map and the variation of excavation rates due to tunnel position are given in Figures 3.7. - 3.9.

The main reasons of the selection of these tunnels for the study may be stated as follows:

- All the geotechnical and excavation data could be obtained from the excavation records
- Rich formation changes on both tubes have been observed
- Same rock samples from these tunnels were already existed in the İ.T.Ü. laboratories.
Figure 3.7. Istanbul Metro Construction - estimated underground geology [7]
Figure 3.8. Average excavation rate at experimental tunnels - line 1

Average: 1.10 m / day
Figure 3.9. Average excavation rate at experimental tunnels - line 2

Average: 1,10 m / day
Experimental tunnels excavation was realised with Fiat Hitachi and Volvo BM 70 Jack Hammers operated by Montabert hydraulic rock breakers and the muck which was transported by means of tunnel trucks.

Table 3.2. Experimental Tunnels - Line 1 Excavation Figures

<table>
<thead>
<tr>
<th>Km</th>
<th>P.Rate (m/d)</th>
<th>Overbrake (m³)</th>
<th>Exc. Quality</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>13+430</td>
<td>1.03</td>
<td>2.21</td>
<td>A3</td>
<td>Mudstone</td>
</tr>
<tr>
<td>13+440</td>
<td>0.91</td>
<td>2.21</td>
<td>A3</td>
<td>Fault zone</td>
</tr>
<tr>
<td>13+450</td>
<td>1.36</td>
<td>3.67</td>
<td>A2</td>
<td>Diabase Dayk</td>
</tr>
<tr>
<td>13+460</td>
<td>1.61</td>
<td>4.23</td>
<td>A2</td>
<td>Sandstone</td>
</tr>
<tr>
<td>13+470</td>
<td>1.31</td>
<td>3.01</td>
<td>A2</td>
<td>Sandstone</td>
</tr>
<tr>
<td>13+480</td>
<td>1.38</td>
<td>3.38</td>
<td>A2</td>
<td>Sandstone</td>
</tr>
<tr>
<td>13+490</td>
<td>1.19</td>
<td>4.19</td>
<td>A2</td>
<td>Sandstone</td>
</tr>
<tr>
<td>13+500</td>
<td>1.15</td>
<td>4.64</td>
<td>A2</td>
<td>Sandstone</td>
</tr>
<tr>
<td>13+510</td>
<td>1.42</td>
<td>3.81</td>
<td>A3</td>
<td>Mudstone</td>
</tr>
<tr>
<td>13+520</td>
<td>1.05</td>
<td>3.39</td>
<td>A3</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+530</td>
<td>1.41</td>
<td>2.61</td>
<td>A3</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+540</td>
<td>1.68</td>
<td>3.97</td>
<td>A2</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+550</td>
<td>1.72</td>
<td>4.19</td>
<td>A2</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+560</td>
<td>1.61</td>
<td>3.62</td>
<td>A2</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+570</td>
<td>1.39</td>
<td>4.14</td>
<td>A2</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+580</td>
<td>1.75</td>
<td>2.54</td>
<td>A3</td>
<td>Diabase Dayk</td>
</tr>
<tr>
<td>13+590</td>
<td>1.46</td>
<td>2.57</td>
<td>A3</td>
<td>Sandstone</td>
</tr>
<tr>
<td>13+600</td>
<td>1.52</td>
<td>2.98</td>
<td>A3</td>
<td>Sandstone</td>
</tr>
<tr>
<td>13+610</td>
<td>1.37</td>
<td>2.41</td>
<td>A3</td>
<td>Diabase Dayk</td>
</tr>
<tr>
<td>13+620</td>
<td>1.55</td>
<td>3.49</td>
<td>A3</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+630</td>
<td>1.67</td>
<td>2.74</td>
<td>A3</td>
<td>Sandstone-Mudstone</td>
</tr>
</tbody>
</table>
Table 3.3. Experimental Tunnels - Line 2 Excavation Figures

