DEVELOPMENT OF A COMPUTER BASED MONITORING SYSTEM AND ITS USAGE FOR POWER SHOVELS' MONITORING

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Approval of the Graduate School of Natural and Applied Sciences.

Prof.Dr. Tayfur Öztürk

Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Doctor of Philosophy.

Prof.Dr. Çetin Hoşten

Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Doctor of Philosophy.

Prof.Dr. Celal Karpuz

Supervisor

Examining Committee Members

Prof.Dr. Naci Bölükbaşı (Chairman)

Prof.Dr. Seyfi Kulaksız

Prof.Dr. Celal Karpuz (Supervisor)

Assoc.Prof.Dr. Atilla Ceylanoğlu

Assoc.Prof.Dr. Bahtiyar Ünver

ABSTRACT

DEVELOPMENT OF A COMPUTER BASED MONITORING SYSTEM AND ITS USAGE FOR POWER SHOVELS' MONITORING

Hindistan, Mehmet Ali
Ph.D., Department of Mining Engineering
Supervisor: Prof. Dr. Celal Karpuz

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Over the past few years improvements in mining technology have been forcing the mining industry towards the exploitation of coal and lignite deposits under thick overburden formations economically by open pit mining methods. The major operations in an open pit mining complex (i.e., ground preparation, excavation, loading, transport) are interdependent activities. Selecting excavation equipment in isolation may not, therefore, be a good practice, but the selection of the proper digging machine is of major importance.

Being digging the result of an interaction between the excavating tool and the rock mass, diggability should be considered as a function of both the characteristics of the excavating equipment and those of the excavated material. In this research, monitoring of electric mining shovels was aimed to investigate the interaction between the machine and the excavated material from the digging difficulty point of view. The results of the monitoring trials were evaluated to establish a quantitative empirical criteria for predicting digging difficulty of the material by relating work abilities of the shovels to various operating parameters.

By taking its advantages into account, a computer based monitoring system has been developed and successfully utilised on the power shovels. The system is designed to monitor the power consumption of the machine in digging since the amount of power generated mainly depends on the conditions of operation. During the design studies of the system, a special attention was given on providing the system, as well as to be precise and adequate for the aims, to be flexible and modular in use and adaptable for future uses. Furthermore, the developed system was also capable of detecting the dipper position during digging operation and it monitors related variables concurrently with the power variables. This provided the necessary data to obtain the digging profile geometry of the dipper precisely and to determine the depth of cut quantitatively since digging path of the dipper greatly affects the performance parameters.

An extensive field study was carried out to obtain data from the electric mining shovels which operate at different ground conditions in several open pit mines of Turkish Coal Enterprises (TKİ). A data evaluation software package was also developed to find the performance variables of the machine in digging operation by processing the massive amounts of the monitored data. Although these variables were determined separately for three main components of a cycle (i.e., swing to face, digging and swing to dump) a special attention was given on digging component where the machine properly interacts with the excavated material.

Among the studied parameters, both specific digging energy and hourly digging capacity parameters provided good correlation with rock mass and material properties. On the basis of these parameters, definitions of digging difficulty are proposed for electric power shovels.

Key Words : Diggability, Shovel Monitoring System, Digging Energy, Depth of Cut, Digging Profile.

ÖZ

BİLGİSAYARA DAYALI BİR İZLEME SİSTEMİNİN GELİŞTİRİLMESİ VE ELEKTRİKLİ EKSKAVATÖRLERİN İZLENMESİNDE KULLANIMI

Hindistan, Mehmet Ali
Doktora, Maden Mühendisliği Bölümü
Tez Yöneticisi: Prof. Dr. Celal Karpuz

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Son yıllarda madencilik alanındaki gelişmeler bu endüstriyi kalın örtü tabakaları altındaki kömür ve linyit yataklarının ekonomik olarak açık ocak yöntemleri ile işletilmesine doğru yönlendirmiştir. Bir açık ocak işletmesinde yapılması gereken, saha hazırlıkları, kazı, yükleme, taşıma gibi ana faaliyetler bir bütün olarak düşünülmektedir. Bu nedenle, kazı ekipmanın bunlardan bağımsız seçimi iyi bir uygulama olmamakla birlikte uygun kazıcının seçimi oldukça önemlidir.

Kazının kazı makinası ile kaya kütlesi arasındaki bir etkileşim sonucunda gerçekleştiği bilindiğinde, kazılabilirlik hem makinanın ve hem de kazılan malzemenin özelliklerini içine alacak şekilde düşünülmelidir. Bu araştırmada, elektrikli ekskavatörlerin izlenmesi yöntemiyle makina ile kazılan malzeme arasındaki etkileşimin kazı zorluğu şeklinde belirlenmesi amaçlanmıştır. İzleme çalışmalarından elde edilen sonuçlar, ekskavatörlerin iş yeteneklerinin farklı çalışma değişkenleri ile ilişkilendirilmesi ve böylece malzemenin kazı zorluğunu tanımlayan sayısal bir görgül (ampirik) ölçütün çıkarılması amacıyla değerlendirilmiştir.

Sağlayacağı avantajlar dikkate alınarak, bilgisayara dayalı bir izleme sistemi geliştirilmiş ve elektrikli ekskavatörlerin izlenmesinde başarı ile kullanılmıştır. Makinanın kazı için harcadığı gücün miktarı esas olarak çalışma koşullarına bağlı olduğu için izleme sistemi bu gücü ölçecek şekilde tasarlanmıştır. Tasarım aşamasında, sistemin, bu çalışmanın amaçlarına uygun ve kusursuz olması kadar kullanımda esnek ve modüler olmasına, ve ilerde doğabilecek benzer ihtiyaçlar için kolayca uyarlanabilecek özelliklere sahip olmasına özellikle dikkat edilmiştir. Bunların yanısıra, geliştirilen sistem kazı esnasında kepçenin hareketleri ile ilgili değişkenleri diğer güç değişkenleri ile birlikte eş zamanlı izleyebilec özelliklere sahiptir. Bu sayede kepçe kazı profilinin ve bunun kullanımıyla da uygulanan kazı derinliğinin, ki bu makinanın verimlilik değişkenleri üzerinde önemli bir etkiye sahip, matematiksel olarak ifade edilebilmesi için gerekli sayısal bilgi sağlanmıştır.

TKİ kurumuna bağlı, farklı yapısal özelliklere sahip açık işletmelerde faaliyette olan elektrikli ekskavatörlerden veri toplamak amacıyla bir dizi arazi çalışması yapılmıştır. Araziden elde edilen veriler, geliştirilen bir yazılım kullanılarak makinanın kazıdaki üretim değişkenlerini belirlemek amacıyla değerlendirilmiştir. Bu değişkenler bir devirin üç ana bölümü (bunlar; kazı için arına dönüş, kazı, malzemeyi dökmek için kamyona dönüş) için ayrı ayrı hesaplandıysa da, makina ile malzeme arasında tam bir etkileşimin gerçekleştiği kazı bölümüne ağırlıklı olarak önem verilmiştir.

Elde edilen üretim değişkenleri arasında özgül kazı enerjisi ve saatlık kazı kapasitesi değişkenlerinin, kaya kütlesi ve malzeme özellikleri ile daha iyi uyum sağladığı saptanmıştır. Bu nedenle, elektrikli ekskavatörler için kazı zorluğu tanımlamaları bu değişkenlere göre önerilmiştir.

Anahtar Kelimeler : Kazılabilirlik, Ekskavatör İzleme Sistemi, Kazı Enerjisi,
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To My Family

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INTRODUCTION

Excavation of overburden material is the most important operation in an open pit mining complex. Recent improvements in machines manufactured to excavate the ground supply a wide range of equipment with different capacities and powers to customers. But the selection of a proper excavation equipment arises as the most crucial question for engineers because the selected excavation equipment also determines the equipment required for loading and dumping, as well as the mode of the mining operation and they are the key to low-cost production. As far as the equipment is concerned, the basic problem to be solved by the modern open cast mine management is to select, size and schedule the equipment in order to maximise profits and minimise adverse environmental impacts.

In today's modern open pit mines, heavy-duty excavation equipment such as bucket wheel excavators, draglines and shovels are widely utilised to remove overburden material above coal and lignite deposits. Depending on the material characteristics and the equipment properties, excavation is achieved either directly or after loosening the ground. Therefore, factors such as type and size of the equipment, material characteristics, geological conditions, blasting parameters, etc. have to be considered at the same time in the selection of excavation equipment. It should also be remembered that an equipment is only as efficient as the man operating the controls.

In selecting a shovel, *its digging ability* (i.e., the measure of how easy it can dig rock or coal) is the most critical parameter has to be determined. The ideal procedure to determine the ability of a shovel to dig efficiently a geological formation is to conduct a trial excavation at the mine site, but this is almost always impractical. Hence alternative approaches have been studied by several investigators to relate work abilities of open pit equipment to various geological and geotechnical parameters of the ground and to establish qualitative or quantitative empirical criteria of diggability.

Many researchers and equipment manufacturers have been working on the performance monitoring of open pit equipment, such as drilling machines, electric mining shovels, draglines, bucket wheel excavators, etc. These monitoring systems can be grouped under two categories which are commercial and scientific.

Commercial monitoring systems produced for excavation equipment are used to record production parameters such as production in a period of excavation time, cycle time, swing angle, idle time, etc. (Anon, 1991). This system is provided optionally by manufacturing companies and can be mounted on the machines. On the other hand, scientific monitoring systems are mainly used to obtain the results of interaction between machine and excavated material, together with operating parameters.

In this study a scientific monitoring system is developed to use on electric mining shovels operating at several surface lignite mines of Turkish Coal Enterprises. Results of excavation trials are analysed and discussed from the digging difficulty point of view by considering both the machine parameters and the material characteristics. As a result of these analysis, a quantitative classification is provided to predict digging difficulty for electric mining shovels.

Literature on the previous studies are reviewed and discussed in the following chapter. The operating mechanism of power shovels, the details of the developed monitoring system hardware and software packages are given in Chapter 3. In chapter 4, basic characteristics of monitored machines and properties of materials are outlined. Results of data analysis and discussions on determined parameters are given in Chapter 5. Finally, conclusions of this study and some recommendations for future studies are summarised in the last chapter.

CHAPTER 2

LITERATURE SURVEY

2.1. Literature Survey

Improvements in mining technology have been forcing the industry towards the exploitation of coal and lignite deposits under thick overburden formations economically by open pit mining methods. Overburden removal is the most important operation in an open pit mining. The major operations in an open pit mining are interdependent activities, but the selection of the suitable digging machine is of major importance since the selected machine also determines the equipment required for ground preparation and transport, as well as the mode of the mining operation. Therefore the basic problem to be solved by the modern open pit mine management is to select suitable equipment.

Bucket wheel excavators, draglines and shovels which are heavy-duty excavation equipment are widely utilised to remove overburden in today's modern open pit mines. Manufacturers supply a wide range of these equipment with different capacities and powers to customers. So the selection of the most suitable one among the alternatives arises as the most crucial question. The more choice you have, the more difficult you take a decision.

In selecting a digging equipment, its digging ability is the most critical parameter has to be determined. Since digging is an interaction between the digging machine and the material excavated, the ideal diggability definition should incorporate both the machine characteristics and the material properties. This can be provided by conducting a trial excavation at the mine site, but it is not always possible or practical. Thus, recent efforts have been made to develop a correlation between work ability of a digging machine and some physical and mechanical properties of rock masses.

Although electric power shovels are concerned in this study, diggability as a wide subject also covers the other open pit excavation equipment such as draglines, bucket wheel excavators and rippers. Different approaches to assess digging difficulty of material are proposed by numerous investigators, i.e., Atkinson (1971), Franklin *et al.* (1971), Bailey (1975), Weaver (1975), Church (1981), Müftüoğlu (1983), Smith (1986), Singh *et al.* (1987), Bozdağ (1988), Paşamehmetoğlu *et al.* (1988), Karpuz (1990a and 1990b), Kolleth (1990), Bölükbaşı *et al.* (1991a and 1991b).

May be one of the earliest reference to assess diggability is provided by Atkinson (1971) who proposed a correlation between the performance of various types of excavators and the in-situ seismic wave velocity obtained from field tests (Figure 2.1). He is not the only one who directly used seismic wave velocity in a classification system. Bailey (1975) and Church (1981) suggested classification systems for estimating ripper performances (rippability). Besides investigators, this parameter is also applied by various bulldozer manufacturers, i.e., Caterpillar Tractor Co. (Anon, 1983 and 1986), Komatsu Ltd. (Anon, 1982), provide charts to predict rippability of its line of bulldozer-ripper combinations by seismic wave velocities for a variety of materials.

Seismic velocity is a function of intact rock properties, discontinuity spacing, degree of fracturing and state of weathering, in this extent is a meaningful parameter in assessing the ease of excavation (Panagiotou, 1990). A classification diagram which incorporates the mean joint spacing of rock mass and the point load index of intact rock (intact rock strength) has been suggested by Franklin *et al.* (1971) in order to classify rock mass quality (Figure 2.2). As it is seen in the figure, type of excavation is not indicated although the limits of modes of loosening the ground included into the diagram. 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 TKİ's surface coal mines, in Turkey (Figure 2.3) (Paşamehmetoğlu *et al.*, 1988; Karpuz *et al.*, 1990a).

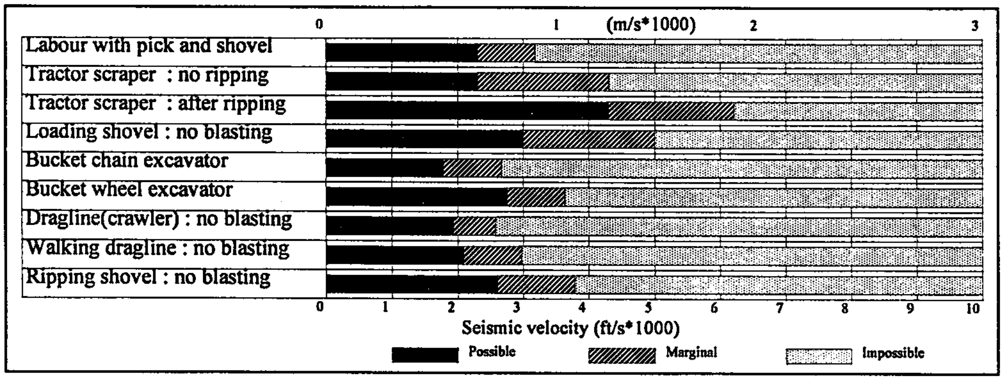


Figure 2.1Determination of excavation possibilities with seismic wave velocity (after Atkinson, 1971).

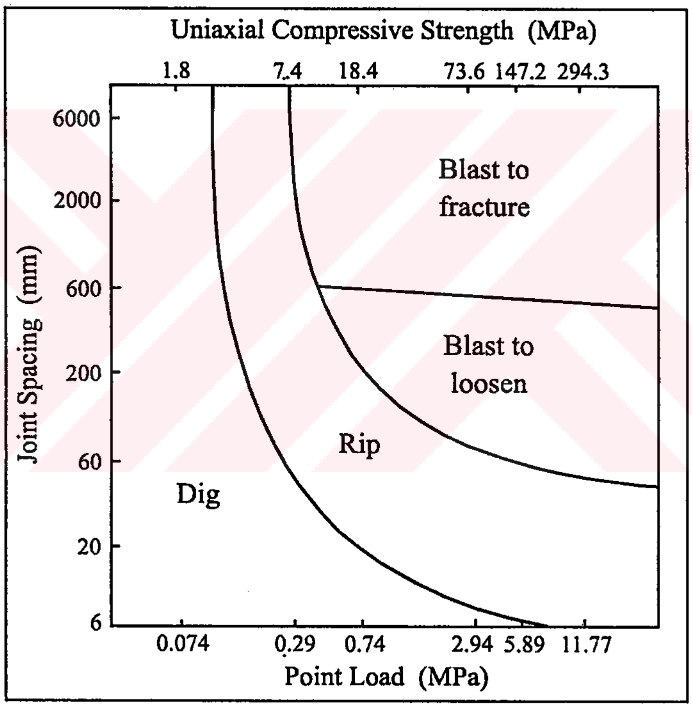


Figure 2.2Excavation prediction classification (after Franklin *et al.*, 1971).

Researchers like Weaver (1975), Smith (1986) and Singh *et al.* (1987) established rippability estimation methods which are mainly based on the usage of seismic velocity together with rock mass and material properties.

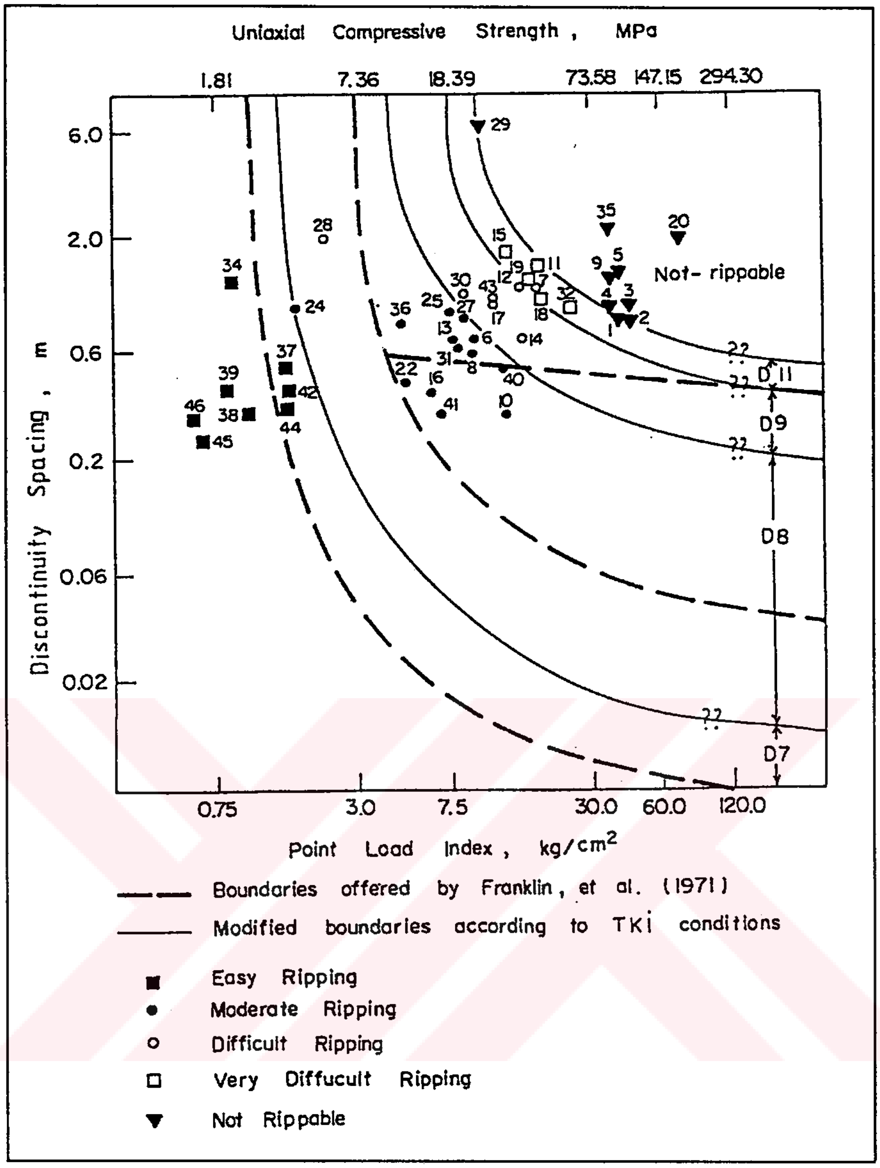


Figure 2.3Modification of Franklin *et al.*'s (1971) excavability chart based on rippability studies at TKİ's surface coal mines (after Bozdağ, 1988).

As well as seismic velocity, the parameters such as rock hardness, rock weathering, rock structure (discontinuities, planes of weakness, dip and orientation) and rock fabric are found as the significant parameters for rippability and therefore, Weaver (1975) proposed a rippability rating system on the base of these parameters. He also included suitable ripper models characterised by their horse powers in his rippability classes.

Weaver's system is modified by Smith (1986) who proposed a systematic means of numerically weighing six rock parameters, namely; rock hardness (in terms of unconfined compressive strength), rock weathering, joint spacing, joint continuity, joint gauge and strike and dip orientation, to produce a rippability rating chart (Table 2.1). He recommended a method of correlating this rating with the seismic velocity and tractor horse power. Although the method demonstrated is systematic and yield specific numerical results; an integrated approach is recommended to its application; taking into account, the rippability rating, seismic velocity, rock mass and material properties and other engineering judgement factors.

Table 2.1 Modified Weaver's rippability chart (after 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 separation	Slightly separation	Separation < 1 mm	Gouge < 5 mm	Gouge > 5 mm
Rating	*5*	*5*	*4*	*3*	*1*
Strike and dip orientation	Very unfavourable	Unfavourable	Slightly favourable	Favourable	Very favourable
Rating	*15*	*13*	*10*	*5*	*3*

*** Corresponding to unconfined compressive strength**

Singh *et al.* (1987) claimed that current rippability indices fail to account for the fracture strength of rock mass and the rock abrasiveness potential. They suggested a new rippability index for mining applications which takes indirect tensile strength, degree of weathering, seismic velocity, discontinuity spacing and rock abrasiveness parameters into account. They also recommended dozer models suitable for defined rippability classes (Table 2.2).

Table 2.2 Rock rippability index (after Singh *et al.*, 1987).

Parameter	**Rock Class**				
	1	**2**	**3**	**4**	**5**
ITS (MPa) *Rating*	< 2 *0 - 3*	2 - 6 *3 - 7*	6 - 10 *7 - 11*	10 - 15 *11 - 14*	> 15 *14 - 17*
Weathering *Rating*	Completely *0 - 2*	Highly *2 - 6*	Moderately *6 - 10*	Slightly *10 - 14*	Unweathered *14 - 17*
Seismic vel. (m/s) *Rating*	400 -1100 *0 - 6*	1100 -1600 *6 - 10*	1600 -1900 *10 - 14*	1900 - 2500 *14 - 18*	> 2500 *18 - 25*
Abrasiveness *Rating*	Very low *0 - 5*	Low *5 - 9*	Moderately *9 - 13*	Highly *13 - 18*	Extremely *18 - 22*
Disc. spacing (m) *Rating*	< 0.06 *0 - 7*	0.06 - 0.3 *7 - 15*	0.3 - 1.0 *15 - 22*	1.0 - 2.0 *22 - 28*	> 2.0 *28 - 33*
TOTAL RATING	**< 30**	**30 - 50**	**50 - 70**	**70 - 90**	**> 90**
Rippability assess.	Easy	Moderate	Difficult	Marginal	Blast
Recommended dozer	none - Class 1 Light duty	Class 2 Medium duty	Class 3 Heavy duty	Class 4 V.heavy duty	-- --
Output (kW) Weight (kg)	< 150 < 25000	150 - 250 25000 - 35000	250 - 350 35000 - 55000	> 350 > 55000	-- --

Kolleth (1990) provided a diagram (Figure 2.4) which shows the applicability of various digging equipment as a function of uniaxial compressive strength, or alternatively point load index (Is), of the material to be dug.

All the references cited above are related to the rippability, except Atkinson (1971) and Kolleth (1990) presented the diggability of various excavators on the basis of in-situ seismic velocity of rock mass and the uniaxial compressive strength respectively. A diggability system based on a single parameter is not a means to assess interaction between machine and material. More comprehensive diggability assessment techniques are proposed by Müftüoğlu (1983), Karpuz (1990b) and Hadjigeorgiou *et al.* (1990).

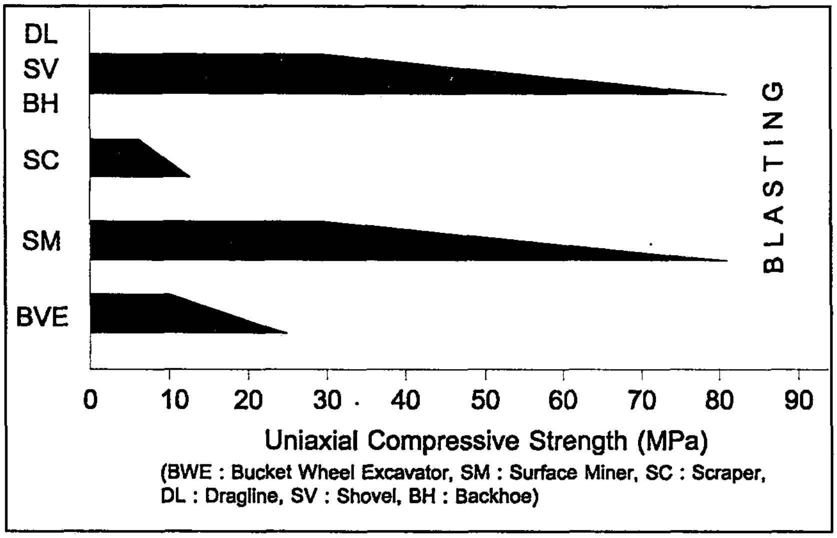


Figure 2.4 Applicability (at nominal output) of digging equipment as a function of uniaxial compressive strength (after Kolleth, 1990).

The diggability system proposed by Müftüoğlu (1983) is based on intact rock strength, weathering, joint and bedding spacing which are observed as the dominant factors control the diggability of coal measures in British coal mines. A diggability index derivation based on these ground parameters (Table 2.3) has been developed to relate observed excavator performance, mainly hydraulic excavators, with a wide range of ground conditions. The index system is related to equipment type and capability (Table 2.4).

Karpuz (1990b) 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 (1990b), 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, proposed an excavation rating system (Table 2.5) which consists of intact rock strength, Schmidth hardness value, discontinuity spacing, degree of weathering and seismic wave velocity based on a two year project carried out at TKİ surface lignite mines (Paşamehmetoğlu *et al.*, 1988). His classification system also suggest the equipment to be used as well as blasting and drilling requirements (Table 2.6).

Table 2.3 Diggability index rating method (after Müftüoğlu, 1983).

Parameter	Class				
	1	**2**	**3**	**4**	**5**
Weathering *Rating (W)*	Completely *< 0*	Highly *5*	Moderately *15*	Slightly *20*	Unweathered *25*
UCS (MPa) Is (50) *Rating (S)*	< 20 < 0.5 *0*	20- 40 0.5 - 1.5 *10*	40 - 60 1.5 - 2.0 *15*	60 - 100 2.0 - 3.5 *20*	> 100 > 3.5 *25*
Joint spacing (m) *Rating (J)*	< 0.3 *5*	0.3 - 0.6 *15*	0.6 - 1.5 *30*	1.5 - 2.0 *45*	> 2.0 *50*
Bedding spacing (m) *Rating (B)*	< 0.1 *0*	0.1 - 0.3 *5*	0.3 - 0.6 *10*	0.6 - 1.5 *20*	> 1.5 *30*

Table 2.4 Diggability classification system (after 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 > 5 m^3 (Ruston Bucyrus 150 RB)
III	Moderately difficult	50 - 60	1. Ripping 2. Shovel digging	A. Ripper-Shovel/F.End Loader (Cat. D9) B. Hydraulic shovel > 3 m^3 (Cat. 245)
IV	Difficult	60 - 70	1. Ripping 2. Shovel digging	A. Ripper - Shovel/F.End Loader (Cat. D10) B. Hyd. shovel > 3 m^3 (Cat. 245 or O&K RH40)
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&H1200 or O&K RH75)
VII	Marginal without blasting	> 100	Shovel digging	Hydraulic shovel > 10 m^3 (Demag H185/H241, O&K RH300)

Table 2.5 Parameters used to create diggability index (after Karpuz, 1990b).

Parameter	Class				
	1	**2**	**3**	**4**	**5**
Uniaxial compressive strength (MPa)	< 5	5 - 20	20 - 40	40 - 110	> 110
$I_{s(50)}$ (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	*0 - 7*	*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 in no distinguishable discontinuity.

Table 2.6 Diggability classification (after Karpuz, 1990b).

Class	Ease of digging	Index	Excavation method			When blasting	
			Power shovel digging	Hydraulic excavator	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	0.13 - 0.20
3	Moderately difficult	45 - 65	Blast	Blast	Difficult to very difficult D9 or D11	1.28	0.20 - 0.28
4	Difficult	65 - 85	Blast	Blast	Marginal to non-rippable D11	0.57	0.28 - 0.35
5	Very difficult	85 - 100	Blast	Blast	Non-rippable (blast)	< 0.42	> 0.35

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

Hadjigeorgiou *et al.* (1990) presented an excavation assessment system which is based on an excavating index rating of the parameters such as block size, material strength, degree of weathering and relative orientation of discontinuities. After defining excavating index ratings for the classes of the four parameters, as given in Table 2.7, they proposed excavating classes according to the excavation index, EI, which is determined by applying the index values of the parameters into the following equation (Table 2.8).

$$EI = (I_s + B_s)\ W * J_s \qquad 2.1$$

Table 2.7 Excavating index rating scheme (after Hadjigeorgiou *et al.*, 1990).

Class	**I**	**II**	**III**	**IV**	**V**
$I_{s(50)}$ (MPa) *Rating I_s*	0.5 *0*	0.5 - 1.5 *10*	1.5 - 2.0 *15*	2.0 - 3.5 *20*	> 3.5 *25*
Block size J_v (joint/m^3) *Rating B_s*	very small 30 *5*	small 10 - 30 *15*	medium 3 - 10 *30*	large 1 - 3 *45*	very large 1 *50*
Weathering *Rating W*	completely *0.6*	highly *0.7*	moderately *0.8*	slightly *0.9*	unweathered *1.0*
Relative ground structure *Rating J_s*	very favourable *0.5*	favourable *0.7*	slightly unfavourable *1.0*	unfavourable *1.3*	very unfavourable *1.5*

Table 2.8 Definition of excavating classes (after Hadjigeorgiou *et al.*, 1990).

Class	Excavation effort	Index range
I	very easy	< 20
II	easy	20 - 30
III	difficult	30 - 45
IV	very difficult	45 - 55
V	blasting	> 55

Among the open pit excavation equipment, bucket wheel excavators have also been worthy machines for many investigators to study their diggability similar to the other equipment. The specific cutting resistance or specific separation force of intact rock (Fa), which is measured from laboratory 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.* (1991a) summarised the available BWE diggability criteria (Table 2.9), and proposed that beside O&K wedge test results, the F_a (cutting resistance) values obtained from direct cutting experiments used mainly for the assessment of performances and selection of tunnel boring machines could be used in the BWE diggability assessments. Bölükbaşı *et al.* (1991b) proposed BWE diggability criteria based on cutting specific energy which has the advantage over O&K wedge test, such that it is not affected by the specimen size and rock anisotropy.

The parameters such as cycle time, bucket/dipper fill factor and hourly capacity are commonly used by excavator manufacturers to indicate their performances. It is considered that cycle time is mainly dependent on digging difficulty unless the swing motions are irregular. As the formation gets harder to dig, it takes longer to fill the dipper. Machine size also affects the cycle time in a way that small machines can cycle in a shorter period than large machines. Cycle times (ts) proposed by some manufacturers for different sizes of electric power shovels are summarised by Paşamehmetoğlu *et al.* (1988) as given in Table 2.10.

It is difficult to excavate and fill the bucket/dipper as the formations tend to be hard. A diggability classification system for electric power shovels is given by P&H (1980) on the base of dipper fill factor as presented in Table 2.11. A classification system depend on such a simple parameter can only be a key for a rough estimation of digging difficulty.

The variables given in Tables 2.10 and 2.11 are used by Paşamehmetoğlu *et al.* (1988) to propose hourly capacities as a measure of digging difficulty for different size of electric shovels (Table 2.12). They indicated combined effect of cycle time and dipper fill factor on digging classifications of different formations at TKİ's surface coal mines by means of hourly capacity which is inversely proportional with cycle time and directly proportional with dipper fill factor.

Table 2.9 Published BWE diggability ctiteria (after Bölükbaşı *et al.*, 1991a).

Criteria	Class	Cutting resistance from O&K wedge test F_a (MPa)
Highvale After Wade&Clark (1989)	Easy	< 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	< 1.00
	Hard	1.00 - 1.50
	Marginal	1.50 - 2.40
	Undiggable	> 2.40
Kozlowski After Kozlowski (1981)	Easy	< 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	< 0.27
	Diggable	0.27 - 0.90
	Hard	0.90 - 1.85
	Marginal	--
	Undiggable	> 1.85

It is stated by Paşamehmetoğlu *et al.* (1988) that neither cycle time nor fill factor could be a sole means of determination of diggability. They found that digging related part of total cycle period is not a reliable indicator for diggability which possibly can be explained by digging trajectory. In difficult digging, the dipper speed is lower, producing a slow speed across a short trajectory (path) and giving a certain time. Conversely, in easy digging, the dipper might have a longer trajectory, but a higher dipper speed, thus the dig-cycle time might still be the same. They also remind the influence of operator experience to be considered.

Table 2.10 The cycle times of electric shovels as a function of digging difficulty (after Paşamehmetoğlu *et al.*, 1988).

Classification of digging	Easy	Easy-Moderate	Moderate	Moderate-Moderately difficult	Moderately difficult	Moderately difficult-Difficult	Difficult
Dipper capacity (yd^3)	t_s (s)	t_s (s)	t_s (s)	t_s (s)	t_s (s)	t_s (s)	t_s (s)
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 2.11 Classifications of digging (after P&H, 1980).

Classifications of digging	Dipper fill factor (FF)
Easy	$FF \geq 0.95$
Moderate	$0.90 \leq FF < 0.95$
Moderately difficult	$0.80 \leq FF < 0.90$
Difficult	$FF \leq 0.80$

Table 2.12 Hourly capacities of electric shovels as a measure of digging difficulty (after Paşamehmetoğlu *et al.*, 1988).

Classification of digging	Easy	Easy-Moderate	Moderate	Moderate-Moderately difficult	Moderately difficult	Moderately difficult-Difficult	Difficult
Dipper capacity (yd^3)	HC (m^3/h)	HC (m^3/h)	HC (m^3/h)	HC (m^3/h)	HC (m^3/h)	HC (m^3/h)	HC (m^3/h)
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	745.5	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	1318.8	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

Most of diggability studies mentioned above tended to relate to a geotechnical approach, with the derivation of a "diggability index", primarily used in equipment selection. No account was made of the excavating equipment and its interaction with the rock mass/muckpile and influence on diggability. The recent advent of microprocessor based monitoring technology has enabled excavation equipment performance to be considered as tools for diagnosis of digging conditions, providing a means to access local variations in bench environment. This has led to a growing interest in the control of open pit excavation equipment to optimise their performances.

Torrance *et al.* (1990) and Humphreys *et al.* (1994) conducted researches on blasting and dragline productivity by using a commercial monitoring system, namely Tritronics 9000 dragline monitor. Torrance *et al.* (1990) provided detailed data base on the performance of a dragline. They reported in their study that changes made to blast design were reflected in dragline performance which allowed the blasting operation to be optimised for a particular pit and dragline. Similarly, Humphreys *et al.* (1994) monitored draglines to assess the major controlling factors affecting both blast performance and subsequent dragline productivity. They indicated that dragline performance was directly affected by both muckpile diggability (looseness) and muckpile shape (profile/geometry). It is noted that the benefits achieved at one location can not be simply transferred to another mine site unless similar improvement strategies are first implemented.

A recent research on the monitoring of draglines are conducted by Paşamehmetoğlu *et al.* (1996) to show their excavatability under different digging conditions in several open pit mines of TKİ. The study revealed that, when a single machine is operating at a site, most of the excavation parameters may be sufficient to reflect the prevealing digging conditions at the bench. However, in a comparison of the parameters of various draglines operating at different mine sites, parameters compensated for time and volume/weight and specific machine powers have to be taken into account. Additionally, the monitoring of bucket position is vitally important to an interpretation of the results and their relationships to the site parameters.

Koncagül (1997) monitored bucket wheel excavators operate Elbistan lignite mine and he established correlations between the laboratory cutting specific energy and the field operational parameters, such as specific digging energy. He found laboratory cutting specific energy as a good criterion to define the diggability of rock materials with a bucket wheel excavator.

Williamson *et al.* (1983) described work to monitor crowd and swing DC motors and relays of P&H electric shovels to derive an index of muckpile diggability at the Mt. Newman Mine, Australia. They also studied effectiveness of blast design. The digging section of the shovel operating cycle was considered in order to focus on diggability and limit the influence of other factors involved in controlling productivity. The index accounted for the effects of size distribution, swell factor and muckpile profile. The effective force is described as the hoist force for digging section of an operating cycle.

