PERFORMANCE MONITORING OF ELECTRICAL POWER SHOVELS FOR DIGGABILTY ASSESSMENT IN SURFACE COAL MINES

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in
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By

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Approval of the Graduate School of Natural and Applied Sciences.

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Dedicated to my wife,

Belgin Ceylanoğlu.

PERFORMANCE MONITORING OF ELECTRICAL POWER SHOVELS FOR DIGGABILITY ASSESSMENT IN SURFACE COAL MINES

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ABSTRACT

This thesis describes the results of performance monitoring of electrical shovels in terms of formation characteristics and their digging difficulty point of view. Diggability assessment methods have first been reviewed and discussed. A performance monitoring system, consisted mainly of wattmeter and data logger, has been developed and utilized for different type and size of power shovels.

An extensive field research program has been undertaken at TKİ's (Turkish Coal Enterprises) surface coal mines. The rock units were characterized in terms of their discontinuities, hardness, seismic wave and some material properties, etc. The shovels were monitored considering the formation properties, the depth of cut and with or without blasting conditions. The measurements were mainly concentrated on the dig portion of a complete cycle. Among those performance parameters, the specific digging energy is determined as the most reflective diggability parameter. Good correlations have been established between the specific digging energy and some rock mass and material properties.

The depth of cut ranges and corresponding specific digging energies have been proposed for blasted and unblasted cases. It has been shown that blasting generally decreases the specific digging energy of shovels around 15%-50% compared to unblasted formations.

Key Words: Shovel monitoring, Depth of cut, Specific digging energy, Effect of blasting, Diggability assessment

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ELEKTRİKLİ EKSKAVATÖRLERİN PERFORMANSLARININ İZLENMESİYLE KÖMÜR AÇIK İŞLETMELERİNDE KAZILABİLİRLİK TAYİNİ

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ÖZET

Bu tez, elektrikli ekskavatörlerin performans izleme sonuçlarını, formasyon karakteristikleri ve onları kazı güçlüğü açısından açıklamaktadır. İlk olarak kazılabilirlik tayin yöntemleri gözden geçirilmiş ve tartışılmıştır. Ana olarak watmetre ve veri düzenleme ünitesinden oluşan bir performans izleme sistemi geliştirilmiş ve değişik model ve kapasitedeki ekskavatörler için kullanılmıştır.

Türkiye Kömür İşletmeleri (TKİ) açık ocaklarında kapsamlı bir arazi çalışma programı sürdürülmüştür. Kayaçlar süreksizlik, sertlik, sismik hız ve bazı malzeme özellikleri vb. yönünden karakterize edilmiştir. Ekskavatörler, formasyon özellikleri, kazı derinliği ve patlatmalı-patlatmasız koşullar göz önüne alınarak izlenmiştir. Ölçümler özellikle ekskavatör periyodunun kazıda geçen kısmı üzerinde yoğunlaştırılmıştır. Performans parametreleri içinde özgül kazı enerjisi en yansıtıcı kazılabilirlik parametresi olarak belirlenmiştir. Özgül kazı enerjisi ve bazı kaya kütle ve madde özellikleri arasında yüksek korelasyonlar tesbit edilmiştir.

Kazı derinliği aralıkları ve bunlara karşılık gelen özgül kazı enerjileri patlatılmış ve patlatılmamış koşullar için önerilmiştir. Patlatmanın genel olarak ekskavatörlerin özgül kazı enerjisini 15%-50% dolaylarında düşürdüğü belirlenmiştir.

Anahtar Sözcükler: Ekskavatör izleme, Kazı derinliği,
Özgül kazı enerjisi, Patlatma etkisi,
Kazılabilirlik tespiti

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CHAPTER I

INTRODUCTION

In many mining projects, the method of overburden removal is a critical factor in the determination of safety and cost of operations. The overburden removal and ore production are directly related with digging action so the prediction of diggability of rock units arises as the most important phenomenon in open-pit mining operations.

Excavation is a complex operation which is affected by many factors such as excavator type, size, operator experience, blasting and formation properties including rock properties and geological conditions. The type and size of the excavator strongly effect the diggability i.e. the production rate and ease of digging can not be the same at a particular geologic formation for all type and size of the excavators. Digging operation sometimes requires loosening the ground by ripping or blasting for a certain type of excavator to increase the digging efficiency and/or to decrease the digging difficulty of the excavator. Therefore, not only the rock mass characteristics but also the performance of the excavator should be considered in the selection of excavation equipment. So the performance of the excavator is a critical factor to quantify the interaction between different sizes of the equipment and the rock types.

In this study, the electrical shovel performance monitoring system is introduced and the results of trial excavation conducted at some surface lignite mines of Turkish Coal Enterprises are discussed and analyzed from the digging difficulty point of view by considering the formation characteristics.

In the following chapter, a review is made on the previous diggability studies. Chapter 3 describes the power measurement system. Experimental procedure is outlined and the study area is given in Chapter 4. In Chapter 5, analysis and discussion of the results of both laboratory and field studies are made. Finally, conclusions and recommendations for future studies are given in Chapter 6.

CHAPTER II

LITERATURE SURVEY

2.1. Literature Survey

Selection of the excavation equipment and mode of loosening (i.e. direct digging, ripping, blasting) the soil/rock material is of major importance in surface mining operations.

Some of the crucial questions to be answered in selection of equipment for a given job and ground conditions are:

i) Could the selected equipment dig efficiently the particular geologic formation or is it better to use other type of excavator?

ii) In order to increase the digging efficiency of the excavator, is it better to use other means of loosening the ground such as ripping or blasting before the digging operation?

iii) How does the type and size of the excavator effect the diggability?

iv) What is the role of rock mass discontinuities in the ease of excavation?

v) How does the quality of blasting affect the performance of the excavator?

vi) How does the skill and experience of the operator affect the performance of the excavator?

vii) Would it be possible to quantify the interaction between different types and sizes of the equipment and the ground types encountered in mines, which can vary across the complete spectrum from soils to boulders or rock of all descriptions, and quality of loosening ground by blasting?

viii) How could the technological improvements in the power and capabilities of the excavators and in their cutting tools and techniques be included in diggability assessments?

ix) Is it really possible to incorporate all these para-meter cited above into a diggability assessment system?

To find answers to all these questions is not possible in the literature. The ideal procedure to determine the ability of an excavator to dig efficiently a geological formation is to conduct a trial excavation at the mine site, but this is almost always impractical. An alternative approach, which has been suggested by several investigators (Atkinson, 1971; Bailey, 1975; Church, 1981; Franklin et.al., 1971; Bozdağ, 1988; Karpuz, 1990; Paşamehmetoğlu et.al., 1988; Weaver, 1975; Smith, 1986; Singh et.al., 1987; Kolleth, 1990; Müftüoğlu, 1983; Bölükbaşı et.al., 1991) is to relate diggability to various geological, geotechnical parameters of the ground and to establish qualitative emprical approach of diggability.

Seismic wave velocity obtained from field tests has been used widely in assessing rock mass diggability. Atkinson (1971) correlated the diggability of various types of excavators with the in-situ seismic wave velocity of rock mass (Figure 1). Various buldozer manufacturers, i.e. Caterpillar Tractor Co., (1983), Komatsu Ltd. (1982) provide charts for estimating ripper performance (rippability) of their line of buldozer-ripper combinations by seismic wave velocities for a variety of materials. Bailey (1975) and Church (1981) also classified the rippability of formations by the direct usage of seismic velocity.

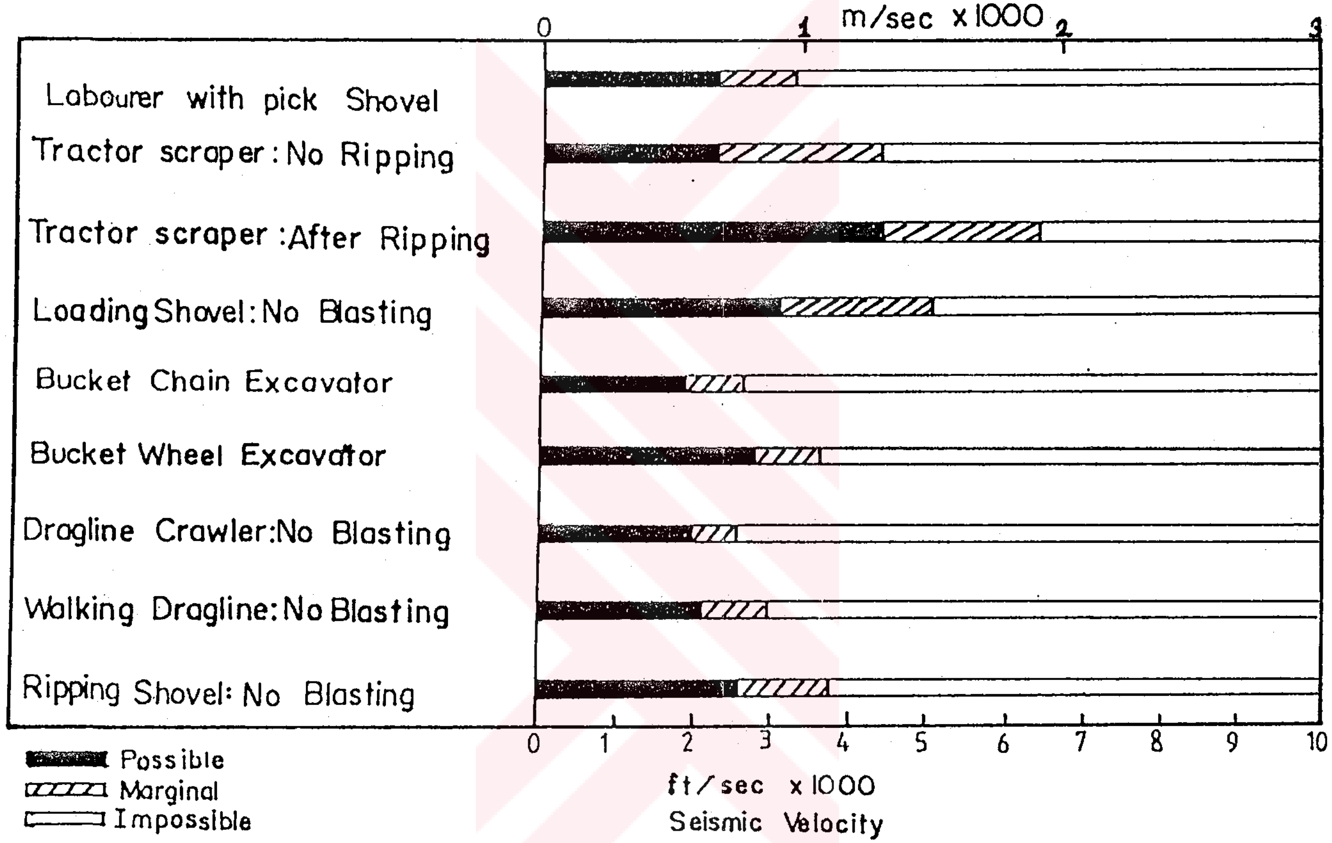


Figure 1. Seismic Velocity Method for Determination of Excavation Possibilities (Atkinson, 1971).

Franklin et.al. (1971) in order to classify rock mass quality for excavation purposes suggested a classification diagram (Figure 2) which incorporates the mean joint spacing of rock mass and the point load index of the intact rock (intact strength of the rock). Rock mass discontinuities, which contribute to the ease of excavation, are taken into account in this excavation prediction. As it can be seen from Figure 2, although the limits of modes of loosening the ground included into the diagram there is no indication of the type of the excavation. Bozdağ (1988) tried to modify Franklin et.al.'s (1971) diagram by including different ripper capacities into it based on detailed studies carried out at TKI's Surface Coal Mines, in Turkey (Figure 3) (Karpuz, 1990; Paşamehmetoğlu et.al., 1988).

Researchers like Weaver (1975), Smith (1986), Singh et.al., (1987) established rippability estimation methods, taking into account rock mass and rock material properties besides their seismic velocities.

Weaver (1975) considered seismic velocity, rock hardness, rock weathering, rock structure (discontinuities, planes of weakness, dip and orientation) and rock fabric as the significant geological parameters for rippability.

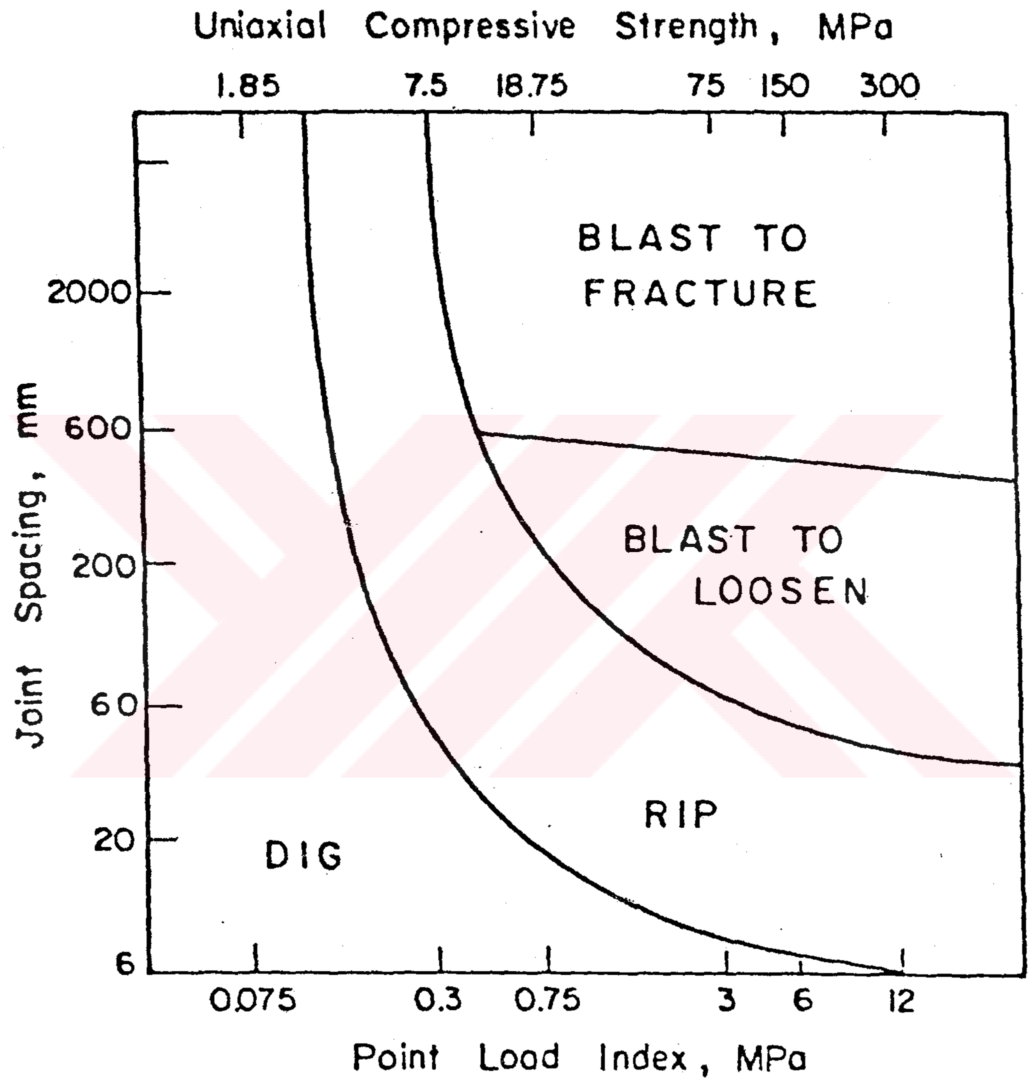


Figure 2. Rippability Chart Proposed by Franklin,et. al. (1971).

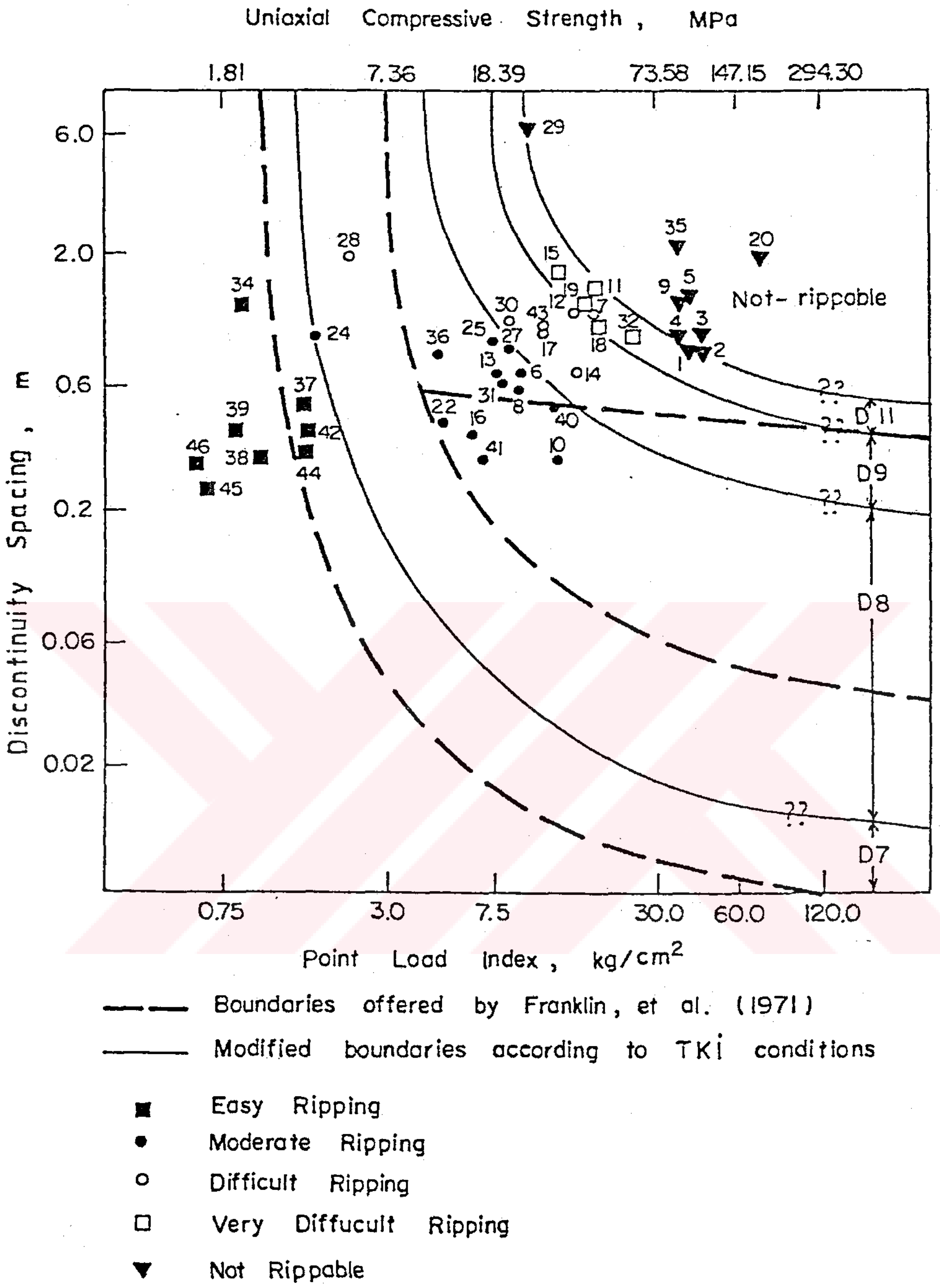


Figure 3. Modification of Franklin, et. al.'s (1971) Rippability Chart for TKİ Open-Pit Coal Mines According to Different Sizes of Bulldozers (Bozdağ, 1988).

Smith (1986) modifying Weaver's system proposed a systematic means of numerically weighing six rock parameters, namely rock hardness (in terms of uniaxial compressive strength), rock weathering, joint spacing, joint continuity, joint gauge and strike and dip orientation, to produce a rippability rating chart. He recommended a method to correlate this rating with the seismic velocity and tractor horse power (Table 1).

Singh et.al. (1987) claimed that current rippability indices fail to account for the fracture strength of rock mass and the rock abrassiveness potential and suggested a rippability index for mining applications taking into account abrassiveness of rock together with indirect tensile strength, degree of weathering, seismic velocity, and discontinuity spacing (Table 2).

It could easily be seen that except Atkinson's (1971) approach all the references cited above are related to rippability, whereas Atkinson (1971) presented the diggability of various types of excavators. Since only in-situ seismic velocity of rock mass is used for correlation with diggability, it is rather a simple system for selection (Figure 1).

Table 1. Modified Version of Weaver's Rippability Rating Chart (Smith, 1986).

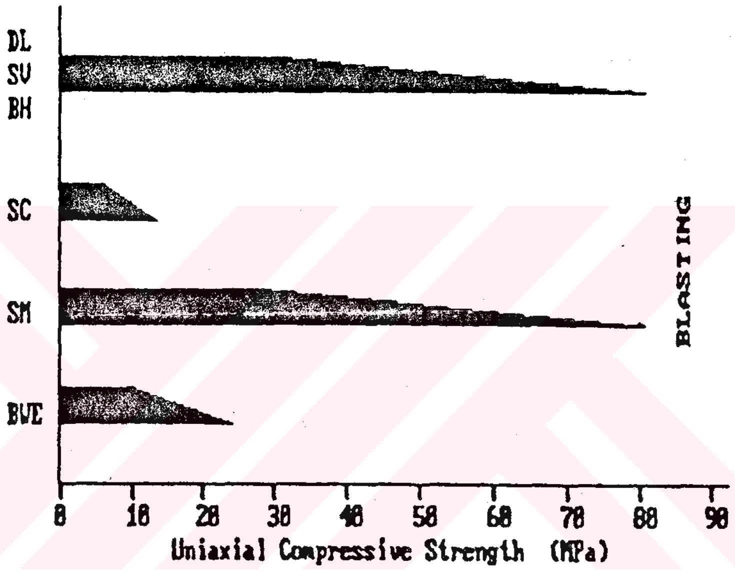
Descriptive Classification	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock
Rock Hardness *	Very hard rock)= 70 MPa	Hard rock 70 - 25 MPa	Medium hard rock 25 - 10 MPa	Soft rock 10 - 3 MPa	Very soft rock (3 MPa
Rating	)= 10	5	2	1	0
Rock Weathering	Unweathered	Slightly weathered	Highly Weathered	Completely weathered	Completely weathered
Rating	10	7	5	3	1
Joint Spacing (mm)	) 3000	3000 - 1000	1000 - 300	300 - 50	(50
Rating	30	25	20	10	5
Joint Continuity	Non continuous	Slightly continuous	Continuous-no gouge	Continuous-some gouge	Continuous-with gouge
Rating	5	5	3	0	0
Joint Gouge	No seperation	Slight seperation	Seperation (1 mm	Gouge - (5 mm	Gouge -) 5 mm
Rating	5	5	4	3	1
Strike and Dip Orientation	Very unfavourable	Unfavourable	Slightly unfavourable	Favourable	Very favourable
Rating	15	13	10	5	3

* Corresponding to unconfined compressive strength

Table 2. Rock Rippability Index (Singh, et.al., 1987).

Parameters	Rock Class				
	1	2	3	4	5
UTS (MPa)	(2	2 - 6	6 - 10	10 - 15	) 15
Rating	0 - 3	3 - 7	7 - 11	11 - 14	14 - 17
Weathering	completely	highly	moderately	slightly	unweathered
Rating	0 - 2	2 - 6	6 - 10	10 - 14	14 - 18
Seismic Vel.(m/sec)	400 - 1100	1100 - 1600	1600 - 1900	1900 - 2500	) 2500
Rating	0 - 6	6 - 10	10 - 14	14 - 18	18 - 25
Abrasiveness	very low	low	moderately	highly	extremely
Rating	0 - 5	5 - 9	9 - 13	13 - 18	18 - 22
Disc. spacing (m)	(0.06	0.06 - 0.3	0.3 - 1.0	1.0 - 2.0	) 2.0
Rating	0 - 7	7 - 15	15 - 22	22 - 28	28 - 33
TOTAL RATING	(30	30 - 50	50 - 70	70 - 90	) 90
Rippability assessm	easy	moderate	difficult	marginal	blast
Recommended dozer	none-Class 1 light duty	Class 2 medium duty	Class 3 heavy duty	Class 4 very heavy duty	- -
Output (Kw)	(150	150 - 250	250 - 350	)350	-
Weight (Kg)	(25000	25000 - 35000	35000 - 55000	) 55000	-

Kolleth (1990) regarding uniaxial compressive strength of intact rock, or alternatively the point load index as the sole input parameter provided a diagram (Figure 4) which shows the applicability of various digging equipment as a function of the uniaxial compressive strength of the material to be dug.



(BWE : Bucket Wheel Excavator, SM : Surface Miner, SC : Scraper, DL : Dragline, SV : Shovel, BH : Backhoe)

Figure 4. Applicability (at nominal output) of Digging Equipment as a Function of Uniaxial Compressive Strength (Kolleth, 1990).

Atkinson's (1971) and Kolleth's (1990) approaches are two examples of diggability assessments in which single rock material/rock mass properties are used. More comprehensive diggability assessment techniques are proposed by Müftüoğlu (1983) and by Karpuz (1990).

Müftüoğlu (1983) in his classification system considered both the ground conditions and type of excavation equipment (Table 3). In the derivation of method, the observation of excavator performance, mainly hydraulic excavators, in a wide range of ground conditions encountered in British surface coal mines indicated that four geotechnical parameters effectively form a basis for diggability index. These are intact rock strength, extent of weathering, joint and bedding spacing.

Karpuz (1990) stated that, although Müftüoğlu's (1983) system considers both sides of excavability, the performance measurements are restricted to hydraulic excavators for a limited range of ground conditions. According to Karpuz (1990), to formulate a comprehensive diggability index, the electric excavator performance measurements, rippability estimate, and the need for drilling and explosives, should be integrated with hydraulic excavator performances as well as ground properties. He, then, based on two years project carried

Table 3. Diggability Classification System (Müftüoğlu, 1983).

Class	Ease of Digging	Index (W+S+J+B)	Excavation Method	Plant to be Employed (Without Resort to Blasting) (With Examples)
I	Very Easy	< 40	1.Ripping 2.Dragline Cast 3.Shovel Digging	A. Ripper - Scraper Cat D8 B. Dragline > 5 m.3 Lima 2400 C. Rope Shovel > 3 m.3 Ruston Bucyrus 71 RB
II	Easy	40 - 50	1.Ripping 2.Dragline Cast 3.Shovel Digging	A. Ripper - Scraper Cat D9 B. Dragline > 8 m.3 Marion 195 C. Rope Shovel > 8 m.3 Ruston Bucyrus 150 RB
III	Moderately Difficult	50 - 60	1.Ripping 2.Shovel Digging	A. Ripper-Shovel/F.E.Ldr. Cat D9 B. Hydraulic Shovel > 3 m.3 Cat 245
IV	Difficult	60 - 70	1.Ripping 2.Shovel Digging	A. Ripper-Shovel/F.E.Ldr. Cat D10 B. Hydraulic Shovel > 3 m.3 Cat 245 or O & K RH 40
V	Very Difficult	70 - 95	Shovel Digging	Hydraulic Shovel > 3 m.3 Cat 245 or O & K RH40
VI	Extremely Difficult	95 - 100	Shovel Digging	Hydraulic Shovel > 7 m.3 Demag H111 , Poclain 1000CK P&H 1200 , O & K RH75
VII	Marginal Without Blasting	> 100	Shovel Digging	Hydraulic Shovel > 10 m.3 Demag H185 / H241 O & K RH300

out at the surface lignite mines operated by Turkish Coal Enterprises (Paşamehmetoğlu et.al., 1988), proposed an excavation rating system which consists of intact rock strength, Schmidt hardness value, discontinuity spacing, degree of weathering and seismic wave velocity (Table 4). The classification system also includes a suggestion of the equipment to be used and blasting and drilling requirements (Table 5).

Although Karpuz (1990) claims that his classification system covers the complete spectrum, from type of excavator to ground conditions, one critism to be raised is that, it does not take size of equipment into consideration.

There exists one other group of excavability study where empasize is only given for the bucket wheel excavator (BWE) diggability. The specific cutting resistance or specific separation force of intact rock (F_a, MPa), which is measured from tests with Orenstein and Koppel (O & K) wedge test ring, has been used extensively as the most important parameter in the formation of BWE diggability criteria. Bölükbaşı et.al. (1991) summarized the available BWE diggability criteria (Table 6), and proposed that beside O & K wedge test results, the F_a values obtained from direct cutting experiments used mainly for the assessment of

Table 4. Parameters Used to Create Diggability Index (Karpuz, 1990).

Parameter	Class				
	1	2	3	4	5
Uniaxial compressive strength (MPa)	< 5	5–20	20–40	40–110	> 110
Is (50) (MPa)	(0.2)	(0.2–0.8)	(0.8–1.6)	(1.6–4.4)	(4.4)
Rating	2	5	10	20	25
Average discontinuity spacing (m)	< 0.3	0.3–0.6	0.6–1.2	1.2–2.0	> 2.0
Rating	5	10	15	20	25
Seismic wave velocity (m/s)	< 1600	1600–2000	2000–2500	2500–3000	> 3000
Rating	5	10	15	20	25
Weathering	Complete	High	Moderate	Slight–Fresh	Slight–Fresh
Rating	0	3	6	10	10
Hardness (SHV)	< 20	20–30	30–45	45–55	> 55
Rating	3	5	8	12	15

Rating system is valid in the presence of bedding and two joint sets. Add to the total: 5 points if there is a bedding and one joint set, 10 points if there is bedding only, 15 points if there is no distinguishable discontinuity.

Table 5. Diggability Classification (Karpuz, 1990).

Class	Ease of digging	Index	Excavation method			When blasting necessary	
			Power shovel digging [1]	Hydraulic excavator [2]	Ripping, ripper type	Drilling rate (m/min)	Specific charge (kg/m^3)
1	Easy	0– 25	Dig	Dig	Easy D7	–	–
2	Medium	25– 45	Blast	Dig	Moderate to difficult D8 or D9	1.48	0.130–0.200
3	Moderately difficult	45– 65	Blast	Blast	Difficult to very difficult D9 or Dll	1.28	0.200–0.280
4	Difficult	65– 85	Blast	Blast	Marginal to non-rippable Dll	0.57	0.280–0.350
5	Very difficult	85–100	Blast	Blast	Non-rippable (blast)	< 0.42	> 0.350

[1] Valid for power shovels of 7.65–19.11 m^3 (10–25 yd^3) bucket capacity

[2] Valid for hydraulic excavators of bucket capacity less than 8.03 m^3 (10.5 yd^3)

Table 6. Published BWE Diggability Criteria (Bölükbaşı, et.al., 1991).

Criteria	Class	Cutting Resistance from O&K wedge test F_a (MPa)
Highvale After Wade&Clark (1989)	Easy	0.00 - 0.60
	Diggable	0.60 - 1.10
	Hard	1.10 - 1.40
	Marginal	1.40 - 1.80
	Undiggable	> 1.80
Goonyella After O'Regan et.al (1987)	Easy	0.15 - 0.45
	Diggable	0.45 - 0.60
	Hard	0.60 - 0.75
	Marginal	0.75 - 1.00
	Undiggable	> 1.00
Neyveli After Rodenberg (1987)	Easy	-
	Diggable	< 1.10
	Hard	1.10 - 2.30
	Marginal	-
	Undiggable	> 2.30
Canmet After Weise (1981)	Easy	-
	Diggable	0.00 - 1.00
	Hard	1.00 - 1.50
	Marginal	1.50 - 2.40
	Undiggable	> 2.40
Kozlowski After Kozlowski (1981)	Easy	0.00 - 0.17
	Diggable	0.17 - 0.36
	Hard	0.36 - 0.54
	Marginal	0.54 - 0.80
	Undiggable	> 0.80
Krzanowski After Krzanowski et.al (1984)	Easy	0.00 - 0.27
	Diggable	0.27 - 0.90
	Hard	0.90 - 1.85
	Marginal	-
	Undiggable	> 1.85

performances and selection of tunnel boring machines, could be used in the BWE diggability assessments.

The performances of excavators, namely cycle time, bucket/dipper fill factor and hourly output are generally used as an indicator of diggability/ excavability by excavator manufacturers. It is considered that cycle time is dependent on digging difficulty and machine size, i.e. small machines can cycle faster than large machines, and as the formation gets harder to dig, it takes longer to fill the dipper. Cycle times (t_B) for different size of electrical shovels proposed by some electric shovel manufacturing companies are tabulated by Paşamehmetoğlu et.al., (1988) and are given in Table 7.

It is difficult to excavate and fill the bucket/dipper as the formations tend to be hard. Classification of digging by means of dipper fill factors for electric excavators given by P&H (1980) is presented in Table 8.

Paşamehmetoğlu et.al. (1988) proposed hourly capacities for different size of electrical shovels as a measure of digging difficulty (Table 9) by using the cycle times (Table 7) and dipper fill factors (Table 8).

Table 7. The Cycle Times of Electrical Shovels as a Function of Digging Difficulty (Paşamehmetoğlu, et.al., 1988).

Classifications of Digging / Dipper Capacity (yd^3)	Easy	Easy - Moderate	Moderate	Moderate-Moderately Difficult	Moderately Difficult	Moderately Difficult-Difficult	Difficult
	t_s (sec)	t_s (sec)	t_s (sec)	t_s (sec)	t_s (sec)	t_s (sec)	t_s (sec)
4.5	20.43	22.56	24.69	26.55	28.40	30.02	31.63
10	23.04	25.17	27.30	29.16	31.01	32.63	34.24
10.5	23.24	25.37	27.50	29.36	31.21	32.83	34.44
15	24.70	26.83	28.96	30.82	32.67	34.29	35.90
17	25.17	27.30	29.43	31.29	33.14	34.76	36.37
20	25.67	27.80	29.93	31.79	33.64	35.26	36.87
25	25.96	28.09	30.22	32.08	33.93	35.55	37.16

Table 8. Classifications of Digging by Means of Dipper Fill Factors (P&H, 1980).

Clasifications of Digging	Dipper Fill Factor (FF)
Easy	$FF \geq 0.95$
Moderate	$0.90 \geq FF < 0.95$
Moderately Difficult	$0.80 \geq FF < 0.90$
Difficult	$FF < 0.80$

They indicated the combined effect of cycle time and dipper fil factor on digging classifications of different formations at TKI's surface coal mines by means of hourly capacity which is inversely proportional with the cycle time and directly proportional with the bucket/dipper capacity and fill factor.

One of the conclusion, drawn from the two years detailed research carried out at Turkish Coal Enterprises, surface lignite mines by Paşamehmetoğlu et.al., (1988) was that neither cycle times nor fill factors could be sole means of determination of diggability. Dig cycle-times especially the most effective and digging related part of the total cycle times were found not to be a reliable indicator of

Table 9. Hourly Capacities of Electrical Shovels as a Measure of Digging Difficulty (Paşamehmetoğlu, et.al., 1988).

Classifications of Digging / Dipper Capacity (yd^3)	Easy	Easy - Moderate	Moderate	Moderate-Moderately Difficult	Moderately Difficult	Moderately Difficult-Difficult	Difficult
	HC (m^3/hr)	HC (m^3/ hr)	HC (m^3 / hr)	HC (m^3 / hr)	HC (m^3 / hr)	HC (m^3 /hr)	HC (m^3 /hr)
4.5	591.1	521.6	464.1	414.1	370.7	330.1	293.7
10	1164.8	1038.9	932.6	837.8	754.5	674.9	602.9
10.5	1212.5	1082.3	972.2	873.7	787.1	704.3	629.4
15	1629.8	1461.9	1316.8	1189.0	1074.2	963.3	862.6
17	1812.6	1628.3	1470.7	1327.2	1200.2	1077.0	964.9
20	2091.0	1881.2	1701.4	1536.9	1391.0	1249.0	1119.8
25	2584.5	2327.3	2106.3	1903.8	1723.9	1548.6	1388.9

diggability. A possible explanation is that an operator realizes that when he is digging difficult material he cannot stay in the bank as long. In difficult digging, the dipper speed is lower, producing a slow speed across a short trajectory (path) and giving a certain cycle time. Conversely, in easy digging, the dipper might have a longer trajectory but a higher dipper speed, so the dig cycle-time might still be the same. Of course, one should not also forget the influence of operator experience.

Performance monitoring of excavators can provide an accurate and realistic measure of the diggability and/or effectiveness of production blasting over a range of rock types.

Deslandes et.al. (1990) described a program to improve dragline performance and safety through the use of computer monitoring and control. It was shown that the implementation of computer monitoring and control can lead to significant improvements to dragline performance and safety. Strain gauges were installed at thirteen locations on the dragline to measure the stress regions and four strain gauges were selected for continuous monitoring with the developed system. Then the hourly stress ranges have been used to identify the operator and the nature of the overburden being excavated. Swing angle, cycle time, bucket load and operational statistics such as digging, walking (i.e. propel motion) were considered as the important production parameters. They indicated that a computer programming of pertinent production parameters is to be undertaken. This study is currently in progress.

Müftüoğlu (1983) instrumented a Caterpillar 245 hydraulic shovel to monitor stick, boom and bucket hydraulic pressures during the dig cycle. Table 10 shows the hydraulic shovel digging condition in five different rock masses of surface coal mine. Digging performance was related to the size distrubition and profile, and geology. The bench height control over the dig cycle time was also considered in this study.

Williamson et.al. (1983) developed a system to monitor crowd and swing D.C. motors and relays of P&H electric shovels to study the effectiveness of blast design. They also derived an index of muckpile diggability at the Mt. Newman Mine, Western Australia. The digging section of the operating cycle was used and the index was based on crowd voltage and current, together with dig cycle time. The total horse power of the crowd motor is 130 (97 kW) and the total horse power of the hoist motor is 600 (448 kW) for a 10 yd3 dipper capacity electrical shovel. The crowd action just

Table 10. Hydraulic Shovel Diggability Monitoring Studies (Müftüoğlu, 1983).

CASE No.			1	2	3	4	5
ROCK UNIT DESCRIPTION			Slightly Weathered Silty Mudstone U1	Slightly Weathered Laminated Mudstone U2	Slightly Weathered Sandstone With Mudstone Bands U9	Slightly Weathered Massive Sandstone U8	Slightly Weathered Massive Sandstone U9
GROUND PREPARATION			Nil	Nil	Blasting	Blasting	Blasting
AVERAGE BLOCK VOLUME (after preparation)			0.4	< 0.03	0.03	0.2	0.04
BENCH HEIGHT (m)			5	4	1.5	7	3.5
DUMP TRUCK FILLING TIME (sec.)			186±30	187±23	243±47	176±37	195±32
NO.OF PASSES			7-8	6-7	7-10	6-7	6-8
MEAN CYCLE TIME (sec.)		OBSERVED	25	28	29	27	26
		COMPUTED	26	28	28	26	27
MEAN DIGGING TIME (sec./cycle)			11.5±3.0	10.4±2.1	11.8±3.4	11.8±4.1	10.7±2.5
MEAN PRESSURE (MPa)	PEAK	STICK	25.03	18.57	19.05	—	18.26
		BUCKET	21.13	13.39	13.35	20.87	13.74
		BOOM	26.54	22.84	22.02	27.77	24.23
	AVERAGE	STICK	12.54	10.73	10.0	—	10.6
		BUCKET	6.72	5.49	5.5	5.95	6.2
		BOOM	14.9	16.17	14.5	15.86	16.5

pushes the lip of the dipper into base of the formation at the start of digging and the the hoist force is exerted until the end of digging. The dipper should not be filled at the bottom of the formation. The effective force is the hoist force during digging section of shovel operating cycle as it is seen from the value of total horse power of the hoist motor.

Hendricks et.al. (1988) studied the influence of bench geology, rock strength and blasting on shovel digging performance, as characterized by dig cycle times in a range of mining environments. They determined that dig cycle times are very closely related to operating characteristics and are not a valid indicator of digging effort or diggability.

Shovel monitoring equipment is not new, but its applications are still being developed. Hendricks et al. (1989) set out a way to determine through shovel instrumentation and monitoring. They used a commercially available shovel production monitoring device, made by General Electric to test the shovel monitoring equipment on several test blasts. The research indicated that it is the performance of the hoist motor that is most reflective of the variations of diggability. Using the response of the hoist motor to create a diggability index, it was shown that this correlates well with digging conditions observed during monitoring (Figures 5 and 6). They stated that dipper trajectory exerts a very pronounced influence over measured diggability and should be considered when trying to establish diggability.

The excavating force of the shovel which is applied at the dipper teeth depends upon the size as well as the depth of cut. Based on the observations, Paşamehmetoğlu et.al. (1988) stated that engine power is the most relevant criterion in the process of digging for different dipper capacities.

The main drive A.C. motor of electrical shovel provides all mechanical power for crowd, hoist, swing and propel motions. The power consumption of main A.C. motor during digging comes from the D.C. motor of hoist. The D.C. motors of the shovel are selectively and independently powered according to the motions of the operation so the power consumption of individual motions can be relatively found by measuring the power consumption of main A.C. motor.

Paşamehmetoğlu et.al. (1988) developed a measurement technique consisting of wattmeter and X-T recorder to measure the power consumptions of electrical shovels during the overburden removal operations of

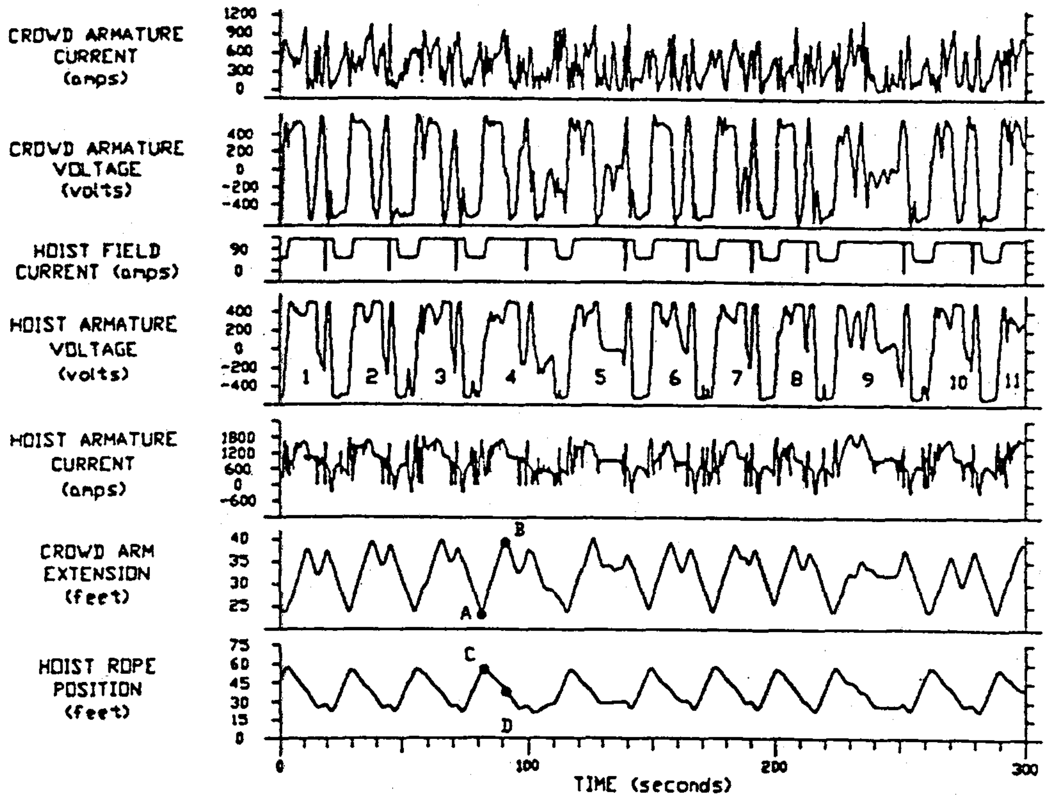


Figure 5. Monitor Traces for Easy Digging Conditions (Hendricks, et. al., 1989).

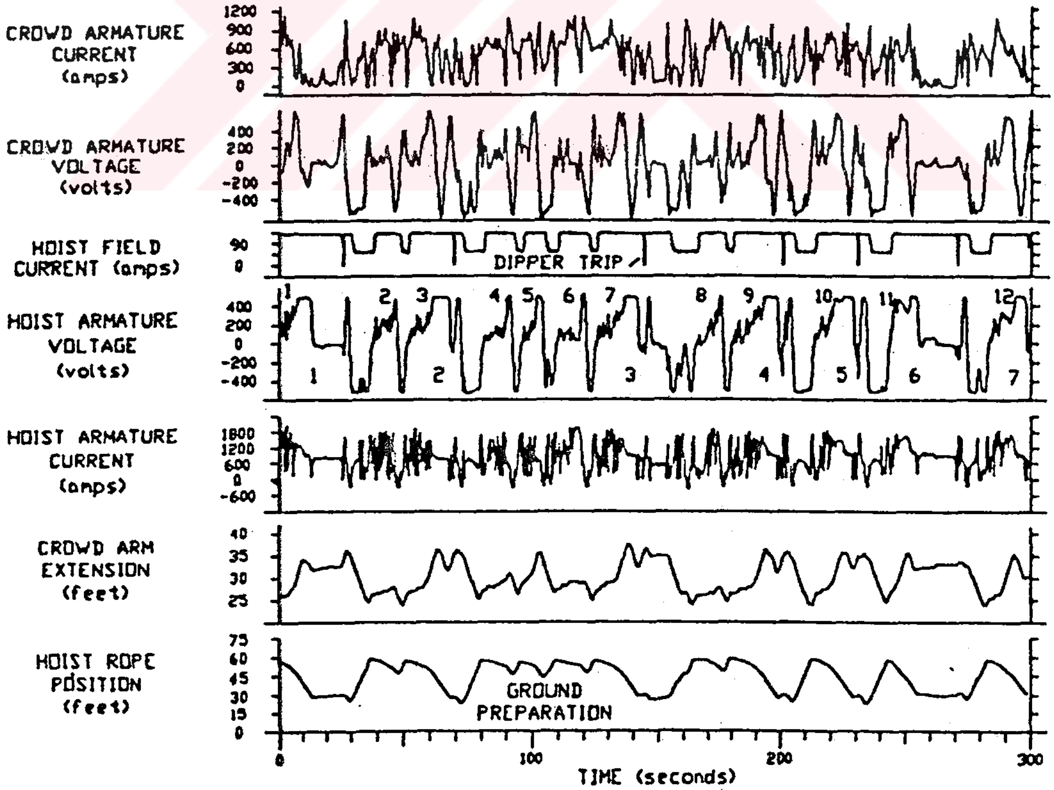


Figure 6. Monitor Traces for Difficult Digging Conditions (Hendricks, et. al., 1989).

different formations encountered in Turkish surface coal mines.

Paşamehmetoğlu (1988) determined that overall hourly output of the shovel and amount of overburden material excavated for unit energy consumed before and after blasting at Yatağan-Eskihisar Mine of Turkish Coal Enterprises and the results of performance of power shovel digging before and after blasting are given in Table 11. It is shown that the output and energy consumption of the excavator is a very important factor in deciding the diggability of a particular material.

2.2. Scope of the Thesis

In the light of previous discussions, the main objectives of this study can be listed as:

- To determine the variations in digging condition by performance monitoring of electrical shovel.

- To monitor different type and size of electrical shovels in a wide range of ground conditions.

- To investigate the effect of depth of cut and blasting on shovel digging performance.

- To find out the most effective parameter(s) of shovel digging performance.

- To study the relationships between excavation performance and rock mass/material properties.

Table 11. Results of Performance of Power Shovel Digging the Material Before and After Blasting at Yatağan-Eskihisar Mine (Paşamehmetoğlu, 1988).

Performance Parameter	Squeezed Zone		Fresh Shale	
	Before Blasting	After Blasting	Before Blasting	After Blasting
Seismic P-wave velocity, m/sec	880	793	1402	667
Digging time, sec.	8.86	11.00	7.79	11.28
Total cycle time, sec	28.60	32.45	27.60	31.24
Realized output of shovel, m^3/hr	1033	1114	864	1121
Bucket fill factor	0.91	1.04	0.87	0.99
Output of shovel without waiting, m^3/hr	1173	1309	906	1285
Peak digging power, KW	1436	1436	1587	1415
Average digging power, KW	1099	1114	1406	1199
Output per second per unit power, m^3/sec/MW	0.808	0.948	0.375	0.874

CHAPTER III

POWER MEASUREMENT SYSTEM

3. 1. Introduction

A power measurement system comprising mainly a wattmeter and a data logger developed by Middle East Technical University Rock Mechanics Research Group is utilized to measure the power of any required system at any time.

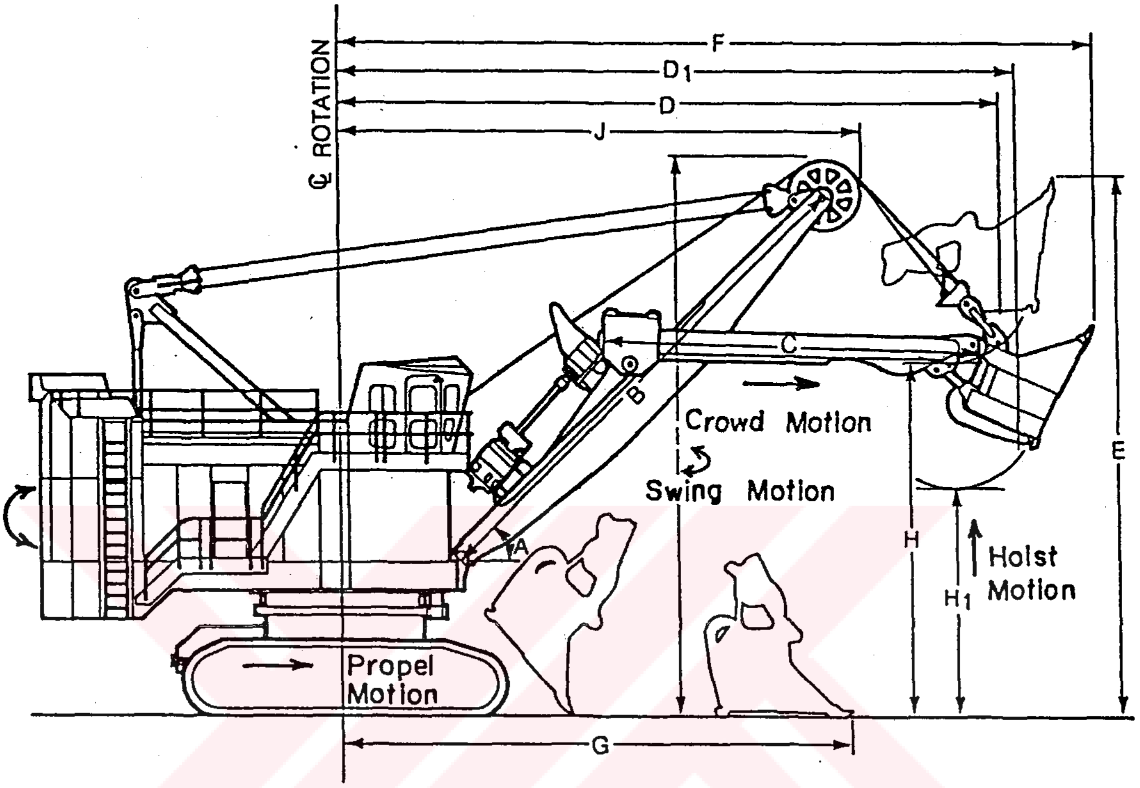
The responses of the main drive A.C. motor of the electrical shovels which can detect relative changes in the diggability of the formation can be continuously measured with this system.

In this chapter, a brief information about the electrical power shovel and detail explanations of the measurement system units will be given.

3. 2. Electrical Power Shovel

The electrical power shovel is designed to push its dipper into the formation from ground level where it is operated at the start of loading material, the dipper moving vertically through the working face of the formation until the end of loading section of the operation and swing to dump its load either to a spoil pile or into a haulage unit and return for the next cycle. The operating ranges may not be the same for all shovel models but they can be constant for different dipper capacities. The working ranges of the shovel and four operating motions of crowd, hoist, swing and propel are shown in Figure 7. The operating motions involved in the cycle process are individually powered and functioned independently. The crowd and propel motions can not be operated at the same time, these motions being selectively operated to prevent the pushing of the dipper into the formation with propel motion.

As the name implies electrical shovel is powered by electricity which is economic but less mobile than the hydraulic shovels operated by diesel power. Electrical shovels have a main drive A.C. motor transferring power to the D.C. generators which supply power for D.C. motors. Then mechanical powers of crowd, hoist, swing and propel motions are obtained from D.C. motors. In some type of electrical shovels, main drive A.C. motor is synchronized i.e. A.C. motor can also work as a generator which can supply power to the source especially during the reverse motion of the hoist. The energy consumption of the different motions of the operation can be successfully evaluated with power measurements for this type of electrical shovels too. The working system of an electrical shovel is simply illustrated in Figure 8.