<table>
<thead>
<tr>
<th>Km</th>
<th>P. Rate (m/d)</th>
<th>Overbreak (m³)</th>
<th>Exc. Quality</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>13+400</td>
<td>0.47</td>
<td>2.52</td>
<td>A3</td>
<td>Sandstone</td>
</tr>
<tr>
<td>13+410</td>
<td>0.73</td>
<td>3.31</td>
<td>A3</td>
<td>Sandstone</td>
</tr>
<tr>
<td>13+420</td>
<td>0.77</td>
<td>3.53</td>
<td>A2</td>
<td>Sandstone</td>
</tr>
<tr>
<td>13+430</td>
<td>1.33</td>
<td>3.58</td>
<td>A2</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+440</td>
<td>1.64</td>
<td>4.18</td>
<td>A2</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+450</td>
<td>1.58</td>
<td>3.98</td>
<td>A2</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+460</td>
<td>1.14</td>
<td>4.33</td>
<td>A2</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+470</td>
<td>1.37</td>
<td>4.47</td>
<td>A2</td>
<td>Daibase Dayk</td>
</tr>
<tr>
<td>13+480</td>
<td>2.13</td>
<td>4.32</td>
<td>A2</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+490</td>
<td>2.21</td>
<td>4.67</td>
<td>A2</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+500</td>
<td>2.14</td>
<td>4.02</td>
<td>A2</td>
<td>Mudstone</td>
</tr>
<tr>
<td>13+510</td>
<td>1.99</td>
<td>4.93</td>
<td>A2</td>
<td>Mudstone</td>
</tr>
<tr>
<td>13+520</td>
<td>1.22</td>
<td>3.32</td>
<td>A3</td>
<td>Mudstone</td>
</tr>
<tr>
<td>13+530</td>
<td>1.51</td>
<td>2.67</td>
<td>A3</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+540</td>
<td>1.65</td>
<td>3.38</td>
<td>A3</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+550</td>
<td>1.65</td>
<td>2.46</td>
<td>A3</td>
<td>Daibase Dayk</td>
</tr>
<tr>
<td>13+560</td>
<td>1.53</td>
<td>2.53</td>
<td>A3</td>
<td>Daibase Dayk</td>
</tr>
<tr>
<td>13+570</td>
<td>1.98</td>
<td>3.77</td>
<td>A2</td>
<td>Sandstone-Mudstone</td>
</tr>
<tr>
<td>13+580</td>
<td>1.42</td>
<td>3.84</td>
<td>A3</td>
<td>Daibase Dayk</td>
</tr>
<tr>
<td>13+590</td>
<td>1.49</td>
<td>3.33</td>
<td>A3</td>
<td>Sandstone</td>
</tr>
<tr>
<td>13+600</td>
<td>1.42</td>
<td>2.18</td>
<td>A3</td>
<td>Sandstone</td>
</tr>
</tbody>
</table>
3.2.1. Volvo BM EL70 Excavation Machine

Volvo BM EL70 is a four-wheel drive excavator-loader with articulated frame steering in the 11 ton weight category. This machine is used for excavating the fault zones, weak formations and treatment of excavation by using the Montabert BRH 250 hydraulic rock breaker. The general view of a hydraulic breaker is given in Figure 3.10. The engine is four-cylinder, four-stroke, direct-injected, turbocharged diesel engine type Volvo BM TD 45B. The engine has a crankshaft carried in five main bearings and pistons made of light alloy. The cylinder capacity is 4.48 liters. The transmission is electro-hydraulic controlled and all gears are in constant mesh. Between the engine and transmission there is an hydraulic torque converter which steplessly controls the output torque. The front and rear axles have planetary hub gears which take the strain off the drive shafts. The rear axle is provided with a differential lock which increases the traversability of the machine. The front axle can be obtained with a differential lock. The machine is provided with a dual-circuit all-hydraulic brake system with one circuit for the front wheels and one for the rear wheels.

![A Montabert hydraulic breaker](image)

