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The performance prediction of impact hammers from Schmidt hammer rebound values in Istanbul metro tunnel drivages

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Abstract

The construction of the first metro line in Istanbul was realized between Galata and Beyoglu by a French Engineer Henry Gavand in January 1875. Six different metro projects were submitted since then to the Turkish authorities. The construction of 7-km metro tunnels phase 1 started in 1992 and the metro line of the phase 1 is opened to the service in 2000. The tunnels of the phase 2 between Taksim and Yenikapi are under construction. This paper summarizes the construction methods of the Istanbul metro tunnels, the performance of the impact hammers, the factors effecting daily advance rates and the previous studies on Schmidt hammer test and performance prediction of impact hammers. At the end, a prediction model concerning instantaneous breaking rates of hydraulic impact hammers from Schmidt hammer rebound values is explained in detail.

Keywords: Performance prediction; Impact hammers; Schmidt hammer tests; Rock quality designation; Istanbul metro tunnels

1. Introduction

Hydraulic impact hammers have been used widely in mining industry and civil engineering applications since 1960 (Rodford, 1974, p. 57; Pelizza et al., 1994, p. 618). Almost 11 km of metro tunnels were driven in Istanbul with impact hammers, since the initial capital investment was relatively lower and rock formation were highly fractured in some zones, RQD values ranging from 0 to 100. The impact hammers may be mounted in any type of excavator and operated easily. However, a contractor is always interested in predicting the machine performance prior to starting a tunnel project that will definitely define the tunnel drivage economy. A research team of several research staff and students has collected data in Istanbul metro tunnels from 1994 to present days. A detailed work-study was realized and analyzed to make some recommendations to increase tunneling efficiency. Discontinuities were measured in the face, Schmidt hammer tests were realized, and rock samples from the tunnel face were collected and subjected to a broad range of physical and mechanical tests in the Laboratories of Istanbul Technical University, Mining Engineering Department. Net breaking rates of the impact hammers were measured in the tunnel face and the time spent for each tunneling operations were recorded carefully, i.e. time to spend for rock breaking, mucking, bolting, shotcreting, supporting etc. At the end, a prediction model to predict the performance of impact hammers from rock mass properties and Schmidt hammer rebound values was developed and some recommendations were made to improve the tunneling work efficiency.

2. Istanbul metro project

The construction of the first metro line in Istanbul was realized between Galata and Beyoglu by a French Engineer Henry Gavand in January 1875. Six different metro projects were submitted since then to the Turkish authorities and the final project planned by Istanbul Rail-Tunnel Consultants (Parsons Brinckerhoff, Kaiser Engineers etc.) in 1988 became the basis of the current undergoing metro project (Yalcin, 1994).

In 1992 Istanbul City Council appointed Yüksel Proje and IGT (Salzburg) to undertake the tendering, execu-

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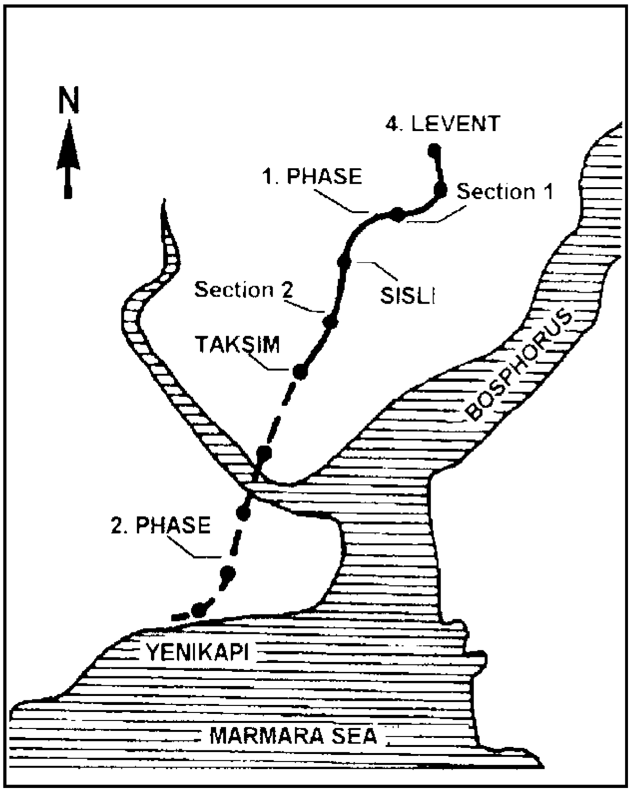

Fig. 1. Main route of Istanbul metro.

tive planning and supervision of the initial construction of 7 km long metro line phase 1. The tendering documents were completed in June 1992 and the contractors Tekfen–Garanti, Koza, Enka, Doğuş were awarded the construction of the first and second section of phase 1. The lines of the first phase were opened to the public in 2000 and the tunnels of the phase 2 are under construction by Anadolu Metro Ortakligi (Yüksel–Guris–Reha–Basyazicioglu). The route of metro line phases 1 and 2 are shown in Fig. 1.

The dimensions of the main underground structures of Istanbul metro are given in Table 1 (Ayaydin 1994, p. 113) and typical cross section of a single-track tunnel is seen in Fig. 2.

2.1. The geology

Trakya formation of the Carboniferous age is found in the area consisting of fine-grained, laminated fractured and interbedded siltstone, sandstone and mudstone. The RQD values of Trakya formation mainly range from 0 to 75%. Some diabase or andesite dykes have also been encountered while driving the tunnels and these affected progress rates, as they are significantly stronger and more massive (with RQD of approximately 100%) than rock excavated along the major part of the route.

Many faults and geologic discontinuities are developed in the area due to Hercinian and Alpine Orogenies. Rock Quality Designation (RQD) values varies between 0 and 100% and uniaxial compressive strength between 30 and 150 MPa.

2.2. Method of construction

New Austrian Tunneling Method (NATM) has been used since the tunnel diameter and ground structure vary frequently along the route. Three to four meters long rock bolts, wire mesh and shotcrete were used as temporary tunnel support. Depending on tunnel diameters the final lining is undertaken with 35–45 cm thick in-situ cast concrete. Typical cross section of a single-track tunnel, type A is given in Fig. 2.