A	Boom Angle	45°	45°
	Dipper Capacity (Nominal)	12 cu. yd.	9 cu. m
	Dipper Capacity (Range)	10-25 cu. yd.	7.5-19.1 cu. m
B	Boom Length	40 ft. 0 in.	12.19 m
C	Effective Dipper Handle Length	27 ft. 0 in.	8.23 m
D	Dumping Radius at Max. Lift	52 ft. 0 in.	15.85 m
D_1	Dumping Radius (Max.)	53 ft. 0 in.	16.15 m
E	Height of Cut (Max.)	42 ft. 6 in.	12.95 m
F	Digging Radius (Max.)	58 ft. 6 in.	17.83 m
G	Floor Level Radius	39 ft. 0 in.	11.89 m
H	Dumping Height (Max.) — Door Open	27 ft. 0 in.	8.23 m
H_1	Dumping Height at Max. Radius — Door Open	19 ft. 0 in.	5.79 m
I	Clearance Height of Boom Point Sheave	43 ft. 0 in.	13.11 m
J	Clearance Radius of Boom Point Sheave	40 ft. 3 in.	12.27 m

Figure 7. Operating Specifications and Operating Motions of 12yd^3 Electrical Power Shovel (P&H, 1980).

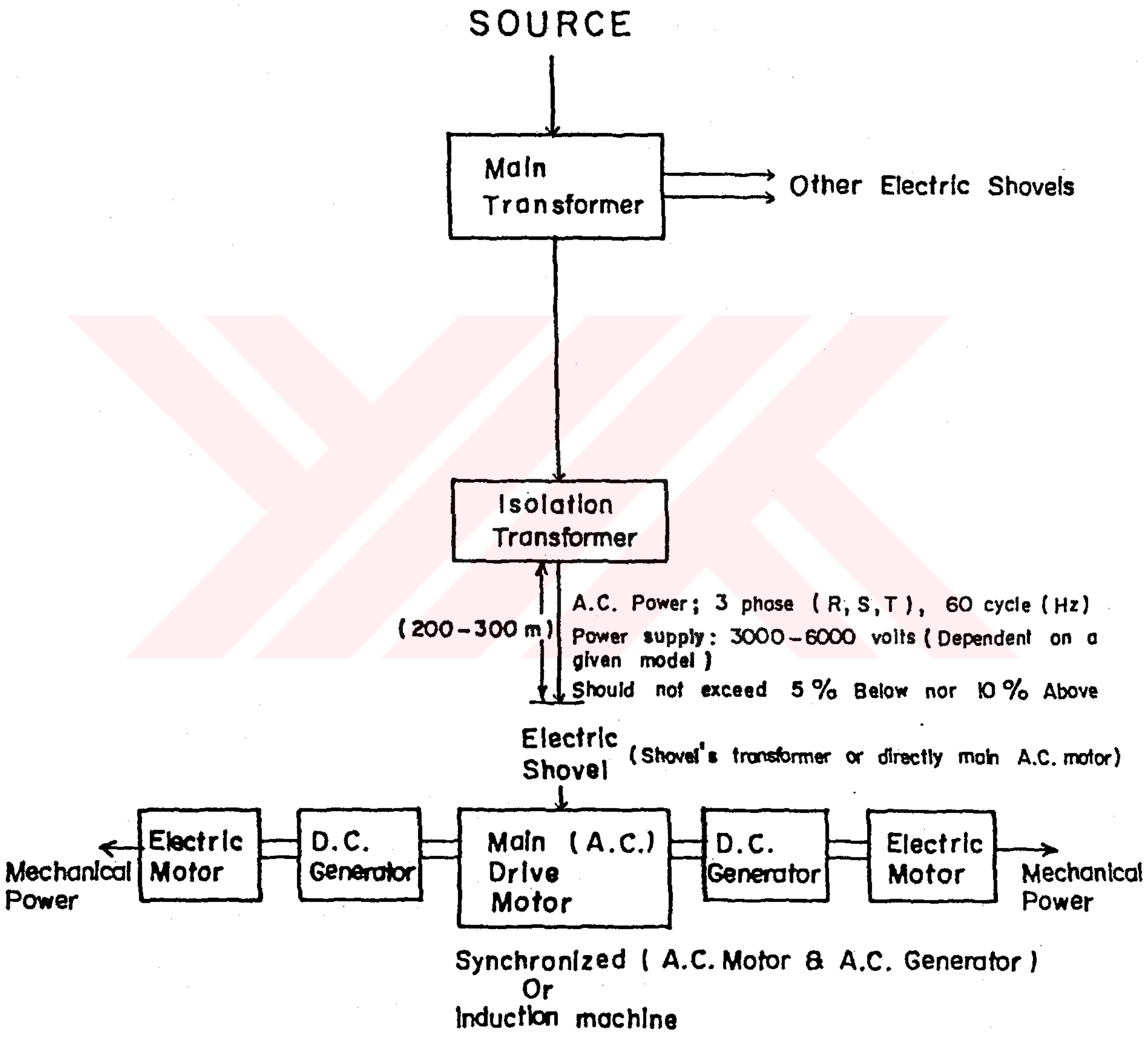


Figure 8. Working Principle of an Electrical Power Shovel.

3. 3. Power Measurement Set-up

The measurement system aimed to investigate electrical shovel performance by continuous monitoring the power consumption variations during excavation of materials is consisted of three main parts, which are A.C. Wattmeter, Isolated Measurement Pod and Data Acquisition Controller.

The block diagram given in Figure 9 illustrates the power measurement system schematically. The D.C. Volt from wattmeter corresponds to the actual power exerted by the shovel main drive A.C. motor which provides all mechanical power for crowd, hoist, swing and propel motions is converted to the digital signal by means of "isolated measurement pod". Then recordings of digital signals are converted to actual power with wattmeter and isolation transformer variables and stored in memory module with respect to time by using data acquisition controller.

Figure 10 shows a general view of the power measurement set-up connected to the isolation transformer of the electrical shovel. It is believed that this system is the first of its kind used on every types of electrical shovels. It can also be used on draglines.

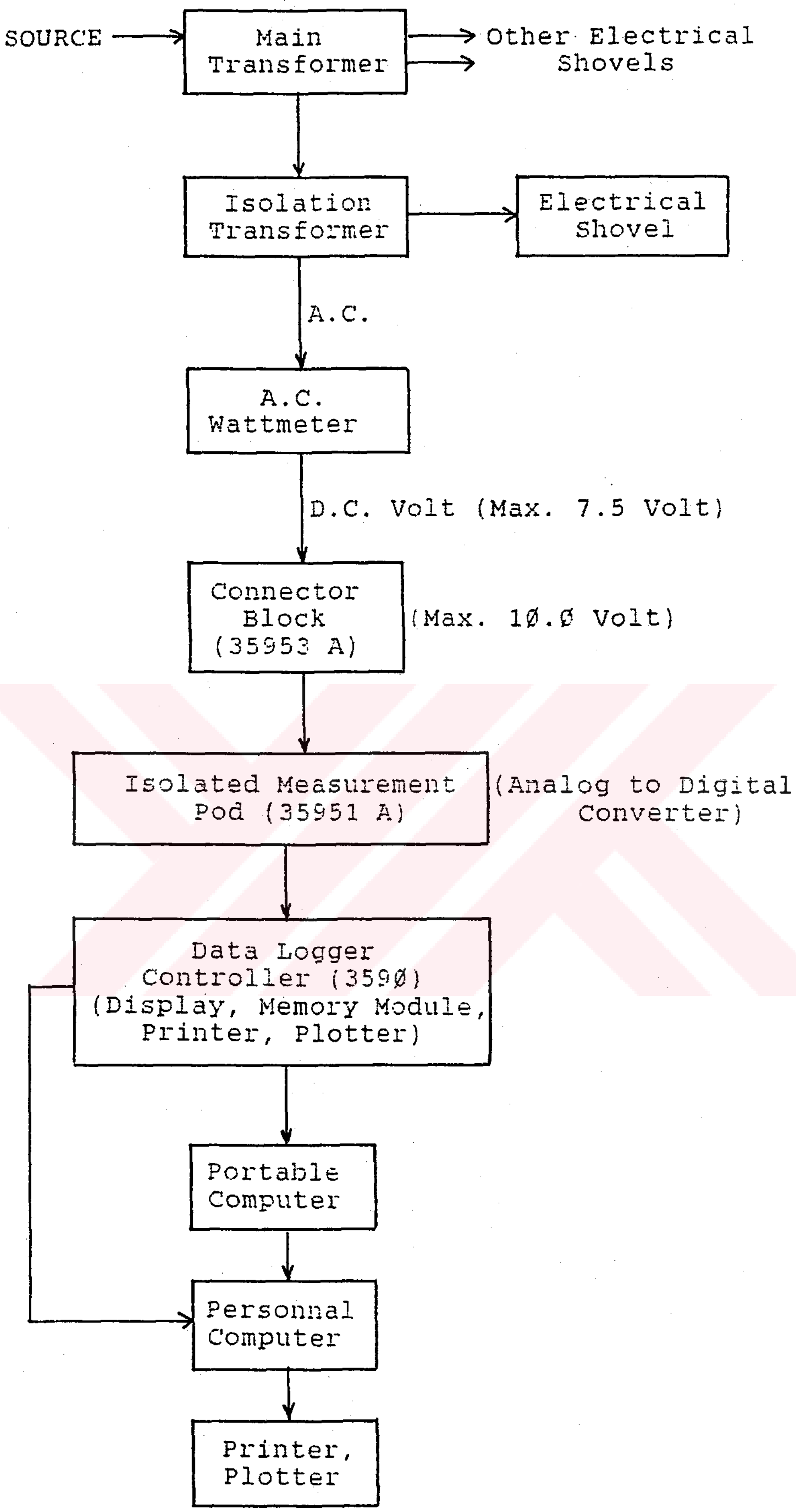


Figure 9. Power Measurement System.

Front View

Back View

Figure 10. Front and Back Views of the Power Measurement Set-up.

3. 3. 1. Wattmeter

The wattmeter is specially designed to measure the power of any required system and output D.C. Volt according to the power consumption of the measured system continuously.

The working principle of the wattmeter is shown in Figure 11. The measured power of the system can also be observed from the indicator of wattmeter at any time during the measurement.

The weight of the wattmeter is approximately 7 kg and the size is 40*30*15 cm. Figure 12 shows the back and front views of the wattmeter.

The wattmeter is easily connected to a given transformer system and read-out device as shown in Figure 13. The measurement procedure given below should be applied to monitor the power consumption of the given system correctly.

1. Connect the wattmeter to the given transformer system and read-out device.
2. Note the current and voltage turn ratios of the given system.
3. Supply 220 volt A.C. for wattmeter and read-out device.
4. Select the current and voltage ranges of the wattmeter. If the high current indicators light on, select

the other range (5 Amp.) and if the high voltage indicators light on, select another range (300 Volt). Note the measurement ranges.

5. Control the polarity of three phases from the indicator by using the function button of the wattmeter. All three phases, P_R, P_S and P_T must be in the same direction to measure the total power, P_Σ correctly. If they are not in the same direction, control the connections of current input and output.

6. Select the function which can be P_R, P_S, P_T or P_Σ and set the suitable reading coefficient of indicator. The largest value of the reading coefficient which is 500 should be set at the beginning of the measurement and the reading coefficient can be decreased according to the indicator of the wattmeter to increase the sensitivity of the indicator readings.

The power of the measured system at any time during the measurement is derived from the wattmeter indicator by employing the following equation.

$$W\ (\text{Watt}) = \begin{array}{c}\text{Wattmeter}\\\text{Indicator}\\\text{Number}\end{array} * \begin{array}{c}\text{Wattmeter}\\\text{Reading}\\\text{Coefficient}\end{array} * a * b$$

where; a: Current Transformer Turn Ratio

b: Voltage Transformer Turn Ratio

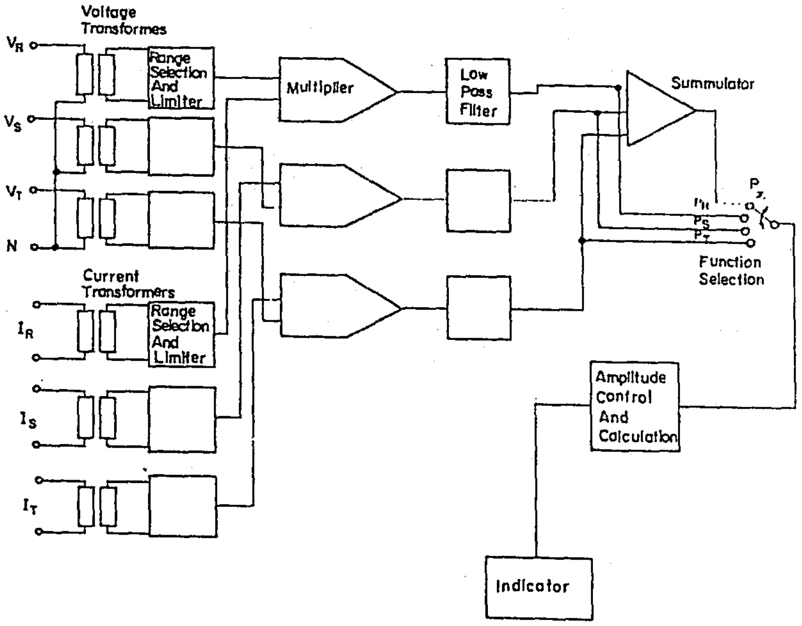
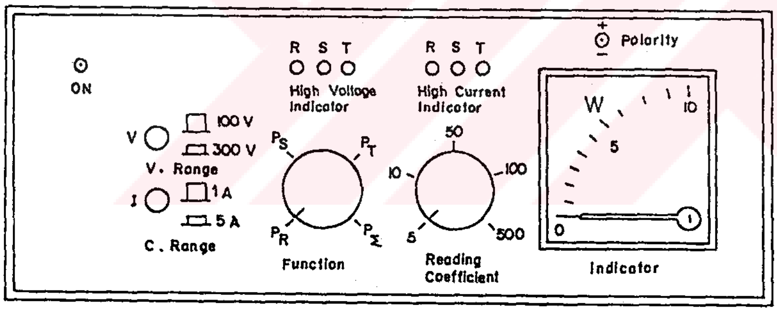
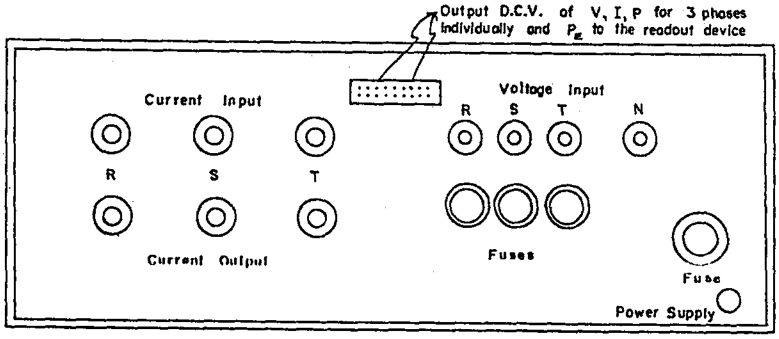


Figure 11. Working System of the Wattmeter.



Front view



Back view

Figure 12. Front and Back Views of the Wattmeter.

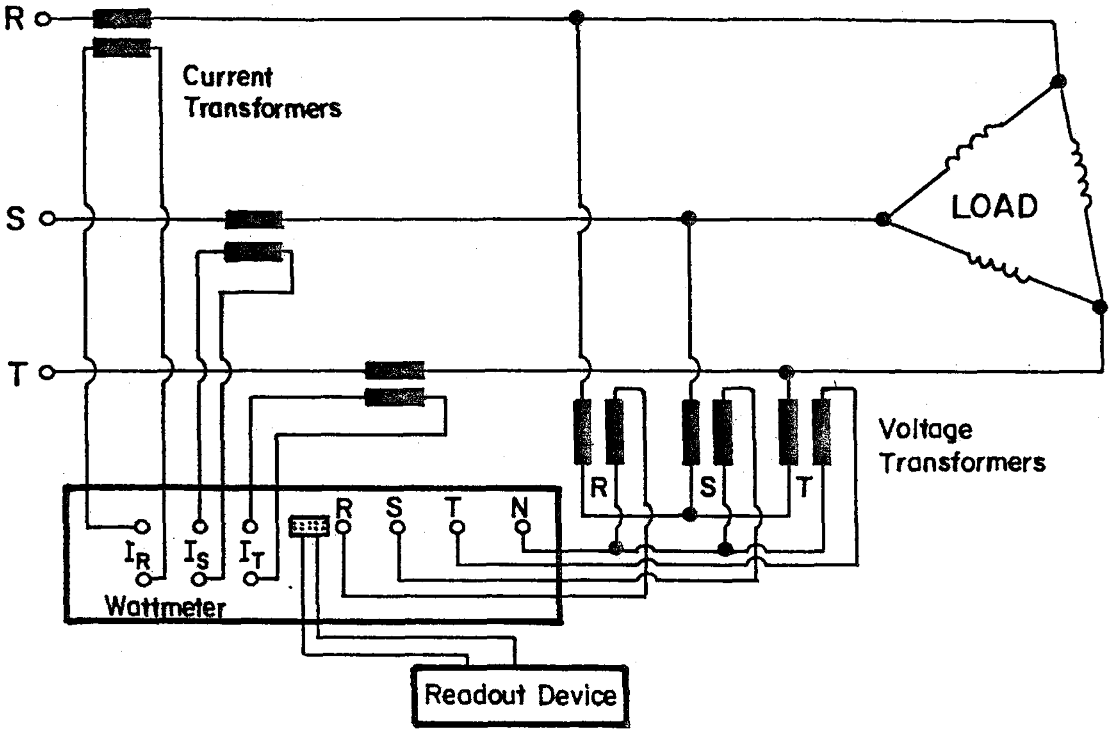


Figure 13. Connections of the Wattmeter to an Electrical Shovel Transformer System.

The analog output of the wattmeter related with the power of the measured system for each P_R, P_S and P_T phases is 2.5 D.C. Volt at the nominal power of the selected current and voltage ranges. Therefore, the total analog output for P_Σ is 7.5 D.C. Volt at the desired conditions. The 2.5 D.C. Volt output corresponds to 100 Watt nominal power for a single phase at the 100 Volt and 1 Amp. ranges and at the same ranges the 7.5 D.C. Volt output of P_Σ corresponds to 300 Watt nominal power. At the 300 Volt and 5 Amp. ranges the 2.5 D.C. Volt output corresponds to 1500 Watt nominal power for one phase and 7.5 D.C. Volt output of P_Σ corresponds 4500 Watt nominal power.

The total power consumption of the given system at any time corresponds to the measured D.C. Volt output of wattmeter is calculated as follows:

First the nominal power of P_Σ at the selected ranges is calculated.

$$N \text{ (Watt)} = \begin{array}{c}\text{Wattmeter}\\ \text{Current}\\ \text{Range}\end{array} * \begin{array}{c}\text{Wattmeter}\\ \text{Voltage}\\ \text{Range}\end{array} * 3 * a * b$$

where; a and b are used to find the actual power of the measured system,

a: Current Transformer Turn Ratio

b: Voltage Transformer Turn Ratio

Then, total power consumption of the system at any time is:

$$P_\Sigma \text{ (Watt)} = X \text{ (D.C. Volt)} * N \text{ (Watt)} / 7.5 \text{ (D.C. Volt)}$$

where; X is the output voltage of the wattmeter at that time.

3. 3. 2. Isolated Measurement Pod

The isolated measurement pod (IMP) supplied by Schlumberger Solartron Instruments is multi-channel data collecting station, designed to be operated remotely by a host computer or data logger. The IMP is linked to the data acquisition controller by one simple 2-wire cable which is called S-net, up to 1 km long. IMP can be powered either locally from a D.C. source, or it can receive its power from the data logger by the S-net cable.

An analog measurement 35951A IMP with its 35953A connector block to which all IMP connections are made by screw terminals is used as a read-out device in the measurement system. The isolated measurement pod is connected to the wattmeter and data logger by using the connector block which has a voltage range of 0 to ±10 Volt with 1 mV sensitivity. IMP will operate from -20 to +70 °C. It will operate in dust and will withstand liquid jets. The IMP provides twenty channels which can be individually configured to measure voltage, current or temperature.

IMP functioned as analog to digital converter in the monitoring system allows signals from the wattmeter to be read as voltages and converted into numbers so that the data logger can understand. All results, in digital form are then transmitted to the data logger.

3. 3. 3. Data Acquisition Controller

An impact data acquisition controller (3590) developed by Schlumberger Solartron Instruments is used in the power measurement system.

Data logger includes an intelligent controller which organizes the measurements made by the isolation measurement pod and receives data from it. Data logger can log, in engineering units, by both storing, printing and plotting the results. Power supply is provided by rechargeable 12 Volt battery module or A.C. line power. An integral charger unit automatically recharges the battery during A.C. operation.

All results received by the data logger which are D.C. Volt in digital form can be multiplied by wattmeter and transformer variables to obtain corresponding power consumption of the given system with the help of the conversion feature of the controller. Then data logger scans the converted data at a number of scanning intervals which can be chosen, where the fastest scanning for a single channel is 0.2 second, i.e. 5 data in one second. At the same time it can record the converted data with respect to time according to its real-time clock, having an accuracy of 2.5 seconds per day. On two memory modules, which can contain 64 kilobytes of information, providing a total capacity of 128 kilobytes, and can be changed with the new free ones easily when they have no space to store.

The recorded readings can be replayed later for a particular time span to the display, the printer in tabular or plot form or an output device as selected in the replay menu of the controller. By using the replay facility of the controller a statistical analysis can be also performed upon the replayed data, such that four separate results are produced which are the average of the readings, the standard deviation, the maximum and minimum readings noted.

The data logger also contains connection for RS-232 C interface to send data to a personal or portable computer during measurement. The Epson PX-8 portable computer which has a microcasette tape deck is used for saving data to increase the storage capacity of the measurement system.

A Yokogawa Hokushin Electric Model 3021 strip chart recorder which contains two channels to measure D.C. Volt and remote control pen that draws straight line to indicate the required time intervals may be used as a read-out device instead of isolated measurement pod and data logger in the monitoring system. The recorder is utilized to record the output D.C. Volt of the wattmeter corresponds the power of the measured system with respect to time continuously where the volt range and velocity of the record are selected from the strip chart recorder.

CHAPTER IV

FIELD AND LABORATORY STUDIES

4. 1. General

Field study involves geotechnical description including seismic survey and Schmidth hammer testing, drilling performance, blast evaluation, performance measurement of electrical shovels and collection of intact block samples which represent and characterize the studied rock units for laboratory tests.

Field studies based on the determination of some rock mass and material properties and performance monitoring of electrical shovels are carried out at surface coal mines of Turkish Coal Enterprises (TKI). The diggability assessment by performance parameters of excavators can be more effectively used if it is supported by the means of quantitative data derived from seismic surveys, observation and monitoring of drilling and blasting operations.

4. 2. Field Study Techniques

The performance measurements of electrical power shovels and some field data were undertaken for diggability prediction of overburden material at various producing surface coal mines of Turkish Coal Enterprises, on a number of rock benches, which are summarized in Table 12.

Table 12. TKİ Sites where the Field Studies are Carried out.

Enterprise	Region	Panel	Rock Type
E.L.İ	Merkez	Kısrakdere-Doğu	Marl
		Kısrakdere-Batı	Marl
		Işıklar A Pano	Marl
		Işıklar DE Pano	Marl
		Elmalı	Marl
		Sarıkaya	Marl
	Deniş	Çamtarla	Marl
G.L.İ	Tunçbilek	Beke	Marl
		Ömerler	Marl
		36. Pano	Marl
		Kuşpınar	Marl,Limestone
	Seyitömer	S - 28 S - 20	Marl
		S - 19	Marl
		S - 18	Marl
G.E.L.İ	Yatağan	Eskihisar	Marl
	Tınaz-Bağyaka	Tınaz	Conglomerate,Marl Limestone
	Milas	İkizköy	Marl, Limestone
		Sekköy	Marl
S.K.L.İ	Kalburçayırı		Marl, Clayish Marl Limestone

Those geotechnical descriptions of the rock units and Schmidt hammer, seismic P-wave velocity, penetration rate and specific charge values incorporated with the shovel performance data to evaluate the diggability of those rock units. Generally, the rock units with relatively high penetration rate and low seismic velocity and Schmidt hammer values indicate relatively very easy digging.

4. 2. 1. Rock Mass Description

All of the studied rock units were mainly consisted of sedimentary rocks which contain, in addition to joints, weak shear zones and bedding planes which separate the rock into layers.

The rock unit description for each of shovel monitoring includes rock name or type, colour and degree of weathering which is a qualitative information and hardness determination by Schmidt hammer which is very suitable for field use. Bedding thickness, number of joint sets, joint spacing and shear zones are recorded. Block size and distribution are also determined during performance studies of electrical shovel. Photographs of the bench face are taken with a lens camera to provide a permanent record of the each case. A rock mass description data sheet is prepared for each measurement and it is given in Appendix A. Intact block samples which represent the studied rock unit are collected for each case of a particular sites besides of the rock mass description.

The degree of weathering is an important parameter which should be considered in determining diggability. The weathering grade recommended by ISRM (1978) which divides weathering into 6 main groups as fresh, slightly, moderately, highly, completely, and residual soil is used during the determination of state of weathering.

Joint spacing is determined as a mean spacing in meters by using scanline technique. The spacing between adjacent joints are measured by counting the number of joints intersecting a line of known length of steel tape and expressed as a mean spacing.

The relative hardness of rock material at each location is determined by Schmidt hammer. Five continuous readings of Schmidt hammer are taken on the same spot and the peak rebound value is selected. The mean of peak rebound values is expressed as Schmidt hardness value at that location which is also suggested by Poole and Farmer, 1980. Table 13 represents the rock hardness description according to Schmidt hammer values.

4. 2. 2. Seismic Surveys

Seismic P-wave velocity depends on rock hardness, stratification, degree of fracturing and amount of decomposition (Caterpillar, 1983). Seismic velocity was

Table 13. Rock Hardness Description According to Schmidt Hammer Values (ISRM, 1978).

Schmidt Hammer Value	Descriptive Term
0 - 10	Soft
10 - 20	Slightly Soft
20 - 40	Slightly Strong
40 - 50	Strong
50 - 60	Highly Strong
> 60	Extremely Strong

utilized many times as an indicator of degree of digging difficulty of formation in literature.

Seismic refraction surveys were performed on the same well leveled rock benches in different directions and lengths which consisted of mainly marl and limestone units to determine seismic P-wave velocities through the body of rock masses. A portable 12 channel signal enhancement type, "ES- 1225 Exploration Seismograph" supplied by EG and Geometrics firm (USA) is used for these surveys. The seismograph contains a sledge hammer with a trigger, a metal plate, a blasting trigger, 12 geophones for 12 channels and geophone cable. The source of seismic waves is produced by a hammer blowing to the metal plate which is on the ground surface or by a dynamite explosion in 80-100 cm depth of ground. The geophones were spaced at 1.5 m to 2 m intervals up to 10m. Seismic profiles were taken along dip and strike directions and at least two profiles were done with various lengths according to the field conditions.

4. 2. 3. Drilling Performance Studies

The resistance of rock to penetration is defined as drillability. Penetration rate is a function of many factors which are mainly related with the properties of rock, since the excavator performance measurements are supported with the drilling performance data.

Penetration rate is determined by using blasthole rotary drilling performance data. During performance studies on the rotary drilling machines in the sites, drilled meters, net drilling time and operating variables including thrust, rotational speed, bit type and diameter were recorded for series of blasthole production drilling. Field data sheet of drilling performance is given in Appendix A.

All rotary drilling machines observed in each of the sites during blasthole production work were operated with tricone milled tooth bit type and compressed air to eject rock cuttings. All the tricone bits have a diameter of 22.86 cm (9 in) and the rotational speed 120 rpm was common for all measurements.

Penetration rate values are calculated with excluding other times needed in drilling operations by dividing drilled meters to net drilling times. Penetration rate values for the same conditions that tricone bit diameter and rotational speed are constant at 22.86 cm and 120 rpm respectively at different thrust values (kN) which are the net weight on rotary bit have been normalized into a single value for each formation by dividing thrust to penetration rate, which was also suggested by Leighton (1982) as Rock Quality Index (RQI). RQI value, which is a characteristic property of the formation makes the drilling performance data analysis easier.

4.2.4. Blasting Studies

In hard rock masses, direct digging can not be done. Drilling and blasting which is the only way to loosen or to break the rock for ground preparation is desirable to improve the performance of shovel digging and operational efficiency, that is why the blasting operations were observed during the field study.

The geometrical parameters as bench height, burden, spacing and depth of holes are measured using a steel tape. Blastholes are loaded with emulsion-based explosives (ANFO). The amount of explosive is also noted. Field data sheet prepared for bench blasting is given in Appendix A. The maximum and average block sizes and size distributions are recorded while the performance measurement of electrical shovel at this blasted mass is carried out for the assessment of the efficiency of a blast and difficulty of excavation. Bench blasting data can be effectively analyzed by specific charge value, defined as a weight measure of explosive required to break a unit volume or weight of rock (Afrouz, et al., 1988).

It has been observed that the bench slope is approximately 90°, the number of holes to be blasted in a group is around 10 and the number of rows is usually 2 during the field studies.

4. 2. 5. Performance Measurement of Electrical Shovels

Although overburden removal operations at TKI surface coal mines are mainly carried out by electrical shovel and haul truck combination where different models and sizes of cable shovels are being used, there is little information about digging performance. Electrical power shovel has excellent digging ability due to its weight, traction and high powered hoist and crowd motions where its production is mainly based on the dipper size, cycle time, dipper fill amount and formation type. The performances of currently used electrical shovels are monitored as they excavated different formations with observed digging conditions. Table 14 lists the monitored electrical shovels during overburden excavation at surface coal mines of TKI.

The electrical shovel performance monitoring at each location involves not only cycle and digging times but also dipper loads and power consumption at any time. The excavation performance information form about electrical shovel, operational conditions and power measurement variables given in Appendix A is completed at the beginning of the each performance measurement.

The power measurement system explained in Chapter 3 is connected to the secondary ends of the isolated transformer of the shovel or directly to the shovel's transformer which is inside the shovel to record the total power consumption of the main drive A.C. motor of the electrical shovel with respect to time continuously during operations of shovel. Data logger used in the power measurement system is capable to start and finish the measurement automatically at given time intervals according to its real time clock, having an accuracy of 2.5 seconds per day. The chronometer used for cycle time measurements exactly matches the real time clock of data logger during performance measurement. Power consumption of electrical shovel can be also measured with wattmeter and recorder continuously, as explained in Chapter 3 during cycle time measurement. In those cases, two handheld radios are used for communication to indicate the shovel's different steps of cycle with remote control pen of the chart recorder. A typical D.C. Volt record corresponds to the power of the measured system at any time is given in Figure 14.

The performance measurements are taken for 30-40 cycles at each location which can characterize the excavation activity. Power measurements are recorded at 1 second scanning interval on memory module of data logger, so 1800 data points can be obtained for a performance monitoring period of 30 minutes. It is observed

Table 14. Electric Shovels Monitored During Overburden Excavation at TKİ Surface Coal Mines.

Manufacturer	Model	Dipper Capacity (yd3)	Number
P & H	1900	10	3
P & H	1900 AL	10	9
P & H	2100 BL	15	9
P & H	2300 XP	20	3
Marion	191M-I	17	2
Marion	191M-II	20	5
Marion	201M	25	2
Mach.Exp.	-	4.5	1
Mach.Exp.	EKG-8i	10.5	2

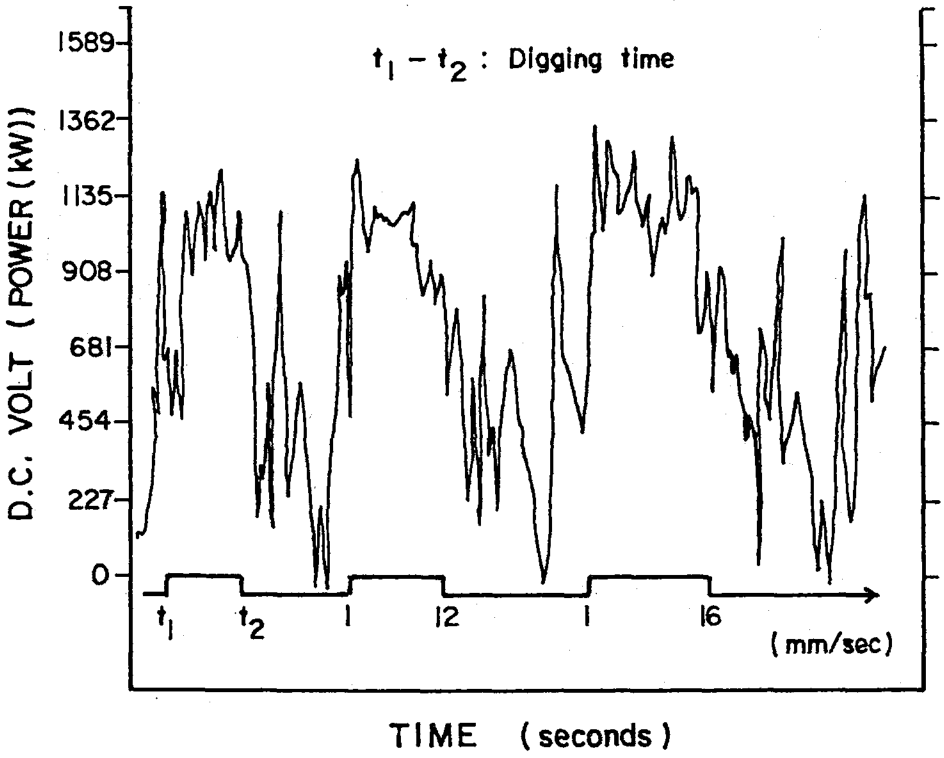


Figure 14. A Typical Output of Wattmeter and Recorder System.

that there is no significant changes in the average of measurements as the duration of measurements increased and the scanning interval decreased.

Data collection by usig wattmeter and data logger system is certainly much easier than wattmeter and recorder. The evaluation of data with this system is sufficiently accurate and also much easier and time saving than the recorder output. The graphics program installed in data logger enables the user to plot power recordings of any selected time interval. An example of power recordings with data logger printer in plot form can be seen in Figure 15.

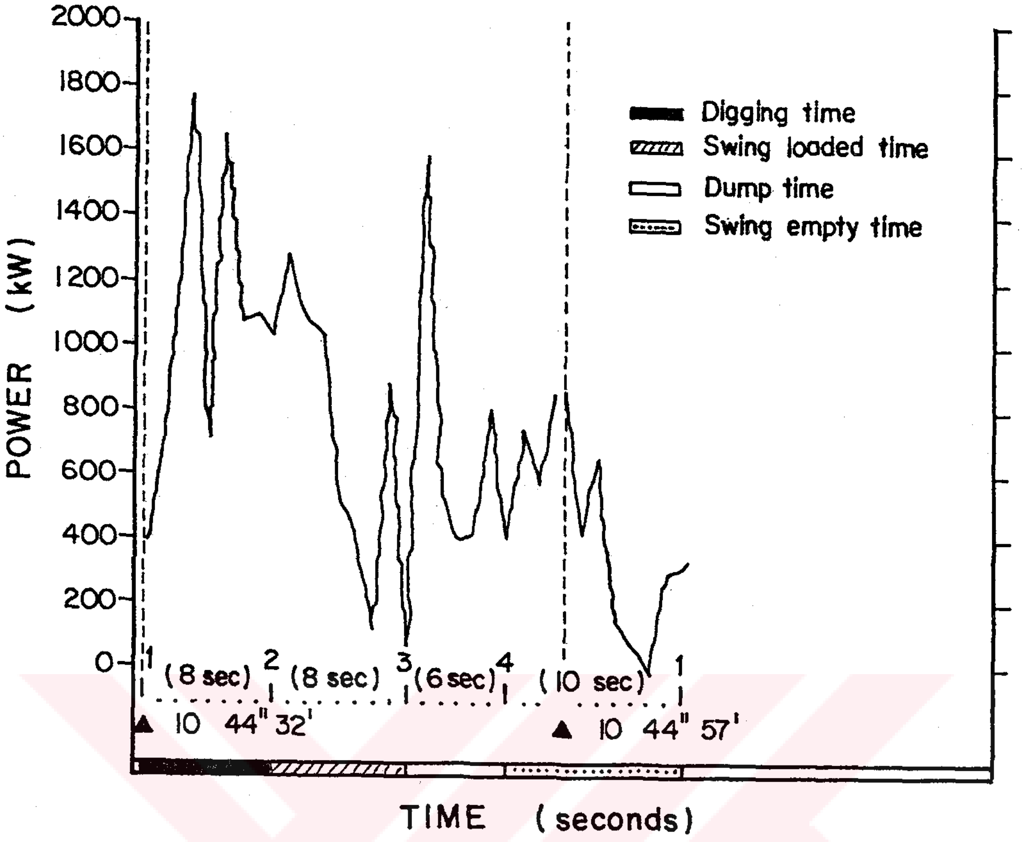


Figure 15. A Typical Power Record of Wattmeter and Data Logger System.

The individual digging sections and cycle times are measured manually by using a chronometer while power recordings are stored with respect to the same time of manual study. The amount of dipper filling in order to assess shovel output and excavation difficulty observation such as easy, moderate or difficult are also noted for each pass. Delays associated with digging cycles are also recorded during the whole measurement period.

Cycle time and power measurements data sheet have been formed and given in Appendix A for each performance measurement of electrical shovel. The sheet is divided into horizontal columns to permit the calculation of performance parameters. Dipper loading time is found from the difference between second and first vertical columns for each individual digging cycle. From the subsequent values of first column, excluding down time, cycle time is derived. Power recordings for a digging cycle or any required time interval can be statistically analyzed by the help of replay mode of data logger and the results for that time interval which are average power, highest power and lowest power can be written on the data sheet after the measurement. A key to the various symbols used for different operations of the shovel is prepared and given at the base of the data sheet.

4. 3. Laboratory Studies

Rock material characteristics for each location are determined in rock mechanics laboratory in order to search the relationships between rock material properties and performance parameters. The following laboratory tests according to ISRM's suggested methods are performed on drill cores obtained from representative intact rock samples which were collected during field studies.

- Uniaxial compression test
- Indirect tensile test (Brazilian test)

- Rock toughness test
- Shore hardness
- Cone indenter value
- Natural unit weight
- Natural moisture content

CHAPTER V

ANALYSIS AND DISCUSSION OF RESULTS

5.1. General

Performance measurement results of electrical power shovels with the dipper capacity ranging from 4.5 yd^3 to 25 yd^3 which were operated to remove overburden formations of Turkish Coal Enterprises surface lignite mines are evaluated in this chapter. The model and age of electrical shovels were also different.

After the interpretation of power recordings, the performance parameters will be analyzed and discussed from the digging difficulty point of view. Rock mass and material properties obtained from field and laboratory studies as explained in Chapter 4 are also included in this chapter to investigate relationships between excavation performance and rock mass/material properties.

5.2. Interpretation of Power Recordings

A wide range of formations, from soft to very hard, can be excavated by electrical power shovels. The best and surest way to diagnose the performance of any electrical shovels for a definite formation is to measure its power consumption and output with respect to time. Power, energy and time needed to excavate formation change as the formation characteristics and digging conditions change.

The power measurement system explained in Chapter 3 was utilized to examine the diggability through shovel instrumentation and monitoring. Performance monitoring should detect relative changes in the diggability of formation.

5.2.1. Ease of Digging Assessment

Before analysis of performance monitoring data, the ease of shovel digging for each cycle during performance monitoring was qualitatively assessed as either easy, moderate, moderately difficult or difficult on the basis of visual observations made.

The easiest digging condition was distinguished during loading of loose, weathered or well-fragmented material at the toe. Loose materials were produced with digging without loading the dipper during face preparation activities of fresh, hard unblasted formations. Easy digging cycles were observed during excavation of very good blasted fresh formations and moderately to highly weathered unblasted formations, where the shovel dipper was loaded easily. Operational conditions such as model and age of the shovel, operator experience were more effective than formation characteristics in this type of digging. Easy digging was recorded as a base reference case to which shovel performance in the remaining conditions is compared.

In moderate digging observation, the shovel could dig the formation in usual manner without meeting any difficulty and/or excessive wear to the machinery but relatively more difficult than easy digging condition.

Moderately difficult and difficult digging cycles were recorded where the shovel dug the formation with difficulty, unexpected motions due to hard digging were observed during these cycles. Eventually, moderately difficult digging is relatively easier than the difficult digging condition under which the excavation may cause some damages to the machinery.

5.2.2. Data Processing

The calculation sequence of power consumption of any required system at any time was explained in detail in Chapter 3. The main drive A.C. motor power consumption of shovel which provides all mechanical power for crowd, hoist, swing and propel motions was recorded with respect to time by using power measurement system. Power recordings of different electrical shovels taken under different operational and digging conditions will be analyzed with the help of produced parameters explained below which they can be a diagnostic indicator of diggability.

The response of shovel main drive A.C. motor related to digging conditions can be used to quantify diggability. The power measurement system was tested on several electrical shovels and different digging conditions. The total power consumption of the shovel was continuously monitored for each dig cycle during performance study. The power data was stored on memory module of the data logger or presented on strip chart if chart recorder had been used with wattmeter.

Performance measurement also included the cycle times, digging times and amount of individual loads in the dipper for each pass together with ease of digging assessment. The parameters explained below, related to observed digging conditions were evaluated for each performance measurement.

Cycle time: The complete loading cycle of the shovel refers to load its dipper, swing loaded to the haulage unit, dump its load into the haulage unit and return with swing motion. Time required in seconds for these motions is measured to obtain cycle time.

Digging time: The dipper loading section of the shovel operating cycle is measured in seconds which is the time interval between beginning and end of digging to fill its dipper from ground level where it is operated to the vertical direction of the working face.

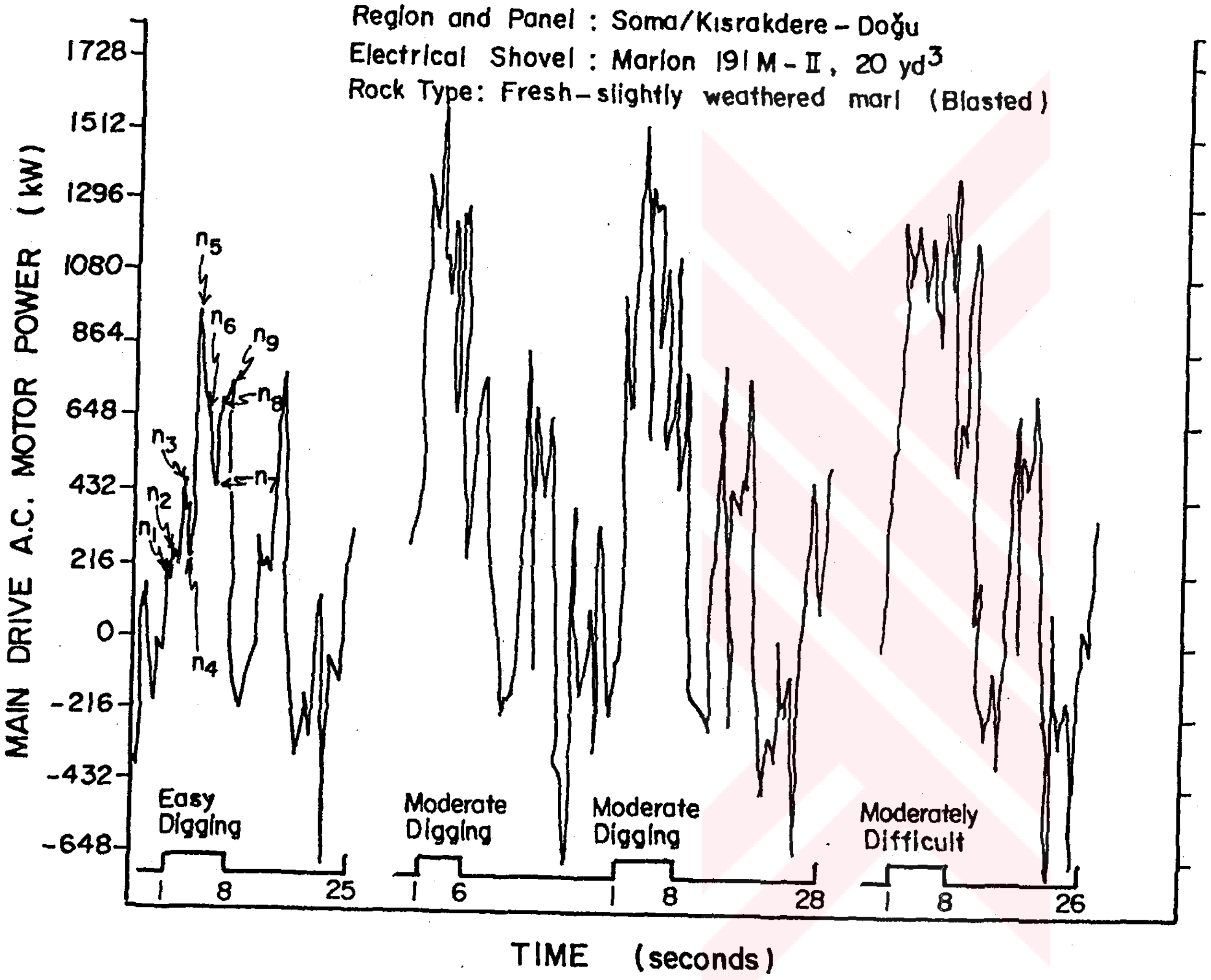
Dipper fill factor: A percentage expression of the amount of the dipper's capacity that is filled with material during digging is the dipper fill factor. The dipper fill factor is 100% plus some fractions by the percent of dipper capacity when the material is heaped to excess of dipper struck measure. On the other hand, the dipper may be filled to less than 100% by the percent of available capacity which is not utilized.

Hourly capacity without waiting: Hourly production capacity of the shovel is directly proportional to the dipper capacity and dipper fill factor and inversly proportional with the cycle time and digging difficulty.

Hourly digging capacity: Another parameter produced from time measurement data which can be an indicator of digging condition is the hourly digging capacity. It is the hourly capacity during the digging action only.

Digging section of the operating cycle relates primarily to digging conditions at the face. The power consumption analysis has been mainly concentrated on the digging sections of the cycles due to diggability point of view and to limit the effect of operational factors. On the other hand, the power consumptions of different models of electrical shovels in each phase of a cycle was different. Because some model of electrical shovels work with an active passive energy consumption system i.e. their main drive A.C. motor which were synchronized can also work as a generator (A.C. power source) during the reverse motion of the hoist (Figure 16).

The power record of digging section is isolated from the remaining cycle elements (swing and dump) either by the help of remote control pen indications of the chart recorder or time measurement data of logger. The duration and nature of the digging event can be also accurately noted and isolated through an inspection of the power recording trends.



n_1 = 1.0 cm x 216 kW/cm = 216 kW

n_2 = 1.2 cm x 216 kW/cm = 259 kW

n_3 = 464 kW

n_4 = 248 kW

n_5 = 972 kW (Peak Power)

n_6 = 680 kW

n_7 = 432 kW

n_8 = 681 kW

n_9 = 756 kW

Average Digging Power = $(n_1 + n_2 \ldots\ldots + n_9)/9$
= 523 kW

Figure 16. A Typical Power Recording Data of Synchronized A.C. Motor, Soma/Kısrakdere.

Time average power of digging: It is possible to evaluate average digging power of each single digging cycle by isolating the digging component. Power record of digging section is divided into 1 mm. divisions i.e. power consumptions can be sampled at the intervals of one second. Then for every division, length of record is measured and multiplied by the unit power which depends on wattmeter and shovel transformer variables as explained in Chapter 3 to obtain exact power consumption of a required period. The total length converted to power is divided by the number of observations to obtain average power consumption for a single digging section of the cycle. This situation is illustrated in the first cycle of Figure 16.

Calculation of average digging power is much easier and time saving if the power record is stored on memory module of the data logger. Average power of digging or any selected time interval can be directly calculated with the help of replay mode of data logger controller which has a built-in statistical analysis software.

Average power of digging is found for all recorded cycles and then it is averaged for a certain observation period to obtain time average power of digging. The average digging powers of second and third cycles are 1213 kW and 1094 kW respectively. Therefore, the time average digging power of moderate digging is the average of those values, that is 1153.5 kW (Figure 16).

Maximum and average of peak digging powers: The highest occurred digging power during a set of recorded data is defined as the maximum of peak digging powers. For example, in Figure 16, the peak powers recorded during digging sections of the two cycles of moderate digging are 1555 kW and 1512 kW, where the maximum peak power is 1555 kW. The average of them, 1533.5 kW, is expressed as average peak power.

Energy consumption of digging: The area under the power recordings of digging phase of the complete cycle refers to energy consumption of digging. For each recorded cycle energy consumption of digging can be determined in terms of kWh by multiplication of average digging power and digging time.

Specific digging energy: The power consumption which is drawn during excavation and the corresponding output of the shovel can be considered to be meaningful parameters in quantifying the performance of electrical shovels in different digging conditions and operation situations. Digging may be characterised by combining these two parameters, in terms of the specific digging energy of the shovel, which is defined as the energy required to excavate one cubic meter of material (kwh/m3).

The calculation of all those parameters, as an example, is presented in Table B-1 of Appendix B.

5.2.3. Discussion on Typical Examples of Power Recordings

Diggability can be defined as the ease of the shovel to dig the muckpile. The adopted measurement system should successfully reflect the variations in digging condition.

Power measurements supported by digging difficulty observations were undertaken in several open pit coal mines of T.K.I. with the aim of defining the relationship between shovel loading performance and signals obtained from main drive A.C. motor of the shovel.

Sample power records representing different digging conditions at various operational conditions are presented in Figures 16 to 26 to illustrate how these have been related to observed digging conditions. Classification of digging categories is based on visual observations. Since the original power measurements presented on these Figures, the determined unit scale of main drive A.C. motor power can not be the same for all recordings. It depends on measurement variables as explained in Chapter 3.

The first field study with wattmeter and data logger has been conducted at Seyitömer open-pit coal mine. The P&H 1900 AL electrical shovel with the dipper capacity of 10 yd3 is monitored during the overburden removal operation (Figure 17). Cycle time, digging time, dipper fill factor and classification of ease of digging according to the visual observation and the corresponding power measurement results are presented in Appendix C.

It is observed that different sections of the shovel operating cycle are reflected in the signals recorded at the main drive A.C. motor. The beginning and end of the different portions of the complete cycle indicated on time measurement data sheet correctly suit the data logger record. As an example, the data of the shovel digging, swing to truck, dump into truck and swing time to bench for two complete cycles of loose material loading is plotted with respect to time (Figure

17). The power recording ranges from 1 to 2 shows digging time, 2 to 3 swing loaded time, 3 to 4 dump time, 4 to 1 shows swing empty time for the next cycle.

The statistical analysis results of power recordings given in Appendix C, show that the highest power and energy consumptions are obtained during digging sections of the complete cycles. The second record given in Figure 18 shows again a loose material loading cycle where the peak power and average power

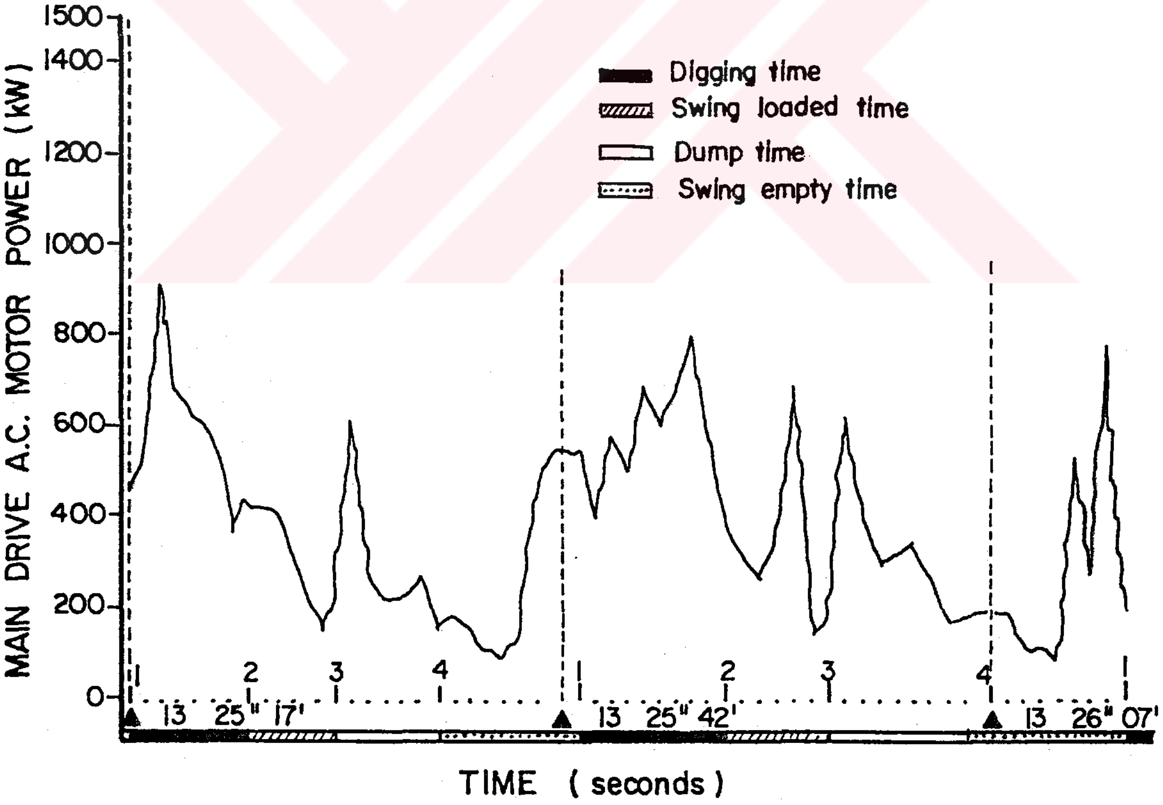


Figure 17. A Typical Power Recordings of Two Complete Loose Material Loading Cycles, Seyitömer/S-28.

consumption of digging are found 801.6 kW and 497.2 kW respectively. While with increasing digging difficulty during loading as defined "Loose+Digging", the peak power and average power consumption of digging are found 905.8 kW and 613.9 kW respectively and the record of this cycle is given in Figure 19.