Figure 3.10. A Montabert hydraulic breaker
<table>
<thead>
<tr>
<th>Attachment, excavator unit</th>
<th>Unit</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Overall length</td>
<td>mm</td>
<td>8,100</td>
<td>8,000</td>
<td>8,100</td>
</tr>
<tr>
<td>(AA) Reach bucket tooth</td>
<td>mm</td>
<td>6,940</td>
<td>6,370</td>
<td>6,370 / 7,320</td>
</tr>
<tr>
<td>(AB) Digging depth bucket tooth</td>
<td>mm</td>
<td>5,180</td>
<td>4,630</td>
<td>4,630 / 5,640</td>
</tr>
<tr>
<td>(AC) Straight length</td>
<td>mm</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>(AD) Reach level bucket to the bucket tip</td>
<td>mm</td>
<td>2,500</td>
<td>2,130</td>
<td>2,145 / 3,105</td>
</tr>
<tr>
<td>(AE) Loading height level bucket</td>
<td>mm</td>
<td>4,320</td>
<td>3,860</td>
<td>3,830 / 4,170</td>
</tr>
<tr>
<td>(AF) Transporting height</td>
<td>mm</td>
<td>4,440</td>
<td>4,150</td>
<td>4,150</td>
</tr>
<tr>
<td>(AG) Approach angle excavator</td>
<td>°</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Max. bucket angle</td>
<td>°</td>
<td>185</td>
<td>185</td>
<td>185</td>
</tr>
<tr>
<td>Max. digging force</td>
<td>kN</td>
<td>39.3</td>
<td>41.3</td>
<td>41.3 / 30.6</td>
</tr>
<tr>
<td>Permissible lifting force in hook</td>
<td>kN</td>
<td>11.8</td>
<td>13.5</td>
<td>11.7 / 8.9</td>
</tr>
<tr>
<td>Max. lifting force in hook</td>
<td>kN</td>
<td>13.7</td>
<td>15.4</td>
<td>13.0 / 10.5</td>
</tr>
<tr>
<td>Slew angle</td>
<td>± °</td>
<td>180</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Lateral angulation</td>
<td>± °</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Breakout force at bucket lip</td>
<td>kN</td>
<td>61.0</td>
<td>61.0</td>
<td>61.0 / 61.0</td>
</tr>
<tr>
<td>Slewing moment</td>
<td>kNm</td>
<td>36.8</td>
<td>36.8</td>
<td>36.8</td>
</tr>
<tr>
<td>Bucket capacity</td>
<td>litre</td>
<td>430</td>
<td>430</td>
<td>320</td>
</tr>
</tbody>
</table>
Figure 3.11. Volvo BM excavation machine
(Machine dimensions are given on Table 3.4.)

The machine has the following specifications:

**Engine**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Specification Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designation, basic version</td>
<td>Volvo BM TD 45 B</td>
</tr>
<tr>
<td>Flywheel output max. SAE (J 1349), gross</td>
<td>84 kW (113 hp) at 33.3 r/s (2000 rpm)</td>
</tr>
<tr>
<td>Flywheel output max. DIN 70020</td>
<td>78 kW (105 hp) at 33.3 r/s (2000 rpm)</td>
</tr>
<tr>
<td>Torque max. SAE (J 1349), gross</td>
<td>440 Nm(44.8 kgf m) at 23.3 rpm(1400 rpm)</td>
</tr>
<tr>
<td>Torque max. DIN 70020</td>
<td>425 Nm(43.3 kgf m) at 23.3 rpm(1400 rpm)</td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>4</td>
</tr>
<tr>
<td>Cylinder bore</td>
<td>105.57 mm (4.156 in)</td>
</tr>
<tr>
<td>Stroke</td>
<td>128 mm (5/039 in)</td>
</tr>
<tr>
<td>Cylinder capacity</td>
<td>4.48 liter</td>
</tr>
</tbody>
</table>
Compression ratio
Compression pressure at 3.3 r/s (200 rpm)
Idling speed, low
high
Limited speed, (applies with tires 18.4x30/14)
Hand-throttle control, position 1
position 2
Valve arrangement
Valve clearance, warm and cold engine
inlet valve
exhaust valve
Air cleaner
Air cleaning in three stages cyclone cleaner-primary filter-secondary filter

Engine lubrication system
Oil pressure, warm engine
Fuel system
Injector opening pressure
Order of injection
Pump timing
Feed pressure
Cold starting device

Cooling system
Coolant normal temperature
Thermostat begins to open at
Power Transmission

Type
Make
Designation
Torque converter
Torque multiplication
Gear-shifting system

Hydraulic-mechanical
Volvo BM
HT 90
1-stage
2.3:1
Electro-hydraulic

Hydraulic system

Type
Oil pumps, type
Flow at 25 r/s (1500 rpm) and 22.5 Mpa
Hydraulic pump unloading pressure
Max. working pressure

Dual circuit, load-sensing “Closed center”
2 pcs. axial piston pumps with variable flow
2x64 liter/min (18.9 US gal/min)
22.5 Mpa (225bar) (3263 psi)
22.5 Mpa (225bar) (3263 psi)

3.2.2. Fiat-Hitachi FH 200 Excavator

Fiat-Hitachi FH 200 is a four-wheel drive excavator in the 20 ton weight category. The engine is six cylinder, direct-injected, turbocharged four-cycle diesel type. 90% of the major excavation has been done with this machine which was equipped by Montabert BRH625 hydraulic rock breaker.