Single-track tunnel type A has a cross section of 36 m^2 and excavated in two steps. The method of construction is explained in Fig. 3 (Sahin, 1995, p. 15). As seen in Fig. 3, the upper bench of 28 m^2 is excavated first and the lower bench of 8 m^2 is excavated later, which is 30 m behind of the first bench. The overall performance of the tunnel drivage in Phases 1 and 2 are summarized in Figs. 4 and 5. As seen from these figures, the utilization of impact hammers in average is 22 and 17% of the total time is spent on mucking. Shotcrete

Table 1
Characteristics of Istanbul metro tunnels (Ayaydin, 1994)

	Excavation area (m^2)	Length (m)
Single track tunnels (type A)	36	11364
Platform tunnels (type P)	64	1366
Connection tunnels-stations (type B1)	42	418
Cross passage tunnels (type B2)	22	413
Inclined shafts escalators (type B3)	44	348
Turnout tunnels (type T)	100	631
Pedestrian tunnels (type P)	64	350
Bored tunnel total length:		14890
Three access tunnels (approx. 30 m^2) with total length of 400 m and two approach shafts (approx. 80 m^2), each 25-m deep, were also provided for.		
Single track	25	206
Double track	55	248

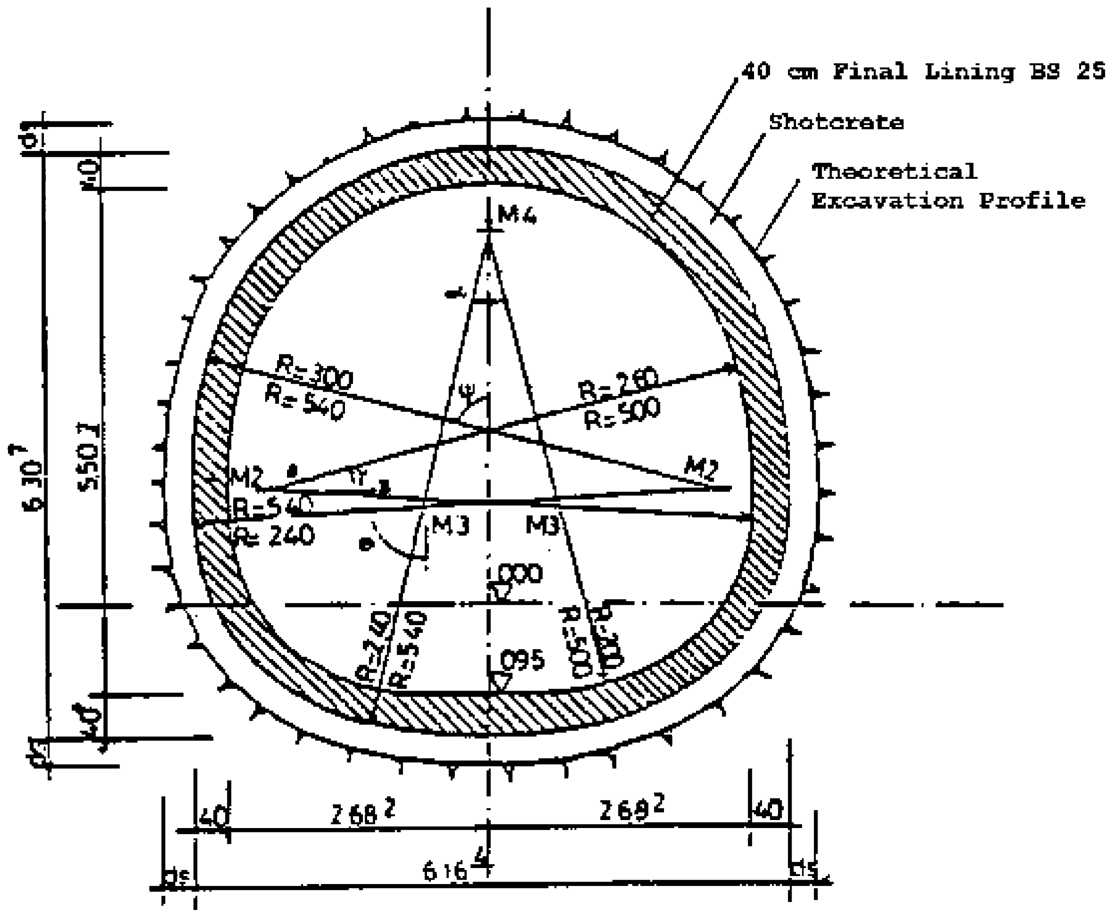

Fig. 2. Typical cross section of single-track tunnel, type A, (Yalcin, 1994).

takes almost 27% of the total time. Machine breakdowns and workers' travel time to reach the face are classified as waiting and takes approximately 6–7%. The rock formation in phase 2 was more fractured than in phase 1, which necessitated forepoling operations in phase 2. The time spent for mucking was substantially different in phases 1 and 2 due to the difference in muck transportation system used. Figs. 6 and 7 give typical values of daily advance rates in Galatasaray–Taksim tunnels lines 1 and 2 (Selimoglu, 2001, p. 79–80). Since the spacing between steel arches was 1 m, the daily advance rates were kept as the multiplier of 1 m provided that the last set of steel arch was set up in the final shift of the day. Daily advance rates change usually between 2 and 3 m.

Alpine ATM 75 transverse type roadheader having a cutting power of 200 kW was used in Taksim platform tunnel 2. Eickhoff ET 250 transverse type roadheader having a cutting power of 250 kW was used in Taksim platform tunnel 1. Platform tunnels have a length of 238 m and cross section of 64 m^2. Krupp HM 185 720 and Montabert BRH 250 jack hammers attached to hydraulic excavators were used in Taksim–Levent line 2 tunnels (Bilgin, et al. 1997, p. 716).

3. The use of impact hammers in tunnel drivage

It is a well-known fact that mechanical impact offers several advantages over other continuous methods of excavation. These advantages are enhanced when the impact energy is increased to very high levels. The working principle of a modern hydraulic hammer is simple. There is a piston moving up and down and striking against the tool end. To produce big energy pulses during downward strokes, the hammer is equipped with an accumulator that is able to supply needed oil volume in a very short time. The accumulator is charged continuously by a hydraulic pump. Different research works demonstrated that specific energy defined as the energy to break the unit volume of the rock is inversely proportional to below energy (Wayment and Grantmyre, 1976, p. 613). Since then continuous works have been done to increase piston speed and piston weight to have higher blow energy values.

