University of Alberta

Key Performance Indicators for Electric Mining Shovels and Oil Sands Diggability

By

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ABSTRACT

A shovel performance monitoring study was undertaken in two oil sands mines operated by Syncrude Canada Ltd. using performance data obtained from P&H 4100 TS and BOSS electric mining shovels. One year of shovel performance data along with geological, geotechnical, and climatic data were analyzed. The approach adopted was to use current and voltage data collected from hoist and crowd motors and to calculate the energy and/or power associated with digging.

Analysis of performance data along with digital video records of operating shovels indicated that hoist and crowd motor voltages and currents can be used to identify the beginning and the end of individual dig cycles. A dig cycle identification algorithm was developed. Performance indicators such as dig cycle time, hoist motor energy and power, and crowd motor energy and power were determined. The shovel performance indicators provide important insight into how geology, equipment and operators affect the digging efficiency. The hoist motor power is a useful key performance indicator for assessing diggability. Hoist motor energy consumption per tonne of material excavated and the number of dig cycles required for loading a truck can be useful key performance indicators for assessing operator performance and productivity.

Analysis of performance data along with operators team schedules showed that the performance of a shovel can be significantly influenced by the operator's digging technique while digging uniform material. Up to 25% variability in hoist motor power consumption and 50% variability in productivity was noted between different operators.

Shovel type and dipper teeth configuration can also influence the power draw on electrical motors during digging.

There is no common agreement existing on the influence of bitumen content on oil sands diggability. By comparing the hoist motor power consumption, it was found that the rich ore was more difficult to dig than the lean ore. Similarly, estuarine ore was more difficult to dig than marine ore. Winter weather was expected to have a significant influence on oil sands diggability but was found to have only a minor and localized influence that depends upon the ore type, temperature conditions and the duration of bench exposure.

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CHAPTER 1 INTRODUCTION

1.1 Problem Description

Syncrude Canada Ltd. operates three surface mines north of Fort McMurray: Base Mine, North Mine and Aurora Mine. The truck and shovel mining method is used for both overburden and ore removal at the North and Aurora mines. These mines produce a combined average of about 500,000 tonnes of oil sands and 470,000 tonnes of waste per day (Syncrude Canada Ltd., 2005). To handle the huge production levels, some of the largest available mining shovels such as P&H 4100 series electric cable shovels with a dipper capacity of up to 46 m^3 and Caterpillar 797 trucks with a payload capacity of 365 tonne (400 ton) are used. As production targets increase in the future, the number and capacity of these shovels is expected to increase, thus the reliability, productivity and effectiveness of these shovels must be optimized. Each piece of equipment costs millions of dollars, therefore, it is important to understand how this equipment operates.

About 50% of the cost to recover bitumen from oil sands is associated with overburden and ore excavation and subsequent hydro-transportation of the oil sands to the extraction plant. Major factors affecting the operating costs are volume of overburden mined, oil sands grade, material handling distance, cost of energy and maintenance, out of which the maintenance cost itself is about 50% of the total operating costs (Alberta Chamber of Resources, 2004). During truck and shovel mining, the direct cost of electricity per barrel of oil produced is about $0.50 (National Energy Board, 2004). The P&H 4100 series shovels require substantial electric power and each MW-h of electric power costs about $60 (Alberta Chamber of Resources, 2004). Therefore, the cost of energy associated with operating the shovels is quite high and a marginal improvement in maintenance and energy consumption can result in significant savings.

The energy used to excavate a unit volume of material defines the performance of a shovel. Performance of a shovel can be influenced by many parameters such as the operator's practice and skill, shovel type, dipper and tooth design, and the digging trajectory (depth of dipper penetration and digging length). In oil sands mining, shovel performance can also be influenced by the diggability characteristics of the oil sands formations. Diggability of a ground is defined as the shearing resistance offered by the ground while digging. Oil sands diggability is related to the geology and depositional environment and depends upon geological parameters such as facies and member, bedding plane orientation, and geotechnical parameters such as shear strength, density, water content, bitumen content, particle size, etc. The presence of hard bands of indurated sediments can make digging difficult. In cold regions, climatic factors resulting in ground freezing and frost penetration can also influence oil sands diggability. The variability in material diggability can result in varying cycle time, mechanical energy input, energy consumption, wear, and stress distribution on the shovel dipper-and-tooth assembly, and influence the shovel performance, maintenance and productivity.

Main shovel activities during its operation include digging, hoisting, swinging, dumping, waiting, propelling, etc. In order to estimate the shovel's digging performance, it is important to isolate the dig cycles from other shovel duty cycle components because the dig cycle represents the actual time the dipper spends digging in the face. The swing and dump cycles provide a material handling service in delivering the excavated material to the trucks. Once the portion of the dig cycle is determined, the next important step is to identify key performance indicators that may be related to the digging effort required by the shovels. In practice, the digging operation of a shovel is very complex and determining the key performance indictors is a challenge.

A literature review found very little previous shovel performance monitoring studies for oil sands mining. Most performance monitoring studies reported in the past are based on blasted muck piles of coal, hard rock and overburden material. Similarly, past studies carried out for determining diggability are mostly applicable for coal and other blasted material and not appropriate to oil sands mining (see Appendix B). It was anticipated that shovel type and operator's practice can influence the shovel performance but these factors were not considered in most of the past studies. Therefore, it was necessary to undertake a shovel performance monitoring study in oil sands mines to understand the influence of various factors on shovel performance and oil sands diggability.

1.2 Thesis Objectives

The primary objectives of this research are to:

- Collect, synthesize and interpret cable electric shovel performance data to develop a dig cycle identification algorithm.
- Determine key performance indicators that can be related to digging effort and other operational parameters using data that are routinely collected by on-board shovel monitoring equipment.
- Determine the influence of ore type (rich versus lean grade oil sands; marine versus estuarine), overburden type and climate (cold temperature) on diggability.
- Determine the influence of operator's digging technique on shovel performance.
- Compare performance of shovel type (TS versus BOSS) and dipper tooth adapter (inline versus down-pitch) while digging similar material.

1.3 Scope and Methodology

The general methodology adopted in this research is shown in Figure 1-1. This research is based on the collection and analysis of electric cable shovel performance data along with the geological, geotechnical and climatic data in two surface oil sands mines, the North Mine and the Aurora Mine, operated by Syncrude Canada Ltd. Shovel performance data from the hoist, crowd and swing motors were collected at one-second time intervals from eight P&H electric cable shovels for a period of one year. Geological (percentage of estuarine, marine, fluvial and transitional facies content), geotechnical (bitumen content, water content, fines content, density etc.) and climatic (temperature and exposure time) information at the shovel locations were also gathered.

The research relied on instrumentation currently on-board the electric shovels for acquiring shovel performance data. Huge datasets are routinely stored in Syncrude's databases. The goal was to collect and analyze the existing data to get insight into how geology, climate and operators affect the shovel performance. Errors are inherent to any industrial data and therefore, the data needed to be carefully evaluated.

A methodology for processing, filtering, and interpreting these data was developed. By comparing the shovel performance data with digital video records of operating shovels, various shovel activities were identified, especially the dig cycles. A computer program was developed to use hoist and crowd motor responses to identify the dig cycles and the dig cycle identification algorithm was validated using the video records.

Several performance indicators such as dig cycle times and energy and power consumption for the hoist and crowd motors were considered to identify the key shovel performance indicators that could be related to the digging effort required by the shovels in various geological, geotechnical and climatic conditions.

Logical grouping and selection of data was one of the most important step for conducting analyses. For determining the influences of various factors on oil sands diggability and shovel performance appropriate datasets were selected by searching through the huge datasets that were collected. While assessing influences of factors on oil sands diggability datasets with minimum operating variability were selected. Similarly, for assessing influences of factors on shovel performance datasets with minimum ground variability were selected.

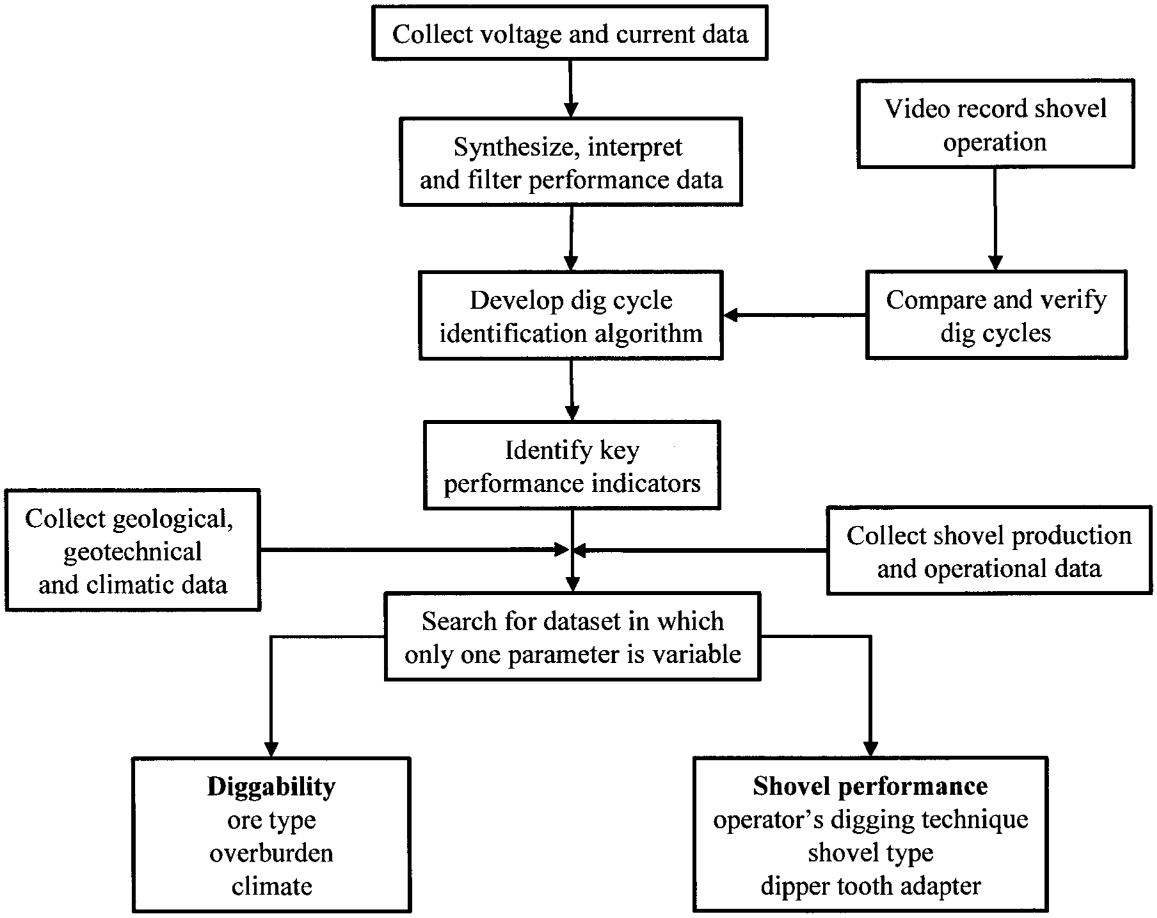


Figure 1-1 Methodology adopted in this research

This study is applicable to both oil sands and overburden excavation. As P&H 4100 series cable electric shovels were the dominant shovel type used at the North Mine and the Aurora Mine this research was focussed toward these cable electric shovels. Although this study was carried out using data from the North and Aurora mines, the results are applicable to other similar mines in the Fort McMurray area. This thesis provides sufficient information to understand the influence of various factors on oil sands diggability and helps improve the shovel performance and overall productivity for Syncrude.

1.4 Thesis Organization

Background information regarding Syncrude's mine site location, geology, climate, and mining operations is discussed in Chapter 2. Information regarding the mining shovels that are in operation at Syncrude mines is given. Data were collected from various sources and influences of geological, geotechnical, climatic, and operator's practice on oil sands diggability and shovel performance were analyzed.

In Chapter 3, the operating principle of a P&H 4100 series shovel is given. Fundamentals of various electrical motors that are associated with digging are discussed. A review of the past shovel performance monitoring studies is also given. This chapter forms the basis of the research carried out in this thesis.

The methodology adopted for collecting, processing and analyzing the shovel performance data is given in Chapter 4. Techniques developed to estimate the shovel performance indicators are discussed in Chapter 5. Several performance indicators are considered and their usefulness for assessing oil sands diggability is discussed.

The influence of operator's practice and skill on shovel performance is discussed in Chapter 6. The influence of various geological and geotechnical parameters on oil sands diggability are presented in Chapter 7. Chapter 8 addresses the effect that the winter climate has on freezing and frost penetration and how oil sands diggability and shovel performance are affected. A comparison between shovel types (BOSS model versus TS model) and tooth adapter types (inline versus down-pitch) with respect to digging power is given in Chapter 9. Chapter 10 contains concluding remarks, and recommendations for future research.

CHAPTER 2 OIL SANDS MINING IN ALBERTA

2.1 Alberta Oil Sands

Alberta has massive deposits of oil sands in the form of a mixture of sands, clay, water, and bitumen and account for a majority of Canada's crude oil reserves. Oil sands are also known as tar sands and bitumen sands. They are unconsolidated sand deposits impregnated with viscous petroleum normally referred to as bitumen. The Alberta Energy and Utilities Board (AEUB) estimate that Alberta has about 335 billion barrels of recoverable oil reserves, which is the largest crude oil reserve in the world with Saudi Arabia second at 259 billion barrels. By 2010, Alberta's oil sands are expected to generate nearly 2 million barrels of crude oil per day representing more than 60% of western Canada's projected production (Alberta Department of Energy, 2005).

Four major reserves of oil sands are found in Alberta: Peace River, Athabasca, Wabasca and Cold Lake (Figure 2-1). The bitumen deposits in these areas are found in sedimentary formations of sand and carbonate that collectively cover roughly six million hectares. Commercial bitumen production from oil sands is achieved either by in situ production for deposits below 75 m or by open pit mining for shallower deposits. In practice, most in situ bitumen and heavy oil production come from deposits buried more than 400 m, while open pit mining is used where the overburden depth is less than about 50 m (Xu, 2005). Of the total recoverable oil reserves about 10% can be mined by surface mining methods and the remainder with in situ techniques. Figure 2-2 shows the regions that can be accessed through surface or in situ methods.

In the in situ process, bitumen is extracted from the sand while the oil sands deposit is still in place. The most common in situ method of bitumen recovery is to add heat to separate the bitumen from sand and make it fluid, allowing it to be pumped up to the surface. Some in situ projects use a cyclic steam stimulation process, in which steam is added to the oil sands via vertical wells and the liquefied bitumen is subsequently pumped to the surface using the same well. Other in situ methods use variations of the steam assisted gravity drainage process. This process consists of adding steam to the oil sands using a horizontal well and simultaneously pumping the liquefied bitumen using another horizontal well located just below the steam injection well. Other emerging approaches to in situ production include vapour recovery extraction method, which involves use of solvents as a supplement or alternative to steam. Another approach to in situ recovery of bitumen is known as primary or cold production, which can be employed in reservoirs where the oil will flow to the bore well without the introduction of heat (Alberta Economic Development, 2004).

During surface mining, oil sands are first exposed by stripping the overburden. The exposed oil sands is then excavated using a truck and shovel mining method. Later, the bitumen is extracted from the sand by a hot water extraction process that relies on the addition of warm water and agitation of the resulting slurry. Surface mining is employed in the Athabasca deposits to the north of Fort McMurray. Major mining companies such as Syncrude Canada Ltd., Suncor Energy Inc., Albian Sands Energy Inc., and Canadian Natural Resources Ltd. are involved in surface mining operations in Fort McMurray region. Alberta production figures for 2004 indicate that surface mining operations accounted for approximately two-thirds of the total of 1 million barrels produced daily, with in situ operations accounting for the other one-third. It takes about 2 tonnes of oil sands to produce one barrel of oil, hence the quantity of oil sands mined each day is truly staggering.

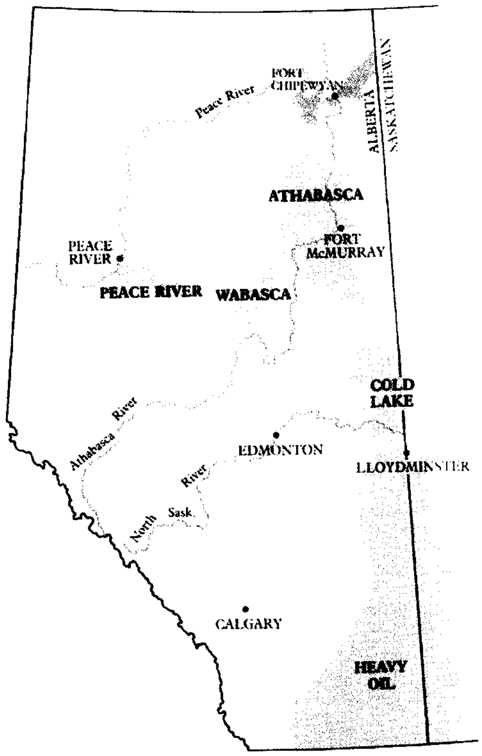


Figure 2-1 Alberta oil sands deposits (after McRory, 1982)

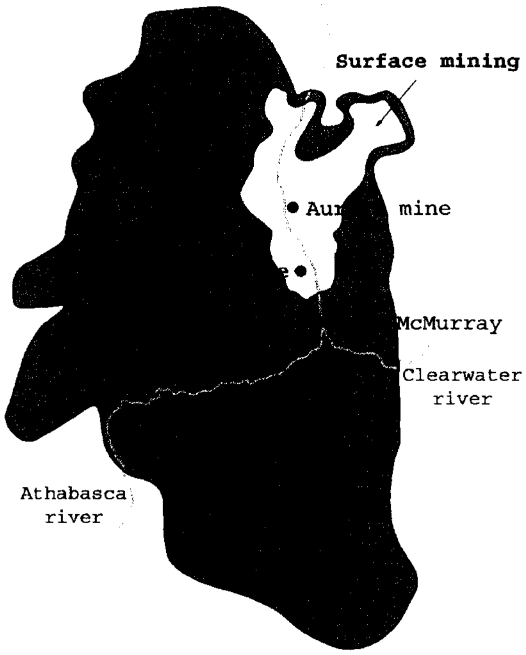


Figure 2-2 Athabasca oil sands: surface versus in situ extraction areas (modified from McRory, 1982)

2.2 Surface Mining Operations at Syncrude

Syncrude Canada Ltd. is located approximately 38 km north of the city of Fort McMurray along highway 63, or 440 km northeast of Edmonton. Syncrude operates one of the largest oil sands synthetic crude oil production facilities in the world. Syncrude's leases in the Athabasca deposit contain approximately 8 billion barrels of reserves. In 2004, Syncrude produced approximately 87.2 million barrels of synthetic crude oil, known as Syncrude Sweet Blend, generating approximately 13% of Canada's total oil production. By 2006, Syncrude's daily production is expected to be about 350,000 barrels (Syncrude, 2005).

Syncrude is a joint venture between eight companies: Canadian Oil Sands Limited Partnership, Canadian Oil Sands Limited, Conoco Phillips Oilsands Partnership II, Imperial Oil Resources, Mocal Energy Limited, Murphy Oil Company Ltd., Nexen Inc., and Petro-Canada Oil and Gas. It is operated and administered under Syncrude Canada Limited, which is responsible for the mining, extraction, upgrading, and utilities facilities at the Mildred Lake site, and the mining, primary extraction and slurry transportation at the Aurora site. Syncrude also has a Research Centre in Edmonton.

Syncrude owns and operates three surface mines north of Fort McMurray: the Base Mine, the North Mine, and the Aurora Mine. The Base Mine was the original mine that started its operation in 1978 and is reaching the end of its mineable life; it is scheduled for decommissioning in 2006 (Parsons, 2005). The North Mine began production in 1997 with a scheduled mineable life until 2032. The Aurora Mine opened in 2000 and is meant to replace the production loss due to the closure of the Base Mine. While the truck and shovel mining method is used in North and Aurora mines, draglines were used in the Base Mine as the primary excavating equipment.

Currently, the annual oil sands production from the North Mine is about 78 million tons and with a stripping ratio of 1.2:1. The annual oil sands production from the Aurora Mine is about 85 million tons with a stripping ratio of 0.7:1. The average oil sands grades in the North Mine and Aurora Mine are about 10.4% and 11.5% respectively (Parsons, 2005).

2.3 Truck and Shovel Mining

The truck and shovel mining method is used for both overburden and ore removal at Syncrude's North and Aurora mines. This method consists of exposing the oil sands by stripping the overburden. The top layer of about 3 m thick muskeg is dewatered over a 2-year period before it is removed. Muskeg is then stockpiled and used for current or future reclamation activities. Below the muskeg, the overburden consists of Pleistocene glacial sediments. In the present mining area of the North Mine, below the Pleistocene deposit, the overburden includes Cretaceous age clay-shale of the Clearwater Formation. The Clearwater Formation is not present in the Aurora Mine where oil sands is being mined currently. Mining shovels excavate the overburden to expose the oil sands. The oil sands is then excavated by mining shovels and delivered by large trucks to double roll crushers. The crushed oil sand is conveyed to a mixing unit where hot water is added to the oil sands to create a slurry that is pumped via pipeline to the extraction plant. This hydrotransportation begins the extraction process by separating the bitumen from sands as the slurry is pumped to the primary extraction plant.

Some of the largest available mining equipment such as P&H 4100 series electric cable shovels with dipper capacity of up to 46 m^3 and Caterpillar 797 trucks with a payload capacity of 365 tonne (400 ton) are used at the North Mine and the Aurora Mine for oil sands and overburden removal. Syncrude operates two main types of shovels: hydraulic and cable-electric. These shovel types vary in a number of ways that make their operation unique. Mobility, breakout force, and digging trajectory are some of the ways that these shovels differ.

Hydraulic shovels, initially used in the construction industries, are now more common in surface mining operations across the globe. In a hydraulic shovel, all of the digging operations are controlled by hydraulics powered by diesel engines. The hydraulic cylinders provide more flexible digging compared to cable-electric shovels. Hydraulic shovel mobility is not restricted due to absence of electric cables and they can be easily transported to different areas of the mine. Hydraulic shovels are a better choice for selective mining compared to electric shovels. However, compared to electric shovels, hydraulic shovels are not well suited to long-term operation in difficult digging environments because the maintenance cost becomes significant due to frequent leakage and breakdown of the hydraulic systems. Syncrude uses O&K RH200 and O&K RH400 hydraulic shovels. The O&K RH200 shovel has a 23 m^3 bucket and is well matched for loading 218 tonne capacity haul trucks with a typical four-pass loading scheme. O&K RH400 shovels have bucket capacities of about 46 m^3 and are better suited for loading the larger 360 tonne+ haul trucks in four passes. Typical bench height for O&K RH200 shovel is about 8 m, but it can mine benches as high as 12 m. Similarly, typical bench height for O&K RH400 shovel is about 12 m with a maximum digging height of 15 m. The lower dumping height and smaller dipper capacity reduces the flexibility of the O&K RH200 shovel, as it cannot properly load the larger 360 tonne+ haul trucks.

In a cable-electric shovel, the digging element is a dipper, with a cutting edge equipped with replaceable teeth by means of an adapter. The dipper is attached to a handle with a latched door that allows the material in the dipper to be dumped. When excavating material, the dipper is pulled through the material by hoist cables, which pass over a boom, while the dipper is held against the face by crowd action that maintains a suitable depth of penetration by extending or retracting the handle lengthwise. Due to the rigid digging motion of electric shovels, bench heights generally do not vary much or else the shovel productivity can diminish significantly. Syncrude operates mostly P&H 4100 series electric shovels with a few Bucyrus-Erie (BE) shovels. Dipper sizes of these shovels vary depending on the model, but are typically 46 m^3. The working benches are typically 14 m to 16 m high. The maximum digging height of these shovels is approximately 20 m.

Although some hydraulic shovels are in operation at Syncrude, P&H electric cable shovels are the primary shovels used at Syncrude for oil sands and overburden excavation. Therefore, this research was focussed on P&H electric cable shovels.