The machine has the following specifications:

Engine

Type
(turbocharged, direct injection, 4-cycle diesel)
Number of cylinders
Bore
Stroke
Total displacement
Governed rpm

8065.25.080
6
104 mm
115 mm
5861 cu in
2000
Forced lubrication by gear pump

Water cooled

Auto-idling device, which automatically reduces the engine rpm about 4 seconds after implement controls are neutral

Hydraulic system

Fiat-Hitachi’s ETS (Electronic Total Control System) can achieve maximum job efficiency and reduce fuel consumption and noise.

The system includes:

- E-P Control (Computer Aided Engine-Pump Control System)
- OHS (Optimum Hydraulic System) assures fully independent and combined operations
- FBS (Fuel saving Pump System)
- Travel system with two speeds and high pressure for high traction force and high travel speeds

Main Pumps

Two variable displacement axial piston type

Maximum flow: 2x220 lt/min (2x48.2 lmp g.pm)

Pilot pump (gear type) max. flow: 33.6 lt/min (7.4 lmp g.pm)

Maximum relief valve pressures:
- boom/dipper stick and bucket: 285 bar
- swing system: 285 bar
- travel system: 325 bar
- pilot system: 40 bar

Figure 3.12: Monoblock dimensions of Fiat-Hitachi excavation machine
(Figures are given on Table 3.5.)
Hydraulic cylinders

The boom and dipper stick hydraulic cylinders are equipped with stroke-end cushion devices:
- boom (two) 125 x 1315 mm (4.92 x 51.80 in)
- dipper stick (one) 135 x 1630 mm (5.32 x 64.17 in)
- bucket (one) 120 x 1055 mm (4.72 x 41.50 in)
- position arm (one, triple articulation ver.) 150 x 1050 mm (5.90 x 41.34 in)

Transmission

<table>
<thead>
<tr>
<th>Type</th>
<th>hydrostatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motors</td>
<td>2 axial piston type, in-shoe mounted</td>
</tr>
<tr>
<td>Brakes</td>
<td>automatic disc type, spring applied, hydraulically released</td>
</tr>
<tr>
<td>Final drive</td>
<td>oil bath, planetary reduction</td>
</tr>
<tr>
<td>Max. gradeability (continuous)</td>
<td>35°C (70%)</td>
</tr>
<tr>
<td>Travel speed, high</td>
<td>0 to 4.4 km/h (2.7 mph)</td>
</tr>
<tr>
<td>Travel speed, low</td>
<td>0 to 3.5 km/h (2.2 mph)</td>
</tr>
</tbody>
</table>

Figure 3.12. Monoblock dimensions of Fiat-Hitachi excavation machine (Figures are given on Table 3.5.)
Table 3.5. Dimensional figures of Fiat-Hitachi excavation machine

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>D'</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>3210</td>
<td>4020</td>
<td>1060</td>
<td>2745</td>
<td>2760</td>
<td>9570</td>
<td>2860</td>
</tr>
<tr>
<td>3560①</td>
<td>4370①</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>G</th>
<th>H</th>
<th>I</th>
<th>L</th>
<th>M</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>2860</td>
<td>915</td>
<td>460</td>
<td>500</td>
<td>2500①</td>
</tr>
<tr>
<td>600</td>
<td>2600①</td>
<td>2800①</td>
<td>2990①</td>
<td>700</td>
<td>2700①</td>
</tr>
<tr>
<td>800</td>
<td>3000①</td>
<td>3190①</td>
<td></td>
<td>900</td>
<td>3100①</td>
</tr>
</tbody>
</table>