Hydraulic impact hammers may be mounted on very many different types of excavators and are thus also connected into many different hydraulic systems. It is very important for safe and efficient operations to match the size of the carrier/excavator to the weight and the

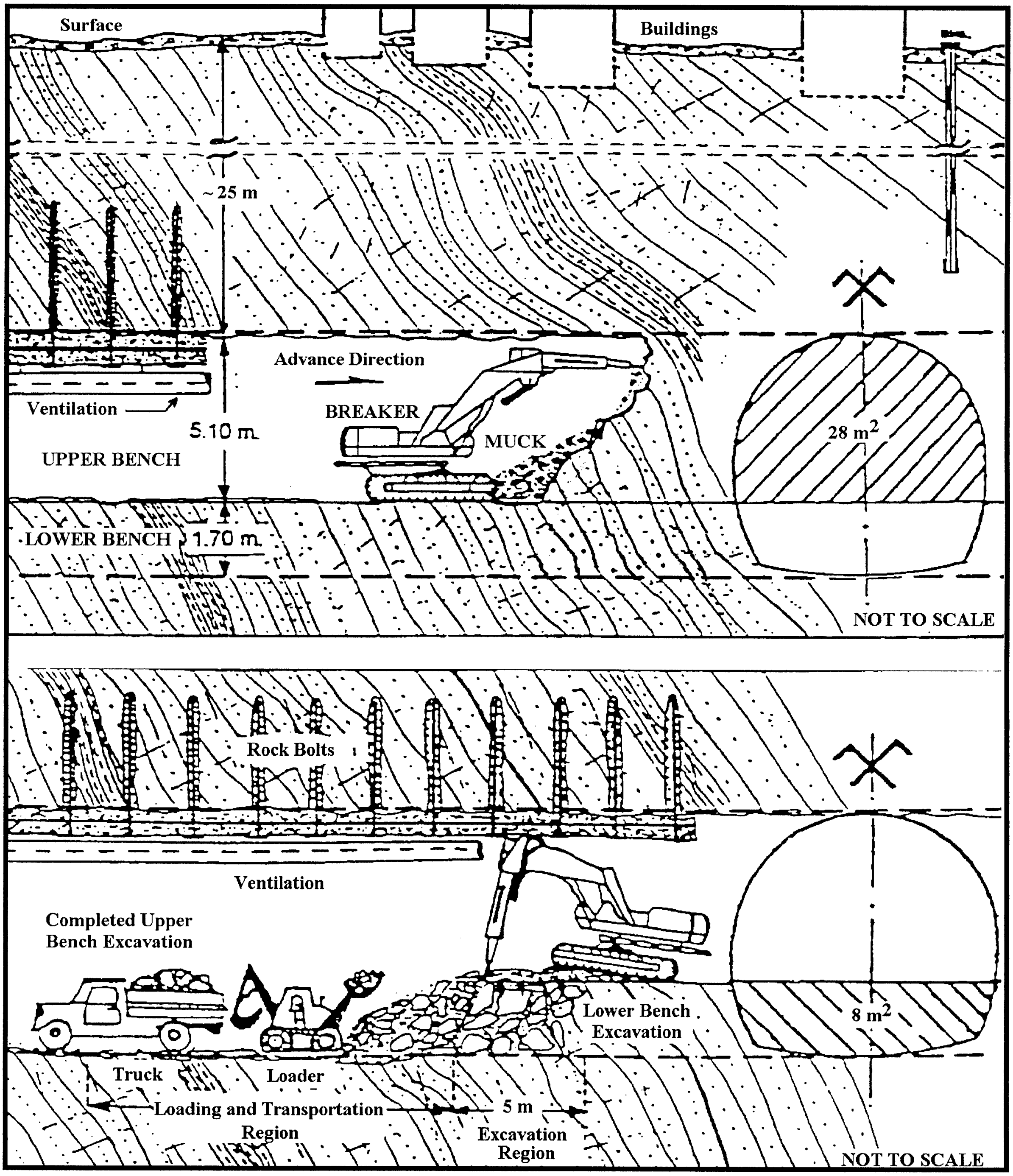

Fig. 3. Method of construction in Istanbul metro tunnels, (Sahin, 1995).

power of the hammer. The excavator/carrier is a more costly unit than the breaker and that is why the manufacturers of the hydraulic hammers build the hammers that have high blow energies relative to their weights (Wyllie, 1985).

The first comprehensive work on the theoretical performance prediction of the hydraulic hammers was done by Evans (1974) pointing out that the susceptibility of the rock to impact breakage was a function of not only the compressive strength but of tensile strength also. Compressive strength alone was found to be a misleading criterion. Formulae were given for calculating the size required for breaking a piece of rock.

Hughes reported that compared with pneumatic hammers, hydraulic jackhammers had a relatively heavier hammer, working at a relatively slower speed. Pneumatic hammers were the noisiest equipment in the mine, approximately 80% of the noise deriving from its

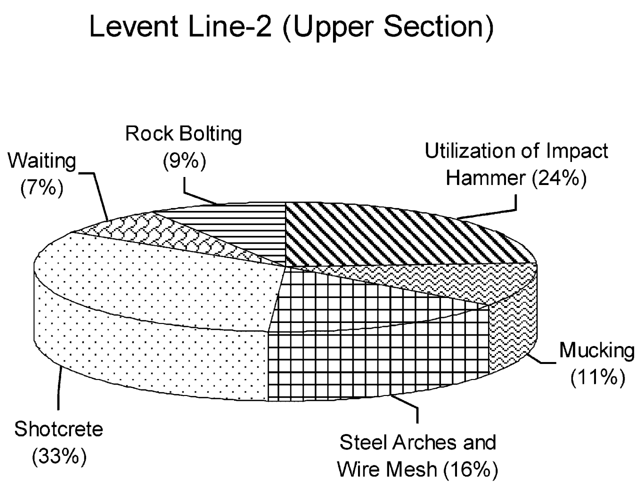

Fig. 4. Overall performance of tunnel drivages in metro tunnels phase 1.

exhaust, hydraulic hammers had no exhaust and were less noisy (Hughes, 1974, p. 85)