CHAPTER 3 P&H ELECTRIC SHOVELS AND PAST PERFORMANCE MONITORING STUDIES

3.1 Introduction

P&H mining equipment are manufactured by Harnischfeger Corporation, Milwaukee, Wisconsin, USA. This company, founded in 1884, is a global leader in the manufacture and service of large excavating and drilling machines used to mine copper, iron ore, silver, gold, diamonds, phosphate, molybdenum, potash, coal, oil sands, and other minerals. Ninety percent of the world's surface mines utilize P&H equipment (P&H Mining Equipment, 2006).

P&H offers three major product lines: electric mining shovels, walking draglines and rotary blasthole drills. P&H electric shovels are available in different sizes and capacities and their working ranges are given in Table 3-1. The company's flagship product line is the 4100 series electric mining shovels that are equipped with sophisticated control systems. These shovels have a dipper size of about 46 m^3 that carry up to 90 tonnes+ of nominal payload in one scoop and can load today's giant mining trucks in just three or four passes as illustrated in Figure 3-1. A P&H 4100 TS shovel costs about CAD $17 million (Oil Sands Discovery Centre, 2005).

P&H 4100TS and P&H 4100BOSS model shovels are in operation at Syncrude mines for both oil sands and overburden excavation. The design and operating specifications for TS and BOSS model shovels are given in Appendix A. A summary of P&H shovels in use at the North and Aurora mines is given in Table 3-2. Figure 3-2 shows a P&H 4100 BOSS shovel loading a haul truck.

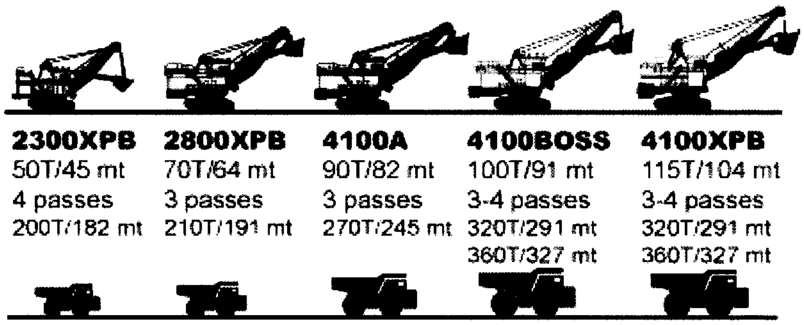


Figure 3-1 P&H shovel and truck combinations (after P&H Mining Equipment, 2006)

Table 3-1 Working ranges of different P&H shovels (after P&H Mining Equipment, 2006)

Model	Nominal payload capacity (tonne)	Dipper capacity range (m^3)
1900	19.1	7.6 – 19.1
2100	22.7	10.7 – 21.4
2300XPB	45.4	19.9 – 36.7
2800XPB	59.0	25.2 – 53.5
4100A E-Plus	82.0	30.6 – 61.2
4100A/LR	59.0	25.2 – 53.5
4100BOSS*	90.7	30.6 – 61.2
4100TS*	90.7	30.6 – 61.2
4100XPB	104.0	35.9 – 76.5

*Operating in Syncrude

Table 3-2 Summary of P&H shovels in North Mine and Aurora Mine

Model	Shovel ID	
	North Mine	Aurora Mine
P&H 4100TS	11-78, 11-79, 11-80	11-81
P&H 4100BOSS	11-86, 11-87	11-82, 11-83, 11-84, 11-85, 11-88
TOTAL	5	6

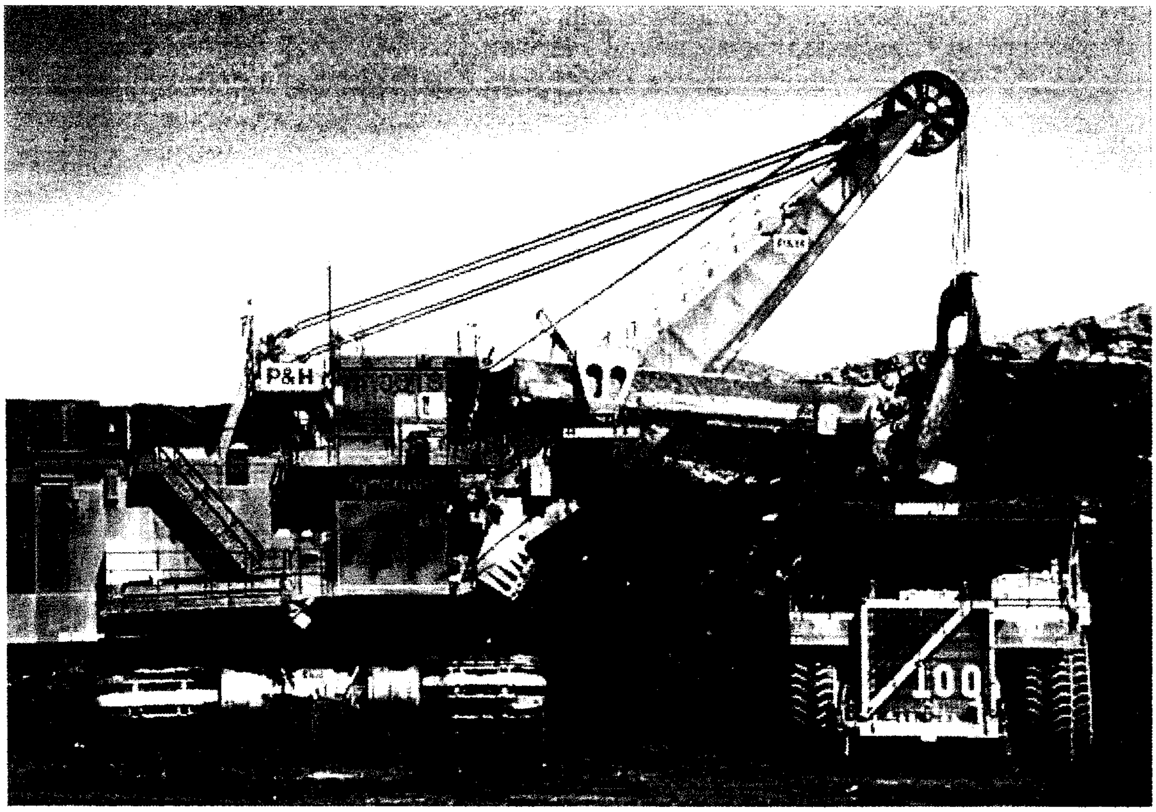


Figure 3-2 P&H 4100 TS shovel excavating oil sands

3.2 Basics of Shovel Operation

Main activities of a shovel during its operation include digging, hoisting, swinging, and dumping. The sequence of activities in an ideal simple shovel duty cycle consists of digging, hoisting, swinging the dipper towards the truck, dumping and swinging back to the face (Figure 3-3). For diggability assessment, the dig cycle is most important as it represents the actual time the dipper spends digging in the face. The swing and dump cycles merely provide a material handling service in delivering the excavated material to the trucks.

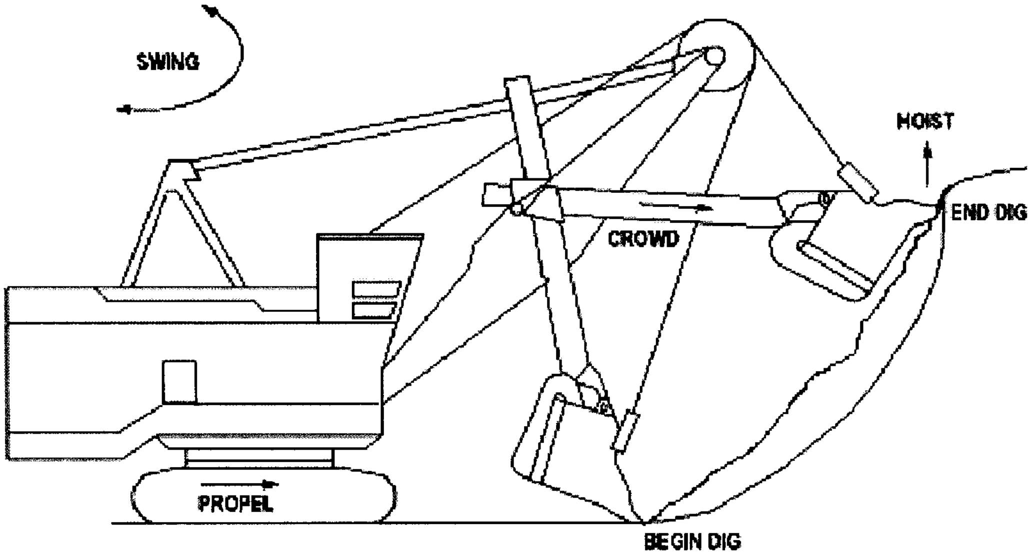


Figure 3-3 Various shovel activities

The dig component of a shovel duty cycle is a combination of two elements: hoisting and crowding. The hoist action is responsible for pulling the dipper up through the face, while the crowd action provides a thrust on the dipper to force it into the ground. During hoisting, the crowd action maintains the dipper at a suitable depth of penetration into the ground throughout the digging cycle. Therefore, if the crowd element for each dig cycle is equivalent, i.e., same optimal depth of penetration is maintained during each dig cycle, then the hoist element of the dig cycle would represent the effort required to dig the material.

Because crowd action provides the thrust required to penetrate the dipper into the bench face, the crowd energy or power may provide an indication of ground penetrability which depends upon the material strength and stiffness. Measures of ground diggability may differ from the ground penetrability since there are different deformation modes involved. Penetration of the dipper into the bench face causes local shearing and local volumetric straining of the oil sands around the dipper teeth and lip whereas the hoisting action rips the dipper upwards through the full face height and involves significantly more shearing action combined with fragmentation and fluffing of the oil sands as it fills the dipper.

Penetrability is the result of a simpler deformation mode much like the standard cone penetration test. After the dipper has penetrated into the bench face, it has to overcome the shearing resistance of the soil while the hoist is in action. Therefore, the hoist energy or power consumed during a dig cycle is a good measure of the ground diggability. This hypothesis will be evaluated later in this thesis.

Although the performance of a shovel is related to the ground diggability, one should understand the difference between the shovel performance and diggability. The diggability is related to ground characteristics (resistance to shearing), while the shovel performance is related to the excavating equipment itself and the operator. The energy used to excavate a unit volume of material could define the performance of a shovel. A shovel operator has no control over the material diggability, but with optimization of hoist and crowd actions the operator can achieve better shovel performance.

3.3 Electrical Systems

A detailed description of the shovel electrical systems is beyond the scope of this thesis. For general understanding, a brief overview of the electrical systems and motors used in P&H 4100 series shovels is given here. The shovels listed in Table 3-2 have similar capacity, operating characteristics and electrical systems.

The P&H 4100 series shovel is controlled by an Electrotorque Plus control system. This system is capable of producing controlled delivery of adjustable DC power, from the pit supplied AC power, to the shovel. In more recent TS and BOSS machines, the Electrotorque Plus control system is replaced with a Loading Control Center and Centurion system. The Centurion system, introduced in 2004, is a supervisory control and data acquisition system for P&H electric shovels. Centurion provides three coordinated motion control modules: Optidig II, which optimizes crowd, and hoist motions to prevent stalling in the bank; single-point boom profiling, which protects against dipper contact with the boom after rope change-outs; and Enhanced reactive power compensation diagnostics, which corrects inherent network power fluctuations. Another Centurion standard feature is production monitoring that provides real-time feedback on shovel performance (Suppliers Report, 2005). All the shovels studied in this research did not have the Centurion system and used an Electrotorque Plus control system.

The main incoming pit 13.8 kV AC power is stepped down to a practical working voltage of 600 V AC in a 2.5 MVA transformer. The stepped down 600 V AC power is then routed through the converter cabinets where the AC power supply is converted to DC operating power and is supplied in a controlled manner to the hoist, crowd, swing, and propel DC motor armatures through two three phase 600 V secondaries. The control unit regulates DC power delivery to each of these motors and responds to the operator command during various shovel activities. The motors then adjust to the voltage and current outputs synchronous with motor speeds and torques as desired by the operator. For these DC motors, current represents torque across the motor armature and voltage represents the speed of rotation (rev/min).

The P&H 4100 series shovel uses two identical extra heavy duty DC continuous motors (K-1690 for TS and K-1690B for BOSS) for hoist drive power. The motors are placed one fore and one aft of the hoist drum gear. The armatures of the two hoist motors are connected in series and this configuration results in equal sharing of current and hence, equal production of torque from each motor. Two relatively smaller motors are used instead of a single larger motor because they offer lower mechanical inertial resistance to changes in their direction of motion. Hence, the lower inertial resistance of two smaller armatures working in unison can accommodate faster acceleration and retardation, bringing the hoist drums to maximum speed quicker than a single larger armature of a single motor of equivalent horsepower. A TS model shovel develops a total of 1775 kW (2380 HP) with a peak output of 2535 kW (3400 HP) whereas a BOSS model develops a total of 1887 kW (2530 HP) with a peak output of 2946 kW (3950 HP).

Lowering of the dipper is achieved by gravity-controlled modulation of the hoist motor. During dipper lowering the hoist motors work in a regenerative capacity and the kinetic energy from the controlled gravity fall of the dipper is fed back into the mine main AC line as usable AC current (Hendricks, 1990; Wong, 2005).

The crowd motor in a P&H 4100 series shovel is a single heavy duty K-700 DC continuous high torque motor, which develops 537 kW (720 HP). The peak power output for a TS model is 727 kW (975 HP) and for a BOSS model is 766 kW (1027 HP). The crowd stall for this motor is higher in retraction than in extension. The reason for lower extension stall is that the weight of the dipper is used as useful energy while crowding and the demand on crowd current is low.

3.4 Past Shovel Performance Monitoring Studies

The performance of mining equipment such as electrical cable shovels varies with the diggability characteristics of the ground. By monitoring the performance of shovels in a range of digging environments, it is possible to assess material diggability based on key shovel performance indicators. For example, the variation of power consumption during a single duty cycle given by Joseph and Hansen (2002) is reproduced in Figure 3-4. Digging cycle time, as shown in Figure 3-4, is expected to vary with the diggability of the oil sands. Therefore, the digging cycle time could be used as a simple performance indicator. Similarly, the area of the shaded portion corresponding to the digging cycle time represents the digging energy and this could be used as a performance indicator. A Diggability Index (*DI*) can also be derived based on the performance indicator(s) that best quantifies the ease of digging.

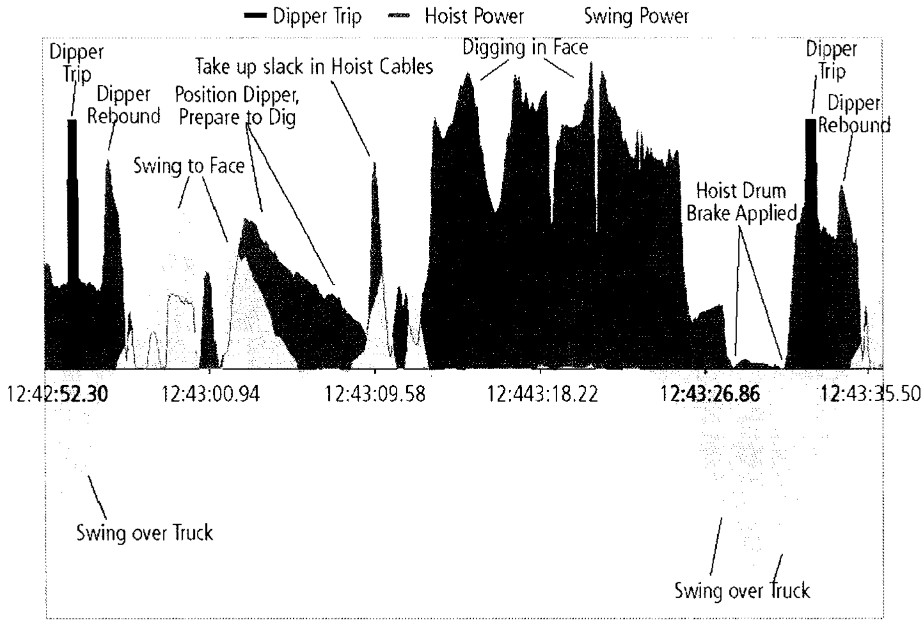


Figure 3-4 Cable shovel single duty cycle (modified from Joseph and Hansen, 2002)

With the availability of microprocessor based monitoring systems, it is now possible to reliably measure shovel performance parameters. Shovel performance parameters that have been measured in the past include cycle times (digging, swinging and dumping), dipper payloads, dipper fill factor, and power and energy consumption during digging. Monitoring of shovel parameters such as hoist rope position, crowd arm extension, hoist armature current and voltage, hoist field current, crowd armature voltage and current have been reported by Hendricks et al. (1989) and Hendricks (1990). Karpuz et al. (1992) measured loading cycle time, digging time, dipper fill factor, and power on the main drive AC motor to find the influence of depth of cut and blasting on shovel performance. Hansen (2001) reported measurement of dipper payload of electric shovels for improving shovel performance and blasting techniques. A literature review highlighted that although a few shovel performance-monitoring studies have been reported while loading broken material for evaluating blasting efficiency, very little study has been reported on shovel performance while digging in situ material, especially oil sands.

Researchers in the past have used either hoist or crowd motor responses for assessing diggability of blasted material. The first performance monitoring study was reported by Williamson et al. (1983) while monitoring DC motors in P&H 1900 and 2100 electric shovels in an iron ore mine in Australia to determine the diggability of blasted muck piles. Crowd armature voltage and current, swing armature voltage, hoist brake relay, crowd propel transfer relay and dipper trip relay were measured during the shovel operation. The swing voltage signal was used to determine the position of the dipper relative to the face and truck at any instant by integrating the signal over time. Crowd motor responses were used for assessing material diggability characteristics and changes in the shape of crowd voltage signal were used to predict difficulty in digging. Signals were found to become increasingly ragged with increasing digging difficulty as the dipper velocity changed through the face. Three different ways to quantify the variability in the crowd voltage signal throughout the digging cycle were proposed as a method for assessing diggability. They concluded that although crowd motor voltage was useful in assessing diggability, crowd motor power did not correlate well to the digging conditions. An example of their analysis illustrating the behaviour of motor responses in easy and difficult digging conditions is shown in Figure 3-5.

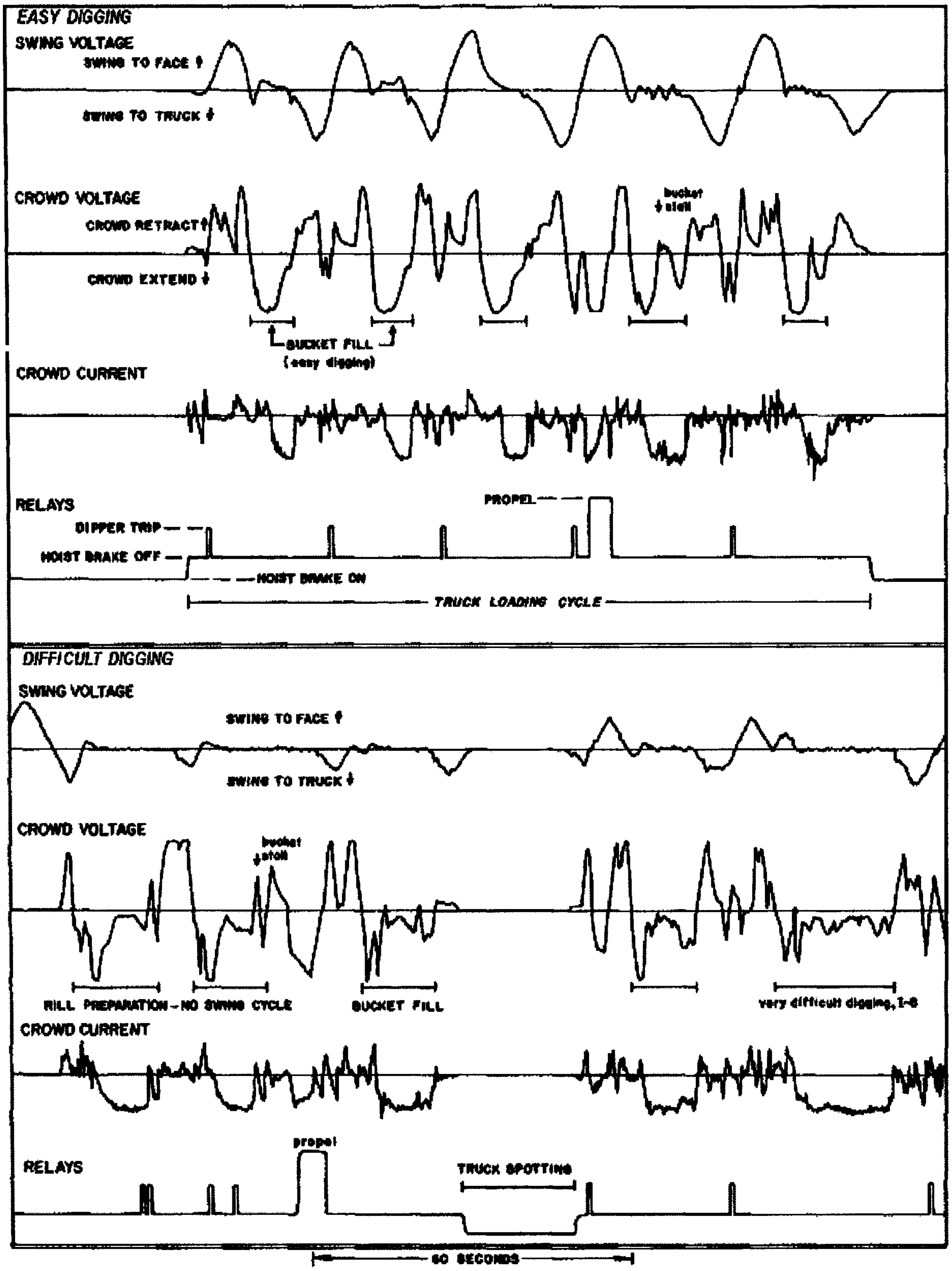


Figure 3-5 Response of monitored parameters in easy and difficult digging conditions (after Williamson et al., 1983)

Mol et al. (1987) monitored P&H 2300 electric shovels used for blasted overburden removal in a coal mine in Australia. In their study, crowd armature voltage and current, hoist armature voltage and current, swing armature voltage, dipper trip and crowd/propel relays were monitored. Swing voltage was used to identify the dig cycles. An example of the performance data analysis showing various shovel activities is reproduced in Figure 3-6. Crowd motor responses were used for assessing material diggability characteristics and a combination of crowd voltage, crowd current and dig time was used for deriving a diggability index.