① Model FH200LC
② Model FH200
③ Model FH200E

3.2.3. Hydraulic Breakers

Operating Jack Hammers are equipped with Ingersoll Rand - Montabert hydraulic breakers. More technical data has given on the Appendix 3 regarding the Montabert hydraulic breakers. As it is usual, these breakers are selected due to the machine weight. The technical specifications of the hydraulic breakers, which has used on the Mecidiyeköy Tunnels, are given on Table 3.6. It is better to remained that BRH-250 has been operated with Volvo-BM and BRH-625 with Fiat-Hitachi excavation machines. The selection of the hydraulic breakers due to their weight and hydraulic liquid flow rate has also given on Figure 3.13.
Figure 3.13. Selection of Montabert hydraulic breakers due to the machine weight (ton) and hydraulic liquid flow rate (L/min)
Table 3.6. Technical specifications of the Experimental - Tunnel excavation hydraulic breakers

<table>
<thead>
<tr>
<th>TECHNICAL MAIN DATA</th>
<th>BRH 250</th>
<th>BRH 625</th>
</tr>
</thead>
<tbody>
<tr>
<td>App. weight in working order (kg)</td>
<td>650</td>
<td>1030</td>
</tr>
<tr>
<td>Height with standard moi point (mm)</td>
<td>1700</td>
<td>2010</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>480</td>
<td>496</td>
</tr>
<tr>
<td>Oil supply required (lt/mn)</td>
<td>36/90</td>
<td>80/130</td>
</tr>
<tr>
<td>Striking rate proportional to supply (c/mn-b/mn)</td>
<td>230/600</td>
<td>400/860</td>
</tr>
<tr>
<td>Adjusted pressure on breaker (bar)</td>
<td>100</td>
<td>115</td>
</tr>
<tr>
<td>Min. Press. at excavator pressure relief valve (bar)</td>
<td>140</td>
<td>210</td>
</tr>
<tr>
<td>Shock absorber on hydraulic circuit</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Automatic stop</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Diameter of HP hose - inner (mm)</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Diameter of LP hose - inner (mm)</td>
<td>25</td>
<td>30</td>
</tr>
</tbody>
</table>
CHAPTER IV.

PUNCH PENETRATION EXPERIMENTS AND CORRELATION WITH OTHER ROCK PROPERTIES AND TUNNEL ADVANCE RATES

4.1. Punch Penetration Tests and Results

As it was mentioned on pervious chapters, punch penetration tests were carried out in two groups due to the characteristics of the test samples. In the first group, the first five samples were tested with 0,5 kN/sec loading rate with automatic testing machine. The scales that were applied to the LVDT and the load cell were 1/25 and 1/1 properly. By another words, each milimeter of displacement of the bit was equal to 25 mm in horizontal scale, 1 kN of loading was equal to 1 mm in vertical scale on X-Y recorder sheet. However, due to the big scale of these five tests the chipping formation could not be seen in detail on X-Y recorder sheet.

Consequently, next 10 punch penetration tests have been done with 0,25 kN/sec loading rate, 1/25 LVDT and 1/2 load cell recording rate scale. With these calibrations and also the manual arrangements on the X-Y recorder signal tunings, it is achieved to observe chipping records on the X-Y recorder sheet effectively.

During punch penetration tests of Trakya Formation, one sample divided into two pieces. The first one was loaded to parallel to bedding planes (Test 8) and the second perpendicular bedding planes (Test 9). As the result of these tests Punch indexes ($\alpha$) values were recorded 7,64 kN/mm and 3,2 kN/mm respectively. This observational result brings out the importance of the major effect of excavation angle to the bedding planes.
With another words, the same formation, at the same conditions, could only be excavated by minimum double unit force of the excavation machine with the change of the planes from vertical to the parallel to the excavation direction.

Different from the first nine tests, last six punch penetration tests were done with confining pressure in order to be more realistic to the in-situ conditions. Artificial environmental pressure has been obtained by steel moulds fulfilled with white cement.

All the results obtained from the punch penetration tests are given the figures 4.1. to 4.14. on the following pages.

### 4.2. Schmidt Hammer Tests and Results

The strength of the first nine samples were tested with Schmidt Hammer. Schmidt values which have been obtained from these tests are given with the Figures 4.15. to 4.22. These values were evaluated together with the first nine punch penetration $\alpha$ (kN/mm) test results. The linear relationship was found out between the rock strength and the punch penetration index ($\alpha$) according to the type (hardness) of the samples examined. This relationship has given in the figure 4.23.