Scoble and Müftüoğlu (1984) instrumented a Cat 245 hydraulic shovel to monitor stick, boom and bucket hydraulic pressures during the dig cycle. The results were related to shovel digging performance in a range of coal mine bench environment (Table 2.13). Digging performance was related to muckpile size distribution and profile, and geology. The control of bench height over dig cycle time was also evident in this study.

Two complementary researches are conducted by Hendricks *et al.* (1988 and 1989) by applying a General Electric SPM 8000 shovel monitor to gather data on shovel performance parameters. After the analysis of data, they found that dig cycle time can be a diagnostic indicator to characterize fully the shovel performance. It is stated that the shovel monitoring should record not only cycle times but also dipper loads and hoist-crowd power consumption which then the ease of digging can be ralated to both the material characteristics and the shovel productivity, in terms of both tonnage and time. In their second research, Hendricks *et al.* (1989), they studied the influence of bench geology on the blast and, thus, on muckpile characteristics. They provided data on hoist and crowd motors as well as on the exact position of the dipper in the muckpile. This research indicated that the hoist motor responses sufficiently sensitive to variations in muckpile diggability which is, therefore, used to develop a diggability index. It has been shown that motor responses are much more responsive to changes in dipper trajectory than to material characteristics. It is noted that the dipper trajectory should be considered when trying to establish a diggability criterion.

Table 2.13 Case studies of hydraulic shovel monitoring (after Scoble and 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 preperation)			0.4	< 0.03	0.03	0.2	0.04
BENC HEIGHT (m)			5	4	1.5	7	3.5
DUMP TRUCK FILLING TIME (s)			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 (s)	OBSERVED		25	28	29	27	26
	COMPUTED		26	28	28	26	27
MEAN DIGGING TIME (s/cycle)			11.5 ± 3.0	10.4 ± 2.1	11.8 ± 3.4	11.8 ± 4.1	11.7 ± 2.5
Mean presure (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	22.94	22.02	27.77	24.23
	Average	STICK	12.54	10.73	10	--	10.6
		BUCKET	6.72	5.49	5.5	5.95	6.2
		BOOM	14.9	16.17	14.5	15.86	16.5

Deslandes *et al.* (1990) described a program to improve dragline performance and safety through the use of computer monitoring and control. Strain gauges were installed at thirteen locations on a Marion 8200 to measure the stress regions and four of them selected for continuous monitoring with the developed system. 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) have been considered as the important production parameters.

Danell and Mol (1990) described the monitoring of P&H electric shovels to derive a diggability index in Broken Hill Pty. mines, Australia. The digging section of the operating cycle is used and the diggability index developed is based upon the variations of the crowd voltage and current signals. He used seven different classes of the index value to define digging condition (Table 2.14). The index is empirical and requires calibration to be used on other shovels.

Table 2.14 Classification of diggability index values to represent different digging conditions (after Danell and Mol, 1990).

Index value	Digging condition
Less than 1	extremely easy
1 - 2	very easy
2 - 4	easy
4 - 6	normal
6 - 8	difficult
8 - 9	very difficult
Greater than 9	extremely difficult

Hrebar (1990) presented a model and computer program that address the equipment selection aspects which are capital and operating costs, and, ultimately, the price of coal required to provide a reasonable return on investment. Using overburden production versus depth data for each dragline, machine requirements and capital and operating costs are determined for a series of draglines. It is shown that, with proper inputs, the model appears to provide a reasonable approximation with regard to mining sequence and dragline selection.

It is stated by Panagiotou (1990) that characterisation of ground as "diggable" or "not diggable" provides no means in selecting or designing excavators, as well as in optimising the operation of existing equipment. It is, therefore, necessary to quantify the ease of digging on the basis of material characteristics, equipment parameters and method of excavation. Consequently, a mathematical excavating equipment-ground interaction model based on the appropriate digging theory, equipment physical and operational characteristics and excavation geometry was developed by Panagiotou (1990) to assess diggability quantitatively. He characterised the ground by combining two parameters, which are the excavator's power drawn during excavation and the corresponding effective output of the excavator, in order to derive the specific digging energy of the ground which is defined as the energy required to excavate one cubic meter of loose material.

The excavating force of the shovel which is applied at the dipper teeth depends upon the size as well as the depth of cut. Paşamehmetoğlu *et al.* (1988) stated that engine power is the most relevant criterion in the process of digging for different capacities. A shovel performance monitoring system, consisted mainly of wattmeter and data logger, has been developed by Ceylanoğlu (1991) and utilised for different type and size of power shovels during overburden removal operations of different formations encountered in Turkish surface coal mines. He monitored the power consumption of main drive AC motor of electric shovel. Various performance parameters are introduced through shovel monitoring, in order to assess a diggability classification system. The specific digging energy, which is defined as the amount of energy necessitated to remove one cubic-meter of swell material, is found as the most effective parameter which is used to propose a diggability classification for different sizes of shovels (Table 2.15). It is, therefore, shown that the output and energy consumption of the excavator is a very important factor in deciding the diggability of material. He also suggested that current and voltage of different DC motors such as crowd, hoist, swing should be measured separately for the diggability purpose.

Ceylanoğlu (1991) also studied the effect of cut depth on the performance parameters. After numerous cut depth trials conducted for both blasted and unblasted material, he determined significant increases in the performance parameters as the depth of cut increases and its effect is higher in unblasted material than blasted material as expected.

Table 2.15 Proposed diggability classification (after Ceylanoğlu, 1991).

Dipper capacity (yd^3)	Specific Digging Energy (kWh/m^3)			
	Ease of Digging			
	Easy	Moderate	Mod. 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

2.2. Scope of the Thesis

In the light of previous studies, the main objectives of this study can be summarised as:

- To develop a monitoring hardware and integrated software packages controlling the monitoring hardware and evaluating the monitored data.

- To investigate effects of operation conditions on the performance parameters of electric power shovels by conducting monitoring trials at the site.

- To monitor different type and size of power shovels in a wide range of ground conditions on the basis of both power and time consumption.

- To determine depth of cut quantitatively by monitoring dipper motion during digging and then investigating its correlation with the performance parameters.

- To find out the most effective parameter(s) which indicate the interaction between the machine and the material, and then relating the performance parameters with digging difficulty of material for power shovels.

CHAPTER 3

DEVELOPMENT OF A MONITORING SYSTEM AND SOFTWARE PACKAGES

3.1. Introduction

Draglines and shovels are heavy-duty machines which are widely used in open pit mines to remove overburden material above coal and lignite deposits. Whereas draglines are generally applied for casting operations, shovels are preferably utilised for loading and they operate excavation process in a combination with high capacity trucks. Power of shovels may be supplied by diesel engines or electric motors up to about 12 yd^3 capacity, beyond which electric drive is by means of the Ward Leonard System. The availability of high capacity draglines and shovels which are equipped with electric motors provide economics in the exploitation of the deposits under thick overburden formations. But optimum utilisation of an excavation machine is as important as its selection.

Many researches are conducted to determine working abilities of open pit excavation equipment by monitoring them and thus studied to provide optimum excavation conditions to increase their performances. Studies on the monitoring of excavation machines generally use commercial monitoring devices, multi-channel recorders, data-loggers, etc. In general commercial monitoring systems are expensive and rigid, and they are not suitable for extensive use with different models of excavation machines. Besides, it is not practical to dismantle the system for using in the monitoring of other machines.

Almost the whole of the large lignite deposits in Turkey are exploited by the state under the commitment of TKİ. Therefore a huge number of open pit mining equipment, including draglines and shovels in different models and sizes operate at many mine sites of TKİ. Nearly 80 % of the shovels and all kinds of the draglines are powered by DC electric motors.

Because of the reasons and conditions explained above, a project regarding the overburden removal operations of TKİ open pit mines was launched by Middle East Technical University Rock Mechanics Research Group to develop a monitoring system which can be utilised to investigate the working performances of open pit equipment, such as drilling machines, draglines and electric mining shovels (Paşamehmetoğlu, *et al.*, 1995). The author was mainly responsible from the developments of hardware and software of the monitoring system of the project, together with Dr. Taylan Bozdağ. At the end of the project studies, a monitoring system was developed and successfully used on the sample models of electric mining shovel, dragline and drilling machine.

Following the project studies, by taking the objectives of this thesis into account, the necessary modifications on both the hardware and the software of the monitoring system were done by the author and then it was extensively used to monitor different models and sizes of electric mining shovels which at several open pit mines of TKİ, removing the overburden material. The data obtained for different digging conditions were processed to investigate the working abilities of the machines and the results were evaluated by including operating parameters to establish a general diggability classification system for electric mining shovels.

Using a monitoring system is aimed to detect power related variables of machine DC motors which generate the necessary mechanical power to perform the operating motions and thus to predict the effects of digging condition variables on the performance variables of the machine. Besides, monitoring of the dipper motion concurrent with power is also aimed to use the results in the evaluation of power modifications, by interpreting power results together with corresponding dipper position. The whole monitoring system mainly consists of two sections: hardware and software. Initially a monitoring system hardware to obtain data of the motor powers and the dipper motion was designed. It was followed by developing a monitoring software package both to control the hardware and to collect properly arranged data. A second software package was formed to use in the evaluation of the monitored data adequately for the aims of this study.

More information about operating characteristics of electric mining shovels and the details of the developed monitoring system hardware and software packages are given in the following sections.

3.2. Electric Mining Shovels

Full-revolving crawler-mounted shovels can be considered as a logical choice for many hard-rock and ore excavations where long life and sustained high production are necessary under exacting but fixed working conditions. Although their powers are supplied by diesel engines or electric motors they have common mechanical parts as given in Figure 3.1.

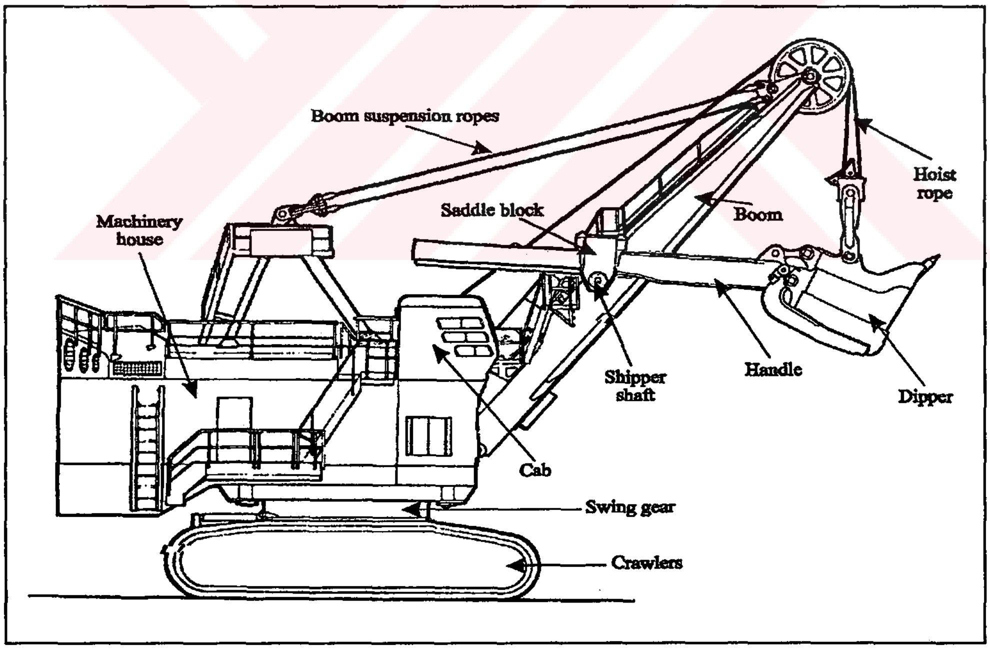


Figure 3.1 Shovel nomenclature.

In general, shovels perform the excavation of material by some basic motions which are swinging, crowding and hoisting. A fourth motion, propelling, is performed to position the machine for digging operation and it is done selectively by using a transfer switch to perform either dig or propel. These four operating motions of a shovel, illustrated in Figure 3.2, are individually motored and function independently.

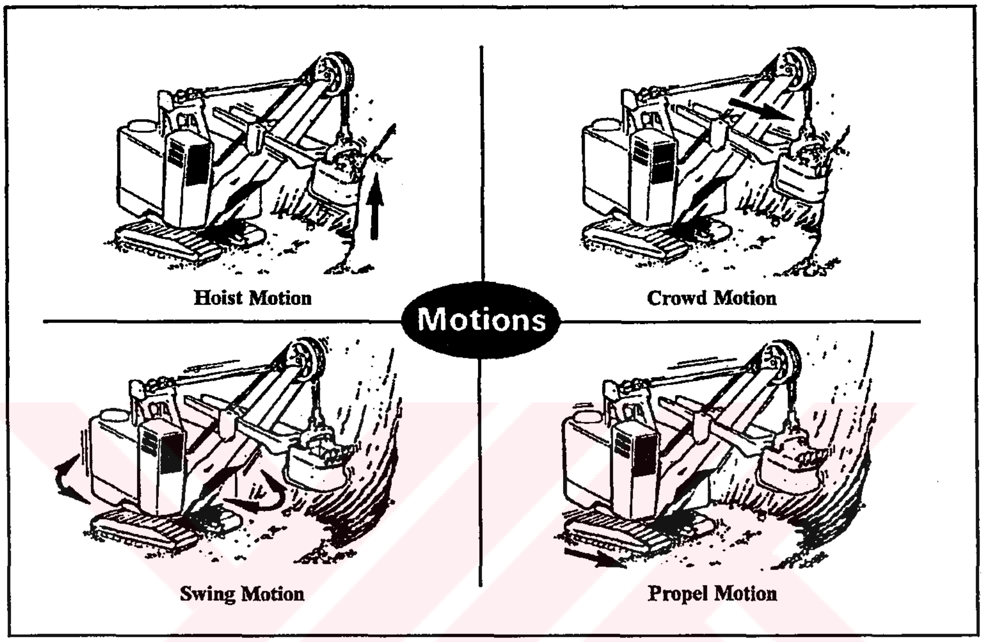


Figure 3.2 The four operating motions of a shovel (after Anon, a).

The shovel is firstly positioned in front of a working face at an optimum distance by propelling before digging operation is started. Loading of material into dipper is provided by digging the ground starting from ground level and going on up the face of the cut until the dipper is full. This operation usually takes place by a combination of crowding and hoisting, therefore no swing motion is expected meanwhile. Digging is followed by a combined motion of hoisting and swinging to dump its load either into a haulage truck or to a spoil pile. After dumping, the returning and lowering of the dipper for next digging are also a combined motion. Thus the excavation is achieved by a combination of these motions in a sequence and each motion is repeated after a period of time. This period consists of swing to face, digging, swing to dump and dump and the period is commonly defined as a cycle.

As the name implies electric mining shovels are operated by electricity and they are equipped with DC motors generating mechanical power to dig the formation. Electric drive of high capacity shovels are based on the Ward Leonard system. In this system, the input is high-voltage alternating current to motors which drive DC generators, which in turn drive DC motors of suitable characteristics for the several motions of the shovel. The efficiency of the Ward Leonard system, that is, the power output/power input ratio, is about 82 percent. A brief sketch of the Ward Leonard system is given in Figure 3.3 which illustrates the conversion of incoming AC power into mechanical power and its control. A main transformer steps down incoming 6000 volt AC power to practical working voltages of 600 volt AC power for the armature power supplies. The static converter functions as to convert the AC supply to DC operating power for the motion drive motor armatures.

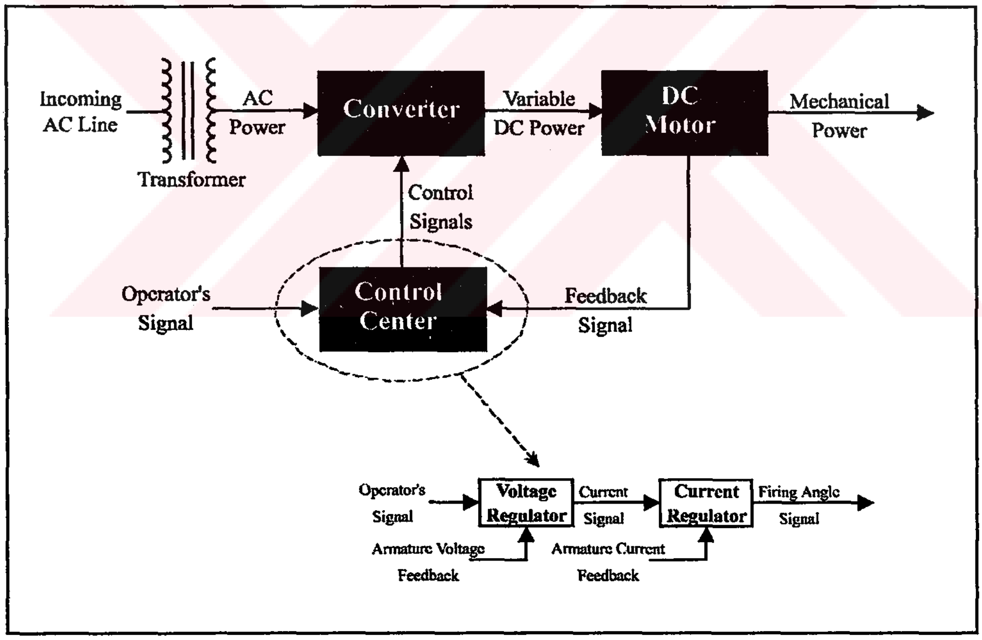


Figure 3.3 Working principle of an electric mining shovel (after Anon, b).

The operator gives a command -a reference signal- to the control electronics of the work motion. He does this by moving the controller lever to suit a particular working situation. The control system has information as to operation of the motion motor at the instant just prior to receipt of the command signal. This information is continuously compiled from voltage feedback data regarding conditions of the voltage (a measure of speed) of the motor armature and current feedback data regarding conditions of the current (a measure of torque) of the motor armature. The control system correlates the data and establishes the firing angle of the converter thyristors, to provide the voltage and current they must deliver to accommodate the new working situation.

3.3. Monitoring System Hardware

3.3.1. General

At the beginning of this research, it was decided to develop a computer based monitoring system by knowing the advantages of digital data-acquisition for further data processing. By comparison with the standard data-acquisition procedure involving analog data recording (e.g., strip chart recorder) and manual data reduction, the process of digital data-acquisition represents a very significant reduction in time and effort.

As a result of technological improvements in the last decades, features of testing instruments, such as capacities, types, speed, etc. have been developed and more sophisticated devices are produced. The developed instruments provide conduction of more complex and detailed investigations in any fields for the researches. They are produced either in compact form or in modular form, that is a monitoring system can be arranged by the user for a defined job as well as a commercial monitoring device which suits the job can be purchased. Although designing and arranging a monitoring system is difficult and takes more time, it provides advantages to the designers, such as flexibility in design, low cost, adaptability for future uses, etc. Essential parts to set up a monitoring system can be obtained providing the objectives of the research are first clearly outlined and then all information regarding the objectives are accumulated.

Since the aim of this study was to monitor electric mining shovels, the documents, specially the technical catalogues of these machines were reviewed to get information about technical and mechanical characteristics of them. These information were increased and supported with the field observations.

After doing an analysis of the obtained information, studies were carried on with outlining the monitoring system hardware and selecting essential parts of the system from the instrument catalogues by taking the needs and the characteristics of the research into account. It was followed by arranging the parts to set up the system hardware.

3.3.2. Catalogue Survey and Site Investigations

At the beginning of the study, technical and mechanical catalogues of electric mining shovels were reviewed to get information about their features and operating mechanisms. As it is explained in Section 3.2, electric mining shovels practises four types of motions to perform excavation of material and the motions are provided by electric powered individual DC motors. Therefore detailed information about power generated by individual motors during excavation can be obtained by monitoring each motor separately rather than the monitoring the whole machine from the main power supply. Besides some amount of the supplied energy is used by auxiliary motors and for illumination which is not related with the characteristics of the excavated material at all.

Studies were continued at the mine site to get more information about their working principles and to observe the machines during the operations. As a result of studies conducted together with site engineers and technicians on the machines and on their circuit diagrams, it was found out that each DC motor transmits reduced armature voltage and current feedback signals to the control center in analog forms (Figure 3.3) and these signals have constant proportions to motor armature voltage and current values. The reduced signals of each motor can easily be detected from the related test points on the armature voltage and current regulators which are located in the control cabinet of the machine. Thus the power generated by a motor at a time can be determined if the reduced feedback signals of that motor are obtained.

The digging profile that the dipper follows during the digging operation, which is defined as dipper trajectory, is entirely controlled by the operator and the magnitude of the power is greatly affected by the geometry of the digging profile as well as the material characteristics, especially when the depth of cut is concerned. Therefore further field studies were carried on with observing the dipper motions during the excavation to gather essential information to develop a technique for monitoring of dipper position at the same time with the power.

It is known that the loading of a dipper is provided by a combined motion of crowding and hoisting, therefore swing motion is not expected. While the dipper is hoisted in vertical direction the amount of penetration of the dipper into the formation is controlled by crowd or retract motion of the dipper handle. Therefore change in dipper position during digging operation can be defined as two-dimensional, in crowd direction and in hoist direction. Whereas motion of the dipper handle in crowd direction is provided by a shipper shaft pinion which is driven by the crowd motor, the hoist motor controls its position in vertical direction. Then the amount of motion in crowd direction can be determined if the rotational change of the shipper shaft pinion is detected. A second parameter, the inclination of the dipper handle can also be monitored with a proper instrument. Thus two parameters, the length and the angle can be obtained which are used to define the position of a point on a rectangular co-ordinate system with its horizontal and vertical components.

The information gathered at the end of the field investigations were primarily taken into consideration to set up the system hardware. The details of instrumentation and set up studies are given in the following sections.

3.3.3. Power Monitoring System Instrumentation and Set up Studies

It was aimed to develop a computer based monitoring system for a proper data-acquisition and quicker data processing. Therefore, the parameters such as capacity, precision, resolution, speed, availability, etc. of necessary instruments to set up the system hardware were studied by considering the needs.

As it is explained in the previous section, the variables which are needed to determine motor powers can be obtained from the voltage and current regulators as analog signals in the form of DC volt. Because of the design feature of electric mining shovels, especially the polarity of a motor armature voltage changes if the direction of the motion is changed. For instance, the hoist motor indicates a positive armature voltage when the dipper is lowered and it indicates a negative armature voltage when the dipper is hoisted. So the polarities of the voltage feedback signals on the voltage regulators change accordingly. An analog signal coming either in the form of voltage or in the form of current must be first converted to a digital format before the computer recognises it.

The analog to digital (A/D) converter establishes the link between the analog signals measured and the digitally equivalent signal in the computer. Its role is to convert an analog signal into digital form suitable for processing storage within the computer. The characteristics of the A/D converter control the accuracy of data reading, data reading speed, and the resolution and cost of the system. As discussed by Gates (1984), a 12-bit resolution A/D converter is necessary for most scientific applications. The speed of an A/D converter is called the "sample rate" and gives the number of times the analog input signal is sampled in one second. It is important that your A/D board has a sampling rate around three times higher than the highest frequency of the input.

By considering both the characteristics of monitored signals and those of the instruments, a multi-function data acquisition card with 16 single-ended analog input channels and with an A/D converter on it, namely PCL-812PG, was firstly provided. The A/D converter on the card has a 12-bit resolution and the capability of sampling at 30 kHz. In general any type of DC signal include noise and AC components which have to be isolated to obtain pure DC signals. This was provided by using input modules which function as low-pass filter and signal conditioner. They have an input range of +/-10 volt and an output range of +/-5 volt. A PCLD-5B16 module carrier board capable of 16 input channels was used to fix the input modules on the appropriate channels of the board (Figure 3.4). Because of the input range of the modules, a voltage divider was designed in the laboratory to decrease the magnitude of a signal if it was out of the range of the system (Figure 3.4). After supplying parts of the system, they were arranged as it is shown in Figure 3.5. The developed monitoring system hardware consists of four main parts: pre-conditioning unit, signal conditioning module, data acquisition card and data storage unit.

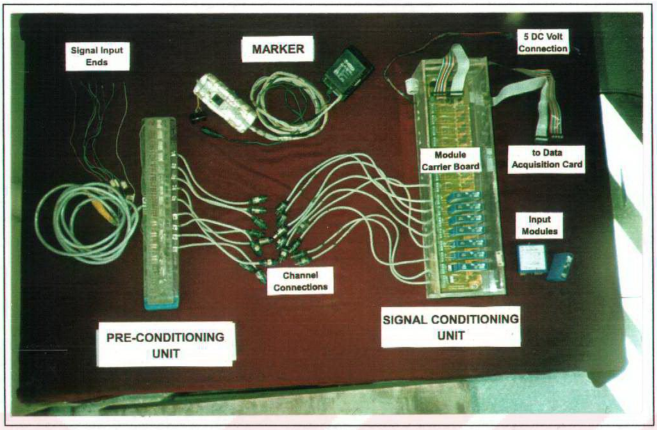


Figure 3.4 Pre-conditioning unit, signal conditioning module and marker.

An analog input signal which is detected by the system from any of the signal sources is first pre-conditioned by means of the voltage divider as to fit the input range of the system. Then the signal goes through the signal conditioning module to be isolated from the ac and noise components by a low pass filter and to be conditioned. Then the conditioned analog DC signals within the range of +/-5 V are digitised by the A/D converter and finally they are temporarily stored in the data storage unit.

As the system hardware was designed, the PC bus of the system was equipped in a minimum level to reduce the cost of the system providing the necessary capacity for the research. Then a 386 DX-40 personal computer with a static RAM of 3.2 Mbyte capacity was chosen, and it was equipped with a 3.5" floppy disk drive and a serial RS-232 C communication port which were used to transfer the temporarily stored data in the storage unit to the external devices, such as floppy disks or a portable computer. The dynamic memory of the system was capable enough to store data of a two-hour monitoring trial.

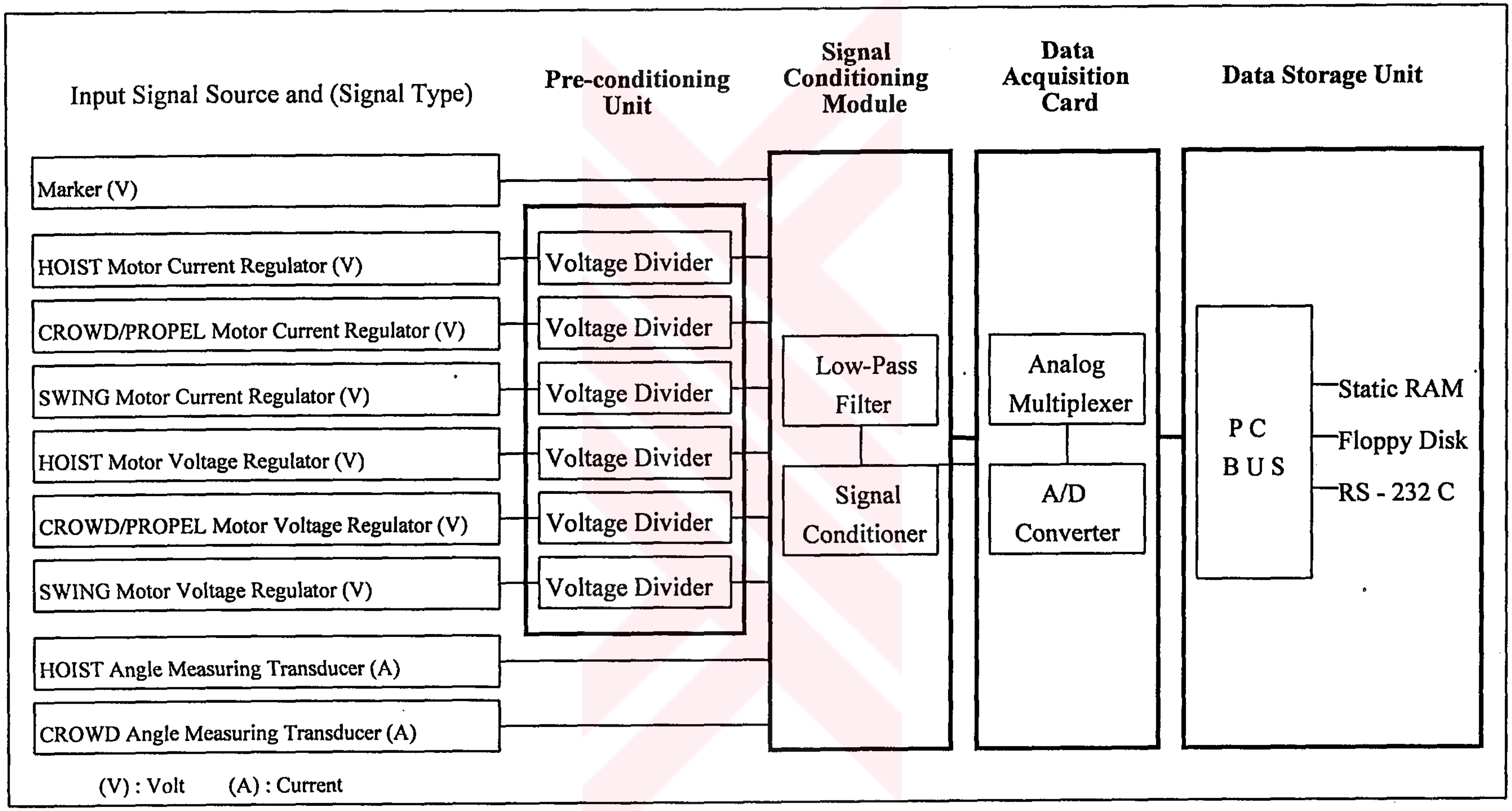


Figure 3.5 Schematic view of the power shovel monitoring system hardware.

3.3.4. Dipper Position Monitoring System Instrumentation and Set up Studies

Two electrical measuring transducers for angle of rotation were used to monitor rotation of shipper shaft pinion and inclination of dipper handle. The KINAX 7W1 electrical measuring transducers, Figure 3.6, convert the angular position of a shaft into a load-independent direct current proportional to the measured value (Anon, 1987). The angular deflection to be measured is transferred to the rotor of differential capacitor by using a mechanical coupling and it is converted into a change of capacitance proportional to the angle.

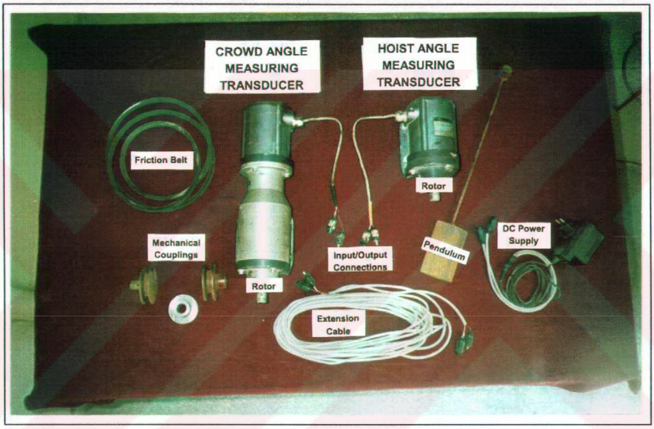


Figure 3.6 The KINAX 7W1 electrical measuring transducers and the accessories.

Each transducer has an angle measuring range of 0-270 degree, but an additional gear system with a reduction ratio of 27:1 is provided in front of crowd angle measuring one to increase its measuring range. They operate with a constant power supply between 12.7-36 DC volt and they generate a current type analog output which ranges from 0 to 20 mA. Therefore two current type input modules which have an input range of 0-20 mA and output range of +/-5 volt were fixed to the related channels of the module carrier board. The output signals of the transducers were supplied to the system by connecting them directly to the signal conditioning module (Figure 3.5). Similar to the other signals, the signals acquired from the transducers were first filtered and conditioned by the modules before they were converted into digital form by the A/D converter.

3.4. Monitoring System Software

Application software establishes an important link between the computer and the data acquisition hardware. The system software is either provided together with the data acquisition hardware or it is developed by the user for his own needs. If the user is familiar with the hardware units, the second approach is useful because it provides flexibility to the user to adjust the parameters of the hardware system, such as the speed of data collection, the ranges and the number of input signals, etc. as desired. Furthermore, data storage way can easily be defined by the user for an optimum use of the system.

A system software to control the hardware and to collect appropriately arranged data for further processing, therefore, was developed by using Quick Basic 4.5 programming language. Some basic routines are defined in the program to provide the processes such as; recognition of digitised signals coming from A/D converter, conversion of the digitised signals into binary numbers and collection of the acquired data randomly in the storage unit. An individual column for each signal source is defined in the program to obtain a regular data file. Because of the low capacity of the dynamic memory of the storage unit, obtained data were stored in random format to occupy less memory and thus to provide more monitoring time. Three important parameters of a monitoring system, sampling rate, input signal range and number of input channels, regarding the control of the system are defined in the program such that the user can adjust them to fit the needs. Besides, the program is able to store time related parameters such as date, beginning and end times of the monitoring trial in the storage unit.

3.5. Laboratory Trial Studies of the Monitoring System

Before the system was utilised at the field for a real case, many trials were conducted in the laboratory to control the accuracy of the system and to complete essential calibrations.

First of all a number of channels of the data acquisition card were designated for all possible signal input sources to obtain an identical signal from a channel at any time of monitoring study. As it is mentioned in the previous sections, the power of an electric motor can be determined when the magnitudes of two motor variables, armature voltage and armature current, are obtained. Although the shovels have four different operating motions which are controlled by separate DC motors, digging motions and propelling are selective operations and they are not operated at the same time. During field investigation studies, it was recognised that the feedback signals of the crowd and the propel motors are obtained from the same current and voltage regulators. As a result of this investigation, six sequential channels of the card, the same channels for crowd and propel motor signals, were defined for armature current and voltage feedback signals of the motors. Two more channels were designated consequently for the angle measuring transducers which were used to monitor the dipper position.

After arranging the monitoring system hardware in the laboratory as it is seen in the Figure 3.5, armature voltage and current feedback signal lines were connected to an adjustable DC power supply which was used to supply analog input signals to the system. Then the monitoring and the collection of input signals were initiated by running the system program. As the magnitudes of the input signals were recorded from a digital multimeter which is connected to the power supply, the corresponding output values of the monitoring system were stored in the PC bus. This process was repeated many times for different but constant input voltage levels and continued till getting enough data from each channel of the data acquisition card. It was observed that any input signal supplied to the system steps down to a system output value proportionally because of the characteristic features of the pre-conditioning unit and the input modules. So the data obtained from the laboratory trials were evaluated to find out the proportions between the input values and the output values. The evaluations were done for each of the feedback signal channels separately and the obtained proportion constants which are named as the System Reduction Factors (SRF) are presented in Table 3.1 together with the channel numbers of the data acquisition card, the signal sources and the definitions of the input signals. More trials were conducted in the laboratory to check the validity of the SRF values.

Table 3.1 The system reduction factors.

Channel no.	Input signal source (Definition of the input signal)	System Reduction Factor, SRF
1	HOIST motor current regulator (Hoist motor armature current feedback signal)	5.236
2	CROWD/PROPEL motor current regulator (Crowd/Propel motor armature current feedback signal)	5.191
3	SWING motor current regulator (Swing motor armature current feedback signal)	5.271
4	HOIST motor voltage regulator (Hoist motor armature voltage feedback signal)	7.164
5	CROWD/PROPEL motor voltage regulator (Crowd/Propel motor armature voltage feedback signal)	7.147
6	SWING motor voltage regulator (Swing motor armature voltage feedback signal)	7.128

Similar trials in the laboratory were conducted on the transducers to obtain their calibration curves and to generate the equations which were used to convert their output signals into corresponding angular positions. Having regards to the operational features of the transducers, a constant input power between 12.7-36 DC volt was supplied to one of the transducers and then the monitoring process was initiated. As the rotor of the transducer was rotated an amount of previously defined angles, both the angles and the corresponding digitised output values of the system were recorded. Numerous trials were first conducted for one of the transducers to get a reliable correlation between the output values and the angular positions of the transducer. After the same procedure was repeated to obtain the similar data from the second transducer, different regression methods were applied on the resulted data. Among the equations were obtained from the regression analysis, the one with the highest correlation coefficient was used as the conversion equation for that transducer. The calibration curves of the hoist and the crowd angle measuring transducers are given in Figures A.1 and A.2 respectively. Resulted calibration equations which were used to convert the output signals into the angular positions are as follows:

$$\theta_h = 29.131 V_h^{0.988} \qquad r^2 = 0.9989 \qquad 3.1$$

$$\theta_c = 1785.92V_c + 62.6397 \qquad r^2 = 0.9999 \qquad 3.2$$

where:

θ_h is the angular position of the hoist transducer, deg
V_h is the output signal of the hoist transducer, V
θ_c is the angular position of the crowd transducer, deg
V_c is the output signal of the crowd transducer, V
r^2 is the correlation coefficient

At the end of the laboratory trial studies, the precision of the monitoring system and the essential calibrations were successfully provided. In the following stage of the research, the system was used at the field for real case conditions to check its adaptability.