Energy consumption which changes according to the average power and time, also increases with increasing excavation difficulty. Energy consumptions during dipper loading time of "Loose" and "Loose+Digging" cycles where the power records with respect to time given in Figure 18 and Figure 19 are found 1.105 kWh and 1.535 kWh respectively.

Digging without loading; the dipper is engaged in producing loose material at the toe is quite common during face preparation activities. Power consumptions of digging without loading are also measured as supplementary information to help to understand the digging environment and a typical power record of digging without loading trials is given in Figure 20. The power record taken during wait time of shovel for truck with the average power consumption of 150 kW is given in Figure 21 which clearly reflects the difference in the power spent between the wait time and the digging cycles of the shovel. The performance measurement of

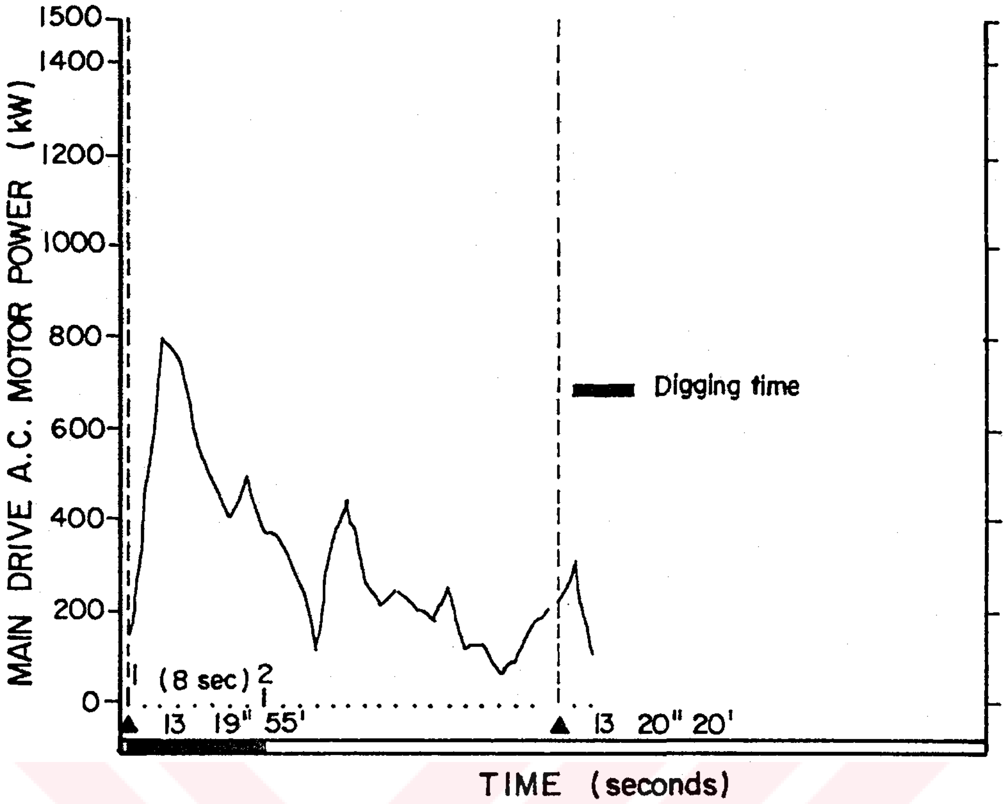


Figure 18. Power Recordings Taken under "Loose" Loading Cycle, Seyitömer/S-28.

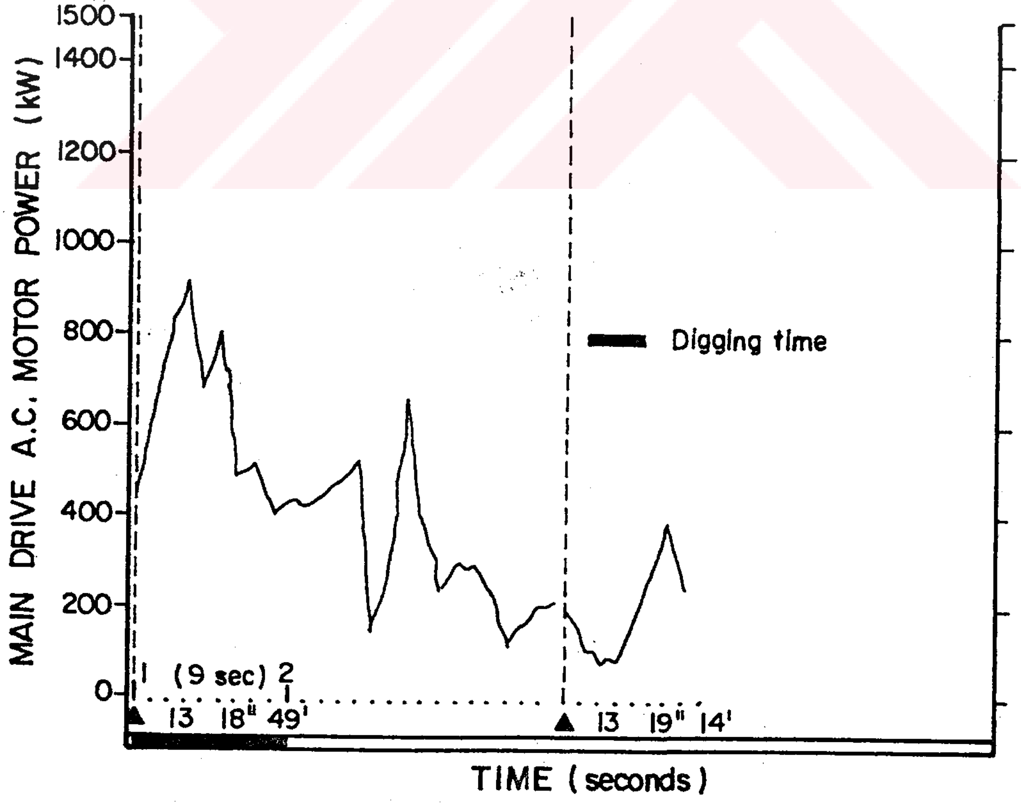


Figure 19. Power Recordings Taken under "Loose+Digging" Loading Cycle, Seyitömer/S-28.

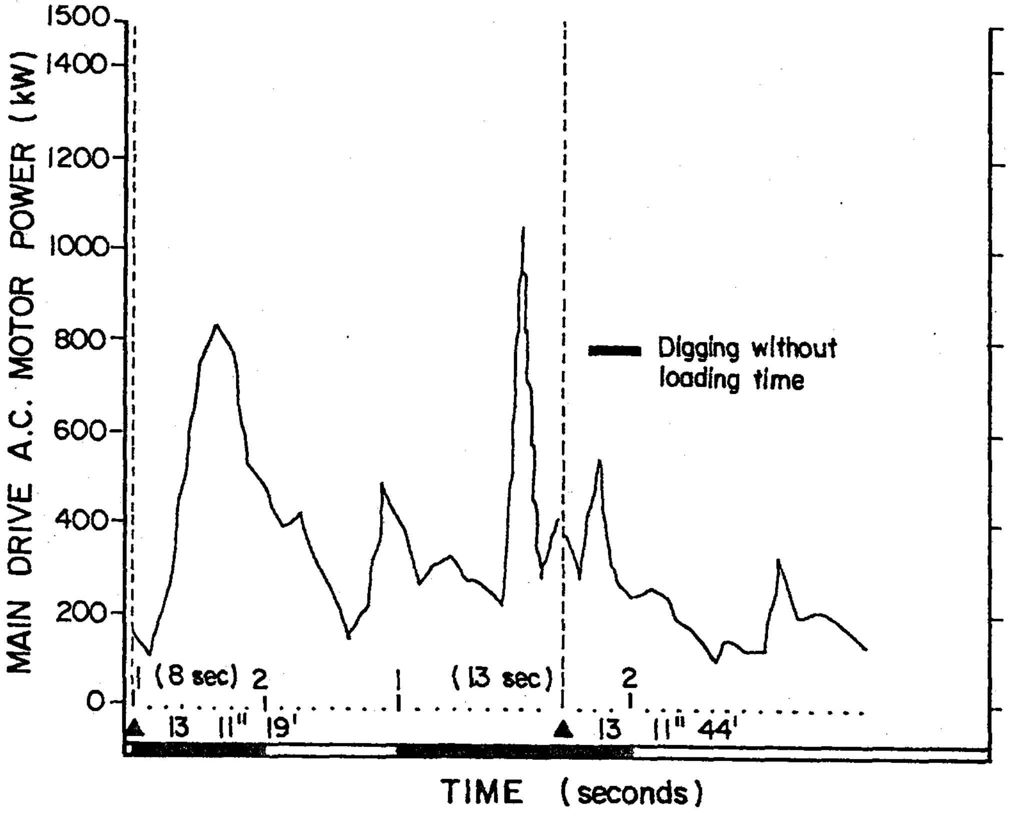


Figure 20. Power Recordings of Digging without Loading, Seyitömer/S-28.

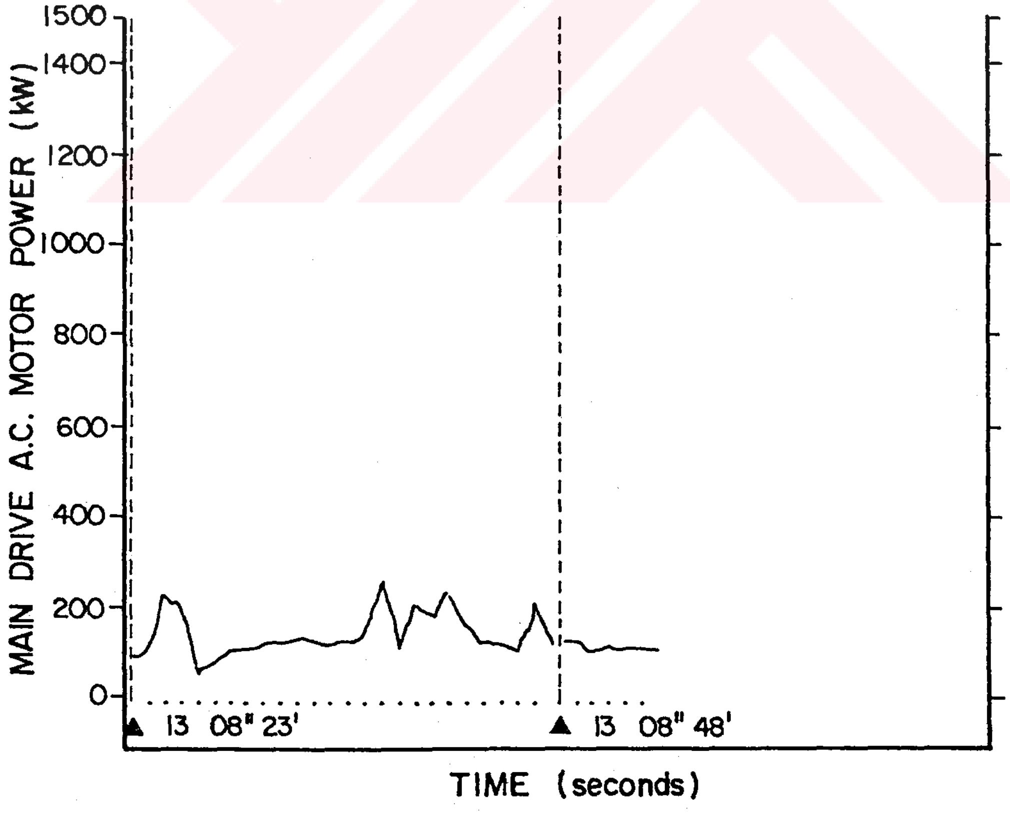


Figure 21. Power Recordings of Wait Time of Shovel, Seyitömer/S-28.

electrical shovel considering the excavation condition is summarized in Table 15. This performance study shows the ability of the power measurement system and indicates that performance parameters such as digging time, power and energy consumptions are strongly related to the degree of excavation difficulty.

By an inspection of the power recordings, the activity of the shovel can also be inferred. Digging activity is characterized by the increase of power consumption. With increasing difficulty in digging condition, it is observed that extra time and power consumption are required to enable effective dipper filling. It should be noted that a complete loading cycle refers to the digging, swinging and dumping elements for each dipper load. Individual loading cycles begin at point which the power consumption increases rapidly as the dipper enters the bench with crowd motion and begins to travel through the face with hoist motion. The power record drops rapidly at the end of the dig cycle. Increasing of power after digging section represents the initial power consumption for swing motion. Hoisting sometimes applied during the swing cycle to elevate the dipper to a level that will clear the box of the haulage truck. The operator may be adjusting the dipper position of rapidly to avoid contact with the truck or better position of the dipper for

Table 15. Shovel Performance Summary at Seyitömer/S-28 Panel.

Electrical Shovel : P&H 1900 AL , 10 yd^3
Rock Type : Slightly to moderately weathered marl (Blasted)

Performance Parameter	Observed Digging Condition		
	Loose Material Loading Cycle	Loose + Digging Loading Cycle	Digging Without Loading Trials
Average Cycle Time (sec)	28.19 ± 4.05	31.22 ± 6.59	-
Time Average Power of Complete Cycle (kW)	361.5 ± 23.5	371.7 ± 18.7	-
Average Energy Consumption of Complete Cycle (kWh)	2.831	3.223	-
Average Digging Time (sec)	7.86 ± 1.46	8.33 ± 1.67	-
Time Average Power of Digging (kW)	550.5 ± 65.2	585.4 ± 56.9	380.7 ± 75.4
Average Energy Consumption of Digging (kWh)	1.202	1.355	-
Maximum Peak Power (kW)	971.0	952.3	1021.0
Average of Peak Power (kW)	842.7 ± 96.1	880.5 ± 51.2	775.0 ± 174.3
Average Dipper Fill Factor	1.04 ± 0.05	1.06 ± 0.07	-
Hourly Capacity Without Waiting (m^3/hr)	1015.5	934.6	-
Hourly Digging Capacity	3642.1	3502.7	-
Specific Energy Consumption of Complete Cycle (kWh/m^3)	0.356	0.398	-
Specific Digging Energy (kWh/m^3)	0.151	0.167	-

opening the lid. The crowd position came into effect as not all trucks would be located on equal distance from the shovel, thus requiring the operator to crowd or retract the dipper for dumping. This sort of changes caused some deviations in usual trend of power recordings.

For the purposes of this study it had been thought that only the digging sections of complete loading cycles would be the best period in which to reflect digging condition, as mentioned in previous pages. Analysis was undertaken in order to try and determine if the power recordings of digging elements were related to the digging conditions. Beginning and end of the digging sections of the shovel operating cycles indicated at the lower parts of these Figures.

Longer bucket fill time is usually an indication of difficult digging condition, but the shovel operator sometimes expends more time in manoevering the dipper to obtain optimal fill factor in limited volumes of loose material at the toe like in the first record of Figure 16. The loose material loading time is found 8 sec. which is equal to the digging time obtained in moderately difficult digging condition. On the other hand the digging time can be decreased with fast movement of the shovel during excavation, but in this case the power consumption would be higher compared to relatively difficult digging cycles. Two moderate digging cycles, in Figure 16, where the digging times are 6 sec. and 8 sec. with the average digging power consumptions of 1213 kW and 1094 kW respectively. The average power of digging is found 1207 kW in moderately difficult digging cycle which is less than the first record of moderate digging cycle. Digging energy consumption is another good indicator which reflects the ease of digging. In Figure 16, the digging times of the second record of moderate cycle and moderately difficult digging cycle are equal, but the power consumption increases 10% with increasing difficulty. The digging power consumption of the first record in moderate cycle is slightly greater than the moderately difficult cycle, which is unexpected but when digging times are also considered reasonable result can be obtained in terms of energy consumption of digging rather than power and time alone. The energy consumptions of digging for these moderate and moderately difficult digging cycles are 2.022 kWh and 2.682 kWh respectively. In easy digging, it is 1.162 kWh, where the energy consumption of digging increases 74% from easy to moderate digging and 131% from easy to moderately difficult digging. Peak powers of digging for each cycle are also compared with each other, where they are 972 kW, 1555 kW and 1382 kW for easy, first record of moderate and moderately difficult digging cycles respectively. The maximum peak power obtained during the moderate digging condition may not indicate always the digging difficulty. The amount of dipper filling was also observed for each dig cycle during measurement in order to assess shovel output and specific digging energy consumption. In easy digging, the specific digging energy is found 0.108 kWh/m3 and the highest specific digging energy of 0.251 kWh/m3 is found to arise in the moderately difficult digging condition (Figure 16).

Power measurement of the actual cycle repeated two to four times as if the shovel is digging while the dipper is empty i.e. no contact with muckpile. These experiments are expressed as empty cycle and the hoisting section of these cycles is defined empty digging motion. The empty cycle measurements used as a base reference for the comparison of different digging conditions. This procedure has been repeated before implementing the performance monitoring studies at most of the site conditions. In such a way, the differences resulting from operator experience, model and age of excavators were all eliminated. Obviously, the time required for empty digging motion should be expected less than easy digging time. This situation is well presented in Figure 23. The operator sometimes spent more time to show this motion clearly, but in these cases, the corresponding powers are less than the powers of smaller times. A typical example illustrating the longer empty digging time, obtained at Seyitömer S-20 panel, is presented in Figure 22. The energy consumptions of those empty cycles are 0.447 kWh and 0.593 kWh respectively, and the corresponding energy consumptions of loose material loading cycles are 1.215 kWh and 1.040 kWh respectively, although 2 sec. less time obtained in these cycles. Dipper fill amount also considered to assess the effective energy consumption of digging. The observed dipper fill factors are 1.10 and 0.60 for the first and second loose material loading cycles and the corresponding average digging powers are 729 kW and 624 kW respectively in Figure 22. Although the average digging power consumption decreases 17% with decreasing dipper fill amount, the specific digging energy increases 58%. It clearly shows the inefficient loading due to the limited amount of loose material to be loaded for the second loading cycle. The dipper fill factor observed for the last cycle of Figure 22, is 1.00, and the specific digging energy is 0.403 kWh/m3. The specific energy consumption of the first example of loose material is 0.144 kWh/m3. When they are compared, the specific digging energy consumption of last cycle is 2.8 times greater than the loose cycle, although their fill factors are more or less the same. The last cycle is

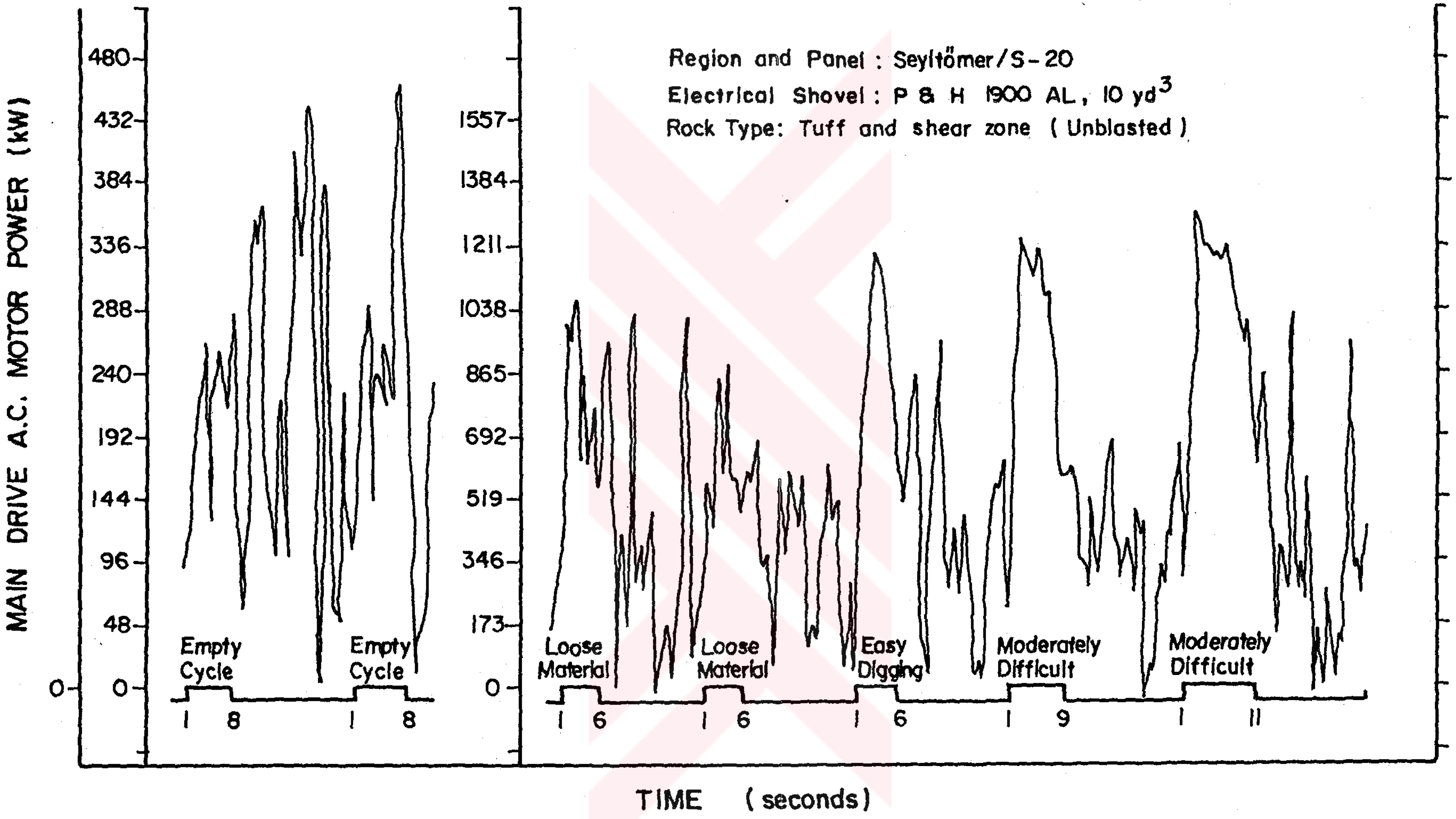


Figure 22. Power Recordings Illustrating the Longer Empty Cycles.

classified as moderately difficult digging, and it is seen that it agrees with the description of visual inspection during field studies.

Figure 23 illustrates three different digging conditions and empty cycles of a 10 yd3 bucket capacity shovel. Empty digging motions having not only the shortest dig time, 4 sec., but also the lowest average powers 250 kW and 225 kW. The average dig powers of loose material loadings are low, 720 kW and 749 kW, and digging times are shorter with the dipper fill factor of 1.00, indicating fast and easy travel of the dipper. In moderate and moderately difficult digging cycles, the average digging powers are 821 kW and 914 kW respectively with the same dipper fill factor of 1.10 and dig time also increases with increasing digging difficulty (9 and 10 seconds). The average specific digging energy values for loose, moderate and moderately difficult cycles of blasted marl are 0.146, 0.244 and 0.302 kWh/m3 respectively. The increase in average specific energy for moderately difficult digging condition, compared to loose, is 107%.

Figure 24 illustrates some typical examples at different digging conditions of unblasted marl formation by a 10 yd3 capacity shovel at Yatağan-Eskihisar mine. The dipper fill factor was around 1.00 for all digging

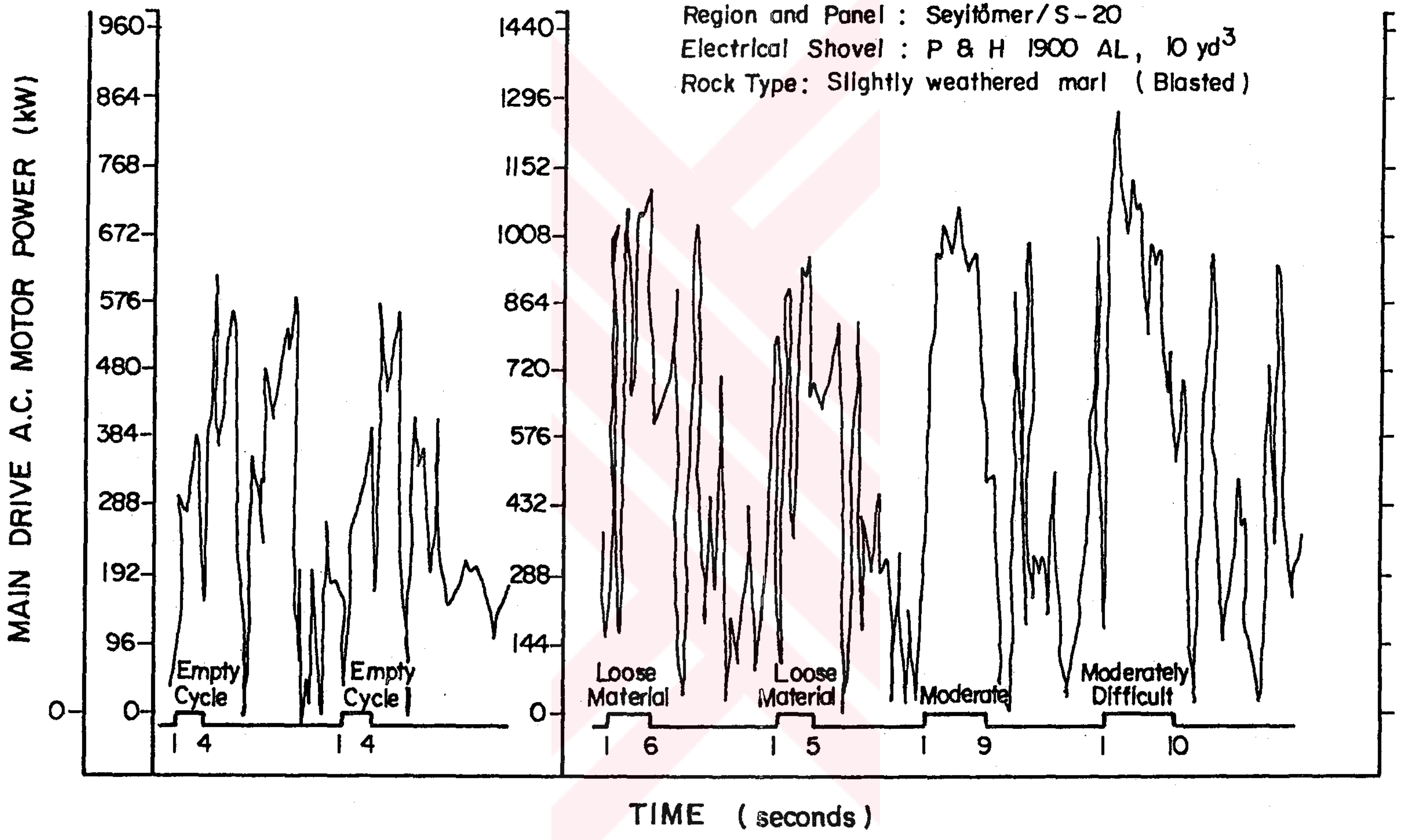


Figure 23. Power Recordings of a 10 yd^3 Bucket Capacity Shovel for Wide Range of Diggability.

cycles. Easy digging condition was recorded during loading of loose material at the toe with a specific digging energy value of 0.317 kWh/m^3. The specific digging energy values are 0.532 kWh/m^3 and 0.648 kWh/m^3 for moderate and moderately difficult digging respectively. The specific digging energy values are rather high compared to the values obtained in Figure 23, although the same bucket capacity was used. It is due to the higher average power consumption of empty digging motion, 448 kW, in Figure 24.

Figure 25 illustrates the power monitoring recordings of a 15 yd^3 capacity shovel at Tınaz unblasted conglomerate. The shapes of the records which depend on power and time clearly reflect the variations in digging condition. Values of digging power consumption and time needed during difficult digging cycle are significantly high compared to other digging cycles, indicating slow and difficult travel of the dipper. As the digging difficulty increases, all the performance parameters such as average digging power, peak power of digging, energy consumption of digging and digging time are also increasing. Although the observed maximum dipper fill amount was 1.10 during difficult digging, the highest specific digging energy of 0.383 kWh/m^3 was obtained in the same digging condition. The specific digging energy values for loose material loading and

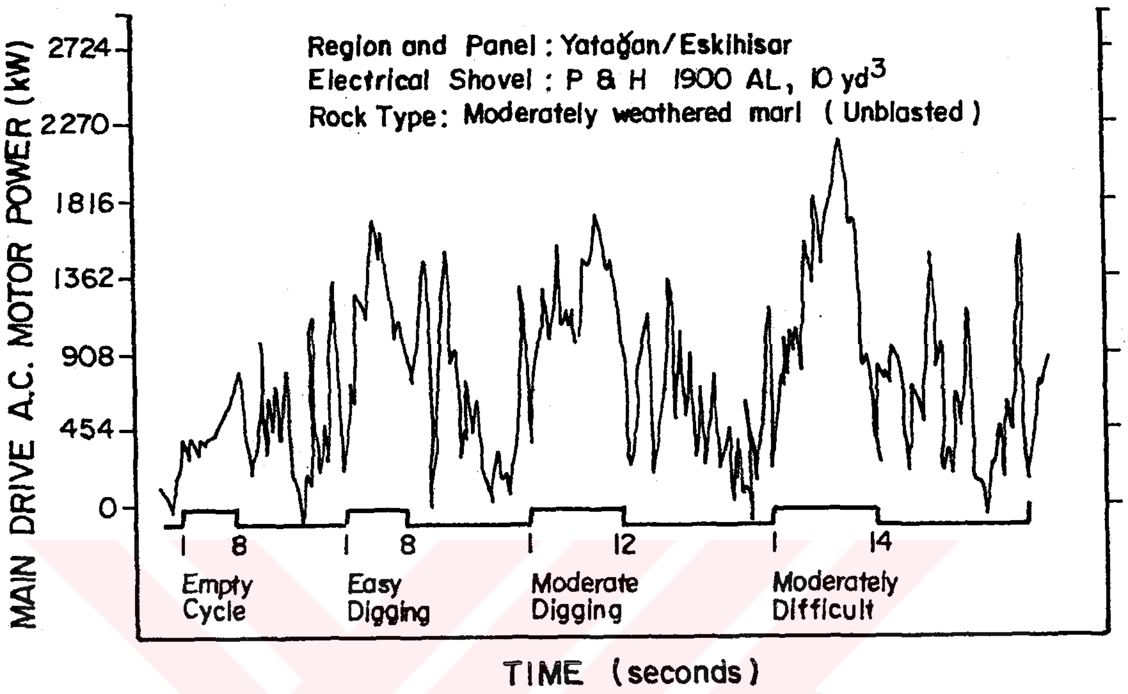


Figure 24. Power Recordings of Unblasted Marl at Yatağan Site.

moderately difficult digging cycles are 0.220 kWh/m3 and 0.318 kWh/m3 respectively. The increase of specific digging energy is 74% from easy to difficult digging.

The effectiveness of any particular blast can be better evaluated in terms of shovel performance in loading the blasted and unblasted formation. Sample power recordings of a 15 yd3 dipper capacity shovel as monitored for blasted and unblasted marl formation of Milas-İkizköy are given in Figure 26. Moderately difficult digging condition was observed during loading

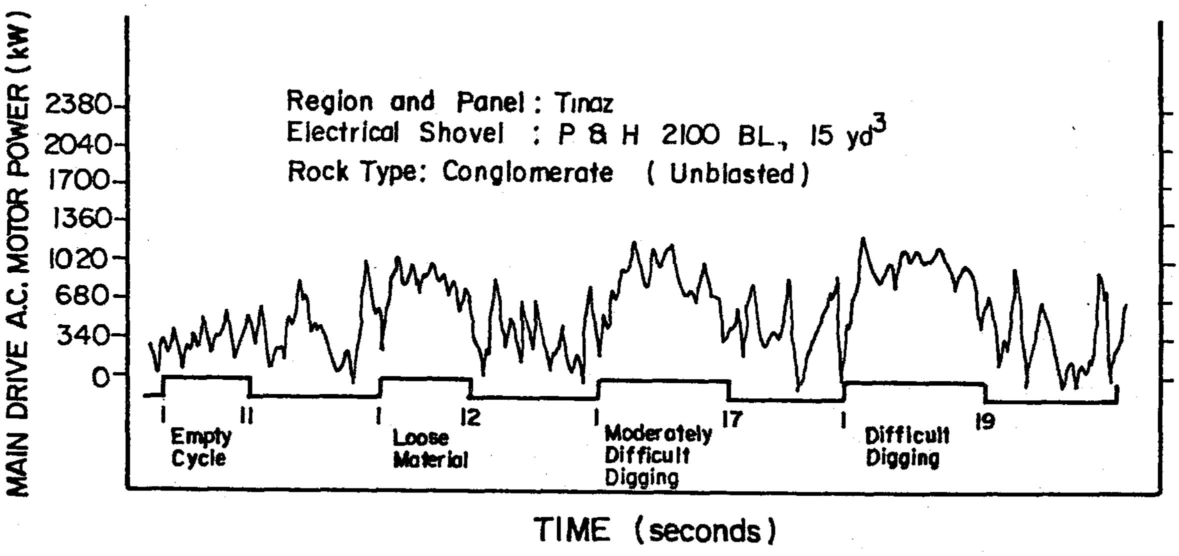
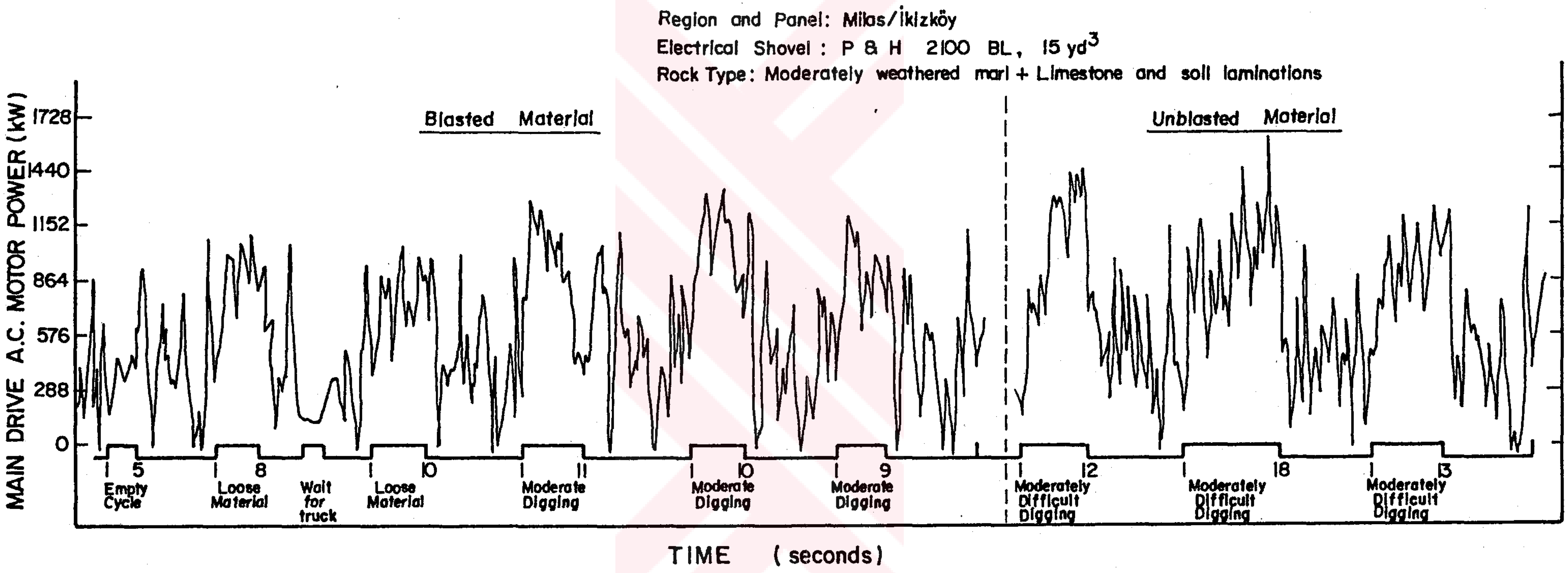


Figure 25. Power Recordings of Unblasted Conglomerate at Tınaz Site.

of unblasted formation, where the ease of digging assessment based on shovel digging activity, irrespective of the formation characteristics and blasting. Not only the high power consumptions but also longer digging times were recorded during loading of unblasted formation. The average specific digging energy found for three moderately difficult digging cycles of Figure 26 is 0.301 kWh/m3. The average specific digging energy of moderate digging cycles observed during blasted case is found 0.228 kWh/m3, which is 32% lesser. For the loose material loading cycles it is found



Region and Panel: Milas/İkizköy
Electrical Shovel : P & H 2100 BL, 15 yd^3
Rock Type: Moderately weathered marl + Limestone and soil laminations

Figure 26. Comparison of Blasted and Unblasted Performance Monitoring Data, Milas/İkizköy.

0.169 kWh/m3. Table 16 lists the calculated shovel performance parameters for each cycle of Figure 26 and demonstrates the capability of such data to reflect variations in muckpile diggability.

The shovel monitoring can provide an accurate and realistic measure of diggability over a range of actual ground conditions. Results of shovel monitoring indicate that a knowledge of main drive A.C. motor effort, digging time and excavated amount of material provide an effective means to correlate the ease of digging assessments.

The following deductions can be made from the above discussions:

i. The digging times show a slight increase from easy to difficult digging.

ii. Digging power consumptions show a remarkable increase from easy to difficult digging.

iii. The specific digging energy values change significantly with the change in digging conditions.

Table 16. Shovel Performance Parameters Related To Different Digging Conditions of Figure 26.

Observed Digging Condition	Cycle Time (sec)	Digging Time (sec)	Dipper Fill Factor	Average Digging Power (kW)	Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m^3)
Empty Cycle	20.0	5.0	-	338	461	0.469	-
Easy Digging (Loose material loading)	25.0 28.0	8.0 10.0	1.00 1.00	822 740	1123 1008	1.827 2.056	0.159 0.179 (Av:0.169)
Moderate Digging	31.0 27.0 26.0	11.0 10.0 9.0	1.00 1.00 1.00	926 1039 845	1296 1368 1354	2.829 2.886 2.112	0.247 0.252 0.184 (Av:0.228)
Moderately Difficult Digging	30.0 35.0 30.0	12.0 18.0 13.0	1.00 1.10 1.10	942 944 895	1454 1613 1224	3.140 4.720 3.232	0.274 0.374 0.256 (Av:0.301)

5.3. Interpretation of Depth of Cut Studies

5.3.1. Influence of Depth of Cut and Blasting on Shovel Digging Performance

Field studies of shovel monitoring related to depth of cut and blast performance have also concentrated on examining factors affecting the production rate and digging activity. The following parameters are considered to be the most significant:

i. Cycle time
ii. Digging time
iii. Dipper fill factor
iv. Power and energy consumptions of digging

In this section, the electrical shovel performance results of Yatağan-Eskihisar and Tınaz open-pit coal mines of T.K.I. both before and after blasting will be discussed considering the field and laboratory data.

Typical examples of power recordings presented in the previous section show that the main drive A.C. motor of electrical shovel responses are sufficiently sensitive to different digging conditions. Depth of cut is an important consideration in evaluating shovel performance. The path of the dipper greatly influences the power consumption of digging. For example, the power and energy consumptions may indicate easy digging condition if the dipper makes short, shallow pass through the formation in hard digging condition. Similarly the records of easy digging condition may show hard digging formation with excessive depth of cut.

5.3.1.1. Establishment of Depth of Cut

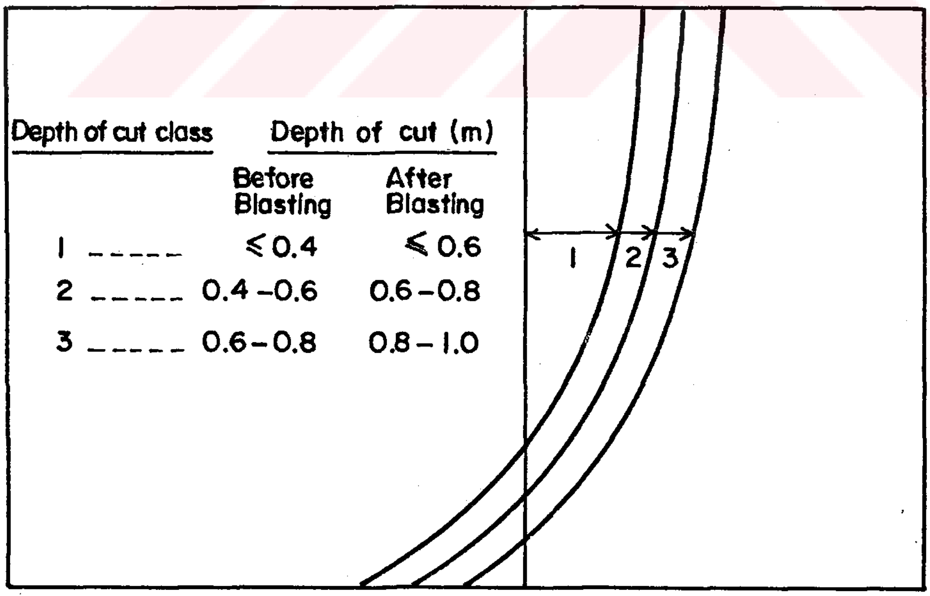
During power measurements of digging, the depth of cut was carefully observed for numerous digging trials before and after blasting including dipper fill factor. Being digging the result of an interaction between the excavating tool and the rock mass, the digging section of the complete shovel cycle should be considered which relates primarily to depth of cut at the face and be less sensitive to operator behaviour, truck availability, swing speed and angle and the various other factors that affect productivity.

The dipper arm was maintained at the same angle at the beginning of the cycle for all digging trials. It should be noted that the dipper trajectory for different depths of cut was also the same, which was provided with the same distance between shovel and the face by shovel movement to the face, regardless of arm movement since the response of main drive A.C. motor could be influenced by the position of dipper. Then the digging power consumptions of different depths of cut had been measured successfully with the power measurement system, which is explained in detail in Chapter 3.

The indicated lines drawn on the shovel dipper before the measurements, and the depths of cut during digging trials were determined from the closely observation of the dipper at excavation faces. The indicated lines of a shovel dipper used for the prediction of cut depth during measurements are presented in Figure 27.

Three classes of cut depth were established during field studies. The bench face profiles nearly vertical in all digging trials. Figure 28 shows the shapes of the dipper trajectories associated with each of the three cut depth classes observed at Yatağan-Eskihisar and Tınaz open-pit coal mines.

Figure 27. The View of the Indicated Lines of a 15 yd3 Shovel Dipper for the Prediction of Cut Depth.



Depth of cut class	Depth of cut (m) Before Blasting	Depth of cut (m) After Blasting
1 -----	≤ 0.4	≤ 0.6
2 -----	0.4 – 0.6	0.6 – 0.8
3 -----	0.6 – 0.8	0.8 – 1.0

Figure 28. The Dipper Trajectories and Classification of Different Depths of Cut.

Ranges of each depth of cut classes, before and after blasting, were different. Where in class 1, it was difficult to limit the depth of cut to a certain value for the blasted material which might be up to 0.6 m. It was determined 0.4 m for unblasted formations in class 1. The majority of dig cycles during usual operation of shovel, irrespective of digging conditions, fell within the ranges of depth of cut class 2, where 0.4 m to 0.6 m for unblasted formations and 0.6 m to 0.8 m for blasted cases. In this study, lower and higher depths of cut were applied for classification purpose. Before blasting, it could be possible to reach the cut depth of 0.8 m. After blasting the depth of cut could be increased to 1.0 m.

5.3.1.2. Field Case Studies

The influence of depth of cut through the formation on electrical shovel performance before and after blasting is investigated in these field case studies. It is also aimed to show the essential difference between shovel performance with blasting or without blasting (direct digging) conditions.

Field case studies involved power and performance measurements of four different cases of the electrical shovels related with depth of cut and blasting efficiency are carried out at Yatağan-Eskihisar and Tınaz open-pit coal mines. Seven years old P&H 2100 BL electrical shovels in Yatağan-Eskihisar and four years old P&H 2100 BL electrical shovels in Tınaz with the dipper capacity of 15 yd^3 are monitored during the excavation of overburden formations. Some rock mass and material properties of the formations are also included in this study. The studied formations are described for each of the case study and operational conditions of each case are also given. The rock mass and material properties of four studied cases are presented in Table 17. The representative sections of each formation before and after blasting taken during the performance measurements are given after the formation description.

Case 1 (Yatağan-Eskihisar): Formation is fresh banded gray marl and horizontally bedded, where the bedding thickness ranged from 0.4 m to 1.5 m with an average thickness of 0.8 m. There are two joint sets,

Table 17. Some Rock Mass and Material Properties of Case Studies.

Case No.	Region	Rock Type	Uniaxial Compressive Strength (MPa)	Natural Unit Weight (gr/cm^3)	Moisture Content (%)	Schmidt Hardness	Bed Seperation (m)	Joint Spacing(m) (No. of Joints)	Penetration Rate(m/min) Thrust=60 kN (MPa)	Specific Charge (kg(ANFO)/m^3)
1	Yatağan Eskihisar	Marl	10.23	1.63	30.8	34	0.80	0.85 (2)	1.852 (130)	0.088
2	Yatağan Eskihisar	Marl	10.01	1.59	30.7	31	0.50	1.00 (2)	-	-
3	Tınaz	Conglomerate	-	-	-	-	-	-	0.696 (120)	0.879
4	Tınaz	Marl	17.86	1.90	15.5	34	0.70	0.60 (2)	0.873 (130)	0.287

where the first one is 60° to bedding with the spacing of 1.0 m and the second joint set is perpendicular to first set and the spacing is 0.7 m. The 70% of the block size is 0.5x0.6x0.7 m and the maximum block size is 1.5x1.0x1.0 m before blasting. The 90% of the total muckpile block size, after blasting, is 0.3x0.3x0.4 m and the maximum block size is 1.0x0.8x0.7 m. The working bench of the shovel is approximately 12 m and double side loading of trucks is used where the average swing angle is 90°. Shovel operator has been worked for four years. Figure 29 and Figure 30 show the shovel working bench before and after blasting respectively.

In each case study, time and power consumptions of shovel operating cycles for three depth of cut classes before and after blasting are measured several times. Power records of the dig cycles are isolated and evaluated according to depth of cut considering dipper fil amount for all case studies.

The results of measurement show that A.C. motor response to variations in depth of cut and also reflect the effects of blasting on shovel digging performance. As an example, the power recordings of various digging cycles before and after blasting taken under different depths of cut in Yatağan-Eskihisar fresh marl formation (Case 1) are illustrated in Figure 31 and the

Figure 29. Shovel Working Bench Before Blasting at Yatağan-Eskihisar Mine, Case 1.

Figure 30. Shovel Working Bench After Blasting at Yatağan-Eskihisar Mine, Case 1.

corresponding performance parameters of each cycle are presented in Table 18. The data on digging power consumption indicate that variations in depth of cut exert a pronounced influence over the response of the main drive A.C. motor, and hence will significantly influence the performance parameters. A deep cut through a muckpile will result in a higher power consumption than for a shallow cut. The power consumpiton of the shovel during hoist motion with no contact with the excavation face is measured to regard as a base case for comparitive depth of cut studies. The first and second cycles of Figure 31 are recorded during empty cycles, where the empty digging motions take 9 sec. with the average power of 441.1 kW and 432.8 kW. Average energy consumption of these two empty digging motions is calculated 1.092kWh with the standard deviation of 0.015 kWh. In Figure 31, at the maximum depth of cut before blasting which is established as 0.8 m, there are two digging cycles with the average digging power of 1206.9 kW and 1250.4 kW, and the energy consumptions of 4.358 kWh and 5.210 kWh. Energy consumption of digging cycles for the first depth of cut class before blasting ranged 1.745 kWh to 2.236 kWh with an average value of 1.942 ± 0.209 kWh. Before or after blasting as the depth of cut increases the power and energy consumptions of digging also increase. On the other hand, there is a significant difference in the specific digging energy consumed

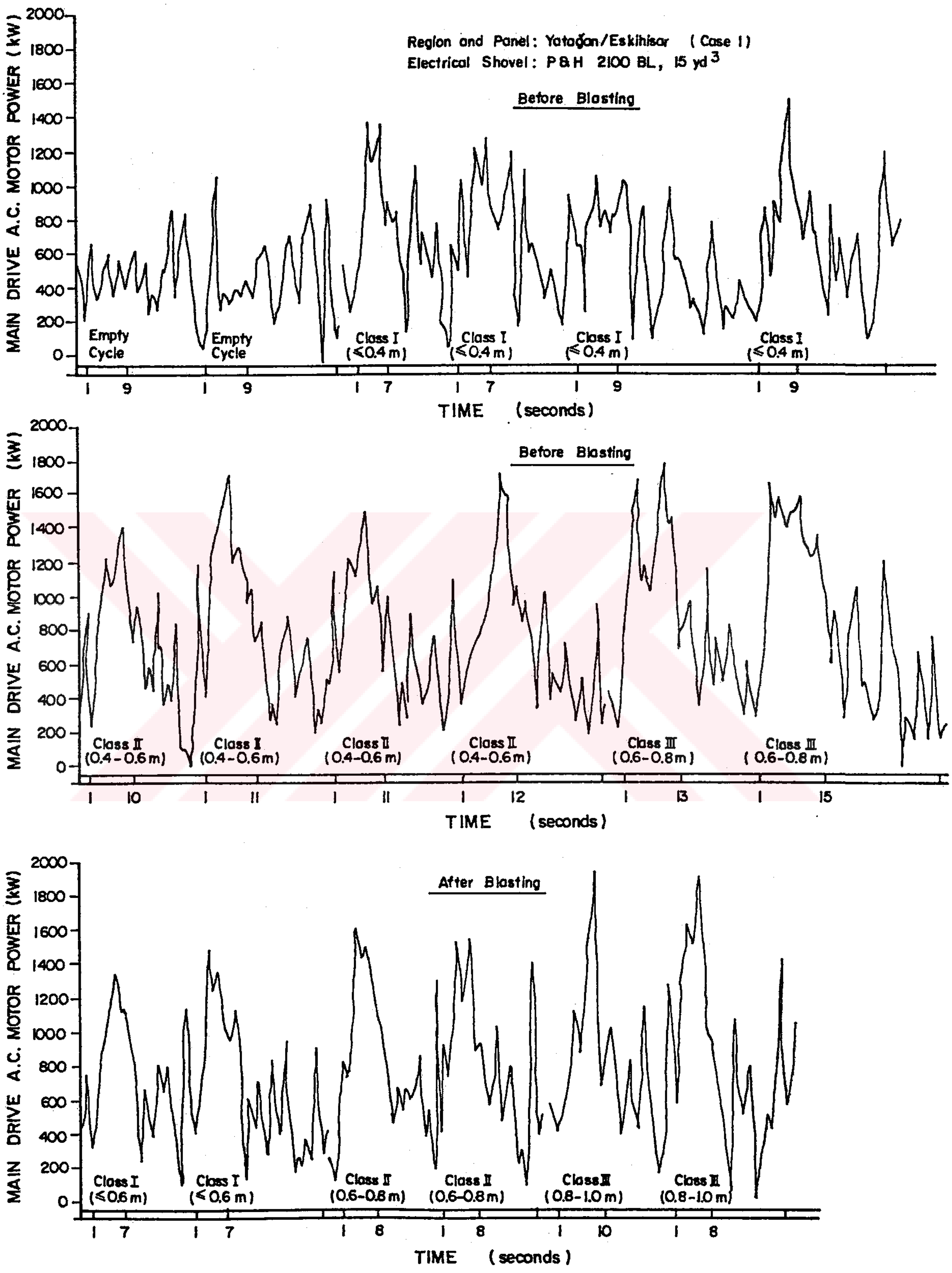


Figure 31. The Typical Power Recordings of Different Depths of Cut in Case 1 (Yatağan Fresh Marl).

Table 18. Shovel Digging Performance Parameters Related to Different Depths of Cut.

Case No: 1 (Figure 31)

Region and Panel: Yatağan/Eskihisar

Electrical Shovel: P&H 2100 BL, 15 yd^3

Dept of Cut Class		Cycle Time (sec)	Digging Time (sec)	Dipper Fill Factor	Average Digging Power (kW)	Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m^3)
Before Blasting	I (≤0.4m)	23.0	7.0	0.90	988.5	1343.2	1.922	0.186
		27.0	7.0	1.00	897.6	1265.5	1.745	0.152
		41.0	9.0	1.00	745.5	1032.7	1.864	0.163
		28.0	9.0	1.00	894.2	1476.1	2.236	0.195
	II (0.4-0.6m)	26.0	10.0	1.10	963.7	1380.1	2.677	0.212
		29.0	11.0	0.90	1161.9	1674.4	3.550	0.344
		29.0	11.0	0.90	1023.1	1464.7	3.126	0.303
		31.0	12.0	1.00	1007.3	1712.8	3.358	0.293
	III (0.6-0.8m)	31.0	13.0	1.00	1206.9	1749.2	4.358	0.380
		41.0	15.0	1.00	1250.4	1657.6	5.210	0.454
After Blasting	I (≤0.6m)	23.0	7.0	1.10	959.1	1337.8	1.865	0.148
		28.0	7.0	1.10	980.4	1487.9	1.906	0.151
	II (0.6-0.8m)	23.0	8.0	1.10	1172.4	1599.4	2.605	0.207
		21.0	8.0	1.10	1078.4	1525.8	2.396	0.190
	III (0.8-1.0m)	26.0	10.0	1.10	1015.6	1915.7	2.819	0.224
		25.0	8.0	1.00	1284.4	1864.8	2.855	0.249
Empty Cycle		27.0	9.0	-	441.1	633.0	1.103	-
		29.0	9.0		432.8	1056.0	1.082	

between direct digging and digging after blasting when the same depth of cut is considered.