As it could be observed from the figure a direct relationship existing between the hardness of the formation and excavation rate. By another words, excavation rate dramatically decreases with the increasing of the rock hardness.

### 4.3. Determining Punch Penetration Test Conditions

According to the experimental observations and the test results the following test conditions could be realised during the Punch Penetration experiments.

- The loading rate of the testing machine should be not greater than 0,25 kN/sec. The author strongly believes that overpassing this loading rate brings
Figure 4.1. The relationship between bit loading rate and depth of penetration (Test - 1)

Formation: Anhydrite
Loading Rate: 0.50 kN/sec
α = 6.11 kN/mm
Schmidt Value = 33
Figure 4.2. The relationship between bit loading rate and depth of penetration (Test - 2)
Figure 4.3. The relationship between bit loading rate and depth of penetration (Test - 3)
Figure 4.4. The relationship between bit loading rate and depth of penetration (Test - 4 & 5)

Formation: Trakya Formation
Loading Rate: 0.25 kN/ sec
\(\alpha = 12.78\) kN/ mm
Schmidt Value = 45
Figure 4.5. The relationship between bit loading rate and depth of penetration (Test - 6)
Figure 4.7. The relationship between bit loading rate and depth of penetration (Test - 8)
Figure 4.8. The relationship between bit loading rate and depth of penetration (Test - 9)
Formation: Sandstone
(From Istanbul Metro KS.01.8, Investigation Drill)
Loading Rate: 0.25 kN/sec
\[ \alpha = 9.11 \text{ kN/mm} \]
Figure 4.10. The relationship between bit loading rate and depth of penetration (Test-11)
Formation: Laminated Mudstone
(From Istanbul Metro Mecidiyeköy Shaft Construction)
Loading Rate: \(0.25 \text{ kN/sec}\)
\(\alpha = 3.12 \text{ kN/mm}\)

Figure 4.11. The relationship between bit loading rate and depth of penetration (Test -12)
Formation: Laminated Mudstone
(Istanbul Subway Mecidiyeköy Shaft Construction)
Loading Rate: 0.25 kN/sec
\[ \alpha = 4.5 \text{ kN/mm} \]

Figure 4.13. The relationship between bit loading rate and depth of penetration (Test -14)
Figure 4.14. The relationship between bit loading rate and depth of penetration (Test -15)
Figure 4.17. Schmidt Hammer Test Results (Test - 3)
Figure 4.19. Schmidt Hammer Test Results (Test - 6)
Figure 4.22. Schmidt Hammer Test Results (Test - 9)

Schmidt Hammer Value

Number of Tests

44. Pile Load Tests and Results

For determining a relationship with laboratory studies and inserted Metro Piles, in the side applications, 6 samples (3 from investigation drills and 3 from Metro Piles) were tested with a load index test. The measured pile head and pile tip capacity strength values from these samples are given in the Table 4.4 together. These values are evaluated together with the tunnel axis. Formation: Trakya (Parallel bedding planes to excavation)

S. Value: 34
impossibility to the observation of chip failure on the XY/t recorder sheet.

- The scale applied for the LVDT and the load cell should be 1/25 and 1/2 respectively. This means that every 1 mm LVDT displacement is going to be recorded as 25 mm on the XY/t recorder sheet. Meanwhile, every 1kN of loading should be recorded as 2 mm displacement.

- The penetration index values may be more realistic if the samples are tested in white cement or similar protector fulfilled steel molds. This protector will keep the sample as it is in the natural environment, thus the sample behaves as it is on the field.

- It is also very important to take care about the XY/t recorder manual tuning arrangements. In this understanding, the researcher has to calibrate the paper ‘A3’ scale by several tests.

- The XY/t recorder does not carry a scale note or any other records. So that, it is strictly recommended that the calibrations of each test have to be noted by the researcher.

4.4. Point Load Tests and Results

For determining a realtionship with laboratory studies and İstanbul Metro Project side applications, 6 samples (3 from investigation drills and 3 from Mecidiye köy shaft) were tested with point load index test. The measured and calculated point load index and uniaxial compressive strength values from these samples are given on the Table 4.1. together. These values are evaluated together with the tunnel advance rate and overbreak records.
The linear relationship was found between the punch advancement rate and variable resistant strength. This relationship is given on the Figure 4.23.