3.6. Field Trial Studies of the Monitoring System

Although the developed monitoring system is universal, that is it can be easily adapted to any model of electric mining shovels, the first field experiments were conducted on a P&H 2300-XP electric mining shovel, with 20 yd^3 dipper capacity, operates in GLİ open pit mine.

As it is investigated during the initial studies, the connections between the monitoring system channels and the feedback signal sources were first provided by fastening the signal input ends of the system to the analog signal output points of the voltage and the current regulators which are located in the control cabinet of the machine (Figure 3.7). These connections were done for all motors in an order as given in Table 3.1, from channel 1 to channel 6 of the data acquisition card. The transducers used to monitor the dipper position were fixed on the shovel by using some mechanical couplings, as it is seen in Figure 3.8. The one used to detect crowd motions was fastened to the parapets of the boom-side platform and the rotation of the shipper shaft pinion was directly transferred onto the rotor by means of a friction belt. The other transducer used to detect the inclination of the dipper handle was fastened on an attachment which was welded on the outer face of the saddle block. A pendulum was previously designed and fixed on the rotor of the transducer to provide the rotation of the rotor as the inclination of the dipper handle changes with hoisting or lowering motion. Since the output signals of the transducers were always in the acceptable range of the current input modules, they were directly connected to the channels 7 and 8 of the data acquisition card via the signal conditioning module.

Figure 3.7 The P&H 2300-XP electric mining shovel showing the control cabinet.

A manually operated device, named as marker (Figure 3.4), was also designed to supply 4 unlike power levels to the system and it was used to mark the periods of specific motions such as, digging, dumping, propelling, waiting idle or any other specified motion. Each power level of the marker defines a different operation and the appropriate switch on the marker was switched on as soon as the operation was started and it was switched off when it was finished. The marker signals were forwarded to the channel 0 of the module.

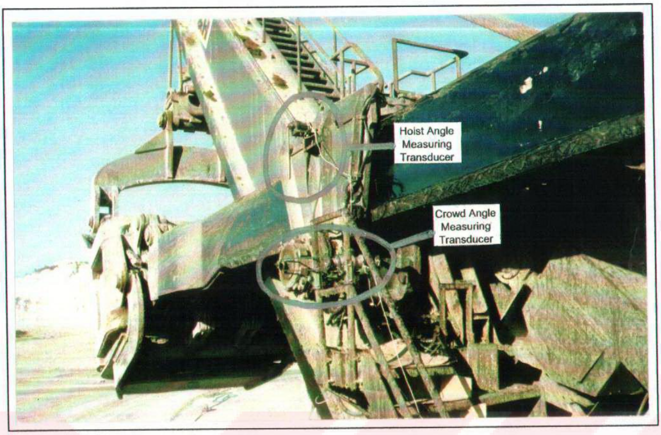


Figure 3.8The P&H 2300-XP electric mining shovel showing the locations of the electrical transducers.

The individual parts of the monitoring system, pre-conditioning unit, signal conditioning module, data acquisition card and data storage unit are connected to each other in the order. The channels of these individual parts have to be connected in the serials such that the 1st channel of the signal conditioning module to the 1st channel of the data acquisition card. A general view of the arrangement on the machine is given in Figure 3.9. Before data collection was initialised, the dipper was positioned such that the dipper handle was parallel to ground and vertical to the hoist rope. The initial position of the dipper was used as reference position during the evaluation of the data obtained from the transducers. After all, data collection was initialised by running the system software and thus a continuous data flow to the system was provided as machine operated and the monitored signals were stored in a file. Another file which provides information about the date, beginning and end times of the monitoring trial was also stored. Obtained data files over a period of excavation operation was then transferred to the external data storage units for further evaluations.

Besides the monitoring system records, the operating motions of the shovel were concurrently recorded on a tape by using a video-camera. It was made good use of these visual records of machine activity when data evaluation software package was formed and its outputs were checked. Furthermore, many site parameters related to the machine, the operator and the excavated material were recorded to use in the evaluations.

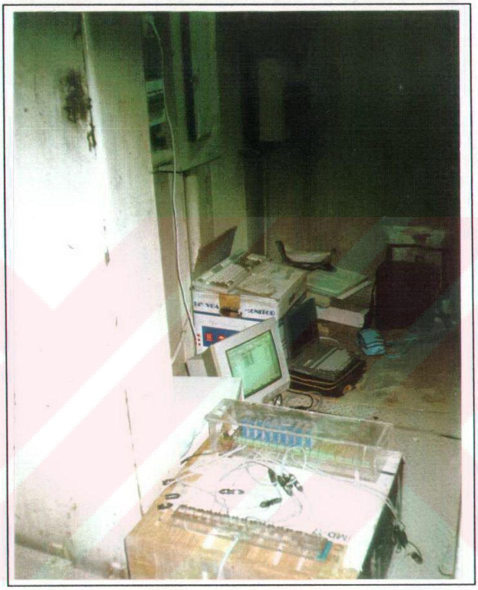


Figure 3.9P&H 2300-XP electric mining shovel showing the monitoring system arrangement onboard.

3.7. Processing of Monitored Data

3.7.1. General

The primary role of a data-acquisition system is collection of experimental data. Once this has been accomplished, however, the obvious question that arises is: "what do we do with the data?".

During a trial, a set of rough data is obtained. Such a set of data requires further processing, which may involve, for example, the conversion of the recorded output voltage to appropriate engineering units, e.g., the transducer deflection (degree), the motor armature voltage (volt) or the motor armature current (ampere). They should be organised into suitable tables for easy reference, and often, for the further processing. On occasion, portions of several trials must be combined in order to emphasise some important experimental findings. Usually, as a result of the data reduction process, graphs presenting the data in a suitably illustrative manner are desired. Therefore, the post-processing of the data is a complex task, often requiring a number of decisions which are relevant to a particular trial or a series of trials. In order to process and manipulate the data in an efficient manner, suitable software(s) must be used.

Data processing in this study was accomplished by using the existing office possibilities. A 486 DX-60 personal computer equipped with a hard disk (static memory) of 340 Mbyte capacity was engaged for this research. Besides the data processing software developed by the author for this study, some supplementary programs such as Excel 5.0, QBasic 4.5, Windows 3.1, Word 2.0, etc. were loaded into the hard disk to apply some of them for post-processing of data and the others for organising the computer.

3.7.2. Data Processing Software Package

As stated earlier, data-acquisition hardware system developed in this study was capable of monitoring analog signals and storing them in digital format to be recognised by the computer during their processing. Therefore, it was aimed to develop a system complementary software which was utilised to process massive amounts of data, e.g., 9 signal sources and average 10 data per second from any of the sources. The data processing software package, named as SHOVEL, was formed by using Quick Basic 4.5 programming language. The SHOVEL was designed as to provide the user advantages, such as an optimum use of data for the aims, easy control of the processing steps, generation of suitable outputs for further evaluations, etc. A general flow chart of the program is given in Figure 3.10. The program consists of three main parts: inputs, arithmetical operations and outputs. Together with the monitored data, some machine constants, such as model, dipper size, motor power, etc. and material constants, such as swell factor, unit weight, etc. were provided as inputs of the program. The raw data were first converted to appropriate units by applying the reduction factors and then corresponding motor powers, periods of the motions, the amount of energy required for defined motions and dipper position parameters were determined in the second part. In the last part, the results were sorted according to the specified variables and they were stored in different files for further graphical or mathematical evaluations.

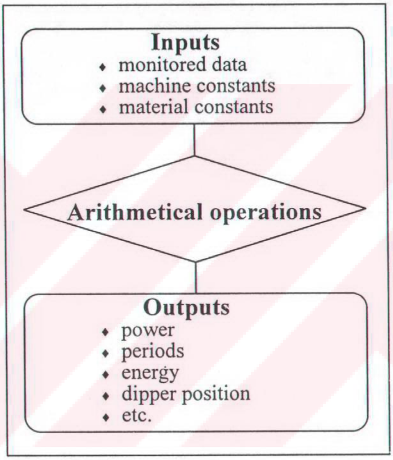


Figure 3.10 General flow chart of the SHOVEL.

3.7.2.1. Routines of the SHOVEL

As the data evaluation software package was formed, a special attention was given on to provide an optimum use of data by the program, maximum speed in calculations, easy control of the program flow and production of adequate and reliable outputs. Therefore menu driven type screens were formed in the program which provide easy control of the routines. The software package mainly consists of a main menu and associated three sub-menus as presented in Figure 3.11.

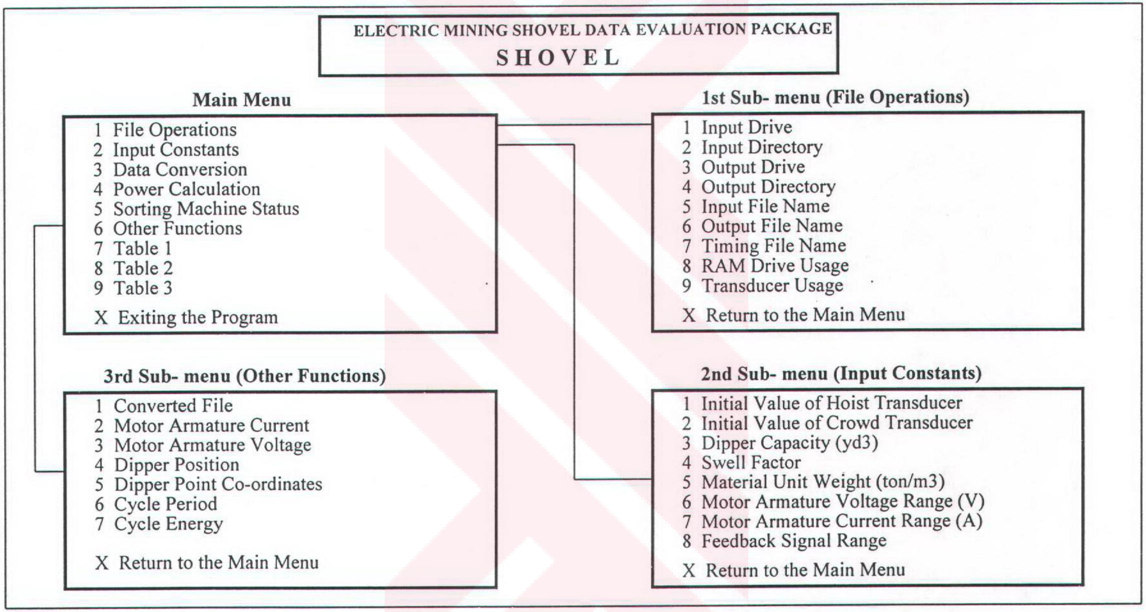


Figure 3.11 Menus of the data evaluation software package.

Any desired operation defined on a screen menu is activated by typing the icon number or letter in front of the definition, e.g., the program terminates if 'x' or 'X' is typed when the main menu is active on the screen.

The drive paths and the names of the input data files are defined in the main menu of the program. Similar definitions are done for output files. Although they are defined as default in the program, SHOVEL lets the user to make a change on any of them by using the related menu icon in the file operations sub-menu. As it is mentioned before, some constants related to the monitored machine and the excavated material are supplied as input parameters and they are easily controlled from the items in the input parameters sub-menu. Data conversions are first processed following the input operations. So the converted values are used to complete power, time and energy related calculations and the results are stored in different output files when the functions in the other functions sub-menu are activated. Furthermore, the table items in the main menu are activated to collect the power and the energy results and the periods of the motions in different tables.

At the end of an evaluation process many output files are obtained. Some of them, such as armature voltage values are used for graphical evaluation and the others, such as tables provide a quick look on the results of important parameters.

3.7.2.2. Data Conversions and Calculations

Obtained data files stored either in the floppy disks or in the static memory of the portable computer at the field were first transferred to the static memory of the office computer before they are converted into ASCII system since they were stored randomly during the monitoring process. For easy recognition of the monitored data by the data processing program, a singular column was assigned for each of signal types and the next monitored data from the same source is presented in the next line. Thus 9 different signals, 6 of the voltage and current regulators of the motors, 2 of the transducers and 1 of the marker, were regularly stored in 9 columns as they are given in Table 3.2 together with definitions of the columns.

Table 3.2 A sample of raw data obtained from an electric mining shovel.

Marker signal	Armature current feedback signals			Armature voltage feedback signals			Transducer signals	
	Hoist	Crowd*	Swing	Hoist	Crowd*	Swing	Hoist	Crowd
(1st cl.)	(2nd cl.)	(3rd cl.)	(4th cl.)	(5th cl.)	(6th cl.)	(7th cl.)	(8th cl.)	(9th cl.)
3.153	1.687	1.342	0.002	-0.626	-1.025	0.031	2.308	1.227
3.143	1.694	1.355	0.003	-0.622	-1.032	0.038	2.320	1.225
3.145	1.697	1.356	0.003	-0.622	-1.039	0.034	2.321	1.225
3.143	1.687	1.358	0.001	-0.624	-1.035	0.037	2.318	1.222
3.146	1.682	1.349	0.003	-0.633	-1.042	0.044	2.306	1.218
3.144	1.679	1.337	0.003	-0.649	-1.039	0.038	2.291	1.217
3.160	1.665	1.343	0.003	-0.652	-1.070	0.041	2.269	1.211
3.165	1.659	1.325	0.004	-0.674	-1.090	0.044	2.222	1.213
3.155	1.653	1.324	0.002	-0.688	-1.103	0.044	2.189	1.214
3.151	1.655	1.333	0.003	-0.689	-1.103	0.042	2.148	1.206
3.151	1.651	1.327	0.009	-0.692	-1.100	0.039	2.115	1.210
3.143	1.676	1.341	0.009	-0.689	-1.086	0.046	2.066	1.210
3.135	1.667	1.341	0.027	-0.697	-1.095	0.045	2.007	1.211
3.130	1.666	1.338	0.111	-0.693	-1.097	0.049	1.980	1.206
3.120	1.645	1.338	0.207	-0.695	-1.077	0.080	1.950	1.205
3.112	1.650	1.336	0.393	-0.703	-1.089	0.115	1.945	1.200
3.092	1.644	1.335	0.717	-0.708	-1.089	0.157	1.936	1.202
3.064	1.640	1.318	1.094	-0.717	-1.090	0.168	1.930	1.201
3.031	1.636	1.310	1.437	-0.724	-1.093	0.200	1.942	1.199
3.025	1.629	1.209	1.506	-0.739	-1.086	0.200	1.963	1.198
3.036	1.624	0.899	1.603	-0.736	-1.060	0.197	1.978	1.195

(*) Crowd and propel signals are obtained from the same signal source.

As it is explained in the previous sections, all data were obtained either as reduced levels of actual values (e.g., armature voltage and current feedback signals) or in different forms (e.g., electrical measuring transducers' signals). Therefore the rough data had to be converted into corresponding operational values before the performance parameters of the machine were determined. Data conversion was performed by activating "file conversion" operation in the main menu providing the paths and the input constants were defined in the previous steps.

When the file conversion process was initiated, the program was first recognising the marker signal in the 1st column of the data file. It was checking its magnitude to decide whether the marker was 'on' or 'off'. Whereas the marker has four distinguishable voltage levels to define different operations, the program was realising that there was an operation marked if it was reading a positive value greater than zero, otherwise it was off. If the marker was on, the program was comparing that value with the voltage ranges of the operations which were previously defined in the program and thus the program distinguishes the type of the operation. Afterwards a particular integer to define the operation was assigned into the 1st column of the converted file. For instance, marker signals in Table 3.2 are around 3 which denotes that digging operation was processed so the program assigned 1 into the 1st column of the converted file.

Armature feedback signals obtained as reduced values are converted into corresponding motor armature voltage and current values by applying the following equations respectively.

$$\mathrm{MAC} = \mathrm{ACFS} \ast \mathrm{SRF} \ast \mathrm{MRF} \tag{3.3}$$

$$\mathrm{MAV} = \mathrm{AVFS} \ast \mathrm{SRF} \ast \mathrm{MRF} \tag{3.4}$$

where:

MAC	is the motor armature current, A
MAV	is the motor armature voltage, V
ACFS	is the armature current feedback signal, V
AVFS	is the armature voltage feedback signal, V
SRF	is the System Reduction Factor
MRF	is the Machine Reduction Factor

The System Reduction Factors used in the above equations are given in Table 3.1. The other variable, defined as the Machine Reduction Factor (MRF) is the ratio between the motor armatures and corresponding feedback signals. However they are machine operating parameters, they may change according to the model and the capacity of a shovel. These parameters are defined as ranges and their values were obtained from the machine operating manuals. Both motor armature and corresponding feedback signal intervals are given in Table 3.3 for the power shovels monitored in this study. According to the table, a 10 volt signal on the voltage regulator of P&H 2300-XP shovel figures a motor armature voltage of 550 volt, so the MRF was calculated as 550/10=55.

Last two signals, the transducer signals, were converted into the angular positions by applying the equations 3.1 and 3.2 respectively.

Table 3.3 Motor armature and feedback signal ranges of electric mining shovels.

Shovel model and dipper capacity		Motor armatures				Feedback signals (V)
		Hoist	Crowd	Swing	Propel	
P&H 2300-XP 20 yd^3 (15.3 m^3)	Voltage (V)	± 550	± 550	± 550	± 550	± 10
	Current (A)	0 - 1800	0 - 1010	0 -1450	0 - 1350	0 - 10
P&H 2100-BLE 17 yd^3 (13 m^3)	Voltage (V)	± 550	± 550	± 550	± 550	± 10
	Current (A)	0 - 1100	0 - 1010	0 -1000	0 - 1350	0 - 10
Marion 191 M-II 20 yd^3 (15.3 m^3)	Voltage (V)	± 600	± 600	± 600	± 600	± 8.1
	Current (A)	± 2740	± 880	± 660	± 1570	± 8.1
Marion 191 M 17 yd^3 (13 m^3)	Voltage (V)	± 600	± 600	± 600	± 600	± 8.1
	Current (A)	± 2740	± 880	± 660	± 1570	± 8.1
Marion 191 M-HR 15 yd^3 (11.5 m^3)	Voltage (V)	± 600	± 600	± 600	± 600	± 8.1
	Current (A)	± 2740	± 880	± 660	± 1570	± 8.1

The conversion process of the first data line was ending with including the monitoring time of the line. The program was obtaining the beginning and the end times of the monitoring trial from the timing file and then calculates the total period of the monitoring process in seconds. The total period was divided by the total amount of data lines to find the elapsed time between the consecutive lines and it was denoted by Δt. Thus the monitoring time of a data line with respect to the beginning of the monitoring process was determined by multiplying the line number with Δt and the determined value was assigned into the end of the line.

The above conversions were performed for each line of the raw data file and the converted values were stored in an output file for further evaluations. A small division of a converted file is given in Table 3.4.

After the raw data were converted and stored in a file, further calculations were carried on with evaluating the powers consumed by the motors to perform the operations, the periods of the operations and the energy requirements.

Table 3.4 A sample of converted data.

Marker status	Motor armature current (A)			Motor armature voltage (V)			Angular position (deg)		Time (s)
	Hoist	Crowd	Swing	Hoist	Crowd	Swing	Hoist	Crowd	
(1st cl.)	(2nd cl.)	(3rd cl.)	(4th cl.)	(5th cl.)	(6th cl.)	(7th cl.)	(8th cl.)	(9th cl.)	(10th cl.)
1	1588	702	2	-246	-402	12	30.9	155.7	166.57
1	1595	709	2	-245	-405	15	31.2	152.1	166.67
1	1598	710	2	-245	-408	13	31.2	152.1	166.76
1	1588	711	1	-246	-406	15	31.1	146.8	166.86
1	1583	706	2	-249	-409	17	30.8	139.6	166.95
1	1581	700	2	-255	-408	15	30.4	137.9	167.05
1	1567	703	2	-257	-420	16	29.7	127.1	167.14
1	1562	693	3	-265	-428	17	28.4	130.7	167.24
1	1556	693	2	-271	-433	17	27.5	132.5	167.33
1	1558	698	2	-271	-433	16	26.3	130.2	167.43
1	1554	694	7	-272	-432	15	25.4	125.3	167.52
1	1578	702	7	-271	-426	18	24.0	125.3	167.62
1	1569	702	21	-274	-430	18	22.3	122.1	167.71
1	1568	700	85	-273	-431	19	21.5	118.2	167.81
1	1549	700	158	-274	-423	31	20.6	116.4	167.90
1	1553	699	300	-277	-428	45	20.5	114.5	168.00
1	1548	699	547	-279	-428	62	20.2	111.1	168.09
1	1544	690	835	-282	-428	66	20.1	109.3	168.19
1	1540	686	1096	-285	-429	78	20.4	105.7	168.28
1	1534	633	1149	-291	-426	78	21.0	103.9	168.38
1	1529	470	1223	-290	-416	77	21.4	98.6	168.47

By definition, the magnitude of power generated by a DC motor is calculated by multiplying the voltage and the current levels drawn by the motor. As a result the power parameters were calculated for each motor separately by applying the determined armature voltage and current values of the motors into the following common equation.

$$P = MAV * MAC / 1000 \qquad 3.5$$

where:

P is the power, kW
MAV is the motor armature voltage, V
MAC is the motor armature current, A

Although the power consumed by a motor to do a work gives an idea about work difficulty, an energy related parameter is a better measure to define the performance of a heavy-duty machine. Before defining the necessary calculations to find the amount of energy consumed by the motors to perform the operations, the question; how would the computer recognise the beginning and the end of an operation, had to be answered. The armature voltage and current levels of the motors and the corresponding powers obtained in the previous steps of the program were graphically evaluated to develop a model which could confidently and easily applied in the program to overcome the above problem. As a result of this evaluation, the swing motor armature voltage was perceived as the best variable to distinguish the periods of the cycles and their segments which are empty swing to face, digging and full swing to dump. As it is mostly observed during the field investigation studies, unloading operation of the dipper into the truck dumper is initiated by opening the dipper door as soon as the dipper reaches to the dumper and the swing travel is slowed down meanwhile and the process is finished before the dipper leaves the dumper as it is swinged in reverse direction to return to the face for next digging operation. Therefore the dump operation was defined as a moment time in this study rather than a period of time and the program distinguished the moment by checking any change in the polarity of the swing motor armature voltage values as a result of the swing travels in the opposite directions before and after unloading operation. Swing motor armature voltage versus cumulative time curve of a typical cycle is given in Figure 3.12 and the periods of cycle segments and dump points are shown on it. The results of this model with regard to the periods were compared with the results which were obtained from both the video records and the marker signals to consolidate the model in the evaluation package. Thus the periods of the operations were obtained by processing swing motor armature voltage values and then the amounts of energy required to perform the operations were determined.

In general, energy is a power dependent variable and its amount required by a power system to do a work over a defined period (e.g., the beginning time of the period, t_1, the end time of the period, t_n) can be expressed as follows.

$$\text{Energy} = \int_{t_1}^{t_n} \text{Power}\; dt \qquad 3.6$$

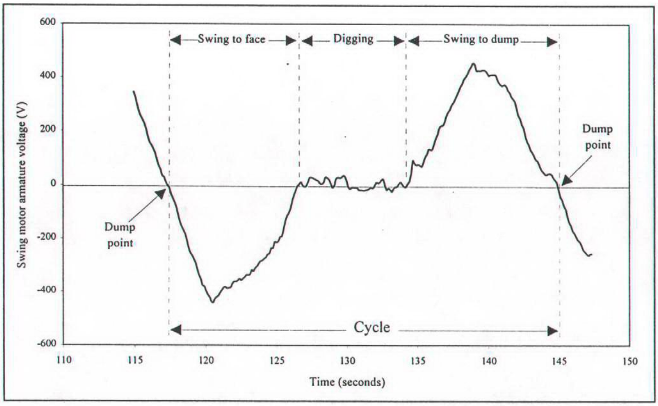


Figure 3.12 The curve of swing motor armature voltage vs time for a typical cycle period.

A numerical solution of the above integral is defined in the SHOVEL to determine the amount of energy consumed by the machine over the defined period of an operation. It was obtained by first determining the areas of ith elements under the power curve and then summing up these individual areas from the beginning to the end of the period (Figure 3.13). This solution is quite reliable to apply in this study since the sampling rate of the system is high enough to obtain a continuous-like data from the signal sources. As a result, the following simplified equation of the numerical solution is used in energy calculations.

$$E = \left(\frac{|P_1| + |P_n|}{2} + |P_2| + |P_3| + \ldots.. + |P_{n-2}| + |P_{n-1}| \right) * \left(\frac{t_n - t_1}{n} \right) / 3600 \quad 3.7$$

where:

E is the energy, kWh

$P_1, P_2, \ldots., P_n$ are the powers, kW

t_1 is the beginning time of the period, s

t_n is the end time of the period, s

n is the number of data obtained in the period

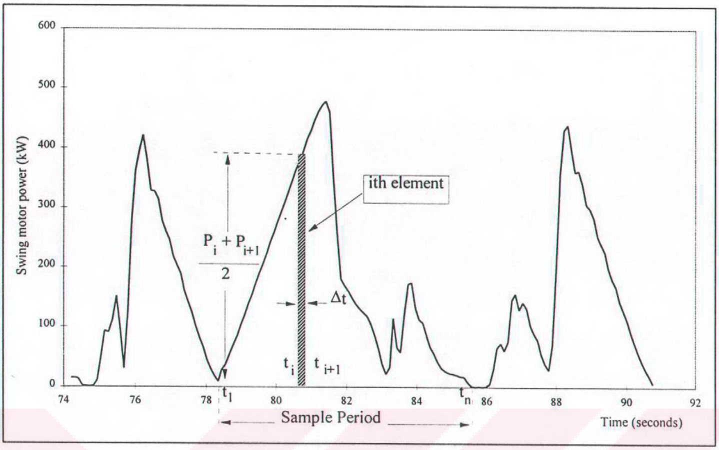


Figure 3.13 The curve of swing motor power vs time.

The period and the energy parameters of the motions other than excavation and waiting idle were found as well as those of cycles. Besides, average and peak power values in the periods were also obtained by the program while the energy consumption parameters were determined. The following relationships are used to determine average and peak power values.

$$P_{ave} = \frac{\sum_{i=1}^{n} P_i}{n} \qquad 3.8$$

$$P_p = \max(P_i; i = 1, n) \qquad 3.9$$

where:

P_{ave} is the average power, kW

P_p is the peak power, kW

P_i is the power in the ith depth interval, kW

The results of period, average and peak power, and energy calculations are stored in different files as given in Table 3.5 and Table 3.6. As it is seen in Table 3.5, beginning and end times of cycle segments which are swing to face (S EMPTY), digging (D TOTAL) and swing to dump (S FULL) are given as well as those of whole cycle (C TOTAL) and the corresponding periods of time for these operations. As it was observed at the field, the operator occasionally performed some excavation operations in which the excavated material is left at the face instead of dumping to the truck. Therefore this kind of operations were sorted. They were defined as irregular operations and denoted by EMPTY, as given in Tables 3.5 and 3.6. Besides, the machine was occasionally waiting idle because of some short fault brakes or delays in truck arrivals. These were also sorted and denoted by WAITING. Power and energy values were also determined in details as they are given in Table 3.6. Not for swing periods but for both digging and whole cycle periods, power and energy variables were obtained on the basis of motor type to provide detailed information for a better evaluation of the performance results. In the table, parameters of hoist, crowd and swing motors in digging are denoted by D-HOIST, D-CROWD and D-SWING respectively whereas D-TOTAL denotes total energy consumption in digging. Similar definitions of the parameters are also done on the basis of the motors in cycle and irregular operations. But, only the amount of energy consumed by the machine during a waiting period was obtained. It is expected to be quite close to zero because the motors are idle during waiting period of the machine. Rather than the energy, the amount of time spent for waiting idle was found more important.

Table 3.5 Sample output of time related parameters of the operations.

Machine status (*)	Cycle No	Beginning time (s)	End time (s)	Period of the motion (s)
S EMPTY	1	62.32	73.19	10.87
D TOTAL	1	73.19	80.51	7.32
S FULL	1	80.51	87.93	7.42
C TOTAL	1	63.32	87.93	25.61
EMPTY	1	29.49	63.22	33.73
WAITING	1	0.00	29.38	29.38

(*) S EMPTY : Swing to face
D TOTAL : Digging
S FULL : Swing to dump
C TOTAL : Total cycle
EMPTY : Irregular operation
WAITING : Machine is idle

Table 3.6 Sample output of power and energy related parameters of the operations.

Machine status (*)	Cycle no	Average power (kW)	Energy consumed (kWh)	Peak power (kW)
S EMPTY	1	130	0.686	341
S FULL	1	135	0.641	394
S TOTAL	1		1.327	
D HOIST	1	213	0.426	397
D CROWD	1	96	0.193	271
D SWING	1	20	0.039	50
D TOTAL	1		0.658	
C HOIST	1	131	0.889	397
C CROWD	1	66	0.454	271
C SWING	1	98	0.673	331
C TOTAL	1		2.016	
E HOIST	1	101	0.943	406
E CROWD	1	45	0.424	257
E SWING	1	67	0.633	328
E TOTAL	1		2.000	
WAITING	1		0.045	

(*) S : Swing D : Digging C : Cycle E : Empty
WAITING : Machine is idle

As the dipper motions during the excavation operations were monitored concurrently and the essential conversions were performed in the previous parts of the program, further arithmetical functions were defined in the package to obtain the essential outputs which were used to figure out the digging profile of the dipper. Since digging is achieved by a combined motion of hoisting and crowding, swinging is not expected if the small vibrations of the dipper in swing directions were ignored. Therefore the dipper motion during digging operation was defined as a two-dimensional motion which is performed on a vertical plane. By taking this situation into account, first of all, a rectangular co-ordinate system, which was used to define the motion of a point on a plane with its components, was needed to be described. For practical considerations, the origin of the system was fixed on the center of the shipper shaft pinion where the crowd transducer was connected (Figure 3.14). The tip of the farthest tooth on the dipper was defined as the dipper point and it was taken as the reference point to simulate the dipper motion. Besides a line passing through the center of the shipper shaft and goes parallel to the dipper handle was imagined. Thus the distance between the center of the shipper shaft pinion and the tip of the farthest tooth measured on this imaginary line was defined as the dipper distance, L, and the inclination of the imaginary line with respect to the horizontal reference axis was defined as the dipper inclination, β. The position of co-ordinate system axes and the other variables used to define the dipper position are illustrated in Figure 3.14.

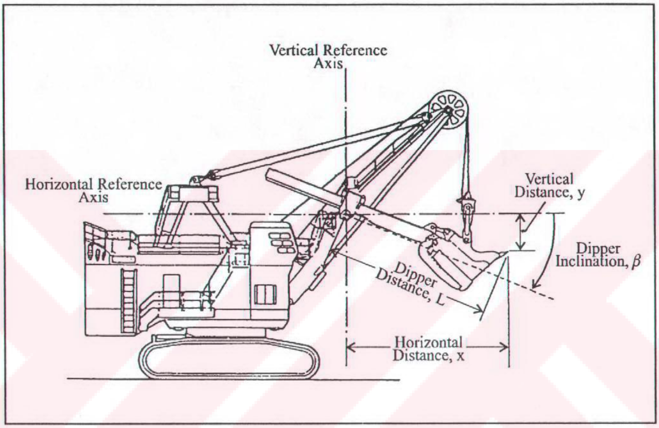


Figure 3.14 Position of rectangular co-ordinate system on a shovel.

As it is explained previously, the rotational change in the shipper shaft pinion and the inclination change in dipper handle are essential parameters to be obtained to define the dipper position. This was achieved by connecting two angle measuring transducers to the adequate points on the machine and their outputs were monitored concurrently during the digging process. Before a monitoring process was initialised, the initial position of the dipper was provided so that the dipper handle was parallel to the ground and perpendicular to the hoist rope. Then the dipper distance was measured and the dipper inclination was taken as zero for the initial reference position of the dipper. Thus the values of a new position were determined after finding the changes in both the dipper distance and the dipper inclination with respect to their initial reference values.

Monitored output signals of the transducers were first converted into the corresponding angular positions by using the equations 3.1 and 3.2. Then the angular positions of the crowd angle measuring transducer were converted into corresponding length measures to determine the change in the dipper distance with respect to the initial distance, in other words the amount of crowd or retract motion was determined. The following equation, in which the ratio 160/360 denotes that a 160 cm crowd or retract motion to the handle is provided when the shipper shaft pinion revolves 360 degree, is applied for its calculation.

$$\Delta L = (\theta_c - \theta_{co}) * (160 \div 360) \qquad 3.10$$

where:

ΔL is the change in the dipper distance, cm

θ_c is the angular position of the crowd transducer at a time, deg

θ_{co} is the initial angular position of the crowd transducer, deg

The dipper distance at a time is calculated by using the following equation.

$$L = L_o + \Delta L \qquad 3.11$$

where:

L is the dipper distance, cm

L_o is the initial dipper distance, cm

The second parameter, the dipper inclination, β, is directly obtained when the initial angular position of the hoist transducer is subtracted from its value at a time since the initial inclination of the dipper, θ_{ho}, is adjusted as zero.

$$\beta = \theta_h - \theta_{ho} \qquad 3.12$$

Once the dipper distance and corresponding the dipper inclination are found, the position of the dipper point on the rectangular co-ordinate plane is defined by its horizontal and vertical components (Figure 3.15). The shovels are designed so that their handles can easily be moved on an arc greater than 90°

during the digging operations. Therefore the dipper inclinations were defined with respect to the horizontal reference axis to simplify the calculations related with the components of the dipper point. The inclinations below the horizontal was defined positive otherwise negative for the cases above the horizontal. Thus the components, the horizontal distance, x, and the vertical distance, y, are calculated by using the following equations.

$$x = L \cos\beta \qquad 3.13$$

$$y = -L \sin\beta \qquad 3.14$$

where:

x is the horizontal distance of the dipper point, cm
y is the vertical distance of the dipper point, cm

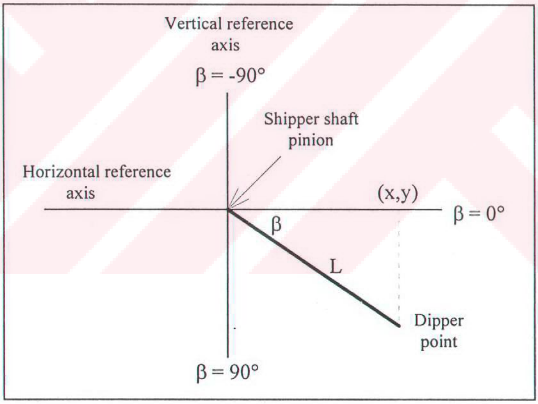


Figure 3.15 Rectangular co-ordinate system and the variables used to define digging profile.

Calculated components of the dipper points were applied to obtain the digging profile geometry of the dipper (Figure 3.16).

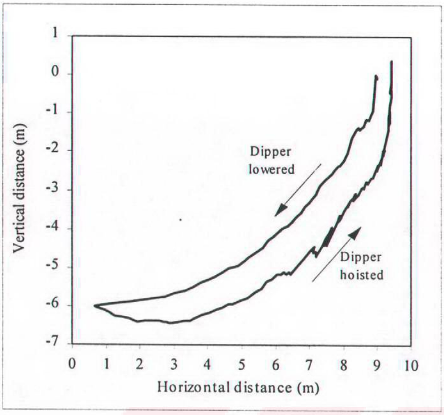


Figure 3.16 A typical digging profile geometry of the dipper.

Time, power and energy parameters were obtained as they are explained above, but these parameters are direct results of the monitored motor variables and none of them have relation especially with the characteristics of the excavated material. It is clear that diggability should be considered as a function of both the characteristics of the excavating equipment (i.e., dipper size, available power, etc.) and those of the excavated material (i.e., unit weight, swell factor, etc.) since digging is a result of interaction between the excavating tool and the material. It is, therefore, necessary to quantify the digging difficulty on the basis of material characteristics and equipment parameters.

The shovel's power which is drawn during excavation operation and the corresponding output of the machine were considered to be meaningful parameters in quantifying the performance of shovels in different ground and operation conditions.