Another typical power recordings of shovel cycles as recorded for different depths of cut in Tınaz conglomerate (Case 3), which was the hardest formation encountered during field case studies, are illustrated in Figure 32. Table 19 lists the shovel digging performance parameters for each cycle of Figure 32. The data, especially specific digging energy, clearly reflects the variations in digging performance due to depth of cut and blasting. The formation properties are described below.

Case 3 (Tınaz): Formation is tightly cemented conglomerate and limestone blocks are distributed randomly and rarely. There is not any visible joint set. Pebble size of the conglomerate ranged between 2 to 40 cm and average pebble size is about 10 cm. The 80% of in situ block size is around 0.3x0.4x0.4 m and the maximum block size is 1.5x1.0x0.7 m before blasting. The block size after blasting is less than 0.2 m (80%) and the rest of the block size is 0.3x0.4x0.4 m. The bench height is 9.5 m. Double side loading is used and the operator experience is four years. Shovel working bench before and after blasting can be seen in Figure 33 and Figure 34.

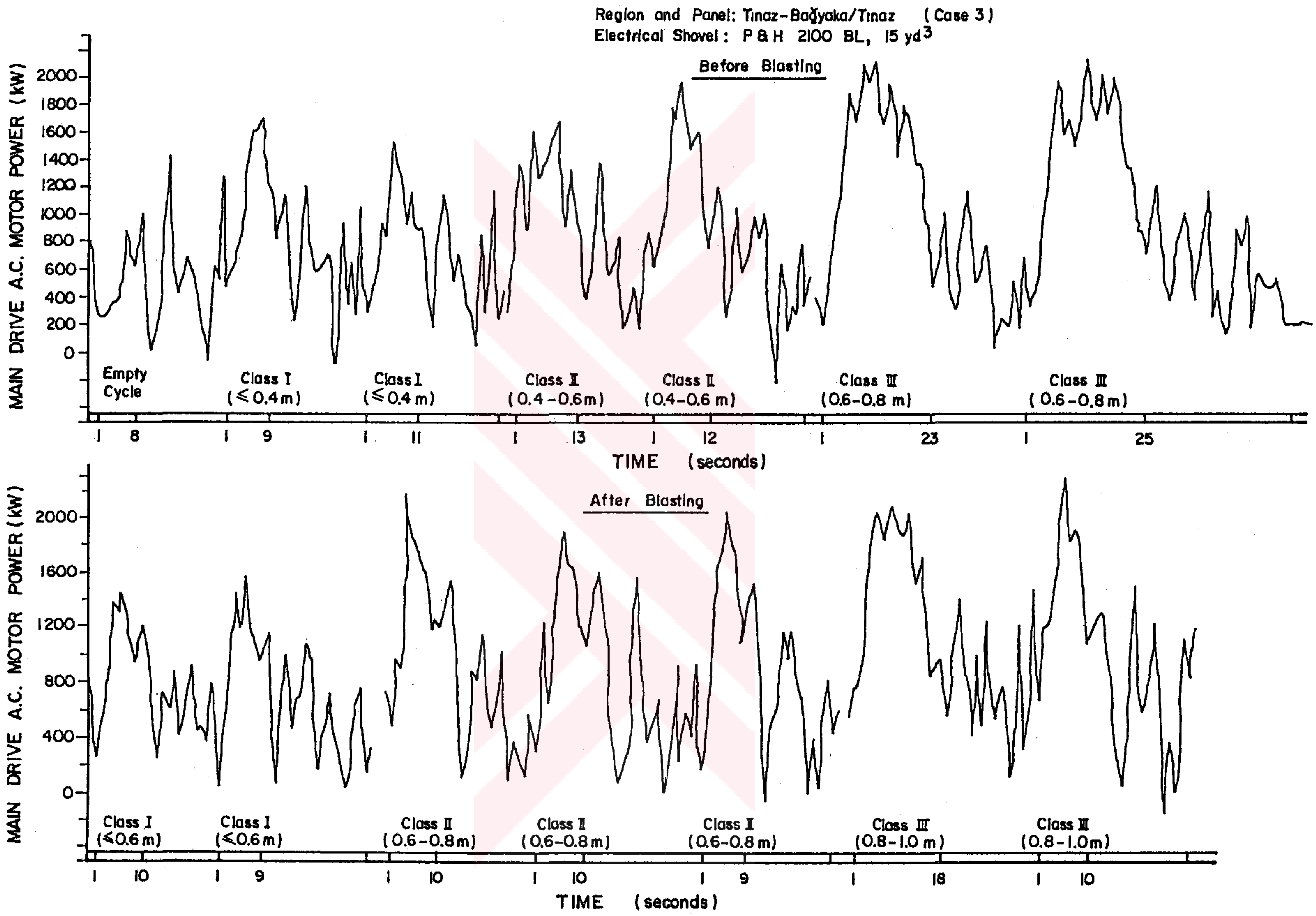


Figure 32. The Typical Power Recordings of Different Depths of Cut in Case 3 (Tınaz Conglomerate).

Table 19. Shovel Digging Performance Parameters Related to Different Depths of Cut.

Case No: 1 (Figure 32)

Region and Panel: Yatağan/Eskihisar

Electrical Shovel: P&H 2100 BL, 15 yd3

Dept of Cut Class		Cycle Time (sec)	Digging Time (sec)	Dipper Fill Factor	Average Digging Power (kW)	Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)
Before Blasting	I (≤0.4m)	29.0	9.0	1.10	1144.7	1691.0	2.862	0.227
		28.0	11.0	1.00	926.3	1517.2	2.830	0.247
	II (0.4-0.6m)	29.0	13.0	1.00	1236.3	1662.2	4.464	0.389
		32.0	12.0	1.10	1309.4	1906.0	4.365	0.346
	III (0.6-0.8m)	43.0	23.0	1.10	1448.0	2105.0	9.251	0.733
		56.0	25.0	1.10	1444.0	2104.3	10.028	0.795
After Blasting	I (≤0.6m)	26.0	10.0	1.10	1040.5	1446.3	2.890	0.229
		31.0	9.0	1.10	1078.0	1549.5	2.695	0.214
	II (0.6-0.8m)	31.0	10.0	1.10	1343.3	2106.1	3.731	0.296
		35.0	10.0	1.10	1271.0	1860.4	3.531	0.280
		27.0	9.0	1.10	1430.6	2019.9	3.577	0.283
	III (0.8-1.0m)	39.0	18.0	1.10	1526.2	2075.6	7.631	0.605
		31.0	10.0	1.10	1578.6	2267.9	4.385	0.348
Empty Cycle		27.0	8.0	-	493.8	858.4	1.097	-

Figure 33. Shovel Working Bench Before Blasting at Tınaz Mine, Case 3.

Figure 34. Shovel Working Bench After Blasting at Tınaz Mine, Case 3.

Shovel digging performance parameters of each recorded cycle related to digging trials of depth of cut are tabulated in Table D.1 for each case study and given in Appendix D. The rock units describtions of Case 2 and Case 4 are also included to Appendix D.

Table 20 presents the results of statistical analysis of the data given in Appendix D and also provides the ranges of digging energy consumption and specific digging energy within three depth of cut categories before and after blasting for each case study. Time average power of digging, energy consumption of digging and specific digging energy values (Table 20) are plotted with respect to depth of cut for the blasted and unblasted cases in Figures 35, 36 and 37 respectively.

The importance and effect of depth of cut on the power and energy consumptions of shovel during excavation is easily being shown on these Figures. The power consumption variation due to digging with different depths of cut has been found to be significant. The results of digging power consumption of each case before or after blasting indicate the relative increase of digging power with increasing depth of cut (Figure 35).

Table 20.a. Digging Power Consumptions Related to Depth of Cut (For All Cases).

Region and Panel	Formation Description	Shovel: Model Dipper Capacity(yd^3)	Performance Parameter	Depth of Cut (m)						Empty Digging Motion
				Before Blasting			After Blasting			
				≤0.40	0.40-0.60	0.60-0.80	≤0.60	0.60-0.80	0.80-1.00	
Yatağan Eskihisar (Case 1)	Fresh-slightly weathered banded gray marl	P&H 2100 BL 15yd^3	Time Average Power(kW)	879.9±95.5	1024.1±81.3	1228.7±30.8	974.0±18.7	1088.6±62.3	1179.6±115.1	447.8±19.3
			Avrg. of Peak Power(kW)	1240.5±155.4	1543.8±143.1	1703.4±64.8	1415.2±68.3	1527.2±77.5	1741.0±176.4	872.5±217.0
			Maximum Peak Power(kW)	1476.1	1712.8	1749.2	1496.4	1603.2	1915.7	1056.0
			Avrg. Digging Time(sec)	7.71±0.95	10.60±1.14	14.00±1.41	7.50±1.05	8.00±0.71	8.25±1.26	9.00±0.00
			Avrg.Dipper Fill Factor	0.97±0.05	1.00±0.10	1.00±0.01	1.08±0.04	1.11±0.02	1.05±0.06	-
Yatağan Eskihisar (Case 2)	Slightly-moderately weathered marl consisting of clay layers	P&H 2100 BL 15yd^3	Time Average Power (kW)	832.4±67.6	999.7±79.7	1169.4±101.4	-	-	-	448.6±53.2
			Avrg.of Peak Power (kW)	1186.1±101.7	1459.1±98.6	1545.8±58.8	-	-	-	723.3±157.5
			Maximum Peak Power (kW)	1302.5	1616.7	1619.4	-	-	-	816.4
			Avrg.Digging Time(sec)	8.83±0.75	10.25±1.75	16.75±4.03	-	-	-	9.00±1.73
			Avrg.Dipper Fill Factor	1.00±0.01	1.01±0.04	1.00±0.01	-	-	-	-
Tınaz (Case 3)	Conglomerate	P&H 2100 BL 15yd^3	Time Average Power (kW)	1026.7±112.8	1316.4±140.2	1512.4±136.7	1122.8±62.4	1280.4±100.7	1538.6±35.4	493.4±0.6
			Avrg.of Peak Power (kW)	1544.8±159.7	1899.3±196.3	2116.8±31.4	1683.0±164.9	1885.4±128.1	2090.1±171.0	857.0±2.1
			Maximum Peak Power (kW)	1697.1	2104.7	2160.0	1897.1	2106.1	2267.9	858.4
			Avrg.Digging Time(sec)	10.67±2.34	15.14±3.53	18.29±7.80	9.17±0.41	10.22±1.09	11.67±1.69	8.5±0.71
			Avrg.Dipper Fill Factor	1.02±0.04	1.07±0.05	1.04±0.05	1.10±0.01	1.10±0.01	1.10±0.01	-
Tınaz (Case 4)	Fresh-slightly weathered marl consisting of clay layers	P&H 2100 BL 15yd^3	Time Average Power (kW)	746.1±69.8	937.3±54.5	1004.0±53.7	800.0±40.2	923.1±32.9	988.0±41.2	353.0±26.7
			Avrg.of Peak Power (kW)	1080.5±108.5	1384.8±85.6	1419.8±67.2	1165.0±98.1	1365.2±67.8	1520.9±109.1	552.1±184.4
			Maximum Peak Power (kW)	1273.5	1484.4	1513.4	1318.5	1480.0	1630.0	754.5
			Avrg.Digging Time (sec)	14.83±0.98	18.00±2.74	21.33±1.21	8.40±0.55	9.00±0.00	9.33±1.21	11.67±2.89
			Avrg.Dipper Fill Factor	1.03±0.05	1.08±0.04	1.03±0.05	1.04±0.05	1.10±0.01	1.10±0.01	-

Table 20.b. Digging Energy Consumptions (kWh) Related to Depth of Cut (For All Cases).

Region and Panel	Formation Description	Shovel: Model Dipper Capacity(yd^3)	Depth of Cut (m)						Empty Digging Motion
			Before Blasting			After Blasting			
			≤0.40	0.40-0.60	0.60-0.80	≤0.60	0.60-0.80	0.80-1.00	
Yatağan Eskihisar (Case 1)	Fresh-slightly weathered banded gray marl	P&H 2100 BL $15yd^3$	1.881±0.270 (1.514-2.236)	3.025±0.473 (2.412-3.550)	4.784±0.602 (4.358-5.210)	2.027±0.275 (1.669-2.456)	2.425±0.313 (1.997-2.826)	2.678±0.235 (2.342-2.855)	1.020±0.048 (1.082-1.774)
Yatağan Eskihisar (Case 2)	Slightly-moderately weathered marl consisting of clay layers	P&H 2100 BL $15yd^3$	2.043±0.249 (1.769-2.430)	2.830±0.408 (2.277-3.574)	5.507±1.596 (3.142-6.482)	-	-	-	1.109±0.159 (0.963-1.279)
Tınaz (Case 3)	Conglomerate	P&H 2100 BL $15yd^3$	3.062±0.856 (2.224-4.573)	5.622±1.887 4.365-8.976)	7.787±3.639 (4.459-13.63)	2.855±0.120 (2.695-3.003)	3.620±0.305 (3.097-4.009)	4.985±2.403 (4.385-7.631)	1.165±0.096 (1.097-1.233)
Tınaz (Case 4)	Fresh slightly weathered marl consisting of clay layers	P&H 2100 BL $15yd^3$	3.057±0.357 (2.554-3.672)	4.682±0.749 (3.491-5.854)	5.950±0.478 (5.299-6.527)	1.869±0.165 (1.684-2.119)	2.308±0.082 (2.218-2.404)	2.565±0.389 (2.190-3.176)	1.150±0.334 (0.895-1.528)

Table 20.c. Specific Digging Energy (kWh/m3) Related to Depth of Cut (For All Cases).

Region and Panel	Formation Description	Shovel: Model Dipper Capacity(yd^3)	Depth of Cut (m)					
			Before Blasting			After Blasting		
			≤0.40	0.40-0.60	0.60-0.80	≤0.60	0.60-0.80	0.80-1.00
Yatağan Eskihisar (Case 1)	Fresh-slightly weathered banded gray marl	P&H 2100 BL 15yd^3	0.170±0.030 (0.132-0.215)	0.269±0.065 (0.191-0.344)	0.417±.052 (0.380-0.454)	0.164±0.025 (0.132-0.195)	0.191±0.026 (0.158-0.224)	0.223±0.019 (0.204-0.249)
Yatağan Eskihisar (Case 2)	Slightly-moderately weathered marl consisting of clay layers	P&H 2100 BL 15yd^3	0.175±0.017 (0.154-0.193)	0.244±0.037 (0.199-0.312)	0.480±0.139 (0.274-0.565)	-	-	-
Tınaz (Case 3)	Conglomerate	P&H 2100 BL 15yd^3	0.264±0.076 (0.194-0.399)	0.456±0.144 (0.346-0.712)	0.651±0.311 (0.389-1.188)	0.226±0.009 (0.214-0.238)	0.287±0.024 (0.246-0.318)	0.395±0.190 (0.348-0.605)
Tınaz (Case 4)	Fresh slightly weathered marl consisting of clay layers	P&H 2100 BL 15yd^3	0.259±0.023 (0.246-0.291)	0.380±0.071 (0.277-0.510)	0.502±0.036 (0.462-0.564)	0.157±0.016 (0.133-0.173)	0.183±0.007 (0.176-0.191)	0.204±0.031 (0.177-0.252)

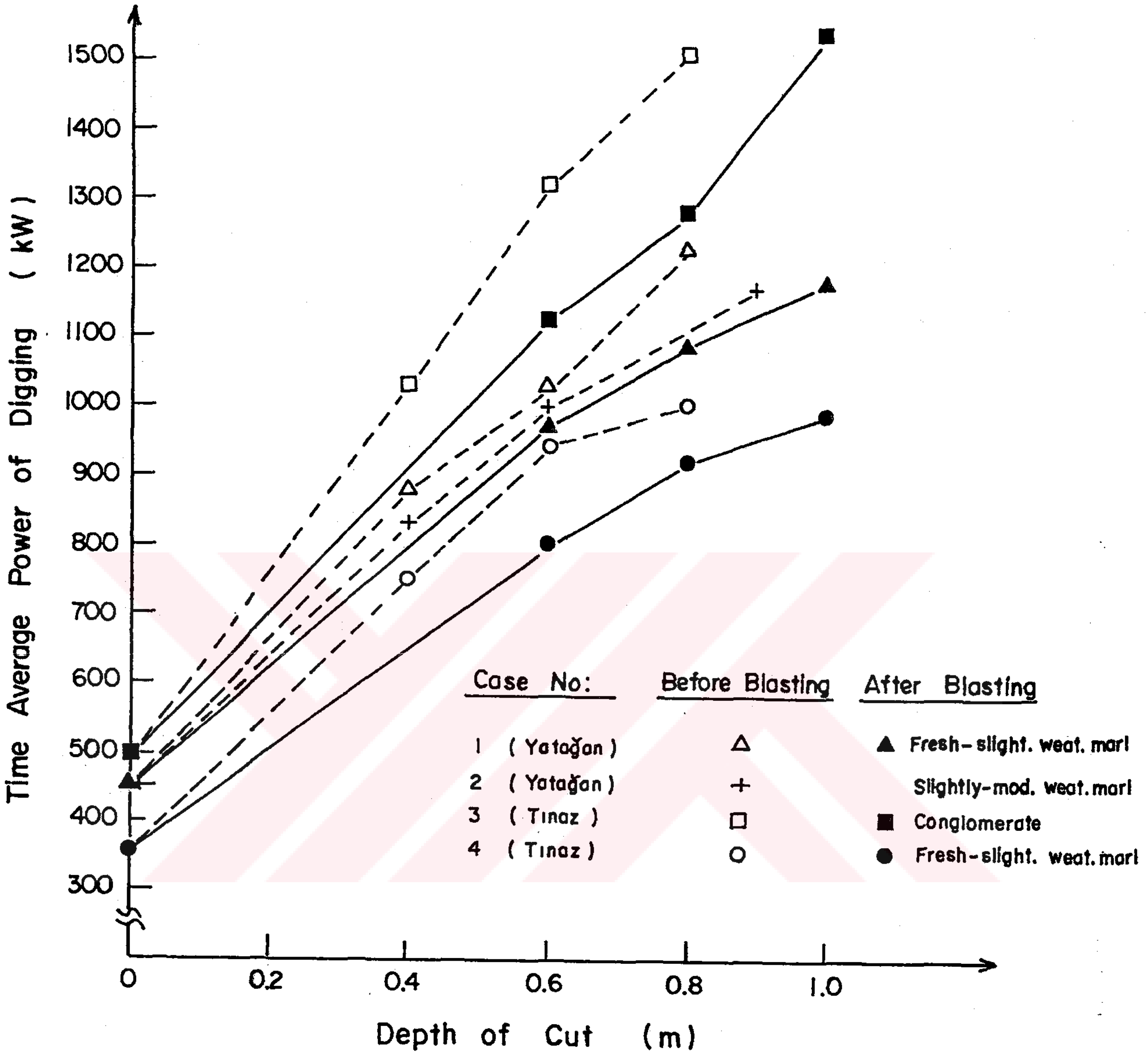


Figure 35. Digging Power Consumption-Depth of Cut Relation.

Energy consumption of digging which embodies both digging power and digging time gives more reasonable results than the digging power consumption when the blasting effect is taken into account (Figure 36).

Based on the interpretation of data from numerous monitored dig cycles, the specific digging energy which depends on power consumption, digging time and amount of excavated material is found the most effective parameter that relates well to depth of cut and formation digging characteristics. When the rock mass/material properties and blasting effects are considered, the relationship between specific digging energy and depth of cut for each case shows a better trend than the other performance parameters (Figure 37). It gives correct order on ease of digging in terms of formation characteristics and blasting effect. The most difficult digging condition is observed in Tınaz conglomerate before blasting excavation, since it does not include the discontinuity set, which can be also seen in Figure 37. In marl formations, Tınaz marl resulted more difficult digging than Yatağan-Eskihisar marl formations according to the specific digging energy with respect to depth of cut, which are compatible with rock material properties. Because marl at Tınaz has higher strength than Yatağan fresh marl where the uniaxial compressive strengths are 10.23 MPa and 17.86 MPa. Similarly, the

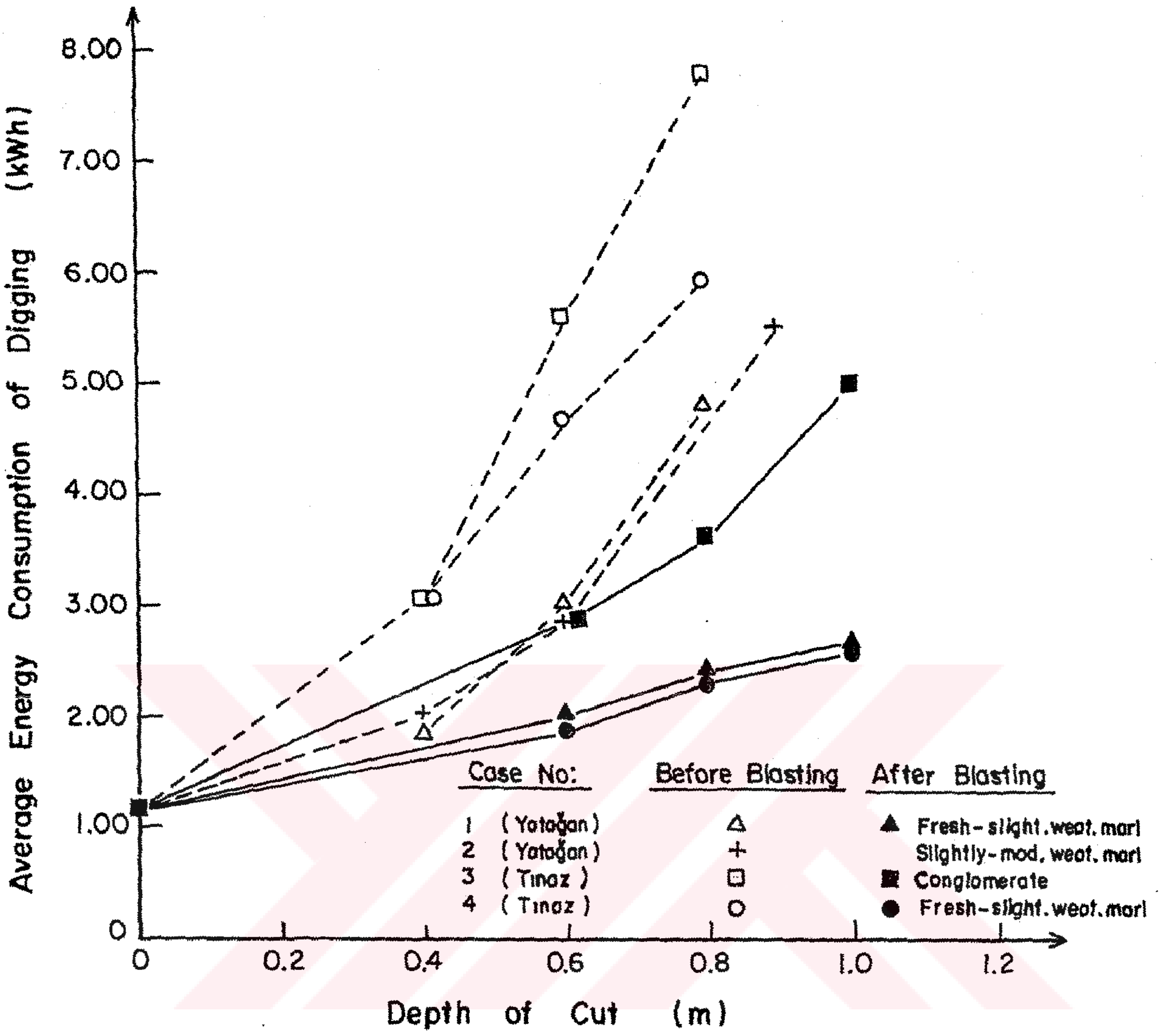


Figure 36. Digging Energy Consumption-Depth of Cut Relation.

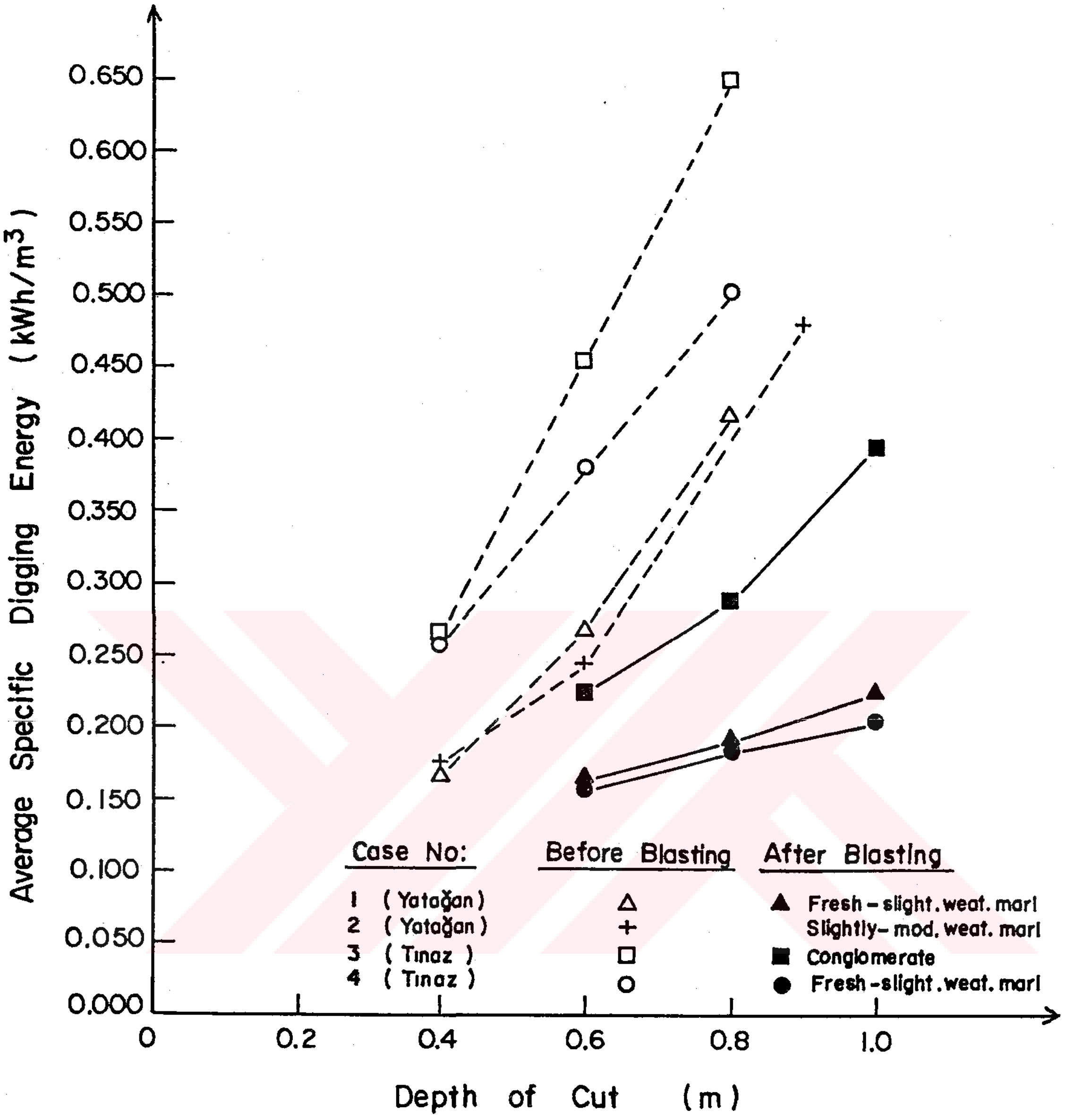


Figure 37. Specific Digging Energy-Depth of Cut Relation.

penetration rate obtained for Tınaz and Yatağan marl formations are 0.873 m/min and 1.852 m/min respectively at the same thrust (Table 17). As it is expected, after blasting the specific digging energy value of each depth of cut decreases in each case study. In blasted cases, although the maximum specific charge value of 0.679 kg (ANFO)/m3 is found for Tınaz conglomerate, it resulted most difficult excavation according to the specific digging energy. Specific digging energy values of Tınaz and Yatağan-Eskihisar marl rock units after blasting show nearly the same trend with respect to depth of cut in terms of excavation difficulty. When the mean values (Table 20.c) are compared it is evidently shown that blasting decreases the specific digging energy around 15%-50% compared to that of unblasted formations. It is most effective for the well blasted (Tınaz marl) and non-jointed formation (Tınaz conglomerate). On the other hand, the effect of blasting increases as the digging difficulty increases for all formations (Table 20.c).

Another purpose of this study is to use power measurement system in order to relate the shovel performance variation caused by blasting.

A major aim of blasting is to fracture and loosen the consolidated geological structures to heave the material sufficiently so that the available excavating or loading unit can dig the material without meeting any difficulty and/or excessive wear to the machinery. The assessment of variations in blasting practices on excavator effectiveness is generally based on visual examination of the muckpile and qualitative comments from excavator operators. This system is inherently unreliable, since the surface of the muckpile is not representative and operator comments on the same muckpile can vary significantly from operator to operator. The degree of success of blasting can be reflected in the digging performance of excavating unit. Therefore, monitoring of electrical shovels before and after blasting to produce performance parameters can be considered a good way in order to obtain a reliable and quantitative measure of the blasting effectiveness.

To assess the general performance of the shovel before and after blasting, the performance measurement during normal operation of shovel is taken for a certain period which can characterize the excavation activity in each case study. It was around 40-60 minutes for the study. The average value of each performance parameter has been calculated for blasted and unblasted cases at each location from the time and power measurement data.

Table 21 summarises the general performance measurement results for each case study. In Yatağan-Eskihisar fresh marl (Case 1), hourly output of shovel for unblasted overburden material and specific energy consumed are found 1421.4 m3/hr and 0.495 kWh/m3 respectively. After blasting, the output of shovel rised to 1864.3 m3/hr and specific energy consumed decreased to 0.396 kWh/m3, which corresponded to an increase of 31% in digging capacity and a decreasing of 25% in specific energy consumed.

The specific digging energy obtained for Tınaz conglomerate (Case 3) before and after blasting are 0.426 kWh/m3 and 0.267 kWh/m3 respectively. This means around 60% higher energy given during direct digging. The hourly capacity of shovel shows almost 29% less compared to the value obtained for blasted case, where they are found 1175.9 m3/hr and 1513.9 m3/hr before and after blasting respectively.

Significant differences in the performance parameters between direct digging and digging after blasting have been obtained for all case studies. Cycle

Table 21.a. Shovel Performance Summary.
Location: G.E.L.I. Yatağan-Eskihisar
Shovel : P&H 2100 BL, 15 yd^3
Case No : 1

Performance Parameter	Before Blasting	After Blasting
Average Cycle Time (sec)	28.85±5.47	23.75±2.08
Average Digging Time (sec)	9.21±2.42	7.78±1.34
Average Dipper Fill Factor	0.99±0.08	1.07±0.05
Hourly Capacity Without Waiting (m^3/hr)	1421.409	1864.323
Time Average Power of Complete Cycle (kW)	702.117±79.685	737.050±52.815
Time Average Power of Digging (kW)	976.819±136.120	1069.970±93.050
Maximum Peak Power (kW)	1900.4	1917.2
Average of Peak Power (kW)	1475.460±206.386	1566.070±152.763
Average Energy Consumption of Complete Cycle (kWh)	5.627	4.862
Average Energy Consumption of Digging (kWh)	2.499	2.312
Specific Energy Consumption of Complete Cycle(kWh/m^3)	0.495	0.369
Specific Digging Energy (kWh/m^3)	0.220	0.188
Swing (Loaded) Time (sec)	6.00±0.89	4.67±0.58
Power Consumption During Swing (Loaded) (kW)	671.350±69.615	722.800±85.156
Dump Dipper Time (sec)	4.67±0.52	4.00±0.00
Power Consumption During Dump Dipper (kW)	561.583±75.918	559.033±79.107
Swing (Empty) Time (sec)	8.20±1.48	7.00±1.00
Power Consumption During Swing (Empty) (kW)	513.358±50.471	536.833±78.207
Power Consumpiton During Propel Motion (kW)	345.8 ± 94.3	
Power Consumption During Downtime (kW)	203.1 ± 4.3	

Table 21.b. Shovel Performance Summary.

Location: G.E.L.I. Yatağan-Eskihisar
Shovel : P&H 2100 BL, 15 yd^3
Case No : 2

Performance Parameter	Before Blasting	After Blasting
Average Cycle Time (sec)	28.10±3.40	-
Average Digging Time (sec)	10.07±2.63	-
Average Dipper Fill Factor	0.99±0.09	-
Hourly Capacity Without Waiting (m^3/hr)	1465.655	-
Time Average Power of Complete Cycle (kW)	720.057±74.516	-
Time Average Power of Digging (kW)	941.303±133.107	-
Maximum Peak Power (kW)	1998.1	-
Average of Peak Power (kW)	1449.690±244.519	-
Average Energy Consumption of Complete Cycle (kWh)	5.620	-
Average Energy Consumption of Digging (kWh)	2.633	-
Specific Energy Consumption of Complete Cycle(kWh/m^3)	0.493	-
Specific Digging Energy (kWh/m^3)	0.232	-
Swing (Loaded) Time (sec)	7.17±0.75	-
Power Consumption During Swing (Loaded) (kW)	695.620±58.933	-
Dump Dipper Time (sec)	4.50±0.84	-
Power Consumption During Dump Dipper (kW)	652.620±58.933	-
Swing (Empty) Time (sec)	8.67±1.21	-
Power Consumption During Swing (Empty) (kW)	483.283±38.167	-
Power Consumpiton During Propel Motion (kW)	3.54.7±112.7	
Power Consumption During Downtime (kW)	192.1±52.6	

Table 21.c. Shovel Performance Summary.

Location: G.E.L.I. Tınaz
Shovel : P&H 2100 BL, 15 yd^3
Case No : 3

Performance Parameter	Before Blasting	After Blasting
Average Cycle Time (sec)	37.00±9.13	30.00±3.00
Average Digging Time (sec)	14.38±9.09	9.65±1.17
Average Dipper Fill Factor	1.05±0.05	1.10±0.00
Hourly Capacity Without Waiting (m^3/hr)	1175.938	1513.908
Time Average Power of Complete Cycle (kW)	906.167±132.358	834.447±76687
Time Average Power of Digging (kW)	1287.080±221.471	1255.890±154.439
Maximum Peak Power (kW)	2160.0	2267.9
Average of Peak Power (kW)	1881.890±254.793	1838.870±197.546
Average Energy Consumption of Complete Cycle (kWh)	9.313	6.954
Average Energy Consumption of Digging (kWh)	5.141	3.366
Specific Energy Consumption of Complete Cycle(kWh/m^3)	0.773	0.551
Specific Digging Energy (kWh/m^3)	0.426	0.267
Swing (Loaded) Time (sec)	7.67±2.88	5.33±2.31
Power Consumption During Swing (Loaded) (kW)	770.700±7.686	730.333±105.510
Dump Dipper Time (sec)	4.33±1.53	4.33±0.58
Power Consumption During Dump Dipper (kW)	719.767±38.015	707.1±67.866
Swing (Empty) Time (sec)	10.67±1.53	10.00±3.61
Power Consumption During Swing (Empty) (kW)	478.600±54.056	501.267±39.144
Power Consumpiton During Propel Motion (kW)	440.9 ± 162.1	
Power Consumption During Downtime (kW)	194.3 ± 6.8	

Table 21.d. Shovel Performance Summary.

Location: G.E.L.I. Tınaz
Shovel : P&H 2100 BL, 15 yd^3
Case No : 4

Performance Parameter	Before Blasting	After Blasting
Average Cycle Time (sec)	37.54±3.47	24.00±1.53
Average Digging Time (sec)	18.08±3.36	8.74±0.95
Average Dipper Fill Factor	1.05±0.05	1.08±0.03
Hourly Capacity Without Waiting (m^3/hr)	1159.573	1867.784
Time Average Power of Complete Cycle (kW)	720.883±69.995	652.142±530
Time Average Power of Digging (kW)	932.637±103.940	894.126±78.400
Maximum Peak Power (kW)	1546.4	1630.0
Average of Peak Power (kW)	1346.040±134.406	1326.280±143.665
Average Energy Consumption of Complete Cycle (kWh)	7.517	4.348
Average Energy Consumption of Digging (kWh)	4.684	2.171
Specific Energy Consumption of Complete Cycle(kWh/m^3)	0.624	0.351
Specific Digging Energy (kWh/m ^{3})	0.389	0.175
Swing (Loaded) Time (sec)	7.50±1.05	5.50±0.55
Power Consumption During Swing (Loaded) (kW)	660.517±27.894	699.550±78.073
Dump Dipper Time (sec)	4.00±0.63	3.00±0.63
Power Consumption During Dump Dipper (kW)	584.450±54.806	482.902±106.617
Swing (Empty) Time (sec)	9.17±2.40	7.50±1.05
Power Consumption During Swing (Empty) (kW)	439.967±49.351	447.550±78.019
Power Consumpiton During Propel Motion (kW)	430.5 ± 154.8	
Power Consumption During Downtime (kW)	179.0 ± 40.8	

time, digging time, digging power and energy consumptions obtained in excavating the unblasted material are higher than the values obtained in the case of digging after blasting. Dipper is filled better in the case of after blasting and also outputs obtained after blasting are higher than those before blasting.

Comparison of each performance parameter before and after blasting in each case indicates the effectiveness of shovel monitoring on blast performance.

Variation in depth of cut throughout the entire performance study was not unexpected, however most of the monitored dig cycles during normal operation of shovel in the case studies are associated with the depth of cut class 2, where the depth of cut ranged 0.4 m to 0.6 m before blasting and 0.6 m to 0.8 m after blasting. This is also proved with the performance measurement results. The results of the entire performance measurement and the results obtained from digging trials of cut depth class 2 are nearly the same for all case studies. For example, the sepcific digging energy values of depth of cut class 2 before and after blasting in Case 4 are 0.380 kWh/m3 and 0.183 kWh/m3 respectively. The corresponding from the general performance measurements of Case 4 are 0.389

kWh/m3 and 0.175 kWh/m3 before and after blasting respectively.

Power consumptions of main drive A.C. motor during different motions of the shovel are also recorded for each case. The results of time and power measurements of these motions are also presented in Table 21.

5.4. Variation of Performance Parameters According to Ease of Digging

The performance parameters are analyzed considering the observations of shovel digging difficulty and operational conditions. All the results of performance studies are given in Table 22, for each entire measurement with a brief description of formation and operational conditions such as blasted or unblasted formation, type of loading, operator experience and shovel model, capacity and age.

Observed digging conditions are discussed for each performance parameter given below in order to find the best related parameter(s).

i. Average cycle time (sec).

ii. Average digging time (sec).

iii. Average dipper fill factor.

iv. Hourly capacity without waiting (m3/hr).

v. Hourly digging capacity (m3/hr).

vi. Time average power of digging (kW).

vii. Maximum peak power of digging (kW).

viii. Average of peak digging power (kW).

ix. Energy consumption of digging (kWh).

x. Specific digging energy (kWh/m3).

5.4.1. Average Cycle Time

The suggested averaged cycle times of different electrical shovel manifacturing companies as a function of digging difficulty and bucket capacity is arranged by Paşamehmetoğlu et.al., (1988) and given in Chapter 2. This relation is used to evaluate the cycle time measurements.

Table 22. The Results of Performance Measurements.

Code No	Region and Panel	Formation Description	Shovel: Model Dipper Capacity Age	Operational Condition: Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
1	Soma Kısrakdere Doğu	Fresh-slightly weathered marl and top soil	Marion 191M-II 20 yd3 1.5 years	Double side loading 12 years	Easy Digging (Loose material)	25.00	8.00	0.70	1541.4	4817.0	523	972	972	1.162	0.109	-	-
2	Soma Kısrakdere Doğu	Fresh-slightly weathered marl and top soil	Marion 191M-II 20 yd3 1.5 years	Blasted Double side loading 12 years	Moderate Digging	28.13	8.50	0.70	1369.9	4533.6	954	1555	1376	2.253	0.210	-	-
3	Soma Kısrakdere Doğu	Fresh-slightly weathered marl and top soil	Marion 191M-II 20 yd3 1.5 years	Blasted Double side loading 12 years	Moderately Difficult Digging	26.00	8.00	0.70	1482.1	4817.0	1207	1382	1382	2.682	0.251	-	-
4	Soma Işıklar DE Pano	Fresh-slightly weathered marl	Marion 191M-II 20 yd3 1 year	Blasted Double side loading 1 month	Moderate Digging	26.50	6.63	0.50	1038.7	4151.7	911	1447	1287	1.678	0.219	-	-
5	Soma Kısrakdere Batı	Highly weathered marl	Marion 191M-I 17 yd3 1 year	Blasted Single side loading 2 years	Easy Digging	28.30	7.80	1.00	1653.5	5999.2	800	1296	1115	1.733	0.133	-	-
6	Soma Kısrakdere Batı	Slightly-moderately weathered marl	Machine Export 4.5 yd3 17 years	Blasted Single side loading 8 years	Easy Digging	26.80	7.80	0.70	323.5	1111.6	250	393	370	0.542	0.225	-	-

Table 22.Continued

Code No	Region and Panel	Formation Description	Shovel : Model Dipper Capacity Age	Operational Condition : Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
7	Soma Işıklar A Pano	Moderately to highly weathered tuff, marl	Marion 191M-II 20 yd3 1.5 years	Unblasted Double side loading 1 year	Moderate Digging	33.22	9.56	0.75	1242.9	4318.9	850	1243	1145	2.257	0.197	-	-
8	Soma Elmalı	Fresh-slightly weathered marl	EKG-6i 10.5 yd3	Blasted Single side loading : ~ 50° 20 years	Moderately Difficult Digging	32.00	12.00	0.60	541.9	1445.1	545	1017	1017	1.817	0.377	-	-
9	Soma Sarıkaya	Moderately to highly weathered marl, tuff and top soil	P&H 2100 BL 15 yd3 1 year	Unblasted Double side loading 20 years	Moderate Digging	27.43	8.29	0.75	1128.9	3735.4	872	1416	1311	2.008	0.233	-	-
10	Deniş Çamtarla	Fresh-slightly weathered marl	Marion 191M-II 20 yd3	Blasted Double side loading	Moderate Digging	25.00	5.00	0.40	880.8	4404.1	916	1361	1242	1.272	0.208	333	0.555
11	Deniş Çamtarla	Fresh-slightly weathered marl	Marion 191M-II 20 yd3	Blasted Double side loading	Moderately Difficult Digging	27.55	8.18	0.49	979.1	3297.7	923	1566	1362	2.097	0.280	333	0.555
12	Deniş Çamtarla	Fresh-slightly weathered marl	P&H 1900 AL 10 yd3	Blasted Double side loading	Moderate Digging	25.80	8.40	0.90	960.2	2949.2	811	1080	1032	1.892	0.275	299	0.748

Table 22.Continued

Code No	Region and Panel	Formation Description	Shovel : Model Dipper Capacity Age	Operational Condition : Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
13	Deniş Çamtarla	Fresh-slightly weathered marl	P&H 1900 AL 10 yd3	Blasted Double side loading	Moderately Difficult Digging	28.25	10.37	0.94	915.9	2495.1	955	1282	1183	2.751	0.383	299	0.748
14	Tunçbilek Beke	Fresh-slightly weathered marl and top soil	P&H 2300 XP 20 yd3 0.5 year	Blasted Double side loading 12 years	Moderate Digging	30.50	6.67	0.90	1624.5	2428.2	1105	1786	1670	2.047	0.149	-	-
15	Tunçbilek Beke	Fresh marl	P&H 1900 10 yd3 15 years	Blasted Double side loading 2 years	Easy Digging	21.83	5.00	1.08	1361.8	5945.5	1157	1987	1805	1.607	0.195	-	-
16	Tunçbilek Beke	Fresh marl	Marion 191M-I 17 yd3 1 year	Blasted Double side loading 12 years	Easy Digging	24.13	5.50	0.90	1745.3	7657.1	843	1194	1130	1.288	0.110	-	-
17	Tunçbilek Ömerler	Moderately weathered marl and top soil	P&H 2300 XP 20 yd3 1 year	Unblasted Single side loading 12 years	Easy Digging	32.50	7.00	1.00	1693.9	7864.5	1175	1814	1757	2.285	0.149	-	-
18	Tunçbilek Ömerler	Moderately weathered marl and top soil	P&H 2300 XP 20 yd3 1 year	Unblasted Single side loading 12 years	Moderate Digging	29.40	5.70	1.05	1966.1	10141.0	1492	2218	2029	2.362	0.147	-	-

Table 22.Continued

Code No	Region and Panel	Formation Description	Shovel : Model Dipper Capacity Age	Operational Condition : Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
19	Tunçbilek Ömerler	Moderately weathered marl and top soil	P&H 1900 10 yd3 19 years	Unblasted Double side loading 10 years	Moderate Digging	28.00	7.50	1.00	1058.7	7340.2	1823	2174	2155	3.798	0.497	878	1.707
20	Tunçbilek Ömerler	Moderately weathered marl and top soil	P&H 1900 10 yd3 19 years	Unblasted Double side loading 10 years	Moderately Difficult Digging	28.00	8.00	1.10	1081.4	7569.5	2024	2174	2174	4.498	0.535	878	1.707
21	Tunçbilek Ömerler	Highly-completely weathered marl	P&H 1900 10 yd3 19 years	Unblasted Double side loading 10 years	Easy Digging	25.67	7.67	1.03	1104.5	7392.8	1799	2153	2143	3.833	0.487	878	1.707
22	Tunçbilek 36.Pano	Completely weathered marl (Bottom of the bench 70cm thick fresh marl.)	P&H 2300 XP 20 yd3 0.5 year	Unblasted Double side loading 10 years	Moderate Digging	28.60	8.20	1.08	2078.9	7250.6	1519	2203	2073	3.460	0.210	616	1.283
23	Tunçbilek 36.Pano	Fresh-slightly weathered marl	P&H 1900 AL 10 yd3 1 year	Single side loading 10 years	Easy Digging (Loose material)	23.50	7.00	0.90	1054.2	3539.0	738	1102	1091	1.435	0.209	276	0.460
24	Tunçbilek 36.Pano	Fresh-slightly weathered marl	P&H 1900 AL 10 yd3 1 year	Blasted Single side loading 10 years	Moderately Difficult Digging	26.79	10.14	0.96	986.4	2606.0	811	1253	1117	2.284	0.311	276	0.460

Table 22.Continued

Code No	Region and Panel	Formation Description	Shovel : Model Dipper Capacity Age	Operational Condition : Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
25	Tunçbilek Kuşpınar	Completely weathered marl (Bottom of the bench 1. m thick fresh marl.)	EKG-8i 10.5 yd3 12 years	Unblasted Single side loading 5 years	Moderate Digging	24.75	8.75	0.78	910.8	2576.4	845	1426	1256	2.054	0.328	602	0.920
26	Tunçbilek Kuşpınar	Completely weathered marl (Bottom of the bench 1. m thick fresh marl.)	EKG-8i 10.5 yd3 12 years	Unblasted Single side loading 5 years	Moderately Difficult Digging	24.00	8.20	0.72	867.1	2537.7	968	1622	1418	2.205	0.381	602	0.920
27	Tunçbilek Kuşpınar	Slightly-moderately weathered marl	P&H 1900 10 yd3 10 years	Double side loading 6 years	Easy Digging (Loose material)	23.00	7.00	0.80	957.4	3145.8	594	927	927	1.155	0.189	321	0.624
28	Tunçbilek Kuşpınar	Slightly-moderately weathered marl	P&H 1900 10 yd3 10 years	Unblasted Double side loading 6 years	Difficult Difficult Digging	29.00	12.00	0.70	664.4	1605.7	699	1022	1022	2.230	0.435	321	0.624
29	Seyitömer S-20	Fresh clayish marl and tuff	P&H 1900 AL 10 yd3 1 year	Double side loading 11 years	Easy Digging (Loose material)	22.00	6.00	1.00	1251.2	4587.6	474	684	684	0.790	0.103	234	0.520
30	Seyitömer S-20	Fresh clayish marl and tuff	P&H 1900 AL 10 yd3 1 year	Blasted Double side loading 11 years	Moderate Digging	26.00	9.00	0.70	741.1	2140.9	508	744	686	1.270	0.237	234	0.520

Table 22.Continued

Code No	Region and Panel	Formation Description	Shovel : Model Dipper Capacity Age	Operational Condition : Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
31	Seyitömer S-20	Tuff and shear zone	P&H 1900 AL 10 yd3 1 year	Double side loading 11 years	Easy Digging (Loose material)	25.25	5.75	0.93	1013.8	4452.0	714	1123	1039	1.140	0.160	234	0.520
32	Seyitömer S-20	Tuff and shear zone	P&H 1900 AL 10 yd3 1 year	Unblasted Double side loading 11 years	Easy Digging	24.33	7.33	1.03	1165.3	3867.8	821	1227	1181	1.672	0.212	234	0.520
33	Seyitömer S-20	Tuff and shear zone	P&H 1900 AL 10 yd3 1 year	Double side loading 11 years	Moderately Difficult Digging	28.25	10.00	1.05	1023.1	2890.2	968	1296	1253	2.689	0.335	234	0.520
34	Seyitömer S-20	Slightly-weathered marl	P&H 1900 AL 10 yd3 1 year	Blasted Single side loading 4.5 years	Easy Digging (Loose material)	23.00	5.50	1.00	1198.8	5004.6	734	1094	1030	1.121	0.147	237	0.263
35	Seyitömer S-20	Slightly-weathered marl	P&H 1900 AL 10 yd3 1 year	Blasted Single side loading 4.5 years	Moderate Digging	29.25	9.00	1.05	988.1	3211.3	828	1234	1142	2.070	0.258	237	0.263
36	Seyitömer S-20	Slightly-weathered marl	P&H 1900 AL 10 yd3 1 year	Blasted Single side loading 4.5 years	Moderately Difficult Digging	28.00	10.00	1.10	1081.4	3027.8	914	1238	1238	2.539	0.302	237	0.263

Table 22.Continued

Code No	Region and Panel	Formation Description	Shovel : Model Dipper Capacity Age	Operational Condition : Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
37	Seyitömer S-20	Slightly-weathered marl	P&H 1900 AL 10 yd3 1 year	Double side loading 2 years	Easy Digging (Loose material)	22.50	7.00	0.90	1101.0	3539.0	741	1195	1159	1.441	0.209	316	0.658
38	Seyitömer S-20	Slightly-weathered marl	P&H 1900 AL 10 yd3 1 year	Blasted Double side loading 2 years	Moderate Digging	27.00	9.50	0.95	968.5	2752.6	774	1247	1235	2.043	0.281	316	0.658
39	Seyitömer S-19	Fresh to moderately weathered marl	P&H 1900 AL 10 yd3 3 months	Unblasted Single side loading 5 years	Moderately Difficult Digging	26.50	10.00	1.05	1090.6	2890.2	869	1238	1207	2.414	0.301	308	0.342
40	Seyitömer S-19	Fresh to moderately weathered marl	P&H 1900 AL 10 yd3 3 months	Single side loading 5 years	Easy Digging (Loose material)	25.25	6.00	1.00	1090.1	4587.6	740	1080	1073	1.233	0.161	308	0.342
41	Seyitömer S-19	Fresh to moderately weathered marl	P&H 1900 AL 10 yd3 3 months	Unblasted Single side loading 5 years	Moderately Difficult Digging	28.00	11.00	1.10	1081.4	2752.6	854	1202	1170	2.609	0.310	308	0.342
42	Seyitömer S-18	Moderately to highly weathered clayish marl	P&H 1900 AL 10 yd3 1 year	Double side loading 18 years	Easy Digging (Loose material)	23.25	5.50	0.90	1065.5	4504.2	628	1008	931	0.959	0.139	301	0.418

Table 22.Continued

Code No	Region and Panel	Formation Description	Shovel : Model Dipper Capacity Age	Operational Condition : Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
43	Seyitömer S-18	Moderately to highly weathered clayish marl	P&H 1900 AL 10 yd3 1 year	Unblasted Double side loading 18 years	Moderate Digging	24.50	6.00	0.90	1011.1	4128.8	840	1274	1238	1.400	0.203	301	0.418
44	Seyitömer S-18	Highly weathered clayish marl	P&H 1900 AL 10 yd3 10 years	Unblasted Double side loading	Moderate Digging	25.03	7.20	1.05	1154.7	4014.2	1092	1749	1551	2.184	0.272	-	-
45	Yatağan Eskihisar	Highly weathered marl and soil	P&H 2100 BL 15 yd3 4 years	Double side loading 4 years	Easy Digging (Loose material)	26.93	8.43	1.04	1594.5	5093.7	637	1161	1047	1.492	0.125	267	0.593
46	Yatağan Eskihisar	Highly weathered marl and soil	P&H 2100 BL 15 yd3 4 years	Unblasted Double side loading 4 years	Easy Digging	29.33	11.33	1.10	1548.5	4008.6	671	1143	1075	2.112	0.167	267	0.593
47	Yatağan Eskihisar	Slightly-moderately weathered marl	P&H 2100 BL 15 yd3 4 years	Blasted Double side loading 4 years	Easy Digging	26.30	7.60	1.10	1726.9	5976.0	683	1234	1114	1.442	0.114	267	0.593
48	Yatağan Eskihisar	Slightly-moderately weathered marl	P&H 2100 BL 15 yd3 4 years	Double side loading 4 years	Easy Digging (Loose material)	26.00	8.00	1.00	1588.0	5161.1	710	1089	1089	1.578	0.138	267	0.593