Figure 4.23: Punch Penetration Index versus Schmidt Value

- Gypsum
- Trakya Formation
- Anhydrite
- Trakya Formation

\[ R^2 = 0.7774 \]
The linear relationship was found between the tunnel advance rate and uniaxial compressive strength. This relationship is given on the Figure 4.24.

Another relationship was found between the tunnel advance rate and overbreak quantity. This linear relationship is given on the Figure 2.25.

Table 4.1. Measured and calculated sample figures obtained from Istanbul Metro Construction.

<table>
<thead>
<tr>
<th>Sample Location</th>
<th>Average Ex. Rate (m/day)</th>
<th>Overbreak (m$^3$)</th>
<th>Point Load Index Value</th>
<th>U. Compressive Strength (kg/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KS.01.08</td>
<td>1.24</td>
<td>4.80</td>
<td>26.25</td>
<td>630.00</td>
</tr>
<tr>
<td>KS.01.08</td>
<td>1.24</td>
<td>4.80</td>
<td>27.28</td>
<td>654.70</td>
</tr>
<tr>
<td>Shaft (Line 1)</td>
<td>1.20</td>
<td>3.80</td>
<td>28.60</td>
<td>673.40</td>
</tr>
<tr>
<td>Shaft (Line 1)</td>
<td>1.20</td>
<td>3.80</td>
<td>28.22</td>
<td>677.30</td>
</tr>
<tr>
<td>KS.01.01</td>
<td>1.00</td>
<td>2.75</td>
<td>38.87</td>
<td>932.60</td>
</tr>
<tr>
<td>Shaft (Line 2)</td>
<td>0.80</td>
<td>0.62</td>
<td>42.50</td>
<td>1.020.00</td>
</tr>
</tbody>
</table>
Figure 4.24. Relationship between tunnel advance rate and uniaxial compressive strength.
Figure 2.25: Relationship between tunnel advance rate and overbreak quantity

The linear relationship is given by the equation:

\[ R^2 = 0.9565 \]

![Graph showing the relationship between overbreak and average excavation rate](image)
CHAPTER V.

CONCLUSION

In this study, several sets of experiments were carried out at Istanbul Technical University - Mining Engineering Department, Rock Mechanics and Excavation Laboratories in order to apply the Punch Penetration Test results to rock cutability determination. These tests were later correlated with the Istanbul Metro Excavation tunnel advance rates.

First of all, the optimum test conditions for Punch Penetration Test were to be clarified. For this reason, the gypsum and anhydrite samples already existed in the laboratories were tested together with the Trakya Formation samples which have been obtained from Istanbul Metro tunnels. The tests were realised by forcing a spherical indenter into rock samples using a hydraulic press. The indentation depth and the force were recorded using a load cell and a displacement graph which the slope is later named as Punch Penetration Index ($\alpha$)

During the tests mentioned above, the optimum conditions for the Punch Penetration test were tried to be determined. These were done by changing the calibration constants of the tests apparatus and observing the results and test conditions. The calibration constants of the test apparatus in order to achieve effective chip formation were as follows:

- Loading Rate : 0.25 kN/sec
- LVDT Scale : 1/25
- Load Cell Scale : 1/2

According to the achieved experience, the test results were also much more effected
if the samples had been tested surrounded with cement filled in a steel mould. This brings a kind of confining pressure to the test which the samples act like that they are at their origin.

It is also worth mentioned that the best results were obtained with the samples casted in cement within steel tubes, otherwise the samples splitted prior getting satisfactory results.

According to the test results, punch Penetration Index value ($\alpha$) of the tested rocks were found to be between 2.66 kN / mm to 12.78 kN / mm, Schmidt Hammer Values between 12 to 45, Point load index values between 26.25 to 42.50 and finally, uniaxial compressive strength between 630 to 1020 kg/cm$^2$.

If all these test results are evaluated together with the data obtained from Istanbul Metro tunnel advance rates and over brake quantities, it may be concluded that Punch Penetration Index value ($\alpha$) is directly related to the Schmidt Hammer Value, uniaxial compressive strength and finally the advance tunnel excavation rates.

As a result, it may be concluded that Punch Penetration index is directly related to rock cuttability.


REFERENCES