Ground can be characterised by combining two parameters which are the amount of energy consumed by the machine over a period of operation and the amount of material passed within the same period. In the light of this definition and depending on the period selected (i.e., a complete cycle or digging component of the cycle), the Specific Cycle Energy (SCE) and the Specific Digging Energy (SDE) of the ground were derived in this study as the ratio between the energy consumed in a period and the corresponding amount of material dug in the same period. For easy of calculations, a complete cycle and its digging component were defined as the periods and then corresponding SCE and SDE values are determined individually.

Because of not being able to monitor the amount of material passed in a dipper, some parameters were defined and observed in this study to determine it indirectly. Therefore, two parameters which are Fill Factor (FF) of the dipper and Conversion Factor (CF) of material were defined to reduce the dipper volume of the material passed in a cycle into the equivalent bank volume .

As it is observed during field studies, the dipper's capacity of the shovel is not always utilised in the same amount even if the operation conditions do not change. Therefore the amount of the material passed in each dipper was observed during the monitoring process and it was recorded as fill percentage of the dipper for that cycle. When the dipper was filled to less than struck measure (dipper capacity), the fill percentage was less than 100 %, by the percent of available capacity not utilised. On occasion, material could heap to excess of dipper struck measure, meaning the fill percentage was 100 % plus. Thus the FF of the dipper was described for each individual cycle as a rate of utilised fill percentage to the available percentage and it is determined as:

$$\text{FF} = \text{Fill Percentage Utilised} / 100 \qquad 3.15$$

The second parameter, the conversion factor, was used to reduce the loose volume into the bank volume which is defined by Church (1981) as:

$$\text{CF} = \text{Bank Volume} / \text{Loose Volume} \qquad 3.16$$

As it is known, if the bank material is loosened by any mean, the volume of bank material will increase by a percentage which depends on loosening operation and mass properties of the material. The percentage increase in volume is characterised by a parameter which is swell percentage and the volume of the swelled material (loose material) is determined as:

$$\text{Loose Volume} = \text{Bank Volume}\left(\frac{100 + \text{Swell Percentage}}{100}\right) \qquad 3.17$$

The multiplier (100+Swell Percentage)/100 in the above equation is generaly defined as swell factor of the material. If this definition is substituted into the equation 3.17 and it is resolved for the CF, the following equation is obtained.

$$\text{CF} = 1\ /\ \text{Swell Factor} \qquad 3.18$$

Thus to reduce the volume of material passed through the dipper in a cycle to the bank volume the formula is:

$$\text{BV} = \text{DC} * \text{FF} * \text{CF} \qquad 3.19$$

where:

BV	is the bank volume of the material passed in a cycle, m^3
DC	is the dipper capacity (struck measure), m^3
FF	is the fill factor of the dipper utilised in the cycle

As well as the volume, the amount of material passed in the dipper was also defined in weight to embody another material property which is the natural unit weight. The bank weight of the material removed in a cycle is simply determined by:

$$\text{BW} = \text{BV} * \gamma \qquad 3.20$$

where:

BW	is the bank weight of the material passed in a cycle, t
γ	is the natural unit weight of the material, t/m^3

The specific cycle energy value defined as the amount of energy required to remove one cubic-meter or one ton of the bank material is determined on the basis of energy consumed in complete cycle by using the following equations respectively.

$$\text{SCE}_v = \text{CE}\ /\ \text{BV} \qquad 3.21$$

$$SCE_w = CE / BW \qquad 3.22$$

where:

SCE_v is the specific cycle energy by bank unit volume, kWh/m^3
SCE_w is the specific cycle energy by bank unit weight, kWh/t
CE is the cycle energy, kWh

Similarly, specific digging energy was determined on the basis of energy consumed in digging component of the cycle and the amount of material dug in the same period. It is, therefore, noted that the same amount of material is naturally considered in the calculations of SCE and SDE of a typical cycle. Thus the following equations for SDE are obtained by replacing CE parameter in the equations 3.21 and 3.22 with digging energy (DE).

$$SDE_v = DE / BV \qquad 3.23$$

$$SDE_w = DE / BW \qquad 3.24$$

where:

SDE_v is the specific digging energy by bank unit volume, kWh/m^3
SDE_w is the specific digging energy by bank unit weight, kWh/t
DE is the digging energy, kWh

As well as the energy parameters, amount of material dug in an hour period of operation could be used to quantify the performance of a shovel. Hence the hourly amount of excavated material is also determined on the basis of both cycle and digging times separately as follows.

$$HC_v = BV * 3600 / CT \qquad 3.25$$

$$HC_w = BW * 3600 / CT \qquad 3.26$$

$$HDC_v = BV * 3600 / DT \qquad 3.27$$

$$HDC_w = BW * 3600 / DT \qquad 3.28$$

where:

HC_v	is the hourly capacity by bank volume, m^3/h
HC_w	is the hourly capacity by bank weight, t/h
HDC_v	is the hourly digging capacity by bank volume, m^3/h
HDC_w	is the hourly digging capacity by bank weight, t/h
CT	is the cycle time, s
DT	is the digging time, s

These calculations were conducted for each cycle separately and the average values of all cycles performed over the period of a monitoring process were evaluated at the end. The results of these calculations were also stored in different files as tables.

CHAPTER 4

FIELD AND LABORATORY STUDIES

4.1. General

Performance monitoring studies are carried out at different coal mining districts of Turkish Coal Enterprises (TKİ). Although the most common overburden rock type in these districts is marl, rock mass and material properties of them are considerably different as well as the characteristics of the machines operate to remove the overburden in the districts. Therefore some qualitative and quantitative studies regarding both the material properties and the machine characteristics were conducted for each monitoring case to obtain the parameters which can describe the excavation environment as much good as possible. These studies specially provided the required information to make a better interpretation on the performance parameters and to use the diggability classification results more effectively.

Some routine field works before and during a monitoring process were done to gather the necessary information about the excavated material, the machine and the digging condition. In addition to the field works, some material properties of the intact rock were also studied in the laboratory, on the representative block samples collected in the field.

4.2. Field Study Techniques

Field studies were carried out wherever electrotorque controlled power shovels are in operation and active for overburden removal. In this manner, the measurements were utilised at five different districts and on more panels of TKİ to predict the digging abilities of the shovels (Table 4.1)

Table 4.1 TKİ districts where the monitoring studies have been conducted.

Enterprise	District	Panel	Rock type*
G.L.İ.	Tunçbilek	36 Pano	Marl
		Beke	Marl
E.L.İ.	Merkez	Işıklar A Pano	Marl
		Kısrakdere	Marl
		Sarıkaya	Marl
	Deniş	Çamtarla	Marl
Ç.L.İ.	Çan	K-2 Pano	Marl
		Çan-1 Pano	Agglomerate
B.L.İ.	Orhaneli	A 3/1 Pano	Marl

* Rock names are given as named by TKİ field engineers.

As it is seen from Table 4.1, most common rock type of overburden material is marl, but it is observed that the characteristics (e.g., makes, model, capacity, power, etc.) of the shovels operate at these districts are very unlike. The typical characteristics of the monitored electric power shovels are summarised in Table 4.2. In this table, continuous and peak motor powers are given. It is noted that two hoist and two swing motors are assembled on P&H shovels whereas there are two swing motors on Marion shovels. Two motors are synchronised which means that both motors operate simultaneously. Powers of hoist and swing motors given in Table 4.2 are sum of two motors. As the design characteristics of the motors, they can generate its peak capacity for a very short period whereas its continuous capacity can be utilised all the time. As they are seen in the table, power capacities of the motors differ according to both manufacturers and the models. Rather than their powers, specific hoist power defined as the ratio of hoist motor power to the dipper capacity was found more meaningful since it incorporates the dipper capacity as well as the power magnitude. The hoist motor, the dominant motor in digging, is preferred in this study and these values are taken into account during the discussion of the results in the next chapter.

Before a monitoring trial was initiated, some descriptions of rock properties of the excavation area were carefully done. During this pre-monitoring work, the parameters such as rock type, discontinuity set(s) (e.g., number of sets, spacing, etc.), weathering (or alteration) and blasting parameters (e.g., type, amount, blasting quality, block dimensions, etc.) were studied and recorded.

Table 4.2 Typical characteristics of the monitored power shovels.

Manufact-urer	Model	Dipper capacity (yd^3)		Continuous and peak motor powers (kW)				Total power (kW)	Specific hoist power* (kW/yd^3)
				Hoist	Crowd	Swing	Propel		
P&H♣	2300 XP	20	con.	1081	298	380	302	2061	88
			peak	1432	377	738	470	3017	128
P&H	2100 BLE	17	con.	656	194	328	280	1458	70
			peak	966	388	507	507	2368	109
MARIONΨ	191 MII	20	con.	779	190	290	313	1572	63
			peak	1155	276	422	541	2394	93
MARION	191 MI	17	con.	597	190	290	313	1390	63
			peak	867	276	422	541	2106	92
MARION	191 MHR	15	con.	597	190	290	313	1390	72
			peak	867	276	422	541	2106	104

♣ P&H shovels have two hoist and two swing motors. Powers given are total of two motors.

Ψ Marion shovels have two swing motors. Powers given are total of two motors.

* Specific hoist power = Hoist motor power (kW) / Dipper capacity (yd^3)

Existence of discontinuity sets were examined and their dimensions were obtained if any exists. Similarly, degree of weathering (or alteration) of the rock mass was described as fresh, slightly weathered, moderately weathered, etc. according to the definitions given by Barton (1978). Furthermore information about blasting parameters were acquired from the site blasting engineers and the dimensions of the typical blocks after blasting were measured. Together with these parameters, view of the face both before and after the monitoring trial were photographed by using scaled sticks on the face (Figure 4.1). Both block measurements and the views taken at the field were used to define the average block size and the volumetric joint count according to the classification system recommended by Anon (1977) in Table 4.3. Another site parameter, the swell percent value of the material was obtained from the results of the measurements done by the site engineers previously.

Figure 4.1 Photograph taken at the face before an excavation trial.

Table 4.3 Description of block size (after Anon, 1977).

Term	Block size	Equivalent discontinuity spacing in blocky rock	Volumetric joint count (J_v)* (joints/m^3)
Very large	> 8 m^3	Extremely wide	< 1
Large	0.2 - 8 m^3	Very wide	1- 3
Medium	0.008 - 0.2 m^3	Wide	3 - 10
Small	0.0002 - 0.008 m^3	Moderately wide	10 - 30
Very small	< 0.0002 m^3	Less than moderately wide	> 30

* After Barton (1978).

In addition to the field works, some laboratory tests were conducted on the representative material samples which were collected during the field studies to find the uniaxial compressive strength and the natural unit weight. As the natural unit weight value was used in calculation of material weight, the strength of the material was tested just to characterise the monitored rock unit.

At the last stage of pre-monitoring site works, the specific characteristics of the monitored machine, as given in Table 4.2, were recorded. The other supplementary information such as the local name of the excavated bench, bench height, observed digging condition, date and time of the monitoring trial, operator's experience, loading condition (single or double sided), number of trucks scheduled for the machine, distance of the dump area, etc. were also noted.

A summary of the above parameters concerning the monitored cases are presented in Table 4.4. As it is seen from the table, a specific code number is assigned for each monitoring case and they are used in the following sections of this thesis to refer to the cases.

After the pre-monitoring field works explained above were completed, the monitoring process was initiated to collect the motor variables of the machine and the dipper position parameters. During the whole period of the monitoring process, all the operations of the machine were followed by the author in the operator's cab and the important observations were noted to use during the evaluation of the monitored data and interpretation of the results.

During the initial stages of this study, monitored motor signals were cautiously investigated to indicate the amount of excavated material in the dipper after establishing a relationship between any motor signal and the material amount. At the end of these investigations, it was determined that neither the armature voltage nor the armature current of any motor purely indicates the amount of material in the dipper. Therefore a relationship between any of the monitored motor signals and the material amount could not be established for the purpose. As a result of this investigation, the dipper fill percentage utilised in each individual cycle was carefully observed and noted to determine the amount of material in the dipper during data evaluation process. As defined in section 3.7.2.2, fill percentage of the dipper was taken as 100% when it was filled to its struck measure (dipper capacity), otherwise it was defined as percentage of struck measure. Together with this observation, the position of loaded truck which indicates the swing direction as well as its amount both before and after digging operation was also observed and swing direction and amount were noted. As a result of blasting, huge amount of blasted material are often fall down from the

Table 4.4 Rock mass and material properties of the monitored cases.

Case code no	Region and panel	Shovel model (Dipper capacity) [Shovel age]	Digging condition Loading type	Observed digging difficulty	Rock mass properties			Material properties		Swell factor	Blasting parameters		Block size distribution parameters		
					Description	Disc. spacing (No of sets)* (m)	Volumetric joint count (J_v) (joints/m^3)	UCS♣ (MPa)	Natural unit weight (t/m^3)		Specific charge (kg.ANFO/m^3)	Blasting quality	Block size term	Homogenity	Block dimensions (cm*cm*cm)
1	E.L.İ. Deniş	Marion 191 MII (20 yd^3), [12 yrs]	Rehandle Double side	Easy	Completely weathered marl	–	–	–	2.47	1.05	–	–	–	Homo-geneous	–
2	E.L.İ.Merkez Kısrakdere	Marion 191 MHR (15 yd^3), [14 yrs]	Rehandle Double side	Easy	Completely weathered marl and residual soil	–	–	–	2.46	1.05	–	–	–	Homo-geneous	–
3	E.L.İ.Merkez Kısrakdere	Marion 191 MII (20 yd^3), [12 yrs]	Rehandle Double side	Easy	Highly to completely weathered marl	–	–	–	2.46	1.10	–	–	–	Not homo-geneous	Max: 80*60*40 Ave.: 20*20*15
4	E.L.İ.Merkez Işıklar A Pano	Marion 191 MII (20 yd^3), [12 yrs]	Blasted Single side	Easy	Slightly weathered marl	0.3-0.8 (3)	3-10	86.5	2.46	1.25	0.320	Good	Medium	Homo-geneous	Max: - Ave.: 30*30*20
5	E.L.İ.Merkez Işıklar A Pano	Marion 191 MII (20 yd^3), [12 yrs]	Blasted Single side	Moderately difficult	Slightly weathered marl	0.2-0.6 (3)	10-30	86.5	2.46	1.25	0.320	Good	Small	Homo-geneous	Max: - Ave.: 30*25*10
6	Ç.L.İ.Çan K-2 Pano	Marion 191 MII (20 yd^3), [10 yrs]	Blasted Single side	Moderately difficult	Fresh marl, laminated	0.1-0.8 (3)	10-30	31.9	2.04	1.35	0.240	Good	Small	Homo-geneous	Max: - Ave.: 20*20*10
7	E.L.İ.Merkez Sarıkaya	P&H 2100 BLE (17 yd^3), [10 yrs]	Blasted Double side	Easy	Fresh marl	0.1-0.5 (3)	10-30	67.3	2.48	1.30	0.300	Good	Small	Homo-geneous	Max: - Ave.: 25*25*10
8	G.L.İ.Tunçbilek 36 Pano	P&H 2300 XP (20 yd^3)	Blasted Double side	Easy	Fresh marl	0.2-1.0 (3)	1-10	68.3	2.28	1.37	0.180	Good	Medium to large	Homo-geneous	Max:120*100*60 Ave.: 40*30*30
9	G.L.İ.Tunçbilek 36 Pano	P&H 2300 XP (20 yd^3), [11 yrs]	Blasted Double side	Moderate	Slightly weathered marl	0.1-0.7 (3)	3-30	68.3	2.28	1.37	0.145	Good	Small to medium	Homo-geneous	Max: 40*40*20 Ave.: 20*20*10
10	G.L.İ.Tunçbilek 36 Pano	P&H 2300 XP (20 yd^3), [11 yrs]	Blasted Double side	Moderate	Fresh marl	0.3-1.2 (3)	1-10	60.5	2.20	1.37	0.145	Good	Medium to large	Homo-geneous	Max: 100*60*40 Ave.: 40*30*30
11	G.L.İ.Tunçbilek 36 Pano	P&H 2300 XP (20 yd^3), [11 yrs]	Blasted Double side	Moderate	Fresh marl	0.3-1.2 (3)	1-10	60.5	2.20	1.37	0.145	Good	Medium to large	Homo-geneous	Max: 100*60*40 Ave.: 40*30*30
12	G.L.İ.Tunçbilek 36 Pano	P&H 2300 XP (20 yd^3), [11 yrs]	Blasted Double side	Moderate	Fresh marl	0.2-0.7 (3)	10-30	68.3	2.28	1.37	0.145	Good	Small	Homo-geneous	Max: - Ave.: 30*20*10

* Including bedding in horizontal direction. ♣ Uniaxial Compressive Strength.

Table 4.4 continued

Case code no	Region and panel	Shovel model (Dipper capacity) [Shovel age]	Digging condition Loading type	Observed digging difficulty	Rock mass properties			Material properties		Swell factor	Blasting parameters		Block size distribution parameters		
					Description	Disc. spacing (No of sets)* (m)	Volumetric joint count (J_v) (joints/m^3)	UCS♣ (MPa)	Natural unit weight (t/m^3)		Specific charge (kg.ANFO/m^3)	Blasting quality	Block size term	Homogenity	Block dimensions (cm*cm*cm)
13	G.L.İ.Tunçbilek 36 Pano	P&H 2300 XP (20 yd^3), [11 yrs]	Blasted Double side	Moderate	Fresh marl	0.3-1.2 (3)	3-10	68.3	2.28	1.37	0.145	Good	Medium	Not homo-geneous	Max: 100*70*20 Ave.: 40*30*20
14	G.L.İ.Tunçbilek Beke Pano	P&H 2300 XP (20 yd^3), [11 yrs]	Blasted Double side	Easy	Slightly to moderately weathered marl	0.2-1.0 (3)	1-10	39.7	2.14	1.35	0.145	Good	Medium to large	Homo-geneous	Max: 100*50*40 Ave.: 40*35*25
15	G.L.İ.Tunçbilek Beke Pano	P&H 2300 XP (20 yd^3), [11 yrs]	Blasted Double side	Moderate	Slightly to moderately weathered marl	0.2-0.8 (3)	1-10	39.7	2.14	1.35	0.145	Good	Medium to large	Homo-geneous	Max: 100*50*40 Ave.: 40*35*25
16	G.L.İ.Tunçbilek Beke Pano	P&H 2300 XP (20 yd^3), [11 yrs]	Blasted Double side	Moderate	Slightly to moderately weathered marl	0.2-0.8 (3)	1-10	39.7	2.14	1.35	0.145	Good	Medium to large	Homo-geneous	Max: 100*50*40 Ave.: 40*35*25
17	Ç.L.İ.Çan K-2 Pano	Marion 191 MII (20 yd^3), [10 yrs]	Blasted Single side	Difficult	Fresh marl	0.5-1.7 (3)	1-10	16.2	2.10	1.31	0.240	Good	Medium to large	Not homo-geneous	Max:180*120*70 Ave.: 40*30*25
18	E.L.İ.Merkez Işıklar A Pano	Marion 191 MI (17 yd^3), [12 yrs]	Blasted Double side	Moderate	Fresh marl	0.7-2.0 (3)	1-10	78.6	2.37	1.35	0.320	Good	Medium to large	Not homo-geneous	Max: 150*120*50 Ave.: 40*40*30
19	E.L.İ.Merkez Işıklar A Pano	Marion 191 MI (17 yd^3), [12 yrs]	Blasted Double side	Difficult	Fresh marl	0.7-2.0 (3)	1-10	78.6	2.37	1.35	0.320	Good	Medium to large	Not homo-geneous	Max: 150*100*50 Ave.: 40*30*30
20	E.L.İ.Merkez Işıklar A Pano	Marion 191 MII (20 yd^3), [12 yrs]	Blasted Double side	Moderately difficult	Fresh marl	0.7-2.0 (3)	1-10	78.6	2.37	1.35	0.320	Good	Medium to large	Not homo-geneous	Max: 150*120*40 Ave.: 40*40*30
21	Ç.L.İ.Çan Çan-1 Pano	Marion 191 MII (20 yd^3), [10 yrs]	Blasted Single side	Difficult	Aglomerate (with earth material)	--	--	51.2	1.80	1.25	0.280	Poor	Very small to very large	Not homo-geneous	Max: 300*300*200 Ave.: -
22	B.L.İ.Orhaneli A 3/1 Pano	Marion 191 MI (15 yd^3), [11 yrs]	Blasted Double side	Difficult	Fresh marl	0.3-1.5 (3)	3-10	14.0	2.26	1.42	0.180	Poor	Medium to large	Not homo-geneous	Max: 150*120*80 Ave.: 40*40*20

* Including bedding in horizontal direction. ♣ Uniaxial Compressive Strength.

face and form pile of loose material in front of the machine. Therefore a special attention was given on this situation and the dipper filling type achieved in each cycle was noted as if the dipper was filled by digging loose material at toe of the face or by digging blasted material at the face. This information is especially used to group the cycles according to the dipper filling type and to make a comparison between different dipper filling operations. Similarly if any irregular operation such as swing motions remarkable higher or lower than 90° because of unusual truck position, very long digging periods because of trials to remove extraordinary large blocks or digging very strong bedding planes, or very long cycle periods because of waiting the manoeuvre of the trucks with the full dipper was observed during a monitoring period, the irregularity was noted together with number of related cycle. During the evaluation, these irregular cycles were not included in regular operations. Another work done during monitoring processes was to mark the specific operations of the machine such as digging, dumping, propelling, waiting idle or any other specified operation by using the manually controlled marker.

Shovels perform the excavation operation by regular combinations of the motions which are supplied by hoist, crowd and swing drive motors. Propelling motion is achieved occasionally to reposition the machine in front of the face when the distance of the machine from the face is not suitable for digging or to park the machine in a safe position at the end of shift periods. Although the cycle related operations and the propelling motions are the most common observations during an excavation period, it was also observed that the machines rarely wait idle because of insufficient truck number. The operator sometimes prefer to dig the ground instead of waiting the truck, but the material is dumped to the face. This kind of operation is named as face preparation in this study. A certain part of a monitored case which includes all above observations was extracted and the curves given in Figure 4.2 were plotted. Since the monitoring time was recorded separately in a file as the beginning and the end times of the monitoring process, recorded data file has no time component. Therefore x-axes of the graphs are defined as data line number. The first curve of this figure illustrates changes in marker's voltage value according to type of operation. A different, but a unique voltage level is defined for each different operation. The other curves in figure illustrate signal traces of motors and transducers. As it is observed on the curves, all the motor signal values are zero and the transducers' signals are constant during the waiting period. Both the armature voltage and the armature current feedback signal values of a motor deviates from zero as soon as the related motor is activated according to the characteristics of the operation. For instance, those of the propel motor are zero unless the propelling motion is achieved. Similar to the motor signals, the transducers' signals deviate from their constant values as the position of dipper in hoist or crowd direction is changed.

As it is explained in Chapter 3, the monitored raw data were processed systematically on the base of an algorithm and the real values of all the motor variables and the transducer variables were obtained by converting the corresponding monitored signals. Figure 4.3 illustrates the curves obtained by plotting the converted values of the parameters which exactly correspond to the raw data given in Figure 4.2. In the new figure, time is used in x-axis since a specific monitoring time is assigned to each line during data conversion process. The characteristics of the curves in Figure 4.3 are similar to those in Figure 4.2. As defined in both Figures 4.2 and 4.3, changes in the polarity of the armature voltage values of the motors indicate the change in the direction of the related motion. For instance, polarity of the hoist motor armature voltage is positive when the dipper is hoisted and it is negative when the dipper is lowered. Similar definitions have been done for crowd, swing and propel motions.

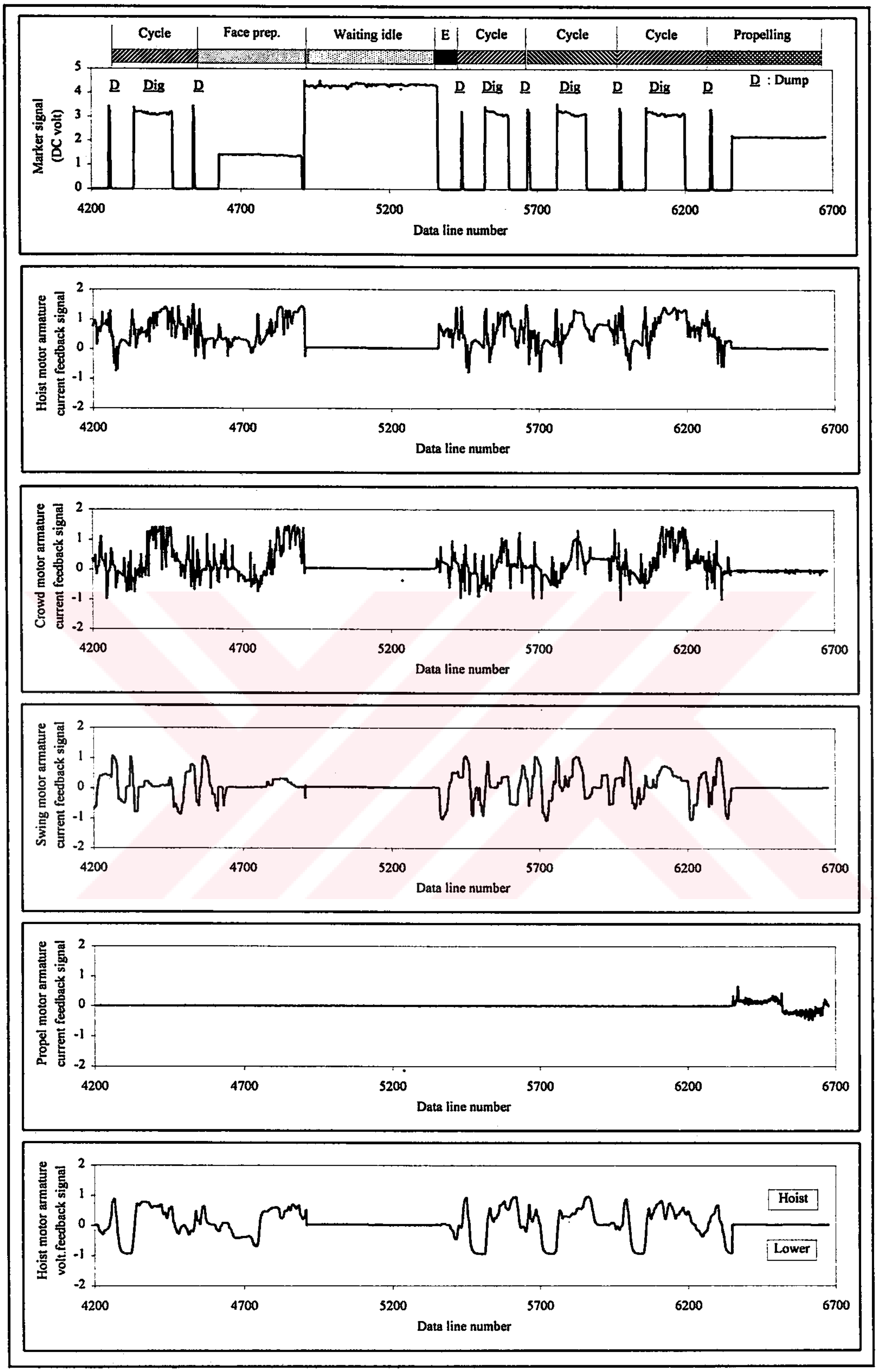


Figure 4.2 Signal traces of the marker, the motors and the transducers.

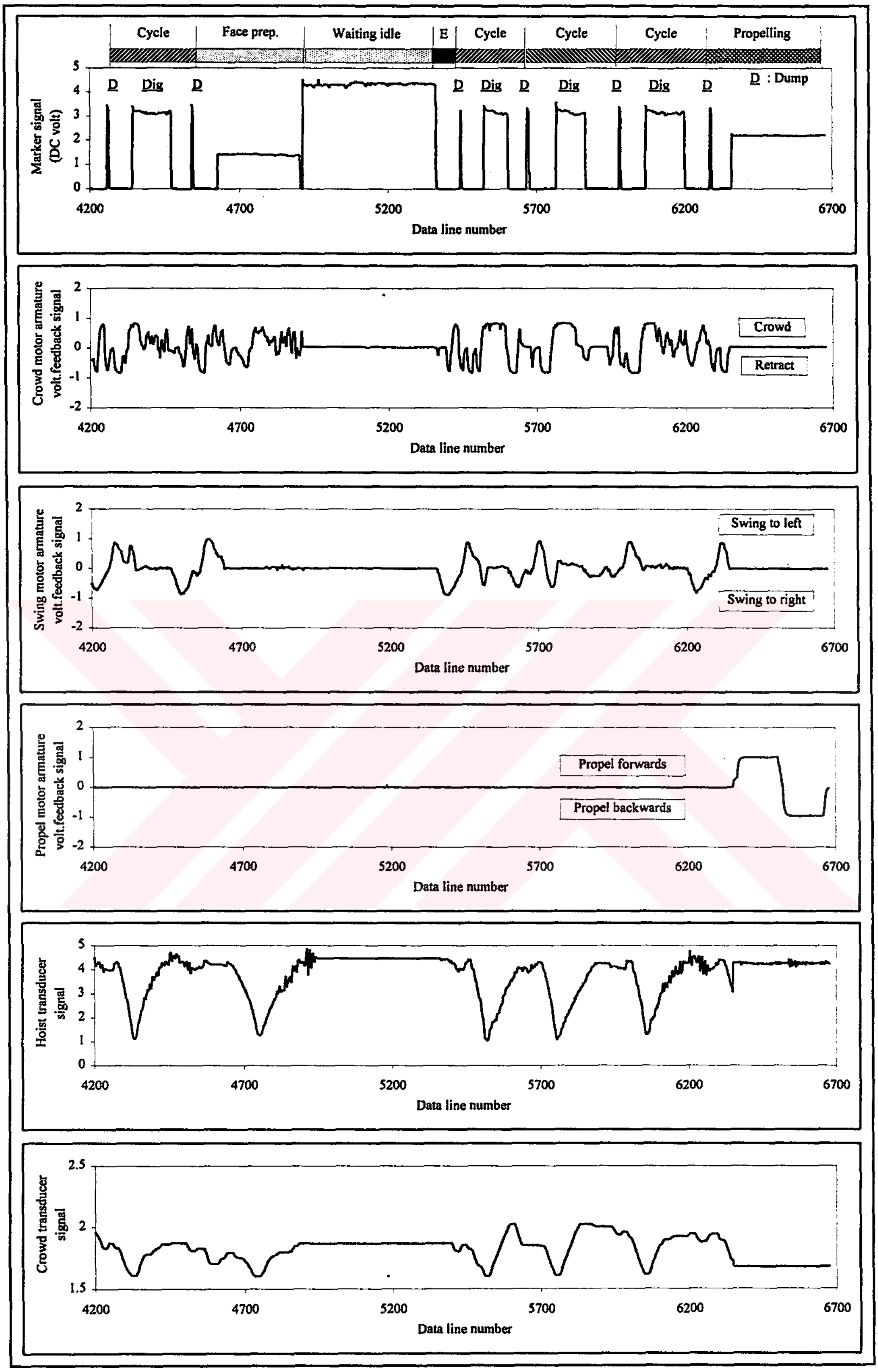


Figure 4.2 Continued

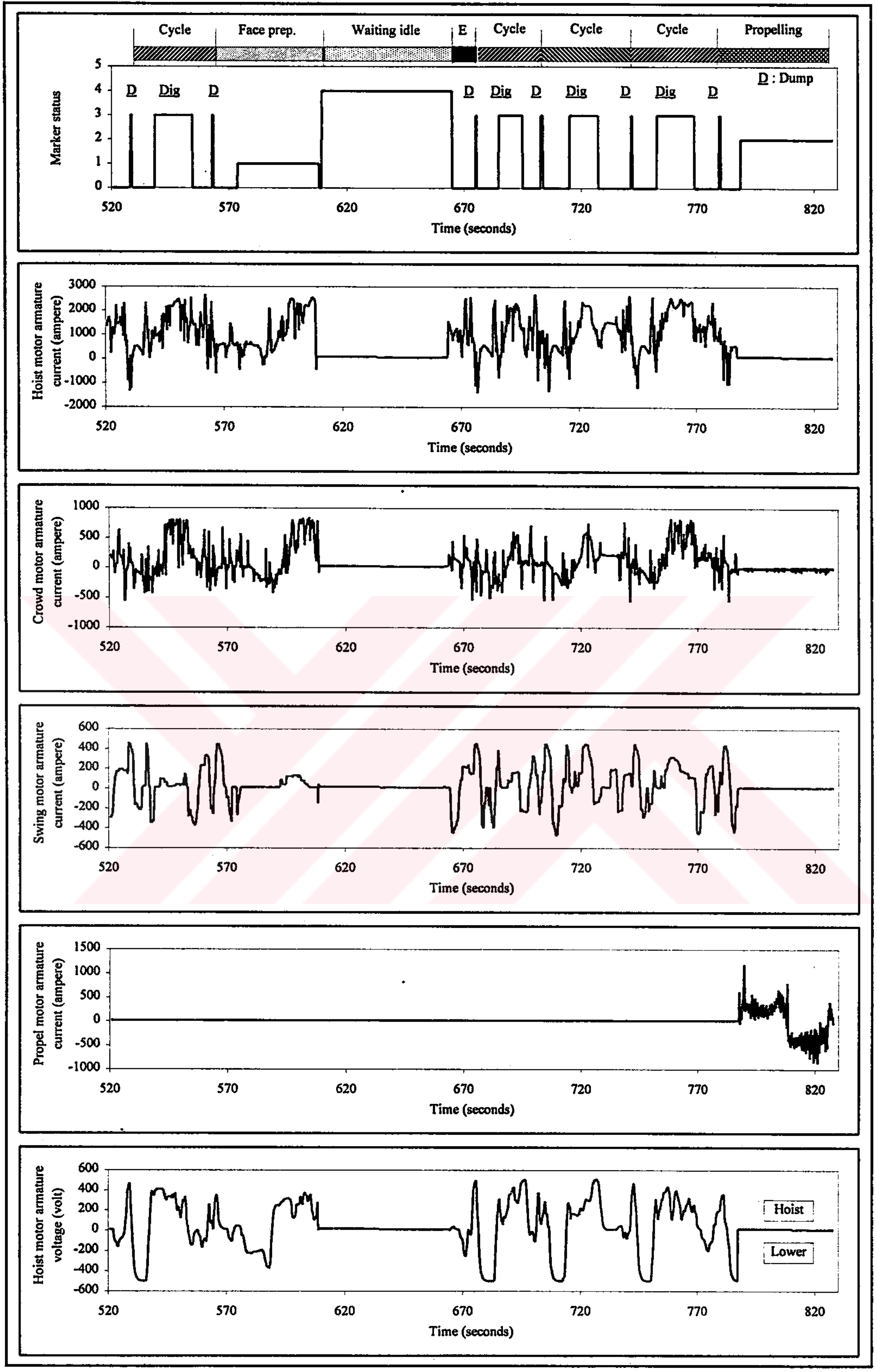


Figure 4.3 Converted value traces of the marker, the motors and the transducers.