Hydraulic impact hammers can be used in several phases of mining as in breaking of oversized boulders in quarries and open pit mines, trenching when the ground is too hard to be removed with an excavator. Driving tunnels or roadways in fractured zones is also very frequent and goes back to the 1970s in European Coal Mines. It was reported that there were thirteen hydraulic impact hammers working in the UK in roadway drivage in 1973 (Rodford, 1974) and several were in technological development stage (Gaskell and Phillips, 1974; Levetus and Cagnioncle, 1974). Since then, the use of hydraulic impact hammers has gained worldwide acceptance both in mining and civil engineering applications. The technical processes made available today are very highly powered machines (up to 150 kW for hammers weighing more than 78 tons) with impact energy values up to more than 12 kJ/blow, (Pelizza et al., 1994). Pelizza reported that hydraulic hammers were widely used in Italy in the construction industry mainly due to the quite stringe Italian regulations on the use and transportation of explosives. The main reason supporting the selection of hydraulic impact hammers in Italian tunneling operations were cited as: the tunnels were usually driven in quite altered and geologically disturbed zones and rock geomechanical characteristics could remarkably vary along the tunnel axis, and tunnel boring machines and roadheaders might have discontinuous and uneconomical performance.

4. Previous work on performance prediction of impact hammers

Tunneling performance data collected by many research students, during seven years of in-situ site investigations in Istanbul metro were analyzed statistically and a model to predict the net breaking rate in m^3/h was developed. The performance of roadheaders and jackhammers were compared and discussed in World Tunnel Congress 1997, Vienna, by Bilgin et al. In that study, detailed in-situ studies and accumulated data led to a statistical model for the prediction of instantaneous or net breaking rate of the hydraulic impact hammers and the following prediction equation was driven.

$$IBR = 4.24\ P\ (RMCI)^{-0.567} \tag{1}$$

$$RMCI = \sigma_c\ (RQD/100)^{2/3} \tag{2}$$

Where, IBR = Instantaneous or net breaking rate, m^3/h.

P = Cutting power of the hydraulic hammer, HP.

RMCI = Rock mass cuttability index, MPa.

σ_c = Uniaxial compressive strength, MPa.

RQD = Rock quality designation,%.

Fig. 8 represents typical relationship between net breaking rate and rock compressive strength for a given RQD value and power of the jack hammers.

5. Previous works on Schmidt hammer

The Schmidt hammer is a portable, cost effective instrument capable of estimating the rock properties with several advantages over traditional rock testing methods. It was developed in Switzerland in 1948 by Ernest Schmidt for estimating the in situ strength of concrete. Since then, a lot of research work has been carried out using the Schmidt Hammer to estimate the intact and rock mass properties, to characterize mine roof stability, to estimate the performance of roadheaders etc. The mechanism of operation is simple, a plunger released by a spring impacts against the rock surface and then the rebound distance of the plunger is read directly from the numerical scale ranging from 10 to 100. Schmidt hammers are available in several different

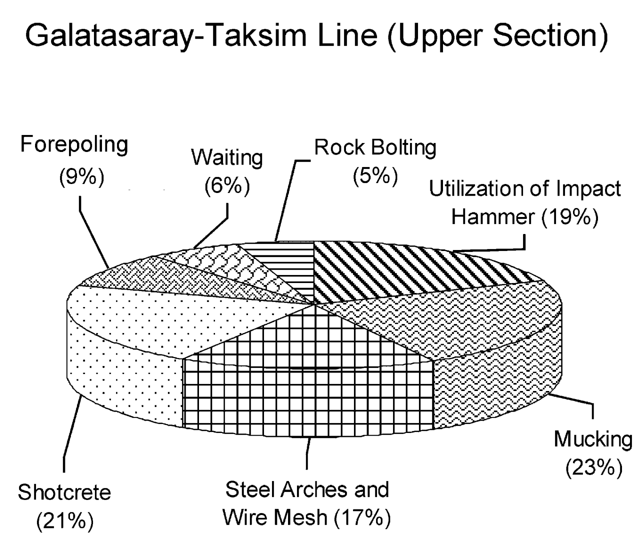

Fig. 5. Overall performance of tunnel drivages in metro tunnels phase 2.

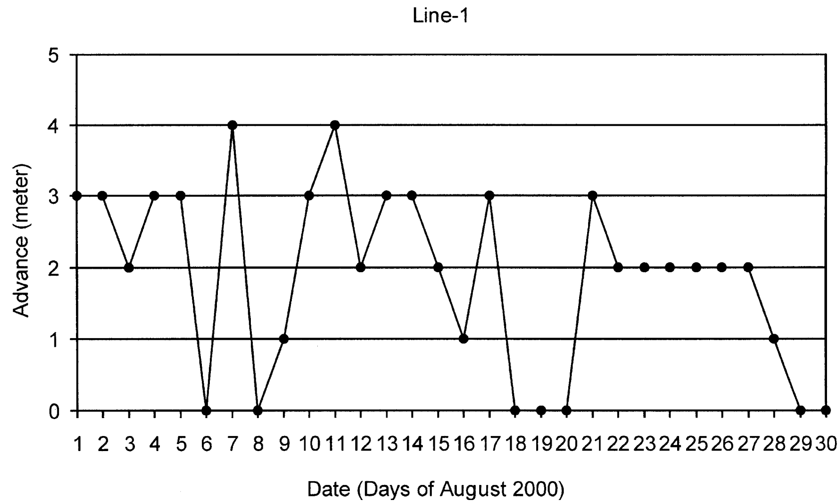

Fig. 6. Tunneling advance (m) in August 2000 in line 1, (Selimoglu, 2001).

energy ranges, which include types L, N, M having 0.735, 2.207 and 29.43 Nm impact energies, respectively (Atkinson, 1993, p. 107).

The early comprehensive studies with Schmidt hammers were carried out by Hucka (1965), Deer and Miller (1966). They found out that the rock compressive strength might be predicted from rebound values with a reliable accuracy. Hucka recommended that 10 impacts had to be carried out at each point and the peak values had to be recorded. Deer and Miller concluded that the relation between compressive strength and rebound number might be improved by multiplying the rebound number by the rock density. N type Schmidt hammer test results and the quantitative description of roof conditions from 73 longwall faces in 11 coal mines in upper Silesia were analyzed by Kidybinski (1968). He pointed out that there was close relationship between the rebound values and roof quality. The method proposed appears useful, especially when new longwall faces in the mines are recommended and a suitable system of their support is being considered.