Table 22.Continued

Code No	Region and Panel	Formation Description	Shovel : Model Dipper Capacity Age	Operational Condition : Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
49	Yatağan Eskihisar	Slightly-moderately weathered marl	P&H 2100 BL 15 yd3 4 years	Unblasted Double side loading 4 years	Moderate Digging	28.67	11.17	1.05	1512.1	3881.2	762	1397	1131	2.364	0.196	267	0.593
50	Yatağan Eskihisar	Moderately weathered clayish marl and soil	P&H 1900 AL 10 yd3 4 years	Double side loading 1 year	Easy Digging (Loose material)	24.00	8.00	1.00	1146.9	3440.7	1091	1678	1878	2.424	0.317	448	0.871
51	Yatağan Eskihisar	Moderately weathered clayish marl and soil	P&H 1900 AL 10 yd3 4 years	Unblasted Double side loading 1 year	Moderate Digging	28.25	11.00	1.05	1023.1	2627.4	1343	2155	1973	4.104	0.511	448	0.871
52	Yatağan Eskihisar	Moderately weathered clayish marl and soil	P&H 1900 AL 10 yd3 4 years	Unblasted Double side loading 1 year	Moderately Difficult Digging	34.00	14.00	1.07	866.2	2103.7	1321	2177	2147	5.137	0.628	448	0.871
53	Yatağan Eskihisar	Slightly-moderately weathered marl	P&H 1900 AL 10 yd3 4 years	Single side loading 1 year	Easy Digging (Loose material)	23.00	5.50	1.00	1196.8	5004.6	1197	1746	1690	1.829	0.239	448	0.871
54	Yatağan Eskihisar	Slightly-moderately weathered marl	P&H 1900 AL 10 yd3 4 years	Unblasted Single side loading 1 year	Moderately Difficult Digging	29.40	12.20	1.00	936.2	2256.2	1326	2291	1982	4.494	0.588	448	0.871

Table 22.Continued

Code No	Region and Panel	Formation Description	Shovel : Model Dipper Capacity Age	Operational Condition : Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
55	Yatağan Eskihisar	Highly weathered clayish marl and soil	P&H 2100 BL 15 yd3 4 years	Unblasted Double side loading 1 year	Easy Digging	32.50	9.33	1.00	1270.4	4425.3	891	1240	1154	2.309	0.201	-	-
56	Yatağan Eskihisar	Moderately to highly weathered marl and soil	P&H 2100 BL 15 yd3 4 years	Unblasted Single side loading 3.5 years	Easy Digging	29.00	6.80	0.92	1309.8	5586.1	976	1512	1400	1.844	0.175	387	0.968
57	Tınaz	Slightly weathered clayish and sandy cemented conglomerate	P&H 2100 BL 15 yd3 1.5 years	Unblasted Double side loading	Moderately Difficult Digging	26.58	11.08	0.99	1537.8	3689.1	1009	1348	1259	3.105	0.274	435	0.846
58	Tınaz	Slightly weathered clayish and sandy cemented conglomerate	P&H 2100 BL 15 yd3 1.5 years	Unblasted Double side loading	Difficult Digging	33.08	15.33	1.13	1410.4	3043.4	1077	1555	1395	4.586	0.354	435	0.846
59	Tınaz	Slightly weathered clayish and sandy cemented conglomerate	P&H 2100 BL 15 yd3 1.5 years	Double side loading 4.5 months	Easy Digging (Loose material)	29.50	11.50	1.05	1469.6	3769.8	830	1089	1089	2.651	0.220	367	1.121
60	Tınaz	Slightly weathered clayish and sady cemented conglomerate	P&H 2100 BL 15 yd3 1.5 years	Unblasted Double side loading 4.5 months	Moderately Difficult Digging	35.83	16.83	1.13	1302.1	2772.2	931	1225	1196	4.352	0.336	367	1.121

Table 22.Continued

Code No	Region and Panel	Formation Description	Shovel : Model Dipper Capacity Age	Operational Condition : Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
61	Tınaz	Slightly weathered clayish and sady cemented conglomerate	P&H 2100 BL 15 yd3 1.5 years	Unblasted Double side loading 4.5 months	Difficult Digging	36.25	17.50	1.20	1366.8	2831.2	992	1429	1344	4.822	0.350	367	1.121
62	Tınaz	Highly weathered limestone	P&H 2100 BL 15 yd3 1.5 years	Unblasted Double side loading	Moderate Digging	37.60	11.86	1.21	1327.3	3150.0	895	1296	1198	3.943	0.284	331	1.057
63	Tınaz	Moderately weathered clayish limestone and marl	P&H 2100 BL 15 yd3 1 year	Double side loading	Easy Digging (Loose material)	24.00	10.00	1.10	1892.4	4541.7	945	1191	1191	2.625	0.208	-	-
64	Tınaz	Moderately weathered clayish limestone and marl	P&H 2100 BL 15 yd3 1 year	Unblasted Double side loading	Moderate Digging	31.78	12.56	1.20	1559.0	3944.8	1014	1406	1299	3.538	0.257	-	-
65	Tınaz	Moderately weathered clayish limestone and marl	P&H 2100 BL 15 yd3 1 year	Unblasted Double side loading	Moderately Difficult Digging	34.50	15.00	1.28	1531.9	3523.3	1073	1361	1349	4.471	0.305	-	-
66	Milas İkizköy	Moderately to highly weathered marl and limestone blocks	P&H 2100 BL 15 yd3 0.5 year	Blasted Double side loading 1.5 years	Easy Digging (Loose material)	25.25	7.75	0.85	1389.9	4528.4	800	1181	1091	1.722	0.177	353	0.686

Table 22.Continued

Code No	Region and Panel	Formation Description	Shovel : Model Dipper Capacity Age	Operational Condition : Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
67	Milas İkizköy	Moderately to highly weathered marl and limestone blocks	P&H 2100 BL 15 yd3 0.5 year	Blasted Double side loading 1.5 years	Moderate Digging	30.44	11.44	0.89	1207.2	3212.1	873	1354	1298	2.774	0.272	353	0.686
68	Milas İkizköy	Moderately to highly weathered marl and limestone blocks	P&H 2100 BL 15 yd3 0.5 year	Blasted Double side loading 1.5 years	Moderately Difficult Digging	36.00	16.00	1.00	1146.9	2580.5	978	1382	1382	4.347	0.379	353	0.686
69	Milas İkizköy	Fresh-slightly weathered marl	P&H 1900 AL 10 yd3	Double side loading	Easy Digging (Loose material)	22.30	7.20	1.00	1234.3	3823.0	729	1022	988	1.458	0.191	431	0.658
70	Milas İkizköy	Fresh-slightly weathered marl	P&H 1900 AL 10 yd3	Blasted Double side loading	Moderate Digging	26.25	10.50	0.98	1027.6	2569.1	758	1080	1025	2.211	0.295	431	0.658
71	Milas İkizköy	Moderately weathered marl, limestone and soil	P&H 2100 BL 15 yd3 0.5 year	Double side loading	Easy Digging (Loose material)	26.33	9.00	1.00	1568.1	4587.6	781	1123	1051	1.953	0.170	353	0.686
72	Milas İkizköy	Moderately weathered marl, limestone and soil	P&H 2100 BL 15 yd3 0.5 year	Blasted Double side loading	Moderate Digging	28.38	9.88	1.03	1498.5	4304.4	997	1440	1363	2.736	0.232	353	0.686

Table 22.Continued

Code No	Region and Panel	Formation Description	Shovel : Model Dipper Capacity Age	Operational Condition : Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
73	Milas İkizköy	Moderately weathered marl, limestone and soil	P&H 2100 BL 15 yd3 0.5 year	Unblasted Double side loading	Moderately Difficult Digging	31.67	14.33	1.06	1381.9	3054.1	927	1613	1430	3.690	0.303	353	0.686
74	Milas Sekköy	Weak coal and soil	P&H 2100 BL 15 yd3 1 month	Unblasted 2 years	Easy Digging	26.42	7.42	1.06	1656.5	5898.3	994	1555	1328	2.049	0.189	-	-
75	Kangal Kalburçayırı	Fresh-slightly weathered clayish marl	Marion 201 M 25 yd3 4 months	Single side loading 2 years	Easy Digging (Loose material)	28.00	9.00	0.80	1966.1	8116.8	804	1382	1382	2.010	0.131	-	-
76	Kangal Kalburçayırı	Fresh-slightly weathered clayish marl	Marion 201 M 25 yd3 4 months	Unblasted Single side loading 2 years	Moderate Digging	37.67	11.33	0.77	1406.6	4676.7	1011	1598	1461	3.182	0.216	-	-
77	Kangal Kalburçayırı	Highly weathered limestone, soil (Fresh limestone at the bottom of the bench.)	Marion 201 M 25 yd3 3.5 months	Blasted Single side loading 2 years	Moderately Difficult Digging	33.67	11.83	0.88	1798.5	5118.9	1277	2304	1992	4.196	0.249	752	1.567
78	Kangal Kalburçayırı	Slightly-moderately weathered limestone and soil	P&H 1900 AL 10 yd3 4 months	Blasted Double side loading 2 years	Moderate Digging	26.12	7.57	0.95	1001.1	3454.3	946	1440	1308	1.989	0.274	323	0.583

Table 22.Continued

Code No	Region and Panel	Formation Description	Shovel : Model Dipper Capacity Age	Operational Condition : Blasting Type of Loading Operator Exper.	Observed Digging Condition	Average Cycle Time (sec)	Average Digging Time (sec)	Average Dipper Fill Factor	Hourly Capacity Without Waiting (m3/hr)	Hourly Digging Capacity (m3/hr)	Time Average Power of Digging (kW)	Maximum Peak Power of Digging (kW)	Average of Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)	Time Average Power of Empty Digging Motion (kW)	Energy Consumption of Empty Digging Motion (kWh)
79	Kangal Kalburçayırı	Slightly-moderately weathered limestone and soil	P&H 1900 AL 10 yd3 4 months	Blasted Double side loading 2 years	Moderately Difficult Digging	28.60	10.54	1.02	981.7	2663.8	1072	1696	1536	3.139	0.402	323	0.583
80	Kangal Kalburçayırı	Slightly-moderately weathered limestone	Marion 191M-II 20 yd3 2 months	Blasted Double side loading 2 years	Moderately Difficult Digging	33.27	9.31	0.77	1274.1	4553.1	1400	1500	1500	3.621	0.308	500	1.042

Cycle times of highly to completely weathered marl, fresh to moderately weathered good blasted formations and loose material loading cycles associated with easy digging condition are compared with literature cycle times of easy digging (Figure 38.a). 77% of the measured cycles which has been described as easy digging are fitted with easy digging section of the literature values. As an example to scattering the results; cycle time during loose material loading cycles at Tınaz (Code 59) was 29.50 sec. while maximum suggested literature value is 26.83 sec., clearly indicates the operator affect where the operator experience is 4 months. Swing angle for all double side loading is around 90°. Swing angle during single side loading is greater than 90° and varies between 100° to 120° except the swing angle observed at Elmalı (Code 8) which is 50°. The effect of swing angle on cycle time can be easily seen from the measurement taken at Tunçbilek, Ömerler (Code 17) where the average cycle time was 32.50 sec. during single side loading, while literature maximum value is 27.80 sec. Swing time and dump time are not effected by digging difficulty due to nature of the operations. Swing time is dependent on swing speed and swing angle. Dump time for all measurements is nearly the same. Although cycle time includes swing time and dump time, it is observed that cycle time increases generally as the digging difficulty and dipper capacity increase.

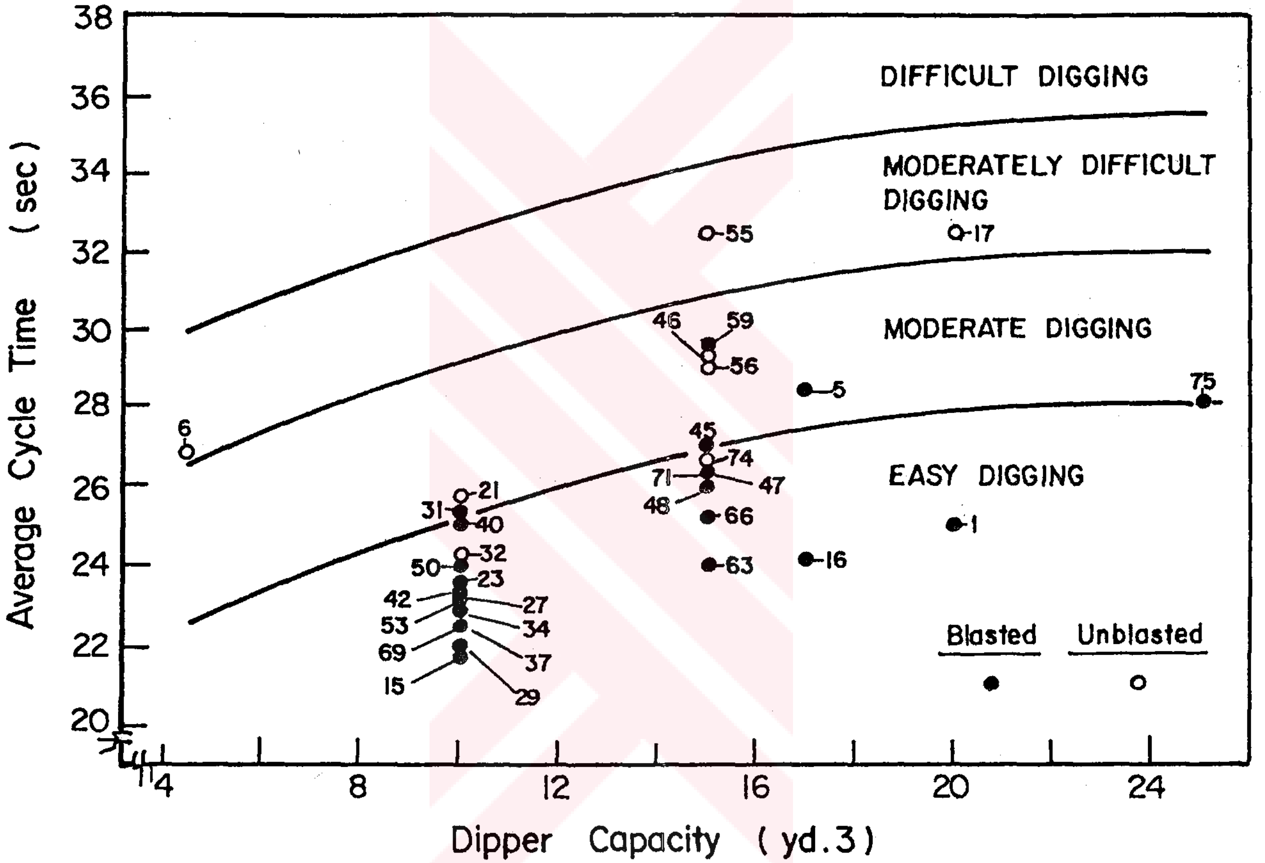


Figure 38. a. Relationship between Average Cycle Time and Dipper Capacity for Easy Digging Condition.

Comparison of cycle time measurements for moderate digging condition (Figure 38.b), shows that 73% of the moderate digging descriptions are in the range of literature values. There are eight points outside the range and four of them are higher than corresponding literature values whereas four points are less than literature values by the affect of operational conditions. Figure 38.c shows the cycle times of moderately difficult and difficult digging conditions where 35% of these points are in the range of literature values indicating the difficulty to classify digging conditions according to the cycle time measurements only.

5.4.2. Average Digging Time

The complete cycle of the shovel is composed four segments where the digging time is much more sensitive to digging conditions than the others.

Average time of empty digging motion is mainly dependent on operator experience. Measurements show that required time for empty digging motion is not related with dipper capacity like swing and dump time. Of course, it is not also related with digging difficulty. Mean empty digging motion time is found as 6.74 ± 1.38 sec. and the results of these

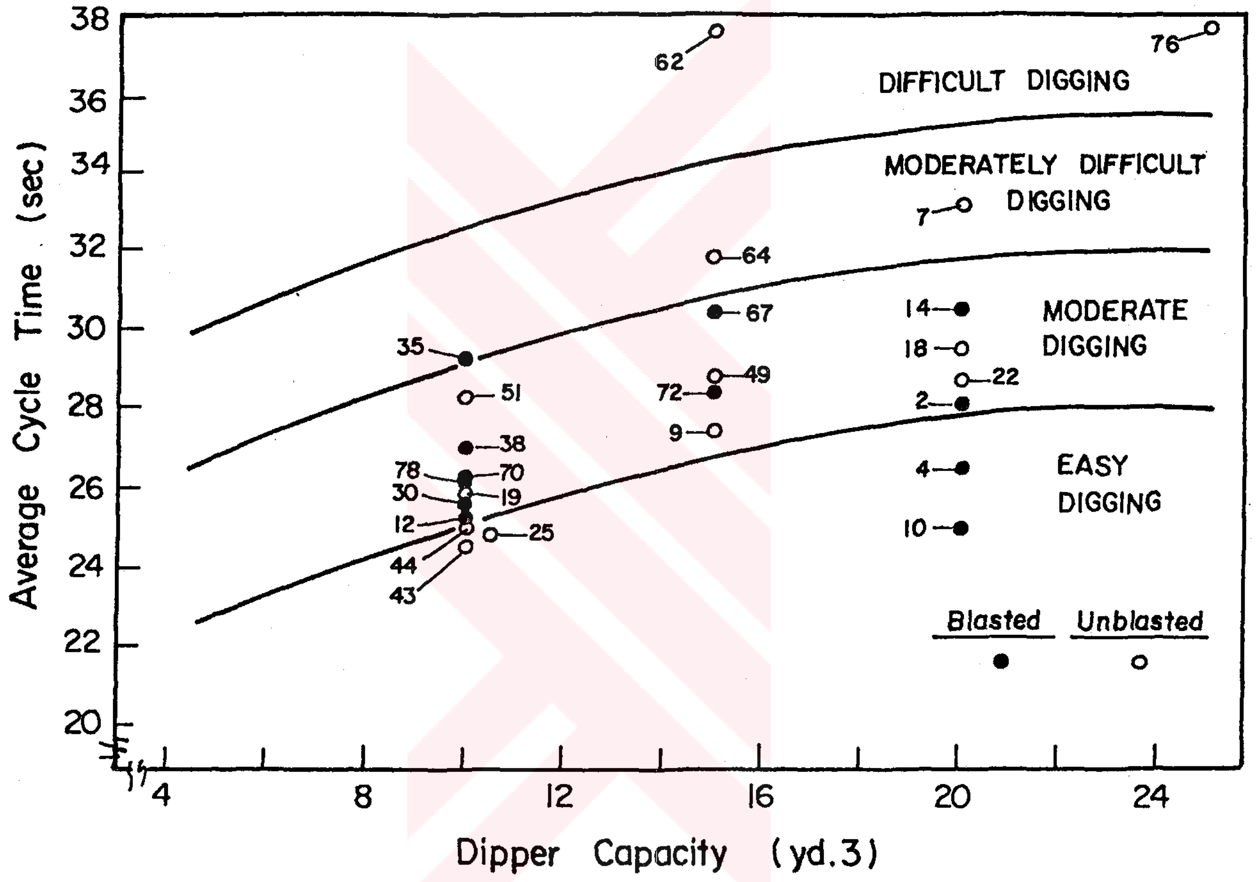


Figure 38. b. Relationship between Average Cycle Time and Dipper Capacity for Moderate Digging Condition.

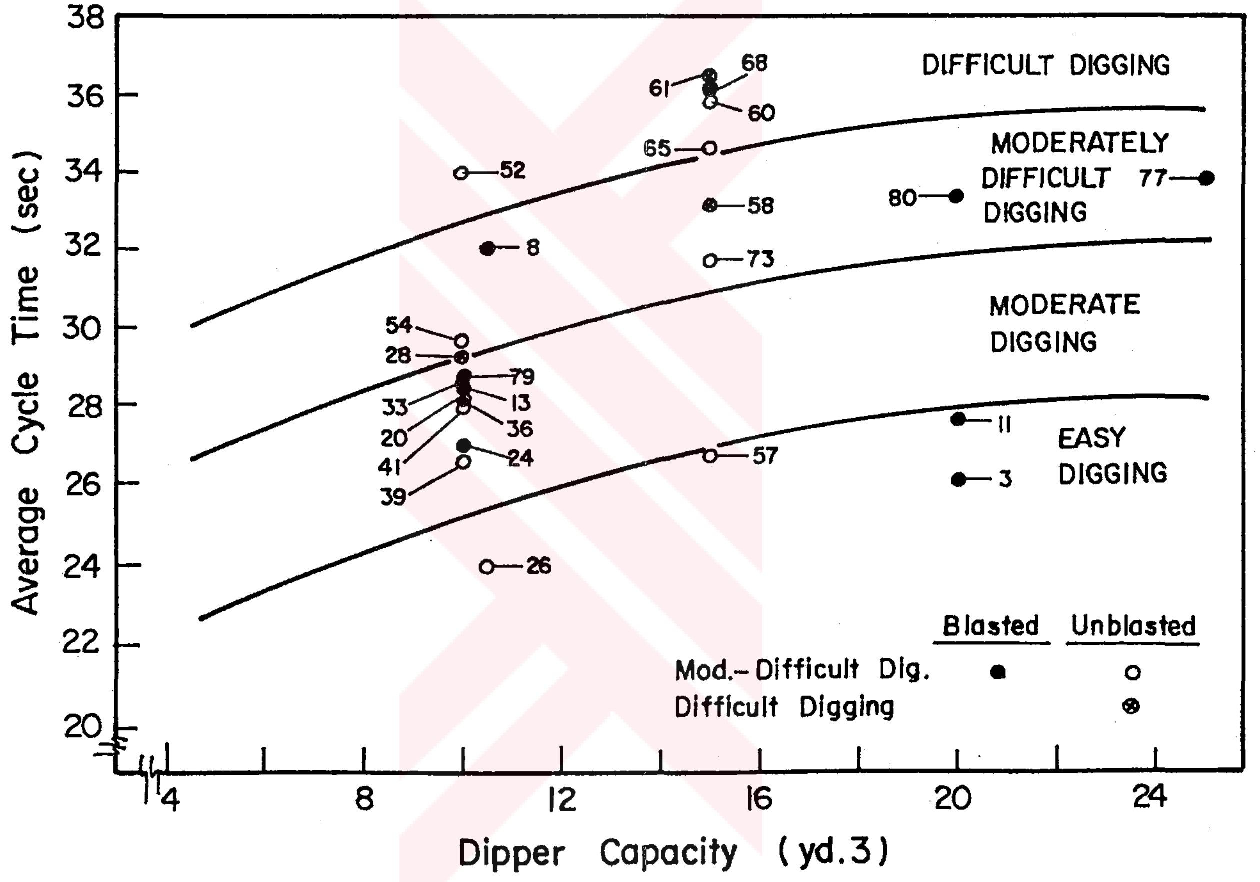


Figure 38. c. Relationship between Average Cycle Time and Dipper Capacity for Moderately Difficult and Difficult Digging Conditions.

measurements are plotted in Figure 39.a. Time measurements of empty digging motion of 15 yd^3 dipper capacity shovels were longer than the other measurements where the less experienced operators had been worked. These values can be used as a base reference case for the digging times of different digging conditions.

It is observed that digging times generally increase as the digging difficulty and dipper capacity increase. Average digging time of each measurement is given in Figures 39.b to 39.d considering the digging difficulty observations. Time ranges between digging conditions are determined two seconds where also increased with dipper capacity by a slope of 0.25 according to the available data.

Comparison of all digging times with respect to observed digging condition doesn not always give good results. The same digging times do not always arise from the same digging condition and dipper capacity. It is observed that digging times can be decreased with fast movement while the power consumption increase in this case, or loading a small portion of dipper. On the other hand, they can be found more than expected, where the dipper fill factor tried to be increased by an

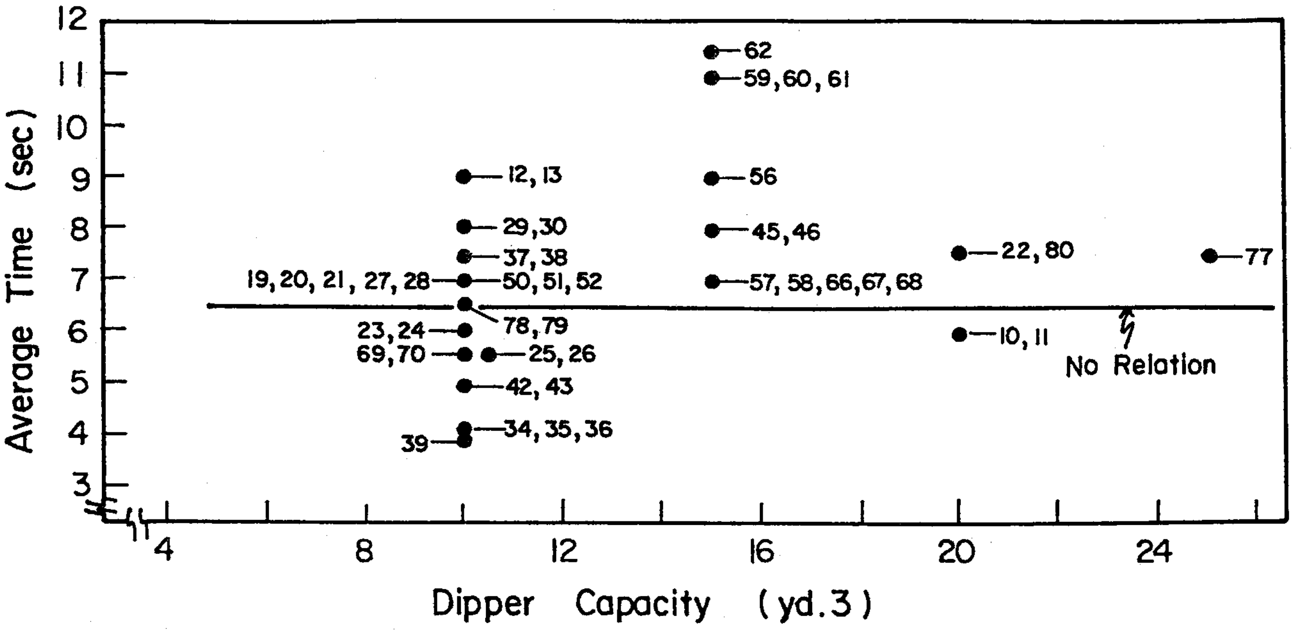


Figure 39. a. Relationship between Average Time of Empty Digging Motion and Dipper Capacity.

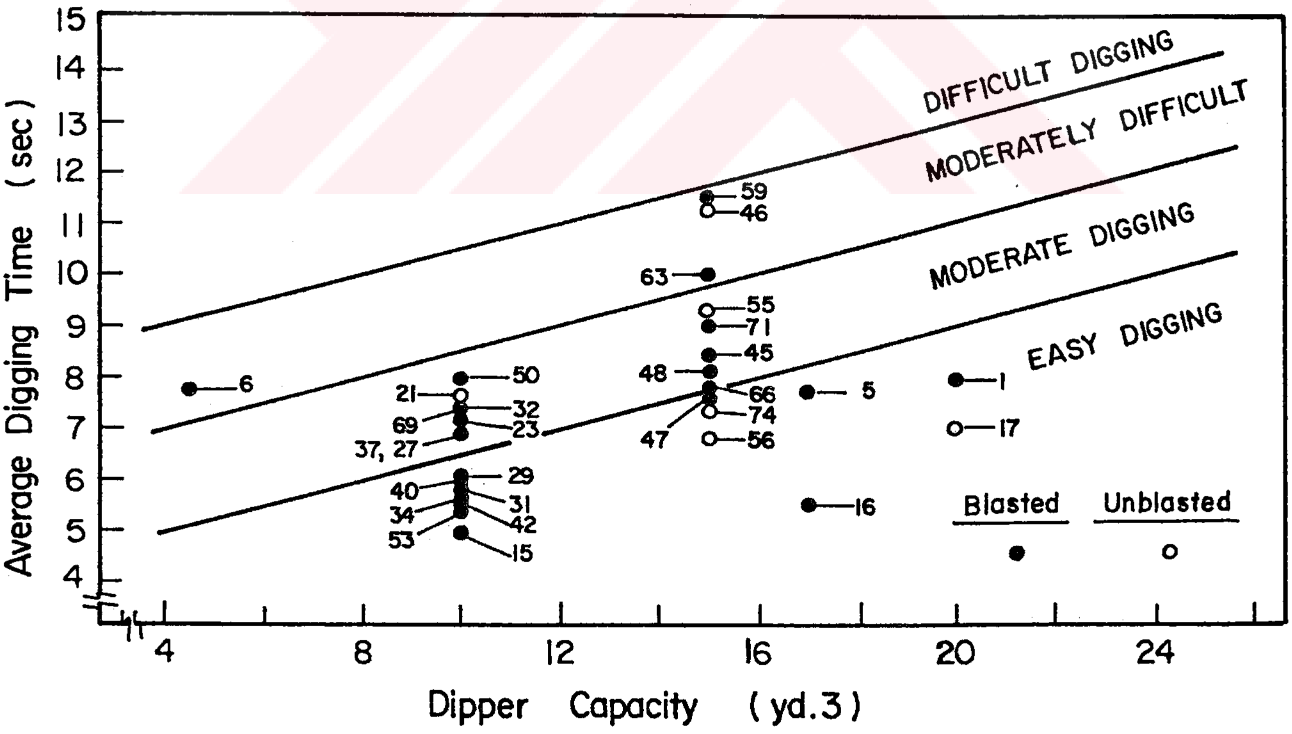


Figure 39. b. Relationship between Average Digging Time and Dipper Capacity for Easy Digging Condition.

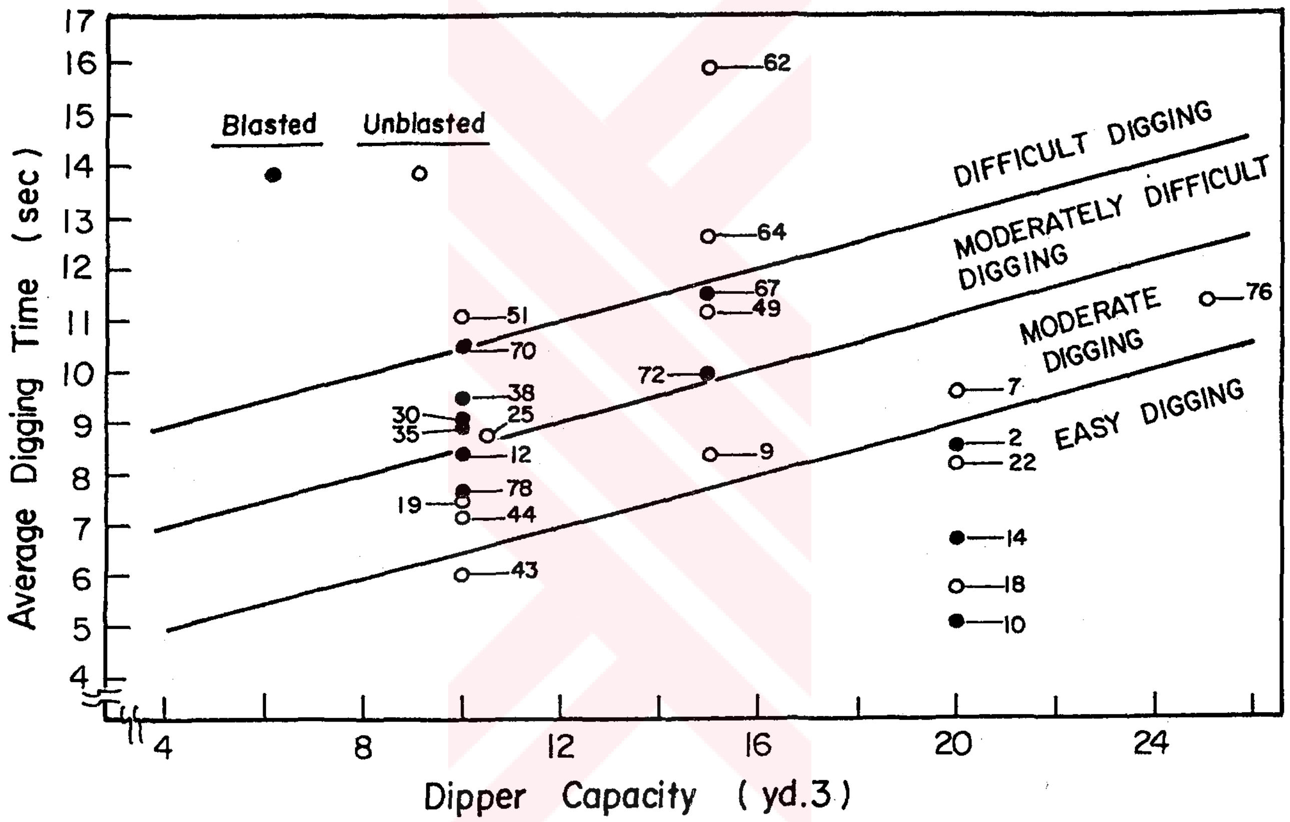


Figure 39. c. Relationship between Average Digging Time and Dipper Capacity for Moderate Digging Condition.

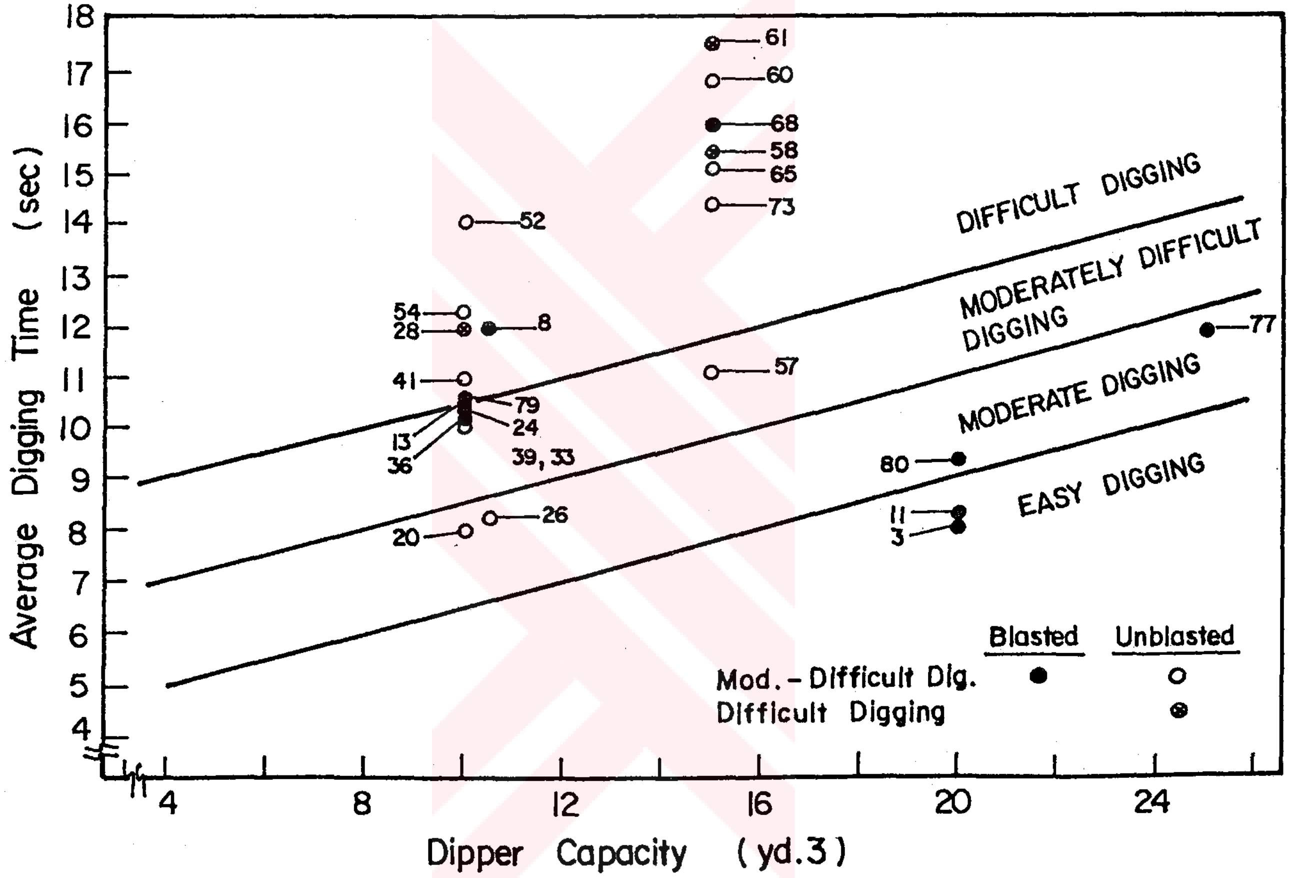


Figure 39. d. Relationship between Average Digging Time and Dipper Capacity for Moderately Difficult and Difficult Digging Conditions.

unnecessarily given time and power. This study clearly shows that time measurement of digging should be supported with power measurement which will also be discussed later on.

5.4.3. Average Dipper Fill Factor

The range of dipper fill factors suggested by P&H (1980) with respect to digging difficulty given in Chapter 2 are used to compare the determined average dipper fill factors of digging conditions (Figure 40.a,b,c).

The dipper fill factor is as important as digging time on the determination of degree of digging difficulty. It is expected that the dipper fill factor decreases as the digging difficulty increases. But it is sometimes possible to find higher dipper fill factors with increased digging time which means easy digging according to the dipper fill factor in difficult digging condition. At Tınaz (Code 58 and 61) the determined dipper fill factors are 1.13 and 1.20, showed easy digging, while the corresponding digging times are 15.33 sec. and 17.50 sec. respectively, yielded difficult digging condition, where the determined values should be less than 0.80 according to the literature. Conversely, the dipper may not be filled sufficiently by the effect

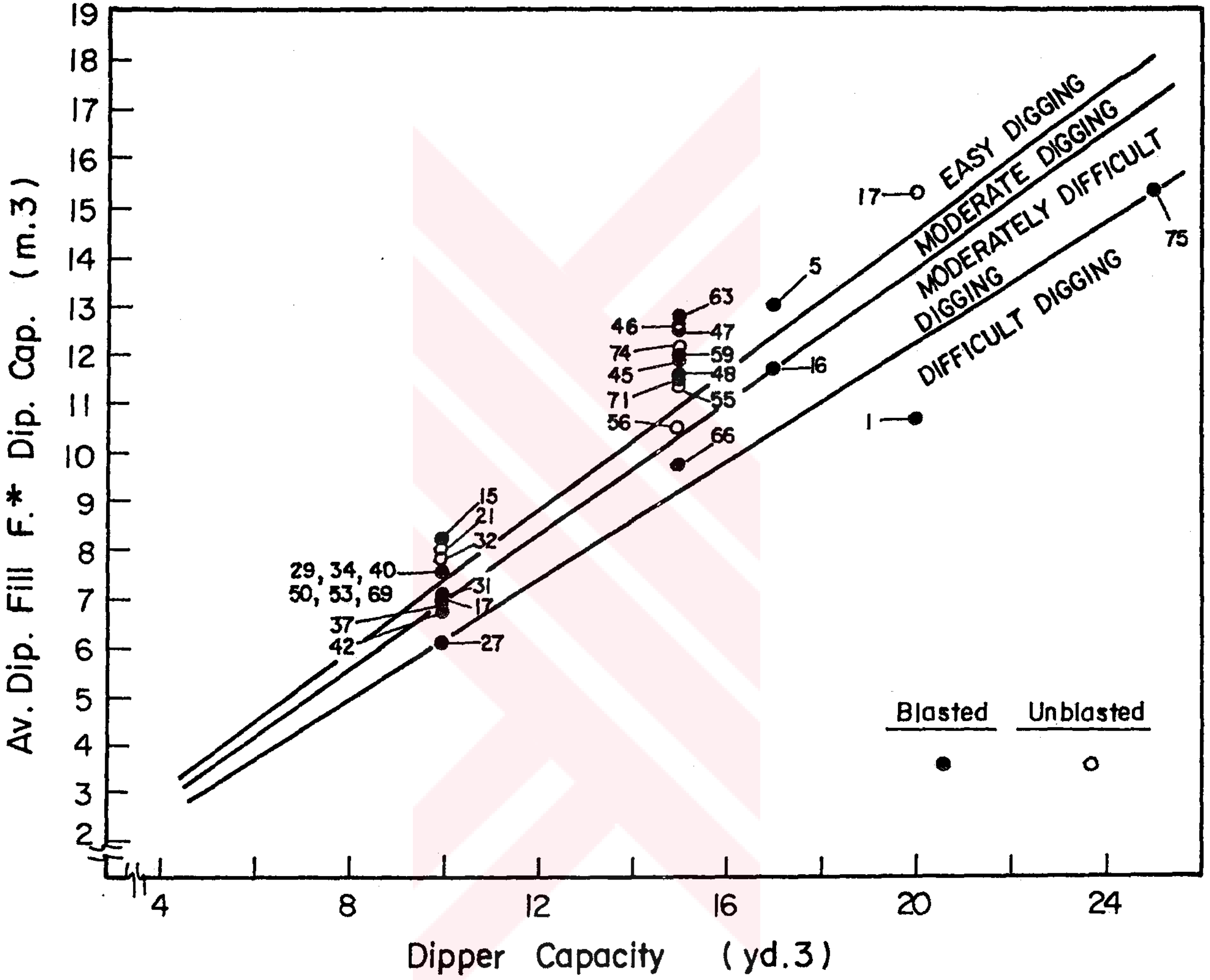


Figure 40. a. Classifications of Formations with Respect to Average Dipper Fill Factor for Easy Digging Condition.

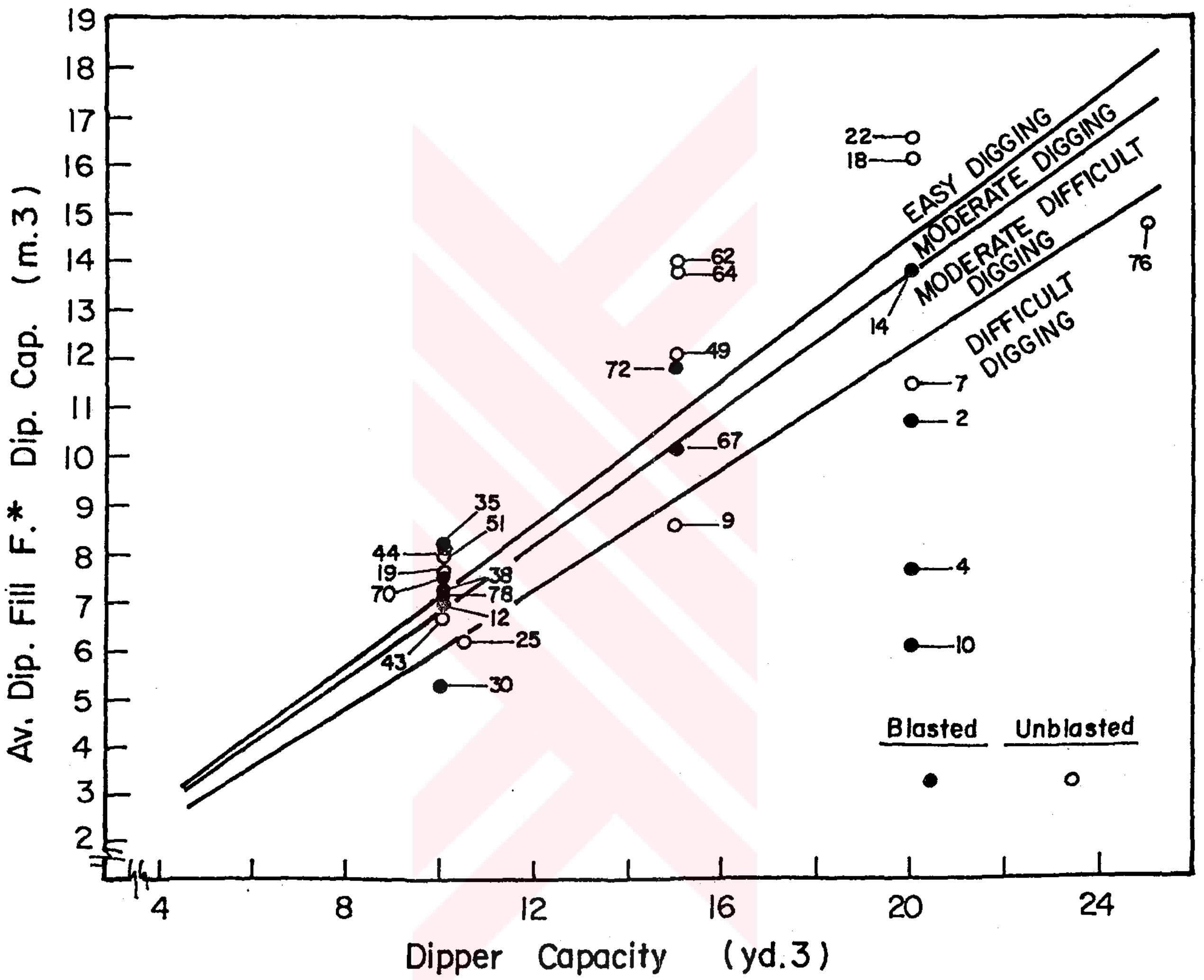


Figure 40. b. Classifications of Formations with Respect to Average Dipper Fill Factor for Moderate Digging Condition.

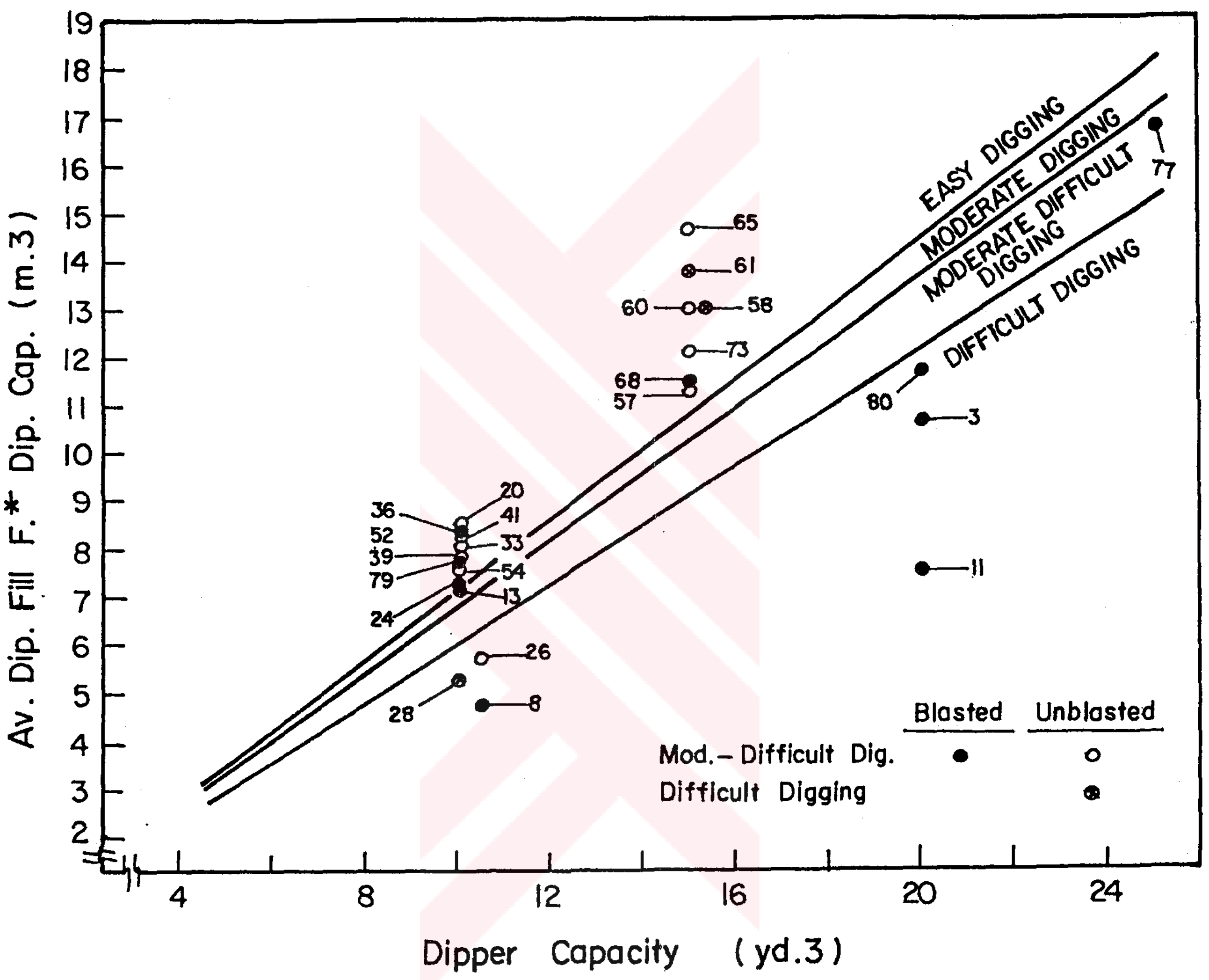


Figure 40. c. Classifications of Formations with Respect to Average Dipper Fill Factor for Moderately Difficult and Difficult Digging Conditions.

of less digging time and operational conditions so the dipper fill factor can be found less than the literature for observed digging condition. The average dipper fill factors of moderate digging condition found 0.50 and 0.40 for Işıklar and Deniş-Çamtarla good blasted marl formations (Code 4 and 10), while the digging times of 6.63 sec. and 5.00 sec. respectively. These are the good examples of digging time effect, where the literature values are in the range of 0.90 and 0.95.

Only 32% of average dipper fill factors of observed digging conditions showed accordance with literature values which indicates the difficulty to classify the digging conditions.

5.4.4. Hourly Capacity Without Waiting

Literature hourly capacities for different size of electrical shovels as a measure of digging difficulty are plotted and used to show the ranges of digging difficulty.

The calculated hourly capacities without waiting of different digging conditions which do not include down times are also compared with the literature values (Figure 41.a,b,c). Fourty-one points (51%) showed good agreement with the range of corresponding literature

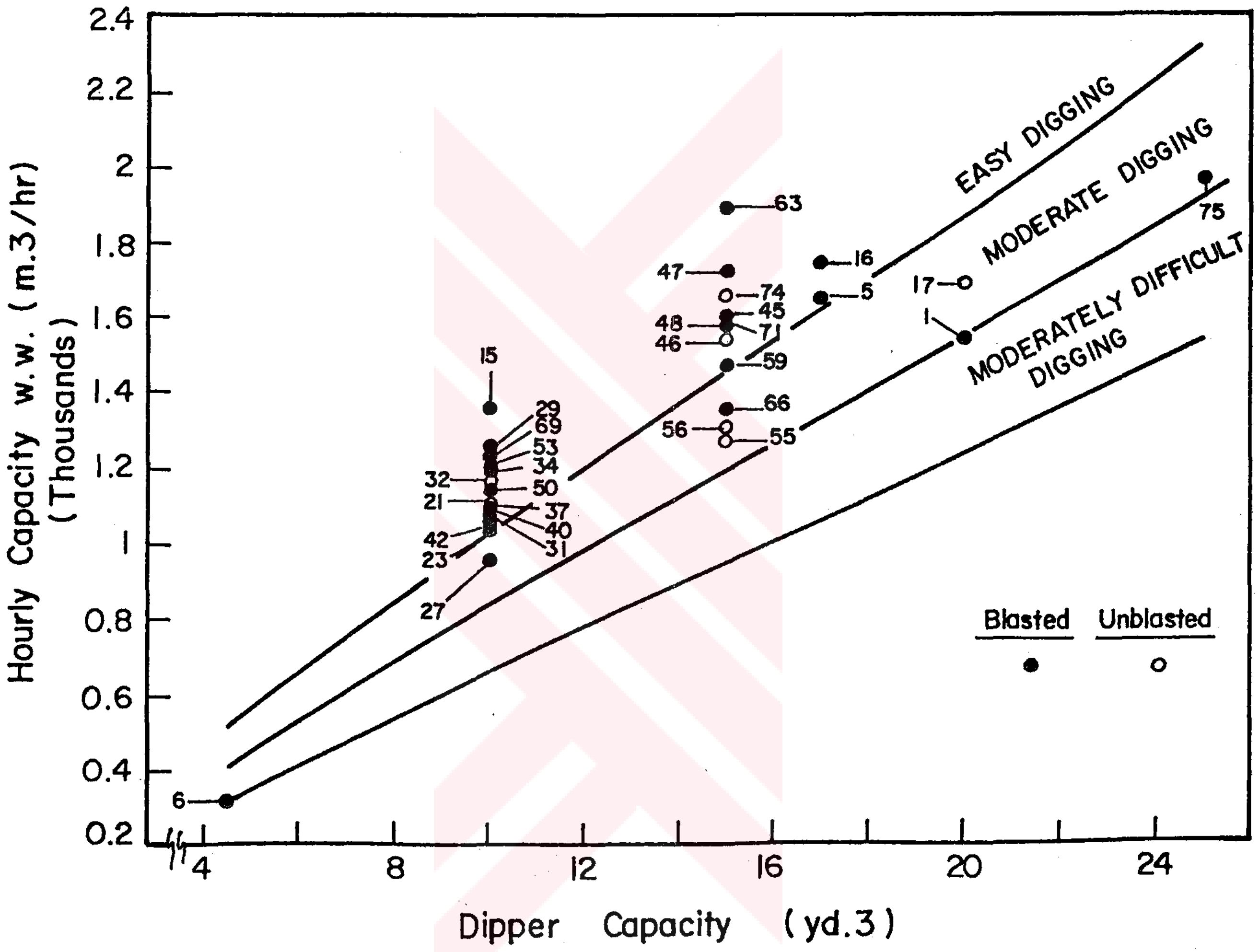


Figure 41. a. Relationship between Hourly Capacity Without Waiting and Dipper Capacity for Easy Digging Condition.