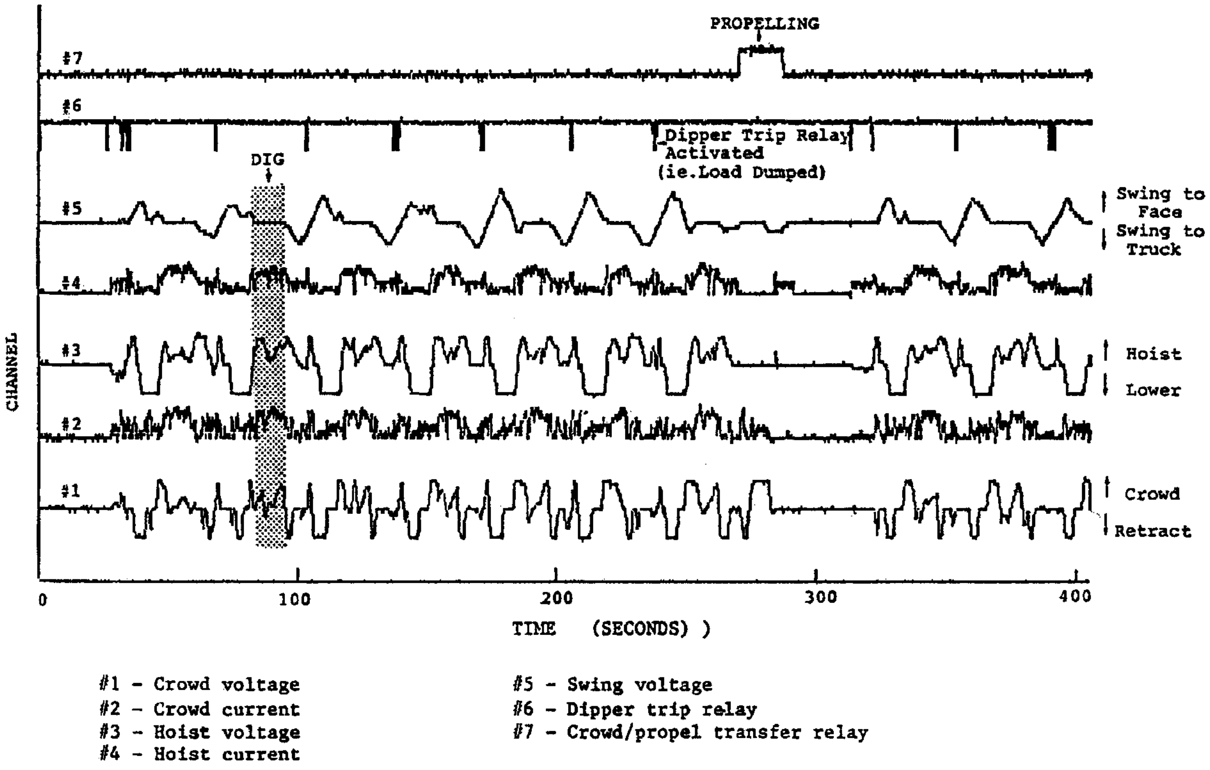


Figure 3-6 Traces of monitored parameters (after Mol et al., 1987)

Hendricks et al. (1989) and Hendricks (1990) reported monitoring of P&H 2800XP shovels while loading blasted material in a coal mine in Canada. Performance data was recorded at 0.1 s time interval. Shovels activities were identified by crowd armature voltage and current, hoist rope position and crowd arm extension signals. Analysis showed that swing voltage was not very useful for isolating dig cycles from other shovel activities (Figure 3-7).

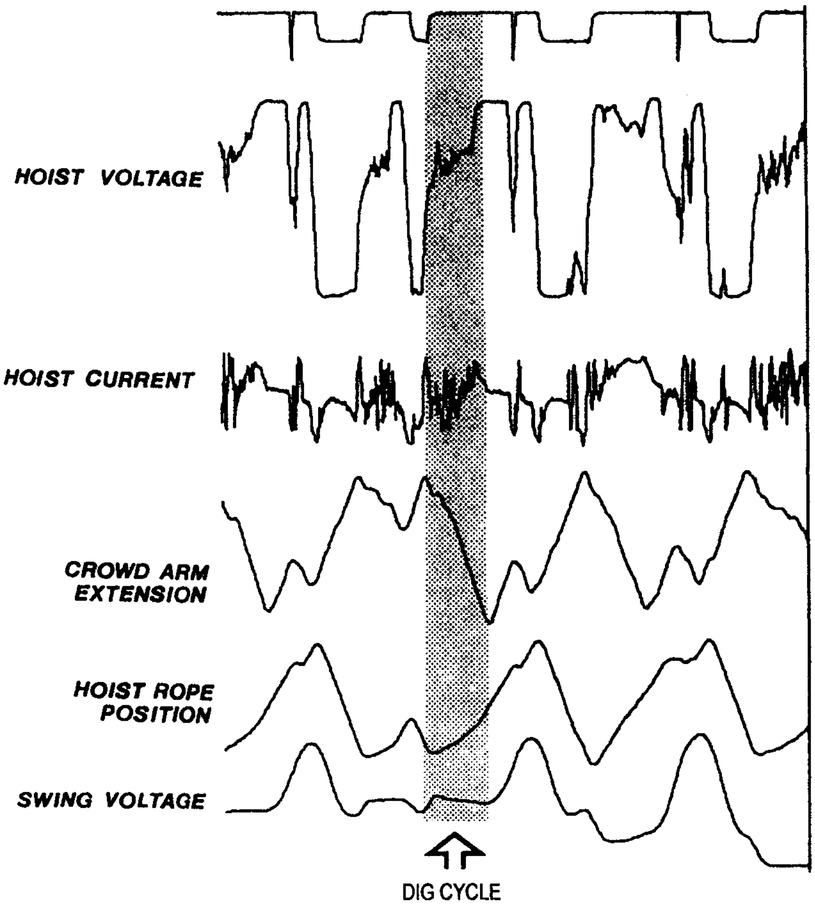


Figure 3-7 Isolation of dig cycle based on swing voltages (after Hendricks, 1990)

Contrary to Williamson et al. (1983) and Mol et al. (1987), Hendricks (1990) concluded that crowd motor responses were not very sensitive to digging conditions. Examples of signal traces monitored by Hendricks (1990) in easy and difficult digging conditions are depicted in Figure 3-8. He concluded that the hoist motor accomplishes the actual work during digging while the crowd motor serves only to complement the hoist action by maintaining a suitable depth of dipper penetration during the dig cycle. So, hoist motor responses were used to assess material diggability. Both voltage and current data were used in the analysis and a diggability index was estimated based on the product of ratios of maximum hoist voltage and current, to areas under these signals. The hoist based *DI* equation used by Hendricks (1990) is given below:

$$Hoist\ DI = \frac{\sum_{i=1}^{n}\left|HV_{i+1} - HV_i\right|}{\sum_{i=1}^{n}\left|SR * HV_i\right|} \times \frac{\sum_{i=1}^{n}\left|HI_{i+1} - HI_i\right|}{\sum_{i=1}^{n}\left|SR * HI_i\right|} \qquad [1]$$

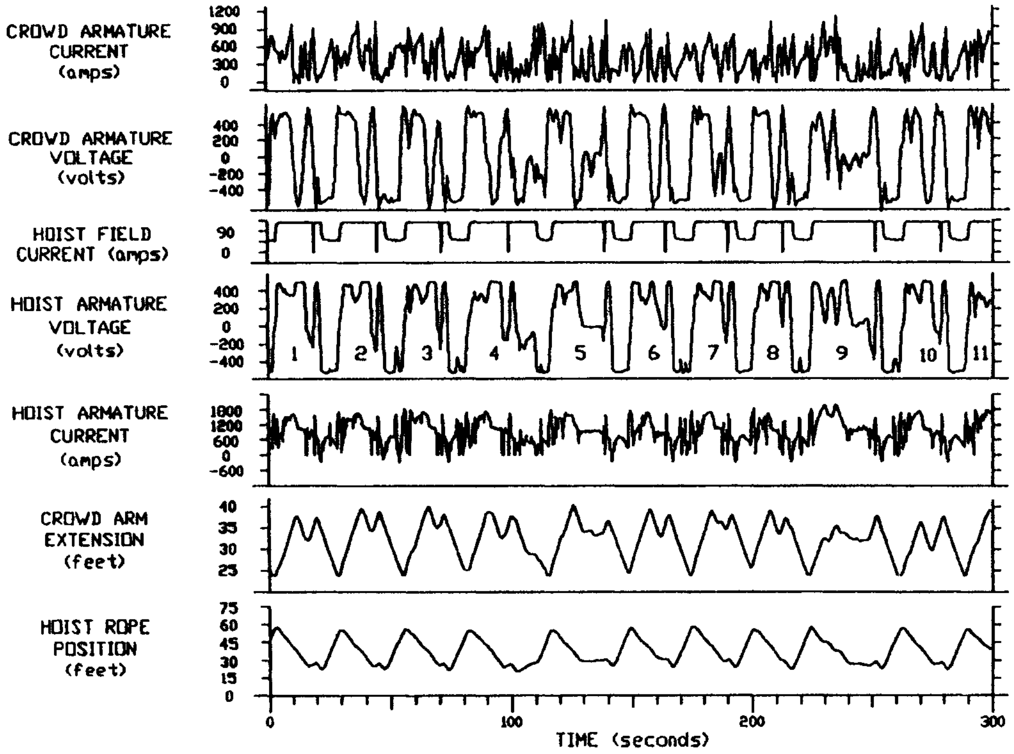
where,

n = number of readings taken during the dig cycle
DI = Diggability Index
HV = hoist armature voltage
HI = hoist armature current
SR = sampling rate

The above equation was used to determine the raggedness in the hoist current and voltage signals, which in turn was used to assess difficulty in digging. For example, in a difficult digging condition the hoist current trace was very ragged and hence, the absolute length of current trace was very long. However, the average value of corresponding hoist current was short and therefore the area under the current signal was low. Therefore, for a difficult digging condition, hoist *DI* was high. Conversely, in an easy digging condition, absolute signal length was short but the area under the signal was large. Hence, *DI* associated with easy digging condition was characteristically low. The study showed that the results could be misleading if average values of voltages and currents are used instead of absolute values. In a hard digging condition, because of high raggedness of signal, the average hoist current would be low compared to an easy digging condition. This average value when used for estimating the power consumption would give a lower value that is incorrect.

The importance of digging trajectory was also considered by Hendricks (1990) while developing a *DI*. It was found that the dipper trajectory, represented by a cut ratio (ratio of distances the dipper travelled in the crowd and hoist directions), can have a significant influence on *DI*. A higher cut ratio gave a higher *DI* compared to a lower cut ratio while digging similar material.

EASY DIGGING



DIFFICULT DIGGING

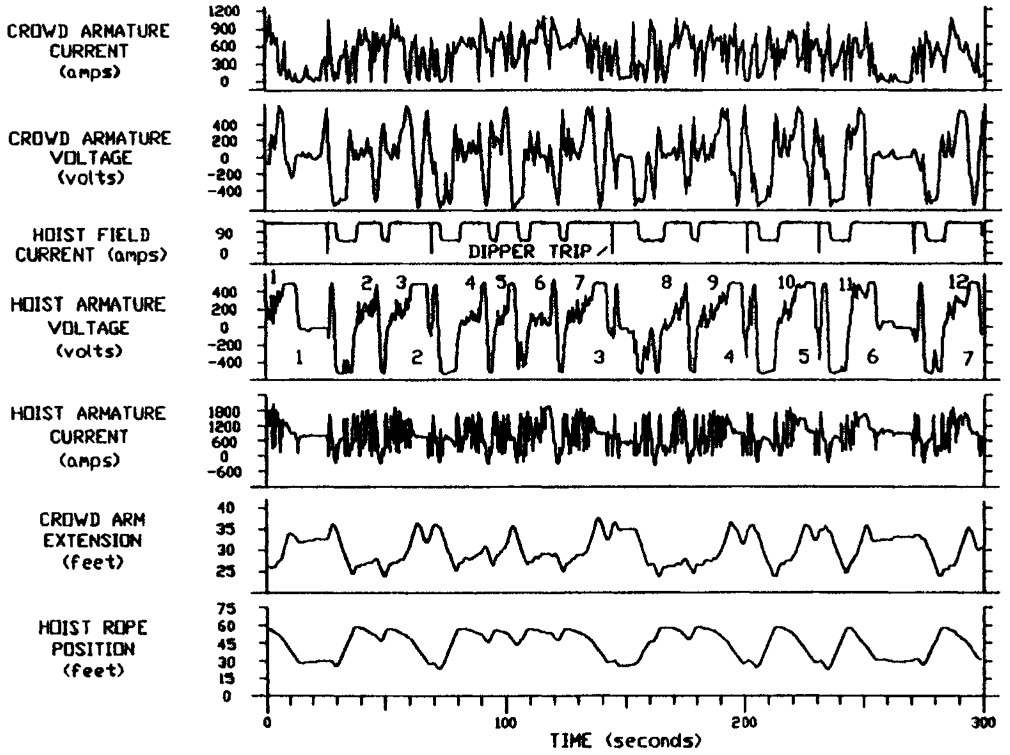


Figure 3-8 Response of monitored parameters in easy and difficult digging conditions (after Hendricks, 1990)

A past study by Harnischfeger Corporation showed that the crowd motor responses were similar in coarse blocky fragmentation and loose, well broken blasted material. The study concluded that crowd responses were relatively independent of material diggability. It has been the general consensus of Harnischfeger Corporation that crowd responses are erratic (unpredictable) and attempts to relate them to ground diggability would lead to erroneous conclusions (Hendricks, 1990).

Karpuz et al. (1992) reported monitoring of P&H 2100BL shovels for determining the influence of depth of cut on shovel performance while digging blasted and unblasted overburden formations. The details of their monitoring scheme are, however, not given. They concluded that shovel performance indicators such as dipper fill factor, digging time, digging power and digging energy can be significantly influenced by the dipper trajectory. A deep cut through a muck pile resulted in higher power consumption than for a shallow cut.

3.5 Summary

P&H 4100 series electric shovels are equipped with DC motors; two motors are used for hoist, two for swing, and one for crowd action. The dig cycle is the most important element of the shovel duty cycle as it represents the actual time the dipper spends digging in the face. The dig component of a shovel duty cycle is a combination of two elements: hoisting and crowding. The hoist action is responsible for pulling the dipper up through the face, while the crowd action provides a thrust on the dipper to force it into the ground. If the crowd element for each dig cycle is equivalent, i.e., same optimal depth of penetration is maintained during each dig cycle, then the hoist energy or power consumed during a dig cycle may be a good measure of the material diggability.

A literature review found that few shovel performance monitoring studies have been reported. Most studies have dealt with loading broken rock for evaluating blasting efficiency. Very little research has been published on shovel performance while digging oil sands. Isolation of dig cycles from other shovel activities is one important step in performance analysis and past studies often used swing voltage to identify the dig cycles.

Most of the studies relied on manual stop watch studies for identifying the dig cycles. Researchers have used either hoist or crowd motor responses to assess diggability of blasted material by analyzing the raggedness in the signal traces. Influence of dipper trajectory on shovel performance has been reported. Only limited work has been reported on shovel performance assessment based on the digging energy or digging power. The influence of temperature, resulting in frost penetration, on shovel performance was not considered.

CHAPTER 4 SHOVEL PERFORMANCE DATA COLLECTION AND DEVELOPMENT OF DIG CYCLE IDENTIFICATION ALGORITHM

4.1 Data Collection

Sensors that measure voltage and current are mounted across the electrical motor circuits in the shovels. The voltage is measured directly across the motor terminals and the current is measured through a line excitation monitor (LEM) that produces a scaled down voltage output. In a TS machine, 1 V output represents 300 A current and for a BOSS shovel 1 V represents 500 A equivalent current. These voltage and current data are stored in Syncrude's Maintenance Decision Support Program (MDSP) database at one-second time intervals. By using the output from existing sensors, the goal was to collect and analyze the data to identify key shovel performance indicators. The MDSP database has been maintained at Syncrude to provide data for fault diagnosis and improving preventive maintenance of the shovels and haul trucks. Although a huge amount of shovel performance data are routinely collected and stored in the MDSP database, the complete value of this data has not yet been fully realised but work, like this thesis, is ongoing at Syncrude.

Current and voltage data from two hoist, one crowd and two swing motors were collected from the MDSP database. The following parameters were collected: date and time, hoist armature voltage and current, hoist field current, crowd armature voltage and current and crowd field current, and swing armature voltage and current. These voltage and current values vary with shovel activity and their possible ranges are given in Table 4-1. Figure 4-1 shows a portion of the raw data illustrating variations recorded during shovel operation.

Data were collected for eight different shovels operating in the North and Aurora mines as listed in Table 4-2. Performance data were not available for 11-86, 11-87 and 11-88 shovels. During the study period, the shovels were excavating either oil sands or overburden. Twelve months (December 2004 to November 2005) of performance data were collected. Given that performance data comprising nine parameters were collected at one-second time intervals, the quantity of data handled was huge. Analysis of performance data along with the video records of operating shovels, described later in this thesis, showed that swing armature voltage and current, and crowd field current did not correlate with the begin and end of the dig cycles. Therefore, these parameters were not further used in the analysis. Other parameters such as the date and time, hoist armature voltage and current, hoist field current, and crowd armature voltage and current were used in the analysis.

Table 4-1 Range of voltage and current parameters

Parameter	Range		
	Hoist motor	Crowd motor	Swing motor
Armature current (A)	2650 to -2650	1650 to -1650	2250 to -2250
Armature voltage (V)	600 to -550	550 to -550	600 to -600
Field current (V)	0 to 150	0 to 150	0 to 150

Table 4-2 Shovels providing performance data used in this thesis

Model	Shovel ID	
	North Mine	Aurora Mine
P&H 4100 TS	11-78, 11-79, 11-80	11-81
P&H 4100 BOSS		11-82, 11-83, 11-84, 11-85
Total	3	5

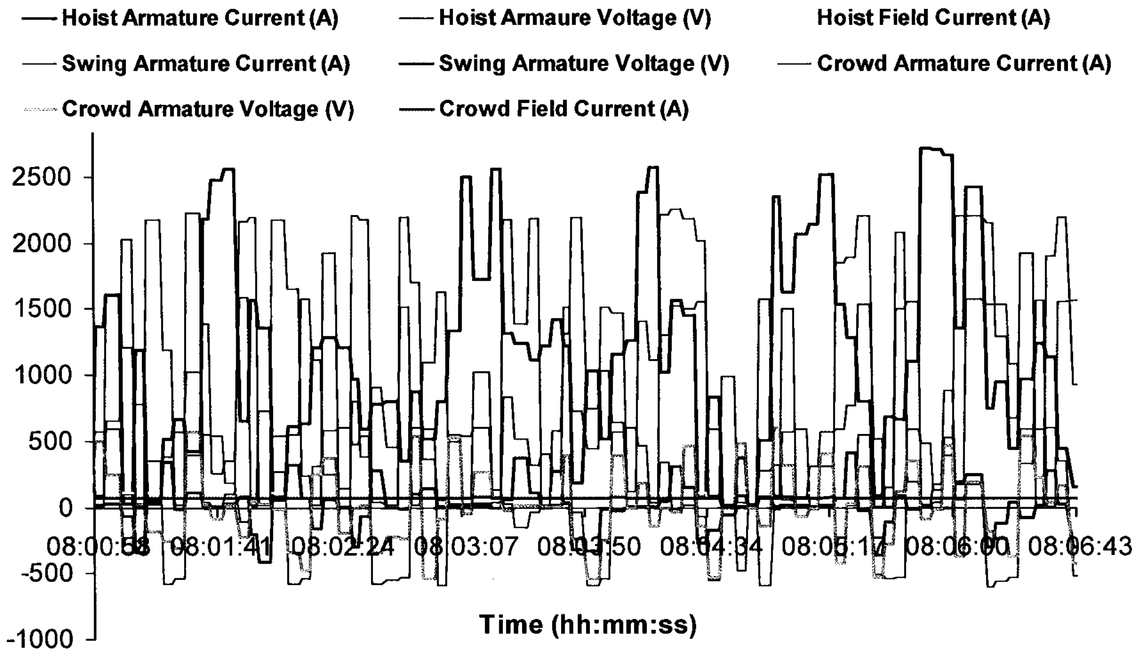


Figure 4-1 Current and voltage parameters during operation of 11-78 Shovel

Performance data are stored in the Syncrude's computing servers at Fort McMurray. Using Syncrude's intranet it was possible to access and retrieve the data at the Syncrude Research Centre in Edmonton. Due to data storage issues, data are archived for 40 days only at Syncrude, so it was not possible to collect performance data for the past operating periods older than 40 days.

It may be noted that the data collected in this study came from shovels operating under a range of digging conditions in active mines unlike the past studies that were mostly done in over short-term controlled digging conditions. The performance data were collected at 1 Hz sampling rate and sometimes erroneous due to GPS error. Therefore, to use this data for detailed analysis was challenging.

Dipper trajectory information with respect to the bench face geometry may help in shovel performance analysis. However, the dipper trajectory data was not available and therefore, could not be collected. It may be noted that while analyzing shovel performance, the dipper trajectory can be taken into account only when the dipper path information along with the bench face profile information is available. Even if the x- and y- coordinates of the dipper path were available, it was almost impossible to obtain the actual bench face profile. Therefore, shovel performance analysis was carried out without the dipper trajectory information. Even with this limitation, the huge volume of data that was processed in this research tended to average out the dipper trajectory variations. Influences of other factors, for which data were available, were analyzed to evaluate how they affect the shovel performance.

4.2 Identification of Dig Cycles

One important step in analyzing the performance data is to identify the 'dig cycle' or the digging portion of the duty cycle. Determination of the dig cycle forms the foundation for further analysis. The challenge was to identify in a consistent manner the dig cycles using only the voltage and current data from different motors. The sequence of activities in an ideal simple shovel duty cycle consists of digging, hoisting, swinging the dipper towards the truck, dumping and swinging back to the face (Figure 3-3). However, in practice the duty cycle activities are more complex because often two or more of the above activities occur simultaneously. For example, the dipper may start swinging towards the truck while it is still digging. Furthermore, some shovel activities such as face cleaning, material loosening, etc. make the dipper motion more complex. Therefore, processing and subsequent interpretation of the shovel performance data to identify the shovel activities was a challenge.

Four digital video recordings of different operating electric cable shovels were taken (Table 4-3) and the corresponding shovel performance data were collected. The video records were examined to identify the start and stop times of specific shovel activities, especially the dig cycle. A total of about 100 dig cycles were observed from the videos. By comparing the video record with the corresponding shovel performance data, it was possible to understand the behaviour of different motor signals for various shovel activities and to establish patterns of signal behaviour that can be used to identify shovel activities independently of video information. The continuous visual record of shovel activity provided an important verification in the analysis of signal traces and for identification of anomalous data.

Table 4-3 Duration of video recordings

Video #	Shovel	Date	Duration	Number of dig cycles
1	11-79	November 16, 2004	35	30
2	11-78	January 28, 2005	33	31
3	11-80	March 10, 2005	22	17
4	11-80	April 20, 2005	27	19

An example of the shovel activities identified from the video observation (Video #1) is given in Figure 4-2. This figure indicates a number of dig cycles that were identified from the video record and shows the corresponding voltage and current for the hoist motor. Clearly, a consistent and clear pattern of signal responses from the hoist motor matches the start of each dig cycle. The behaviour of the hoist voltage and current correlates less strongly with the end of the dig cycle.

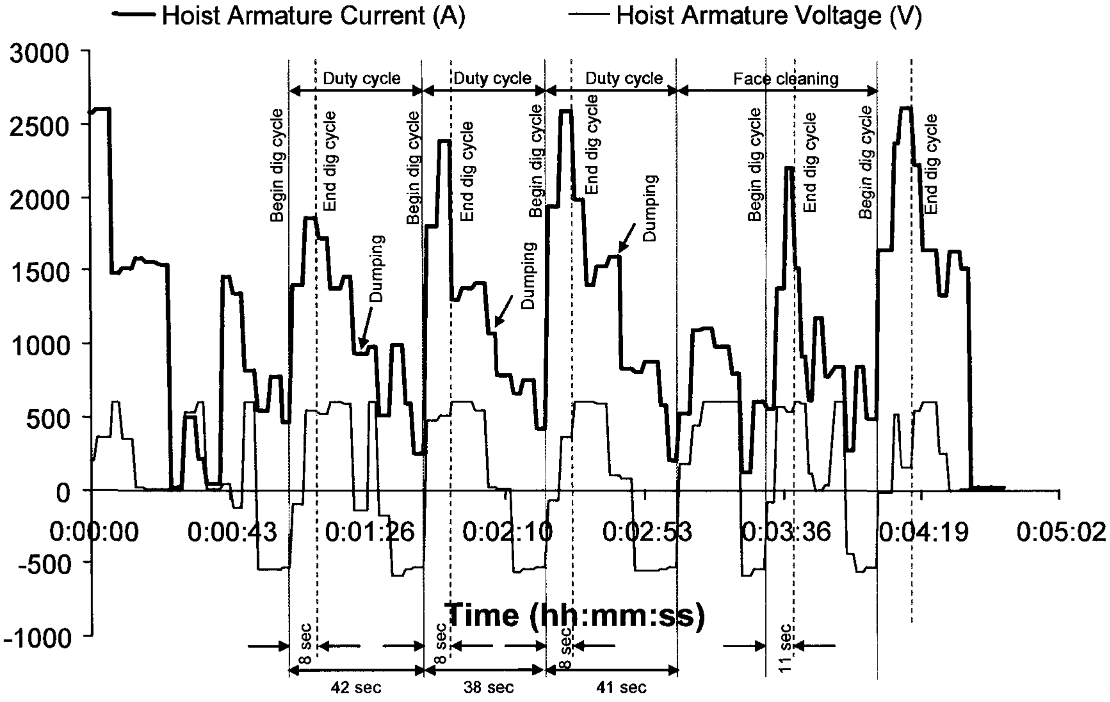


Figure 4-2 Hoist motor responses and shovel activities identified from video observation for the 11-79 shovel

Identification of shovel activities from the shovel performance data was based on the interpretation of motor voltage and current. DC motor speed generally depends on a combination of the voltage and current flowing in the motor coils and the motor load or braking torque. The speed of the motor is proportional to the voltage, and the torque is proportional to the current.