Young and Fowell monitored the performance of Dosco MK II A roadheader during the extension of the Four Fathom Mudstone heading in the UK and they pointed out that in fractured rock formations the primary influence on the performance of the machines were rock discontinuities characteristics rather than the intact material properties and the Schmidt hammer rebound value was a good indicator of rock discontinuity (Young and Fowell, 1978). Similar results were observed by Poole and Farmer (1980). Schmidt hammer values in selected geological zones gave the best correlation with roadheader net advance rates. It is important to note that different investigators used different types of Schmidt hammers, L or N type hammers given different rebound values in the same rock due to the different impact

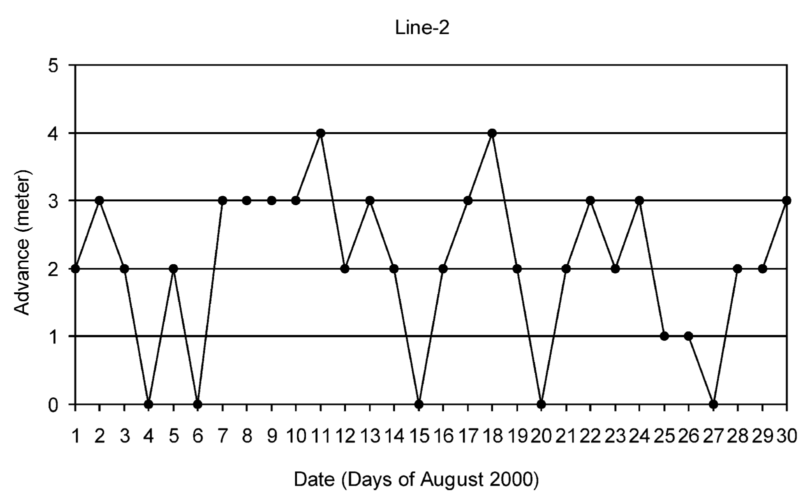

Fig. 7. Tunneling advance (m) in August 2000 in line 2, (Selimoglu, 2001).

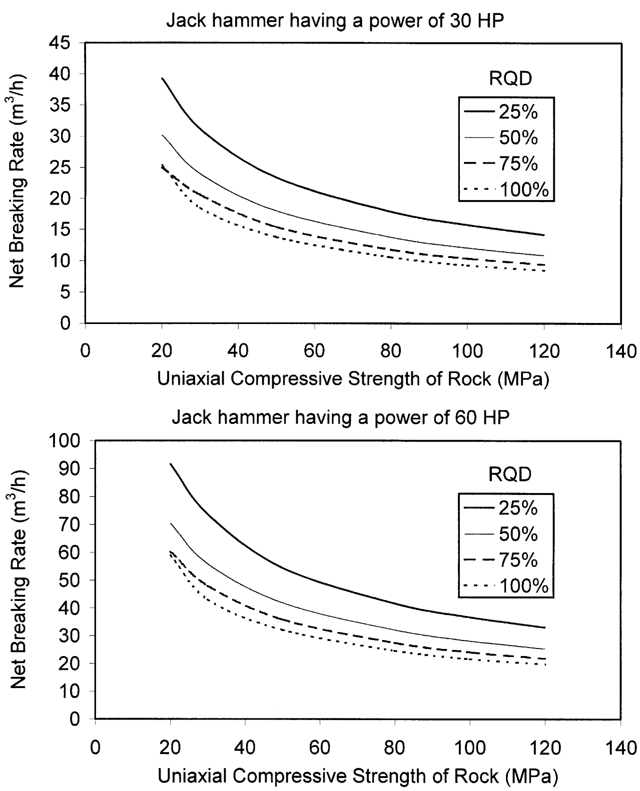

Fig. 8. The statistical relationship between rock compressive strength and instantaneous breaking rate of jackhammers for a given RQD and power of the hammer.

energy levels. One who wants to compare the results of different investigators should know the correlation between rebound values of N and L-type Schmidt hammers.

The most comprehensive work on the comparison between L and N type Schmidt hammer rebound values obtained during field-testing was carried out by Ayday and Goktan (1992). They used the following different test procedures recommended by different investigators (Poole and Farmer, 1980; Hucka, 1965; Brown, 1981):

Test procedure 1—Taking the peak rebound value from five continuous impacts at a point and averaging the peaks of the three sets of tests conducted at three separate points.

Test procedure 2—Taking the peak rebound value from ten continuous impacts at a point and averaging the peaks of the three sets of test conducted at three separate points.

Test Procedure 3—Recording twenty rebound values from single impacts separated by at least a plunger diameter and averaging the upper ten values.

They found RN/RL ratios to be 1.30:1.34:1.47, respectively, where RN and RL are rebound values for N and L type Schmidt hammers, respectively. As seen from these numbers, regardless to the test procedure, the ratio of rebound value of N-type hammer to rebound value of L-type hammer varies between 1.30 and 1.47.

Haramy and DeMarco (1985), Arioğlu and Tokgoz (1991), Vandergrift et al. (1995) analyzed the results of different authors and concluded that the wide range of tests resulted in some uncertainties associated with different rock texture, variable rock lithologies, test environment and test methods. They suggested that the prediction equations could be better improved if the test results were grouped according to rock lithology and rock texture. The importance of these findings is reflected in the results obtained by Sachpazis (1990). He found out that there was a possibility of estimating both compressive strength and tangent Young Modules from rebound numbers with a good certainty in some carbonate rocks.

The work of Janach and Merminod (1982) differed from the others in a way that they used M-type modified Schmidt hammers to test rock abrasivity. For this purpose, the flat front piece was replaced by a disc shape roller having a diameter of 11 mm and hardness of 62HRC. The abrasivity test consisted of conducting between 20 and 50 separate impacts on rock surface measuring the total weight loss of the tool. They concluded that this method allowed to estimate the tool consumption of mechanical cutting machines

6. Predicting the instantaneous breaking rate of hydraulic hammers from in-situ Schmidt hammer values

A model to predict the instantaneous breaking rate of hydraulic impact hammers from rock compressive

Table 2
The characteristics of hydraulic hammers used in Istanbul metro tunnels

Characteristics	Montabert BRH 250	Montabert BRH 625
Weight of the hammer (kg)	650	1030
Length (m)	1.7	2.01
Width (m)	0.48	0.49
Hydraulic oil delivered (l/min)	90/130	80/130
Impact frequency (impact/min)	490/600	400/860
Oil pressure (kg/cm^2)	75	115
Power (kW)	29	44

strength and RQD values was developed before and published elsewhere (Bilgin et al., 1996, 1997). However, it was also mentioned above that Schmidt hammer rebound values were a good indicator of rock compressive strength and rock geological discontinuities (Young and Fowell, 1978). This focused the authors of this paper to design a research program to find the possibilities of using Schmidt rebound values to predict the breaking performance of hydraulic hammers.