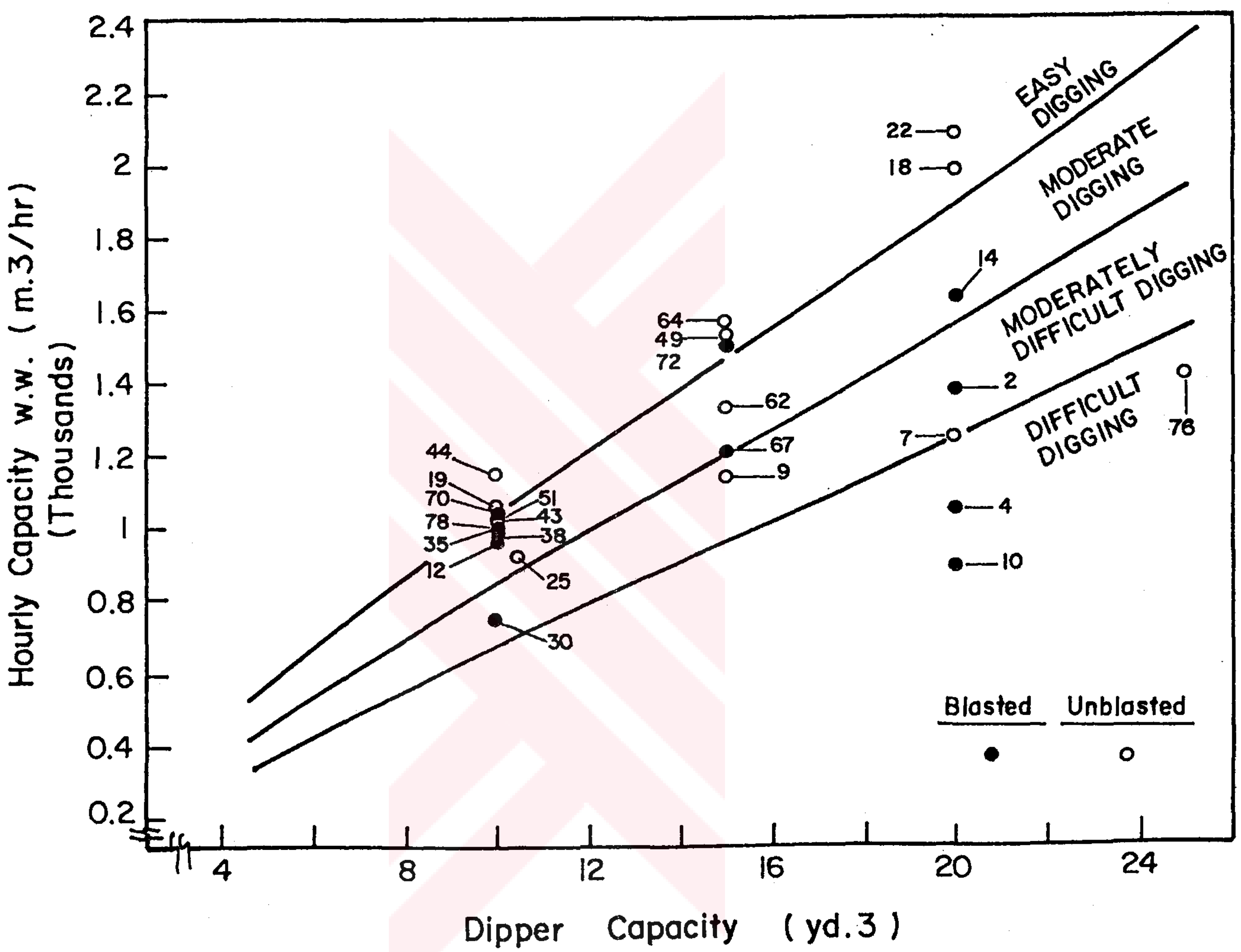


Figure 41. b. Relationship between Hourly Capacity Without Waiting and Dipper Capacity for Moderate Digging Condition.

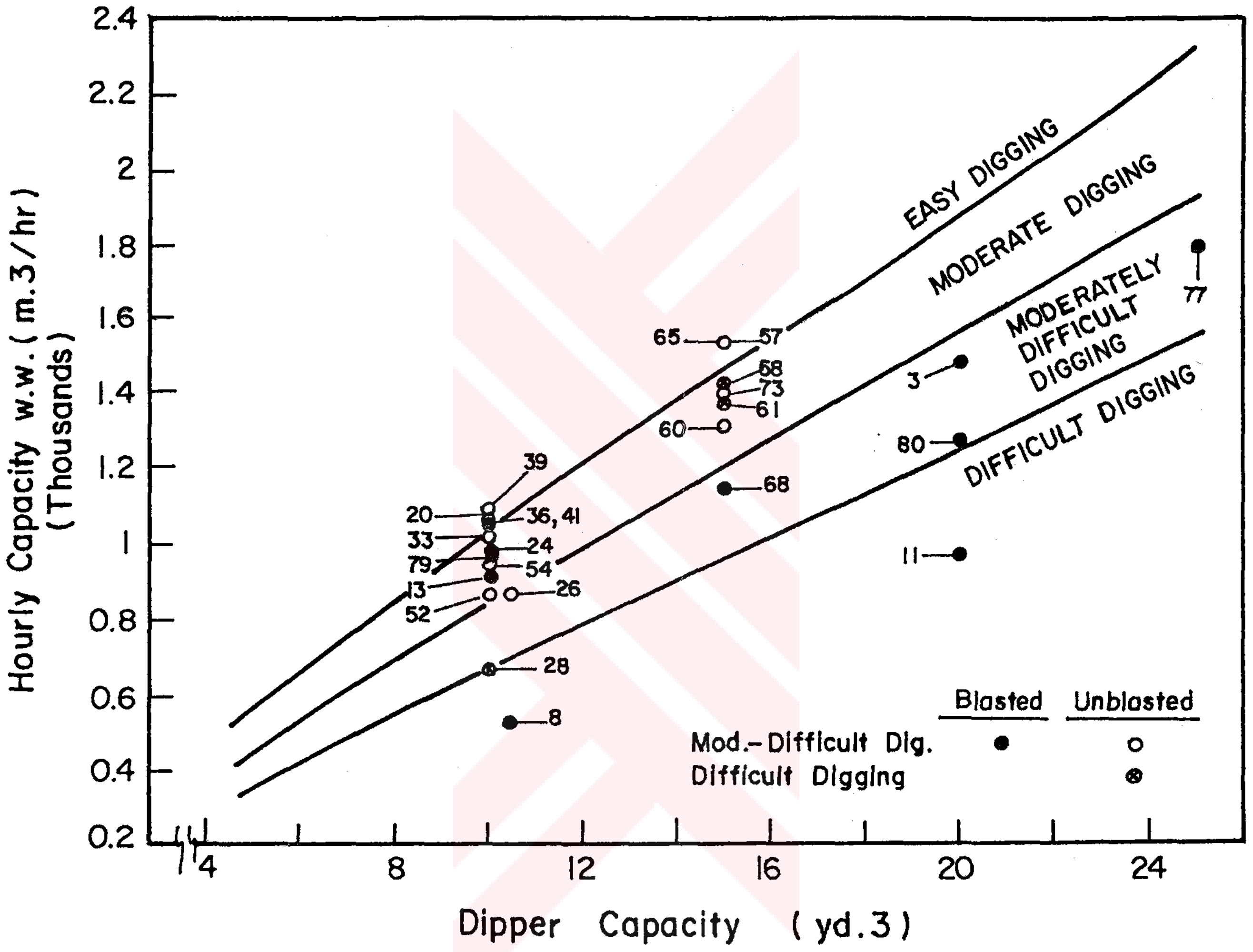


Figure 41. c. Relationship between Hourly Capacity Without Waiting and Dipper Capacity for Moderately Difficult and Difficult Digging Conditions.

values. 28% of the data are greater and 21% are less than the literature values. The combined affect of cycle time and dipper fill factor on classifications of digging condition by means of hourly capacity clearly indicates the need to consider not only time and excavated amount of material but also power and energy consumptions of the shovel during digging. It will be discussed later on.

5.4.5. Hourly Digging Capacity

Hourly digging capacity which embodies both digging time and dipper fill factor can be a better indicator of digging difficulty.

The calculated values of each digging condition are plotted in Figures 42.a to 42.c. It is observed that the ranges of digging difficulty obtained from hourly digging capacity are much better than the hourly capacity without waiting. The 66% and 51% of measurements showed good agreement with the ranges of hourly digging capacity and hourly capacity without waiting respectively.

5.4.6. Time Average Power of Digging

Digging power consumption of the shovel is

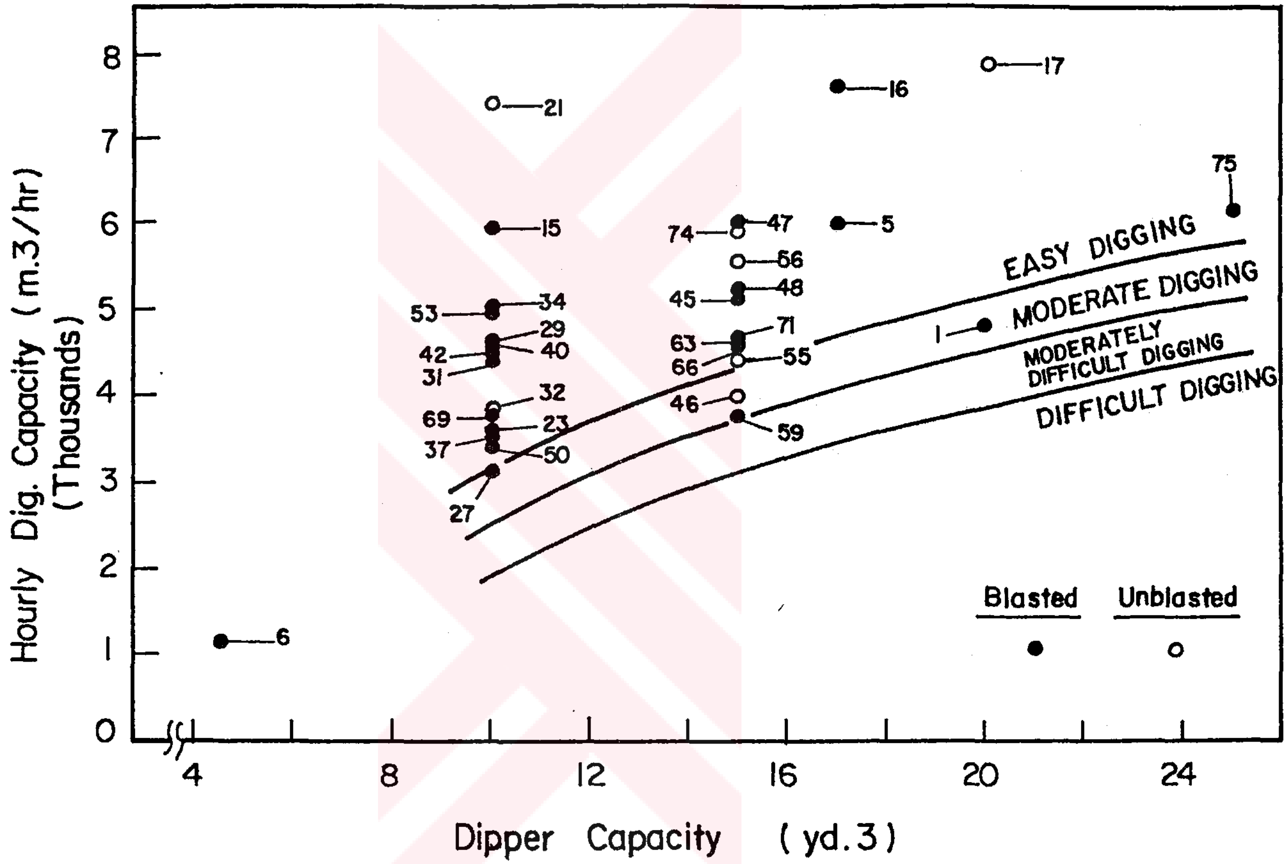


Figure 42. a. Relationship between Hourly Digging Capacity and Dipper Capacity for Easy Digging Condition.

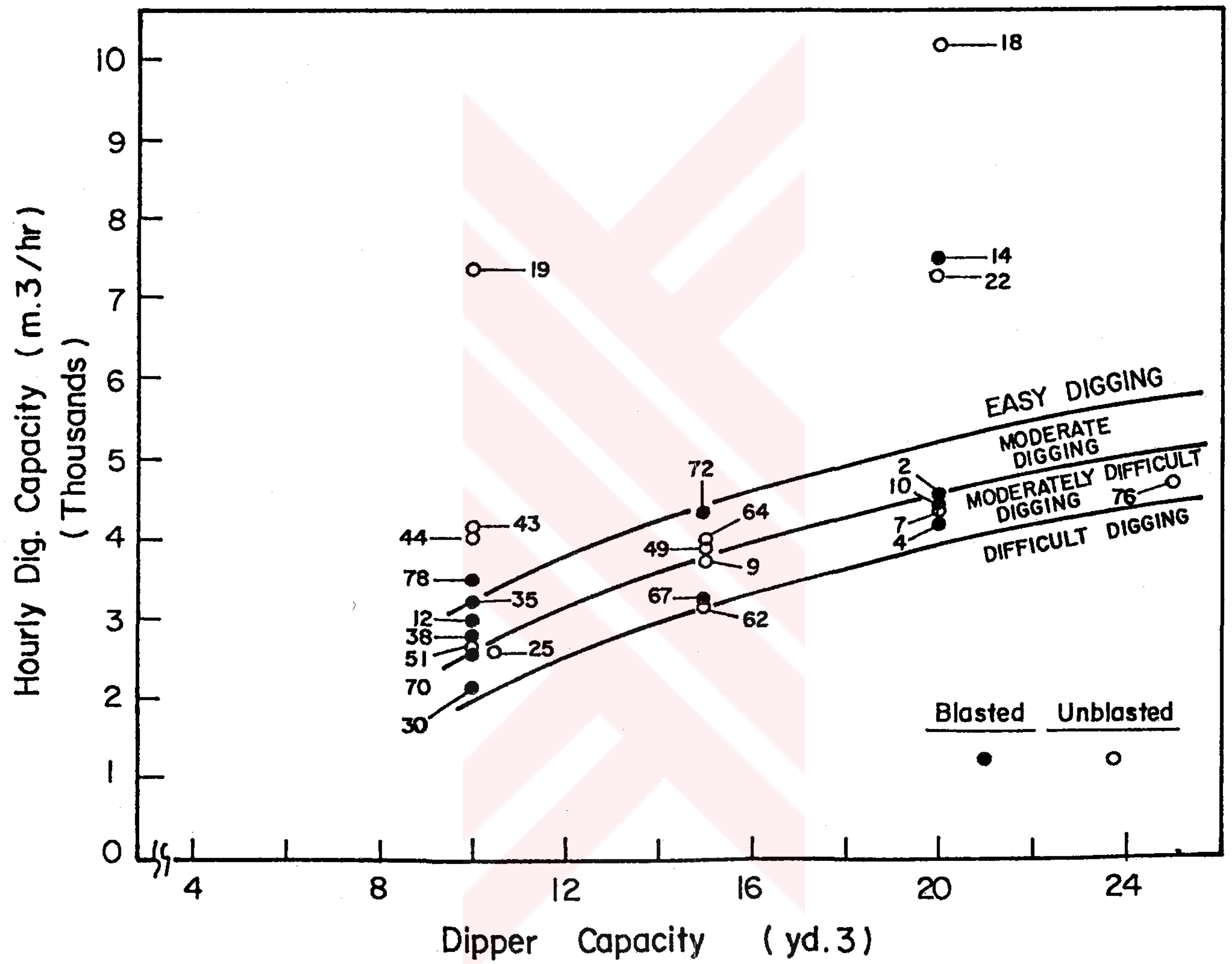


Figure 42. b. Relationship between Hourly Digging Capacity and Dipper Capacity for Moderate Digging Condition.

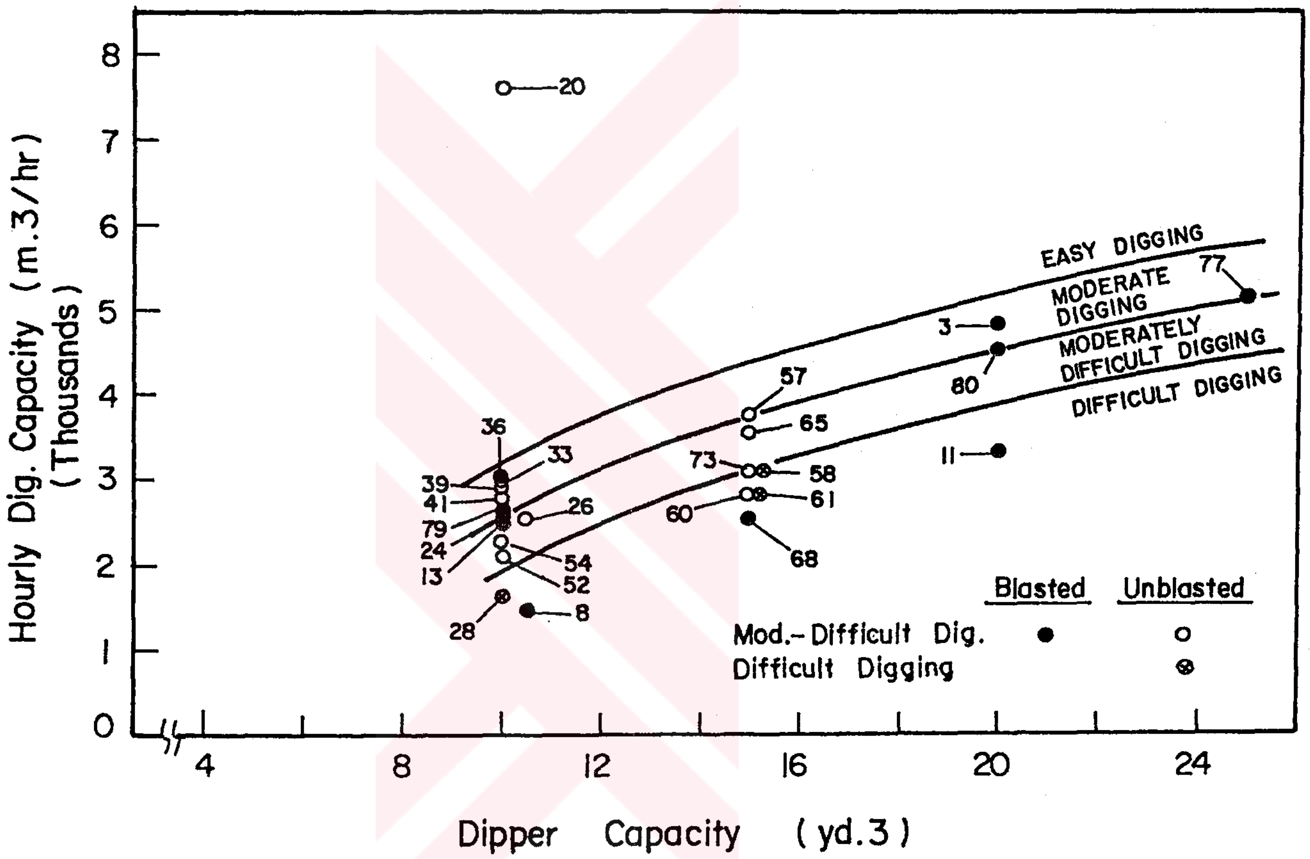


Figure 42. c. Relationship between Hourly Digging Capacity and Dipper Capacity for Moderately Difficult and Difficult Digging Conditions.

directly proportional to machine size and digging difficulty. It is also observed that the power consumption changes as the model and age of the shovel change. Figure 43.a shows the relationship between power consumption of empty digging motion and dipper capacity. The greatest empty digging motion power consumptions indicated in circles in Figure 43.a are found 878 kW and 602 kW for the oldest shovels which are 19 years and 12 years respectively with a 10 yd3 dipper capacity. Time average power consumptions of observed digging conditions with respect to dipper capacity are plotted in Figures 43.b to 43.d. The time average digging power values are rearranged and averaged with respect to the digging conditions and dipper capacities and the results are presented in Table 23.a. The Table may be utilized to determine the optimum ranges of time average power with respect to observed digging conditions which are also indicated in Figures 43.b to 43.d. The points indicated in circles in these Figures are not considered during the determination of digging difficulty ranges because these values belong to older shovels with relatively high empty digging motion power.

Digging power consumption increases as the dipper capacity and digging difficulty increase. As mentioned before, the increasing of power with respect to digging difficulty is easily observed at the same operational

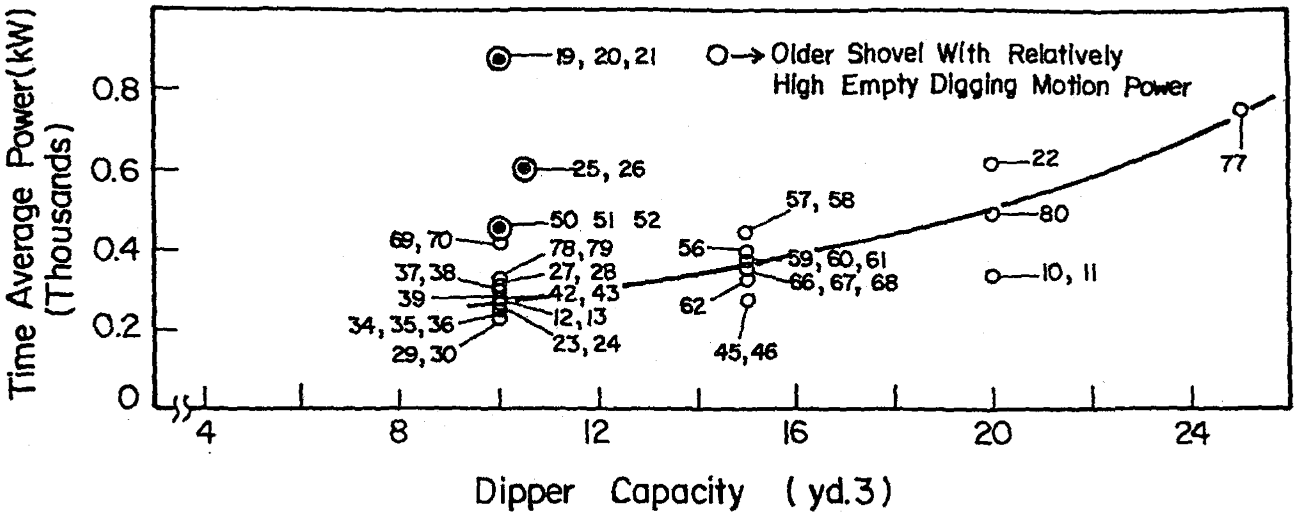


Figure 43. a. Relationship between Time Average Power of Empty Digging Motion and Dipper Capacity.

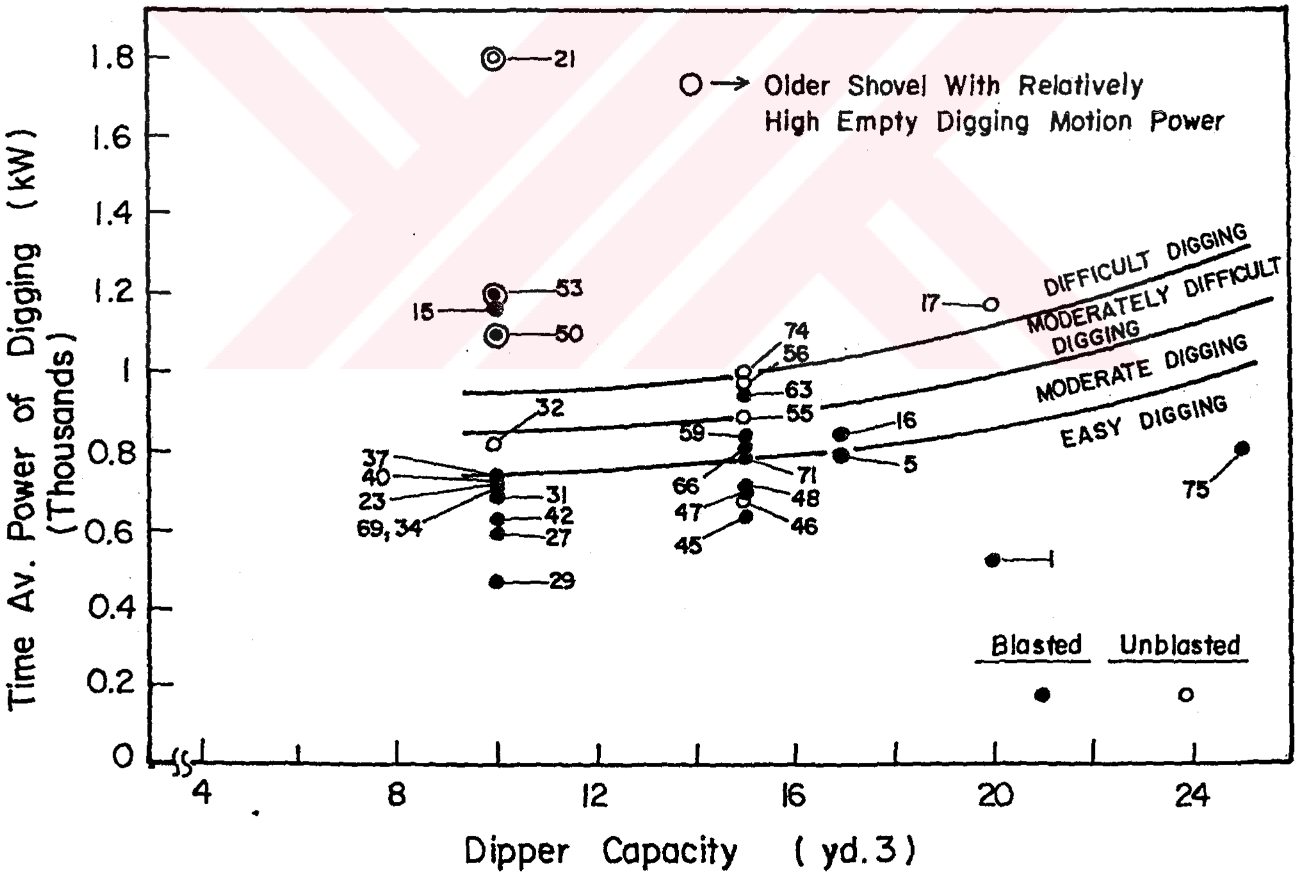


Figure 43. b. Relationship between Time Average Power of Digging and Dipper Capacity for Easy Digging Condition.

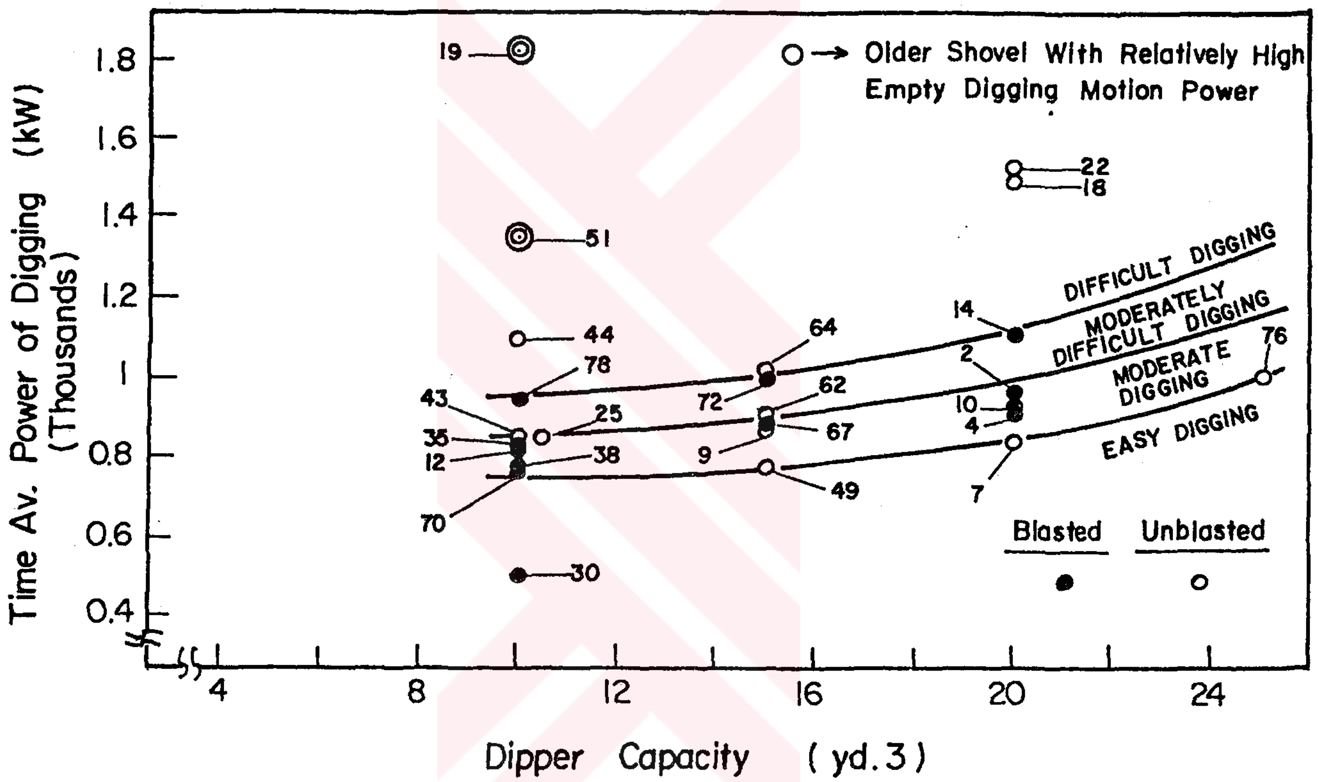


Figure 43. c. Relationship between Time Average Power of Digging and Dipper Capacity for Moderate Digging Condition.

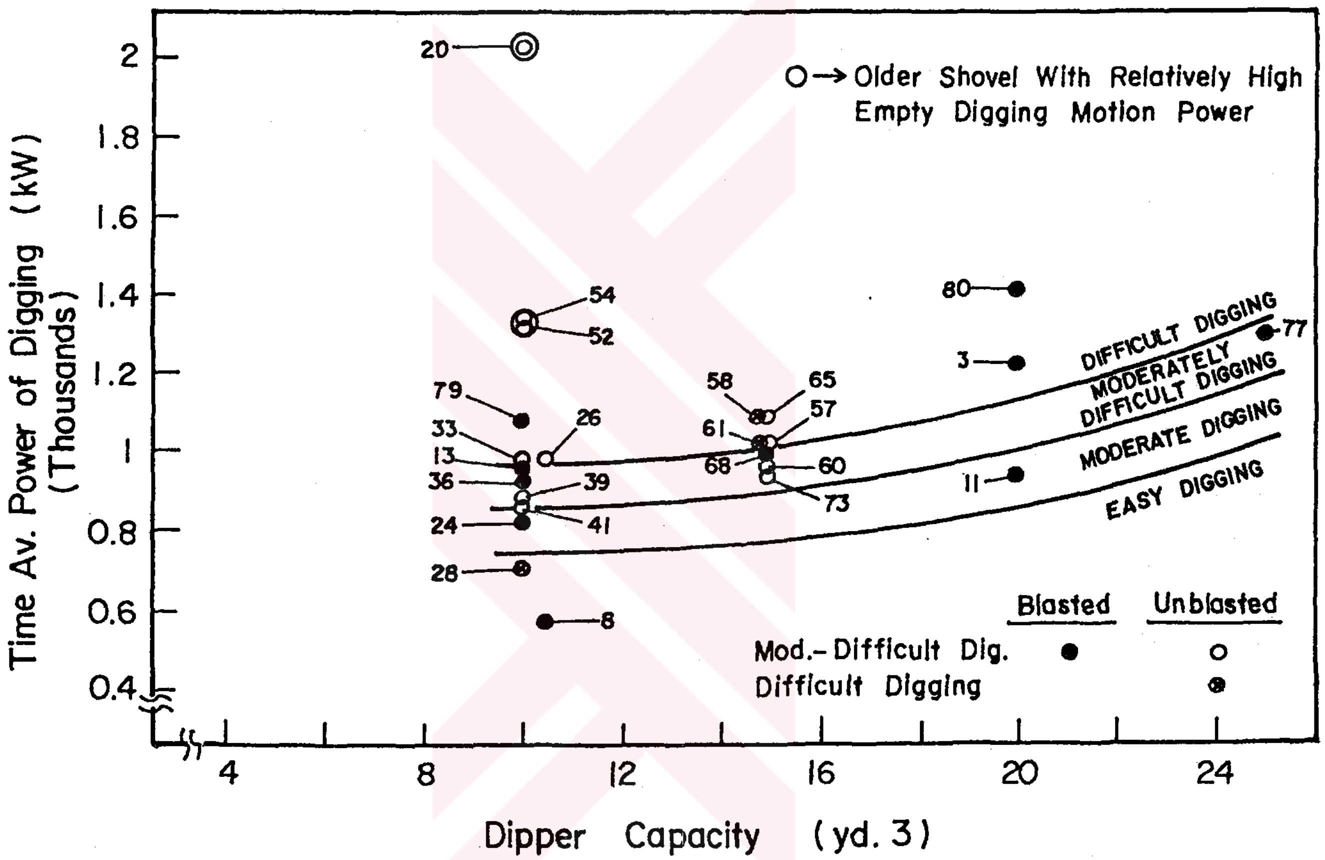


Figure 43. d. Relationship between Time Average Power of Digging and Dipper Capacity for Moderately Difficult and Difficult Digging Conditions.

Table 23.a. Variation of Time Average Power of Digging (kW) According to Ease of Digging.

Ease of Digging / Dipper Capacity (yd^3)	Easy Digging		Moderate Digging		Moderately Difficult Digging		Difficult Digging	Empty Digging Motion
	Blasted	Unblasted	Blasted	Unblasted	Blasted	Unblasted	Unblasted	
4.5	250	-	-	-	-	-	-	-
10	794.8 ± 228.7 (474 - 1197)	821	770.8 ± 144.8 (508 - 946)	1030.0 ± 239.5 (840 - 1343)	859.4 ± 199.1 (545 - 1072)	1051.0 ± 216.4 (854 - 1326)	699	304.60 ± 54.92 (234 - 431)
15	769.4 ± 103.4 (637 - 945)	883.0 ± 148.3 (671 - 994)	935.0 ± 87.7 (873 - 997)	885.8 ± 103.3 (762 - 1014)	978	985.0 ± 69.8 (927 - 1073)	1034.5 ± 60.1 (927 - 1073)	356.67 ± 56.35 (267 - 435)
17	(800 - 843)	-	-	-	-	-	-	-
20	523	1175	971.5 ± 91.0 (911 - 1105)	1287.0 ± 378.7 (850 - 1519)	1176.7 ± 239.9 (923 - 1400)	-	-	483.00 ± 142.26 (333 - 616)
25	804	-	-	1011	1277	-	-	752

conditions. For example, time average digging powers for slightly weathered blasted marl formation at Seyitömer where a 10 yd3 dipper capacity shovel was operated are 734 kW, 828 kW and 914 kW for observed digging conditions of easy, moderate and moderately difficult (Code 34, 35, 36) respectively. Comparisons of all time average powers of digging with each other show that 64% of these values are in accordance with the determined ranges of digging conditions. Therefore, it can be concluded that not only size, age and power consumption of the shovel but also digging time and excavated amount of material should be considered to derive a better indicator of digging conditions.

5.4.7. Maximum and Average of Peak Digging Power

The maximum peak power of digging is also related with digging difficulty, but variation in operational conditions strongly effects the maximum peak power. The maximum peak powers of empty digging motions are relatively greater than the average powers, where the maximum powers are obtained at the maximum lift of the dipper and given in Figure 44.a. Figures 44.b to 44.d show the relationship between maximum peak power and dipper capacity for observed digging conditions. Figures also show the classifications of digging condition with respect to the maximum peak power determined from the

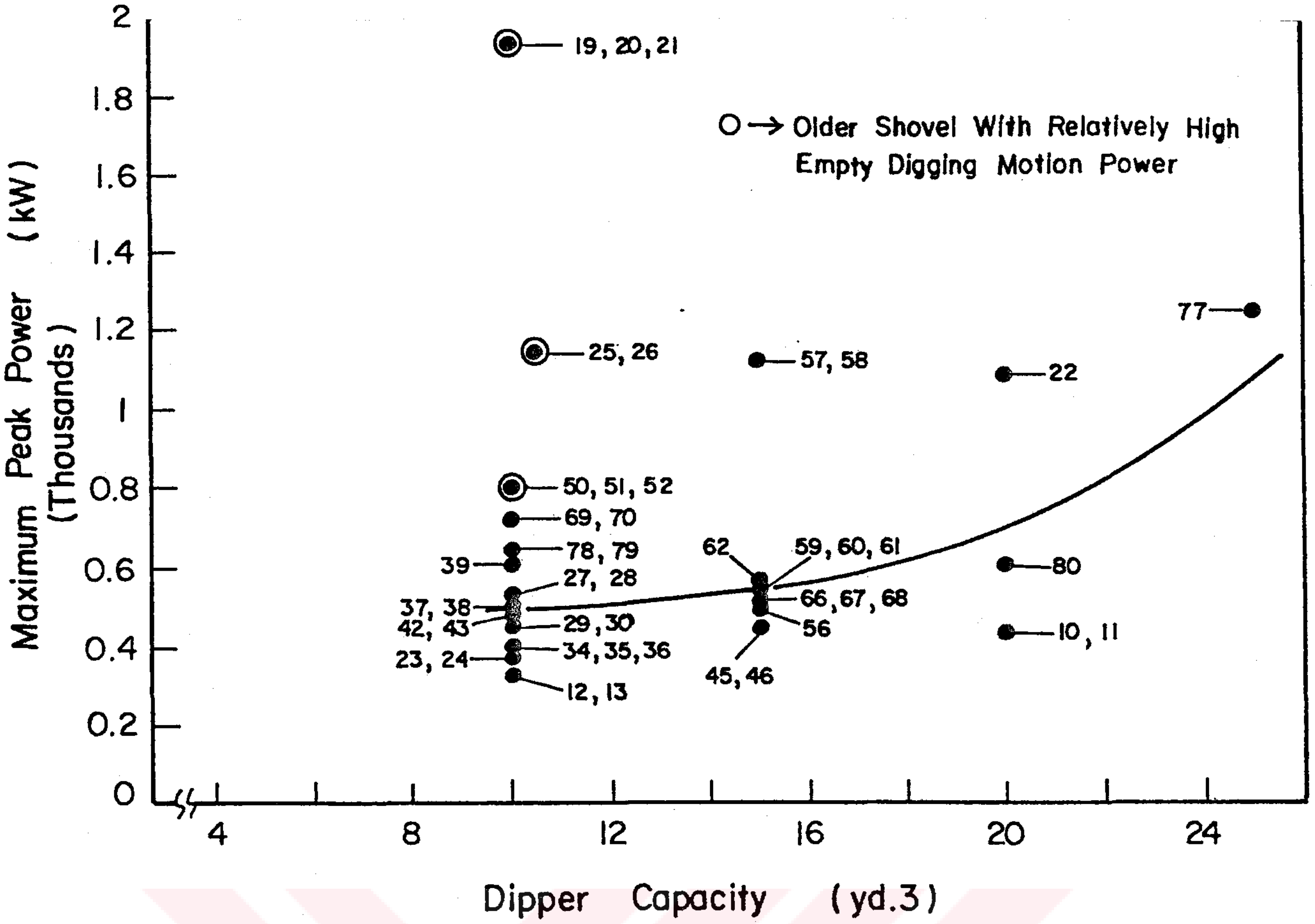


Figure 44. a. Relationship between Maximum Peak Power of Empty Digging Motion and Dipper Capacity.

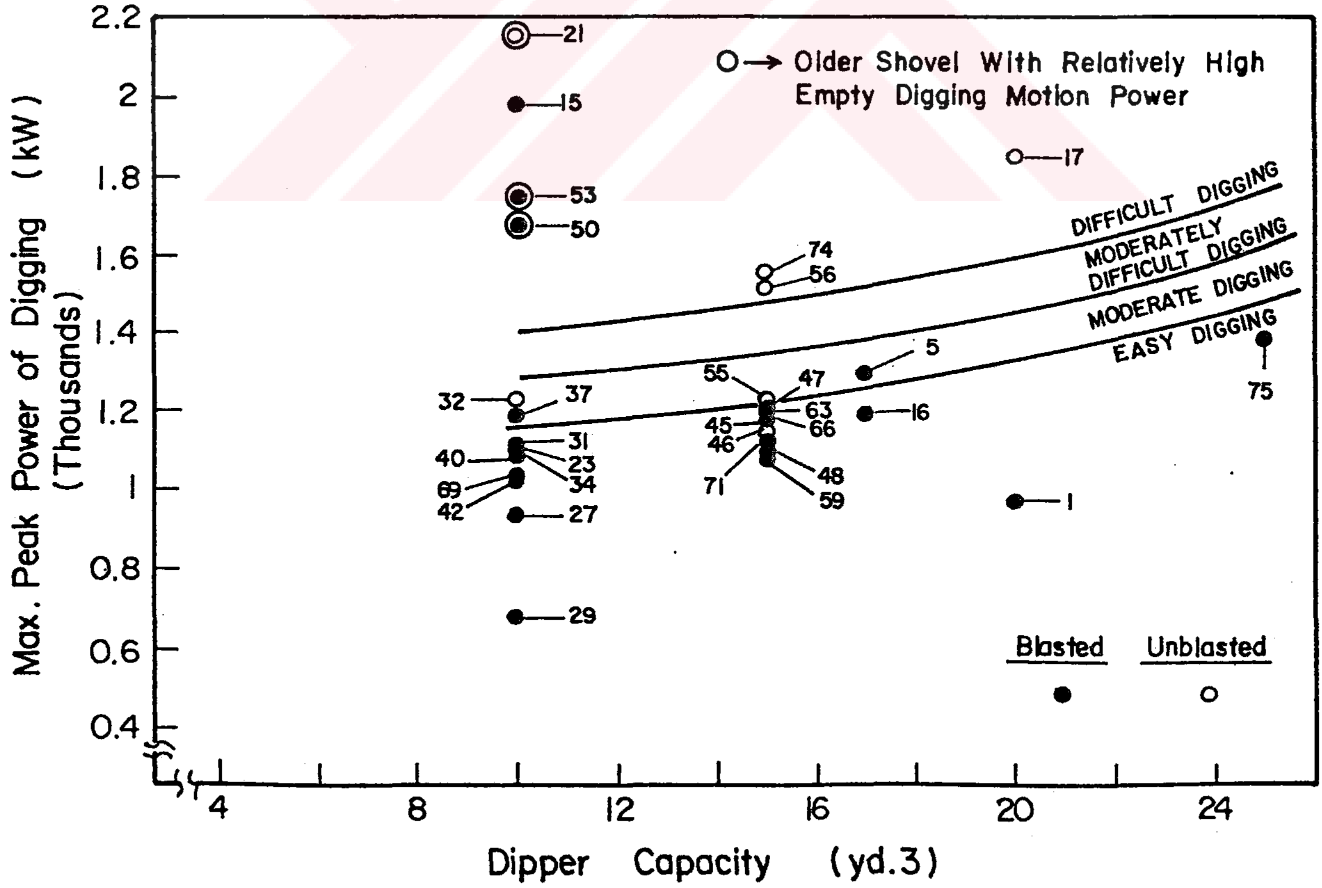


Figure 44. b. Relationship between Maximum Peak Power of Digging and Dipper Capacity for Easy Digging Condition.

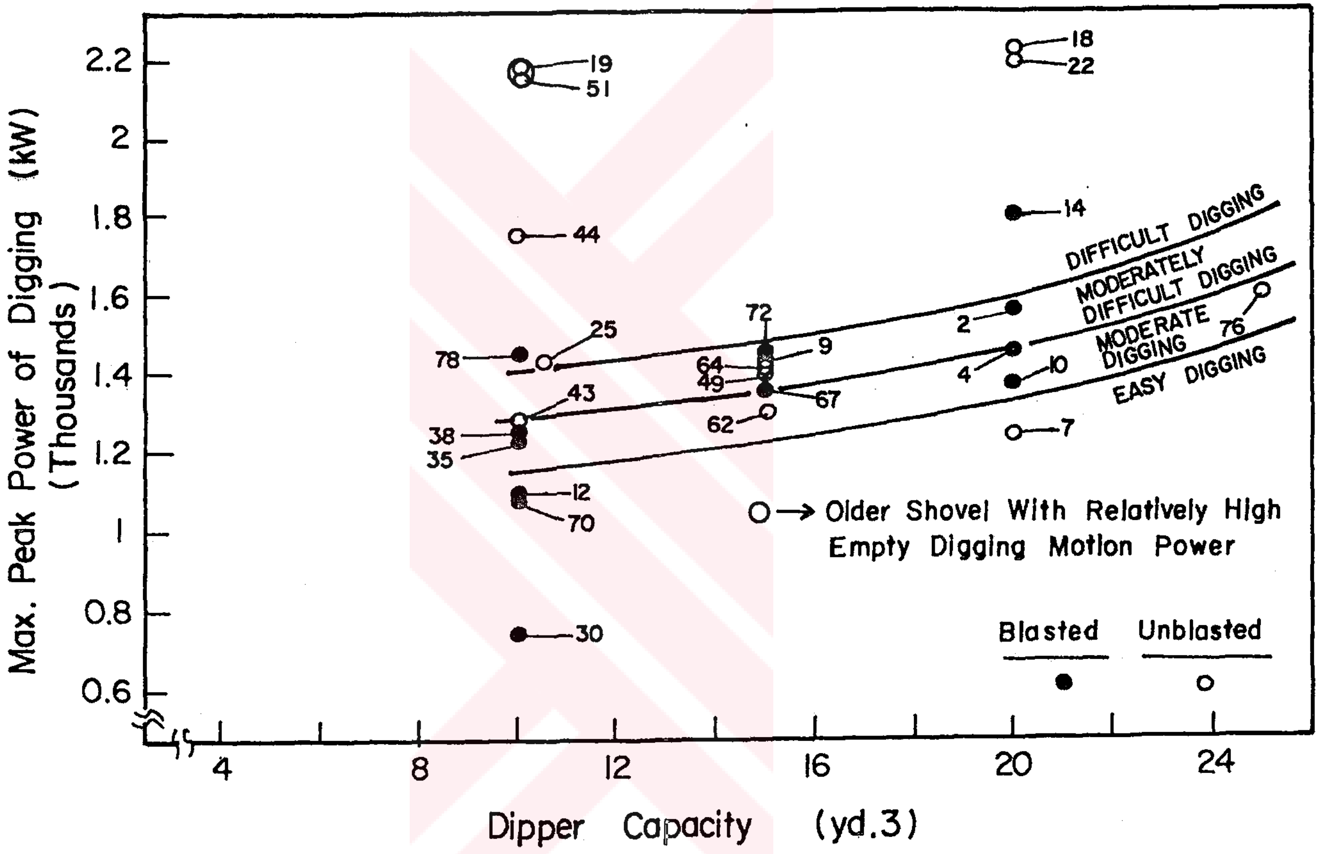


Figure 44. c. Relationship between Maximum Peak Power of Digging and Dipper Capacity for Moderate Digging Condition.

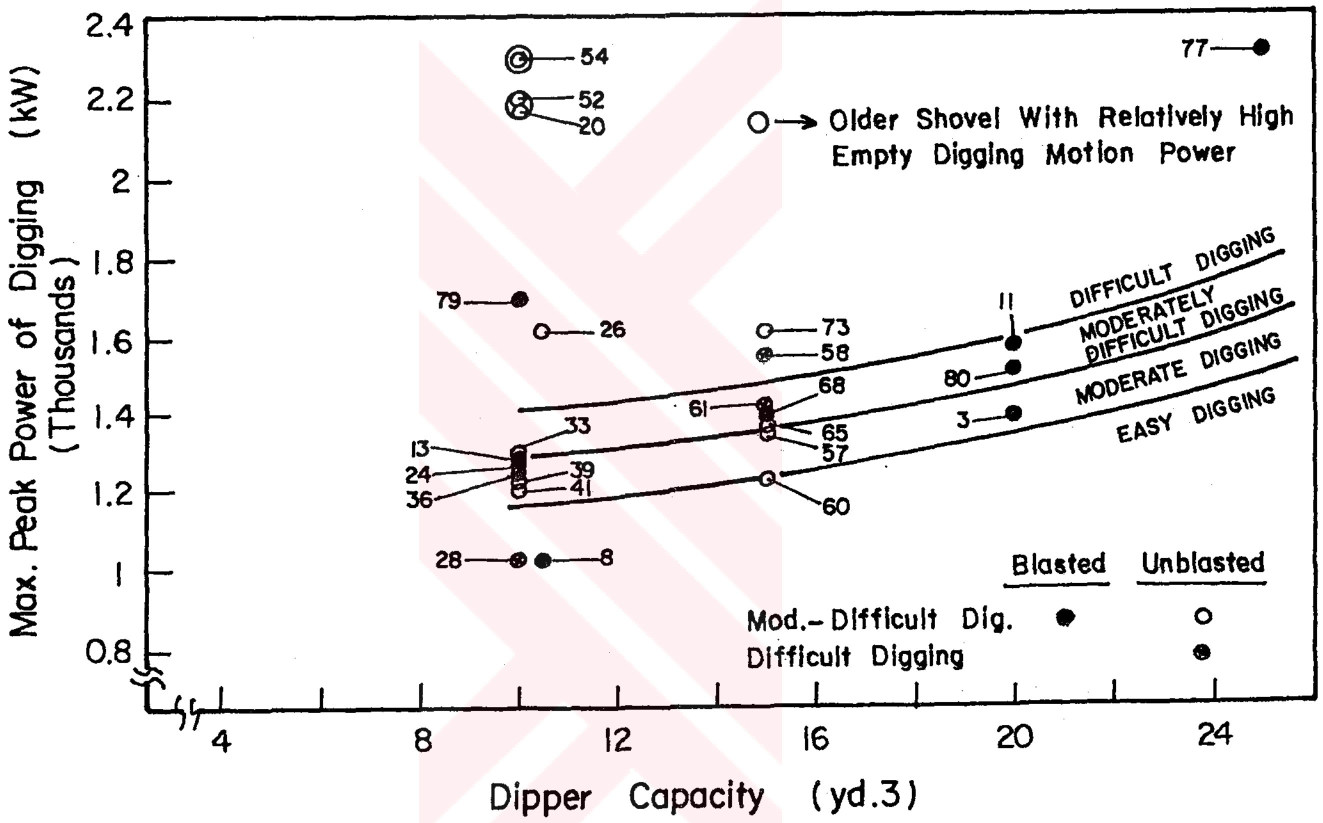


Figure 44. d. Relationship between Maximum Peak Power of Digging and Dipper Capacity for Moderately Difficult and Difficult Digging Conditions.

available data, summarized in Table 23.b, although one measurement is considered for each observed digging condition, 50% of these values are found in the ranges of digging classes.

The average of peak digging power values of digging conditions are analyzed in the same manner and plotted in Figures 45.a to 45.c. 54% of these values are in accordance with the determined ranges of digging conditions. Variation of average of peak digging power according to the dipper capacity and digging condition is also given in Table 23.c.

5.4.8. Energy Consumption of Digging

The relationship between dipper capacity and energy consumption of empty digging motion is shown in Figure 46.a to indicate the relative decreases according to the energy consumption of digging. Digging energy consumptions of observed digging conditions are plotted with respect to dipper capacity in Figures 46.b to 46.d, where the indicated ranges of digging conditions are determined from the comparison of available data. Table 23.d presents the variation of digging energy consumption according to digging condition and dipper capacity.

Table 23.b. Variation of Maximum Peak Power of Digging (kW) According to Ease of Digging.