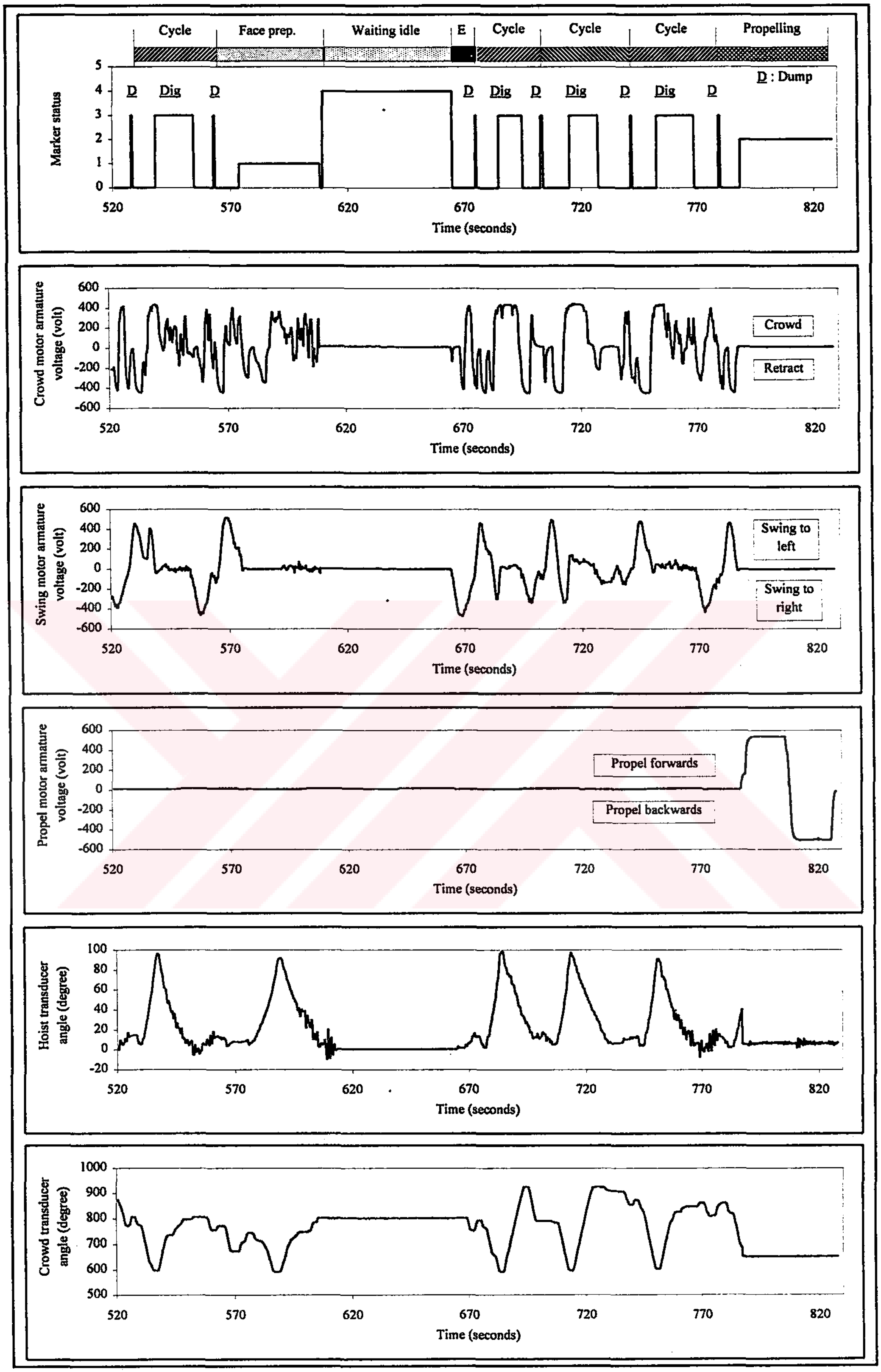


Figure 4.3 Continued

CHAPTER 5

DATA ANALYSIS AND DISCUSSION OF RESULTS

5.1. General

The electrotorque power shovels which operate at open pit lignite mines of TKİ to remove the overburden material were monitored in this study. The characteristics of the shovels change from place to place as well as the properties of the rock mass and the material excavated.

After developing a data processing and evaluation methodology on the basis of the aims, the results obtained from data processing were analysed and discussed from digging difficulty point of view. An interpretation of performance parameters were also done by considering both the machine characteristics and the rock mass/material properties which are given in Chapter 4. Besides overall analysis of the results, effects of some variables, such as the position of lever controller, type of digging operation, depth of cut, etc. on the performance parameters are individually analysed and discussed.

5.2. Processing and Evaluation of Monitored Data

As it is clarified in Chapter 4, the operations were carefully observed by the author during each monitoring process and all the variables and the important observations were noted simultaneously. These observations are as important as the records to evaluate the results properly by taking the parameters which were varied from cycle to cycle into account, although the machine and the material variables were the same for that specific monitoring case. For instance, the results of a cycle in which the dipper was filled with the loose material piled in front of the face should be expected to be different than those of the cycle in which the dipper was filled with the material dug directly at the face.

First of all, the recorded raw data were processed and the parameters were determined according to the algorithm which is explained in Chapter 3 in details. Then the cycles obtained in a monitoring period were sorted according to any different digging operation, as one explained in the above paragraph, and the results were collected under different groups. Thus a similarity in digging type could be provided for the cycles belong to different districts and the results of the same digging type can be compared with each other to see the effects of the material properties.

Besides numerical evaluations of the performance parameters, the results were also evaluated graphically to obtain arithmetical relationships between the parameters. These are explained in details in the following sections.

5.3. Interpretation of Shovel Performance

It is known that the electric shovels are designed to perform a specific job and they use electricity to perform the specified operation. In this manner a shovel can be considered as a working system as illustrated in Figure 5.1. An input of electrical energy is provided to the system and then the system uses the electrical energy to generate a work power needed to perform the specified work. Therefore the performance of the system or the work difficulty can be defined qualitatively and/or quantitatively if the amount of both the input and the corresponding output variables are determined.

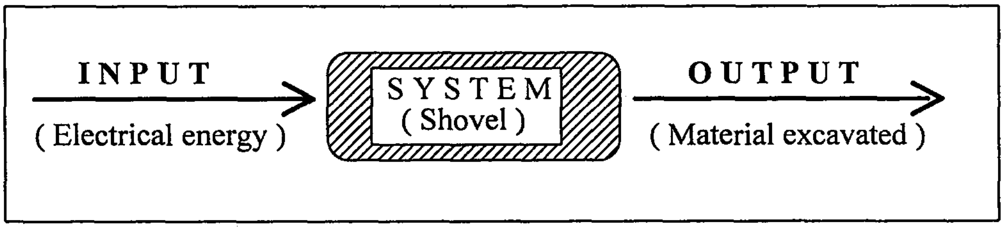


Figure 5.1 An illustration of the working principle of electric power shovels.

The above approach was basically taken into account to define the digging performance of the shovels or the digging difficulty of the ground. Therefore the amount of energy consumed by the machine during the operation and the corresponding amount of the material removed were determined as they are explained in Chapter 3. Together with the amount of energy and the material, the periods, the dipper positions and the power magnitudes are also determined.

A single parameter can not be an adequate variable to define the digging difficulty. Therefore the relationships between the parameters, especially between the energy and the material amount, were studied in detail. Findings related to the basic parameters of the operations such as cycle time and energy, digging time and energy, specific energies in cycle and in digging, etc. are given and discussed in the following sections.

5.3.1. Cycle Time and Cycle Energy

It is well known that the shovels perform the excavation by doing some cyclic operations such that swinging the empty dipper to face, filling the material into the dipper by digging the ground, swinging the loaded dipper to a haulage equipment and dumping the excavated material into the haulage unit. The combination of these cyclic motions is commonly named as a cycle and these motions are repeated in the same sequence in each cycle. It is also noted that the dipper is filled and dumped only once in each cycle in a regular excavation operation. Besides the motions done in a cycle, propelling is also done after a series of cycles to reposition the machine according to changing condition of the face.

Excavation is a continuous process in open pit mines and this process is utilised by repeating the basic operations as they are explained above. In this manner the cycles which are the sub-periods of the operational periods take place one after the other. Therefore an approach to identify the beginnings and the ends of the cycles encountered within an excavation period should be clearly defined if one especially involves in finding the performance parameters of the machine in individual cycles or calculating the cycle related parameters, such as cycle time, cycle energy, etc. Consequently a moment in the cycle, for instance the beginning of digging operation, should be assigned as the reference moment to identify the cycles. Thus a cycle is accepted to start at that moment and to finish as soon as the following reference moment is encountered. The end of a cycle will naturally be the beginning of the next cycle as long as the regular cycle motions are performed. In this study, for ease of control and calculations, end of dumping operation, that is also the beginning moment of swinging the empty dipper towards the face, is taken as the reference moment. As a result the period between the preceding reference moments is defined as a cycle and the related calculations are done accordingly.

Swinging the empty dipper to the face, filling the dipper by digging the ground and swinging the loaded dipper to truck are the basic components of a cycle and these components are respectively named as swing to face, digging and swing to dump in this study. As it is explained in Chapter 3, the periods of these operations easily identified by processing the armature voltage variable of swing motor. A computer based monitoring system provided the advantage of obtaining the results in a shorter time when compared with the conventional monitoring systems and hence giving the opportunity of doing more detailed evaluations. By taking this advantage of the developed system into account, all the calculations and the evaluations have been done for both the basic components of the cycle and the whole cycle.

It was observed that the excavation process of overburden material at TKİ open pit mines are done after loosening the ground by blasting. As observed in the field, if the rock mass is heavily jointed, blasting is more effective and therefore the blasted material at the face can easily collapse when it is disturbed during the digging operation. Consequently the huge amount of the material often piles in front of the face. During the field studies, it was observed that the major part of the excavation operation is achieved by digging the blasted and piled material. Although this type of dipper filling operation is commonly applied, the dipper is occasionally filled with the material dug directly at the face. Therefore, during a monitoring process, the dipper filling type was noted for each cycle and the cycles of the case were sorted accordingly during the evaluation data. The values of the parameters are individually obtained for both types of the dipper filling methods, but the results of the cycles in which the dipper was filled by digging the piled material are given and discussed in this section. The results of the other type of digging will be given and discussed in another section.

The average results of important parameters belong to the cycles in which the dipper was filled by digging the blasted and piled material are summarised in Table 5.1. The relationship between cycle time and cycle energy is illustrated in Figure 5.2. Although the amount of energy consumed in a cycle seems to increase when the cycle time increases, a confident relationship can not be obtained between these parameters. This is partly because of irregularities observed in some cases. For example, cycle time and energy values of the case 15 are 28.92 seconds and 3.242 kWh respectively, but those are 27.19 seconds and 3.802 kWh for the case 16, although both cases belong to the same machine which operate at GLİ Tunçbilek Beke Panel. When the values of the cases are compared, cycle time decreases about 6% , as cycle energy increases more than 17% in the case 16 with respect to the values of the case 15. The reason of this unexpected results can be explained as an effect of a change in the material characteristics, or a change in the operator's application, or a change in another parameter. If the other parameters of these cases given in Table 5.1 are compared carefully, the unexpected increment in cycle energy can be explained with the increments in the energy consumption amount in both swing to face and swing to dump operations. When the energy values of swing to face, digging and swing to dump operations of the case 16 are compared with those of the case 15, it is seen that the swing to face energy and the swing to dump energy values increase 24 and 28% respectively, but the digging energy increases only 1%. Similarly the average power of the swing motor in the second case is almost 60% higher than the value of the first case. After such an interpretation, it can be concluded that the change in cycle energy of the second case is a result of swing operations done both before and after digging, and it is completely related to differences in the operators' applications. Some reasons for this situation can be summarised as; according to the average power values of the swing motor, either the first operator manipulated the swing motor in a level lower than the required level or the second operator manipulated the motor in a very high level; according to the swing times and energies, the truck positions necessitated longer swing motions in the second case, but the operator completed the swing motions in the same periods as so they are in the first case by manipulating the swing motor in a higher level which causes to an unnecessary increase in energy consumption; or the second operator did nonessential hoist and crowd motions during swing motions. Whatever the reason is for this kind of situation, one point is clear that neither cycle time nor cycle energy values can not be a mere parameter which characterises digging difficulty of the material. Similarly the other cycle related parameters, such as time normalised cycle energy, peak or average powers of the motors gained in cycles, etc. can not be the parameters to define digging condition. But these parameters, especially cycle time and energy, can be more meaningful to define overall performance of the shovel.

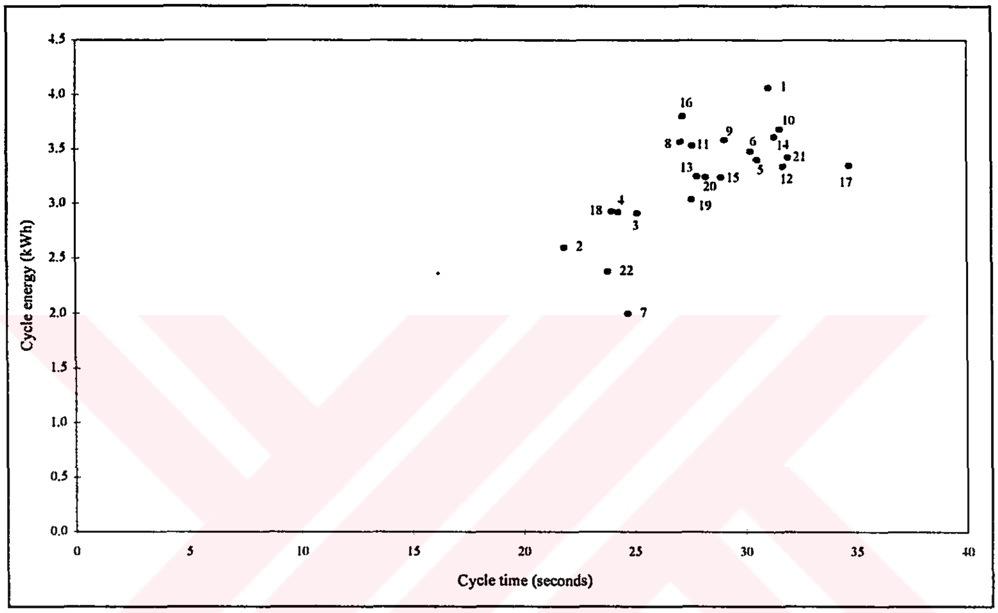


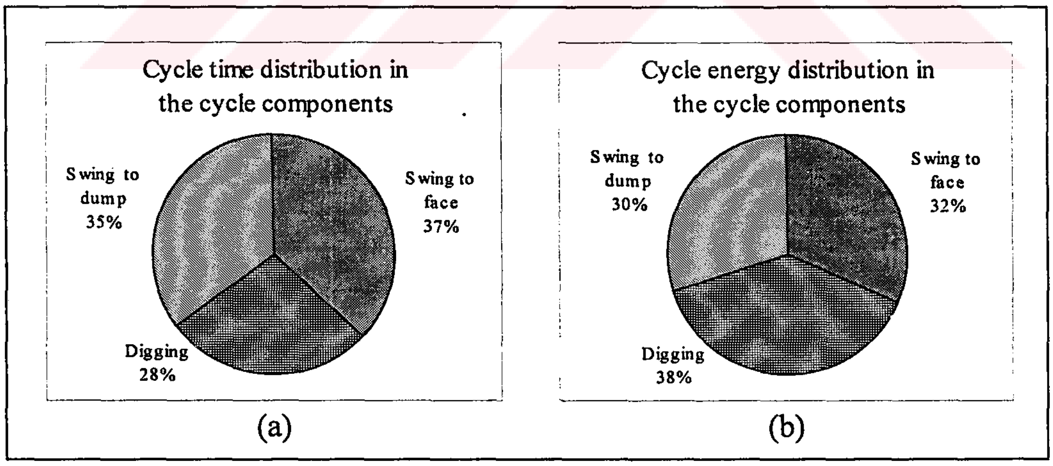
Figure 5.2 Relationship between cycle time and cycle energy.

If the operational characteristics of electric power shovels are considered it can be said that these machines are properly interacted with the ground during the digging operations and the amount of energy consumed for this operation can be a relevant parameter to define the digging condition. Therefore a special attention was always given on the digging components of the cycles and the parameters of this part have been evaluated in detail to obtain a more realistic parameter defining the digging difficulty of the material. So the digging parameters are evaluated and discussed in another section from digging difficulty point of view.

Table 5.1 Average values of the cycle parameters for the monitored cases, the dipper was filled by digging the blasted and piled material at the toe of the face.

Case code no	Number of cycles	Cycle time (s)	Cycle energy (kWh)	Time normalised cycle energy (kWh/s)	Time consumptions in cycle components			Energy consumptions in cycle components			Energy consumptions of the motors in cycle			Peak and average powers of the motors obtained in cycle					
					Swing to face (s)	Digging (s)	Swing to truck (s)	Swing to face (kWh)	Digging (kWh)	Swing to truck (kWh)	Hoist motor (kWh)	Crowd motor (kWh)	Swing motor (kWh)	Hoist motor		Crowd motor		Swing motor	
														Peak (kW)	Ave. (kW)	Peak (kW)	Ave. (kW)	Peak (kW)	Ave. (kW)
1	76	31.07	4.064	0.131	11.08	9.28	10.71	1.174	1.626	1.202	2.958	0.697	0.409	786	344	270	81	173	48
2	70	21.86	2.597	0.120	9.41	5.01	7.45	0.803	1.065	0.690	1.836	0.473	0.288	917	305	254	79	165	48
3	42	25.14	2.909	0.116	9.68	7.16	8.30	0.873	1.236	0.745	2.269	0.322	0.318	826	326	172	47	165	46
4	10	24.29	2.919	0.120	9.23	6.93	8.13	0.844	1.220	0.780	2.111	0.530	0.278	864	315	246	79	161	41
5	43	30.57	3.400	0.112	10.43	9.68	10.45	0.799	1.699	0.856	2.492	0.588	0.321	887	298	242	70	161	38
6	50	30.25	3.479	0.115	10.41	8.02	11.79	1.025	1.264	1.134	2.512	0.533	0.434	882	301	233	64	155	52
7	91	24.71	1.998	0.081	9.71	6.64	8.36	0.724	0.646	0.621	0.855	0.442	0.701	399	125	251	65	412	103
8	45	27.11	3.567	0.132	10.24	7.56	9.32	1.302	1.053	1.184	1.575	0.839	1.153	646	211	345	113	601	153
9	11	29.09	3.584	0.123	10.84	7.44	10.81	1.190	1.139	1.229	1.711	0.789	1.084	646	213	333	99	586	133
10	21	31.59	3.684	0.117	11.92	8.42	11.30	1.321	1.171	1.173	1.754	0.917	1.013	657	201	349	105	551	115
11	36	27.64	3.533	0.128	10.45	7.93	9.30	1.296	1.141	1.076	1.593	0.822	1.118	650	209	351	107	581	145
12	27	31.73	3.339	0.106	11.88	8.92	10.94	1.178	1.221	0.911	1.692	0.830	0.818	644	194	335	94	499	94
13	26	27.84	3.249	0.117	10.63	7.27	9.94	1.145	0.997	1.080	1.528	0.742	0.979	639	200	341	97	558	126
14	36	31.34	3.615	0.115	11.51	7.49	12.35	1.299	0.893	1.394	1.600	0.793	1.223	662	186	328	91	557	139
15	31	28.92	3.242	0.113	10.26	7.59	11.07	1.069	1.129	1.009	1.643	0.808	0.791	674	207	354	101	442	99
16	34	27.19	3.802	0.140	9.70	6.94	10.56	1.330	1.141	1.294	1.731	0.851	1.220	684	231	347	113	545	161
17	27	34.71	3.351	0.096	12.53	10.03	12.15	0.889	1.664	0.778	2.531	0.533	0.287	847	263	212	55	155	30
18	86	24.00	2.926	0.122	9.25	6.18	8.53	0.820	1.163	0.896	2.058	0.530	0.339	876	310	239	80	178	51
19	58	27.58	3.037	0.110	9.88	8.41	9.26	0.823	1.334	0.838	2.219	0.543	0.275	779	291	214	71	145	36
20	28	28.22	3.243	0.115	9.88	8.23	10.11	0.851	1.513	0.840	2.339	0.568	0.336	891	300	243	73	162	43
21	36	31.98	3.420	0.108	10.54	11.25	10.18	0.778	1.770	0.839	2.576	0.534	0.311	864	294	217	61	160	35
22	35	23.81	2.379	0.100	9.08	6.88	7.85	0.745	0.898	0.704	1.569	0.408	0.401	835	238	216	62	174	61
Average		*28.21*	*3.243*	*0.115*	*10.39*	*7.88*	*9.95*	*1.025*	*1.238*	*0.980*	*1.961*	*0.640*	*0.641*	*752*	*253*	*277*	*82*	*331*	*82*
St.dev. (±)		*3.29*	*0.480*	*0.013*	*0.89*	*1.38*	*1.39*	*0.219*	*0.282*	*0.219*	*0.485*	*0.171*	*0.368*	*130*	*58*	*59*	*19*	*193*	*45*

Average time and energy values of the cycle components given in Table 5.1 are considered to obtain Figure 5.3 which shows cycle time and energy distributions in the cycle components. Average time and energy consumption are determined as 10.39 seconds and 1.025 kWh in swing to face, 7.88 seconds and 1.238 kWh in digging, and 9.95 seconds and 0.98 kWh in swing to dump components. It means that 37 and 35% of cycle time is consumed in swing to face and swing to dump operations respectively whereas the remaining time is used in digging. Dissimilar to time distributions, most of cycle energy is consumed in digging as expected. According to the results, 38% of the cycle energy is used in digging, but energy consumption percentages in swing operations are about 30%. These results show that time and energy relations are different in cycle components which is also quite compatible with the real digging phenomena. If time normalised energy, defined as the amount of energy consumed in a second, is calculated for each cycle components, the values of 0.098, 0.157 and 0.098 kWh/s are obtained for swing to face, digging and swing to dump periods respectively. While the same amount of energy is consumed in a second to perform both swing operations, the value of digging operation is obtained 60% higher than the others. Average value of time normalised energy for whole cycle is determined as 0.115 kWh/s.



(a) (b)

Figure 5.3 Cycle (a) time and (b) energy distributions in the cycle components.

An evaluation is also done to see the changes in motor parameters over the cycle components. It can be said that hoist and swing motors are the basic ones when the operations done in the cycle components are considered. Because the digging is mainly achieved by the hoist motor whereas the swing motor is the only one to perform the swing motions. The curves given in Figure 5.4 are obtained by dividing the cycle components into 10 equal intervals and then determining the parameters for each intervals. For instance, the amount of energy consumed by the hoist motor are determined for each interval of the swing to face component after dividing the period into 10 equal intervals. These individual hoist energy values are divided by the total hoist energy value in the period to find the percentages. The same method is applied on the other components of the cycle and for the other parameters as well. Energy consumption parameters are given as percents rather than the magnitudes because even the operation time of the same component differs from cycle to cycle. This evaluation is done for a total of 198 cycles, average 9 cycles from each case, and the average values of the all cycles are used to obtain the charts given in Figure 5.4. If the operations done in the components were linear in all cases, the percents of the intervals would be the same around 10%. But different combinations of the motors are applied during the excavation process and therefore the percents of the motor parameters change over the periods of the components according to the characteristics of the operation utilised in that component. For instance, when the operator wants to swing the dipper in any direction, he excites the swing motor by manipulating the swing lever controller in desired direction and thus the machine starts to swing in that direction. When the shovel is digging, the lower structure is stationary. To facilitate swing motions, a large diameter roller circle is placed between the lower car-body and upper revolving frame. Therefore a shovel can easily complete the swing motion after the motion is initiated at the beginning of the period. As it is also seen from Figure 5.4(b), more than half of the energy used in complete swing to face operation is consumed in the first 4 divisions which corresponds to 40% of the complete period. And its magnitude starts to decrease gradually in the rest divisions of the period. Similar characteristic is observed in swing to dump operation. If enough acceleration is provided to the moving part of the machine during the beginning of the swing period, swing energy distribution within the period will always show the similar characteristics. Swing motion is not expected during the digging component, therefore it is not included in the related chart.

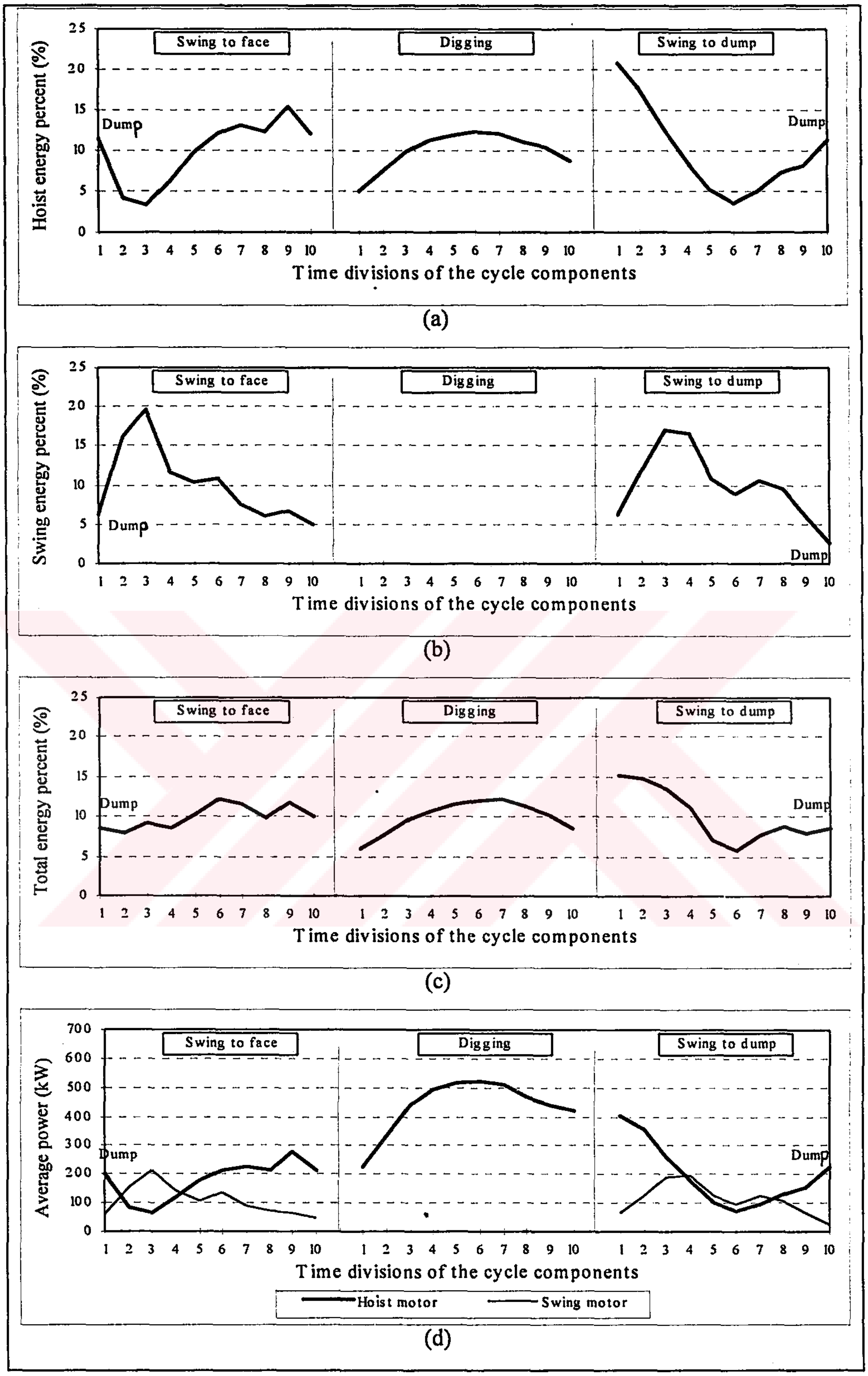


Figure 5.4(a) Hoist, (b) swing, (c) total energy percentage and (d) average power distributions in the time divisions of the cycle components.

When the hoist motor energy distributions in the swing components are evaluated, it is observed that the hoist motor consumes more energy slightly before and after digging operation. During the field studies, it was observed that the dipper is lowered simultaneously as the machine swings back to the face after dump and it is hoisted just before the dipper contacts with the material for digging. When digging is performed on loose material piles, the dipper is filled more easily. Therefore, at the end of digging in such conditions, the position of the dipper in vertical direction is not high enough to dump the material into the truck. Consequently the loaded dipper is hoisted up to the dumping level as it is moved towards the truck. Because of these operational characteristics, the hoist energy consumption are irregular within the swing periods and hoist motor is more active slightly before and after digging.

When the total energy values, including the crowd motor energy as well as the hoist and the swing motor energies, are concerned, total energy percent distributions in the components, except the digging component, are more regular than those of the individual motors (Figure 5.4(c)). Because the energy consumption amount of motors in small intervals of the whole periods are substituting each other especially in the swing components. For instance, total energy percents range from 7.9 to 12.2 in swing to face component and they range from 5.7 to 15.1 in swing to dump component. On the other hand, if the energy percents of the individual motors are considered the difference between the range limits increase for both the hoist and the swing motors. According to the values of Figures 5.4(a) and (b), the hoist energy percent values range from 3.4 to 15.5 and from 3.6 to 20.9 whereas the swing energy percent values range from 4.9 to 19.7 and from 2.5 to 17.1 in swing to face and swing to dump components respectively. If the digging component is considered, there is no remarkable difference between the hoist and the total energy distributions. According to the results, the hoist energy percent values range from 5 to 12.3 and the total energy percent values range from 6 to 12.2 in digging period.

Peak power of a motor is an instantaneous value in a period and therefore it indicates nothing related to the work done, but the average power of the same motor in the same period indicates the difficulty of the work done in the period. Amount of energy consumed by a motor in a period of motion is directly related to the average motor power over the period. As it is observed in Figure 5.4(d), the average power values of the hoist and the swing motors in the swing periods change parallel to the changes in their energy percents.

The results of digging operations are not discussed in details in this section. But, concerning the figure, it can be said that the distributions of different parameters related to the digging component display a typical concave down shape (Figures 5.4(a), (b) and (d)). This typical distribution of the parameters in digging operation can be explained on the basis of both the material and the operational characteristics. As it is mentioned earlier, the results given in this section belong to the cycles which are obtained during digging of loose material piles at the of the face. It is observed that the shape of these material piles are similar to a semi-cone and its dimensions mostly depend on the amount of the material. On the other hand, the digging path followed by the dipper is in arc shape when especially this kind of material is dug to fill the dipper. As a result of these characteristics, amount of dipper penetration into the material, in other words depth of cut, is minimum at very beginning parts of digging operation and gradually increases as the dipper advances in the material. It reaches to its maximum value in the middle parts of the operation and again decreases gradually in the second half of the operation. It is observed during field studies that although the dipper is full with the material it is still in contact with the material at the end of digging. In such a situation, the dipper is retracted in an amount enough to finish the interaction between the material and the dipper, and then swing motion is initiated to dump the loaded material. As a result of above characteristics observed in digging, the curves of energy percents and the average power values of the hoist motor are in concave down shapes.

5.3.2. Digging Time and Digging Energy

Digging is the most important operation in a cycle since the machine properly interacts with the material during this operation. As a result of this reality, the major part of cycle energy is consumed in digging period (Figure 5.3). More detailed parameters of digging operation are given in Table 5.2. In the table, the digging time ranges from 5.01 to 11.25 seconds whereas the digging energy values lie between 0.646 and 1.770 kWh. A 125% increase in digging time and a

174% increase in digging energy are observed between the lowest and the highest values of digging parameters. When the same calculations are done for cycle parameters, increments between the lowest and the highest values of cycle time and cycle energy are found as 59 and 103% respectively. If these results are considered it can also be said that rather than the whole cycle parameters the digging parameters are more sensitive to digging characteristics.

The relationship between the digging energy and the digging time is illustrated in Figure 5.5. As it is seen, the digging energy increases with increasing digging time. Although it is not meaningful in complete cycle period, a good relationship is obtained for the digging parameters. A linear expression of the digging energy as a function of the digging time is obtained as follows.

$$DE = 0.1559 * DT \qquad r = 0.78 \tag{5.1}$$

where:

DE is the digging energy, kWh
DT is the digging time, s
r is the correlation coefficient

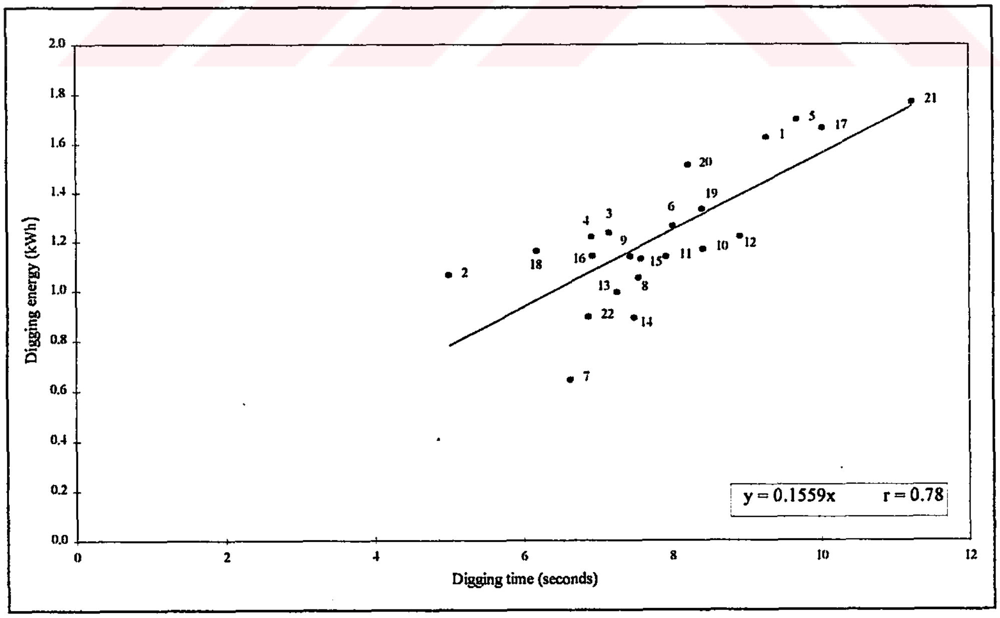


Figure 5.5 Relationship between digging time and digging energy.

Table 5.2 Average values of the digging parameters for the monitored cases, the dipper was filled by digging the blasted and piled material at the toe of the face.

Case code no	Number of cycles	Digging time (s)	Digging energy (kWh)	Time normalised digging energy (kWh/s)	Energy consumptions of the motors in digging			Energy consumption percentages of the motors in digging			Peak and average powers of the motors obtained in digging					
					Hoist motor (kWh)	Crowd motor (kWh)	Swing motor (kWh)	Hoist motor (%)	Crowd motor (%)	Swing motor (%)	Hoist motor		Crowd motor		Swing motor	
											Peak (kW)	Average (kW)	Peak (kW)	Average (kW)	Peak (kW)	Average (kW)
1	76	9.28	1.626	0.176	1.260	0.341	0.024	77	21	2	753	494	270	133	64	10
2	70	5.01	1.065	0.214	0.849	0.201	0.015	80	19	1	914	621	254	148	46	12
3	42	7.16	1.236	0.174	1.078	0.151	0.007	87	12	1	819	549	170	78	28	4
4	10	6.93	1.220	0.176	0.939	0.267	0.014	77	22	1	814	493	246	141	39	7
5	43	9.68	1.699	0.177	1.355	0.332	0.011	80	19	1	875	512	242	125	39	5
6	50	8.02	1.264	0.159	0.994	0.257	0.012	78	21	1	841	456	231	117	31	6
7	91	6.64	0.646	0.098	0.431	0.169	0.046	67	26	7	398	238	247	93	100	26
8	45	7.56	1.053	0.141	0.684	0.347	0.023	65	33	2	625	334	343	168	113	11
9	11	7.44	1.139	0.154	0.820	0.307	0.013	72	27	1	639	401	316	150	68	6
10	21	8.42	1.171	0.140	0.798	0.353	0.020	68	30	2	655	344	346	152	77	9
11	36	7.93	1.141	0.144	0.755	0.347	0.038	66	31	3	629	345	346	159	127	17
12	27	8.92	1.221	0.138	0.896	0.297	0.028	73	25	2	634	365	318	122	95	12
13	26	7.27	0.997	0.138	0.678	0.292	0.026	68	30	2	621	342	338	146	99	14
14	36	7.49	0.893	0.120	0.586	0.259	0.049	66	29	5	572	286	310	126	145	24
15	31	7.59	1.129	0.149	0.773	0.333	0.023	68	30	2	665	372	352	159	69	11
16	34	6.94	1.141	0.166	0.788	0.278	0.075	69	25	6	665	416	343	145	197	40
17	27	10.03	1.664	0.166	1.373	0.271	0.020	82	17	1	823	441	209	88	40	7
18	86	6.18	1.163	0.189	0.909	0.239	0.015	78	21	1	867	536	239	141	41	9
19	58	8.41	1.334	0.159	1.048	0.270	0.016	78	21	1	763	453	213	117	29	7
20	28	8.23	1.513	0.185	1.213	0.290	0.011	80	19	1	883	539	241	127	42	5
21	36	11.25	1.770	0.157	1.457	0.298	0.015	82	17	1	859	534	216	108	48	6
22	35	6.88	0.898	0.131	0.671	0.211	0.015	74	24	2	728	360	216	111	51	9
Average		*7.88*	*1.226*	*0.157*	*0.925*	*0.278*	*0.023*	*75*	*23*	2	*729*	*429*	*273*	*130*	*72*	*12*
St.dev. (±)		*1.38*	*0.282*	*0.026*	*0.272*	*0.057*	*0.016*	*7*	*6*	2	*129*	*99*	*57*	*24*	*44*	*9*

Power generated by the motors show significant differences between complete cycle and digging periods. Overall average powers generated by the hoist motor are obtained as 253 and 429 kW in cycle and digging periods respectively (Tables 5.1 and 5.2). These also verifies that the hoist motor is more active in digging operation than it is in the other components. Similarly, crowd motor does more work in digging than it does in the rest parts of a cycle. But, on the other hand, swing motor is more active in the operations other than digging, therefore 12 kW average power in digging increases to 82 kW in complete cycle.