Positive (+) and negative (-) voltages represent direction of rotation of the motor. For the hoist motor, a positive voltage means the dipper is moving upward and a negative voltage means the dipper is moving downward. For the crowd motor, a positive voltage implies crowd arm extension and a negative voltage implies crowd arm retraction. For the swing motor, the sign of voltage depends on the swing direction.

Armature currents of hoist and crowd motors also change from positive to negative and vice versa. For instance, at the beginning of hoisting, both armature voltages and currents are positive. When the dipper approaches the boom point but is still going up, the operator reverses the joy stick in the downward direction to stop the upward hoisting motion. At this point, the hoist armature voltage remains positive but the hoist armature current becomes negative to cancel out the hoisting, usually referred to as plugging. The behaviour is similar while lowering the dipper. As the operator starts out lowering the dipper, both the armature voltage and current of the hoist motor are negative. When the dipper approaches the pit floor and is still going down, the operator reverses the joy stick to stop the lowering motion. At this point, the hoist armature voltage remains negative but the hoist armature current becomes positive. Armature current response of the crowd motor is similar to the hoist motor. At the beginning of a dig cycle, the dipper starts moving up so the armature current was positive. Similarly, dig cycle ends before the dipper approaches the boom point. Therefore, during the actual dig cycles the armature currents were always positive.

4.3 Development of Dig Cycle Identification Algorithm

One goal was to develop automated data processing algorithms to identify the portion of the shovel performance data that corresponds to each dig cycle. Once the dig cycles are identified accurately, key performance indicators such as the digging cycle time and the associated digging power and energy for both hoist and crowd motors can be estimated, which could later be used as measures of shovel performance.

The behaviour of the hoist, crowd and swing motor parameters during shovel operation is illustrated in Figure 4-2 to Figure 4-4. A combination of these motor responses was used to identify the dig cycles.

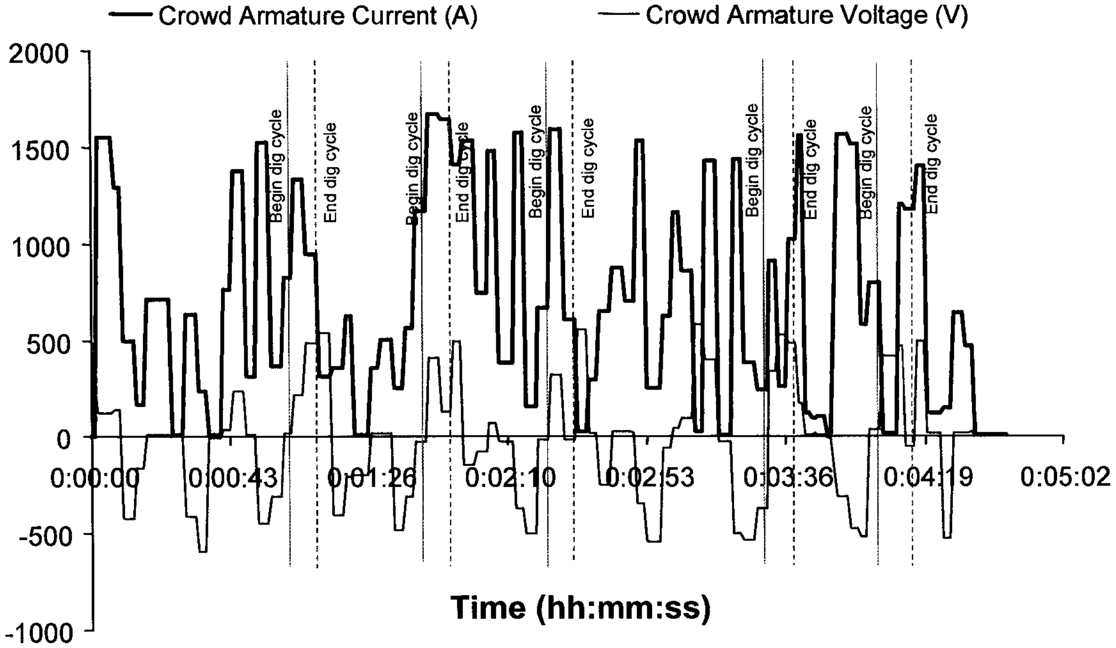


Figure 4-3 Crowd motor responses during shovel duty cycles for 11-79 shovel

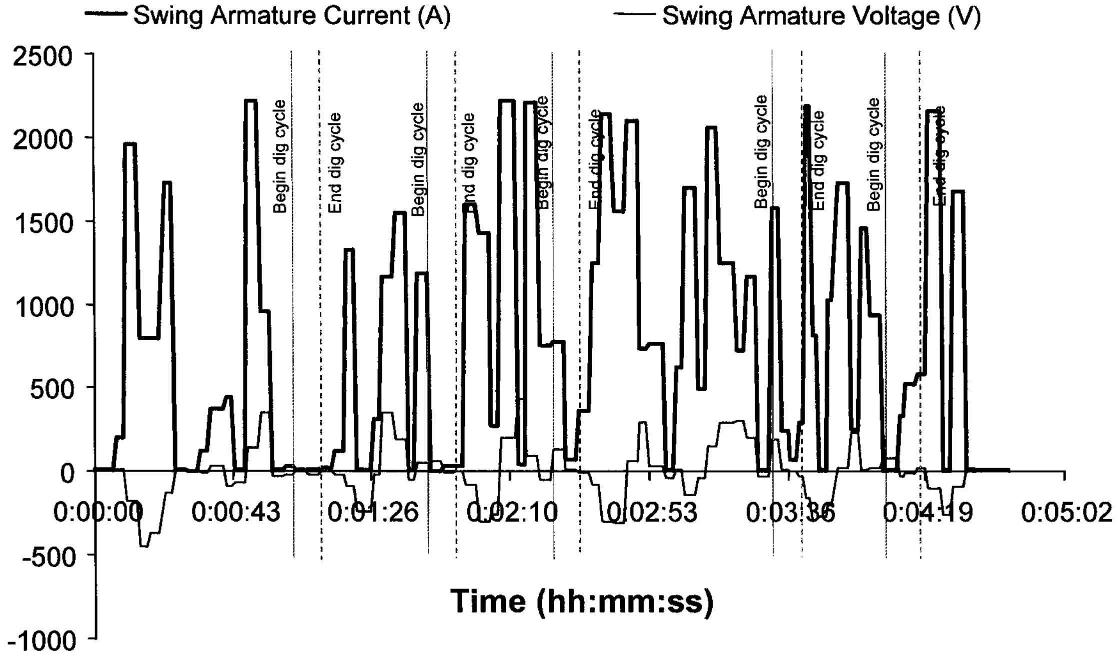


Figure 4-4 Swing motor responses during shovel duty cycles for 11-79 shovel

The time when the hoist armature voltage changes rapidly from maximum negative (dipper nearing pit floor) towards positive (upward dipper movement) indicates the beginning of a dig cycle (Figure 4-2). While digging, the dipper has to overcome the material resistance causing the load (torque) across the hoist motor armature to increase and therefore, the hoist armature current goes up continuously. When the oil sands is fractured or broken and loses contact with the in situ formation, the load on the motor decreases. Accordingly, the hoist armature current drops and indicates the end of the dig cycle. By comparing the MDSP data with video recordings it was found that when the hoist armature current was more than 2600 A for a dig cycle, the dipper was still digging even if there was a minor drop in the armature current from the previous value. A hoist armature current of greater than 2000 A associated with a positive crowd armature voltage (crowd extension) and relatively high crowd current (>900 A) also represented digging action. Similarly, a jump in the hoist field current (difference >50 A), representing a change from a weaker field to a stronger field, indicated digging activity even though other criteria were not satisfied. It was also found that when the dipper was engaged into the face, hoist armature current was typically more than 1500 A. Hoist armature currents less than 1500 A were associated with other activities such as lifting of empty dipper, face cleaning and/or pushing loose material etc. Therefore, the dig cycles having maximum armature current below 1500 A were not treated as actual dig cycles and were excluded from the analysis. The hoist and crowd motor responses, illustrated in Figure 4-2 and Figure 4-3, were fairly consistent for all data that were analysed along with the video records.

Contrary to research by Williamson et al. (1983) and Mol et al. (1987) analysis of swing motor data did not show a clear and systematic pattern for different shovel activities. During an ideal dig cycle, the shovel does not swing and therefore, swing armature voltage is expected to be close to zero. However, Figure 4-4 shows abrupt changes in swing armature voltages during some dig cycles. This is a clear indication of complex dipper motion during digging. Therefore, swing data were not used in further analysis to identify the dig cycles.

Although swing data were not useful when identifying dig cycles, the fluctuation of swing voltage during digging was a clear indication that the dipper was still swinging sideways while it dug. This finding was important because the sidewise motion of the dipper during digging can adversely affect performance of various shovel components. For example, the sidewise motion can induce additional tension on the hoist ropes and reduce rope life. More study on this phenomenon is beyond the scope of this research but it is being investigated by Syncrude.

From the video recordings, it was observed that the dig cycle time could vary between 6 to 25 seconds for a range of bench geometry and digging conditions. Dig cycle times less than 6 seconds were usually associated with face cleaning activities and more than 25 seconds represented some other activities such as the dipper stall in the bank, due to overcrowding, in which case the operator partially retracts the crowd before digging again and in the process takes longer time. Therefore, only the dig cycles with dig time ranging from 6 to 25 seconds were considered for further analysis.

A computer program was developed to use a combination of hoist and crowd motor responses to identify the dig cycles. Three video recordings (#1, 2 and 3) were used to develop the dig cycle identification algorithm. By analyzing the performance data in combination with the video records, it was found that the magnitude and/or trend of the hoist armature current and voltage, crowd armature current and voltage, and hoist field current can be used to identify the dig cycles from other shovel activities. Therefore, these five parameters were used for developing the dig cycle identification algorithm. Analysis showed that the crowd field current had no clear response during beginning and end of the dig cycles, so this parameter was not used in the dig cycle identification algorithm.

A simplified form of the flowchart describing the dig cycle identification algorithm is given in Figure 4-5. The detailed computer code is given in Appendix C. The threshold values for various voltage and current parameters given in Table 4-4 are based on the average of the values obtained for several dig cycles that were observed in the videos. This algorithm is site specific and can be used for the shovels that were studied during this research only.

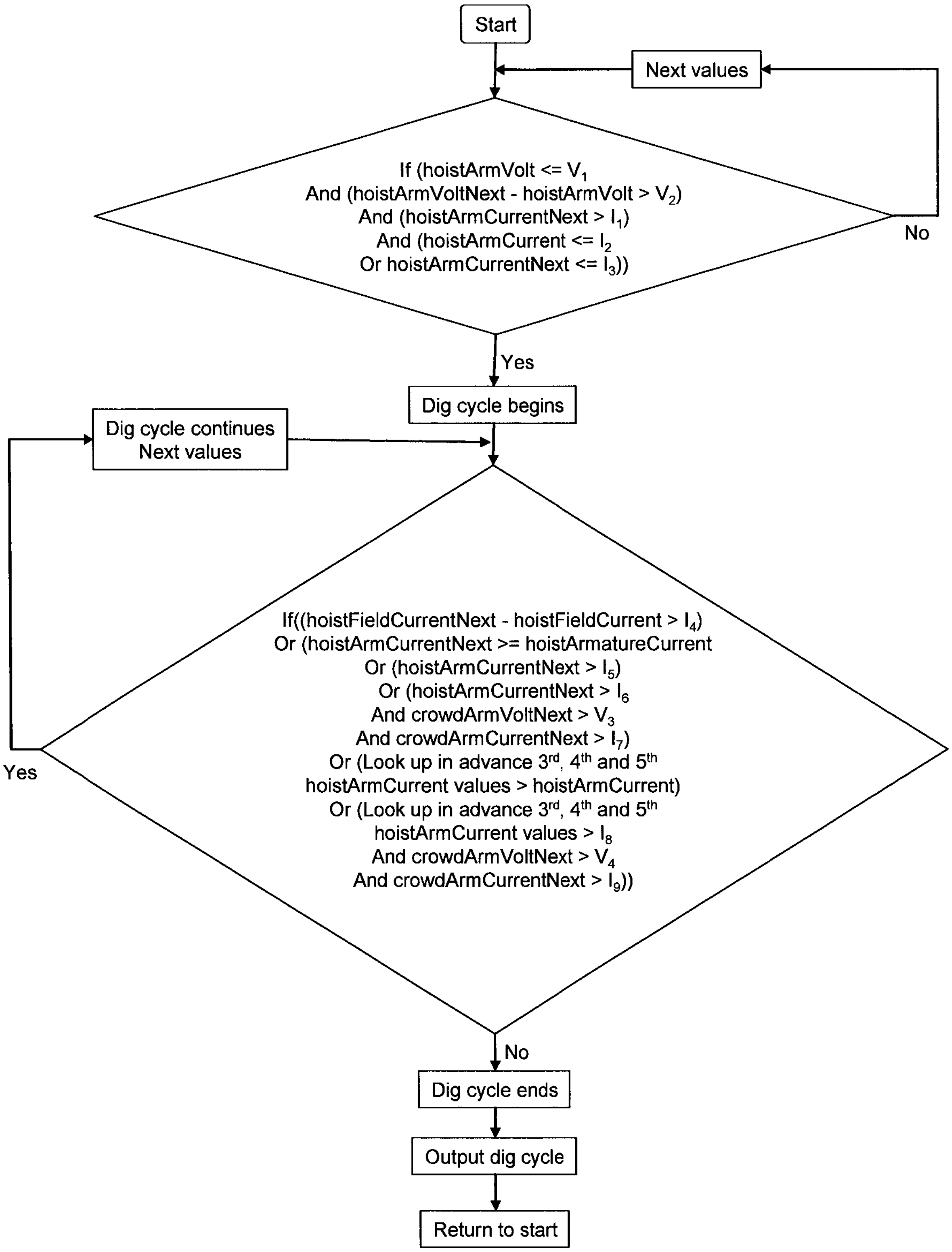


Figure 4-5 Simplified flowchart of dig cycle identification algorithm (site specific)

Table 4-4 Threshold values used in the dig cycle identification algorithm

Variable	Threshold value
V_1	-200 V
V_2	200 V
V_3	150 V
V_4	-150 V
I_1	0 A
I_2	1000 A
I_3	1000 A
I_4	50 A
I_5	2600 A
I_6	1500 A
I_7	900 A
I_8	2000 A
I_9	900 A

A portion of the analysis results obtained using the dig cycle identification algorithm is presented in Figure 4-6. These dig cycles were verified with the video observation.

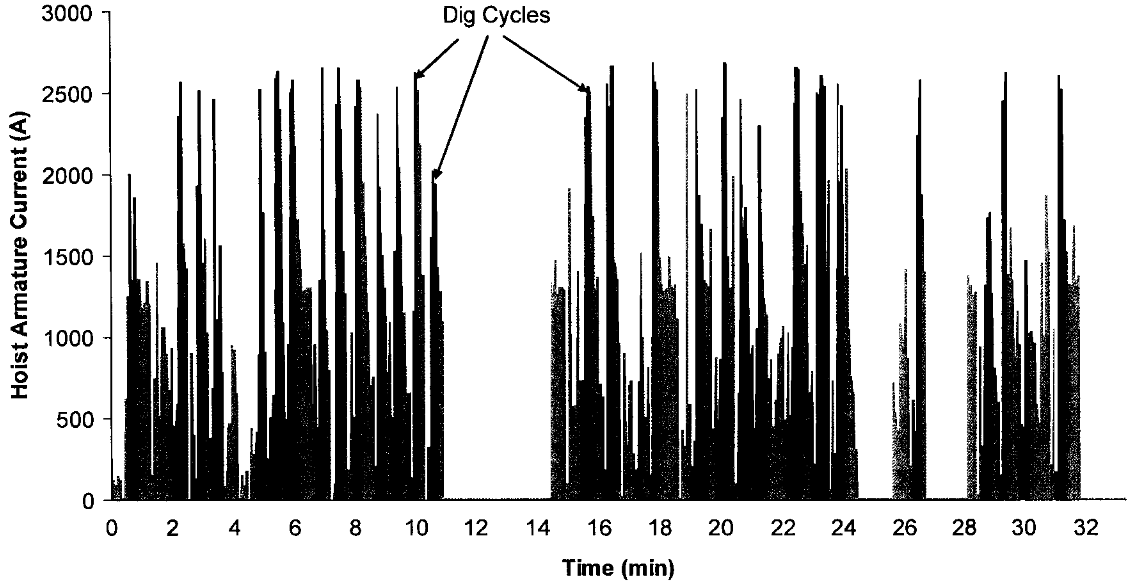


Figure 4-6 Dig cycles identified in shovel duty cycles shown in black (Video #1)

4.4 Verification of Dig Cycle Identification Algorithm

To verify the dig cycle identification algorithm, video #4 along with the corresponding MDSP data was used. The video was of 32 minute duration. A total of 19 dig cycles were observed from the video out of which 16 dig cycles represented full face digging and three dig cycles represented partial face and/or digging loose material at the bench toe. Processing of MDSP data using the dig cycle identification algorithm identified 16 dig cycles that correspond to the full face digging in the video. The results are tabulated in Table 4-5. It may be noted that the goal of developing the dig cycle identification algorithm was not to identify all dig cycles but to identify the dig cycles corresponding to full face only. So, in this specific analysis, 100% of the actual dig cycles were captured. This gave confidence to use the dig cycle identification algorithm for further analysis.

Table 4-5 Verification of dig cycle identification algorithm (Video #4)

Digging activities observed in video			Dig cycles identified by the algorithm			Ideal dig cycle
Begin dig (hh:mm:ss)	End dig (hh:mm:ss)	Dig time (s)	Begin dig (hh:mm:ss)	End dig (hh:mm:ss)	Dig time (s)	
09:35:52	09:36:02	10	09:35:52	09:36:02	10	Yes
09:36:31	09:36:46	15	09:36:31	09:36:46	15	Yes
09:39:54	09:40:14	20	09:39:54	09:40:14	20	Yes
09:40:37	09:40:54	17	09:40:37	09:40:54	17	Yes
09:41:33	09:41:48	15	09:41:33	09:41:48	15	Yes
09:42:18	09:42:30	12	09:42:18	09:42:30	12	Yes
09:42:53	09:43:10	17	09:42:53	09:43:10	17	Yes
09:43:34	09:43:42	8	-	-	-	No*
09:44:26	09:44:42	16	09:44:26	09:44:42	16	Yes
09:46:04	09:46:22	18	09:46:04	09:46:22	18	Yes
09:46:45	09:46:58	13	09:46:45	09:46:58	13	Yes
09:47:20	09:47:31	11	-	-	-	No**
09:47:57	09:48:04	7	-	-	-	No*
09:48:13	09:48:28	15	09:48:13	09:48:28	15	Yes
09:53:53	09:54:13	20	09:53:53	09:54:13	20	Yes
09:54:36	09:54:54	18	09:54:36	09:54:54	18	Yes
09:56:26	09:56:41	15	09:56:26	09:56:41	15	Yes
09:58:42	09:58:56	14	09:58:42	09:58:56	14	Yes
09:59:22	09:59:38	16	09:59:22	09:59:38	16	Yes

* Digging loose material from toe
** Partial face digging

4.5 Use of Dig Cycle Identification Algorithm

This program was very useful for further data processing, analysis, interpretation, and reporting. Once implemented into Syncrude's computing system, the program was capable of working directly on the performance data in the MDSP database to isolate the dig cycles from other shovel activities. For each dig cycle, the program also estimates several performance indicators such as dig cycle time and energy and power associated with hoist and crowd motors. This has eliminated manual processing of voltage and current data files, which significantly reduced the overhead on data handling. This program has been adopted and is now in routine use at Syncrude for various purposes. One application is to assess the influence of sidewise motion of the dipper while digging on the hoist rope life. The program can potentially be used for evaluating performance of shovels on real-time and for determining energy loss during shovel operation. The dig cycle algorithm is actively being considered by Syncrude for developing a tool that will enable the shovel operators to evaluate their performance in real-time while they dig.

4.6 Summary

Analysis of performance data along with digital video records of operating shovels indicated that hoist and crowd motor voltages and currents can be used to identify the beginning and end of individual dig cycles. Due to complex digging action, swing data were not very useful.

A dig cycle identification algorithm was developed based on threshold values for different motor parameters. These threshold values were established by averaging values for several dig cycles that were observed in the videos. The dig cycle identification algorithm was verified by video records.

CHAPTER 5 IDENTIFICATION OF KEY PERFORMANCE INDICATORS

5.1 Dig Cycle Performance Indicators

Once the portion of the shovel performance data corresponding to each dig cycle is determined, the next step is to calculate the key shovel performance indicators. These indicators can then be related to various factors such as how the shovel is operated, dipper design, and oil sands diggability. As previous performance monitoring research was based on shape analysis of signal traces from the shovel motors, a similar analysis was attempted in this study. However, lower data resolution (1 Hz sampling rate) did not permit a successful shape analysis. Hence, an approach based on energy and/or power associated with digging was adopted in this research.

For each dig cycle, as shown in Figure 4-6, dig cycle times and the associated digging power and energy were determined based on hoist and crowd motor voltage and current. Digging energy for each dig cycle was estimated by integrating the product of voltage and current values over the dig cycle time. The digging energy (or power) has two components: hoist and crowd. The hoist energy for a dig cycle was estimated as below:

$$Hoist\ energy = \sum_{i=1}^{n} 0.5 * \left| HV_{i+1} \cdot HI_{i+1} + HV_i \cdot HI_i \right| \times SR \qquad [2]$$

where,

n = number of readings in the dig cycle
HV = hoist armature voltage
HI = hoist armature current
SR = sampling rate = 1 s

Hoist power for a single dig cycle was determined as the average hoist energy per second of dig time.

$$Hoist\ power = \frac{Hoist\ energy}{Dig\ time} \qquad [3]$$

An example of the computation of hoist energy (represented by the shaded area) based on hoist armature current and voltage is given in Figure 5-1.