Lines 1 and 2 Levent, and line 1 Taksim of Istanbul metro were chosen as pilot tunnels and were subjected to a broad range of research investigations (Dincer, 1999). At the first stage of the research, the tunnel was first divided to a grid system of 40 cm intervals and three sets of N type Schmidt hammer readings (RN1, RN2 and RN3) were realized at the intersection of each grid line. In the first set of Schmidt hammer tests, the method proposed by Poole and Farmer was used by selecting the peak rebound value from five continuous impacts at a point and averaging the peaks of the three sets of tests conducted at three separated points (RN1 values). In the second set of tests, the method proposed by Hucka was used selecting the peak rebound value from ten continuous impacts at a point and averaging the peaks of the three sets conducted at three separated points (RN2 values). In the final set of the tests, the method proposed by Fowell and McFeat Smith (1976) was used selecting the mean of the last five values from ten continuous impacts at a point and averaging the results at three separated points (RN3 values).

In the second stage of the research program, volumetric joint count (Jv) was realized by summing the number of joints per meter and RQD values were calculated using the relationship between Jv and RQD described by Brown (1981).

In the third stage, the instantaneous breaking rate in m^3/h of impact hammer BRH 625, mounted on the excavator Fiat Hitachi FH type 200 E, were recorded for each experimental tunnel face. Instantaneous breaking rate is defined as the net breaking rate of the hammer excluding all wanted and unwanted machine stoppages. Hydraulic hammer Montabert BRH type 250 was used for trimming the tunnel face edges. The characteristics of both hammers are presented in Table 2. All the measured values are summarized in Table 3.

As seen from Table 3, there is not a significant difference between standard deviations of the Schmidt hammer results in three different test procedures. However, due to the face conditions, i.e. nature of the fillings in the joints, the moisture content etc., the standard deviation is high in some cases.

Schmidt hammer rebound values (RN1, RN2 and RN3) obtained with different test procedures are compared in Fig. 9. The ratios of RN1/RN2, RN1/RN3

Table 3
RQD, Schmidt hammer rebound values and net breaking rate of impact hammer in different tunnel faces

Tunnel chainage (m)	Schmidt hammer, mean values of the face: RN1 ± S.D.[a]	RN2 ± S.D.	RN3 ± S.D.	RQD	Net breaking rate (m^3/h)
Istanbul metro line 1-Levent					
15+636	41±4	44±3	40±3	66	32.00
15+661	58±5	61±4	57±4	52	22.85
15+663	41±3	42±4	40±3	59	30.00
15+670	48±2	–	–	60	18.20
15+691	51±1	50±1	50±1	40	17.70
15+762	41±1	45±1	41±1	37	22.85
15+769	47±4	49±3	45±4	41	26.60
Istanbul metro line 2-Levent					
15+687	43±3	43±3	37±4	9	17.70
15+695	37±1	–	–	20	18.50
15+704	58	58	55	49	10.60
15+706	54±3	55±3	53±2	49	10.60
15+709	45±2	–	–	55	22.20
15+710	50	52	50	9	17.70
15+722	32	32	31	2	20.00
15+736	45±4	49±4	43±4	4	16.55
15+785	47±4	49±5	49±5	32	20.66
15+790	49±1	51±1	44±1	2	15.00
Istanbul metro line 1-Taksim					
15+264	51±3	52±4	48±3	90	4.27
15+260	61±4	61±4	58±5	30	3.94
15+258	63±1	63±1	61±1	74	Breaking with explosives
15+252	54±2	54±2	52±2	66	2.94
15+247	56±3	59±3	60±3	54	2.77

[a] S.D. = Standard deviation.

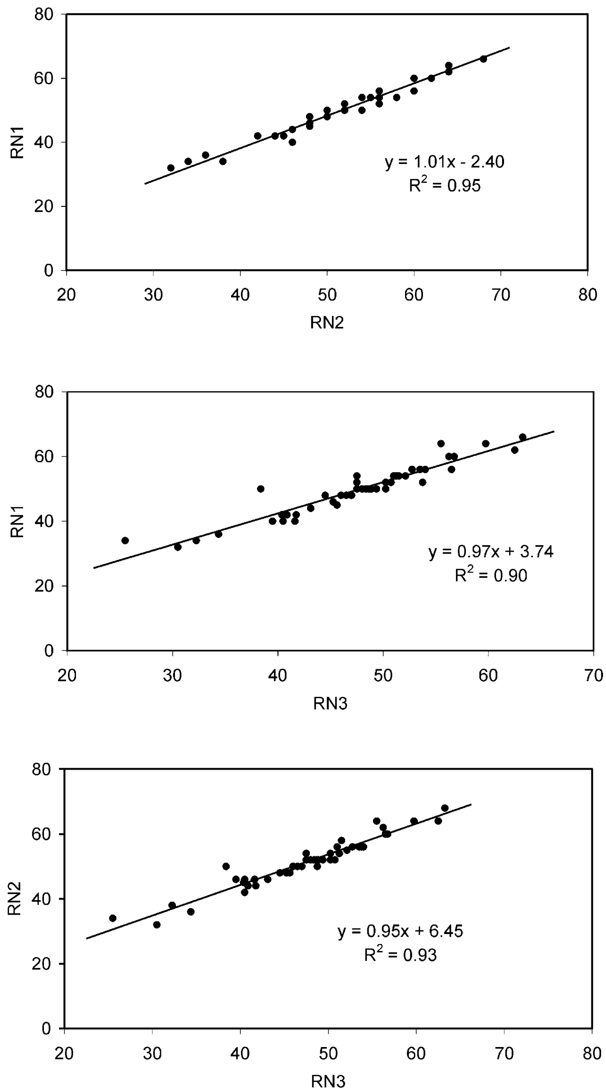

Fig. 9. The relationships within Schmidt hammer rebound values obtained with different test procedures.