Similar to power values, amount of energy consumed by the motors also differ between cycle and digging periods. According to the average energy consumption values of the motors given in Tables 5.1 and 5.2, the distributions of cycle and digging energy values in the motors are obtained as illustrated in Figure 5.6. It is clear on both chart that most of the energy is consumed by hoist motor in both periods. In complete cycle, hoist motor consumes 60% of total energy whereas the rest is consumed by crowd and swing motors equally. But in digging operation, the consumption of hoist motor increases up to 75% as crowd motor consumption slightly increases to 23%. Swing motor consumes only 2% of total digging energy since it is idle. As it is expected, the results show that the hoist motor is the most effective one in digging. When the design characteristics of the machines are considered, it is also recognised that the hoist motors are therefore the most powerful ones in all models of the studied electric shovels (Table 4.2).

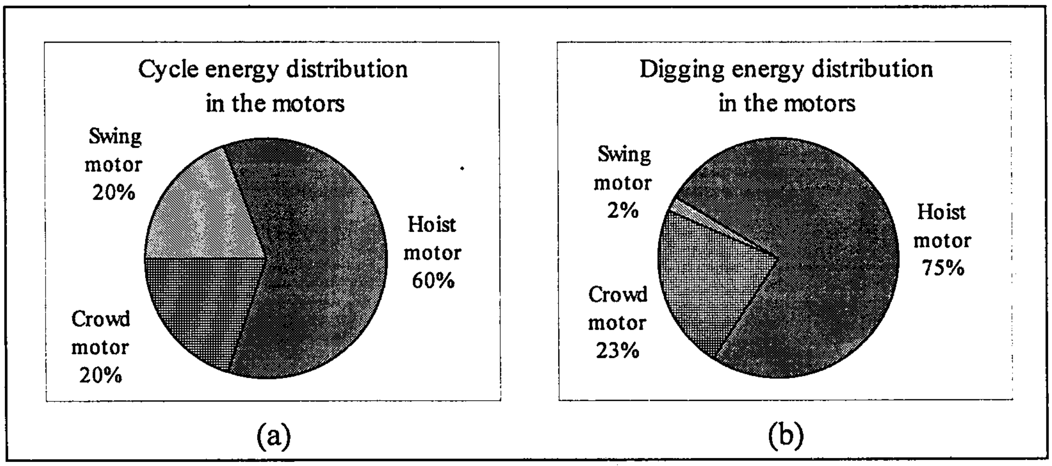


Figure 5.6 (a) Cycle and (b) digging energy distributions in the motors.

5.3.3. Specific Cycle Energy

As it is explained in section 5.3, it is found more meaningful to establish a parameter between input and output variables of any kind of work doing system. If this approach is adapted to electric power shovels, a performance parameter can be generated between the amount of energy and the amount of material passed which are simply the input and the output variables of electric power shovels.

On the basis of above approach and definition, a parameter named as specific cycle energy, SCE, is established between the input and the output variables of the machine obtained for complete cycle period. According to this definition, SCE is used to determine the amount of energy required to dig and remove a unit quantity of the overburden material. In this study, amount of material passed in a dipper is preferably determined in bank measures rather than dipper measures. Because when the overburden removal activity in an open pit mine is being projected, the amount of overburden material will be excavated is generally defined in its bank measures. Therefore the amount of material passed in a cycle is calculated in bank measures in both volume and weight by incorporating swell percent and natural unit weight of the material as well as the dipper capacity and its fill percentage in each cycle. Then the specific cycle energy value is determined by dividing the cycle energy with the amount of material passed in that cycle.

Specific cycle energy values are firstly determined for all of the cycles obtained from the monitored cases, before they are grouped according to some cycle characteristics. The average results of the cycles in which the digging operations is performed to dig blasted and piled material are summarised in Table 5.3. The parameters other than the specific cycle energy are also determined and included in the same table, but those parameters together with the related drawings are evaluated and discussed in the related sections of this chapter.

Specific cycle energy values calculated on the basis of bank volume of material range from 0.2 to 0.336 kWh/m^3 which denotes the amount of energy required to remove 1 m^3 of bank material. A similar expression can be done for the unit weight of bank material. According to the results, minimum and maximum energy consumption amount for 1 ton of bank material are calculated as 0.081 and 0.164 kWh respectively. Weight based SCE values are simply calculated by dividing the volume based SCE values with natural unit weight of the material which ranges from 1.80 to 2.47 t/m^3 (Table 4.5).

Table 5.3 The parameters obtained from cycle variables.

Case code no	Number of cycles	Cycle time (s)	Cycle energy (kWh)	Specific cycle energy (kWh/m^3)	Specific cycle energy (kWh/t)	Hourly capacity (m^3/h)	Hourly capacity (t/h)
1	76	31.07	4.064	0.306	0.124	1552	3835
2	70	21.86	2.597	0.260	0.106	1664	4094
3	42	25.14	2.909	0.219	0.089	1921	4725
4	10	24.29	2.919	0.239	0.097	1825	4490
5	43	30.57	3.400	0.278	0.113	1461	3595
6	50	30.25	3.479	0.307	0.151	1357	2769
7	91	24.71	1.998	0.200	0.081	1464	3630
8	45	27.11	3.567	0.320	0.140	1496	3418
9	11	29.09	3.584	0.321	0.141	1388	3171
10	21	31.59	3.684	0.330	0.144	1279	2922
11	36	27.64	3.533	0.317	0.139	1462	3340
12	27	31.73	3.339	0.299	0.131	1287	2940
13	26	27.84	3.249	0.291	0.127	1458	3330
14	36	31.34	3.615	0.319	0.149	1318	2827
15	31	28.92	3.242	0.286	0.134	1420	3044
16	34	27.19	3.802	0.336	0.157	1508	3233
17	27	34.71	3.351	0.287	0.160	1227	2208
18	86	24.00	2.926	0.304	0.124	1453	3574
19	58	27.58	3.037	0.315	0.128	1263	3106
20	28	28.22	3.243	0.286	0.116	1450	3566
21	36	31.98	3.420	0.280	0.129	1395	3013
22	35	23.81	2.379	0.294	0.164	1228	2203
	Average	*28.21*	*3.243*	*0.291*	*0.129*	*1449*	*3320*
	St.dev. (±)	*3.29*	*0.480*	*0.035*	*0.022*	*176*	*621*

Graphical views given in Figures 5.7 and 5.8 are obtained by plotting the values of specific cycle energy against corresponding cycle time. Although the specific cycle energy display increasing tendencies parallel to cycle time, the trend is not regular enough to acquire an acceptable arithmetical expression for any of these parameters as a function of cycle time. As it is explained in the previous section, a regular relationship between the cycle energy and time is also not obtained because of explained reasons. As a result, similar irregularities are inevitably observed in the specific cycle energy parameters.

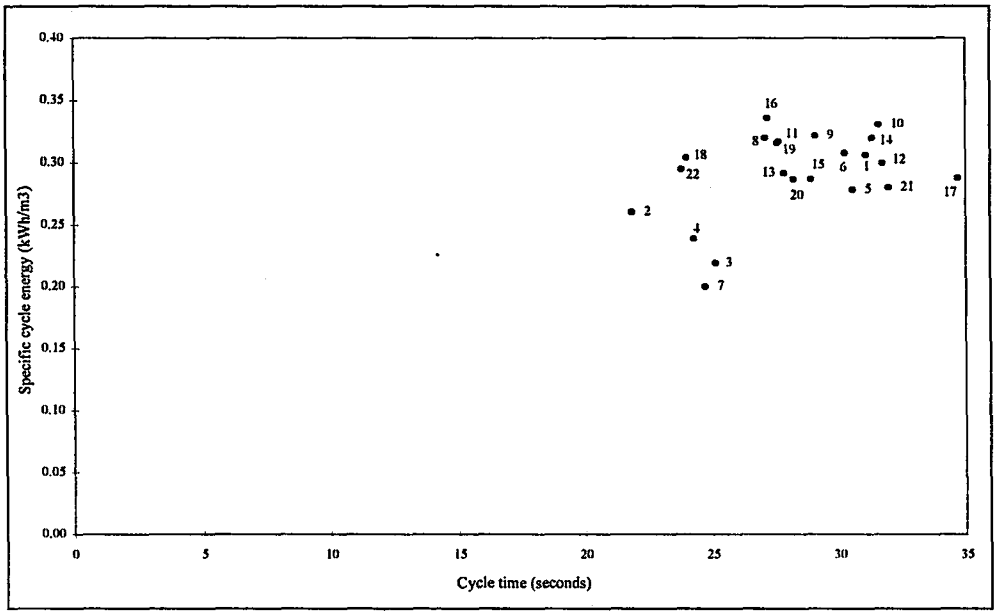


Figure 5.7 Relationship between cycle time and specific cycle energy, kWh/m^3.

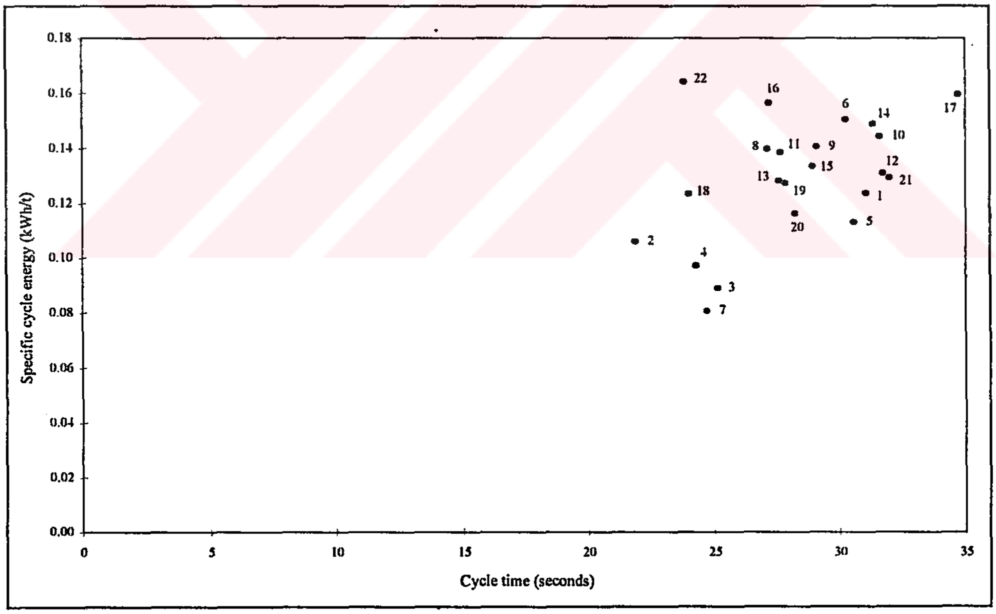


Figure 5.8 Relationship between cycle time and specific cycle energy, kWh/t.

5.3.4. Specific Digging Energy

It is clear that the shovels properly interact with the excavated material during the digging operation periods of the cycles. In the other two components of a cycle which are swing to face and swing to dump components, the effects of excavated material properties are not observed clearly. Although the complete cycle periods include the digging components as well as the others, the performance parameters of the complete cycle periods are not sensitive to the changes in the digging conditions as much as those of the digging periods. Therefore, rather than the whole cycle parameters, the parameters obtained in the digging components of the cycles are considered to be more relevant to study the effects of digging conditions on the parameters.

Similar to specific cycle energy, a parameter named as specific digging energy, SDE, is defined between the amount of energy consumed in digging operation and the corresponding amount of material excavated. This parameter is also determined for both unit volume and unit weight of bank material. The results are tabulated in Table 5.4 together with the other parameters related to the digging period. According to the results, SDE values for bank volume measure are in the range of 0.065-0.145 kWh/m^3 whereas they are between 0.026 and 0.079 kWh/t for bank weight measure. Average values of specific digging energy parameters are determined as 0.11 kWh/m^3 and 0.049 kWh/t. The highest values for both measures are obtained in the case 21 which belongs to ÇLİ Çan-1 Panel and a Marion 191 M-II shovel with 20 yd^3 dipper capacity. The rock type in this panel is agglomerate and therefore very large blocks are observed together with soil material which especially decreases the fill percentage of the dipper and the large blocks increase the amount of energy consumed to remove them. On the other hand, the lowest energy consumption values for per unit amount of material are obtained in the case 7, in ELİ Merkez Sarıkaya panel where a P&H 2100 BLE 17 yd^3 shovel operate. Fragmentation in this panel is homogeneous and block sizes are small because of low discontinuity spacing.

Table 5.4 The parameters obtained from digging component variables.

Case code no	Number of cycles	Digging time	Digging energy	Specific digging energy		Hourly digging capacity	
		(s)	(kWh)	(kWh/m^3)	(kWh/t)	(m^3/h)	(t/h)
1	76	9.28	1.626	0.122	0.050	5200	12844
2	70	5.01	1.065	0.107	0.043	7343	18063
3	42	7.16	1.236	0.093	0.038	6763	16637
4	10	6.93	1.220	0.100	0.041	6421	15797
5	43	9.68	1.699	0.139	0.056	4600	11317
6	50	8.02	1.264	0.112	0.055	5136	10478
7	91	6.64	0.646	0.065	0.026	5488	13611
8	45	7.56	1.053	0.094	0.041	5391	12312
9	11	7.44	1.139	0.102	0.045	5427	12395
10	21	8.42	1.171	0.105	0.046	4820	11009
11	36	7.93	1.141	0.102	0.045	5102	11654
12	27	8.92	1.221	0.110	0.048	4559	10413
13	26	7.27	0.997	0.089	0.039	5582	12749
14	36	7.49	0.893	0.079	0.037	5584	11972
15	31	7.59	1.129	0.100	0.046	5403	11585
16	34	6.94	1.141	0.101	0.047	5941	12737
17	27	10.03	1.664	0.142	0.068	4205	8780
18	86	6.18	1.163	0.121	0.049	5656	13913
19	58	8.41	1.334	0.139	0.056	4162	10238
20	28	8.23	1.513	0.134	0.054	5009	12321
21	36	11.25	1.770	0.145	0.079	3904	7164
22	35	6.88	0.898	0.111	0.049	4314	9750
Average		*7.88*	*1.226*	*0.110*	*0.049*	*5281*	*12104*
St.dev. (±)		*1.38*	*0.282*	*0.021*	*0.011*	*843*	*2588*

Relationships between specific digging energy and digging time values are illustrated in Figures 5.9 and 5.10. As it is seen in these figures, a better relationship is obtained between amount of energy required to remove one ton of bank material and digging time. This result shows that the natural unit weight of the material is also an important variable which must be taken into consideration when the digging difficulty of material is determined. During digging operation, the dipper is filled with the material as it is pulled up by the hoist motor. The hoist motor generates power enough to overcome the forces result from mechanical structure of the machine, physical dimensions of the dipper, material properties, etc. which act in the reverse direction of motion. One of these forces is gravitational force that is characterised by material weight in the dipper and its magnitude increases in digging as the amount of material in the dipper increases.

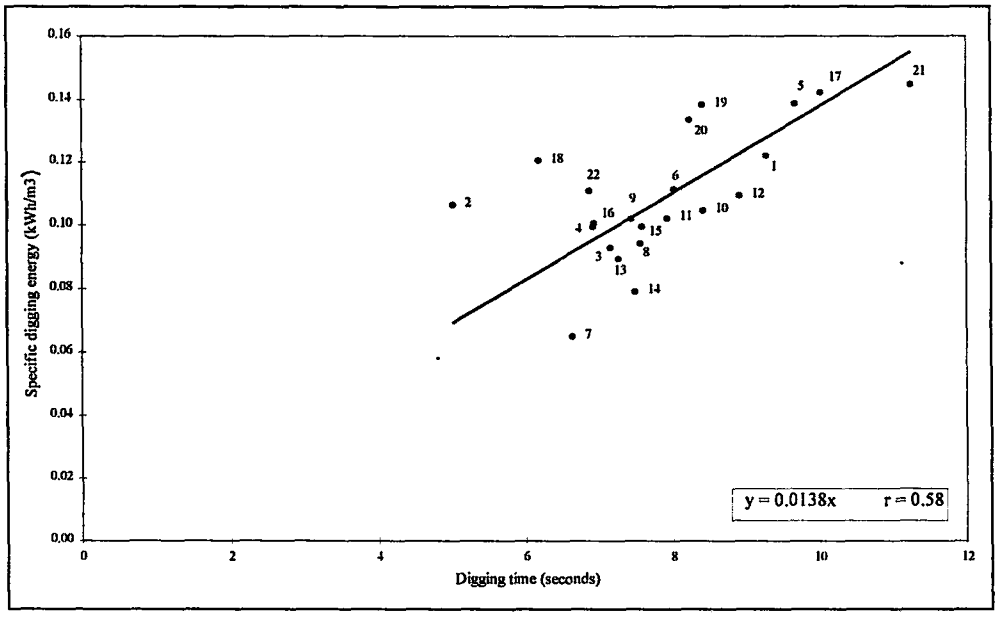


Figure 5.9Relationship between digging time and specific digging energy, kWh/m^3.

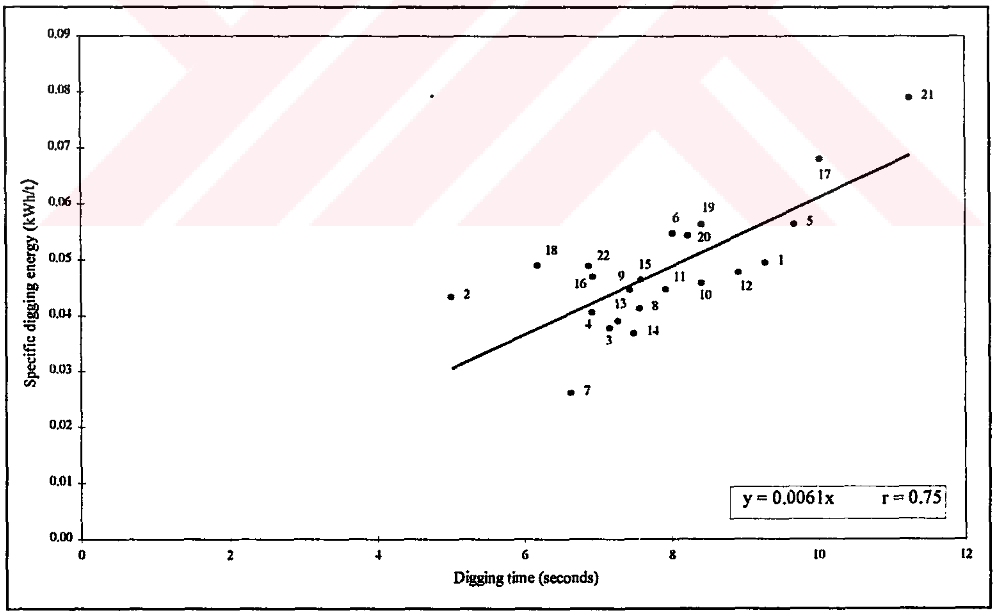


Figure 5.10 Relationship between digging time and specific digging energy, kWh/t.

As a result of regression analysis conducted between specific digging energy parameters and digging times, following expressions are obtained.

$$SDE_v = 0.0138 * DT \qquad r = 0.58 \qquad 5.2$$

$$SDE_w = 0.0061 * DT \qquad r = 0.75 \qquad 5.3$$

where:

SDE_v is the specific digging energy by bank unit volume, kWh/m^3
SDE_w is the specific digging energy by bank unit weight, kWh/t
DT is the digging time, s

5.3.5. Hourly Capacity

Hourly capacity of a shovel which embodies both cycle time and material amount passed in the cycle is a production parameter and it can also be a good indicator of digging difficulty.

Similar to the other cycle parameters, this parameter is also determined separately for each cycle of a case and then the obtained cycle values are averaged to find the case value of the parameter (Table 5.3). Hourly capacities of the shovels are also found as the volume or the weight of bank material removed in an hour. Since these parameters are determined on the base of cycle variables, they do not include the lost times because of waiting idle or any kind of temporary breakdowns or time spent for propelling motions. The results of 22 cases are plotted against cycle time values as they are illustrated in Figures 5.11 and 5.12.

As it is observed in both figures, hourly capacities decrease as cycle time values increase and a better correlation is obtained between the weight based hourly capacities and the cycle times. If the results of all cases are averaged, the parameters are found as 1449 m^3/h and 3320 t/h. Volume based hourly capacities of the cases change between 1227 and 1921 m^3/h whereas the weight based values are in the range of 2208-4725 t/h.

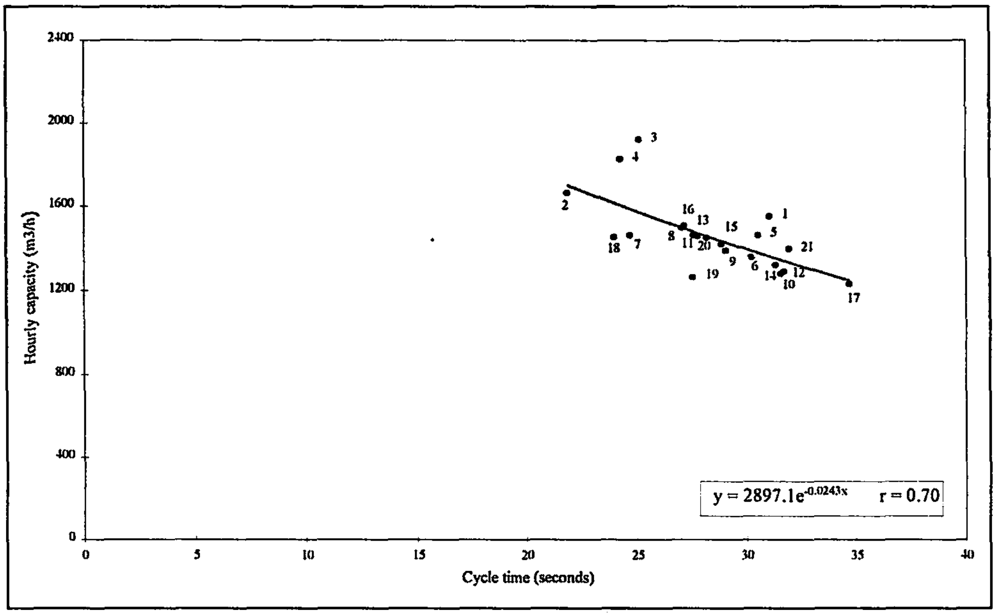


Figure 5.11 Relationship between cycle time and hourly capacity, m^3/h.

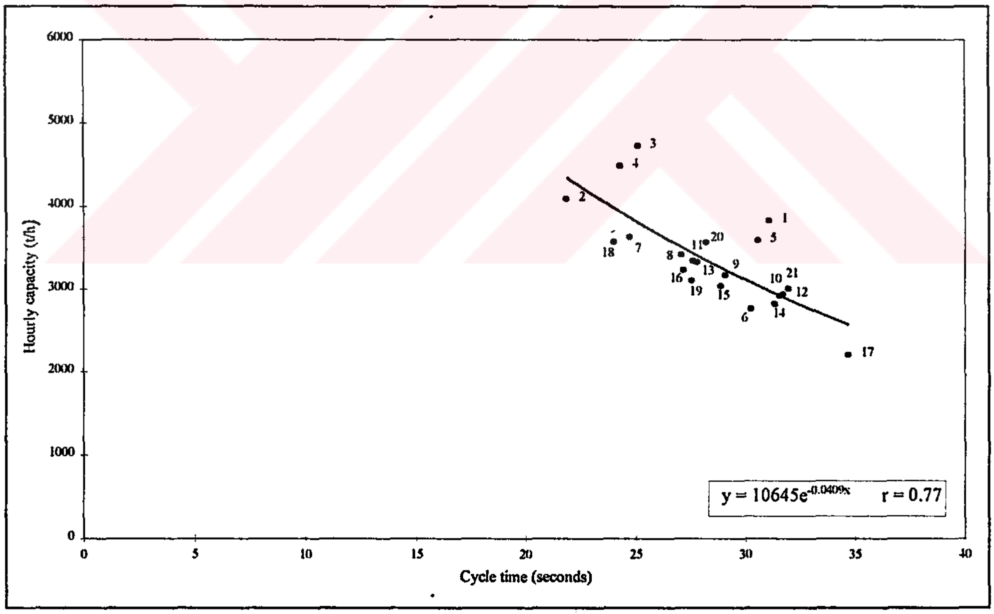


Figure 5.12 Relationship between cycle time and hourly capacity, t/h.

Following equations are obtained from regression analysis conducted between hourly capacities and cycle times.

$$HC_v = 2897.1e^{-0.0243 * CT} \qquad r = 0.70 \qquad 5.4$$

$$HC_w = 10645e^{-0.0409 * CT} \qquad r = 0.77 \qquad 5.5$$

where:

HC_v is the hourly capacity by bank volume, m^3/h
HC_w is the hourly capacity by bank weight, t/h
CT is the cycle time, s

5.3.6. Hourly Digging Capacity

Different than hourly capacities, hourly digging capacities are determined on the basis of digging time instead of cycle time, but the amount of material passed in a cycle is taken same in both calculations. Although hourly digging capacity is not considered as a practical production parameter, it can rather be applied to predict the digging condition. Figures 5.13 and 5.14 illustrate the relationships between hourly digging capacities and digging times.

In both Figures 5.13 and 5.14, the highest capacity is utilised in the case 2 which belongs to a rehandling operation as well as the cases 1 and 3. The characteristics of material removed in these cases are quite distinguishable from the others because the rehandled material was already transported once during the activities done in the previous dates. Therefore the rehandled material is generally highly disintegrated as a result of both the previous transportation and in situ weathering in the course of time. Swell percentage of rehandled material is very low, hence the amount of material passed in a dipper is high. Although the case 1 also belongs to a rehandling operation, its hourly digging capacity is highly lower than those of the other rehandling cases. The rehandled material in the case 3 is comparatively soil type and the material was slightly damp during monitoring process because of rainfall. These properties of the material made the digging operation a bit more difficult and increased both digging time and energy. On the other hand, the lowest digging capacity is obtained in case 21 in which the material size distribution is very non-homogeneous and contains very large blocks. Similar digging condition is observed in case 17.

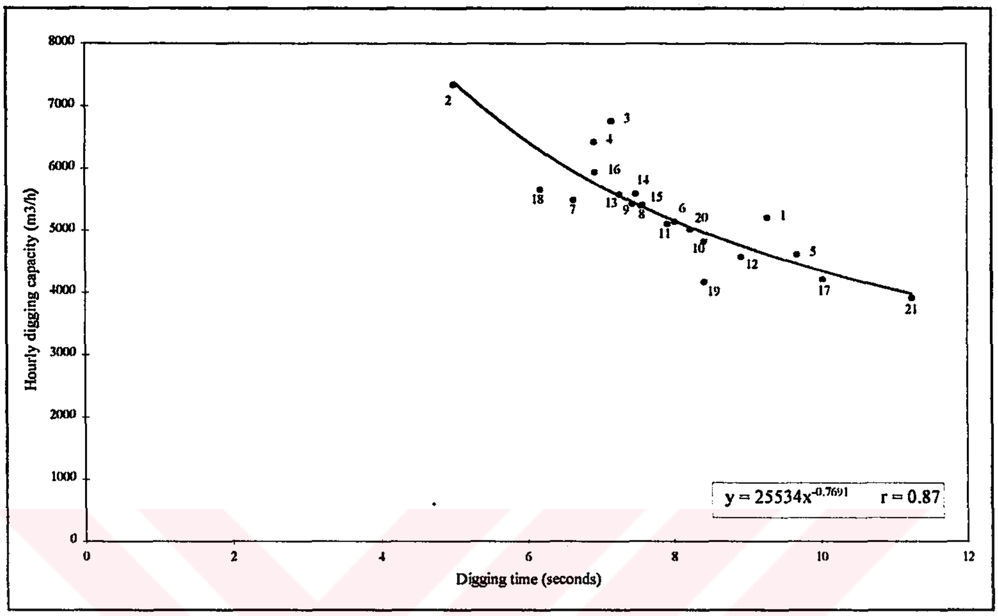


Figure 5.13 Relationship between digging time and hourly digging capacity, m^3/h.

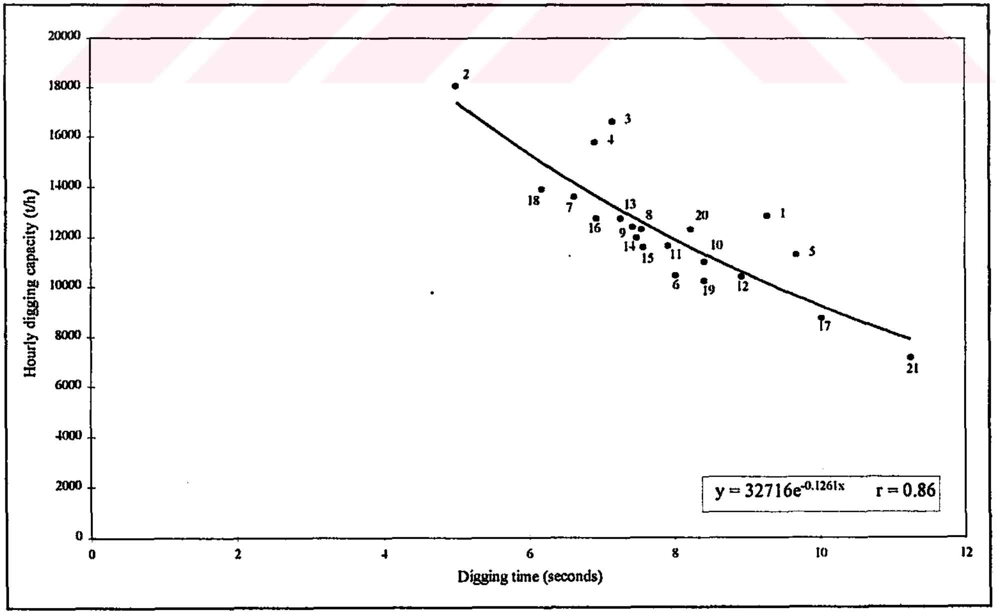


Figure 5.14 Relationship between digging time and hourly digging capacity, t/h.

Rather than hourly capacity, hourly digging capacities had better relations with corresponding time values. At the end of regression analysis done between hourly digging capacities and digging times, good correlation is obtained between the parameters of such a field study.

$$HDC_V = 25534 * DT^{-0.7691} \qquad r = 0.87 \qquad 5.6$$

$$HDC_W = 32716e^{-0.1261 * DT} \qquad r = 0.86 \qquad 5.7$$

where:

HDC_V is the hourly digging capacity by bank volume, m^3/h
HDC_W is the hourly digging capacity by bank weight, t/h
DT is the digging time, s

5.3.7. Relationships between Cycle and Digging Parameters

The results of meaningful parameters which are determined for both whole cycle period and digging component period of cycle are presented and discussed in the previous sections independently. In general, it can be stated that the cycle parameters such as cycle time, cycle energy, etc. are rather applied to estimate production performances of the machines for practical applications. On the other hand, rather than the cycle parameters, the parameters obtained for only digging operation period of a complete cycle are more appropriate variables to investigate digging abilities of the shovels since the machine perfectly interacts with the material during this operation. Although the tendencies of both cycle and digging parameters slightly change in these periods as they are discussed before, meaningful relationships between cycle and digging periods are obtained for some parameters.

The relation between cycle and digging times obtained from all monitored cases is illustrated in Figure 5.15. Despite cycle time generally increases with increasing digging time, this general trend is not satisfied in some cases, for instance the case 21. If the values of the case 21 are compared with those of the case 17, it is found that a longer time is spent in digging operation of the case 21, on the contrary, the complete cycle is completed in a shorter time. While the digging times of the cases 17 and 21 are obtained as 10.03 and 11.25 seconds respectively, the corresponding cycle times are found as 34.71 and 31.98 seconds. It is known that a complete cycle also includes swing operations as well as digging. When the swing operation times of the cases given in Table 5.1 are controlled, it is seen that both swing operations of the case 17 are completed in periods over 12 seconds, but on the other hand the same operations in the case 21 are completed in the periods two seconds shorter than those of the case 17. This irregularity in cycle time is particularly resulted by differences in truck positions which necessitate different amount of swing angles in the related cases. It can be concluded that truck position is also an important parameter when the cycle variables are especially concerned.

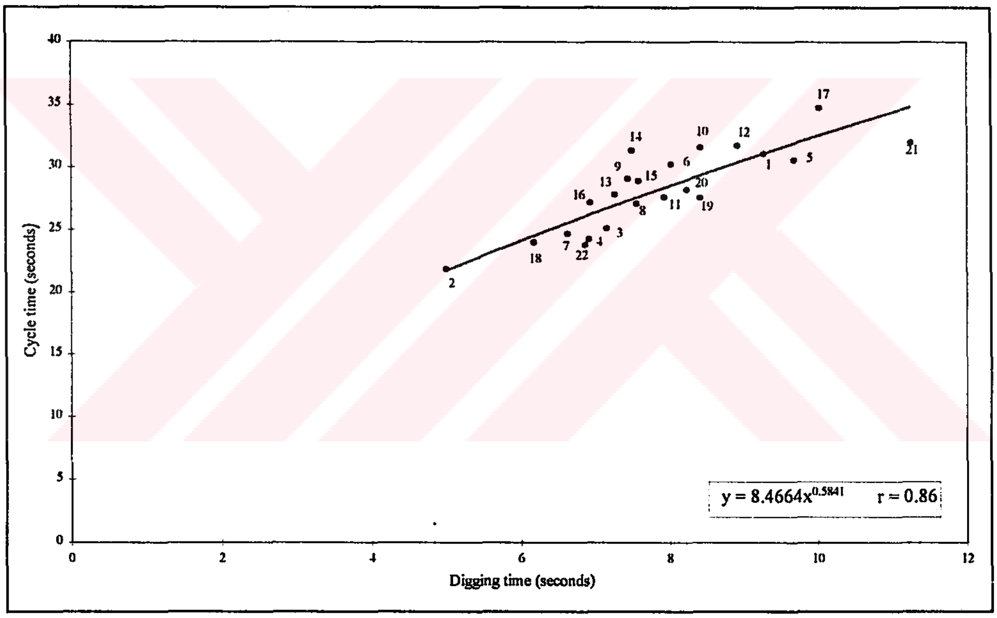


Figure 5.15 Relationship between digging and cycle time.

In spite of irregularities between cycle and digging times are observed in Figure 5.15, a good correlation is obtained between two parameters. Following expression of cycle time as a function of digging time is obtained as a result of regression analysis.

$$CT = 8.4664 * DT^{-0.5841} \qquad r = 0.86 \qquad 5.8$$

where:

CT is the cycle time, s
DT is the digging time, s

Similar to time values, cycle energy values are plotted against digging energy values to obtain a relation between these parameters (Figure 5.16). As it seen in the figure, points of P&H shovels are concentrated in the middle part of the graph since they operate only in GLİ district where the characteristics of the material do not show differences. On the other hand, Marion shovels operate in different districts which characterise a wider spectrum of material characteristics. As a result, a high cocrrelation is obtained for the parameters obtained from the Marion shovels, as illustrated in the figure. The results of P&H shovels indicate an average digging energy of 1.1 kWh and an average cycle energy of 3.7 kWh for GLİ district.