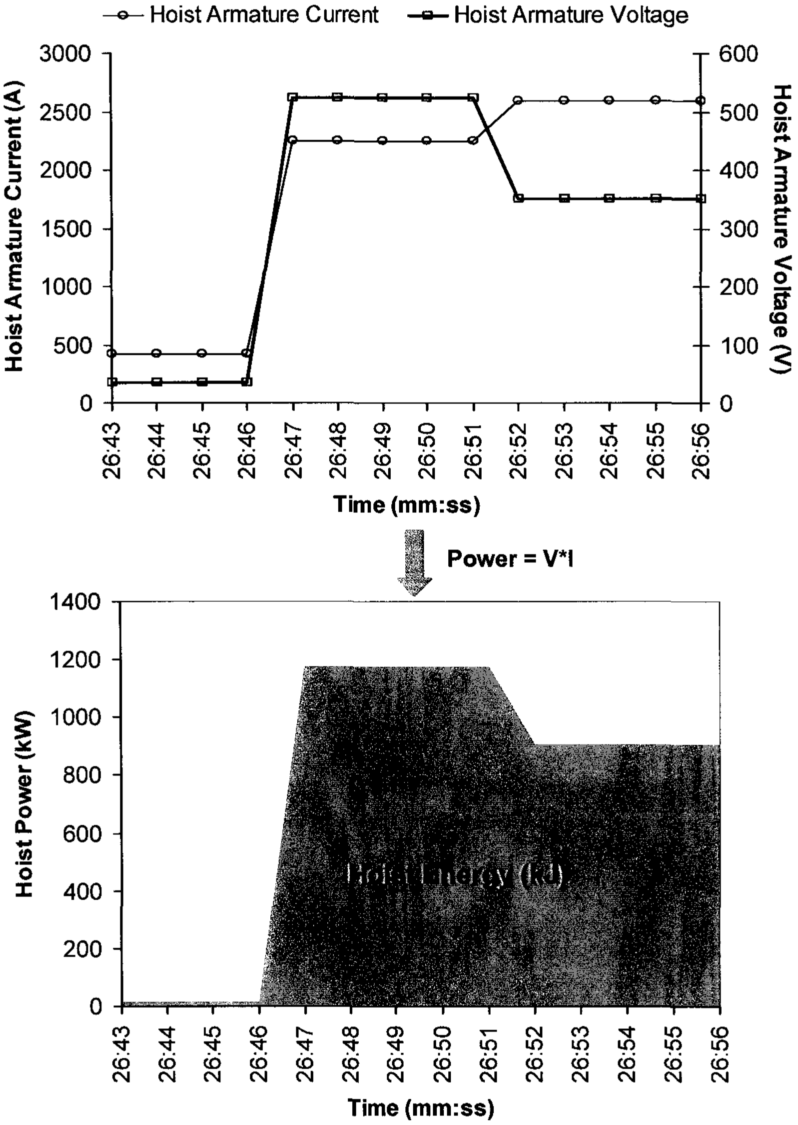


Figure 5-1 Estimation of power and energy from performance data

Crowd motor energy and power was also determined in a similar manner using the crowd motor data.

$$Crowd\ energy = \sum_{i=1}^{n} 0.5 * \left| CV_{i+1} \cdot CI_{i+1} + CV_i \cdot CI_i \right| \times SR \qquad [4]$$

where,

n = number of readings in the dig cycle
CV = crowd armature voltage
CI = crowd armature current
SR = sampling rate = 1 s

Crowd power for a single dig cycle was determined as the average crowd energy per second of dig time.

$$Crowd\ power = \frac{Crowd\ energy}{Dig\ time} \qquad [5]$$

The average hoist energy and hoist power consumption per dig cycle for a number of dig cycles was calculated as:

$$Average\ hoist\ energy = \frac{\sum_{i=1}^{n} Hoist\ energy\ for\ individual\ dig\ cycle}{n} \qquad [6]$$

$$Average\ hoist\ power = \frac{\sum_{i=1}^{n} Hoist\ energy\ for\ individual\ dig\ cycle}{\sum_{i=1}^{n} Dig\ time\ for\ individual\ dig\ cycle} \qquad [7]$$

where n is the number of dig cycles.

It may be noted that the form of Equation 7 is different than Equation 6. By using Equation 7, the cumulative energy used during total (cumulative) dig time is considered. The total dig time depends on the actual digging heights. Hence, by considering the digging time, the actual length of digging is indirectly considered. Therefore, hoist power is less influenced by the variability in bench heights. The average crowd energy and crowd power consumption per dig cycle for a number of dig cycles was calculated in a similar manner.

It must be made clear at this point that the energy and/or power values calculated for the dig cycles are not for activities at the face. These values are calculated at the hoist and/or crowd motor(s). The actual energy/power spent at the face is less than these calculated values due to various losses. The losses can be due to the dipper profile, cutting angle, tooth profile, resistance at the sides and bottom of the dipper. There can be several other mechanical losses due to bearings, seals, ropes, moment of inertia, gears, lubrication resistance etc. For calculating the absolute energy and/or power spent in digging the face these losses should be subtracted from the energy and/or power values calculated at the motors. These losses are, however, unknown and assumed constant. For comparison purpose, the relative values are important rather than the absolute values.

Note that there are two hoist motors on the shovels that equally share in the hoisting activities, however for comparison purposes the power for one hoist motor is used through out this thesis, unless specified for two motors.

5.2 Key Performance Indicators

In addition to the geological, geotechnical and climatic factors, the performance indicators at a shovel location may be controlled by equipment and geometric parameters such as the shovel type, operator's practice and skill, dipper and tooth design, depth of dipper penetration and digging trajectory. Given the interaction of these various factors, it is difficult to isolate direct relationships between one factor and its resulting impact on the shovel performance and/or oil sands diggability. Therefore, analysis to identify key performance indicators requires careful selection of shovel locations, where the variability due to geological, geotechnical and climatic factors are low. An example of the analysis is presented below.

In an attempt to minimize the influence of some parameters and to isolate key performance indicators, one shift (7:30 pm to 7:30 am) of performance data was analyzed for a particular shovel (11-85) for the month of May during which the influences of temperature and frost were expected to be minimum. By analyzing one shift of data, the influence of different operators was eliminated. The shift was selected such that the shovel was operating in a uniform estuarine oil sands formation. The average bitumen grade at the shovel location was 11% and fines content was 22%. The bench face heights at the shovel locations during the shift are shown in Figure 5-2. For this particular analysis, the variability in the ground properties, climate, face height and operator were relatively low, and therefore, the values of the performance indicators were expected to remain fairly constant for all dig cycles identified for this shift. However, the digging trajectories for the individual dig cycles are different and can therefore influence the performance indicators such as dig cycle time, hoist motor energy and power, and crowd motor energy and power.

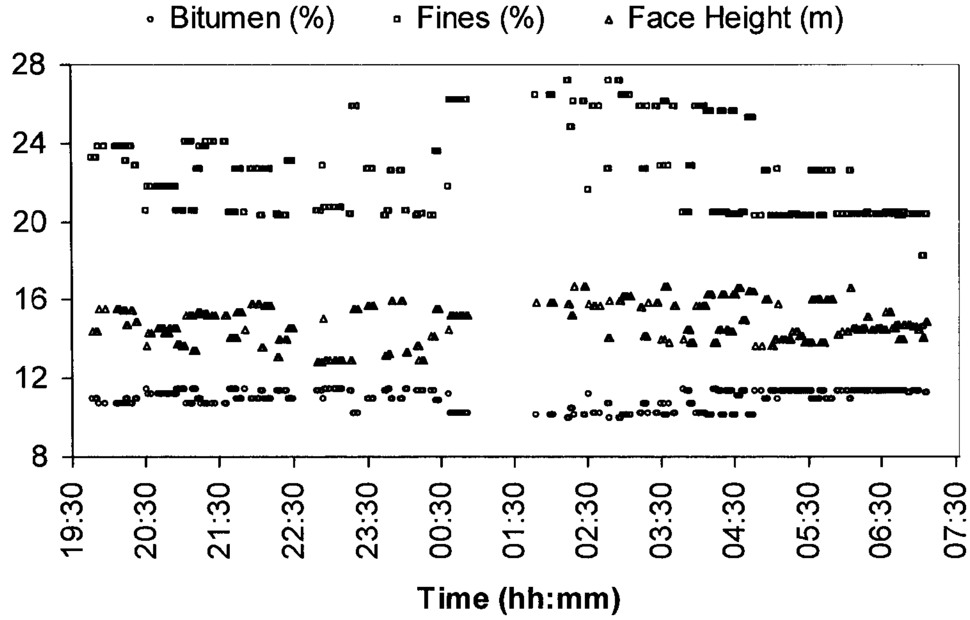


Figure 5-2 Bitumen grade, fines content and face height at shovel locations during one shift (11-85 Aurora Mine shovel)

Using the dig cycle identification program, the MDSP data were processed and the dig cycles were determined. For the shift, a total of 440 dig cycles were identified. Using the MDSP data alone, performance indicators such as dig cycle time, hoist motor energy and power, and crowd motor energy and power were calculated for each dig cycle. The payload and truck status information for each truck is stored in the Quality Production Database (QPD) on a real time basis. By using MDSP and QPD data together performance indicators such as number of dig cycles required for loading each truck and hoist and crowd energy per tonne of material excavated were determined. The payload data collected in the QPD system was not sufficiently accurate always and needed to be carefully evaluated.

5.2.1 Dig Cycle Time

The variation of dig times for the 440 dig cycles identified above is shown in Figure 5-3 and is quite high even though the shovel dug uniform oil sands. One reason for this variability could be non-uniformity in the digging trajectories for the individual dig cycles. It should be noted that the actual digging heights (lengths) could be different from the face height data collected at the shovel locations. The operator may be digging the full-face height or part of the face depending upon the amount of material required for the truck and the dig time between individual dig cycles would vary accordingly. Figure 5-4 shows that there is no clear relationship between face height and dig time.

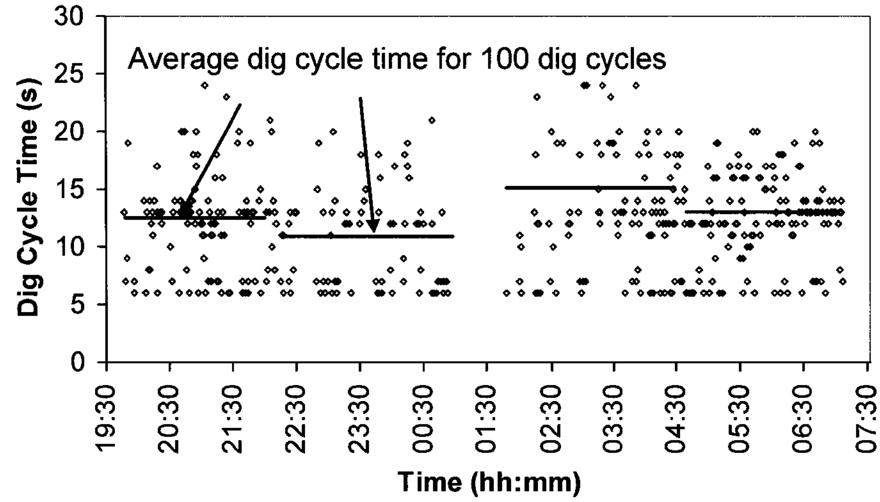


Figure 5-3 Variation of dig cycle times for one shift (11-85 Aurora Mine shovel)

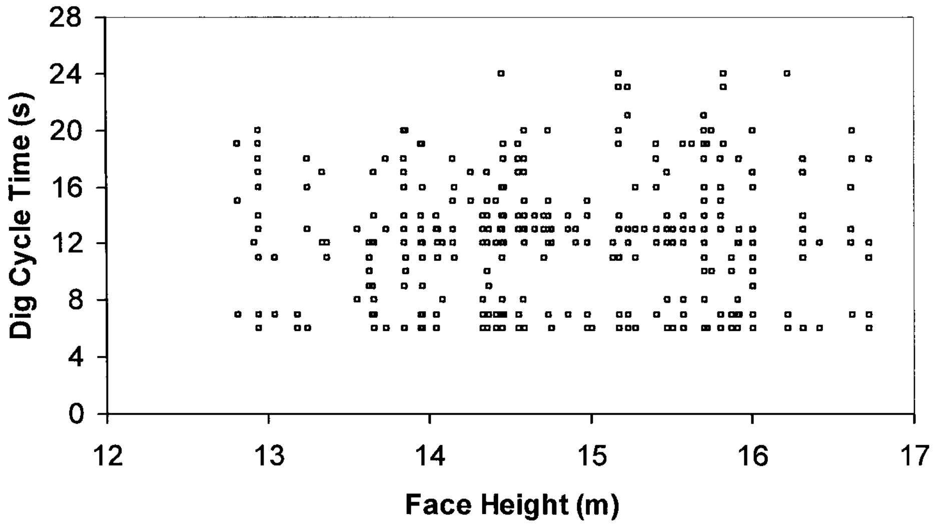


Figure 5-4 Variation of dig cycle time with face height (11-85 Aurora Mine shovel)

Similarly, the depth of dipper penetration into the bench face can vary and hence influence the dig time (Figure 5-5). A shallow dipper penetration and/or digging a part of the face may have a shorter dig time compared to a deeper penetration depth and/or full face digging.

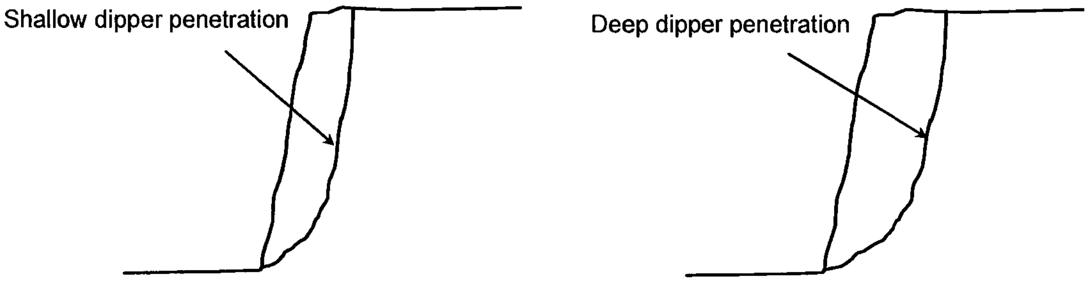


Figure 5-5 Dipper trajectory

A histogram showing the dig times during the shift is shown in Figure 5-6. The dig times are grouped roughly into three ranges. Differences in the digging trajectories may be a possible reason for this. Because no data were available to determine the digging trajectory, it was not possible to consider (and/or isolate) the influence of digging trajectory on dig cycle time. A possible interpretation of the three ranges of dig times is shown on Figure 5-6 by the vertical lines, which are inferred to separate digging performed with an optimum digging trajectory from either partial face digging or full-face digging with deep dipper penetration. Typical digging appears to take 11 to 15 seconds and this has been confirmed from the video records. This observation contradicts the popular belief that a typical dig cycle time is about 8 to 10 s for P&H 4100 series electric shovels operating in oil sands mines.

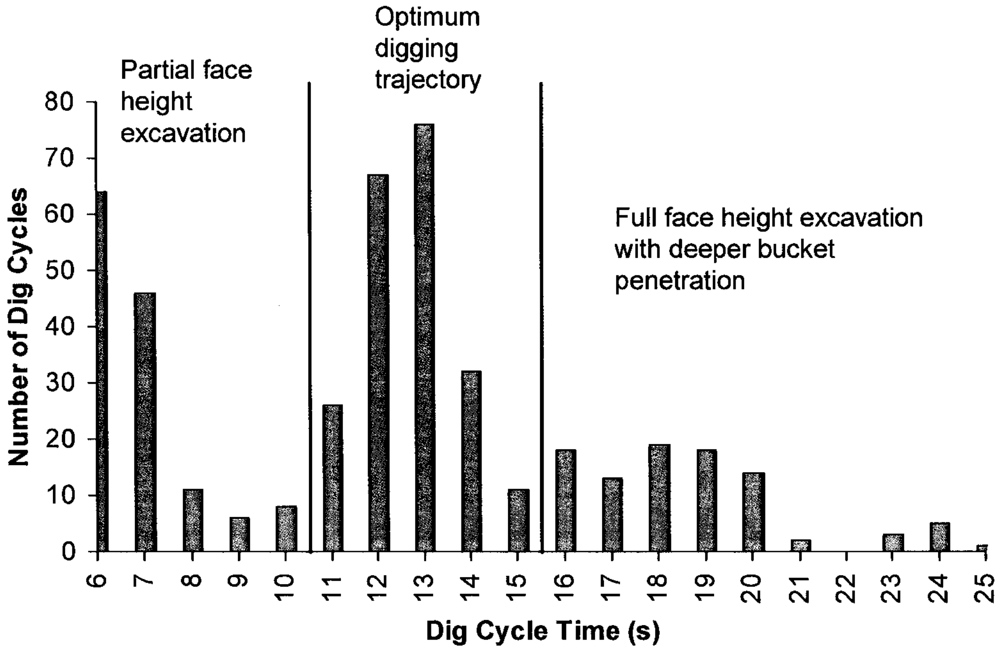


Figure 5-6 Histogram of dig times based on 440 dig cycles during one shift (11-85 Aurora Mine shovel)

The histogram shown in Figure 5-6 was based on the performance data for the 11-85 shovel operating in the Aurora Mine. In the Aurora Mine, dozer-assist mining practice has been used in high-grade areas where no competent floor is available for truck and shovel operation (Figure 5-7). Bull dozers are used to push and blend the oil sands to shovels operating on the pit floor, creating benches as high as 50 m. The shovel is expected to take short dig times while loading the loose material compared to digging the insitu material. Therefore, short dig cycles were expected in the Aurora Mine.

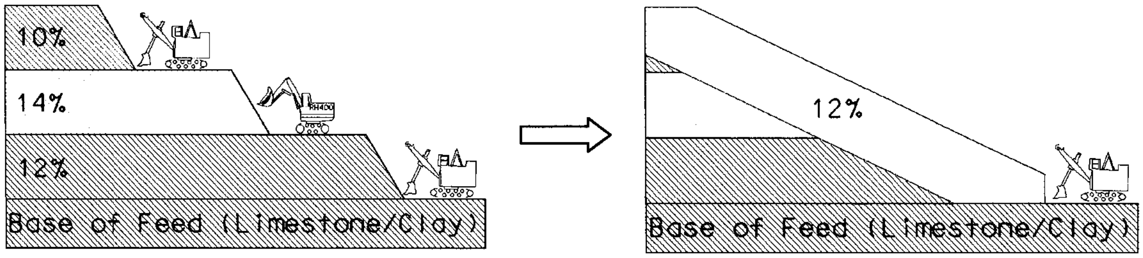


Figure 5-7 Shovel digging on multiple benches at the North Mine versus dozer assist and shovel digging from pit base at the Aurora Mine

In the North Mine, the dozer-assist mining scheme is not used and therefore, fewer short dig cycles were anticipated. Therefore, one shift of performance data for a shovel (11-78) operating in the month of May in the North Mine was analyzed. During the shift 585 dig cycles were identified and a histogram showing the distribution of dig times during the shift is given in Figure 5-8. This shows that the dig cycle times for the North Mine shovel (Figure 5-8) are more evenly distributed and the percentage of short (≤10 s) dig cycles was only 16% compared to 31% for the Aurora Mine shovel (Figure 5-6).

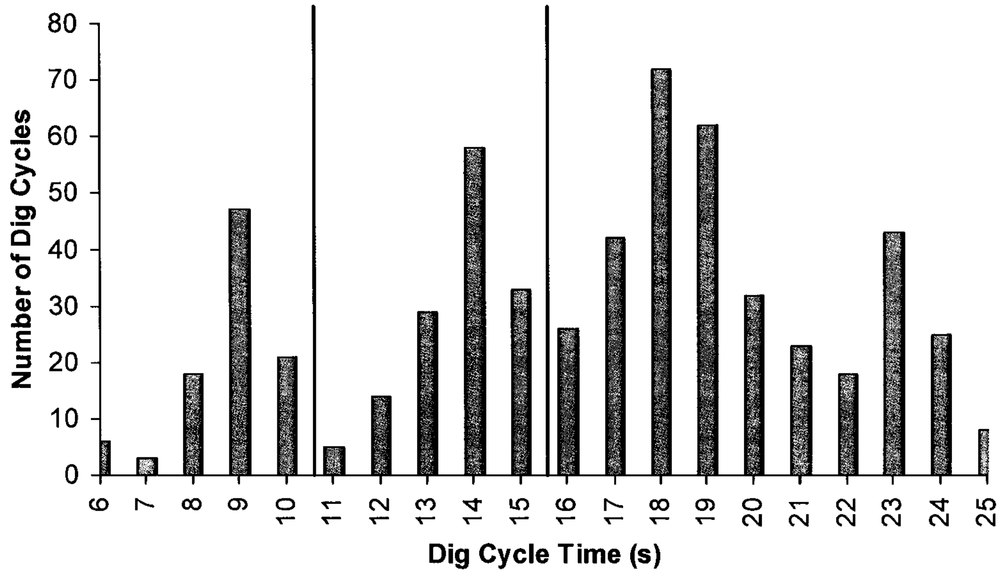


Figure 5-8 Histogram of dig times based on 585 dig cycles during one shift (11-78 North Mine shovel)

The above analysis shows that the dig cycle time can be used as an indicator of digging trajectory. However, one should be careful using dig time as an indicator of ground diggability. For example, in a difficult digging condition, one may anticipate longer digging time compared to an easy digging condition. However, in difficult digging conditions the operator might use a shallower dipper penetration resulting in a shorter dig time. Therefore, one may see little difference in digging times in two different digging conditions. Moreover, the analysis presented in the following chapters shows that the average dig cycle time was about 10 to 15 s in all digging conditions. With such a small range in variation, it was difficult to use dig time as an indicator of digging condition. Therefore, the use dig time alone as an indicator of ground diggability is not recommended.

5.2.2 Hoist Motor Energy and Power

Hoist motor energy for the dig cycles identified for the 11-85 Aurora Mine shovel is shown in Figure 5-9. It can be seen that similar to the dig cycle times, the variation in the hoist motor energy is quite high for the dig cycles. A comparison between Figure 5-9 and Figure 5-3 also shows that the hoist motor energy is a function of dig cycle time. Figure 5-10 also shows that hoist motor energy is a function of dig time, i.e., the hoist motor energy increases with increasing digging time. However, this figure also shows that dig cycles with the same dig times may have different hoist motor energy. This behaviour could be due to the non-uniformity in the digging trajectories. For identical dig times, a shallow dipper penetration will have lower hoist motor energy than a deeper penetration depth.

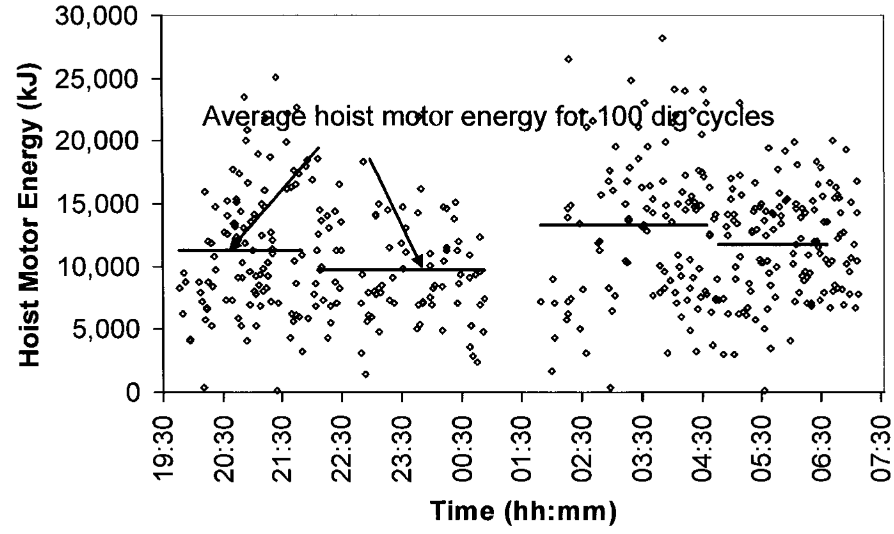


Figure 5-9 Variation of hoist motor energy for dig cycles in one shift for the 11-85 shovel (horizontal lines show average energy values)

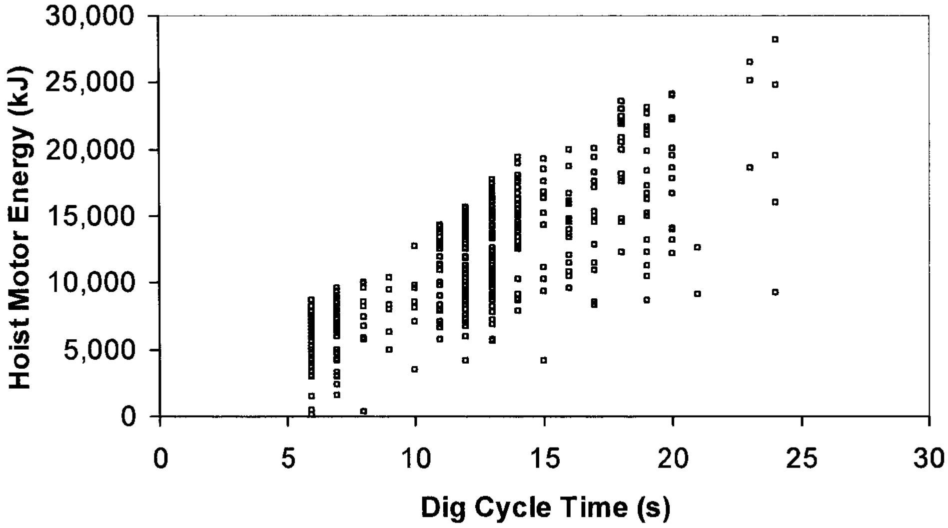


Figure 5-10 Relationship between hoist motor energy and dig cycle time (11-85 shovel)

Hoist and crowd motor energy for the three dig cycle time ranges for the 11-85 shovel shown in Figure 5-6 are given in Table 5-1. The hoist and crowd motor energy associated with the three dig cycle time ranges vary significantly. It was interesting to see that the average ratio between the hoist and crowd motor energy for the three ranges of dig cycles was constant. The dig energies associated with the short dig cycles were significantly less than the long dig cycles. From this, it appears that similar to the dig cycle times, the variations in dipper penetration depths could be a possible reason for the variations in the dig cycle energy. This is in agreement to the findings of Karpuz et al. (1992) that a deep cut through a muck pile results in higher energy consumption than a shallow cut. As the hoist energy is a function of dig time, which may not be a good performance indicator by itself, it is unlikely that hoist motor energy alone will represent ground diggability accurately.