Ease of Digging / Dipper Capacity (yd^3)	Easy Digging		Moderate Digging		Moderately Difficult Digging		Difficult Digging	Empty Digging Motion
	Blasted	Unblasted	Blasted	Unblasted	Blasted	Unblasted	Unblasted	
4.5	393	-	-	-	-	-	-	-
10	1220.5 ± 380.4 (684 - 1987)	1227	1137.5 ± 234.2 (744 - 1440)	1651.0 ± 390.0 (1274 - 2155)	1297.2 ± 246.6 (1017 - 1696)	1637.7 ± 486.7 (1202 - 2291)	1022	503.60 ± 126.24 (324 - 720)
15	1152.6 ± 54.7 (1089 - 1234)	1362.5 ± 202.1 (1143 - 1555)	1397.0 ± 60.8 (1354 - 1440)	1378.8 ± 55.7 (1296 - 1416)	1382	1386.8 ± 162.8 (1225 - 1613)	1492.0 ± 89.1 (1429 - 1555)	614.33 ± 248.44 (448 - 1115)
17	1245.0 ± 72.1 (1194 - 1296)	-	-	-	-	-	-	-
20	972	1814	1537.2 ± 183.8 (1361 - 1768)	1888.0 ± 558.6 (1243 - 2218)	1482.7 ± 93.2 (1382 - 1566)	-	-	704.00 ± 336.29 (432 - 1080)
25	1382	-	-	1598	2304	-	-	1238

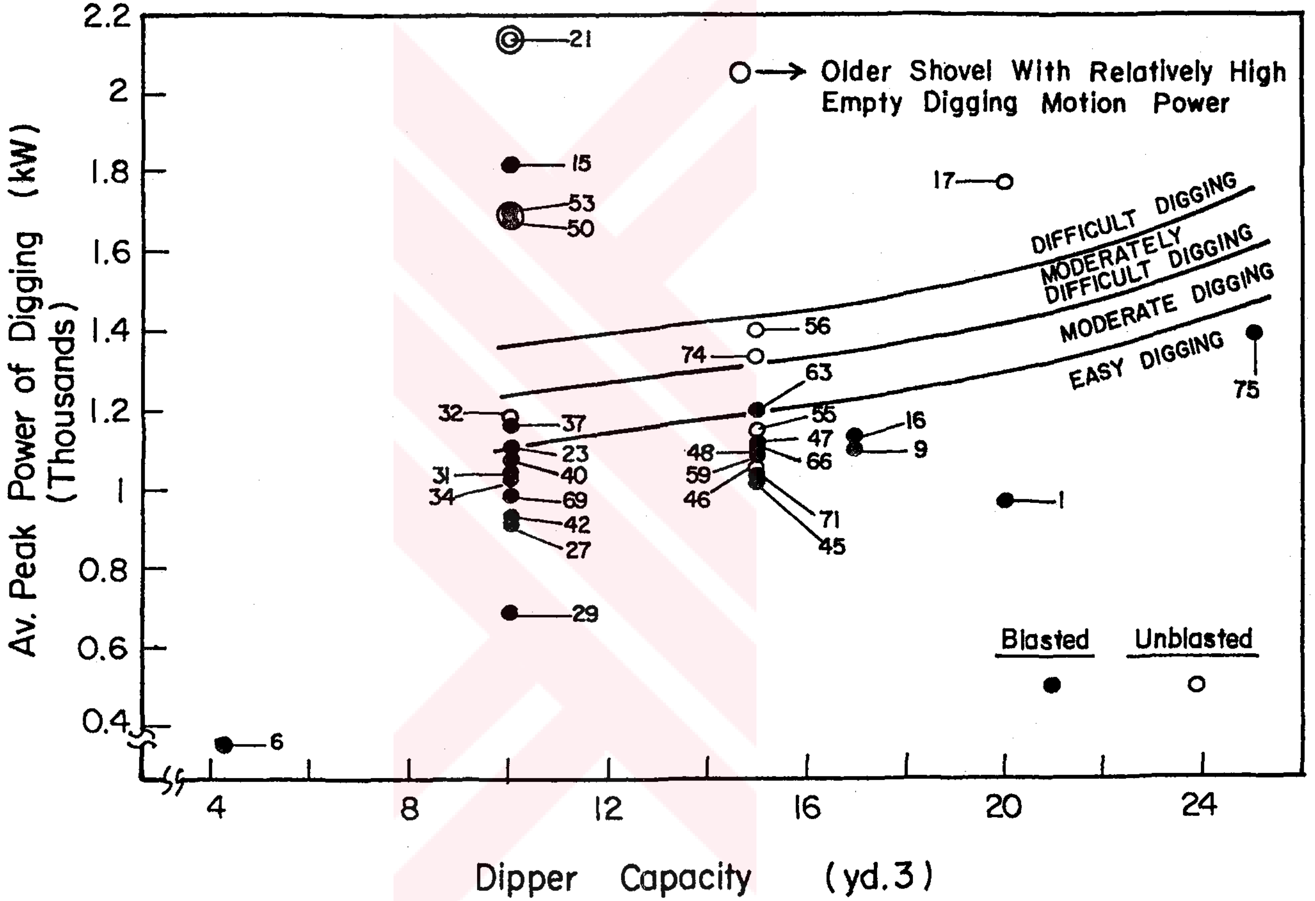


Figure 45. a. Relationship between Average Peak Power of Digging and Dipper Capacity for Easy Digging Condition.

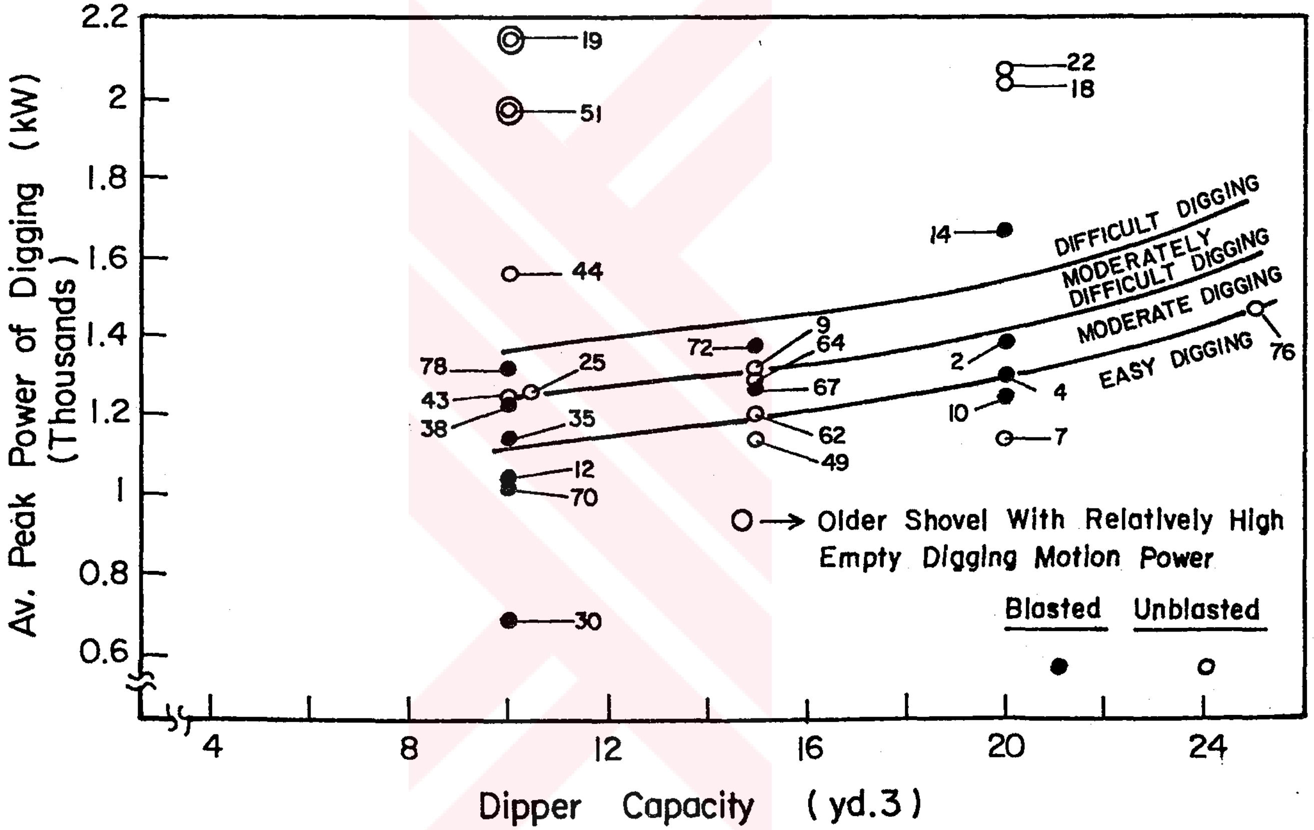


Figure 45. b. Relationship between Average Peak Power of Digging and Dipper Capacity for Moderate Digging Condition.

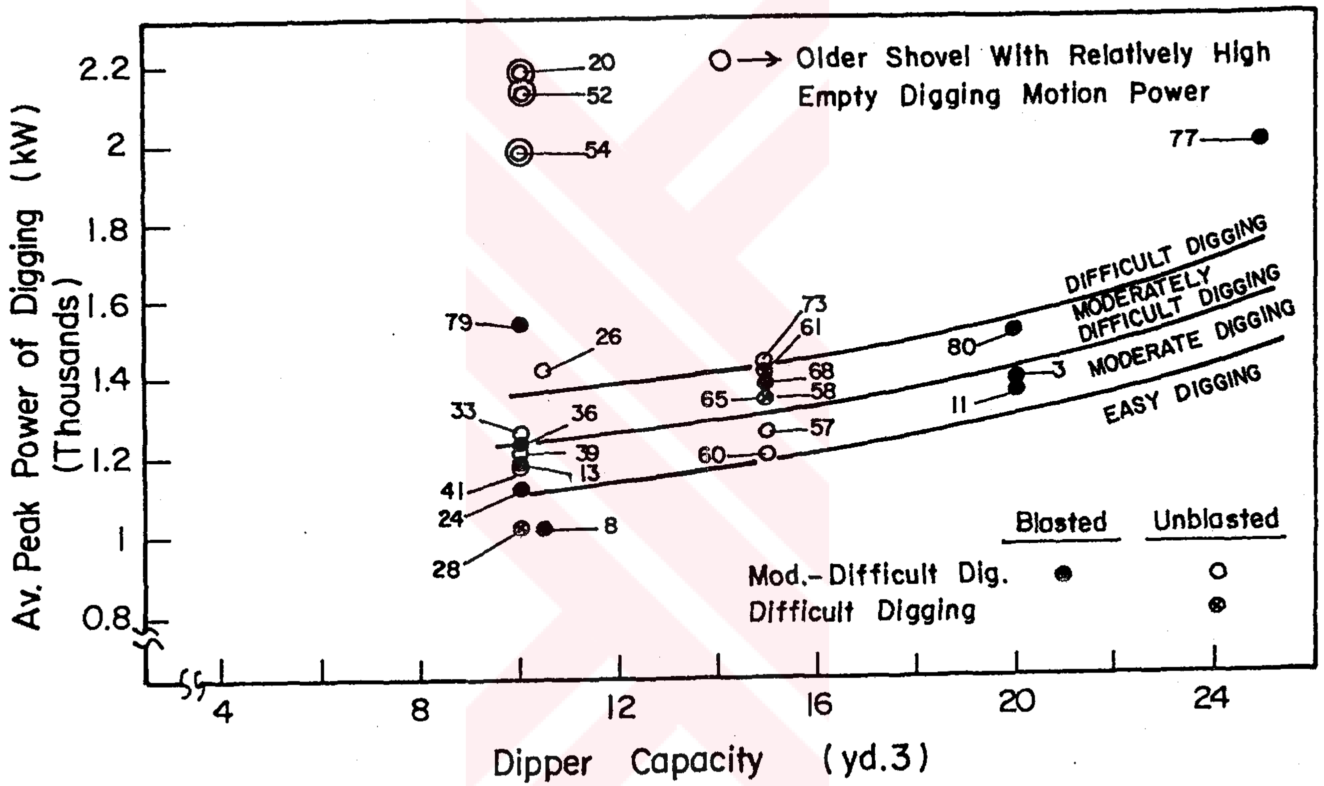


Figure 45. c. Relationship between Average Peak Power of Digging and Dipper Capacity for Moderately Difficult and Difficult Digging Conditions.

Table 23.c. Variation of Average Peak Power of Digging (kW) According to Ease of Digging.

Ease of Digging / Dipper Capacity (yd^3)	Easy Digging		Moderate Digging		Moderately Difficult Digging		Difficult Digging	Empty Digging Motion
	Blasted	Unblasted	Blasted	Unblasted	Blasted	Unblasted	Unblasted	
4.5	370	-	-	-	-	-	-	-
10	1174.6 ± 352.8 (684 - 1805)	1181	1071.3 ± 219.1 (686 - 1308)	1504.5 ± 343.7 (1238 - 1973)	1218.2 ± 195.8 (1017 - 1536)	1529.5 ± 426.2 (1170 - 2147)	1022	-
15	1096.0 ± 48.1 (1047 - 1191)	1239.2 ± 150.5 (1075 - 1400)	1330.0 ± 47.4 (1296 - 1363)	1234.8 ± 85.7 (1131 - 1311)	1382	1308.5 ± 102.5 (1196 - 1430)	1369.5 ± 36.1 (1344 - 1395)	-
17	(1115 - 1130)	-	-	-	-	-	-	-
20	972	1757	1393.8 ± 192.4 (1242 - 1670)	1749.0 ± 523.5 (1145 - 2073)	1414.7 ± 74.6 (1362 - 1500)	-	-	-
25	1382	-	-	1461	1992	-	-	-

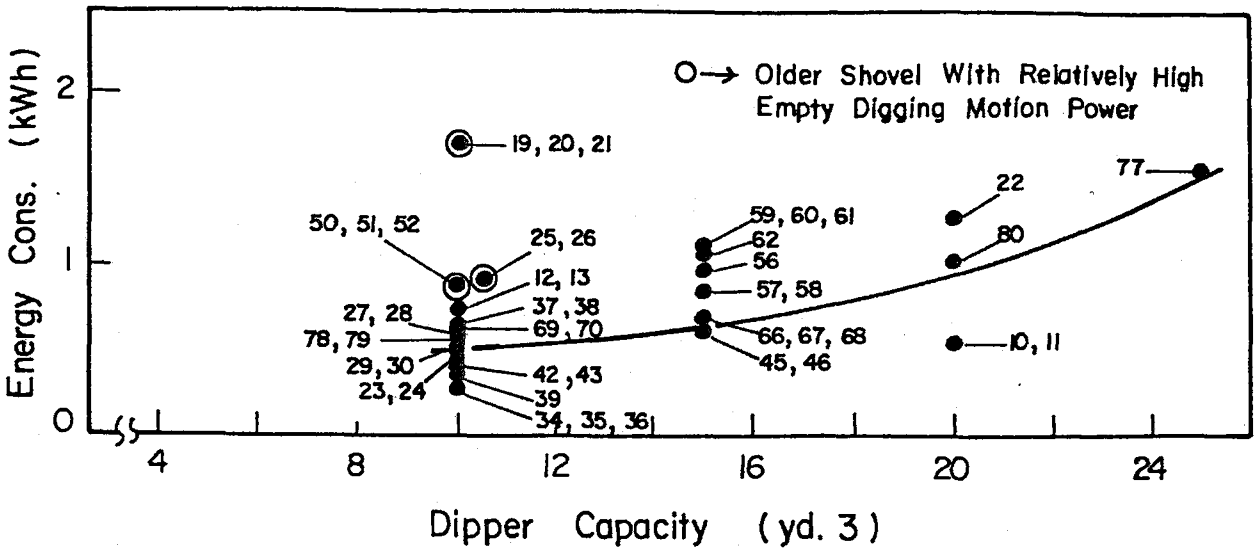


Figure 46. a. Relationship between Energy Consumption of Empty Digging Motion and Dipper Capacity.

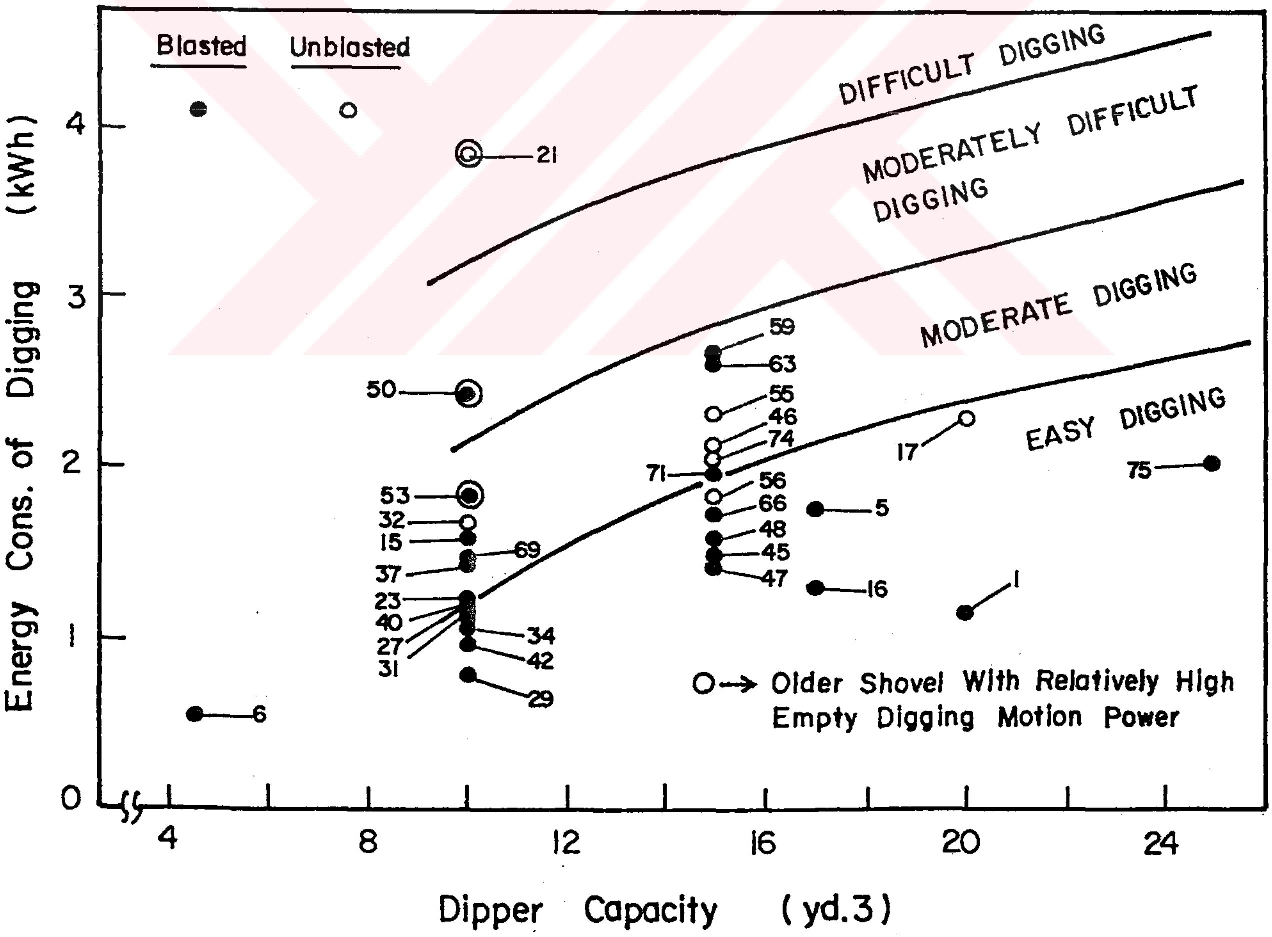


Figure 46. b. Relationship between Energy Consumption of Digging and Dipper Capacity for Easy Digging Condition.

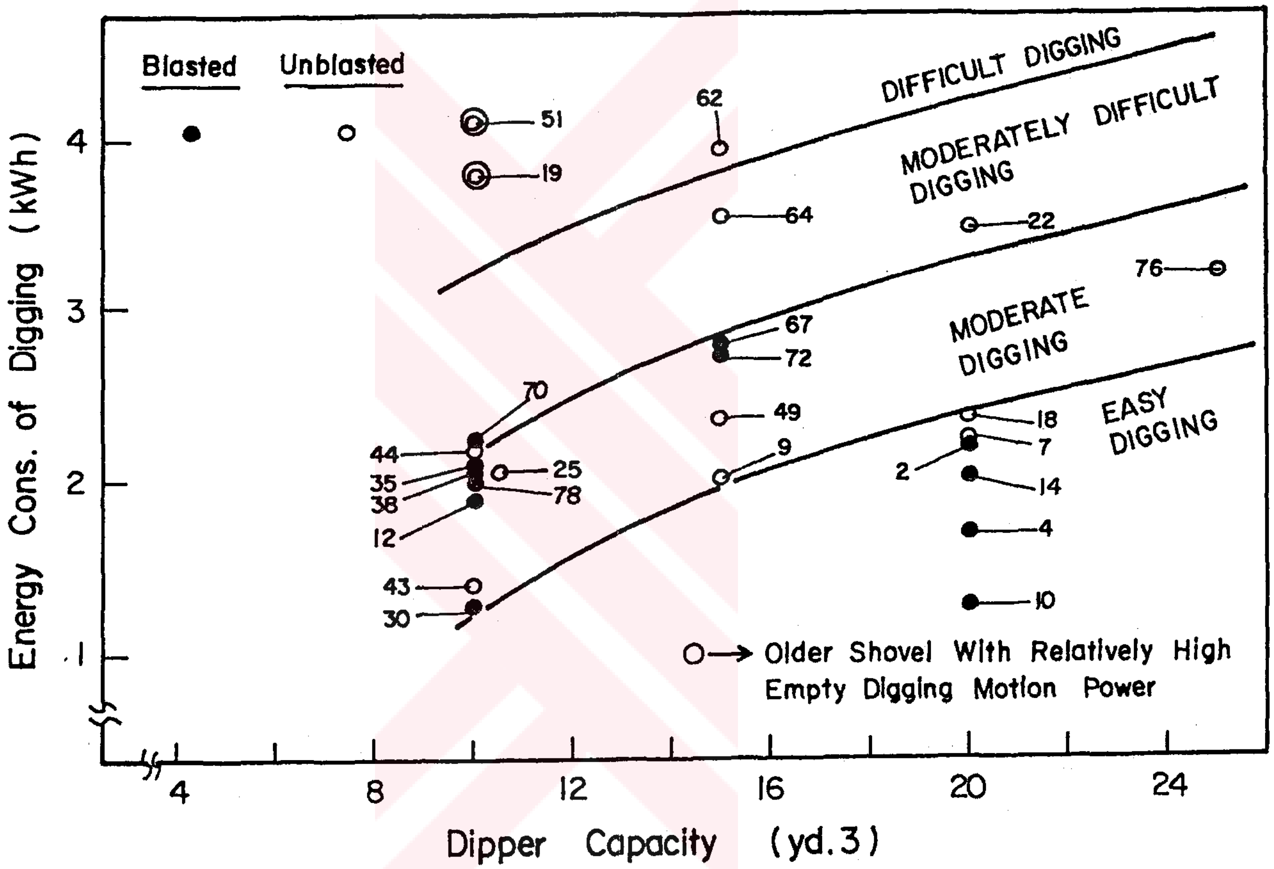


Figure 46. c. Relationship between Energy Consumption of Digging and Dipper Capacity for Moderate Digging Condition.

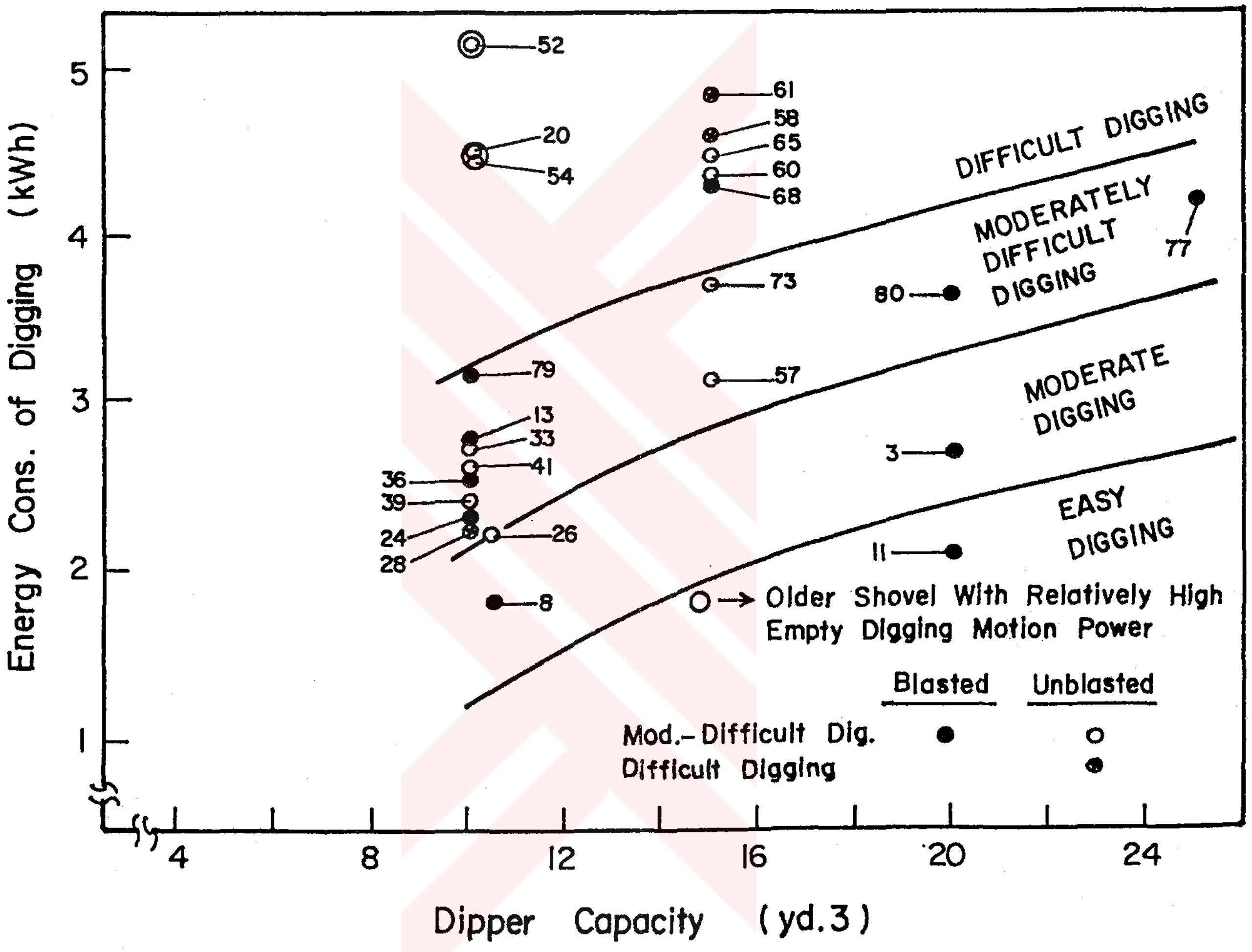


Figure 46. d. Relationship between Energy Consumption of Digging and Dipper Capacity for Moderately Difficult and Difficult Digging Conditions.

Table 23.d. Variation of Energy Consumption of Digging (kWh) According to Ease of Digging.

Ease of Digging / Dipper Capacity (yd^3)	Easy Digging		Moderate Digging		Moderately Difficult Digging		Difficult Digging	Empty Digging Motion
	Blasted	Unblasted	Blasted	Unblasted	Blasted	Unblasted	Unblasted	
4.5	0.542	-	-	-	-	-	-	-
10	1.383 ± 0.435 (0.790 - 2.424)	1.672	1.912 ± 0.332 (1.892 - 2.211)	2.436 ± 1.164 (1.400 - 4.104)	2.506 ± 0.496 (1.817 - 3.139	3.258 ± 1.235 (2.205 - 5.137)	2.230	0.527 ± 0.155 (0.263 - 0.748)
15	1.923 ± 0.516 (1.442 - 2.651)	2.078 ± 0.192 (1.844 - 2.309)	2.755 ± 0.027 (2.736 - 2.774)	2.963 ± 0.924 (2.008 - 3.943)	4.347	3.904 ± 0.634 (3.105 - 4.471)	4.704 ± 0.167 (4.586 - 4.822)	0.733 ± 0.167 (0.593 - 0.968)
17	1.510 ± 0.315 (1.288 - 1.733)	-	-	-	-	-	-	-
20	1.162	2.285	1.812 ± 0.432 (1.272 - 2.253)	2.660 ± 0.693 (2.257 - 3.460)	2.800 ± 0.769 (2.097 - 3.621)	-	-	0.960 ± 0.371 (0.555 - 1.283)
25	2.010	-	-	3.182	4.196	-	-	1.567

Time and power consumption of digging can be effectively analyzed by means of energy consumption. Digging time can be decreased with fast movement but result in increase of average power consumption. The digging times of a 20 yd3 capacity shovel during the excavation of fresh-slightly weathered blasted formation at Kısrakdere-Doğu are 8.50 sec. and 8.00 sec for moderate and moderately difficult digging conditions (Code 2 and 3) respectively. The corresponding energy consumptions of digging are 2.253 kWh and 2.682 kWh for moderate and moderately difficult digging conditions. The energy consumption in terms of the digging power and time increasing for difficult digging is more easily and correctly observed at the same operational conditions.

For example, digging energy consumptions for moderately weathered unblasted marl formation at Yatağan-Eskihisar where a 10 yd3 capacity shovel is operated are 2.424 kWh, 4.104 kWh and 5.137 kWh for observed digging conditions of easy, moderate and moderately difficult (Code 50, 51, 52) respectively. The results of other measurements also clearly show the increasing of digging energy consumption with increasing digging difficulty. The energy consumption of digging also increases as the dipper capacity increases. The energy consumption of digging should be considered during the determination of digging difficulty class where 67% of calculated values fall in the ranges of digging conditions.

5.4.9. Specific Digging Energy

The most important parameter produced from performance measurement which clearly reflects the difference between different digging conditions quantitatively is the specific digging energy.

Figure 47 shows the relationship between specific digging energy and dipper capacity for observed digging conditions. The specific digging energy values (Table 22) are averaged according to the digging condition and dipper capacity and the results are presented in Table 23.e. Ranges of digging conditions in Figure 47 are determined from the comparison of available data.

The digging power consumption, digging time and excavated amount of material are effectively analyzed by means of specific digging energy where 90% of these values are in accordance with the determined ranges of digging conditions. The points

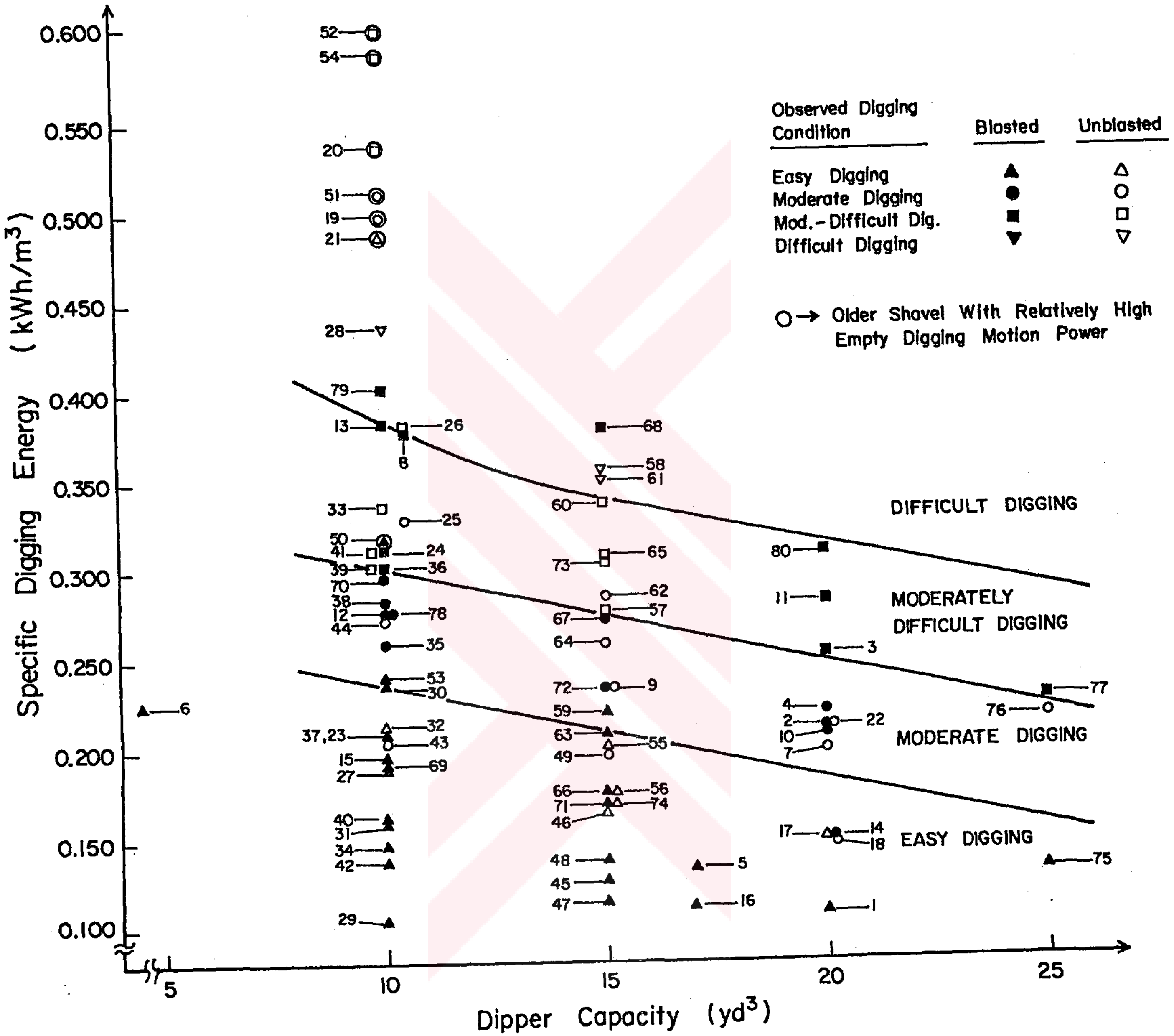


Figure 47. Relationship between Specific Digging Energy, Ease of Digging and Dipper Capacity.

Table 23.e. Variation of Specific Digging Energy (kWh/m3)

According to Ease of Digging.

Ease of Digging / Dipper Capacity (yd^3)	Easy Digging		Moderate Digging		Moderately Difficult Digging		Difficult Digging
	Blasted	Unblasted	Blasted	Unblasted	Blasted	Unblasted	Unblasted
4.5	0.225	-	-	-	-	-	-
10	0.188 ± 0.055 (0.103 - 0.317)	0.212	0.270 ± 0.020 (0.237 - 0.295)	0.328 ± 0.132 (0.203 - 0.511)	0.355 ± 0.045 (0.302 - 0.402	0.424 ± 0.146 (0.301 - 0.628)	0.435
15	0.165 ± 0.041 (0.114 - 0.220)	0.178 ± 0.016 (0.167 - 0.201)	0.252 ± 0.028 (0.232 - 0.272)	0.242 ± 0.037 (0.196 - 0.284)	0.379	0.304 ± 0.025 (0.274 - 0.336)	0.352 ± 0.003 (0.350 - 0.354)
17	0.122 ± 0.016 (0.110 - 0.133)	-	-	-	-	-	-
20	0.109	0.149	0.196 ± 0.032 (0.149 - 0.219)	0.185 ± 0.033 (0.147 - 0.210)	0.280 ± 0.028 (0.251 - 0.308)	-	-
25	0.131	-	-	0.216	0.249	-	-

indicated in circles in Figure 47 which are out of range of digging condition clearly show the affects of older shovels with relatively high empty digging motion power and less experienced operator on the degree of digging difficulty. On the other hand, with worst operational conditions it is logical to define easy digging condition as difficult digging from the economic point of view where more energy is required per unit volume of excavated material like in the case of difficult digging condition. Considering the relationship between specific digging energy, ease of digging and dipper capacity (Figure 47), a diggability classification for electrical shovels based on the energy consumed per excavated amount of material is proposed and given in Table 24.

Table 24. Proposed Diggability Classification.

Dipper Capacity (yd^3)	Specific Digging Energy (kWh/m^3)			
	Ease of Digging			
	Easy	Moderate	Moderately Difficult	Difficult
10	≤0.235	0.236-0.300	0.301-0.390	≥0.391
15	≤0.210	0.211-0.275	0.276-0.345	≥0.346
20	≤0.185	0.186-0.250	0.251-0.315	≥0.316
25	≤0.155	0.156-0.220	0.221-0.290	≥0.291

The results of some rock mass and material properties are presented in Table 25. It may be utilized to search the relationships between excavation performance and rock mass/material properties, in order to be able to determine the digging condition and shovel output where the performance measurements could not be done.

Among the performance parameters, the specific digging energy determined as the most important quantitative one to reflect the best relation between the digging conditions and some rock mass and material properties. However, it needs some modification for comparison purpose. Therefore, the values of specific digging energy correspond to all field and laboratory results (Figure 47) are normalized in terms of dipper capacity and the condition of blasting by using the available data given in Table 26. Although five different capacity shovels are monitored, 48 % of performance measurements belong to 10 yd3 capacity shovel, that is why normalization is carried out in terms of 10 yd3 shovel capacity. Considering the data given in Table 26.a, the normalization factors for 20 yd3 shovels are produced. For all three different cases, those factors are more or less around 1.333. This factor is assumed to be extended to the other cases, based on the slope of the

Table 25. Some Rock Mass and Metarials Properties.

Code No	Enterprise Region & Panel	Formation Description	Uniaxial Compressive Strength (MPa)	Indirect Tensile Strength (MPa)	Rock Toughness Index (kg-cm/cm3)	Shore Hardness	Schmidt Hardness	Cone Indenter Index	Natural Unit Weight (g/cm3)	Moisture Content (%)	Bed Separation (m)	Joint Spacing (m) (No. of joints)	Seismic P-Wave Velocity (m/sec)	Penetration Rate (m/min) RPM=120 (Thrust(kN))	Rock Quality Index (t/(m/min))	Specific Charge (kg(ANFO)/m3)	Normalized Specific Digging Energy (kWh/m3)
1	ELİ-Soma Kısrakdere Doğu	Fresh-slightly weathered marl	103.8	8.9	22.7	40	40	3.32	2.46	1.12	0.60	1.25 (3)	2800	0.311 (80)	24.2	0.313	0.446
2	ELİ-Soma Işıklar DE Pano	Fresh-slightly weathered marl	91.4	6.7	16.7	43	46	3.91	2.46	0.55	0.70	1.30 (3)	2908	0.571 (70)	19.8	0.291	0.390
3	ELİ-Soma Kısrakdere Batı	Fresh-slightly weathered marl	103.8	8.9	22.7	40	47	3.32	2.46	1.12	0.70	1.30 (3)	2800	0.311 (80)	24.2	0.333	-
4	ELİ-Soma Elmalı	Fresh-slightly weathered marl	97.1	7.3	17.5	41	52	3.06	2.48	2.17	1.50	1.50 (3)	2763	-	21.8	0.266	0.565
5	ELİ-Soma Sarıkaya	Fresh-slightly weathered marl	97.1	7.3	17.5	41	52	3.06	2.48	2.17	1.00	0.80 (3)	2763	-	21.8	-	-
6	ELİ-Deniş Çamtarla	Fresh-slightly weathered marl	88.0	8.9	18.1	40	53	3.58	2.47	1.14	1.50	1.25 (3)	2700	0.454 (90)	18.6	0.280	0.426
7	GLİ Tunçbilek Beke	Fresh-slightly weathered marl	31.4	2.6	7.5	32	42	4.16	2.11	4.14	0.30	0.35 (3)	1855	1.016 (70)	7.8	0.160	0.262

Table 25. Continued

Code No	Enterprise Region & Panel	Formation Description	Uniaxial Compressive Strength (MPa)	Indirect Tensile Strength (MPa)	Rock Toughness Index (kg-cm/cm3)	Shore Hardness	Schmidt Hardness	Cone Indenter Index	Natural Unit Weight (g/cm3)	Moisture Content (%)	Bed Separation (m)	Joint Spacing (m) (No. of joints)	Seismic P-Wave Velocity (m/sec)	Penetration Rate (m/min) RPM=120 (Thrust(kN))	Rock Quality Index (t/(m/min))	Specific Charge (kg(ANFO)/m3)	Normalized Specific Digging Energy (kWh/m3)
8	GLİ Tunçbilek Ömerler	Moderately weathered marl	15.0	0.6	-	-	-	-	1.80	-	0.50	0.30 (3)	1460	-	-	-	0.198
9	GLİ Tunçbilek Ömerler	Fresh-slightly weathered marl	27.5	5.5	5.9	39	46	3.90	1.93	7.16	1.00	1.00 (3)	2440	1.235 (80)	7.3	0.154	-
10	GLİ Tunçbilek 36.Pano	Fresh-slightly weathered marl	36.5	8.7	22.5	41	49	3.93	2.16	2.21	1.00	1.50 (3)	1972	1.463 (80)	8.4	0.166	0.334
11	GLİ Tunçbilek Kuşpınar	Fresh-slightly weathered marl	38.3	4.4	16.3	30	46	5.08	2.10	5.73	1.00	>1.50 (3)	2430	-	9.0	0.272	0.377
12	GLİ Seyitömer S-20	Fresh clayish and sandy marl	11.2	1.5	11.2	25	28	2.82	2.02	6.73	0.40	0.50 (3)	1683	1.777 (60)	5.6	0.142	0.243
13	GLİ Seyitömer S-19	Fresh-slightly weathered marl	6.0	1.4	6.6	15	-	-	1.88	-	0.30	0.40 (3)	1683	-	5.2	0.142	0.235
14	GLİ Yatağan Eskihisar	Fresh-slightly weathered marl	3.9	0.6	7.6	11	30	0.45	1.66	25.06	0.80	1.20 (3)	1400	1.784 (40)	5.1	0.131	0.224

Table 25. Continued

Code No	Enterprise Region & Panel	Formation Description	Uniaxial Compressive Strength (MPa)	Indirect Tensile Strength (MPa)	Rock Toughness Index (kg-cm/cm3)	Shore Hardness	Schmidt Hardness	Cone Indenter Index	Natural Unit Weight (g/cm3)	Moisture Content (%)	Bed Separation (m)	Joint Spacing (m) (No. of joints)	Seismic P-Wave Velocity (m/sec)	Penetration Rate (m/min) RPM=120 (Thrust(kN))	Rock Quality Index (t/(m/min))	Specific Charge (kg(ANFO)/m3)	Normalized Specific Digging Energy (kWh/m3)
15	GELİ Tınaz	Conglomerate	26.0	5.0	-	34	-	2.70	2.55	1.39	>1.50	-	3280	0.603 (50)	7.1	0.192	0.402
16	GELİ Tınaz	Moderately weathered marl	11.3	1.7	7.0	15	-	1.85	1.88	6.88	0.30	0.40 (3)	-	-	5.6	-	0.263
17	GELİ Milas İkizköy	Fresh-slightly weathered marl	20.3	1.8	5.1	21	-	2.46	1.90	4.97	1.00	0.80 (3)	1660	-	6.5	0.131	0.309
18	SKLİ Kangal Kalburçayırı	Fresh-slightly weathered clayish marl	2.1	0.3	2.8	9	27	0.98	1.59	21.26	>1.50	1.00 (2)	1400	-	4.9	-	0.234
19	SKLİ Kangal Kalburçayırı	Limestone	86.3	5.3	7.2	-	52	15.35	2.49	1.13	>1.50	>3.00 (1)	2600	0.428 (40)	18.4	0.212	0.518

Table 26.a. Normalization of Specific Digging Energy with Respect to 10 yd3 Dipper Capacity Shovel.

Some Rock Mass and Material Properties Code No.*	Results of Performan. Measurements Code No.**	Observed Digging Condition	Specific Digging Energy (kWh/m^3)		Normalization factor of 20 yd^3 dipper
			20 yd^3 dipper	10 yd^3 dipper	
6	10 & 12	Moderate Digging (Fresh-slightly weathered marl)	0.208	0.275	$\frac{0.275}{0.208} = 1.322$
6	11 & 13	Moderately Difficult Digging (Fresh-slightly weathered marl)	0.280	0.383	$\frac{0.383}{0.280} = 1.368$
19	79 & 80	Moderately Difficult Digging (slightly-moderately weathered limestone)	0.308	0.402	$\frac{0.402}{0.308} = 1.305$

* Obtained from Table 25

** Obtained from Table 22

Table 26.b. Normalization Factors of Specific Digging Energy with Respect to Dipper Capacity and Blasting

Dipper Capacity (yd^3)	For Unblasted Case	For Blasted Case
10	1.000	1.333
15	1.143	1.524
20	1.333	1.777
25	1.429	1.905

Table 26.c. Normalized Specific Digging Energies with Respect to Unblasted 10 yd3 Capacity Shovel Performance Value.

Some Rock Mass and Material Properties Code No*	Results of Performance Measurements Code No**	Specific Digging Energy (kWh/m3)	Normalized Specific Digging Energy (kWh/m3)
1	3	.251	.446
2	4	.219	.330
3	-	-	-
4	8	.377	.503
5	-	-	-
6	10,11 12,13	.208 .28 .275 .383	.426
7	14,15	.149 .195	.262
8	17,18	.149 .147	.198
9	-	-	-
10	22,24	.210 .311	.334
11	25,26 28	.328 .381 .435	.377
12	30,34 35,38	.237 .147 .258 .209	.243
13	39,40 41	.301 .161 .310	.235
14	49	.196	.224
15	58,61	.354 .350	.402
16	63,64	.208 .257	.263
17	69,70	.191 .295	.309
18	75,76	.131 .216	.234
19	77,79 80	.249 .402 .308	.518

* Obtained from Table 25

** Obtained from Table 22

boundary lines of four zones from easy to difficult digging in Figure 47. The normalization factors for 15, 20 and 25 yd3 dipper capacities are 1.143, 1.333 and 1.429 respectively (Table 26.b).

Secondly, in a similar way to dipper capacity, the effect of blasting has been normalized based on the performance measurements of the blasted and unblasted cases of Yatağan-Eskihisar, Tınaz and Milas-İkizköy. Those performance measurements showed that the specific digging energy values of after blasting can be equalized to specific digging energy values of before blasting by a conversion factor of 1.333. Assuming the existence of the same trend for each dipper capacity, the conversion factors of blasted materials with respect to dipper capacities are produced. These developed conversion factors are presented in Table 26.b. Based on those conversion factors, the normalized specific digging energy values of all cases are produced and given in Table 26.c.

From the available data (Table 25), some relationships can be established between normalized specific digging energy and rock/mass material properties. Linear, logarithmic, exponential and power curve fitting approximations are tested and the best approximation equation with highest correlation coefficient is determined.

Penetration rate, seismic velocity, rock quality index, uniaxial compressive strength and tensile strength showed good corelations with normalized specific digging energy, giving an acceptable level of correlation. The specific digging energy therefore appears to relate well to rock mass and material properties over a range of actual ground conditions. Figures 48.1 to 48.9 show these relations with best fit curves and their equations. It should be noted that the relationships between normalized specific digging energy and rock mass properties show a better trend than normalized specific digging energy and rock material properties with the slightly higher correlation coefficients.

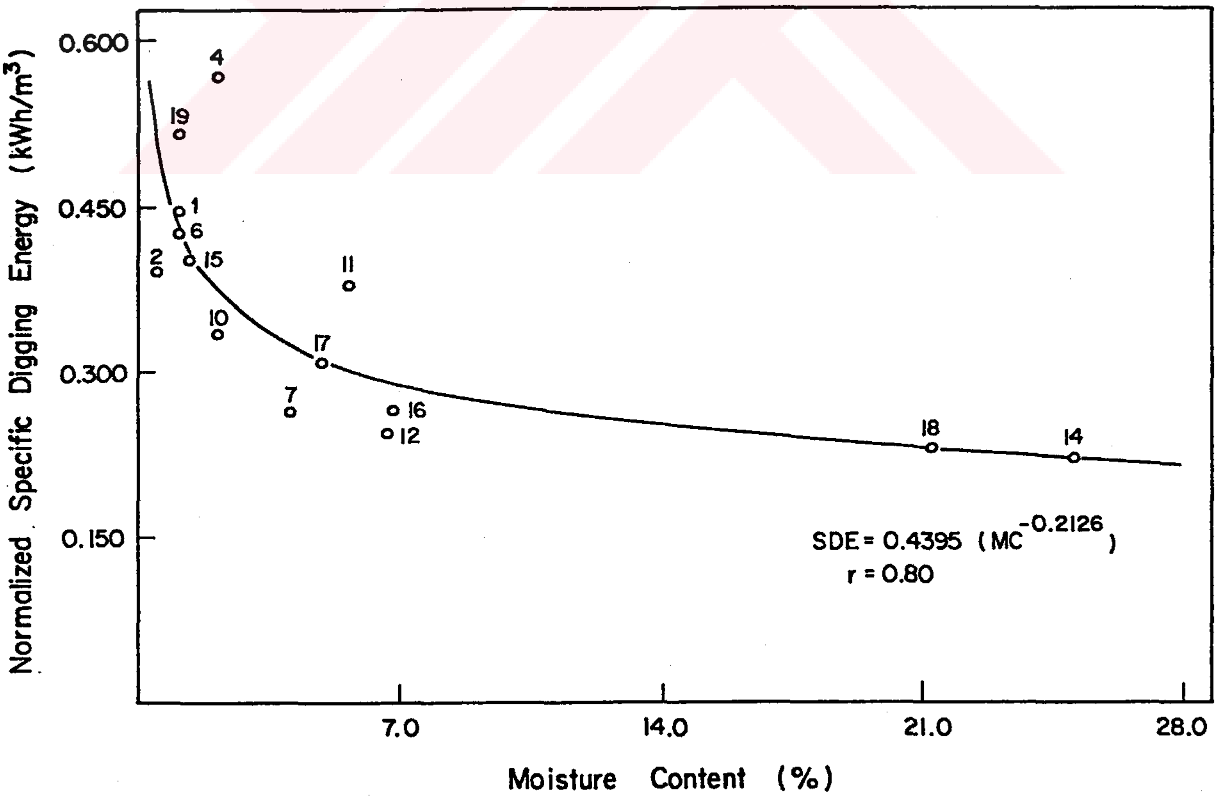


Figure 48.1. Relationship between Normalized Specific Digging Energy (SDE) and Moisture Content (MC).

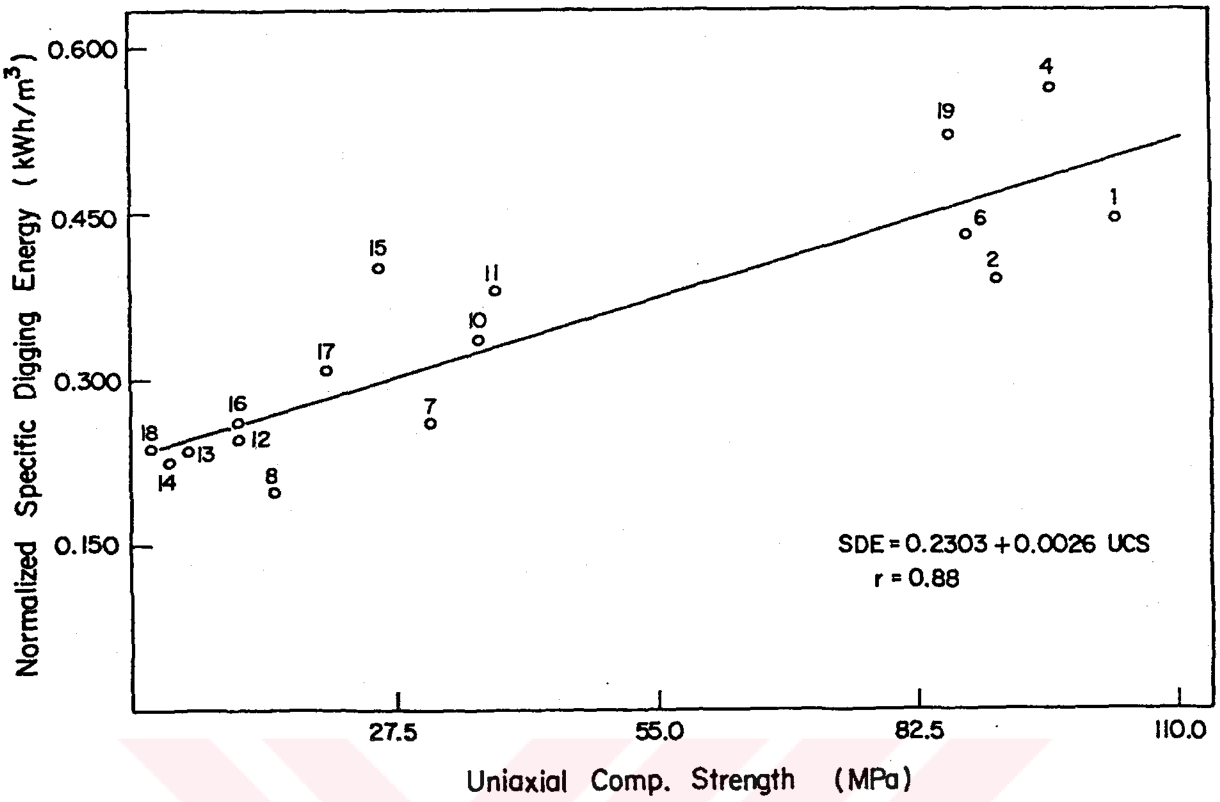


Figure 48.2. Relationship between Normalized Specific Digging Energy (SDE) and Uniaxial Compressive Strength (UCS).