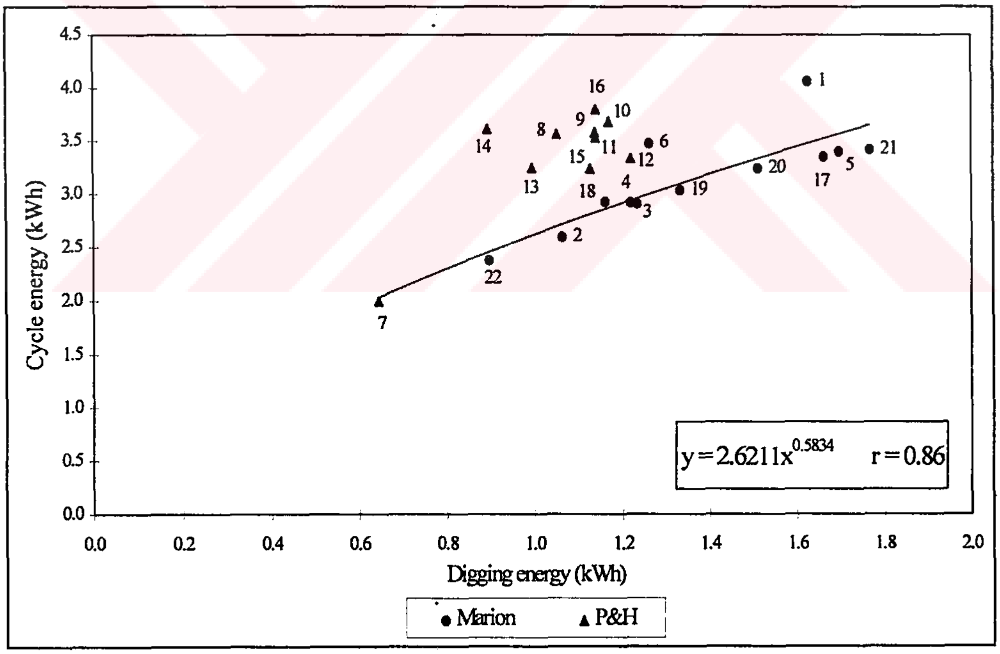


Figure 5.16 Relationship between digging and cycle energy.

As a result of irregularities observed in the energy parameters, very low correlation are obtained between specific cycle energy and specific digging energy parameters of the periods. But, good relations between hourly capacity and hourly digging capacity parameters are obtained as illustrated in Figures 5.17 and 5.18 respectively. Good correlation between the capacity parameters are expected after getting a similar correlation between cycle and digging times, since the same amount of material is used in the calculations of the capacities. These results show that a better correlation is obtained if the capacities are calculated for bank weight of material. According to the results, hourly capacities can be defined as:

$$HC_V = 10.712 * HDC_V^{0.5726} \qquad r = 0.79 \qquad 5.9$$

$$HC_W = 0.2696 * HDC_W \qquad r = 0.84 \qquad 5.10$$

where:

HC_V is the hourly capacity by bank volume, m^3/h

HC_W is the hourly capacity by bank volume, t/h

HDC_V is the hourly digging capacity by bank volume, m^3/h

HDC_W is the hourly digging capacity by bank weight, t/h

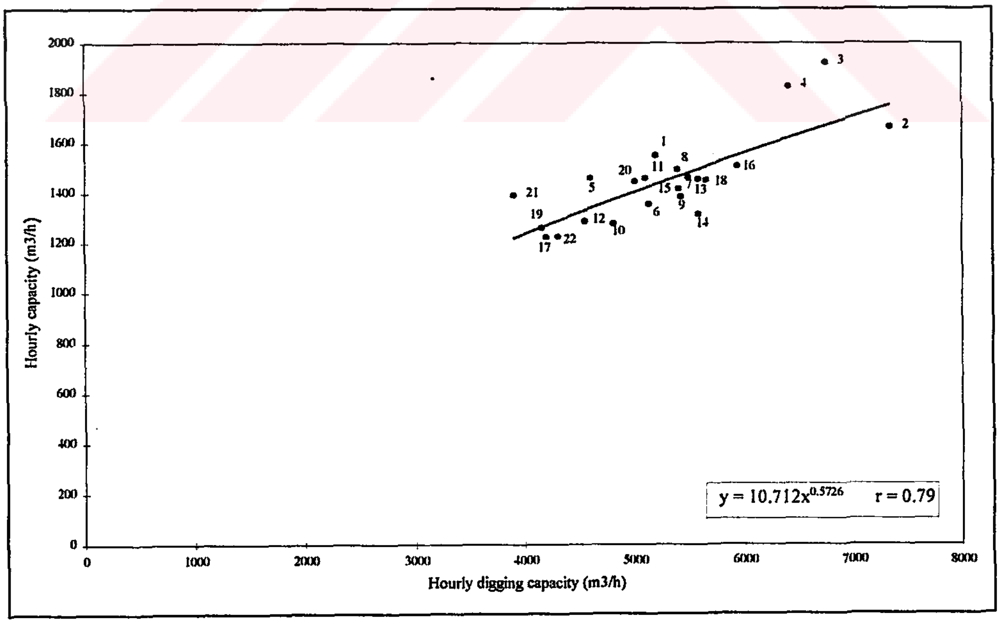


Figure 5.17 Relationship between hourly digging capacity and hourly capacity, m^3/h.

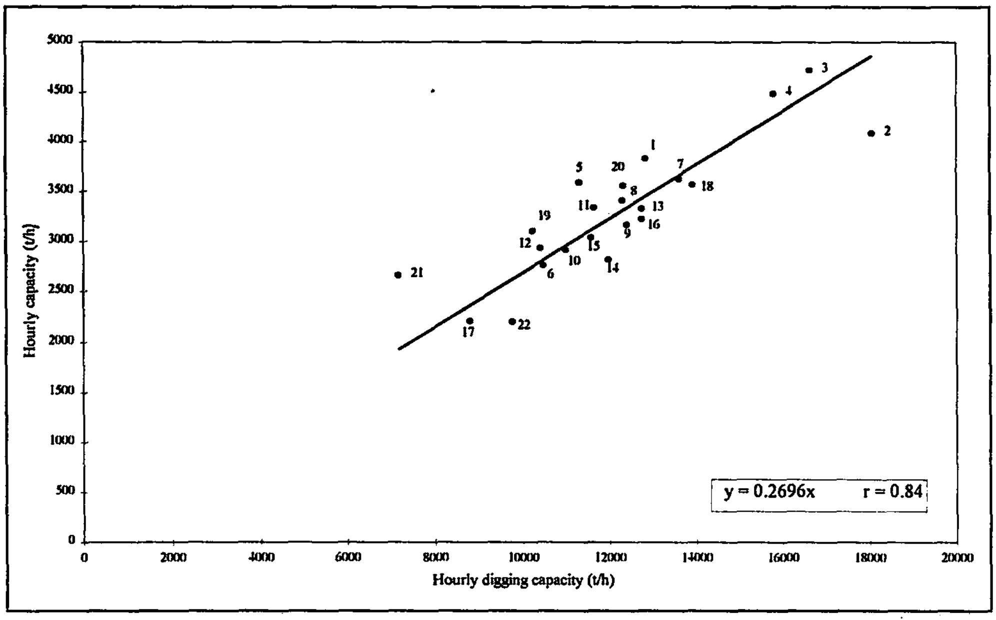


Figure 5.18 Relationship between hourly digging capacity and hourly capacity,t/h.

5.4. Discussion on Some Operational Variables

The monitored cases included in this study are mainly distinguished by their characteristics related to both the machine and the material as they are defined in Table 5.4. As well as the cases, cycles of a specific case are also distinguished by unlike operations observed in different cycles; for instance, various digging applications in different cycles. This kind of important dissimilarities, if any observed, between the cycle operations are noted during monitoring process. Thus the cycles are grouped during data processing operation according to their operational characteristics and then the results of each group are evaluated comparatively to investigate the effects of these operational variables on the parameters.

As it is stated before, the monitored shovels differ in their manufacturers, models and dipper capacities. Therefore, the results obtained for different makes and models are individually evaluated to investigate their effects. Similarly, effects of differences in application of lever controllers which are used by the operators to manipulate the motors are also studied. Besides these general variables related to the machines, different digging applications and different dipper fill percentages utilised are discussed in details by their effects on the parameters point of view. The investigations obtained from these evaluations are presented in the following sections.

5.4.1. Machine Makes and Models

Electric power shovels operate at TKİ open pit mines are mainly grouped in two categories according to their manufacturers; P&H and Marion shovels. Different models of these shovels which are characterised by their dipper capacities are also available. Two different models of P&H shovels with 20 and 17 yd^3 capacities, and three different models of Marion shovels with 20,17 and 15 yd^3 capacities were monitored in this study (Table 4.2). As well as the dipper capacities, the models are characterised by the powers of their hoist, crowd, swing and propel motors. If the shovels of two makes with the same capacity are compared, it is seen that P&H shovels are equipped with more powerful motors with respect to Marion shovels. For instance, if the continuous powers of the motors are taken into account, a P&H 2300-XP model with 20 yd^3 capacity has a total motor power of 2061 kW whereas a Marion 191-MII model with the same capacity has a total power of 1572 kW. Although they differ in their powers, this characteristic is not considered as a variable which can affect the resulted energy consumption in a specific digging condition. When the sites are considered for different make shovels, it is observed that the P&H shovels mostly operate at GLİ enterprise except one in ELİ enterprise. Regardless of their makes, it is believed that they are designed to consume more or less the same amount of energy for the same work.

The monitored cases presented in this study were obtained from the models of both P&H and Marion shovels. As well as the parameters are averaged for entire cases, the cases are sorted according to the make of the shovel and then the average values of the parameters are also determined fro each make separately. The results of motor related parameters given in Table 5.5 are distinguishable. According to the results obtained for two different makes of shovels, it is seen that percentages of energy consumed by hoist motor of a Marion shovel whether in digging period or complete cycle period is much higher than the consumption percentages of the other motors. But the energy consumption distributions between the motors of a P&H shovel are rather smooth. If the complete cycle period is considered, hoist motor of a P&H shovel consumes 47% of cycle energy whereas the same motor of a Marion shovel consumes 73%. As a result of differences in hoist motor consumption, the consumption of the other motors change accordingly. According to the results, the consumption of crowd and swing motors of P&H shovels are found 23 and 30% respectively as they are determined 16 and 11% for those of Marion shovels. Similar characteristics are investigated in the average power values of the motors.

Table 5.5 Change in motor related parameters according to shovel makes.

Parameter		Average values for entire cases			Average values for the cases of P&H shovels			Average values for the cases of Marion shovels		
		Hoist	Crowd	Swing	Hoist	Crowd	Swing	Hoist	Crowd	Swing
Energy consumed by the motors in cycle	kWh (%)	1.961 (60)	0.640 (20)	0.641 (20)	1.568 (47)	0.783 (23)	1.010 (30)	2.298 (73)	0.521 (16)	0.333 (11)
Energy consumed by the motors in digging	kWh (%)	0.925 (75)	0.278 (23)	0.023 (2)	0.721 (68)	0.298 (28)	0.034 (3)	1.096 (80)	0.261 (19)	0.015 (1)
Average powers of the motors in cycle	kW	253	82	82	198	99	127	299	69	44
Average powers of the motors in digging	kW	429	130	12	344	142	17	499	120	7

5.4.2. Position of Lever Controller

The basic motions of a shovel are provided by related DC drive motors. The operator commands the motors by manipulating two joy stick lever controllers which are located forward of his seat, one to the right and one to the left. The specific motions are assigned to the lever controllers such that crowd and propel motions are controlled selectively by the one located to the left whereas swing and hoist motions are controlled by the one located to the right. Figure 5.19 illustrates types of the motions according to the position of the swing/hoist lever controller. As it is seen in the figure, the joy stick can be moved in any direction to select one of the motions at a time or a combination of both motions at the same time. This characteristic of the controller is very useful when full dipper is hoisted and swinged towards the truck to dump or when empty dipper is lowered and swinged towards the face after dump. By applying two motions simultaneously, cycle time is reduced and thus the capacity of the machine is increased.

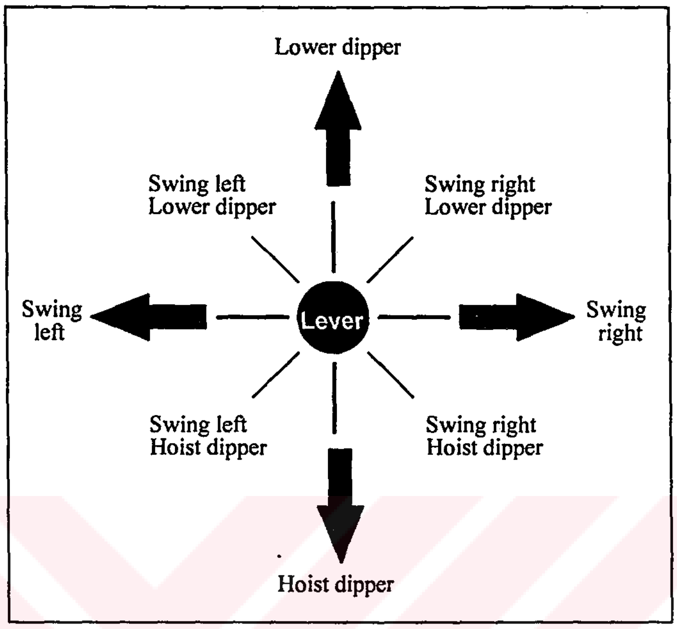


Figure 5.19 The variable positions of the hoist/swing lever controller.

The lever controllers are stepless, that is they automatically return to their neutral positions with springs when they are not in use. But as soon as it is moved in any direction, the command is automatically directed to the related motor and the requested motion is achieved. During the first monitoring trial studies, it is observed that the speed of a motion changes according to the amount of deviation of the lever controller from its neutral position. So that , a swing motion of 180° is completed in a shorter time if the motion is done by pushing the controller to its maximum position rather than by holding it in a middle position. This is, of course, directly related with the amount of power generated by the motor. Therefore a series of data is monitored from the machine when the same amount of swing, hoist and crowd motions are done first by using the controller in its full position and then by using it in its half position. One kind of motion is done each time and it is repeated. The dipper is always empty during these motions.

The monitored data are evaluated to see how the position of the controller affects the parameters. At the end of the evaluation, it is found out that the magnitude of power generated by a motor is significantly affected by the position of the lever controller. The results of these trials are illustrated in Figure 5.20 graphically. As it is seen in the figure, power of a motor clearly changes when the position of the controller is changed. As stated above, the identical motions are done for both positions of the lever controller. For example, by using the lever controller in its full position, a crowd motion is followed by a retract motion for full length of the dipper handle and they are done once more. Afterwards the same motions are repeated by using the controller in its half position. Similarly, the dipper is hoisted from ground to its maximum level and lowered to the ground again, and 180° swing motions are done in both directions. The results of these trials are given in Table 5.6. Time spent to complete a motion increases if the motion is performed by holding the controller in its half position, but on the other hand amount of energy consumed decreases. For instance, the dipper is crowded or retracted in full length of the dipper handle in 6.48 seconds when the lever controller is used in its maximum position, but the same motions are completed in 15.97 seconds (146% increase) if the controller is used in half position. On the contrary, amount of energy consumed by crowd motor during these applications of the lever controller are found 0.084 and 0.038 kWh (55% decrease) respectively. Similar to crowd motions, times for hoist and swing motions increase 97 and 77% whereas energy consumption decrease 26 and 76%. As a result of increase in time and decrease in energy consumption when the lever is applied in half position, corresponding time normalised energy values decrease in higher rates. Besides, peak and average power values of the motors change similar to the changes observed in energy consumption values. According to the results, peak powers of crowd, hoist and swing motors decrease 73 , 71 and 58% while the average powers decrease 81, 50 and 86% respectively.

At the end of these evaluations, it is clearly seen that the position of lever controller highly affects the performance parameters. Therefore, before a monitoring process, the operator is warned not to use the lever controllers arbitrary, rather to use them in its necessitated position for the particular digging condition. Thus the effects of the controller position on the parameters are minimised by trying to provide similar applications for entire cases.

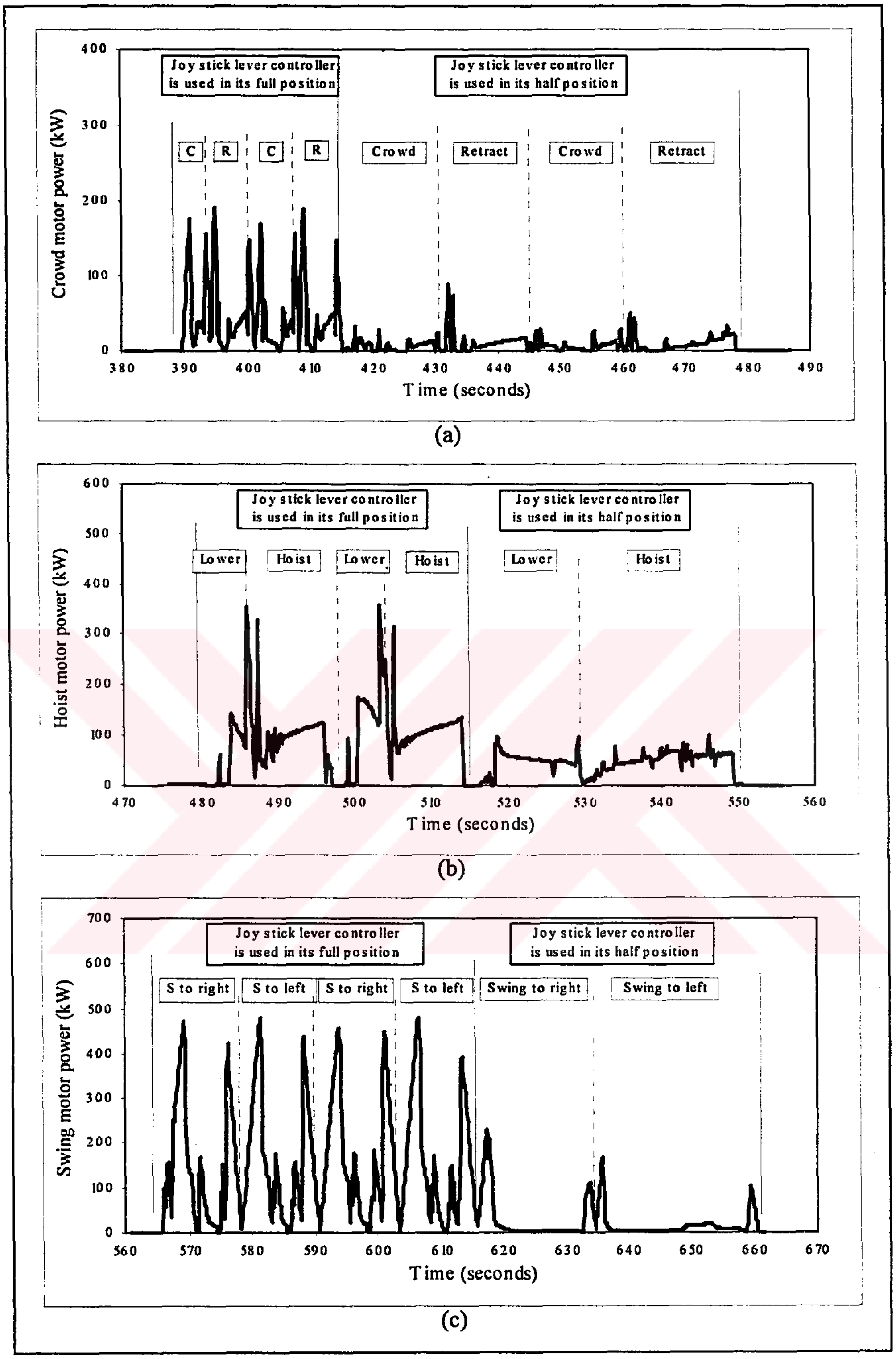


Figure 5.20 Changes in (a)crowd, (b)hoist and (c)swing motor powers in different positions of lever controller on a P&H 2100 BLE 17 yd^3 shovel.

Table 5.6 Results obtained for different positions of the lever controller on P&H 2100 BLE, 17 yd^3 shovel.

Motion type	Position of the lever controller	Time (s)	Energy consumption (kWh)			Time normalised energy (kWh/s)			Peak motor power (kW)			Average motor power (kW)		
			Crowd	Hoist	Swing	Crowd	Hoist	Swing	Crowd	Hoist	Swing	Crowd	Hoist	Swing
Crowding (full length)	Full	5.20	0.082	-	-	0.016	-	-	176	-	-	58	-	-
Retracting (full lenth)	Full	6.69	0.081	-	-	0.012	-	-	191	-	-	45	-	-
Crowding (full length)	Full	7.11	0.082	-	-	0.012	-	-	170	-	-	42	-	-
Retracting (full lenth)	Full	6.90	0.089	-	-	0.013	-	-	189	-	-	47	-	-
Average values		**6.48**	**0.084**	-	-	**0.013**	-	-	**182**	-	-	**48**	-	-
Crowding (full length)	Half	15.60	0.027	-	-	0.002	-	-	32	-	-	6	-	-
Retracting (full lenth)	Half	14.75	0.048	-	-	0.003	-	-	90	-	-	12	-	-
Crowding (full length)	Half	14.64	0.027	-	-	0.002	-	-	29	-	-	7	-	-
Retracting (full lenth)	Half	18.88	0.048	-	-	0.003	-	-	50	-	-	9	-	-
Average values		**15.97**	**0.038**	-	-	**0.003**	-	-	**50**	-	-	**9**	-	-
Lowering (full height)	Full	6.37	-	0.129	-	-	0.020	-	-	355	-	-	73	-
Hoisting (full height)	Full	11.14	-	0.268	-	-	0.024	-	-	327	-	-	87	
Lowering (full height)	Full	6.58	-	0.210	-	-	0.032	-	-	358	-	-	115	
Hoisting (full height)	Full	11.03	-	0.293	-	-	0.027	-	-	314	-	-	96	
Average values		**8.78**	-	**0.225**	-	-	**0.026**	-	-	**339**	-	-	**93**	-
Lowering (full height)	Half	14.11	-	0.127	-	-	0.009	-	-	99	-	-	45	
Hoisting (full height)	Half	20.47	-	0.205	-	-	0.010	-	-	101	-	-	49	
Average values		**17.29**	-	**0.166**	-	-	**0.010**	-	-	**100**	-	-	**47**	-
Swinging to right (180°)	Full	13.05	-	-	0.514	-	-	0.039	-	-	470	-	-	142
Swinging to left (180°)	Full	12.31	-	-	0.551	-	-	0.045	-	-	478	-	-	161
Swinging to right (180°)	Full	12.73	-	-	0.573	-	-	0.045	-	-	457	-	-	162
Swinging to left (180°)	Full	12.42	-	-	0.533	-	-	0.043	-	-	480	-	-	155
Average values		**12.63**	-	-	**0.543**	-	-	**0.043**	-	-	**471**	-	-	**155**
Swinging to right (180°)	Half	18.78	-	-	0.151	-	-	0.008	-	-	228	-	-	29
Swinging to left (180°)	Half	25.99	-	-	0.109	-	-	0.004	-	-	166	-	-	15
Average values		**22.38**	-	-	**0.130**	-	-	**0.006**	-	-	**197**	-	-	**22**

5.4.3. Dipper Filling Applications

As far as it was observed during field studies, suitable fragmentation was commonly obtained after blasting operations. Because of both fragmentation and characteristics of rock masses, bench faces can not sustain for a long time and blasted material often collapse towards the toe of the bench. As a result of such failures, huge amount of loose material piles were shaped in front of the machine. In such cases, most of the cycles in an operation period are performed to remove these piled material first. Then the face becomes stable enough to fill the dipper by digging the formation directly. These two applications conducted to fill the dipper are considered as two different digging operations in the same case.

On the basis of field observations, two types of operations widely applied to fill the dipper are defined in this study; one is filling the dipper by digging blasted and piled material at the toe of the face and the other is filling the dipper with the material which is dug directly at the face. During the monitoring processes, applied filling operation was observed in each individual cycle and its type was noted together with the cycle number. During data evaluation process, cycles were specially grouped according to these two different dipper filling applications and then the results of the groups were comparatively discussed.

At the end of these evaluations, it is determined that the parameters are remarkably affected from change in dipper filling operations. According to average results of 10 cases, it is found that cycle time increases 18% and cycle energy increases 22% when the results of face digging cycles are compared with those of pile digging cycles. Changes in the parameters of digging components are more significant than the changes in the parameters of complete cycle period. The results indicate that digging of blasted material rather than digging of loose material piles necessitates almost 40% more time and energy. These results also indicate how the work difficulty change when the dipper filling operation type is changed. Since time and energy parameters increase nearly the same amount, time normalised energy values of cycle and digging periods are obtained more or less the same in both types of dipper filling operations. Similar to the changes found for above parameters of both cycle and digging periods, specific cycle energy and specific digging energy values in these periods increase 12 and 38% respectively. Different digging applications affect the machine capacity parameter as well as the other parameters. According to the results, a 15% decrease in hourly capacity and a 28% decrease in hourly digging capacity are determined. Entire results show that filling the dipper by digging the face directly is more difficult than digging disintegrated material piles at the toe of the face.

As a result of changes observed in digging time and energy values of pile and face digging applications, the distributions of cycle time and energy values in its components, especially in digging component differ remarkable (Figure 5.21). It is seen that rather than cycle time distribution (Figure 5.21(a)), cycle energy distributions (Figure 5.21(b)) show important changes. As to the average results, nearly half of cycle energy in a face digging operation is consumed in digging whereas this ratio in pile digging operation is obtained as 38% of cycle energy.

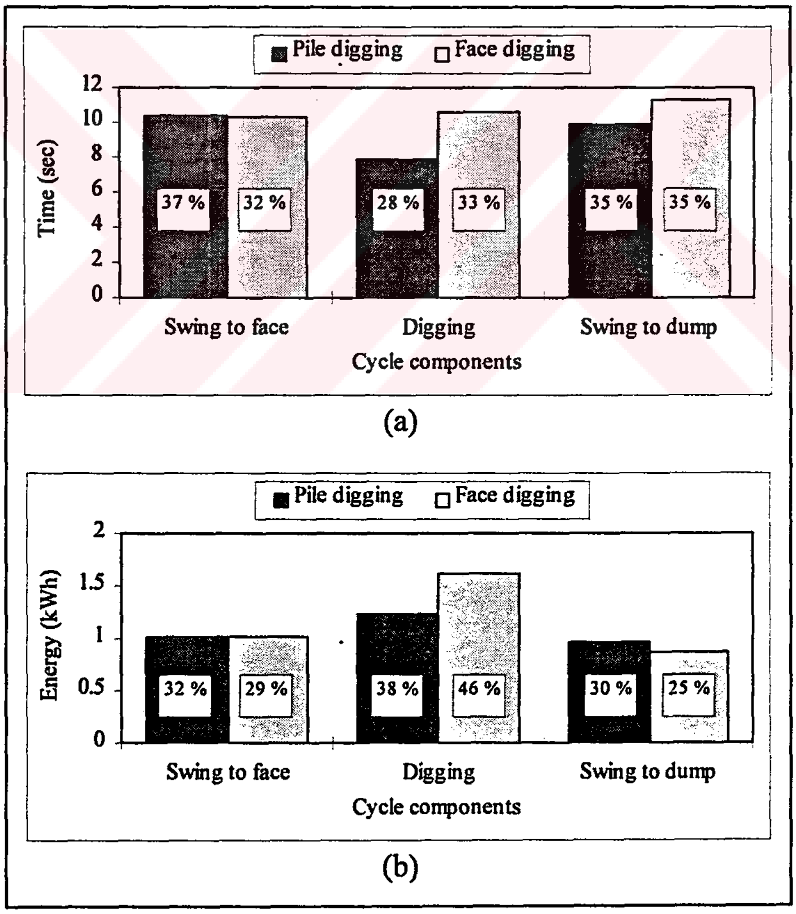


Figure 5.21 Comparison of cycle (a) time and (b) energy distributions in the cycle components obtained from different digging applications.

The curves of two sample cycles with different dipper filling operations are illustrated in Figure 5.22. In this figure, the cycle denoted by no.1 is obtained from a pile digging operation whereas the other one belongs to a face digging operation. As it is explained in Chapter 3, two transducers are used to obtain digging trajectories. Position of the reference point which simulates the dipper's position is defined according to its x-y components. It is reminded that the reference point is selected as the tip of the middle tooth on the dipper.

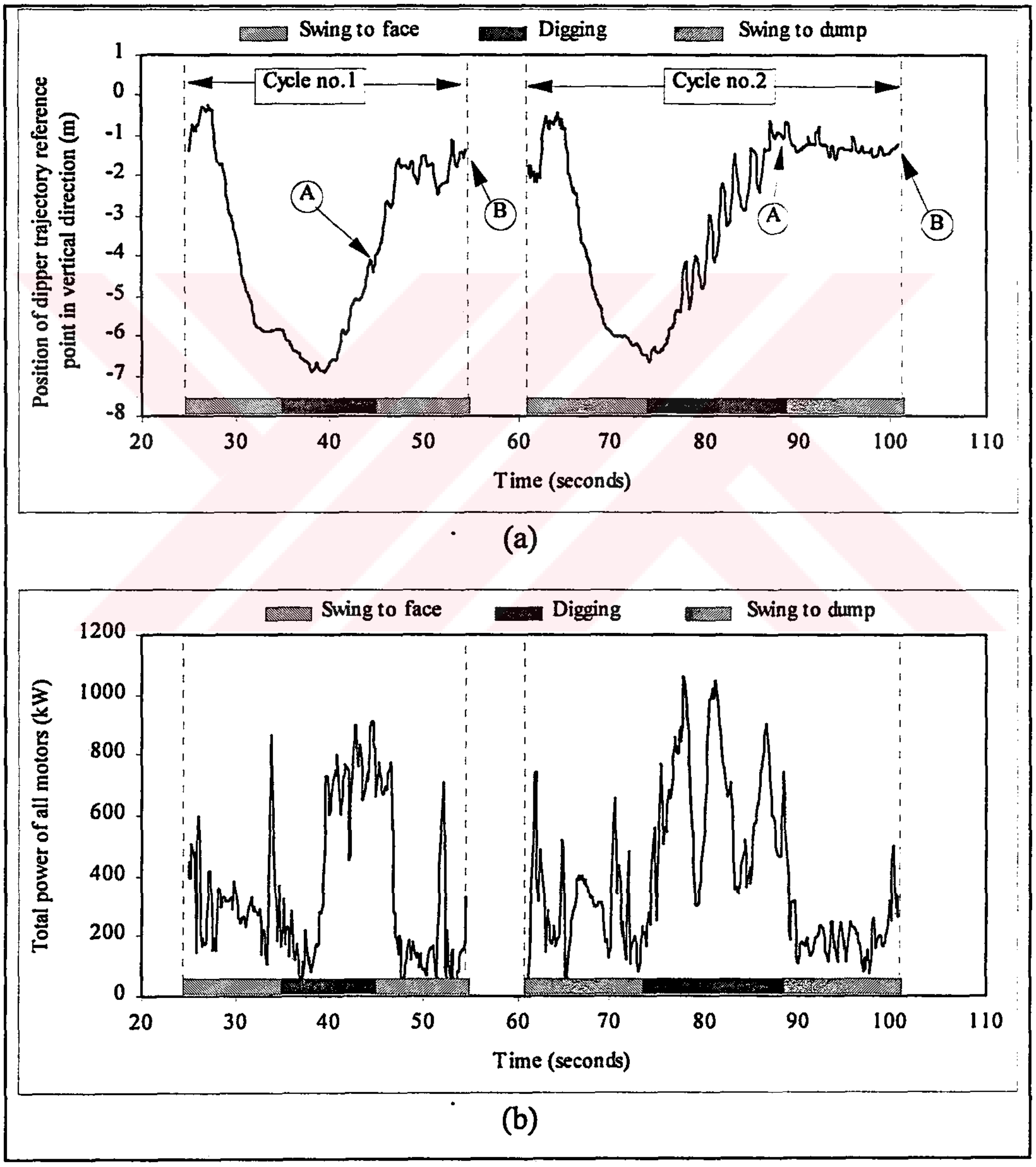


Figure 5.22 (a) Dipper position and (b) total power distributions in two sample cycles with different digging applications.

In Figure 5.22(a), change of reference point in vertical direction is plotted against monitoring time and three main components of the cycles are shown with different shadings along the x-axis. Two important points on the curves of both cycles are marked to indicate ends of digging operations with A and dump moments with B. If a horizontal line is drawn from one of these points to y-axis, the position of the reference point in vertical direction is read for that point which indicates the distance of dipper tooth from the horizontal reference axis (see Figure 3.14). As it is seen in Figure 5.22(a), dump levels in both cycles are almost the same, but a significant difference is observed between the points A. This difference between two identical points, that is both points represent end of digging operation where the dipper is full with material, is simply explained by difference between the characteristics of different dipper filling applications in these cycles. Digging pile material is rather easy, the dipper is filled in a short time since the operator can apply a high amount of cut in this kind of material. On the other hand, a longer trip is necessary to fill the dipper fully because rather a lower depth of cut can be applied in this case. As a result of this, more time and energy require to fill the dipper by digging the face material. If filling height is defined as the difference between elevations of the reference point just before and after digging operation, it is found approximately 3 m in the 1st cycle and 5.5 m in the 2nd cycle. Whereas the vertical positions of the dipper at the end of digging operations are 4.3 and 1 m below the reference axis, they are 1.4 and 1.2 m at dump moments. These results show that in the first example, the loaded dipper is hoisted about 3 m to reach to dump elevation, but the elevation of the dipper at the end of digging operation in the second example is only 20 cm over the dump level. This is may be the only advantage of digging the face instead of digging the pile. Digging part of the curve in the 2nd example is very rough according to the first one, because the pendulum fixed in front of the transducer to measure the dipper handle inclination oscillates very much if digging is rough.

Change in sum of powers generated by three motors during these example cycles is illustrated in Figure 5.22(b). When the power traces of two cycles are compared, it is easily seen that the traces in the 2nd cycle reaches to higher levels. Peak powers are found 912 and 1065 kW respectively. Rather than peak values, general characteristics of power values in digging operations are more interesting. Power values in major part of digging operation of cycle 1 undulate between 600 and 900 kW, whereas they undulate between 300 and 1050 kW in the second cycle. These characteristics observed in power curves may be explained with material properties. Pile material is rather homogeneous and it has free faces in more directions if compared with the face material. Therefore power undulations are rather smooth. On the other hand, some irregularities are unavoidably encountered during face digging, therefore power is increased to overcome these irregularities and they are followed by short relaxation. As it is explained in above paragraph, following digging operation, full dipper is hoisted in an amount to reach dump level in the 1st cycle. This result is also observed in power curve so that, power is still around 700 kW at initial part of swing to dump operation in the 1st cycle, but it immediately drops to 200 kW in the 2nd cycle since dump level is almost reached at the end of digging operation.

The parameters are determined for two example cycles as they are given in Table 5.7. The highest change is obtained in digging energy with 79% increase which also affected specific digging energy values in the same percentages.

Table 5.7 The results of two sample cycles with different digging applications.

Parameter	Sample cycle no.1	Sample cycle no.2	Percent change (in 2 w.r.to 1)
Cycle time (s)	29.63	39.92	35% increase
Cycle energy (kWh)	2.926	4.065	39% increase
Time normalised cycle energy (kWh/s)	0.099	0.102	3% increase
Digging time (s)	10.04	14.88	48% increase
Digging energy (kWh)	1.418	2.548	79% increase
Time normalised digging energy (kWh/s)	0.141	0.171	21% increase
Specific cycle energy (kWh/m^3)	0.259	0.360	39% increase
Specific cycle energy (kWh/t)	0.144	0.201	39% increase
Specific digging energy (kWh/m^3)	0.121	0.217	79% increase
Specific digging energy (kWh/t)	0.067	0.120	79% increase
Hourly capacity (m^3/h)	1418	1048	26% decrease
Hourly capacity (t/h)	2552	1888	26% decrease
Hourly diggingcapacity (m^3/h)	4184	2846	32% decrease
Hourly digging capacity (t/h)	7531	5120	32% decrease
Energy consumed in swing to truck (kWh)	0.768	0.705	9% decrease

5.4.4. Dipper Fill Percentage

As it is observed during monitoring studies, the operators generally utilise maximum dipper capacities successfully in digging operations. Nevertheless, the dipper is occasionally filled less or more than its struck measure. In any situation, amount of material in the dipper at the end of digging is defined as dipper fill percentage utilised in that cycle and this definition is done for each cycle. For different dipper fill percentages, variations of their values with respect to full dipper (100% dipper fill) cycles are determined in percents as given in Table 5.8. The results show that both time and energy values in cycle and digging periods decrease with decreasing amount of material. If variations in cycle and digging parameters are compared with each other, it can be said that digging parameters are more affected by the amount of material removed in a cycle. The results indicate another important point that trying to fill the dipper over its capacity does not provide any profitable advantage. From 110 dipper fill percentage cycles, it is found that hourly capacity increases only 3%, but on the other hand cycle time and cycle energy increase 7 and 9 percents respectively. In the same dipper fill percentage group, specific cycle energy value does not change, but amount of energy required to dig a unit amount of material increases 6% with respect to the cycles of 100% dipper fill.

Table 5.8 Changes in the values of different dipper fill percentage cycles with respect to those of 100% dipper fill cycles.