Table 5-1 Average hoist and crowd motor energy for three dig cycle ranges for the 11-85 shovel

Dig cycle time (s)	Number of dig cycles	Hoist motor energy (kJ)	Crowd motor energy (kJ)	Ratio between hoist motor energy and crowd motor energy
≤10	135	6575	1727	0.26
11 – 15	212	12465	3252	0.26
>15	93	16994	3940	0.23

It was anticipated that by averaging the energy consumption per dig cycle for a number (say 100) of dig cycles, the influence of shallow and deep dipper penetrations could be minimized. Figure 5-9 has four horizontal lines representing the average hoist motor energy over 100 dig cycles. The average values are different through out the shift and indicate that the averaging process can minimize the variability in hoist motor energy but can still be influenced by potential factors such as dipper trajectories.

The energy consumption per unit length of digging can be found by dividing the hoist motor energy by the digging height. However, the actual digging height data was not available. An attempt was made by using the face height as a surrogate for the digging height. Because the actual digging heights are sometimes different from the bench face heights, this exercise was not helpful in the analysis. Syncrude uses an algorithm to calculate the face height at the shovel locations. This procedure uses the GPS values of shovel location and boom heading, and finds the nearest intersection point (Euclidean distance) in the block model. This procedure is known to be inefficient and inaccurate as it may find face heights at points that are up to 300 m away from the actual shovel location (Parsons, 2005). Due to these reasons, the face height data were not used in any further analysis.

Hoist motor power consumed for each dig cycle was estimated from the hoist motor energy divided by the dig time. The variation of hoist motor power for the dig cycles is shown in Figure 5-11. The fact that the peak power output from each of the two hoist motors used for this shovel (BOSS model) is rated at 1473 kW, the calculated values of hoist motor power seem reasonable. The hoist power represents the energy spent per unit dig time. The total dig time depends on the actual digging heights (trajectory). Hence, the calculation of power by diving energy by time indirectly considers the actual digging trajectory.

While a shovel is digging in similar ground conditions, a measure of the ground's diggability characteristics can be taken by averaging the power consumption per dig cycle for a number (say 100) of dig cycles. Figure 5-11 has four horizontal lines indicating the average hoist power. It may be noted that the calculation power for individual dig cycles using Equation 3 considers the digging trajectory. The calculation of average power for 100 dig cycles using Equation 7, which is not the simple average of power values, further helps to eliminate the influence of shallow and deep dipper penetrations and other factors. Therefore, it is expected that the average hoist power should be a better indicator of material diggability compared to other performance indicators. This agrees with findings by Hendricks et al. (1989) and Hendricks (1990) in that hoist motor parameters better represent the digging conditions. It is interesting to note that the average hoist power remains nearly constant at about 940 kW during the shift, which would be expected given that that shovel was digging in relatively uniform ground conditions.

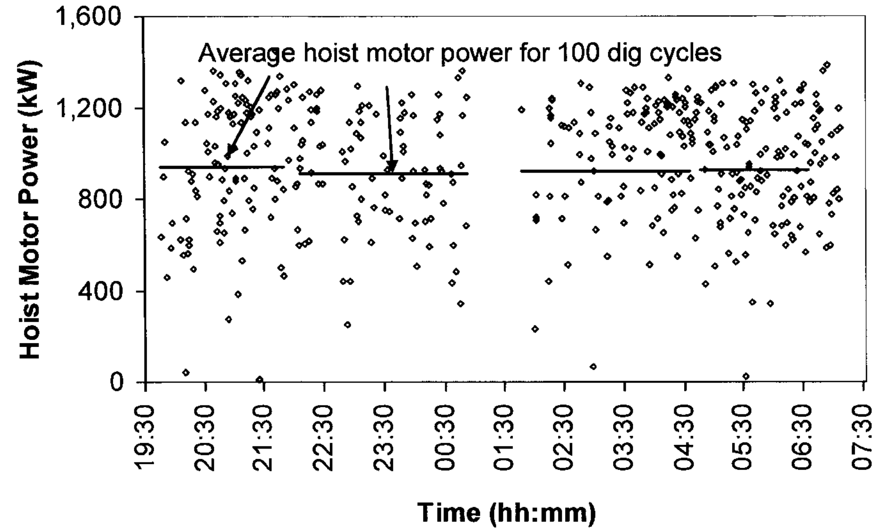


Figure 5-11 Variation of hoist motor power for dig cycles in one shift for the 11-85 shovel (horizontal lines show average power values)

In a uniform digging condition, the hoist motor energy is influenced by factors such as operating technique and the digging trajectory and therefore, the hoist energy is not a good performance indicator. By averaging the hoist power over a number of dig cycles, the average hoist power is less sensitive to dig trajectory and can be used as a key shovel performance indicator.

5.2.3 Crowd Motor Energy and Power

Crowd motor energy and power was estimated for each dig cycle based on the crowd motor data for the 11-85 Aurora Mine shovel and their variations during the shift are shown in Figure 5-12 and Figure 5-13. These figures show that similar to other performance indicators, crowd motor energy and power also vary considerably during the shift. Analysis of performance data combined with the video observations revealed that crowd extension and/or retraction do not correspond well to the material diggability. During digging, the operator generally maintains a suitable dipper penetration by adjusting the penetration depending upon the amount of material required in the dipper. Accordingly, the crowd armature currents and voltages can change abruptly even while excavating uniform material. It can be seen from Figure 5-12 and Figure 5-13 that the crowd motor energy and crowd power for some dig cycles are close or equal to zero, which correspond to the dig cycles for which either the crowd voltage or current values are zero or negative for most part of the dig cycle. It may be noted that the negative voltage or current corresponds to crowd retraction and does not contribute to actual digging. This implies that digging during these cycles can be performed by using little crowd energy or power. This was also confirmed by the feedback from the operators. Therefore, crowd motor parameters are not expected to represent the actual ground diggability. This is in agreement with the findings of Hendricks et al. (1989) and Hendricks (1990) but contradicts Williamson et al. (1983) and Mol et al. (1987) who found that the crowd motor voltage and current represent diggability of a blasted muck pile.

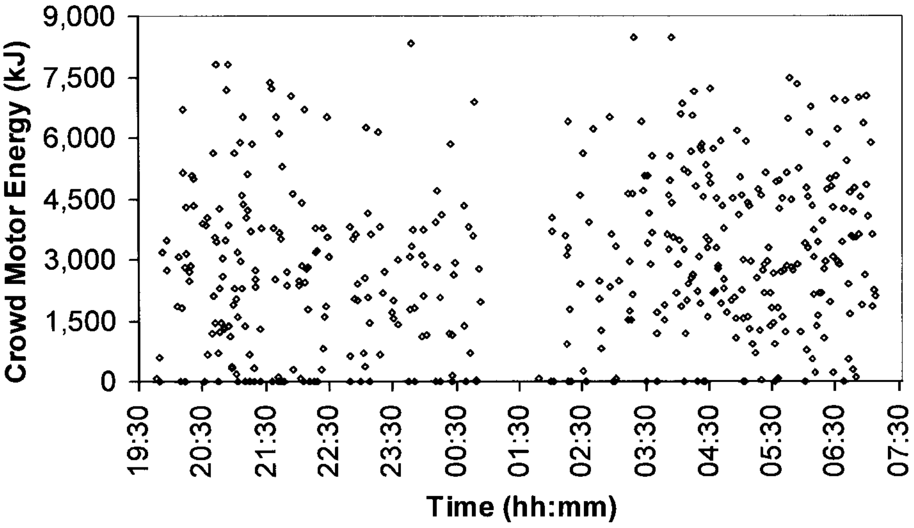


Figure 5-12 Variation of crowd motor energy for the dig cycles in one shift for the 11-85 shovel

It may be noted that the operator must extend the crowd while digging in material with low profile such as blasted muck pile. However, for steep (vertical) insitu faces no crowd extension is required to dig because the arc of boom may even need to retract to keep the dipper from penetrating too deeply.

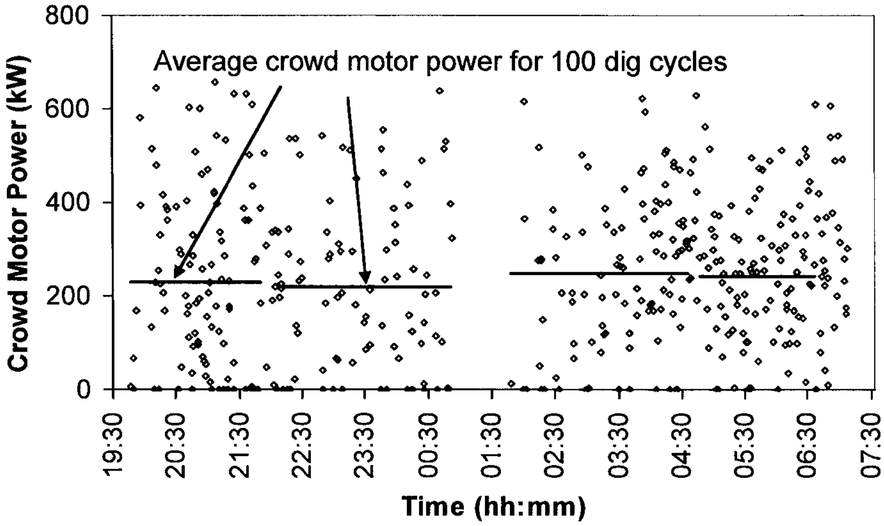


Figure 5-13 Variation of crowd motor power for the dig cycles in one shift for the 11-85 shovel (horizontal lines show average power values)

By considering the average crowd power for a number of (say 100) dig cycles, the influence of shallow and deeper penetrations could be minimized. However, from diggability assessment point of view, because the crowd action provides the thrust required for dipper penetration, crowd energy or power can at best give an indication of ground penetrability which depends upon the material strength and stiffness. The crowd power when used together with the hoist power may give some indication of digging condition, but the crowd power (or energy) should not be used as a performance indicator for assessing ground diggability.

5.2.4 Dig Cycles per Truck and Energy per Tonne

The payload and truck status information for each truck is stored in the QPD system. Time stamping in the QPD system is based on the time when the box has reached full dumping height at the dump location (Cyr, 2004). From the QPD data it was found that 120 truck loads of materials were delivered during the shift. Since there were 440 dig cycles identified, the ratio of number of dig cycles to number of truck loads is about 3.6, i.e., each truck load of material correspond to 3.6 dig cycles. This agrees with practice in that each truck takes about 3 to 4 dipper loads. However, limitations associated with the

QPD system can make data interpretation difficult. In addition to the trucks owned by Syncrude, rental trucks are also used in both North and Aurora mines. It was found that the rental trucks used at Syncrude were not in the real-time data flow. Payload data were typically updated at the end of the shift. For example, a given rental truck will carry multiple loads during a shift but the cumulative payload was recorded as one load at the end of shift (Parsons, 2005). This results in a mismatch between the number of dig cycles identified and the actual number of dipper loads in filling the trucks. Therefore, the calculation of dig cycles per truck may not yield reliable numbers.

Another performance indicator was calculated by normalizing the hoist or crowd motor energy with the amount (tonnage) of material excavated. The payload information for each truck at the shovel location was gathered from the QPD database. Dig cycles associated with loading each truck were identified and the cumulative hoist energy for the dig cycles associated with loading a specific truck was estimated. The cumulative hoist energy was divided by the truck's payload and the energy per tonne of excavated material was determined. Hoist motor energy consumption per tonne of material excavated can be a good indicator of diggability provided the payload information is available and accurate. Unfortunately, the QPD system sometimes contains erroneous truck status and payload data and therefore, the payload data or calculation of energy per digging tonne of material may not be reliable always. In addition to the limitations associated with rental trucks in the QPD system, the errors associated in the payload data can make analysis difficult. The haul road conditions can influence the recorded payload due to the dynamic motion experienced by the trucks. Traveling over bands of soft and hard ground may cause a bouncing motion, which can either increase or decrease the weightometer readings and can skew the recorded payload. Another source of erroneous data arises when the payload data is entered into the dispatch system. Due to various errors associated with QPD system, data selection and analysis was challenging.

5.2.5 Comparison of Variability

The variability in the performance indicators considered above (11-85 Aurora Mine shovel) is quite high, probably due to the variability in digging trajectories. However, the performance indicator least influenced by the digging trajectories should have the lowest variability and would probably be a better indicator of diggability. To compare the variability between the performance indicators, the coefficient of variation *CV*, which is a measure of dispersion of the data, was calculated from the mean and standard deviation *SD* of each indicator over the duration of the shift.

$$CV = \frac{SD}{Mean} \times 100 \qquad [8]$$

The coefficient of variation for each performance indicator is listed in Table 5-3. The coefficient of variation for hoist motor power is smaller than for the other performance indicators. This indicates that hoist motor power should be a better indicator of diggability than the other performance indicators. This finding is consistent with the discussion presented earlier where it seems reasonable that the resistance to the hoisting action may be the best measure of the ground diggability. This further supports the previous findings of Hendricks et al. (1989) and Hendricks (1990). A similar analysis was performed for a different shovel (11-80) in the North Mine at three different shovel locations and the results given in Table 5-3 were quite similar. Hence, hoist motor power is used as a key performance indicator for the analyses of shovel performance seen in the next few chapters. It may be noted that the average hoist motor power of several dig cycles (such as 100 dig cycles, shift or month) can be used as key performance indicator but the hoist motor power for an individual dig cycle is not a good performance indicator.

Table 5-2 Variability of performance indicators for the 440 dig cycles identified during one shift of operation of the 11-85 Aurora Mine shovel

	Dig cycle time (s)	Hoist energy (kJ)	Hoist power (kW)	Crowd energy (kJ)	Crowd power (kW)
Minimum	6	70	12	0	0
Maximum	24	28210	1450	8500	657
Range	18	28140	1438	8500	657
Mean	12	11599	966	2928	244
SD	4	5011	262	2044	168
CV	36	43	27	70	68

Table 5-3 Variation of performance indicators for the 11-80 shovel operating in the North Mine during three different shifts (7:30 am to 7:30 pm) in the year 2005

Performance indicator	Date	Number of dig cycles	Maximum	Minimum	Mean	SD	CV
Dig cycle time (s)	Feb 13	593	24	6	13	5	38
	March 4	461	25	6	15	5	33
	April 30	538	25	6	13	4	38
Hoist energy (kJ)	Feb 13	593	23099	1065	10485	5017	48
	March 4	461	24632	1590	12112	5417	45
	April 30	538	23653	13747	10042	4139	41
Hoist power (kW)	Feb 13	593	1261	138	806	193	24
	March 4	461	1237	179	807	215	26
	April 30	538	1186	161	772	212	27
Crowd energy (kJ)	Feb 13	593	9341	0	3559	1696	47
	March 4	461	10012	0	3744	2014	54
	April 30	538	8760	16	3014	1890	62
Crowd power (kW)	Feb 13	593	717	0	274	121	44
	March 4	461	652	0	249	131	52
	April 30	538	657	2	249	139	56

5.3 Summary

Performance indicators such as dig cycle time, hoist motor energy and power, and crowd motor energy and power were determined using data from different shovels. It appears that non-uniform digging trajectory can cause variability in the performance indicators even while digging relatively uniform ground. Therefore, parameters such as dig cycle time, hoist motor energy and power, and crowd motor energy and power for an individual dig cycle cannot be used as performance indicators. These parameters are useful for assessing shovel performance only when average of several dig cycles are taken into account.

The degree of variability of hoist motor power was found to be the least compared to other performance indicators. By averaging the hoist power over a number of dig cycles, (such as 100 dig cycles, shift or month) the average hoist power can be used as a key performance indicator for assessing the digging resistance. Hoist motor energy consumption per tonne of material excavated and number of dig cycle for loading a truck can be a good indicator of diggability provided the payload information is available and accurate. Crowd energy or power can at best give an indication of ground penetrability and are not useful as key performance indicators for shovels operating in oil sands. Dig cycle time can be used as an indicator of digging trajectory but should not be used alone for assessing ground diggability.

CHAPTER 6 INFLUENCE OF OPERATOR

6.1 Introduction

It was anticipated that the operator could influence the performance parameters recorded from the shovels. Operator influence on shovel performance and Diggability Index of blasted muck piles has been reported by Hendricks (1990). Assessment of the influence and extent of variation in the operating practices amongst the operators is quite complicated because other parameters such as the geology, material type and climate can influence the shovel performance. For the purpose of this analysis, shovel locations were chosen such that the shovels were digging relatively uniform material for several shifts at the selected locations. However, minor variations in the geology and material types could not be avoided and for the present investigation it has been assumed that if variation in operating practice exist, the operating characteristics of each teams of operators will overshadow the influence of material diggability at a given shovel location.

6.2 Data Collection

The operator team schedules for the shovels operating at the North Mine and the Aurora Mine were collected. Operator schedules were collected based on teams rather than specific individuals. The specific operator information was not desired because the goal was not to assess or comment on the skills or performance of a specific operator. The goal was only to evaluate the extent of variation that the operating practice can have on the shovel performance.

The mine operates two twelve-hour shifts per day. Four teams of operators are employed in each shovel over the course of a month. In the Aurora Mine, the team schedule is repeated every 12 days (24 shifts) of operation, and in the North Mine, the team schedule is repeated every 16 days (32 shifts). Therefore, for the Aurora Mine shovels, by considering the average of 24 consecutive shifts of operation, the average hoist (or crowd) power for all the four teams of operators can be calculated. For the North Mine shovels, the average of 32 consecutives shifts of operations have to be taken into account to calculate the average digging power for all four teams of operators. The average value obtained by considering the average of either 24 shifts (Aurora Mine shovels) or 32 shifts (North Mine shovels) of operations should minimize the influence by a specific team. Therefore, in this thesis, the monthly average values are estimated based on either 24 and/or 32 consecutive shifts of operation.

6.3 Analysis of Data from Aurora Mine

To evaluate the influence of the operator practice and skill on shovel performance, data for a specific shovel (11-85) operating in the Aurora Mine were analyzed for 56 consecutive shifts (4 weeks) in the month of February, 2005 and again in May, 2005. During these months, the shovel was excavating uniform high-grade estuarine ore with 13 to 15% bitumen and 20 to 30% fines. The dig cycles were identified using the algorithm presented in section 4.3 and then the hoist power for each dig cycle was calculated using Equations 2 and 3.

The average hoist and crowd motor powers for each shift of operation in May and February are plotted in Figure 6-1 and Figure 6-2. The missing values in the figures correspond to the shifts during which the shovel was either not operating or there were no performance data available. There is a considerable variation in the hoist motor power between individual shifts even though the shovel was operating in uniform oil sands.

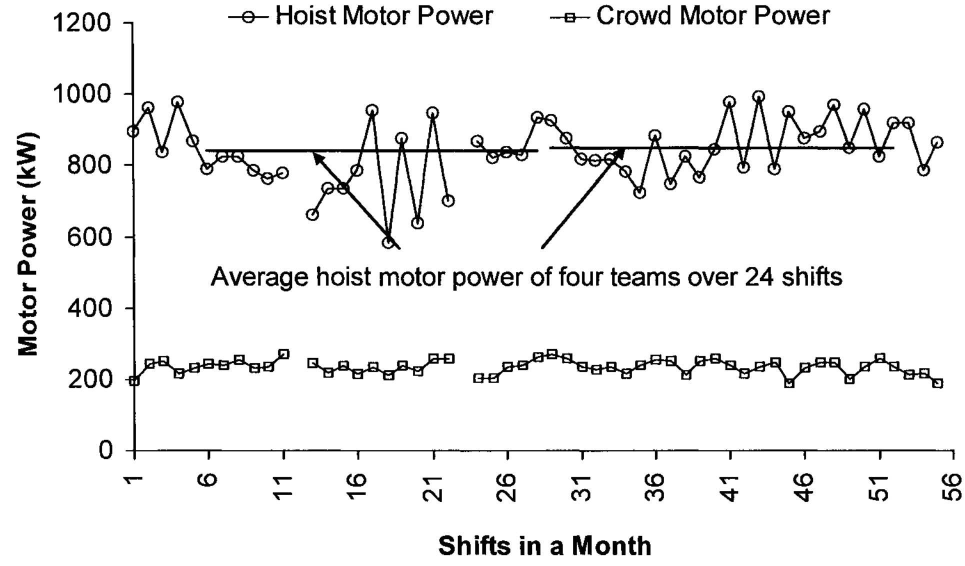


Figure 6-1 Average hoist and crowd motor powers for consecutive shifts in May with the average power over 24 shifts plotted as horizontal lines

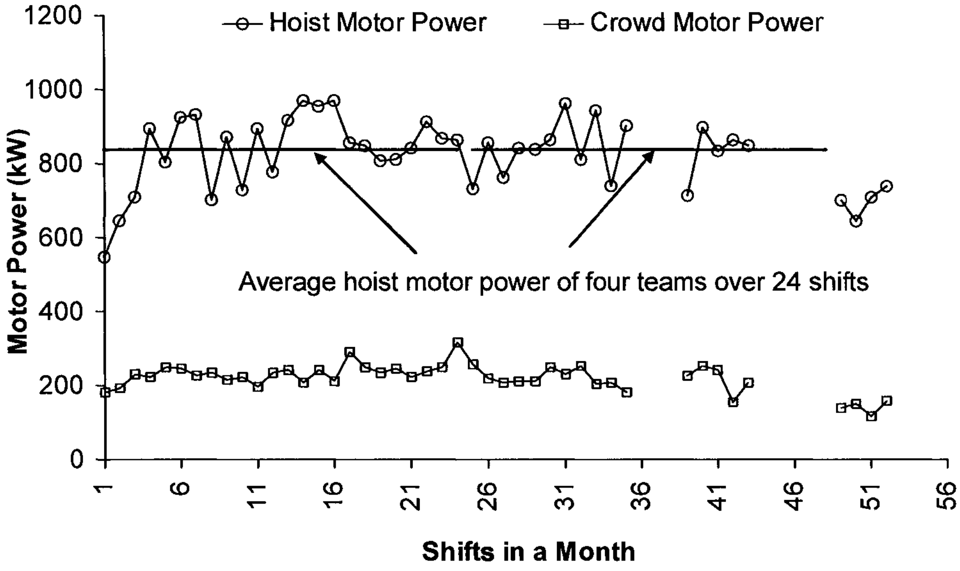


Figure 6-2 Average hoist and crowd motor power for consecutive shifts in February with the average power over 24 shifts plotted as horizontal lines

The average hoist power per shift used by each team of operators for May is shown in Figure 6-3. The average shift hoist powers for a specific team vary from shift to shift even though the shovel was digging uniform ore throughout the month. Figure 6-3 shows that the average hoist power used by Team 3 was higher than Team 2 for all shifts. Team

1 and Team 4 used similar hoist powers. The range and average hoist powers for the different teams of operators are given in Table 6-1 and Table 6-2. Although the hoist power for a specific team of operator varies during different shifts, the average and median hoist power for a month of operations for a specific team is nearly the same for May and February. Note that the average hoist power used by Team 3 was 22% and 28% higher than Team 2 in the months of February and May. The difference in hoist power between Teams 2 and 3 is about 200 kW (25%) and is quite significant when considered over the whole month. This difference in hoist power could be related to the different digging techniques used by the teams.