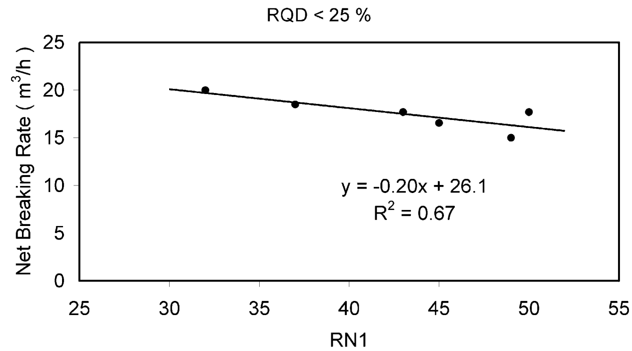

Fig. 11. The relationship between Schmidt hammer rebound values RN1 and net breaking rate of impact hammer Montabert BRH 625, for grouped data of RQD $<25\%$.

and RN2/RN3 were obtained from Table 3, respectively, 0.97:1.07:1.00. This implied that there was not a big difference between the Schmidt hammer test procedures. Due to this fact, only RN1 values are considered in the following discussions on performance analysis.

Fig. 10 shows the relationship between Schmidt hammer rebound values RN1 and net breaking rate of impact hammer Montabert type BRH 625 for all values of RQD ranging from 2 to 90%. It is clearly seen from this figure that the data are highly scattered with a low correlation coefficient of 0.4. However, in a detailed in-situ investigation to predict the cutting performance of roadheaders, Bilgin suggested that the data of advance rates had to be grouped for different values of RQD to obtain more reliable and confident performance prediction models (Bilgin et al., 1988, 1990). Hence, the net breaking rate values of impact hammer were grouped for different values of RQD (RQD$<$25, 25$<$RQD$<$49 and RQD$>$50) and Schmidt hammer RN1 values were plotted against breaking rate values in Figs. 11–14. As it is seen in these figures, the correlation coefficient improved very significantly from 0.4 up to 0.8. This suggests that classification of data for different RQD values give more reliable performance prediction for impact hammers.

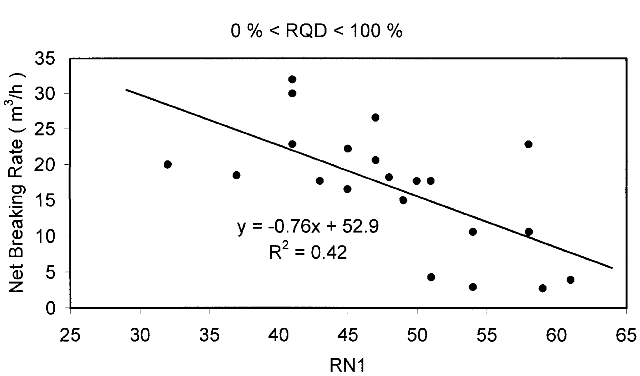

Fig. 10. The relationship between Schmidt hammer rebound values RN1 and net breaking rate of impact hammer Montabert type BRH 625.

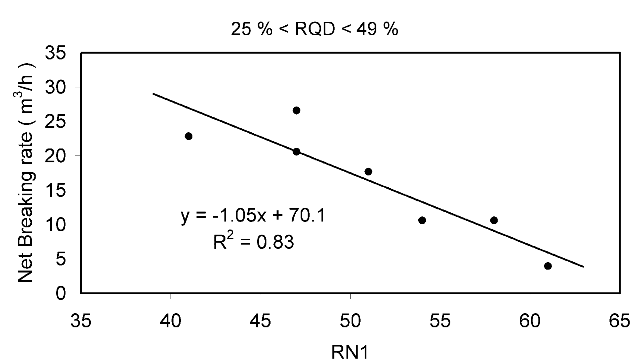

Fig. 12. The relationship between Schmidt hammer rebound values RN1 and net breaking rate of impact hammer Montabert BRH 625, for grouped data of 25$<$RQD$<$49%.

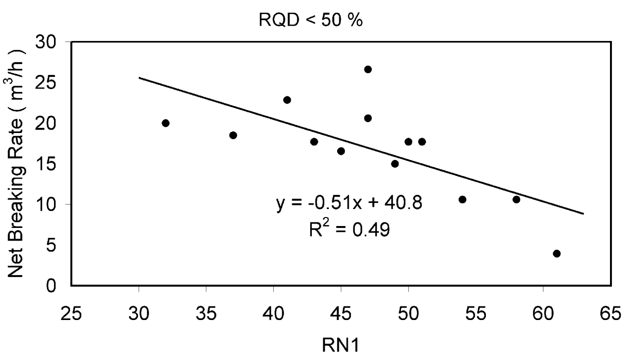

Fig. 13. The relationship between Schmidt hammer rebound values RN1 and net breaking rate of impact hammer Montabert BRH 625, for grouped data of RQD <50%.

7. Conclusions

Hydraulic impact hammers have been used in mining and civil engineering applications since 1960, since their initial capital cost is lower and they may be mounted in any type of available excavator. Almost 11 km of metro tunnels were driven in Istanbul with impact hammers where the new Austrian tunneling method was the main construction method. A detailed research study showed that on average the utilization of impact hammers was approximately 22 and 17% of the total time spent for mucking in Istanbul metro tunnels. This strongly emphasizes that impact hammers mounted on mechanical excavators with gathering arms, such as ITC SA tunnel heading machines, may significantly improve daily advance rates. Data base accumulated for many years in tunnel drivages of Istanbul metro showed that instantaneous breaking rate of impact hammers might be predicted from hammer characteristics, compressive strength and geological discontinuities of rock formations. Schmidt hammer test is a very easy test to conduct and the rebound value is a good indicator of rock characteristics and gives significant correlation with net breaking rates of impact hammers when the rock formation is grouped based on RQD values. It is strictly recommended that further in-situ investigations are needed to improve the proposed model for prediction of the performance of impact hammers.