Parameter	Dipper fill percentage			
	110%	80%	60%	50%
Cycle time (s)	7% increase	6% decrease	14% decrease	20% decrease
Cycle energy (kWh)	9% increase	8% decrease	18% decrease	25% decrease
Digging time (s)	12% increase	16% decrease	26% decrease	39% decrease
Digging energy (kWh)	17% increase	18% decrease	31% decrease	40% decrease
Specific cycle energy (kWh/m^3 or t)	no change	16% increase	36% increase	52% increase
Specific digging energy (kWh/m^3 or t)	6% increase	4% increase	15% increase	20% decrease
Hourly capacity (m^3 or t/h)	3% increase	15% decrease	31% decrease	38% decrease
Hourly digging capacity (m^3 or t/h)	no change	5% decrease	19% decrease	20% decrease

5.5. Depth of Cut

In general, amount of dipper penetration into the material is defined as depth of cut. This is maybe the most important operational variable which affects the crucial parameters such as digging time, digging energy, etc. During digging operation, this amount is adjusted by the help of crowd or retract motion which are manipulated by the operators. Therefore, regardless of dipper filling type, digging either pile material or face material, operator's general experience and his observations during digging are very important to utilise an optimum depth of cut according to local digging conditions. It is believed that applying a depth of cut amount either lower or higher than the optimum amount will affect the parameters in negative way. When a low amount is utilised, dipper will not be full at the end of digging or it will unnecessarily take a longer time to fill the dipper. On the other hand, if a high amount of depth of cut is applied by the operator intentionally or not, it will force mainly the hoist motor and maybe the machine will stop automatically because of over loading the motor or amount of energy required to complete digging operation will increase.

As it is explained in Chapter 3, changes in dipper position in digging are monitored by two electrical measuring transducers which are attached to the monitoring system. This characteristic of the monitoring system is particularly developed to obtain digging profiles which can be used to quantify depth of cut amount utilised in a digging cycle. This can be done if and only if both the face profile and the dipper trajectory in digging which is the path followed by the dipper in formation are defined numerically and/or graphically. Then the depth of cut amount is determined as shortest distance between both profiles.

During a regular cycle operation, the dipper is lowered and positioned for digging process as it is swinged to the face after dump motion and the dipper is moved only in hoist direction in digging. In a regular operation, only digging profile can be obtained, but it is not enough to determine depth of cut. To overcome this problem, unlike regular digging operations, controlled digging application is necessitated to obtain both the face profile and the digging profile. In this application, first the dipper is hoisted to its maximum level then it is crowded until its teeth contact the face. Afterwards the dipper is lowered to the face bottom by providing an adequate speed. Meanwhile, contact between teeth and face at each moment of this motion is provided as good as possible. Data obtained from the transducers during this lowering operation are used to define the face profile. When the face bottom is reached, digging process is initiated by hoisting the dipper as its penetration into the face is adjusted by crowding the dipper. Data obtained in this second part of the application are used to define the digging profile. A series of such operations are obtained in different cases.

Digging profile geometry obtained from a controlled digging operation is graphically illustrated in Figure 5.23. As it is expected, distance between two profiles is not constant since both the face and digging path are not regular. Therefore an average depth of cut amount is determined by taking 3 or 4 sections on the whole profile. For instance, average depth of cut is determined as 75 cm in this example. The next step is to determine related energy and time consumption parameters. These parameters are not determined for the first part of the application which is lowering operation, but for the second part. All these processes are done on the data of a series of controlled digging operations which could only be obtained in three cases denoted by the code numbers 6, 17 and 20. The results are evaluated to find out depth of cut effects on the parameters..

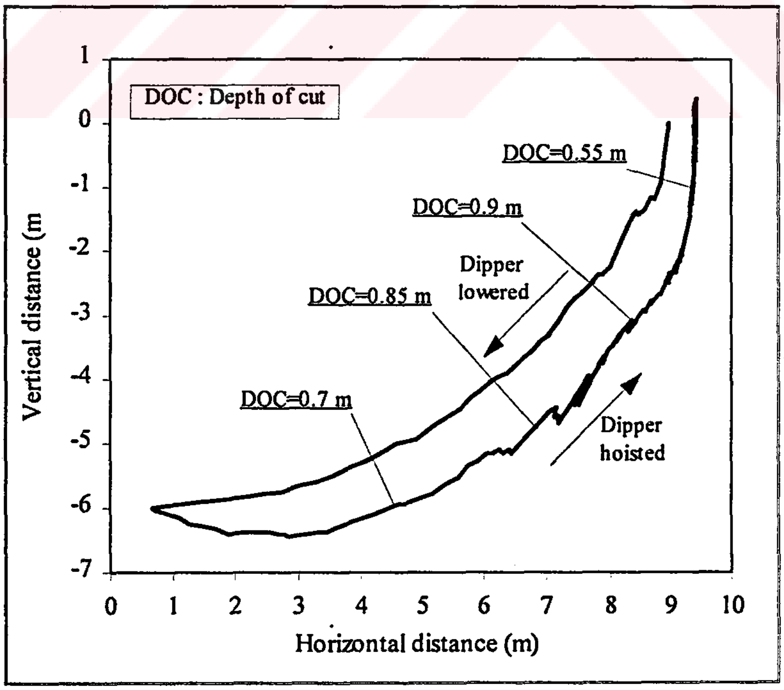


Figure 5.23 Digging profile geometry obtained for a digging operation.

At the end of the evaluations, meaningful relationships are obtained between the average depth of cut values and the values of time normalised digging energy, time normalised hoist energy and hoist motor average power. Neither time nor energy can be a simple variable to define depth of cut effect unless the other variables, such as amount of material dug, are provided the same in each digging application. Therefore energy consumption in digging operations are normalised with corresponding digging time. Effect of depth of cut on time normalised digging energy is presented in Figure 5.24. Curves given in the figure belong to the cases 6, 17 and 20 which are characterised with different material properties. The points which represent dipper empty digging simulations are also included in the graphs and their depth of cut value are taken as zero. There exist exponential relationships between the parameters of the cases, because energy increases more than time when depth of cut amount is increased. In general, it is seen that this parameter increases with increasing depth of cut. There is not enough data to make a general interpretation of digging difficulty, but if digging conditions of these three cases are considered, it can be said that the case 20 is rather difficult and this effect is especially observed when a depth of cut amount higher than 50 cm is applied. Whereas the values of the cases 6 and 17 reach to 0.15 kWh/s when depth of cut is 105 cm, it is over 0.22 kWh/s (almost 50% higher than the other cases) in the case 20.

Similar to time normalised digging energy, energy consumed by hoist motor in digging is also a good parameter to indicate depth of cut effect. Figure 5.25 illustrates effect of depth of cut on time normalised hoist energy values. Since energy consumed by crowd motor is rather low in digging, hoist motor energy and digging energy values show quite similar characteristics. As a result, time normalised hoist energy values have also good relations with depth of cut values as well as average power generated by hoist motor, as given in Figure 5.26. Hoist motor powers obtained in the case 20 are also higher than those of the other cases.

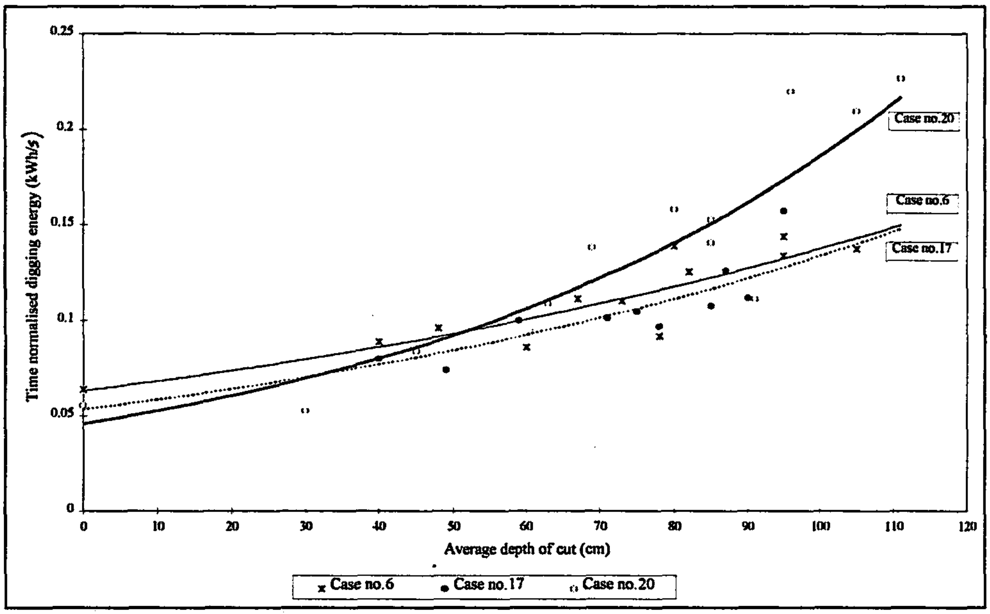


Figure 5.24 Relationship between average depth of cut and time normalised digging energy.

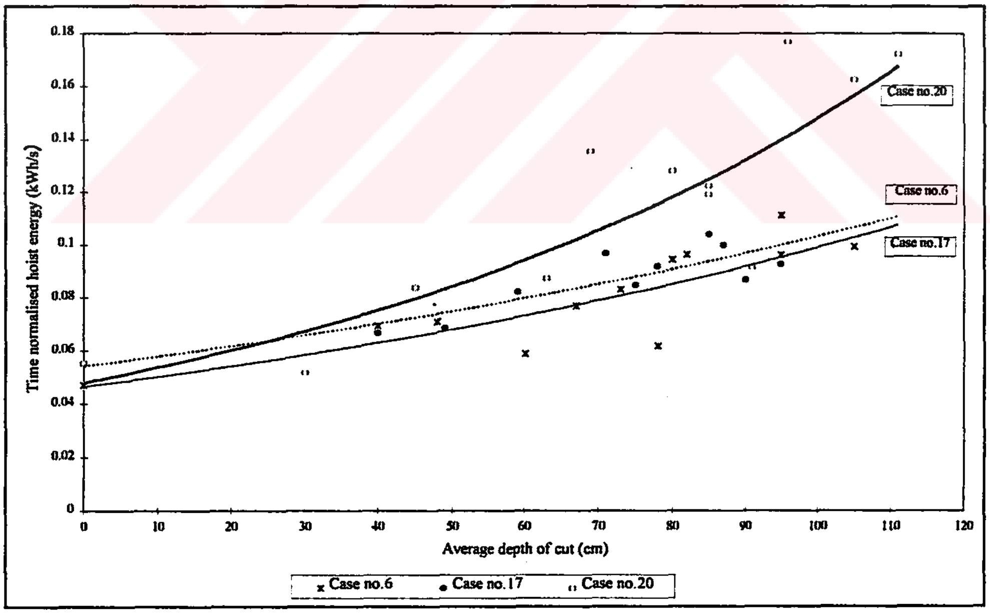


Figure 5.25 Relationship between average depth of cut and time normalised hoist energy.

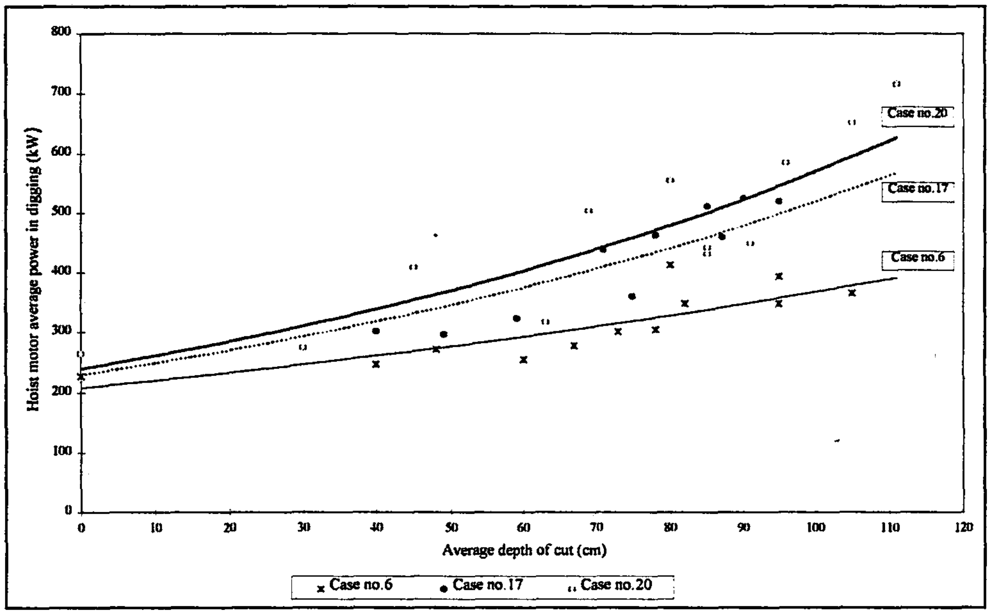


Figure 5.26 Relationship between average depth of cut and hoist motor average power.

According to the results of all three cases presented above, the highest correlation are obtained between time normalised digging energy parameter and depth of cut, as summarised in Table 5.9. Therefore, as it is illustrated in Figure 5.27, all time normalised digging energy values of three cases are plotted against depth of cut values to obtain a more common arithmetical relationship between these two parameters. As a result, following definition of time normalised digging energy as a function of depth of cut is obtained with a high correlation.

$$TNDE = 0.0518 * e^{0.0109DOC} \qquad r = 0.88 \qquad 5.11$$

where:

TNDE is the time normalised digging energy, kWh/s

DOC is the average depth of cut, cm

Table 5.9 Relationships between some parameters and depth of cut.

Parameter	Expression		
	Case no. 6	Case no. 17	Case no. 20
Time normalised digging energy, kWh/s	$= 0.0631 * e^{0.0078DOC\#}$ $(r = 0.91)$	$= 0.0533 * e^{0.0092DOC}$ $(r = 0.93)$	$= 0.0458 * e^{0.014DOC}$ $(r = 0.93)$
Time normalised hoist energy, kWh/s	$= 0.0466 * e^{0.0076DOC}$ $(r = 0.85)$	$= 0.0543 * e^{0.0064DOC}$ $(r = 0.92)$	$= 0.0481 * e^{0.0113DOC}$ $(r = 0.89)$
Hoist motor average power, kW	$= 207.94 * e^{0.0057DOC}$ $(r = 0.85)$	$= 229.41 * e^{0.0082DOC}$ $(r = 0.90)$	$= 239.41 * e^{0.0087DOC}$ $(r = 0.88)$

\# DOC : Average depth of cut, cm

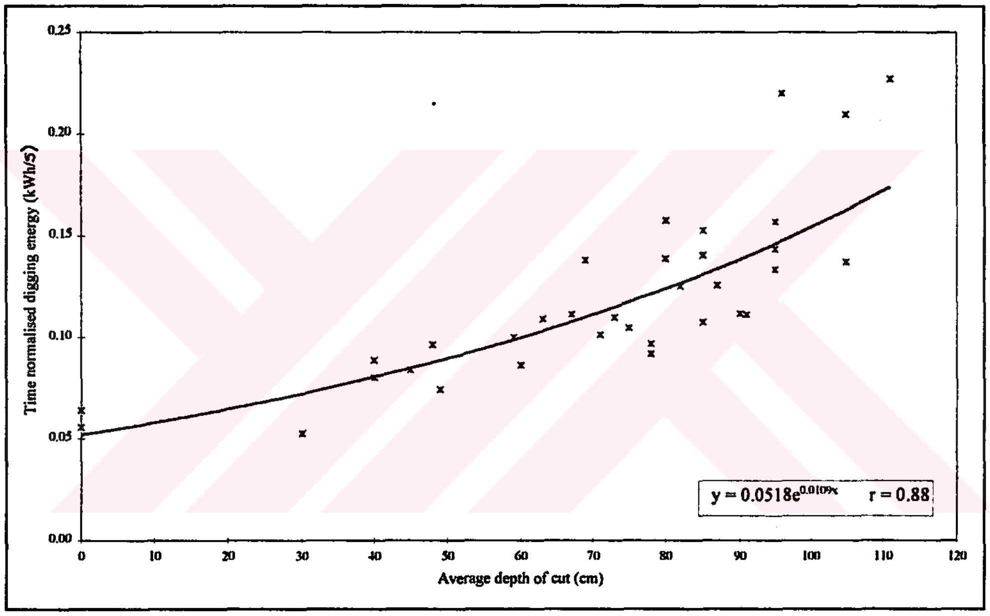


Figure 5.27 Time normalised digging energy vs average depth of cut .

5.6. Interpretation of Digging Difficulty

The results obtained from processing of monitored data are presented and discussed in section 5.3. The parameters such as time, energy, etc. determined for both complete cycles and digging components of the cycles are evaluated to investigate the relationships among them. As it is expected, the evaluations show that rather than the parameters of complete cycles, those of digging components can trustworthy be used to indicate digging difficulty. This outcome also accord with operation characteristics of the shovels which properly interact with the material during digging. Therefore digging components of complete cycles are isolated from the remaining cycle components (swing to face and swing to dump) and the results of digging operations are particularly evaluated in more details to define digging difficulty on the basis of digging parameters.

Digging difficulties of the monitored cases are qualitatively described on the basis of observations before they are defined quantitatively. Each of the cases is described as either easy, moderate, moderately difficult or difficult on the basis of field observations during monitoring processes. Then the calculated values of digging variables are analysed from digging difficulty point of view and values of the parameters are assigned to assess digging difficulties of the cases.

At the end of digging difficulty assessments, it is found that rather than a simple parameter such as digging time or digging energy, a compound parameter gives better indications for digging difficulty. In this manner, good agreements are found between qualitative descriptions and the results of both specific digging energy and hourly digging capacity parameters. These parameters include power generated by the motors in digging and amount of material removed as well as time spent for the operation. As it is explained before, specific digging energy and hourly digging capacity parameters are defined on the basis of both bank volume and weight of the material which also include swell factor and natural unit weight of the material. The results of these parameters are ranged according to digging difficulty as they are tabulated in Table 5.10.

Table 5.10 Digging difficulty predictions for digging of blasted and piled aterial at the toe of the face.

Parameter	Digging difficulty			
	Easy	Moderate	Mod. difficult	Difficult
Specific digging energy (kWh/t)	≤ 0.041	0.042 - 0.053	0.054 - 0.065	> 0.065
Specific digging energy (kWh/m^3)	≤ 0.100	0.101 - 0.120	0.121 - 0.140	> 0.140
Hourly digging capacity (t/h)	> 14000	14000 - 11501	11500 - 9000	< 9000
Hourly digging capacity (m^3/h)	> 6000	6000 - 5201	5200 - 4400	< 4400

When digging difficulties of the cases are defined according to the quantities of the parameters given in Table 5.10, it is seen that good agreements are observed between the quantitative descriptions done according to any of these parameters and the qualitative descriptions done previously on the basis of field observations.

As they are explained in Section 5.4.3, two types of digging operations are observed at TKİ districts: the most common one is digging loose material piles at the toe of the face, and the other one is digging blasted material directly at the face. The quantities given in Table 5.10 are based on the results of loose material digging cycles. Therefore, rather than rock mass properties, digging difficulty of a pile material is especially characterised with block size distribution of the material observed. Of course, rock mass properties are also very important variables, but they affect digging indirectly as a result of material fragmentation which is mainly controlled by rock mass and material properties as well as blasting parameters. According to the results, difficult digging conditions are typically encountered in the cases no.17 and 21 where material size distributions are rather non-homogeneous and large blocks are observed. On the other hand, easy digging conditions are obtained in digging of well fragmented homogeneous material where the dipper is loaded easily. The case 7 is a typical example of easy digging condition. As to the results, weight based specific digging energy show a remarkable increase from easy to difficult digging such that it is obtained 0.026 and 0.079 kWh/t in the cases 7 and 21 respectively. Dissimilar to specific digging energy, hourly digging capacity decreases as difficulty increases. In a difficult digging hourly digging capacity is obtained 7164 t/h whereas it increases to 18063 t/h in an easy digging case.

When the parameters are exclusively evaluated for both digging operations, it is found that most of the parameters differ remarkable from pile to face digging operations. Therefore the results of face digging cycles are also evaluated to define digging difficulty of face material. By using the similar parameters used in pile digging definition, Table 5.11 is obtained on the basis of specific digging energy and hourly digging parameters of blasted material digging operations at the face. Digging difficulty definitions obtained from face digging cases are quite similar to those definitions of pile digging operations. According to Table 5.11, difficult digging conditions are obtained for massive structures whereas highly jointed structures resulted with easy digging condition.

Table 5.11 Digging difficulty predictions for digging of blasted material at face.

Parameter	Digging difficulty			
	Easy	Moderate	Mod. difficult	Difficult
Specific digging energy (kWh/t)	≤ 0.05	0.051 - 0.08	0.081 - 0.11	> 0.11
Specific digging energy (kWh/m^3)	≤ 0.115	0.116 - 0.16	0.161 - 0.205	> 0.205
Hourly digging capacity (t/h)	> 10500	10500 - 8001	8000 - 5500	< 5500
Hourly digging capacity (m^3/h)	> 5000	5000 - 4001	4000 - 3000	< 3000

It is to be noted that almost 80%, i.e. 17 of entire cases, of the shovels monitored in this study have 20 yd^3 dipper capacities. The results of the analysis given above are restricted in dipper size, therefore, it is proposed that the above definitions are more in use for 20 yd^3 electric power shovels.

As it is proposed by Paşamehmetoğlu *et al.* (1988) and Ceylanoğlu (1991), dipper capacity is a good independent machine variable to use in development of a diggability classification system for power shovels. But the kinds of available electric power shovels at TKİ districts that suit the monitoring system used in this study are limited in dipper capacities. Other than 20 yd^3 shovels which are the most common size of both makes, two 15 yd^3 and three 17 yd^3 shovels are monitored in this study. Therefore, further attempts are done to define another independent machine variable. It is found that the shovels differ in equipped motor power even if they have the same dipper capacity (Table 4.2). Consequently a parameter named as specific hoist power is defined as the ratio of hoist motor continuous power to dipper capacity (Table 4.2). It is found that major work in digging operation is achieved by hoist motor and therefore they are sufficiently sensitive to variations in the material. Hence five different specific power values are obtained for three different dipper capacities of the shovels. After this determination, the overall results of pile digging cases are also evaluated to define digging difficulty according to specific hoist power values.

Relationship between specific digging energy which is found more relevant for this purpose and specific hoist power is illustrated in Figure 5.28. It is seen that the value of specific digging energy parameter decreases as specific hoist power value increases which is also stated by Ceylanoğlu (1991) that specific digging energy values decrease as dipper capacity increases for the same digging difficulty definition. The values of the parameters in the figures are concentrated in two typical specific power values since the dipper capacities of the shovels monitored in 17 cases out of 22 belong to 20 yd^3 P&H 2300-XP and Marion 191 M-II models. When the points on the plot are distinguished for different digging conditions, the ranges given in Table 5.12 are obtained for two different makes of 20 yd^3 shovels. It is difficult to say something more concrete according to the relation obtained between specific digging energy and specific hoist power values, but this can be considered in more details if more data are obtained for different shovels characterised in different hoist motor power.

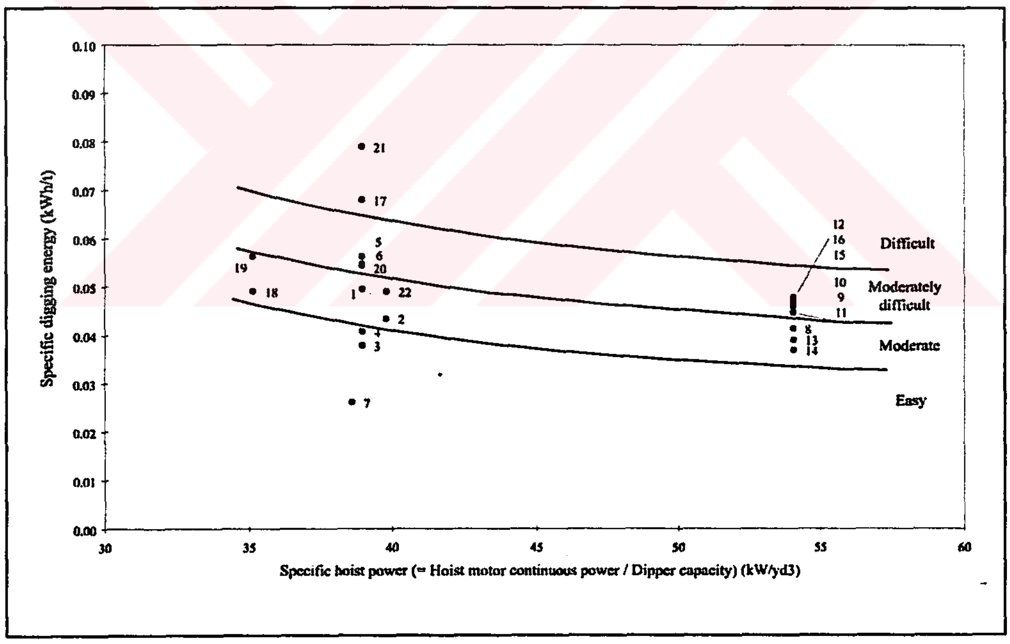


Figure 5.28 Relationship between specific hoist power and specific digging energy for different digging condition.

Table 5.12 Assessment of digging difficulty according to specific hoist power and specific digging energy.

Specific hoist power (kW/yd^3)	Specific Digging Energy (kWh/t)			
	Digging difficulty			
	Easy	Moderate	Mod. difficult	Difficult
39	≤ 0.044	0.045 - 0.055	0.056 - 0.066	> 0.066
54	≤ 0.033	0.034 - 0.044	0.045 - 0.055	> 0.055

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions of this study and the recommendations for future studies are presented as follows:

- The results of this research show that the developed computer-based monitoring system is quite capable and precise to provide data necessary to establish a correlation between shovel performance variables and material characteristics. The system is also modular and universal so that it can easily be attached to and detached from different makes of electric power shovels. Besides, it can also be used on other open pit equipment such as draglines and drilling machines. As well as digging difficulty of material, productivity of an electric power shovel can be predicted by using the system. Furthermore, the developed system is capable of monitoring changes in dipper position so that data necessitated to determine depths of cut quantitatively are provided.

- The developed monitoring system is capable of recording hoist, crowd, swing and propel motor armature voltage and current variables separately at the same time. This peculiarity of the system provides necessary data so that the performance of any motor over a period is investigated individually as well as the machine performance over a period is determined as total of individual motor performances determined for the same period. Swing motor armature voltage variable is found very useful to divide a complete cycle period into its main components which are swing to face, digging and swing to dump as well as to indicate the beginning and the end times of the cycles. Thus, both the machine and the individual motor performances in any component can be analysed after isolating the component from the remaining cycle components. For instance, the variables of hoist and crowd motor which are concurrently active in digging component are analysed independent from each other to investigate their response to digging condition separately. This design characteristic of the system provided an important advantage to be able to conduct a more detailed performance study and to obtain more precise results.

- A system software aimed both to control the hardware and to collect appropriately arranged data for further processing is written in Quick Basic 4.5 programming language. It establishes an important link between the computer and the data acquisition hardware. Once the collection of experimental data has been accomplished, the obvious question that arises is: "what do we do with the data?". Therefore a second software package is also written in the same programming language to process the monitored data by taking the objectives of this study into consideration. While the data processing software is formed, a special attention is given on providing an optimum use of data by the program, maximum speed in calculations, easy control of the program flow by the user and production of adequate and reliable outputs for further evaluations. Processing of a one-hour monitored data file which includes over 30000 rows with 9 columns is completed and the numerical results are obtained in approximately 10 minutes time period when a 486 DX-60 personal computer is utilised for this purpose. By comparison with the standard data-acquisition procedure involving analog data recording (e.g., strip chart recorder) and manual data reduction, the process of computer based data-acquisition represents a very significant reduction in time and effort.

- After overall evaluation of the monitored data, it is found that the parameters defined for digging component of a complete cycle is much more sensitive to the variations in material characteristics and this is also quite compatible with digging phenomena since the machine properly interacts with the material in digging. Therefore further analysis are especially concentrated on digging parameters to relate the values of these parameters calculated from the monitored data with digging conditions as observed during field monitoring trials. As to the results of the analysis, specific digging energy and hourly digging capacity parameters are found quite effective to indicate digging difficulty of the material. However the classification systems to define digging difficulty of the material based on the specific digging energy and hourly digging capacity quantities are proposed separately for digging of blasted and piled material at the toe of the face and blasted material at the face by electric power shovels and they are presented below. It should also be noted that this classification is rather in use for the shovels have a dipper of 20 yd^3 capacity.

Proposed digging difficulty classification for digging of blasted and piled material.

Parameter	Digging difficulty			
	Easy	Moderate	Mod. difficult	Difficult
Specific digging energy (kWh/t)	≤ 0.041	0.042 - 0.053	0.054 - 0.065	> 0.065
Specific digging energy (kWh/m^3)	≤ 0.100	0.101 - 0.120	0.121 - 0.140	> 0.140
Hourly digging capacity (t/h)	> 14000	14000 - 11501	11500 - 9000	< 9000
Hourly digging capacity (m^3/h)	> 6000	6000 - 5201	5200 - 4400	< 4400

Proposed digging difficulty classification for digging of blasted material.

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Specific digging energy (kWh/m^3)	≤ 0.115	0.116 - 0.16	0.161 - 0.205	> 0.205
Hourly digging capacity (t/h)	> 10500	10500 - 8001	8000 - 5500	< 5500
Hourly digging capacity (m^3/h)	> 5000	5000 - 4001	4000 - 3000	< 3000

- Remarkable differences are obtained in digging parameters of pile digging operations and those of face digging operations. The results show that both digging time and energy values increase almost 40% if digging is changed from pile to face. As a result, cycle time and energy values of face digging operations also increase about 18% and 22% respectively according to the values of pile digging operations. Hence the distributions of cycle parameters in its components change with changing digging operation as well. According to average results, 28% of cycle time and 38% of cycle energy are consumed in digging components of pile digging cycles whereas they are found as 33 and 46% respectively in face digging cycles.

- It is shown that the developed system is quite capable of predicting depth of cut quantitatively and thus to provide necessary data to relate this parameter with the performance parameters. Good relationships are obtained between the performance parameters and the depth of cut.

- It is found important how the operator uses the lever controllers to command the motors. The results of initial trials show that motion time increases remarkable, but on the other hand energy required to complete the motion decreases significantly if a motion is done by using the controller in its half position instead of full position. For instance, a crowd or retract motion in full extension of dipper handle is completed in 6.48 seconds by using 0.84 kWh energy if the lever is applied in full position, but time increases to 15.97 seconds and the energy decreases to 0.38 kWh when the same motion is repeated by using the lever in half position. Therefore the operator is warned before a monitoring trial to use the lever in full position as much as possible, thus to minimise the operator's effects by providing similar lever applications in the monitored cases. So, the operator's effects are not taken into account in this analysis.

- The results of this study is restricted with the rock type existing at TKİ districts and therefore can be used in similar conditions where electric power shovels are used to remove overburden material. So the research should be extended to a wide range of rock units rather than marl and agglomerate. Besides, the limited dipper capacities can also be extended to obtain a more general digging difficulty classification.

- It is found that the amount of material passed in a cycle affects the performance variables. Therefore the monitored motor signals are carefully analysed to obtain a correlation between any recorded signal and the amount of material in the dipper, but it failed. But a load cell measurement system to predict the dipper load effectively can be attached to the existing monitoring system.

- Monitoring of swing amounts in the components of cycles other than digging is not very important in prediction of digging difficulty, but a swing angle measuring set-up can also be attached to the developed system which is capable enough for additional.

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APPENDIX A

CALIBRATION CURVES OF THE ELECTRICAL MEASURING TRANSDUCERS

A.1 Calibration Curves of the Electrical Measuring Transducers

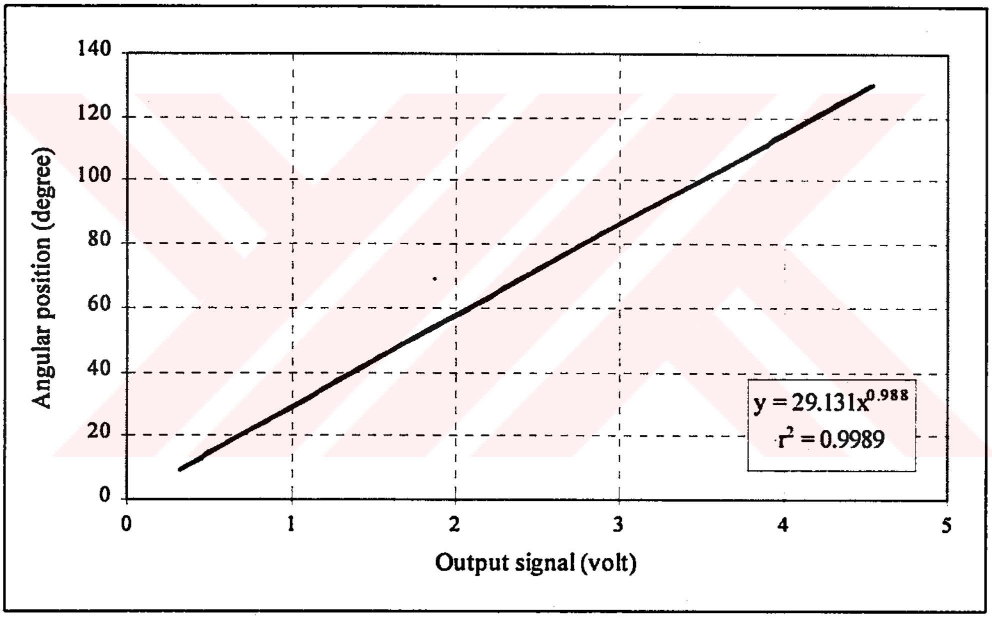

Figure A.1 The calibration curve of the HOIST angle measuring transducer.

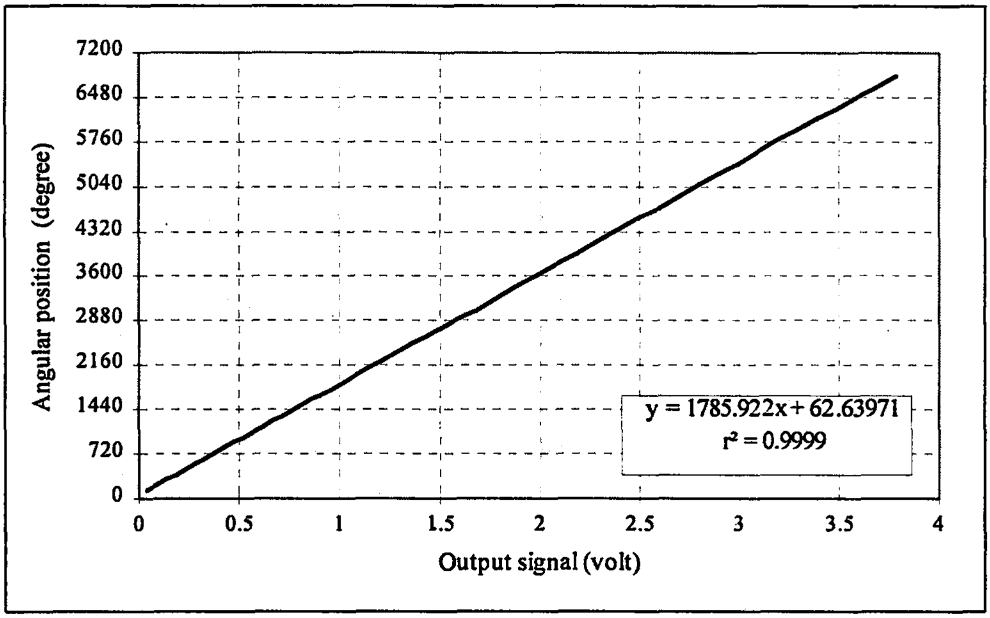

Figure A.2 The calibration curve of the CROWD angle measuring transducer.

VITA

Mehmet Ali Hindistan was born in Fındıklı, Rize on November 4, 1960. He received his B.Sc. and M.Sc. degrees from the Mining Engineering Department of Middle East Technical University in 1984 and 1987, respectively. He has been working as a research assistant in the Mining Engineering Department of Middle East Technical University since 1984. During this period of time he has been to England as a scholar of British Council for 14 months, in June 1988, and studied in Mining Engineering Department of University of NewCastle upon Tyne. He completed his 12 months military service in December 1992. His main areas of interest are rock mechanics, slope stability, computer programming and instrumentation.