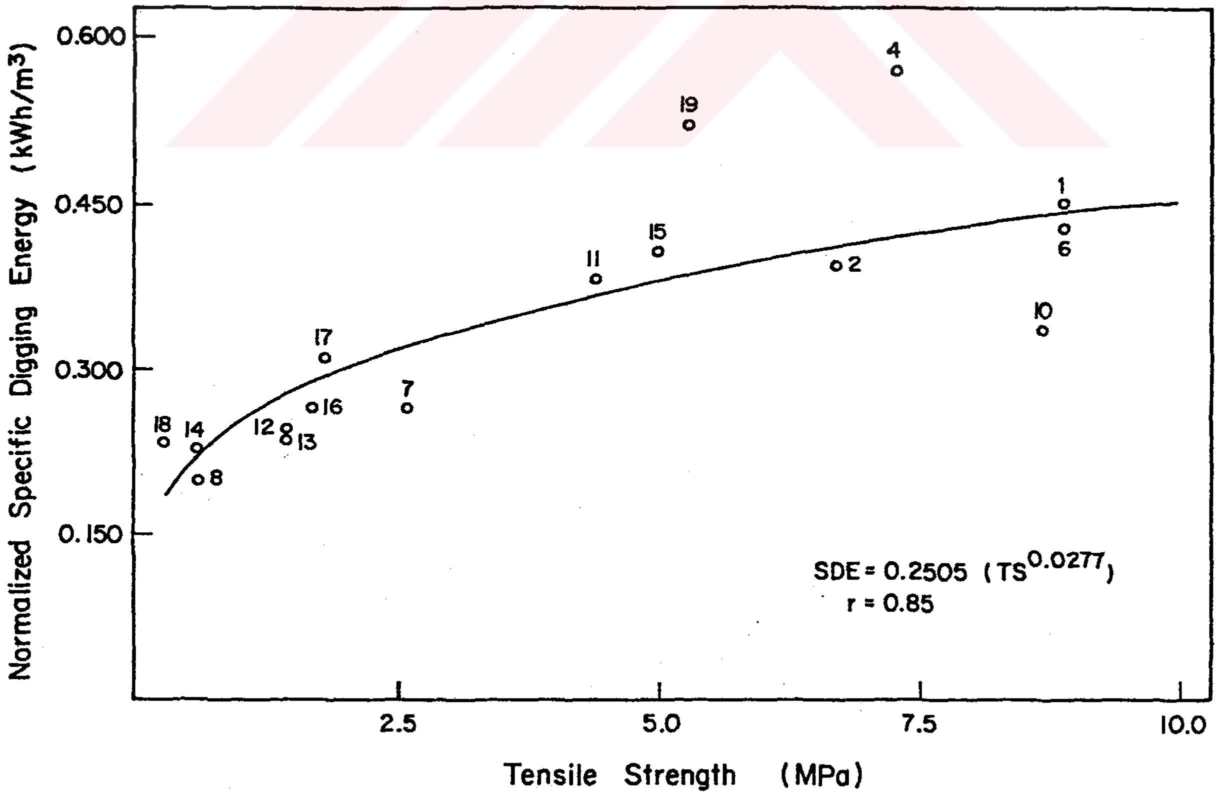


Figure 48.3. Relationship between Normalized Specific Digging Energy (SDE) and Tensile Strength (TS).

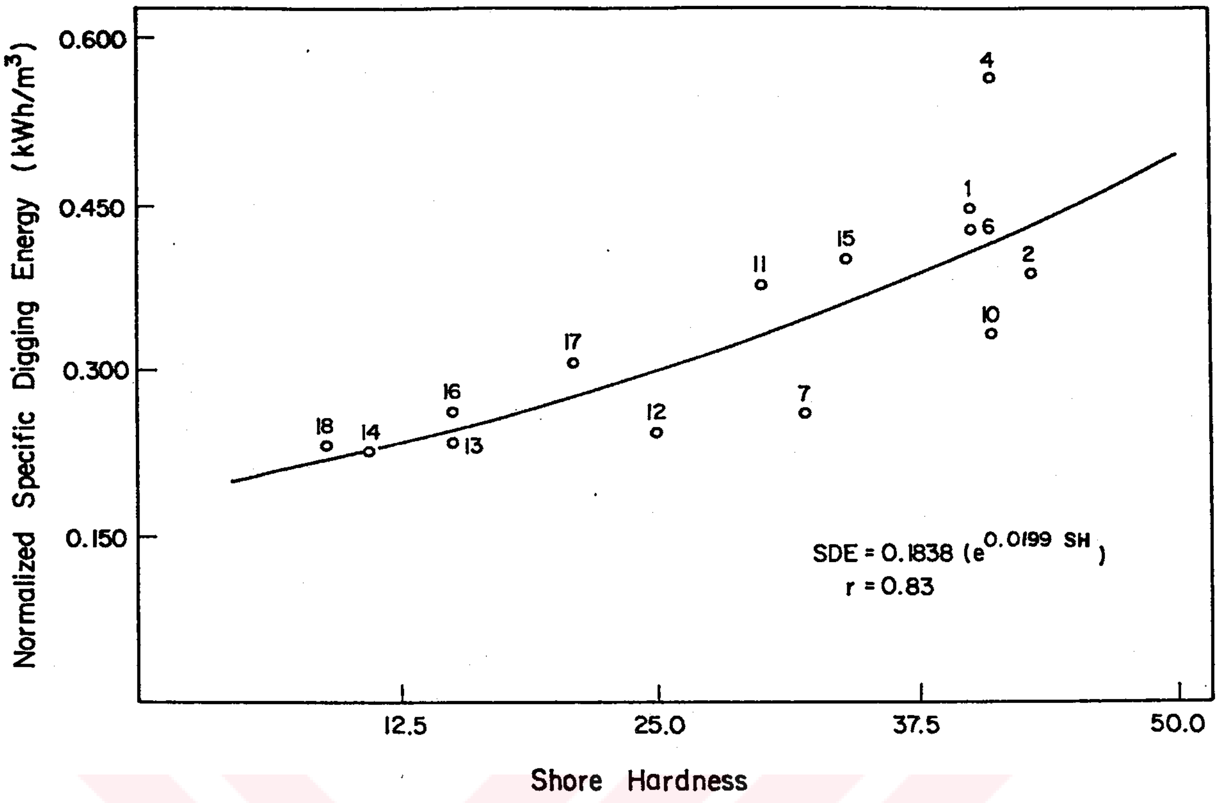


Figure 48.4. Relationship between Normalized Specific Digging Energy (SDE) and Shore Hardness (SH).

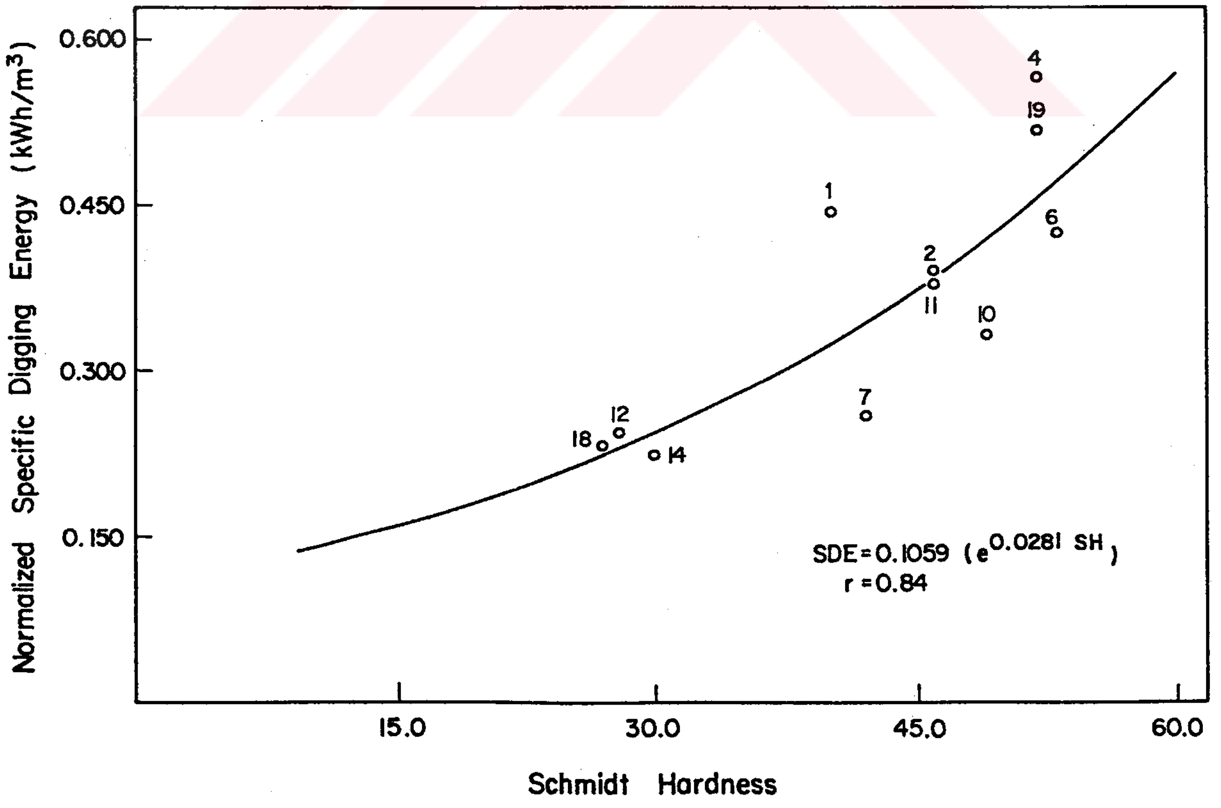


Figure 48.5. Relationship between Normalized Specific Digging Energy (SDE) and Schmidt Hardness (SH).

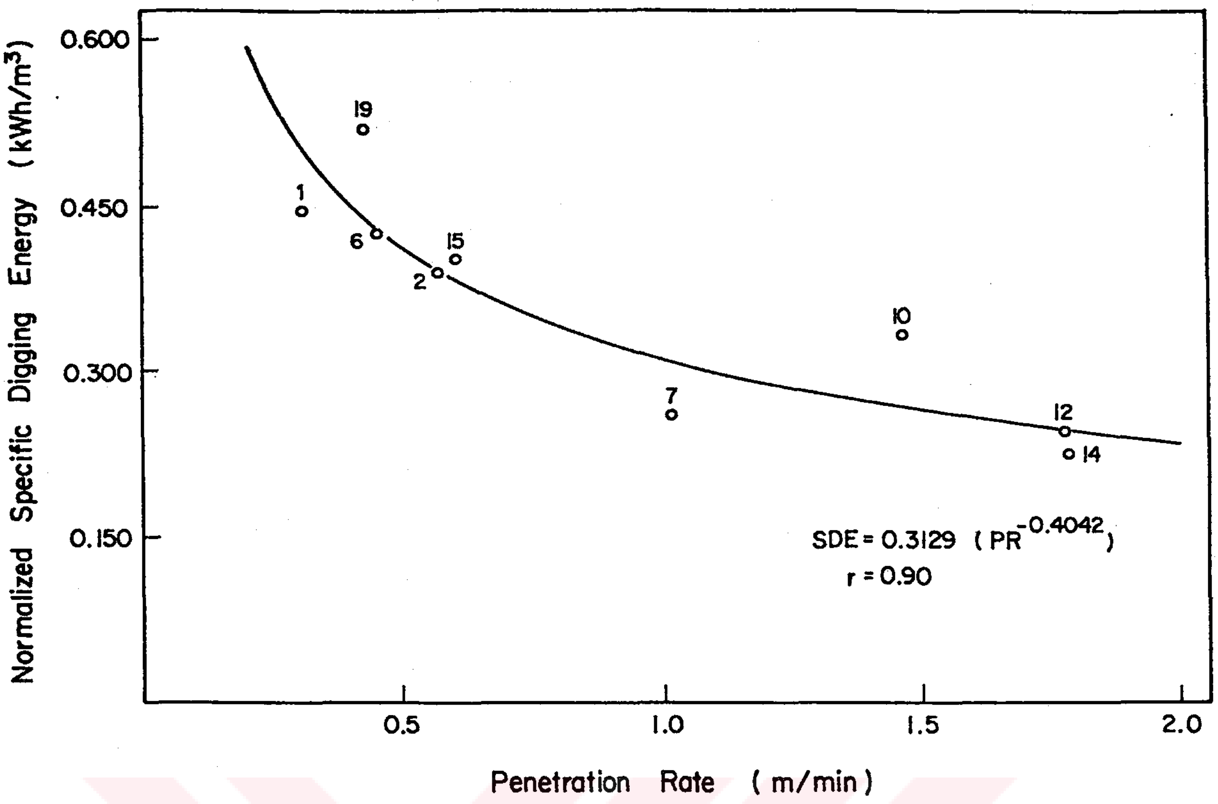


Figure 48.6. Relationship between Normalized Specific Digging Energy (SDE) and Penetration Rate (PR).

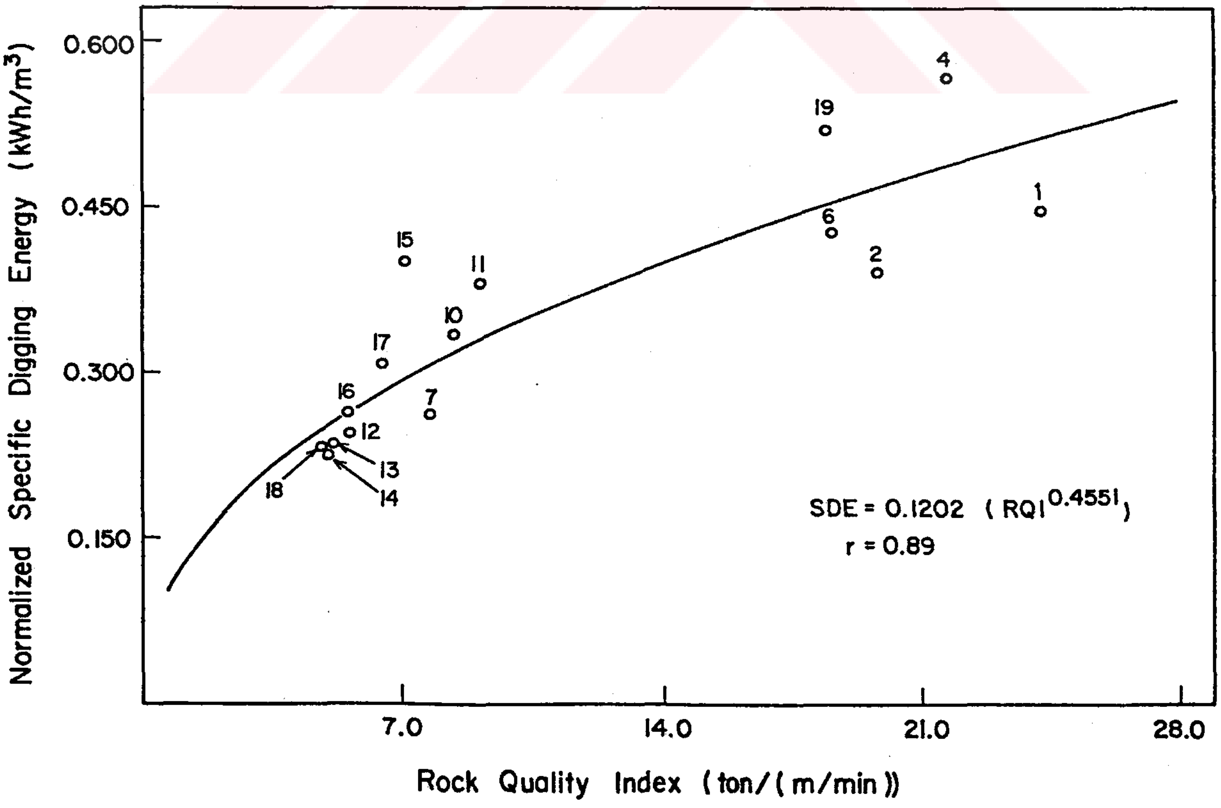


Figure 48.7. Relationship between Normalized Specific Digging Energy (SDE) and Rock Quality Index (RQI).

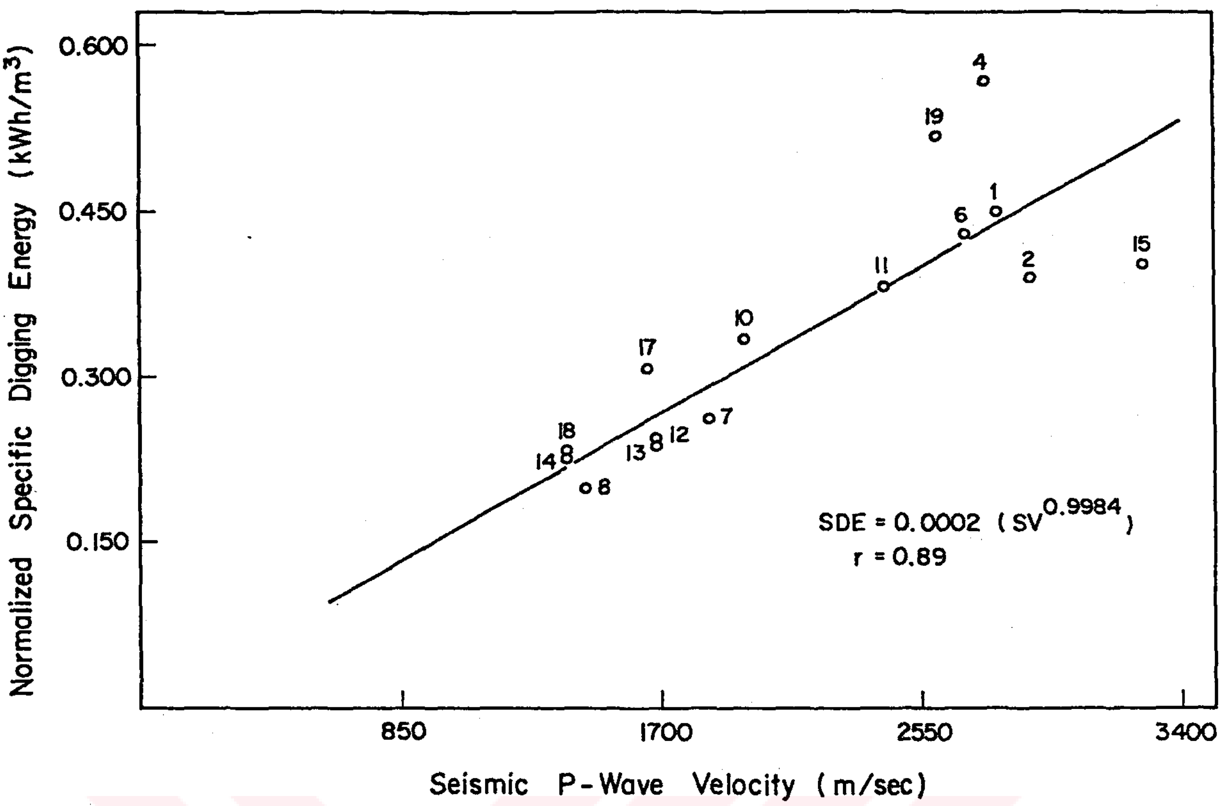


Figure 48.8. Relationship between Normalized Specific Digging Energy (SDE) and Seismic P-Wave Velocity (SV).

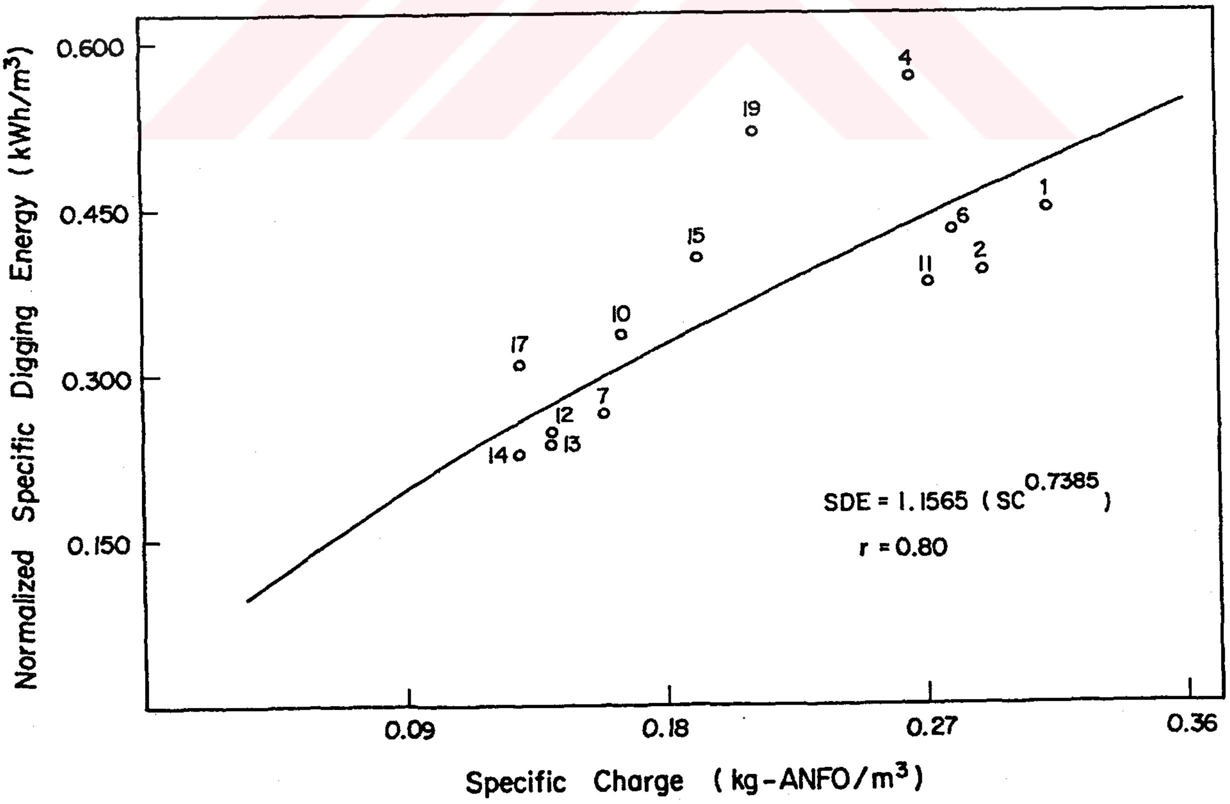


Figure 48.9. Relationship between Normalized Specific Digging Energy (SDE) and Specific Charge (SC).

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions of this work together with recommendations for the future studies are presented below.

- It is shown that the developed measurement system, consisted of wattmeter-recorder, for performance monitoring of electrical shovels, is quite capable to determine the variations in digging condition. The addition of analog to digital converter (IMP) and data acquisition controller as a read-out device to the system increases the accuracy and effectiveness.

- Operator experience, age of excavator, position of shovel with respect to bench face seemed to be the operational factors which mainly caused the discrepancies in the diggability classification. Various performance parameters are introduced through shovel monitoring, in order to asses a diggability classification system. The specific digging energy is determined as the most effective parameter. A proposed diggability classification system for electrical shovels based on the specific digging energy is presented below.

Proposed Diggability Classification.

Dipper Capacity (yd^3)	Specific Digging Energy (kWh/m^3)			
	Ease of Digging			
	Easy	Moderate	Moderately Difficult	Difficult
10	≤0.235	0.236-0.300	0.301-0.390	≥0.391
15	≤0.210	0.211-0.275	0.276-0.345	≥0.346
20	≤0.185	0.186-0.250	0.251-0.315	≥0.316
25	≤0.155	0.156-0.220	0.221-0.290	≥0.291

- From case studies (Yatağan-Eskihısar and Tinaz), as expected, the increasing of depth of cut requires more specific digging energy both before and after blasting and hence increases the degree of digging difficulty. This trend is in accordance with the ranges of general diggability classification proposed above.

- The effect of blasting on diggability is well reflected by performance monitoring. Blasting decreases the specific digging energy around 15%-50% for all bucket capacities compared to that of unblasted materials. It is more effective on non-jointed conglomerate unit, higher depths of cut and difficult digging conditions.

- Specific digging energy is also very closely related to rock mass/material properties but requires to be considered together with dipper capacity and blasting condition. It is seen that, there exists good correlations between normalized specific digging energy and rock mass/material properties, such as seismic velocity, penetration rate, uniaxial compressive strength and tensile strength.

- The results of this study are referenced to the rock types existing at TKI sites and can be applied to similar geological environments where electrical shovels are used in overburden removal operations and will be useful for engineering purposes in the preliminary phase of equipment selection.

- The research should be extended to a wide range of rock units rather than conglomerate, marl and limestone.

-The current and voltage of different D.C. motors such as crowd, hoist, swing should be measured seperately for the diggability purpose. The strain gauge measurement should be conducted at same time to control the dipper load effectively.

- Diggability assessment for different types of stripping equipment considering rock mass and material characteristics can be investigated based on this study.

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APPENDICES

APPENDIX A

APPENDIX A : FIELD MEASUREMENTS DATA SHEETS

Table A.1. Rock Mass Description Data Sheet.

Mine, Region and Panel : Date: ....

Code No. . . . . :

Rock Type . . . . :

Rock Colour . . . . . . :

Degree of Weathering . :

Bedding Thickness . . :

Joint Spacing . . . . :

Blasted or Not . . . :

Block Size . . . . . . :

Schmidt Hardness Value :

Photograph No. . . . . :

Table A.2. Field Data Sheet of Drilling Performance.

Location :

Date :

Code No :

Page No :

Drilling Machine Model :

Bit Type and Diameter :

Operator Experience :

Rock Type	Drilled Distance (m)	Drilling Time (sec)	Thrust (kN)	Rotat. Speed (rpm)	Penet. Rate (m/min)

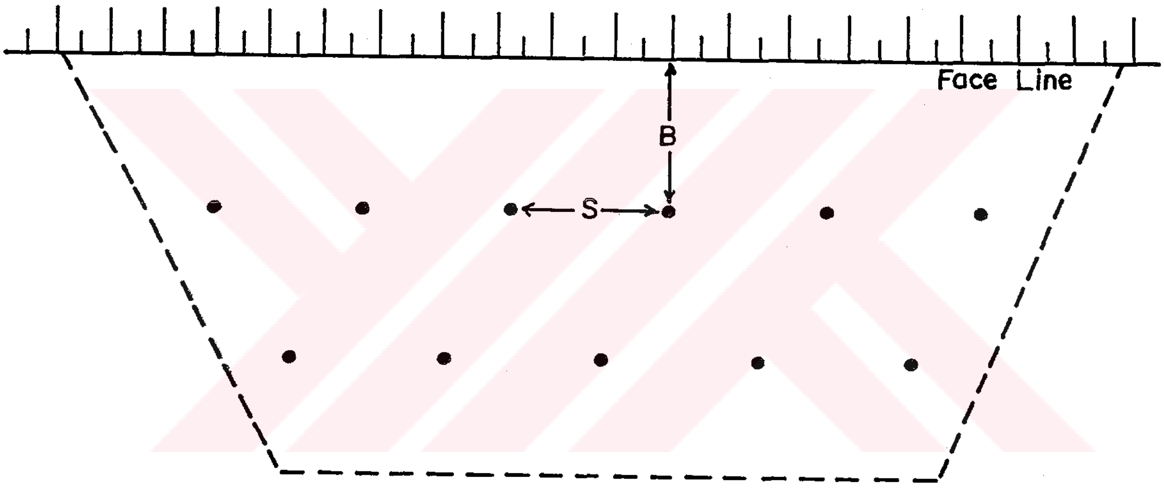
Table A.3. Bench Blasting Data Sheet.

Location....:

Date : ....

Code No.....:

Geometry of Blastholes :



Hole Diameter . . . . :

Amount of Charge per Hole (kg) :

Bench Height (m). . . . . . . :

Average Burden (m). . . . . . :

Average Spacing (m) . . . . . :

Bench Slope (Degree). . . . . :

Table A.4. Excavation Performance Information Form.

Location :

Date: . . . .

Code No :

<u>Electrical Power Shovel:</u>

Model . . . . :

Dipper Capacity . :

Age . . . . :

<u>Operational Conditions :</u>

Blasting or not . . . . :

Bench Height . . . . :

Condition of Shovel Floor . . . . :

Distance Between Face and Shovel . :

Double or Single Side Loading . . . :

Operator Experience . . . . :

<u>Power Measurement Variables:</u>

Turns Ratio of Voltage Transformers:

Turns Ratio of Current Transformers:

Number of Current Transformers . . :

Wattmeter Volt Range . . . . :

Wattmeter Current Range . . . . . :

Wattmeter Reading Coefficient . . :

Data Logger Real Time Clock . . . :

Data Logger Scanning Interval . . :

Recorder Volt Range . . . . :

Recorder Velocity Range . . . . . :

Table A.5. Cycle Time and Power Measurements Data Sheet.

Location : . . . .
Code No. : . . . .

Date: . . .
Page: . . .

*Symbols	Beginning of the cycle *Beginning of any operation	End of dipper loading *End of any operation	Excavation difficulty observation	Dipper fill factor	Swing angle (Degree)	Average power (kW)	Highest power (kW)	Lowest power (kW)	Energy consump. (kWh)	Explanations

<u>Symbols for Different Operations of Shovel</u>:

W: Downtime
X: Dump time
D: Digging without loading
E: Empty digging motion
P: Propel motion
+: Digging trials

APPENDIX B

APPENDIX B: CALCULATION SEQUENCE OF PERFORMANCE PARAMETERS

Table B.1. Sample Shovel Performance Data for the Calculation of Performance Parameters.

Region and Panel : Yatağan / Eskihisar
Electrical Shovel : P&H 2100 BL, 15 yd^3
Rock Type : Highly weathered marl (Unblasted)

Observed Digging Condition	Cycle Time (sec)	Digging Time (sec)	Dipper Fill Factor	Average Digging Power(kW)	Peak Digging Power(kW)
Easy Digging	32.0	9.0	1.00	906	1194
	28.5	9.0	0.90	792	1028
	37.0	10.0	1.10	975	1240

Calculation of Performance Parameters

$$\text{Average Cycle Time (sec)} = \left(\sum_{i=1}^{n} c_{t_i} \right) / n$$

n = The number of observations

c_{t_i} = Cycle time (sec)

Average Cycle Time = (32.0 + 28.5 + 37.0) / 3 = 32.5 sec

$$\text{Average Digging Time (sec)} = \left(\sum_{i=1}^{n} d_{t_i} \right) / n$$

d_{t_i} = Digging time (sec)

Average Digging Time = (9.0 + 9.0 + 10.0) / 3 = 9.33 sec

$$\text{Average Dipper Fill Factor} = \left(\sum_{i=1}^{n} FF_i \right) / n$$

FF_i = Dipper fill factor

Average Dipper Fill Factor = (1.00 + 0.90 + 1.10) / 3 = 1.00

$$\text{Hourly Capacity Without Waiting } (m^3/hr) = (3600 / c_t) * FF * c_d$$

c_t = Average cycle time (sec)

FF = Average dipper fill factor

c_d = Dipper capacity (m^3)

$$\text{Hourly Capacity Without Waiting} = (3600 / 32.5)*1.0*15\ yd^3*0.7646$$

$$= 1270.4\ m^3/hr$$

$$\text{Hourly Digging Capacity } (m^3/hr) = (3600 / d_t) * FF * c_d$$

d_t = Average digging time (sec)

FF = Average dipper fill factor

$$\text{Hourly Digging Capacity} = (3600 / 9.33)*1.0*15\ yd^3*0.7646$$

$$= 4425.3\ m^3/hr$$

$$\text{Time Average Power of Digging (kW)} = \left(\sum_{i=1}^{n} ADP_i \right) / n$$

ADP_i = Average digging power (kW)

Time Average Power of Digging = (906 + 792 + 975) / 3 = 891 kW

Maximum Peak Digging Power (kW) : The highest occured digging power during a set of recorded digging cycles.

Maximum Peak Digging Power = 1240 kW

$$\text{Average of Peak Digging Power (kW)} = \left(\sum_{i=1}^{n} PDP_i \right) / n$$

PDP_i = Peak digging power (kW)

Average of Peak Digging Power = (1194 + 1028 + 1240) / 3 = 1154

$$\text{Energy Consumption of Digging (kWh)} = TAPD * d_t / 3600$$

TAPD = Time average power of digging (kW)

d_t = Average digging time (sec)

Energy Consumption of Digging = 891 * 9.33 / 3600 = 2.309 kWh

$$\text{Specific Digging Energy (kWh/m}^3\text{)} = \frac{E}{V} = \frac{TAPD * d_t / 3600}{FF * c_d}$$

E = Energy required during digging time (kWh)

V = Volume of excavated material (m^3)

$$\text{Specific Digging Energy} = \frac{2.309}{1.0 * 15\ yd^3 * 0.7646} = 0.201\ kWh/m^3$$

APPENDIX C

APPENDIX C: INITIAL POWER MEASUREMENT RESULTS

Table C.1. Initial Power Measurement Results.

Region and Panel : Seyitömer / S - 28 Panel

Electrical Shovel : P&H 1900 AL , 10 yd^3

Beginning of the Cycle	End of dipper loading	Dipper Fill Factor	Observation	Digging Time (sec) (Cycle Time (sec)) [Down Time (sec)]	Average Power (kW)	Peak Power (kW)
13:02:15	13:02:22	-	Digging without loading	[7]	358.260	602.400
13:02:28	13:02:35	-	Digging without loading	[7]	424.326	612.240
13:02:43	13:02:49	1.0	Loose+Digging	6 (27)	477.209 (373.023)	775.440 (")
13:03:10	13:03:15	1.1	Loose	5 (20)	631.592 (394.096)	958.800 (")
13:03:30	13:03:37	1.0	Loose	7 (24)	409.032 (321.606)	798.240 (")
13:03:54	13:04:00	1.0	Loose+Digging	6 (20)	557.188 (337.154)	860.850 (")
13:04:14	13:04:24	-	Digging without loading	[10]	353.647	800.400
13:04:36	13:04:44	1.15	Loose+Digging	8 (37)	596.731 (368.914)	865.680 (")
13:05:13	13:05:20	1.0	Loose	7 (22)	555.954 (377.662)	862.080 (")
13:05:35	13:05:43	1.1	Loose	8 (24)	554.832 (358.610)	832.560 (")
13:05:59	13:06:04	1.1	Loose	5 (29)	576.124 (351.887)	817.200 (")
13:06:28	13:06:36	1.1	Loose	8 (33)	564.569 (371.672)	944.640 (")
13:07:01	13:07:10	1.1	Loose	9 (26)	582.437 (393.824)	884.640 (")
13:07:27	13:07:36	1.1	Loose	9 (25)	491.777 (361.812)	909.360 (")

Table C.1. Continued

Beginning of the Cycle	End of dipper loading	Dipper Fill Factor	Observation	Digging Time (sec) (Cycle Time (sec)) [Down Time (sec)]	Average Power (kW)	Peak Power (kW)
13:07:52	13:07:58	1.1	Loose	6 (31)	603.339 (357.678)	971.040 (")
13:08:23	13:09:00	-	Downtime	[37]	150.015	721.440
13:09:00	13:09:12	1.15	Loose+Digging	12 (42)	594.996 (412.782)	952.320 (")
13:09:27	13:09:33	-	Downtime	[6]	392.013	738.000
13:09:48	13:09:57	1.1	Loose	9 (35)	559.975 (377.653)	897.360 (")
13:10:23	13:10:25	1.0	Loose	6 (26)	613.049 (337.692)	842.640 (")
13:10:49	13:10:58	1.1	Loose	9 (30)	518.024 (339.682)	816.720 (")
13:11:19	13:11:27	-	Digging Without loading	[8]	482.584	838.800
13:11:19	13:11:27	-	Digging Without loading	[8]	482.584	838.800
13:11:35	13:11:48	-	Digging Without loading	[13]	284.759	1020.96
13:12:18	13:12:25	1.1	Loose	7 (33)	544.809 (369.307)	631.680 (")
13:12:36	13:12:40	-	Downtime	[4]	314.789	420.048
13:12:55	13:13:03	1.1	Loose	8 (30)	618.840 (367.966)	906.960 (")
13:13:25	13:13:31	1.0	Loose	6 (24)	584.743 (366.146)	904.800 (")
13:13:49	13:13:56	1.0	Loose	7 (27)	630.564 (370.365)	859.440 (")

Table C.1. Continued

Beginning of the Cycle	End of dipper loading	Dipper Fill Factor	Observation	Digging Time (sec) (Cycle Time (sec)) [Down Time (sec)]	Average Power (kW)	Peak Power (kW)
13:14:16	13:14:24	1.0	Loose	8 (30)	562.653 (364.151)	822.450 (")
13:14:46	13:14:53	1.0	Loose	7 (25)	562.404 (356.866)	942.000 (")
13:15:11	13:15:20	1.0	Loose	9 (27)	529.932 (362.754)	883.440 (")
13:15:38	13:15:47	1.1	Loose	9 (30)	585.912 (367.173)	847.200 (")
13:16:08	13:16:18	1.1	Loose	10 (34)	485.954 (353.210)	836.160 (")
13:16:42	13:16:50	1.1	Loose	8 (25)	581.176 (367.532)	849.360 (")
13:17:07	13:17:14	1.0	Loose	7 (27)	663.918 (399.185)	803.280 (")
13:17:34	13:17:43	1.0	Loose	9 (30)	667.951 (379.707)	904.800 (")
13:18:04	13:18:12	1.0	Loose	8 (33)	447.662 (316.510)	660.960 (")
13:18:24	13:18:36	-	Downtime	[12]	261.140	375.816
13:18:49	13:18:58	1.1	Loose+Digging	9 (33)	613.896 (388.950)	905.760 (")
13:19:22	13:19:31	1.1	Loose+Digging	9 (33)	639.936 (388.684)	931.440 (")
13:19:55	13:20:03	1.0	Loose	8 (27)	497.160 (303.444)	801.600 (")
13:20:22	13:20:33	1.1	Loose	11 (38)	487.586 (362.468)	922.320 (")
13:21:00	13:21:07	1.0	Loose	7 (22)	593.007 (368.990)	755.280 (")

Table C.1. Continued

Beginning of the Cycle	End of dipper loading	Dipper Fill Factor	Observation	Digging Time (sec) (Cycle Time (sec)) [Down Time (sec)]	Average Power (kW)	Peak Power (kW)
13:21:22	13:21:33	1.0	Loose	11 (30)	540.654 (415.413)	955.680 (")
13:21:52	13:22:01	1.0	Loose+Digging	9 (30)	645.494 (371.079)	874.320 (")
13:22:22	13:22:31	1.0	Loose+Digging	9 (34)	519.914 (354.587)	858.000 (")
13:22:56	13:23:03	1.0	Loose+Digging	7 (25)	623.535 (390.839)	900.480 (")
13:23:21	13:23:28	1.0	Loose	7 (25)	559.509 (355.786)	883.680 (")
13:23:46	13:23:53	1.1	Loose	7 (25)	477.393 (316.002)	810.960 (")
13:24:11	13:24:25	-	Downtime	[14]	343.364	698.640
13:21:25	13:21:35	1.0	Loose	10 (28)	560.173 (296.974)	869.760 (")
13:24:35	13:24:59	-	Downtime	[24]	187.714	552.960
13:25:17	13:25:24	1.0	Loose	7 (26)	569.031 (363.760)	858.560 (")
13:25:43	13:25:52	1.0	Loose	9 (32)	562.730 (373.780)	786.960 (")
13:26:15	13:26:23	1.0	Loose	8 (30)	467.411 (327.572)	772.080 (")
13:26:45	13:26:52	1.0	Loose	7 (32)	374.814 (342.144)	490.704 (")
13:27:17						

Table C.1. Continued

Beginning of the Cycle	End of dipper loading	Dipper Fill Factor	Observation	Digging Time (sec) (Cycle Time (sec)) [Down Time (sec)]	Average Power (kW)	Peak Power (kW)
13:25:17	13:25:24	1.0	Load dipper (loose)	7	569.031	898.560
13:25:24	13:25:29	-	Swing loaded to the truck	5	304.077	432.696
13:25:29	13:25:35	-	Dump dipper into the truck	6	270.122	583.680
13:25:35	13:25:43	-	Swing empty for the next cycle	8	259.846	535.680
13:25:43	13:25:52	1.0	Load dipper (loose)	9	562.730	786.960
13:25:52	13:25:58	-	Swing loded to the truck	6	317.076	658.320
13:25:58	13:26:07	-	Dump dipper into the truck	9	284.863	602.400
13:26:07	13:26:15	-	Swing empty for the next cycle	8	261.566	724.560

APPENDIX D

APPENDIX D: SHOVEL DIGGING PERFORMANCE MEASUREMENT RESULTS RELATED TO DIFFERENT DEPTHS OF CUT

The Rock Units Descriptions of Case 2 and Case 4

Case 2 (Yatağan-Eskihisar): Formation is slightly-moderately weathered marl comprising clay layers. Average bed thickness of horizontally layered marl is 0.5 m and ranged between 0.2 m to 1.5 m. There are two joint sets, and they are orthogonal to bedding. The spacing is 1.0 m for two joint sets. The bench height is 12 m. The top of the bench is moderately to highly weathered marl (~2 m thick). Moderately weathered marl is observed at the middle of the bench, where the thickness is about 1.0 m. The rest of the formation is slightly weathered marl. At the bottom of the bench fresh gray marl is situated which has a thickness of 0.5 m. The in situ block size is 0.3x0.3x04 m (90%) and the maximum block size is 1.5x1.0x1.0 m. Blasting is not applied. Double side loading of trucks is used and the operator experience is four years.

Case 4 (Tınaz): Formation is fresh-slightly wheathered marl comprising clay layers. Bedding thickness ranged between 0.3 m to 1.5 m with the average thickness of 0.7 m. The bench height is 14.5 m. The top of the bench (0.5 m) is highly weathered clayish marl. The clay layer which has a thickness of 0.6 m is observed after 0.5 m dark gray and 0.5 m light gray marl. The rest of the formation is banded fresh-slightly weathered marl. There are two joint sets, which are orthogonal to bedding. The spacings are 0.7 m and 0.5 m. The block size is 0.3x0.4x0.6 m (70%) and the maximum block size is 1.5x0.8x0.7 m before blasting. The block size after blasting is less than 0.2 m (80%) and the rest of the block size is 0.8x0.7x0.6 m. Double side loading is used and the operator experience is five years.

Table D.1. Shovel Digging Performance Related to Different Depths of Cut (Case No:1).

Dept of Cut Class		Cycle Time (sec)	Digging Time (sec)	Dipper Fill Factor	Average Digging Power (kW)	Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)
Before Blasting	I (≤0.4m)	30.0	7.0	1.00	857.7	1203.1	1.668	0.145
		26.0	7.0	1.00	778.7	1066.2	1.514	0.132
		23.0	7.0	0.90	988.5	1343.2	1.922	0.186
		27.0	7.0	1.00	897.6	1265.5	1.745	0.152
		41.0	9.0	1.00	745.55	1032.7	1.864	0.163
		28.0	8.0	0.90	996.8	1296.9	2.215	0.215
		28.0	9.0	1.00	894.2	1476.1	2.236	0.195
	II (0.4-0.6m)	27.0	9.0	1.10	964.6	1486.8	2.412	0.191
		26.0	10.0	1.10	963.7	1380.1	2.677	0.212
		29.0	11.0	0.90	1161.9	1674.4	3.550	0.344
		29.0	11.0	0.90	1023.1	1464.7	3.126	0.303
		31.0	12.0	1.00	1007.3	1712.8	3.358	0.293
	III (0.6-0.8m)	31.0	13.0	1.00	1206.9	1749.2	4.358	0.380
		41.0	15.0	1.00	1250.4	1657.6	5.210	0.454
After Blasting	I (≤0.6m)	23.0	7.0	1.10	959.1	1337.8	1.865	0.148
		25.0	9.0	1.10	982.2	1432.3	2.456	0.195
		20.0	6.0	1.10	1001.2	1349.0	1.669	0.132
		28.0	7.0	1.10	980.4	1487.9	1.906	0.151
		25.0	8.0	1.00	973.1	1496.4	2.162	0.189
		24.0	8.0	1.10	947.9	1387.7	2.106	0.167
	II (0.6-0.8m)	26.0	9.0	1.10	1130.2	1603.2	2.826	0.224
		23.0	8.0	1.10	1172.4	1599.4	2.605	0.207
		21.0	8.0	1.10	1078.1	1525.8	2.396	0.190
		24.0	7.0	1.10	1.27.1	1420.1	1.997	0.158
		24.0	8.0	1.15	1035.1	1487.6	2.300	0.174
	III (0.8-1.0m)	25.0	8.0	1.00	1284.8	1864.8	2.855	0.249
		25.0	8.0	1.10	1213.7	1553.8	2.697	0.214
		22.0	7.0	1.00	1204.2	1629.6	2.342	0.204
		26.0	10.0	1.10	1015.6	1915.7	2.819	0.224
Empty Cycle		27.0	9.0	-	441.1	633.0	1.103	-
		29.0	9.0		432.8	1056.0	1.082	
		26.0	9.0		469.6	928.6	1.174	

Table D.1. Shovel Digging Performance Related to Different Depths of Cut (Case No:2).

	Dept of Cut Class	Cycle Time (sec)	Digging Time (sec)	Dipper Fill Factor	Average Digging Power (kW)	Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)
Before Blasting	I (≤0.4m)	29.0	8.0	1.00	879.4	1163.9	1.954	0.170
		30.0	10.0	1.00	874.8	1302.5	2.430	0.193
		26.0	8.0	1.00	822.4	1252.3	1.828	0.159
		29.0	9.0	1.00	707.6	1032.9	1.769	0.154
		25.0	9.0	1.00	822.6	1252.6	2.057	0.179
		26.0	9.0	1.00	887.6	1112.5	2.219	0.193
	II (0.4-0.6m)	29.0	10.0	1.00	914.3	1421.6	2.540	0.221
		29.0	8.0	1.00	1024.7	1475.9	2.277	0.199
		26.0	9.0	1.10	1120.1	16.16	2.800	0.222
		28.0	10.0	1.00	984.9	1413.0	2.736	0.239
		28.0	10.0	1.00	1088.0	1476.9	3.022	0.264
		26.0	10.0	1.00	918.0	1274.4	2.550	0.22
		21.0	11.0	1.00	1028.3	1529.0	3.142	0.274
		31.0	14.0	1.00	919.0	1465.0	3.574	0.312
	III (0.6-0.8m)	39.0	11.0	1.00	1028.3	1479.8	3.142	0.274
		31.0	17.0	1.00	1258.2	1558.7	5.942	0.518
		32.0	19.0	1.00	1224.3	1525.1	6.462	0.563
		49.0	20.0	1.00	1166.7	1619.4	6.482	0.565
After Blasting	I (≤0.6m)	-	-	-	-	-	-	-
	II (0.6-0.8m)	-	-	-	-	-	-	-
	III (0.8-1.0m)	-	-	-	-	-	-	-
Empty Cycle		24.0	7.0	-	495.0	816.4	0.963	-
		33.0	10.0		460.3	812.0	1.279	
		30.0	10.0		390.5	541.4	1.085	

Table D.1. Shovel Digging Performance Related to Different Depths of Cut (Case No:3).

Dept of Cut Class		Cycle Time (sec)	Digging Time (sec)	Dipper Fill Factor	Average Digging Power (kW)	Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)
Before Blasting	I (≤0.4m)	27.0	9.0	1.00	965.7	1542.6	2.414	0.211
		29.0	9.0	1.00	889.4	1258.7	2.224	0.194
		29.0	9.0	1.10	1144.7	1691.0	2.862	0.227
		28.0	11.0	1.00	926.3	1517.2	2.830	0.247
		30.0	11.0	1.00	1136.3	1562.2	3.472	0.303
		34.0	15.0	1.00	1097.5	1697.1	4.573	0.399
	II (0.4-0.6m)	39.0	19.0	1.10	1149.8	2079.2	7.469	0.606
		41.0	21.0	1.10	1538.8	2104.7	8.976	0.712
		29.0	13.0	1.00	1236.3	1662.2	4.464	0.389
		32.0	12.0	1.10	1309.4	1906.0	4.365	0.346
		39.0	14.0	1.10	1256.7	2026.5	4.887	0.387
		30.0	15.0	1.00	1114.6	1610.2	4.644	0.405
		32.0	12.0	1.10	1309.4	1906.0	4.365	0.346
	III (0.6-0.8m)	51.0	19.0	1.00	1613.0	2066.1	8.513	0.742
		43.0	23.0	1.10	1448.0	2105.0	9.251	0.733
		56.0	25.0	1.10	1444.0	2104.3	10.028	0.795
		30.0	9.0	1.00	1284.0	2160.0	3.210	0.280
		50.0	29.0	1.00	1691.0	2123.2	13.629	1.188
		32.0	10.0	1.00	1605.2	2149.8	4.459	0.389
		35.0	13.0	1.10	1500.5	2109.4	5.418	0.429
After Blasting	I (≤0.6m)	29.0	9.0	1.10	1143.2	1705.5	2.858	0.227
		26.0	10.0	1.10	1040.5	1446.3	2.890	0.229
		31.0	9.0	1.10	1078.0	1549.5	2.695	0.214
		26.0	9.0	1.10	1201.0	1808.4	3.003	0.238
		28.0	9.0	1.10	1093.6	1691.0	2.734	0.217
		30.0	9.0	1.10	1180.3	1897.1	2.951	0.234
	II (0.6-0.8m)	29.0	9.0	1.10	1238.9	1784.0	3.097	0.246
		35.0	12.0	1.10	1202.8	1890.5	4.009	0.318
		31.0	10.0	1.10	1434.8	1994.5	3.986	0.316
		27.0	9.0	1.10	1430.6	2019.9	3.577	0.283
		29.0	10.0	1.10	1244.8	1762.2	3.458	0.274
		35.0	12.0	1.10	1156.2	1741.8	3.854	0.305
		35.0	10.0	1.10	1271.0	1860.4	3.531	0.280
		31.0	10.0	1.10	1343.3	2106.1	3.731	0.296
		26.0	10.0	1.10	1201.4	1808.8	3.337	0.265
	III (0.8-1.0m)	39.0	18.0	1.10	1526.2	2075.6	7.631	0.605
		31.0	7.0	1.10	1511.1	1926.9	2.938	0.233
		31.0	10.0	1.10	1578.6	2267.9	4.385	0.348
Empty Cycle		27.0	8.0	-	493.8	858.4	1.097	-
		31.0	9.0		493.0	855.5	1.233	

Table D.1. Shovel Digging Performance Related to Different Depths of Cut (Case No:4).

Dept of Cut Class		Cycle Time (sec)	Digging Time (sec)	Dipper Fill Factor	Average Digging Power (kW)	Peak Digging Power (kW)	Energy Consumption of Digging (kWh)	Specific Digging Energy (kWh/m3)
Before Blasting	I (≤0.4m)	39.0	15.0	1.10	881.3	1273.5	3.672	0.291
		33.0	15.0	1.10	745.6	1134.8	3.107	0.246
		34.0	16.0	1.00	685.7	974.8	3.048	0.266
		35.0	15.0	1.00	740.2	1043.9	3.084	0.269
		32.0	13.0	1.00	707.2	1010.5	2.554	0.223
		37.0	15.0	1.00	716.3	1045.6	2.985	0.260
	II (0.4-0.6m)	38.0	13.0	1.10	966.6	1297.9	3.491	0.277
		37.0	18.0	1.10	827.8	1330.4	4.139	0.328
		43.0	19.0	1.10	883.0	1324.8	4.660	0.369
		34.0	18.0	1.00	970.7	1423.5	4.854	0.423
		43.0	22.0	1.10	932.8	1484.8	5.700	0.452
		39.0	21.0	1.00	1003.5	1371.4	5.854	0.510
		37.0	18.0	1.10	925.3	1401.9	4.627	0.367
		34.0	18.0	1.10	940.8	1281.9	4.704	0.373
		35.0	15.0	1.10	985.5	1546.4	4.106	0.325
	III (0.6-0.8m)	38.0	20.0	1.00	1036.9	1513.4	5.761	0.502
		35.0	20.0	1.00	1019.8	1462.3	5.666	0.494
		42.0	22.0	1.10	978.6	1425.4	5.980	0.474
		41.0	22.0	1.00	1058.8	1350.3	6.470	0.564
		41.0	23.0	1.10	1021.6	1431.2	6.527	0.517
		42.0	21.0	1.00	908.4	1336.0	5.299	0.462
After Blasting	I (≤0.6m)	22.0	8.0	1.10	757.7	1155.7	1.684	0.133
		27.0	8.0	1.00	766.9	1176.5	1.704	0.149
		23.0	9.0	1.00	792.4	1051.2	1.981	0.173
		25.0	9.0	1.10	847.5	1122.9	2.119	0.168
		24.0	8.0	1.00	835.7	1318.5	1.857	0.162
	II (0.6-0.8m)	23.0	9.0	1.10	887.0	1274.9	2.218	0.176
		23.0	9.0	1.10	910.5	1480.0	2.276	0.180
		23.0	9.0	1.10	961.4	1332.1	2.404	0.191
		24.0	9.0	1.10	931.2	1349.6	2.328	0.185
		25.0	9.0	1.10	358.9	1372.3	2.397	0.190
		22.0	9.0	1.10	889.5	1382.0	2.224	0.176
	III (0.8-1.0m)	26.0	8.0	1.10	985.5	1630.0	2.190	0.174
		25.0	10.0	1.10	952.1	1314.7	2.645	0.210
		26.0	9.0	1.10	929.4	1529.9	2.324	0.184
		24.0	8.0	1.10	1005.1	1563.1	2.234	0.177
		24.0	10.0	1.10	1016.6	1511.0	2.824	0.224
		28.0	11.0	1.10	1039.3	1576.7	3.176	0.252
Empty Cycle		41.0	15.0	-	366.7	508.0	1.528	-
		33.0	10.0		370.1	754.5	1.028	
		34.0	10.0		322.2	393.7	0.895	

VITA

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