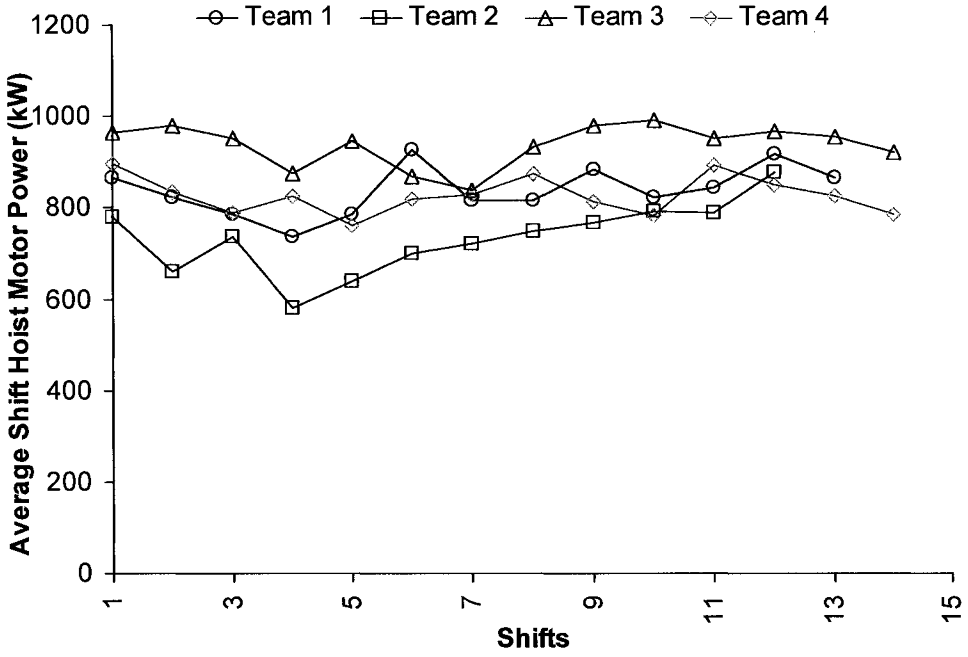


Figure 6-3 Average hoist motor powers for four teams of operators in different shifts in May

Table 6-1 Range and average of hoist motor powers for different teams of operators (11-85 shovel) during February

Team	Hoist motor power (kW)					
	Range for a shift	Monthly average	95% Confidence interval for mean		Median	CV
			Lower bound	Upper bound		
1	800 – 900	835	764	906	849	9.1
2	600 – 800	728	672	784	728	9.1
3	900 – 1000	924	885	963	937	5.4
4	800 – 950	857	795	921	860	8.2

Table 6-2 Range and average of hoist motor powers for different teams of operators (11-85 shovel) during May

Team	Hoist motor power (kW)					
	Range for a shift	Monthly average	95% Confidence interval for mean		Median	CV
			Lower bound	Upper bound		
1	800 – 900	837	805	870	824	6.6
2	600 – 800	732	681	782	741	11.4
3	900 – 1000	937	910	964	952	5.4
4	800 – 900	827	803	851	825	5.6

Figure 6-1 and Figure 6-2 show the variation of average shift hoist power between the individual shifts is high. However, the average value for 24 shifts is about 845 kW for both months. The average value is less influenced by a specific team and would better represent the actual hoist power used by a shovel in a specific ground condition and should be a good parameter for assessing diggability characteristics. Interestingly, one might expect digging conditions in February to be more difficult than in May due to colder temperatures but the average hoist power for the month of May was 843 kW, which is not significantly less than the average hoist power of 847 kW recorded for February.

The average shift crowd motor power used by different teams of operators in May is shown in Figure 6-4. The range and average crowd motor powers for the different teams are given in Table 6-3 and Table 6-4. The difference in crowd motor power between different teams is not significant. The average crowd motor powers used by a specific team are also similar for both months.

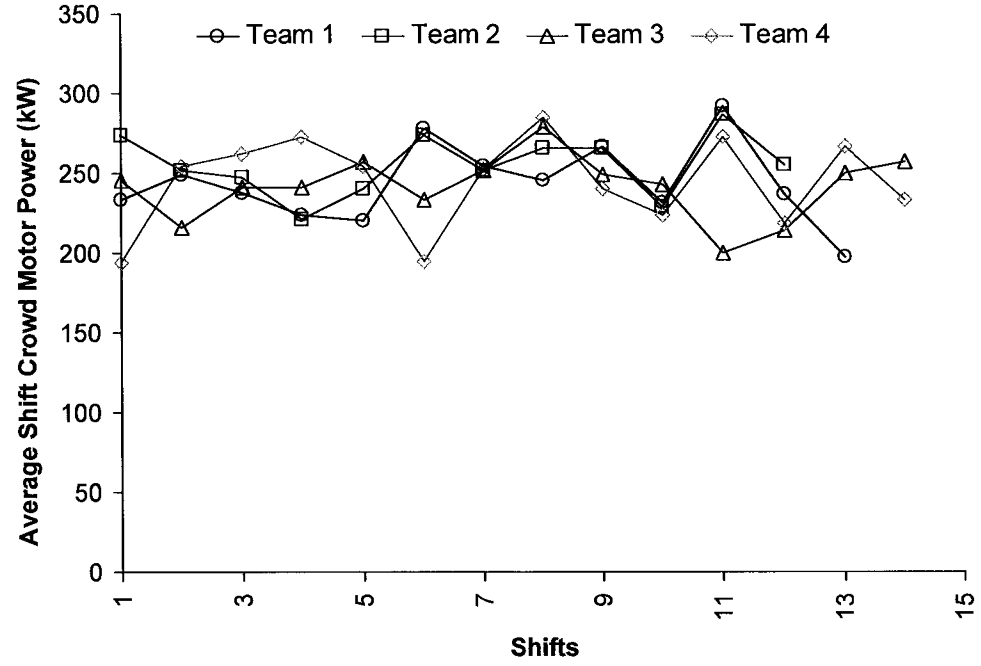


Figure 6-4 Average crowd motor powers for four teams of operators in different shifts in May (11-85 shovel)

Table 6-3 Range and average of crowd motor powers for different teams of operators (11-85 shovel) during February

Team	Crowd motor power (kW)					
	Range for a shift	Monthly average	95% Confidence interval for mean		Median	CV
			Lower bound	Upper bound		
1	160-260	225	210	240	223	14.5
2	135-265	227	207	247	232	18.1
3	160-260	217	203	231	214	14.5
4	180-290	255	229	280	241	10.8

Table 6-4 Range and average of crowd motor powers for different teams of operators (11-85 shovel) during May

Team	Crowd motor power (kW)					
	Range for a shift	Monthly average	95% Confidence interval for mean		Median	CV
			Lower bound	Upper bound		
1	200-290	230	216	244	230	3.9
2	220-290	240	228	252	242	3.5
3	200-280	233	219	246	236	4.4
4	200-290	230	216	244	237	3.4

In order to determine if there exist significant difference between the average powers used by the four teams, one-way analysis of variance (ANOVA) was conducted (Walpole and Myers, 1978). The one-way ANOVA procedure tests the hypothesis that several means are equal. This procedure analyses the variance of a quantitative dependent variable by a single factor (independent) variable. The observed significance level provides the basis for deciding whether or not the mean of the dependent variable is significantly different. If the observed significance level is small enough, usually less than 0.05 or 0.01, then the means are significantly different. The results of ANOVA are given in Table 6-5 and Table 6-6. The significance levels for the hoist powers for both the months are zero, which indicate that the mean hoist powers used by the different teams are not equal. However, the significance levels for the crowd powers are greater than 0.01 indicating that the mean crowd powers used by the different operators are not significantly different from one another.

Table 6-5 One-way ANOVA results for the operating teams for 11-85 shovel for February

		Sum of squares	df*	Mean square	F	Significance level
Hoist motor power (kW)	Between groups	159294	3	53098	10.198	0.000
	Within groups	208265	40	5206		
	Total	367560	43			
Crowd motor power (kW)	Between groups	12074	3	4024	3.307	0.030
	Within groups	48684	40	1217		
	Total	60759	43			

*degrees of freedom

Table 6-6 One-way ANOVA results for the operating teams for 11-85 shovel for May

		Sum of squares	df	Mean square	F	Significance level
Hoist motor power (kW)	Between groups	273771	3	91257	20	0.000
	Within groups	154143	49	3146		
	Total	42791	52			
Crowd motor power (kW)	Between groups	710	3	237	0.5	0.652
	Within groups	21182	49	432		
	Total	21892	52			

In addition to determining that differences exist among the means, using one-way ANOVA it was possible to know which means differ. Once it was determined that differences exist among the means, pair-wise multiple comparison of means was done. Pair-wise multiple comparisons test the difference between each pair of means, and yield a matrix that indicates significantly different group means at a specified level of significance. For this analysis, Tamhane's T2 multiple comparison test method was used because this method does not assume variances are equal (SPSS, 2001). Analyses were carried out for the teams and the results are given in Table 6-7 and Table 6-8. These results show that the significance level of the mean difference between Team 2 and Team 3 is less than 0.01 which clearly indicates that there exists a difference between the means of hoist motor power and crowd motor power used by Team 2 and Team 3.

Table 6-7 Multiple comparisons for means using Tamhane's T2 method for February (11-85 shovel)

Dependent variable	Team (I)	Team (J)	Mean difference (I-J)	Standard error	Significance level
Hoist motor power (kW)	1	2	59	32	0.405
		3	-99	29	0.023
		4	-42	37	0.848
	2	1	-59	32	0.405
		3	-158	23	0.000
		4	-102	33	0.046
	3	1	99	29	0.023
		2	158	23	0.000
		4	56	29	0.422
	4	1	42	37	0.848
		2	102	33	0.046
		3	-56	30	0.422
Crowd motor power (kW)	1	2	2	15	1.000
		3	1	13	1.000
		4	-41	14	0.063
	2	1	-2	15	1.000
		3	-0.5	14	1.000
		4	-43	16	0.081
	3	1	-2	12	1.000
		2	0.5	14	1.000
		4	-43	13	0.042
	4	1	41	14	0.063
		2	43	16	0.081
		3	43	13	0.042

Table 6-8 Multiple comparisons for means using Tamhane's T2 method for May (11-85 shovel)

Dependent variable	Team (I)	Team (J)	Mean difference (I-J)	Standard error	Significance level
Hoist motor power (kW)	1	2	105	27	0.006
		3	-99	19	0.000
		4	10	18	0.996
	2	1	-105	27	0.006
		3	-205	26	0.000
		4	-95	25	0.011
	3	1	99	19	0.000
		2	205	26	0.000
		4	109	16	0.000
	4	1	-10	18	0.996
		2	95	25	0.011
		3	-109	16	0.000
Crowd motor power (kW)	1	2	-10	8	0.813
		3	-2	8	1.000
		4	-1	8	1.000
	2	1	10	8	0.813
		3	7	7	0.922
		4	8	8	0.872
	3	1	3	8	1.000
		2	-7	7	0.922
		4	1	8	1.000
	4	1	1	8	1.000
		2	-8	8	0.872
		3	-1	8	1.000

Performance data for another shovel (11-84) operating in the Aurora Mine were analyzed for April and May during which the shovel dug rich estuarine oil sands. Analysis results are given in Table 6-9, Table 6-10, Table 6-11 and Table 6-12. Results show there is no significant difference between the crowd motor powers used by different teams. The differences in hoist motor powers are however significant, particularly the power used by the Team 1 was much higher than the other teams. From these results, it can be concluded that in a relatively uniform ground, the hoist motor power required by a shovel depends on how a team operates the shovel. The crowd motor power is somewhat independent of the team operating technique.

Table 6-9 Average hoist and crowd motor powers for different teams of operators (11-84 shovel) during May

	Team	Mean	Standard deviation	95% Confidence interval for mean	
				Lower bound	Upper bound
Hoist motor power (kW)	1	821	98	762	881
	2	791	61	754	829
	3	766	80	723	809
	4	761	68	726	796
Crowd motor power (kW)	1	194	26	178	210
	2	197	27	180	213
	3	186	23	174	198
	4	191	27	177	205

Table 6-10 Average hoist and crowd motor powers for different teams of operators (11-84 shovel) during April

	Team	Mean	Standard deviation	95% Confidence interval for mean	
				Lower bound	Upper bound
Hoist motor power (kW)	1	823	56	790	856
	2	723	66	683	763
	3	696	89	639	753
	4	762	40	738	786
Crowd motor power (kW)	1	214	18	204	225
	2	209	15	200	218
	3	209	28	190	227
	4	221	22	207	234

Table 6-11 One-way ANOVA results for the operating teams for 11-84 shovel for May

		Sum of squares	df	Mean square	F	Significance level
Hoist motor power (kW)	Between groups	32987	3	10996	8.810	0.000
	Within groups	334203	55	6076		
	Total	367190	58			
Crowd motor power (kW)	Between groups	911	3	304	0.443	0.723
	Within groups	37689	55	685		
	Total	38600	58			

Table 6-12 One-way ANOVA results for the operating teams for 11-84 shovel for April

		Sum of squares	df	Mean square	F	Significance level
Hoist motor power (kW)	Between groups	120539	3	40180	9.550	0.000
	Within groups	201954	48	4207		
	Total	322493	51			
Crowd motor power (kW)	Between groups	1190	3	396	.884	0.456
	Within groups	21537	48	448		
	Total	22728	51			

The possibility of using the ratio between hoist and crowd power as an indicator of ground diggability was also considered. Hoist to crowd power ratios for each team for various shifts of operation of the 11-85 shovel in May are shown in Figure 6-5. The hoist to crowd power ratio for Team 3 is higher than Team 2. In this specific case, the shovel dug a relatively uniform ore and therefore, the crowd powers used were similar during individual shifts. Comparing Figure 6-3 with Figure 6-5 it appears that higher hoist to crowd ratios are associated with higher hoist powers. This indicates that the ratio of hoist to crowd power may be used as a measure of operator (or shovel) performance while they are digging similar material. For a given digging condition, a lower hoist to crowd ratio may represent better shovel performance, provided similar production targets are achieved by each operator. However, using the hoist to crowd ratios as a measure of ground diggability can be misleading at times. For example, in a non-cohesive and porous (soft) material, one would expect lower crowd and hoist powers. On the other hand, in a stiff and cohesive material both hoist and crowd powers would be higher. The resulting ratios in these two different ground conditions may yield similar values and therefore, the hoist to crowd power ratio cannot be used to characterize the ground diggability. Instead of using the ratio, the hoist and crowd powers should be used separately while comparing different digging conditions.

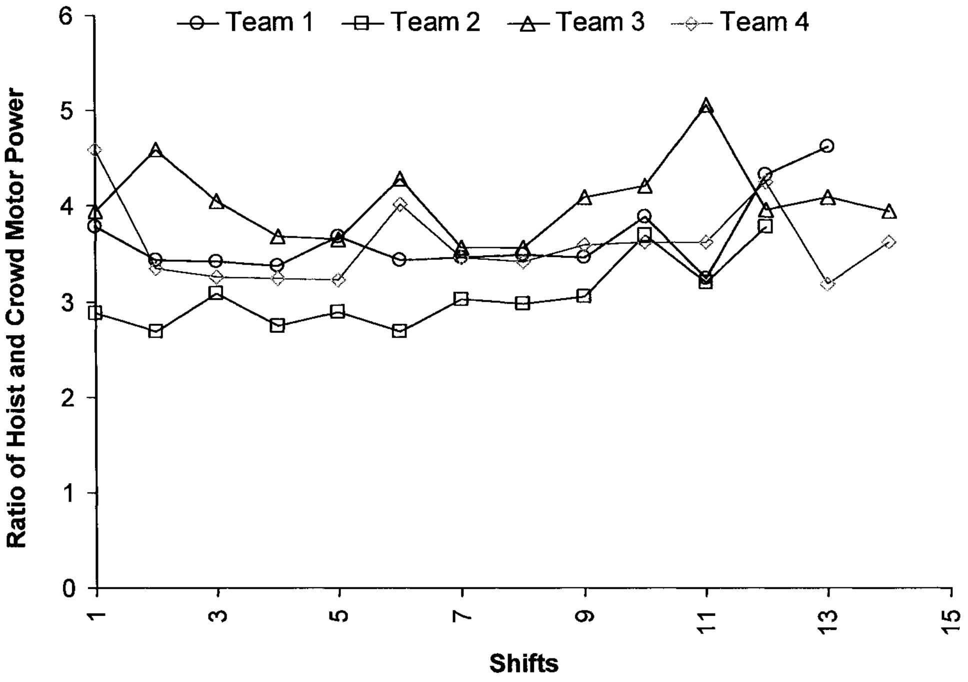


Figure 6-5 Ratio of hoist and crowd motor powers for four teams of operators in different shifts in May (11-85 shovel)

An attempt was made to evaluate the influence of operating practice on hoist energy used per tonne of material excavated. The payload information for each truck was collected and total tonnage of material excavated during each shift was determined (Figure 6-6). Total hoist energy used during a shift was estimated based on the cumulative hoist energy for all the dig cycles determined for that shift. The total hoist energy used during a shift was divided by the total tonnage of material excavated in that shift and the hoist energy used per tonne of material excavated was determined. The results given in Table 6-13 show that hoist energy per tonne of material excavated was least for Team 2 and was maximum for Team 3 in both February and May. This finding is consistent with the results given in Table 6-1. Analysis show that the hoist energy per tonne of material excavated can be used as an indicator of team performance.

It was interesting to see that although Team 3 used maximum hoist power, Team 3 also excavated significantly more oil sands. The quantity of oil sands excavated at a shovel location is often controlled by the blending (or plant) requirement. Therefore, the quantity excavated may not be directly related to the performance of the team. Nevertheless, Team 3 appears to dig faster than the other teams resulting in higher power consumption.

Table 6-13 Average quantity of oil sands excavated and hoist motor energy consumption per tonne by different teams of operators (11-85 shovel)

Team	May		February	
	Average tonne / shift	Hoist motor energy / tonne (kJ/tonne)	Average tonne / shift	Hoist motor energy / tonne (kJ/tonne)
1	26580	132.3	30052	143.3
2	27841	108.0	23868	122.4
3	40260	138.9	37947	146.6
4	25475	136.7	27596	142.2

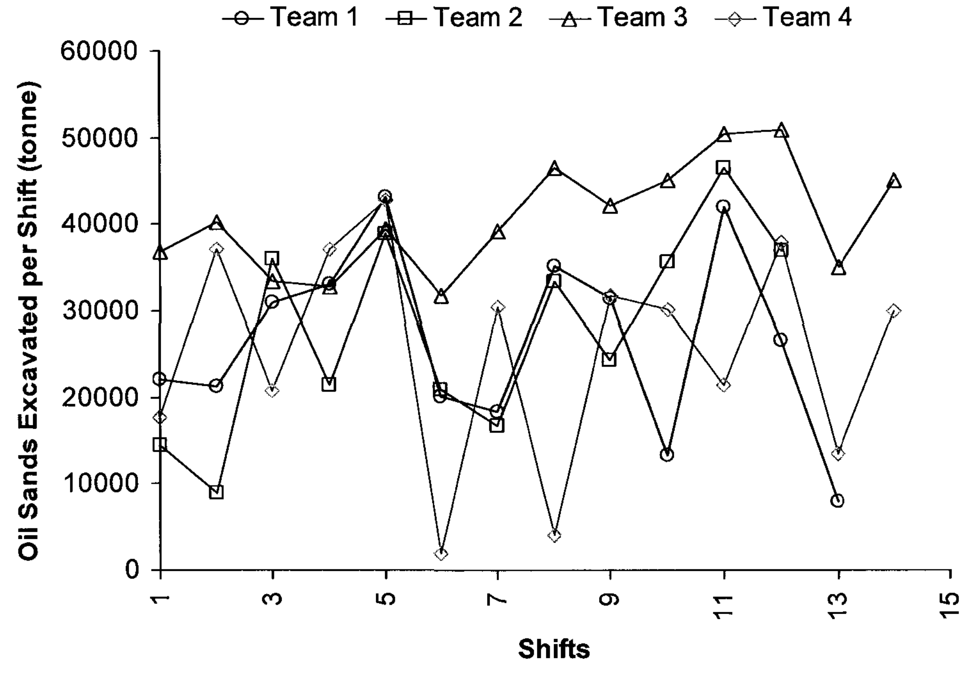


Figure 6-6 Average quantity of oil sands excavated per shift for four teams of operators in different shifts in May (11-85 shovel)

The average number of dig cycles used by each operator to load a truck can be used as an indicator of team performance and productivity. While loading trucks of uniform size, fewer dig cycles to load a truck may represent better performance. The number of shovel dig cycles during individual shifts was determined using the dig cycle identification algorithm. The number of truck loads of material delivered during each shift was collected from QPD (Figure 6-7). The average number of dig cycles used by each team for loading a truck during individual shifts of May is given in Figure 6-8.

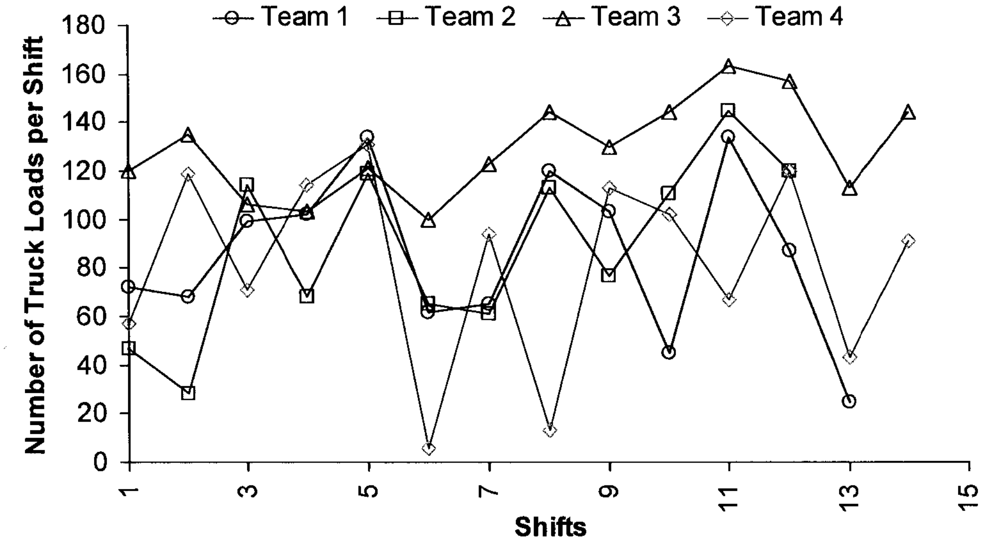


Figure 6-7 Number of trucks loaded by four teams of operators in different shifts in May (11-85 shovel)

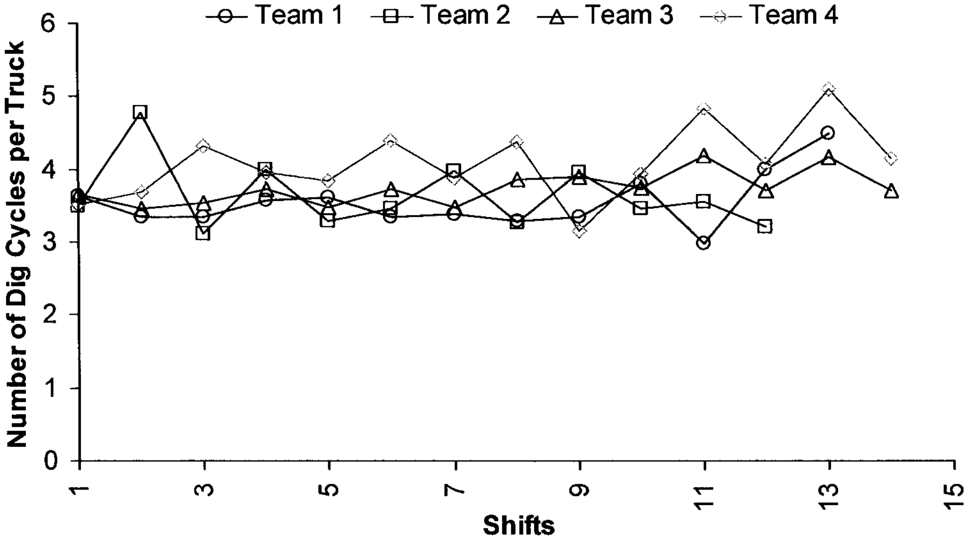


Figure 6-8 Average number of dig cycles used by four teams of operators in different shifts in May (11-85 shovel)

Although the results given in Table 6-14 show that the number of dig cycles used by Team 2 to fill a truck is slightly less than Team 3, comparison is difficult because the truck sizes were not uniform. Syncrude uses mixed truck sizes and the number of dig cycles required to fill a truck depends upon the truck size. A large truck requires more dig cycles to fill compared to a small truck. The average payload of trucks delivered in each shift by different operators is given in Figure 6-9, which shows that different truck sizes were used. Therefore, the results given in Table 6-14 are influenced by the size of trucks the teams were loading, hence, the number of dig cycles used for loading a truck is not a good performance indicator when truck sizes are different.