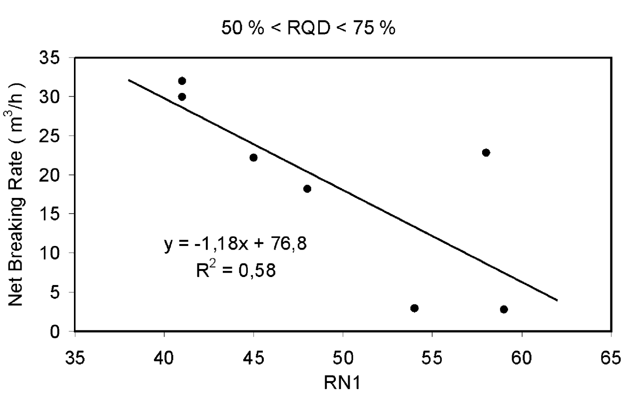

Fig. 14. The relationship between Schmidt hammer rebound values RN1 and net breaking rate of impact hammer Montabert BRH 625, for grouped data of 50%<RQD<75%.

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References

Arioğlu, E., Tokgoz, N. 1991. Estimation of rock strength: rapidly and reliably by the Schmidt hammer. J. Mines, Metals Fuels, September–October: pp. 327–330.

Atkinson, R.H., 1993. In: Hudson, J.A. (Ed.), Hardness Tests for Rock Characterization. A Chapter in Comprehensive Rock Engineering, Vol. 3. Pergamon Press, pp. 107.

Ayaydin, N. 1994. Metro Istanbul. World Tunneling, April, pp. 113–114.

Ayday, C., Goktan, R.M. 1992. Correlations between L and N-type Schmidt hammer rebound values obtained during field testing. Proceedings, Eurock, pp. 47–49.

Bilgin, N., Seyrek. T., Shahriar, K. 1988. Roadheader performance in Istanbul, Golden Horn clean up contributes valuable data. Tunnels and Tunneling, June: pp. 41–44.

Bilgin, N., Seyrek. T., Erdinc, E., Shahriar, K. 1990. Roadheaders glean valuable tips for Istanbul Metro. Tunnels Tunneling, October: pp. 29–32.

Bilgin, N., Yazici, S., Eskikaya, S. 1996. A model to predict the performance of roadheaders and impact hammers in tunnel drivages. Proceedings, Eurock, Balkema, pp. 715–720.

Bilgin, N., Kuzu, C., Eskikaya, S. 1997. Cutting performance of rock hammers and roadheaders in Istanbul Metro drivages. Proceedings, World Tunnel Congress, Tunnels for People, Balkema, pp. 455–460.

Brown, E.T., 1981. Rock characterization testing and monitoring. Pergamon Press, pp. 211.

Deer, D.U., Miller, R.P. 1966. Engineering Classification and index properties of intact rock. Report AFWL–TR-116, Air Force Weapons Laboratory, New Mexico.

Dincer, T. 1999. The effect of some rock properties on performance of roadheaders and impact hammers. Ph.D. Thesis, Istanbul Technical University, p. 108.

Evans, I. 1974. Energy requirements for impact breakage of rocks. Proceedings, Fluid Power Equipment in Mining, Quarrying Tunneling, IMM London, pp. 1–8.

Fowell, R.J., McFeat Smith, I. 1976. Factors influencing the cutting performance of a selective tunneling machine. Proceedings 1st International Symposium on Tunneling, IMM London, pp. 301–309.

Gaskell, J., Phillips, R.A. 1974. The Gullick Dobson impact ripper. Proceedings, Fluid Power Equipment in Mining, Quarrying and Tunneling, IMM London, pp. 73–82.

Haramy, K.Y., DeMarco. 1985. Use of the Schmidt hammer for rock and coal testing. Proceeding, 26th US Symposium on Rock Mechanics, pp. 549–555.

Hucka, V.A., 1965. A rapid method for determining the strength o rocks in-situ. Int. J. Rock. Mech. Min. Sci. 2, 127–134.

Hughes, H.M. 1974. The hydraulic hammer in coal mining. Proceedings, Fluid Power Equipment in Mining, Quarrying and Tunneling, IMM London, pp 83–88.

Janach, W, Merminod, A., 1982. Rock abrasivity test with a modified Schmidt hammer. Int. J. Rock Mech. Min. Sci. Geomech. Abst. 19, 43–45.

Kidybinski, A., 1968. Rebound number and the quality of mine roof strata. Int. J. Rock Mech. Min. Sci. 5, 283–291.

Levetus, F.B, Cagnioncle, G. 1974. Completely hydraulic rotary-percussive rock drills. Proceedings, Fluid Power Equipment in Mining, Quarrying and Tunneling, IMM, London, pp. 67–78.

Pelizza, S., Patrucco, M., Benedetto, G. 1994. Workplace environmental conditions and innovative Tunnel driving techniques. Measurement air contro. Proceedings, Tunneling and Graund Conditions, Balkema, pp. 617–623.

Poole, R.W., Farmer, I.W., 1980. Consistency and repeatability of Schmidt hammer rebound data during field-testing. Int. J. Rock Mech. Min. Sci. Geomech. Abst. 17, 167–171.

Rodford, I.G. 1974. Experience with impact units. Proceedings, Fluid Power Equipment in Mining, Quarrying and Tunneling, IMM London, pp. 57–66.

Sachpazis, C.I., 1990. Correlating Schmidt hardness with compressive strength and young modulus of carbonate rock. Bull. Int. Assoc. Eng. Geology 42, 76–83.

Sahin, B., 1995. Analysis of excavations in Istanbul Metro in Zincirlikuyu Tunnels Phase 1. Diploma Thesis, ITÜ (in Turkish).

Selimoglu, O., 2001. Detailed analysis of excavations in Istanbul Metro in Taksim Yenikapi Line between Galatasaray and Taksim. Diploma Thesis, ITÜ (in Turkish).

Vandergrift, T.L., Conover, D.P, Hanna, K. 1995. Identifying physical property trends in coal mine structures using portable on-site test devices. USA Bureau of Mines RI 9598, p. 86.

Wayment, W, Grantmyre, I. 1976. Development of high blow energy hydraulic impactor. Proceedings, Rapid Excavation and Tunneling Conference, pp. 611-626.

Wyllie, B. 1985. Hydraulic breakers. International Mining, March: 18–24.

Yalcin, A. 1994. Works on Istanbul Metro construction during 1992 and 1993. Interior Report. p. 22.

Young, R.P., Fowell, R.J. 1978. Assessing rock discontinuities. Tunnels and Tunneling, June: pp. 45–48.