Table 6-14 Performance characteristics of different teams on the 11-85 shovel

Team	May			February		
	Number of dig cycles / shift	Number of truck loads / shift	Number of dig cycles / truck	Number of dig cycles / shift	Number of truck loads / shift	Number of dig cycles / truck
1	361	86	4.2	440	96	4.6
2	320	89	3.6	307	75	4.1
3	474	128	3.7	503	120	4.2
4	336	82	4.1	361	90	4.0

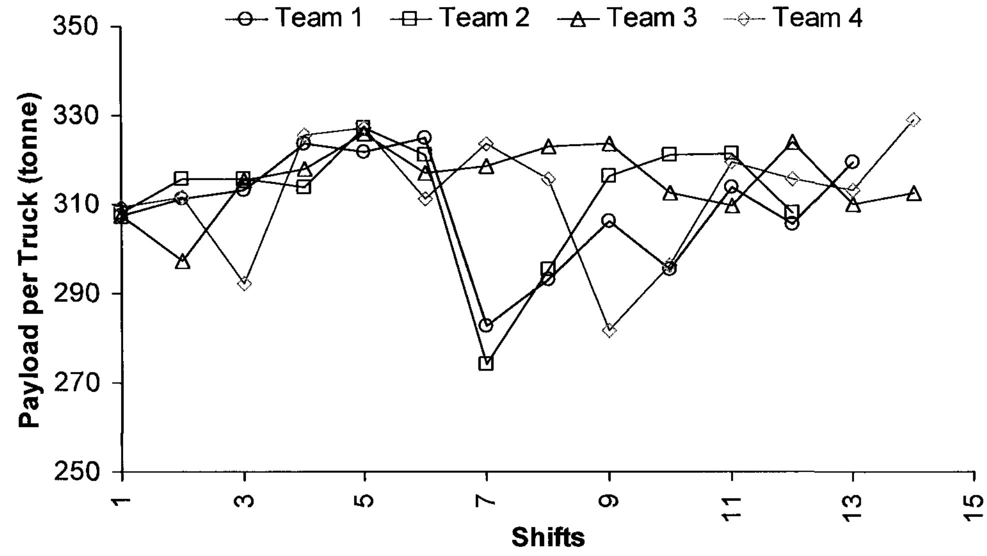


Figure 6-9 Average payload per truck for four teams of operators in different shifts in May (11-85 shovel)

6.4 Analysis of Data from North Mine

To further verify the findings from Aurora Mine a similar analysis was performed using data from the North Mine. Performance data for a shovel (11-78) operating in the North Mine were analyzed for 56 consecutive shifts in the month of February and March during which the shovel dug overburden. Analysis results are given in Table 6-15, Table 6-16, Table 6-17, Table 6-18, Table 6-19, and Table 6-20. The results show there is no significant difference between either the hoist powers or the crowd powers used by different teams. It appears that all four teams of operators working on this shovel had similar operating techniques.

Table 6-15 Range and average of hoist motor powers for different teams of operators (11-78 shovel) for February

Team	Hoist motor power (kW)					
	Range for a shift	Monthly average	95% Confidence interval for mean		Median	CV
			Lower bound	Upper bound		
1	700-800	716	659	773	730	12
2	650-750	704	664	744	697	8
3	600-800	712	670	757	716	10
4	650-750	703	673	740	699	7

Table 6-16 Range and average of crowd motor powers for different teams of operators (11-78 shovel) for February

Team	Crowd motor power (kW)					
	Range for a shift	Monthly average	95% Confidence interval for mean		Median	CV
			Lower bound	Upper bound		
1	200-300	252	225	279	243	16
2	200-300	249	229	269	242	11
3	200-300	264	235	292	262	13
4	200-300	247	219	274	248	15

Table 6-17 Range and average of hoist motor powers for different teams of operators (11-78 shovel) for March

Team	Hoist motor power (kW)					
	Range for a shift	Monthly average	95% Confidence interval for mean		Median	CV
			Lower bound	Upper bound		
1	650-750	737	715	759	735	5
2	700-800	755	743	768	759	3
3	650-800	740	709	772	740	7
4	650-750	745	724	765	749	4

Table 6-18 Range and average of crowd motor powers for different teams of operators (11-78 shovel) for March

Team	Crowd motor power (kW)					
	Range for a shift	Monthly average	95% Confidence interval for mean		Median	CV
			Lower bound	Upper bound		
1	200-250	228	217.7964	238	230	7
2	200-250	232	221.9689	242	230	7
3	200-250	233	214.1266	252	232	12
4	200-250	224	205.5489	242	229	13

Table 6-19 One-way ANOVA results for the operating teams for 11-78 shovel for February

		Sum of squares	df	Mean square	F	Significance level
Hoist motor power (kW)	Between groups	1115	3	372	0.074	0.974
	Within groups	217056	43	5048		
	Total	218171	46			
Crowd motor power (kW)	Between groups	2067	3	689	0.406	0.750
	Within groups	73045	43	1698		
	Total	75112	46			

Table 6-20 One-way ANOVA results for the operating teams for 11-78 shovel for March

		Sum of squares	df	Mean square	F	Significance level
Hoist motor power (kW)	Between groups	2304	3	768	0.592	0.623
	Within groups	58360	45	1297		
	Total	60664	48			
Crowd motor power (kW)	Between groups	640	3	213	0.384	0.765
	Within groups	25001	45	555		
	Total	25641	48			

6.5 Summary

Analysis of performance data along with the shovel operator team schedules showed that the hoist motor power used to excavate uniform material can be significantly influenced by the operator's practice and skill. The average hoist motor power per shift for a given team could vary as much as 25% versus the average for all teams over a 12 hour period of time. In contrast, the crowd motor power used by various operators remains relatively consistent when digging in a relatively uniform ground.

CHAPTER 7 INFLUENCE OF GEOLOGICAL PARAMETERS

7.1 Introduction

In oil sands mining, shovel performance can be influenced by the diggability characteristics of the oil sands formations. At present there is no generally accepted quantitative measure of diggability and assessment is usually made according to the experience of operators (Bell, 2004). A literature review found that various empirical diggability assessment methods for materials other than oil sands have been developed in the past using field observations and/or laboratory measurements of the material physical characteristics. The Orienstein and Koppel (O&K) wedge penetration tests (Appendix B) have been used to establish correlations between cutting resistance and geotechnical properties of coal and soft rock overburden materials. Although this test was used in the past to develop ground diggability classification systems for bucket wheel excavators, the usefulness of this test for assessing oil sands diggability for shovel excavation is questionable. Similarly, the rippability charts developed in the past are not applicable to oil sands mining. A review of the various empirical diggability studies and an assessment of their usefulness to oil sands mining are summarized in Appendix B. The existing empirical diggability classification systems were developed for blasted rock or weak rocks and are often based on rock mass classification systems and rock properties. Therefore, the existing classifications are not very useful for shovel excavation in oil sands.

Oil sands diggability is related to the geology and depositional environment and depends upon geological parameters such as facies and member and geotechnical parameters such as shear strength, density, water content, bitumen content, particle size, etc. The presence of hard bands of indurated sediments can make digging difficult. The direction of digging with respect to oil sands bedding plane orientation may also influence the oil sands diggability. The influence of various geological and geotechnical characteristics on oil sands diggability is discussed in this chapter.

7.2 Geology of North and Aurora Mine

The general geology of the Athabasca region is described by Carrigy (1959), Carrigy and Kramers (1973), Norris (1973), Flach (1984), Cuddy and Muwais (1989), among others and is not discussed in detail in this thesis. The stratigraphy of the Fort McMurray region is comprised of Paleozoic strata overlying the Precambrian basement complex that dips gently to the southwest. The Paleozoic sequence in turn is overlain by Cretaceous, Pleistocene and Holocene age sediments. The Athabasca oil sands deposits is a layered sequence of Cretaceous age silty sand deposits known as the McMurray Formation overlain with Pleistocene glacial sediments and underlain by Devonian limestone. Regional geology of the McMurray Formation is described in detail by Dusseault (1977), Cyr (2004) and others. The geology at Syncrude's North and Aurora mines is typical of the regional geology but local variations occur. Typical cross sections of geology found near the present area of mining at the North Mine and the Aurora Mine are shown in Figure 7-1and Figure 7-2. A brief description of the overburden and oil sands geology found at the North Mine and the Aurora Mine is given along with their major differences.

7.2.1 Overburden Geology

Overburden consists of a mixture of Cretaceous, Pleistocene and Holocene deposits. The Holocene and Pleistocene deposits occurred after the last glaciation, approximately 20,000 years ago. The total thickness of the overburden typically ranges from 2 to 50 m with increasing thickness away from the Athabasca River. The overburden thickness is less at the Aurora Mine compared to the North Mine (Price, 2005).

Holocene deposits consist of lacustrine clays, sands and gravels that form the base for the organic muskeg overlying the majority of the region. The muskeg, typically less than 3 m thick, consists of very soft whitish-grey clay, and whitish-grey to light brown loose sands (Cameron, 2003).

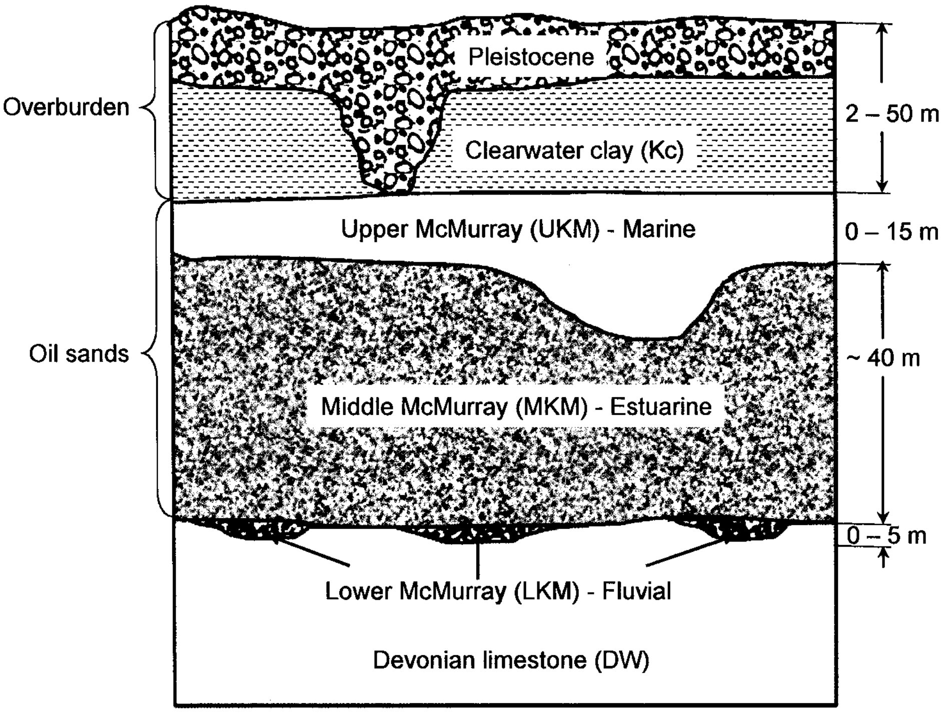


Figure 7-1 Geologic cross-section near the North Mine

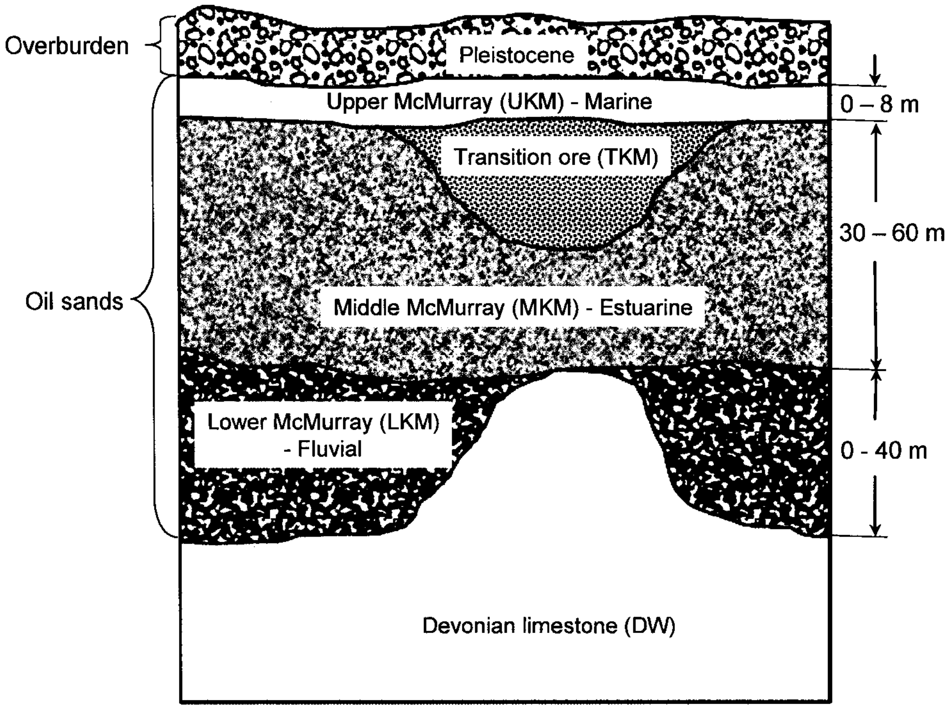


Figure 7-2 Geologic cross-section near the Aurora Mine

Below the muskeg, the overburden consists of Pleistocene deposits. These glacial sediments were formed by the advance and/or retreat of the ice sheet, erosion and/or deposition of discharging melt-water channels and/or sedimentation within glacial lakes. These glacial deposits infilled the erosional surface of the underlying Cretaceous age rocks. Due to this irregular and extremely undulating contact, it is very difficult to estimate the thickness of the Pleistocene units. The Pleistocene sediments at the top consist of sand, gravel, wet clay and glacial till. Overall, Aurora Mine has more loose sand and less till in this unit than at the North Mine. In part of the North Mine, a significant bouldery gravel deposit is present in the Pleistocene deposit, but these areas are not currently mined.

In the present area of mining, below the Pleistocene deposit, in the North Mine, the overburden includes Cretaceous age clay-shale of the Clearwater Formation (Figure 7-1). This unit is a semi-lithified dry shale with beds of tough cemented siltstone and sandstone that range in thickness from 0.15 m to 1 m or even more. The clays within the Clearwater Formation are generally highly plastic, montmorillionitic clays and are sometimes referred as clay shales. Experience of shovel operators has shown that this unit is difficult to dig. This unit is not present in the parts of the Aurora Mine where oil sands is currently mined (Figure 7-2).

Under the Pleistocene deposits at the Aurora Mine and under the Clearwater Formation in the North Mine the overburden in both pits includes an interval of waste grade Cretaceous (McMurray) Formation. This unit is similar in both the pits.

From the current diggability research point of view, the biggest difference between the two pits, so far as overburden is concerned, is the presence of the Clearwater Formation in the North Mine (Price, 2005).

7.2.2 Oil Sands Geology

The regional geologic model for the McMurray Formation is described by Carrigy (1959) as a tripartite layered sequence of fluvial (Lower McMurray), estuarine (Middle

McMurray) and marine (Upper McMurray) deposits. The McMurray Formation can be complex at times with the presence of disconformities, which can be up to 90 m thick.

The Upper McMurray member consists of upward-coarsening sequences from clay-silt in the lower part to fine-grained sand in the upper part. Although the lithology is similar to the Middle McMurray Formation, the Upper McMurray Formation is mostly horizontally bedded and identified by the presence of brackish-water fauna. The thickness of the Upper McMurray member is usually less than 30 m (Dusseault, 1977). In the present mining area, the thickness of the Upper McMurray member varies between 0 to 15 m at the North Mine and between 0 to 8 m at the Aurora Mine (Price, 2005).

The Middle McMurray member consists of upward-fining tidal flat sediments from a fluviodeltaic environment. Two types of sediments are present in this unit: muddy and sandy estuarine sediments. Muddy estuarine sediments are considered as waste and sandy estuarine sediments are considered as ore. The oil sands in this unit are very uniform in mineralogy, but contain interbedded lenticular beds of silt, shale and clay. The sand grains are typically fine and medium-grained and well sorted. A majority of the bitumen bearing oil sands comes from the Middle McMurray member. The Middle McMurray member can be up to 40 m thick (Dusseault, 1977). In the present mining area, the Middle McMurray member is about 40 m thick at the North Mine and varies between 30 to 60 m at the Aurora Mine (Price, 2005).

The Lower McMurray member consists of lenticular beds of conglomerate, sands, shale and silt with a basal strata comprised of residual clay sediments overlying an eroded Devonian limestone. The Lower McMurray member is absent over large areas of the McMurray Formation with its thickness rarely exceeding 25 m (Dusseault, 1977). In the North Mine, the Lower McMurray member is present in thin lenses and in the Aurora Mine, the thickness of this unit varies between 0 to 40 m (Price, 2005).

In the Aurora Mine, an estuarine transition ore of thickness varying between 0 to 30 m is also present. Although this is a high grade ore, it has very low processability (Price, 2005).

Very dense marine and estuarine oil sands and estuarine transition oil sands (reject or ore) can occur within the overburden or in the oil sands as interburden. This can be 0 to 35 m thick and depending upon the thickness is classified as overburden, interburden or ore. These units contain bitumen bearing sands intermixed with bands or pockets of clay, sandstone, siltstone, ironstone and boulders (Cameron, 2003).

From the current research point of view there are no major differences in oil sands geology between the North Mine and the Aurora Mine. Hard digging problems exist in both marine and estuarine units (Pagulayan, 1995).

7.3 Oil Sands Geotechnical Characteristics

Oil sands may be considered as a five-phase system consisting of a dense interlocked skeleton of predominantly quartz sands grains with pore spaces occupied by bitumen, water, gasses and silt/clay (Figure 7-3). Minor amounts of other minerals such as titanium, zirconium, tourmaline and pyrite can also occur. Although there can be considerable variation, a typical oil sands sample is composed of 75-80% inorganic material, 3-5% water, and 10-12% bitumen (National Energy Board, 2004). Additionally, appreciable quantities of methane and nitrogen can be found dissolved in both bitumen and water phases. About 90% of the inorganic material is quartz and the other 10% of fine-grained mineral fraction consists of clay minerals, predominantly kaolinite and illite (Carrigy and Kramers, 1973). One important property of the quartz grains is that they are hydrophyllic, and the oils in the pores are not in direct contact with quartz grains. Rather, each quartz grain is surrounded by a thin film of water and this water-wet feature of the quartz grains ultimately allows the bitumen to be extracted from the oil sands using the Clark hot water extraction process.

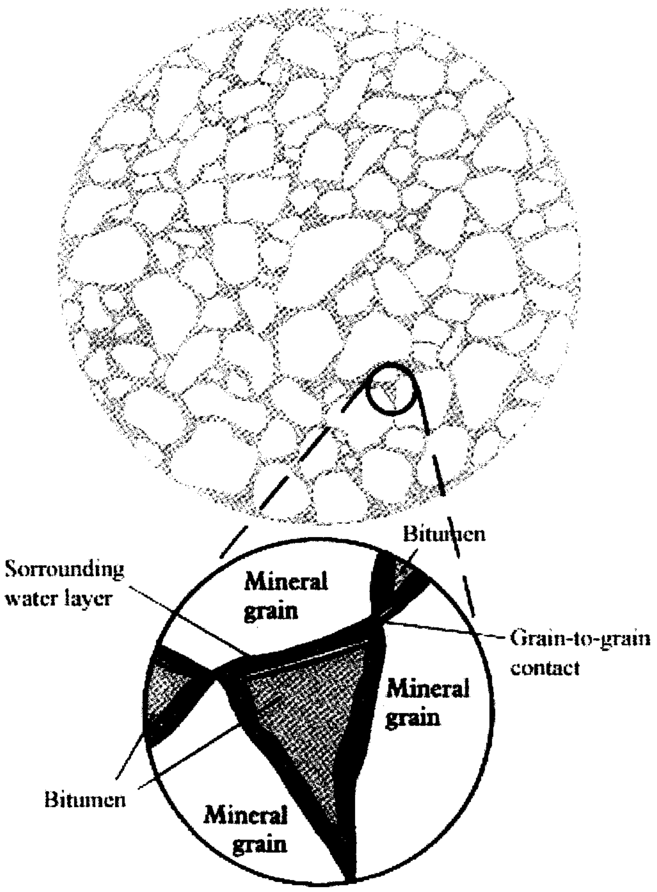


Figure 7-3 In situ structure of Athabasca oil sands (modified from McRory, 1982)

Oil sands diggability is related to oil sands composition (% bitumen, % water, % fines etc.) and various other geotechnical parameters such density, porosity, particle size, etc. The relationship between various geological and geotechnical parameters and their possible influences on oil sands diggability are described below.

7.3.1 Bitumen, Water and Dissolved Gases

Bitumen and water occupy the fluid portion of the pore space with varying degrees of saturation. Bitumen is slightly heavier than water with a specific gravity of about 1.03. Figure 7-4 shows the relationship between various constituents of oil sands. There exists an inverse relationship between the water content and bitumen content, i.e., a bitumen rich ore contains less water, whereas a lean ore contains a high amount of water.

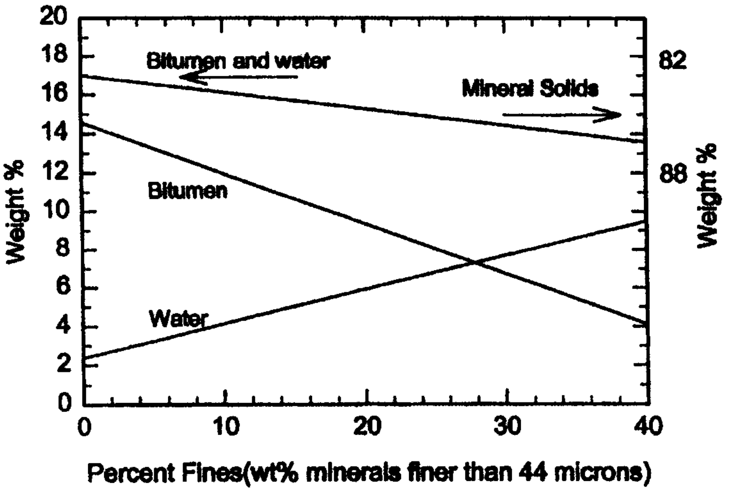


Figure 7-4 Composition of oil sands as a function of fines (after Xu, 2005)

A plot based on more than 12,300 assay values (comprising both North and Aurora mines) obtained from Price (2005) showing the relationship between bitumen (%) and water content (%) is given in Figure 7-5. In agreement to Xu (2005) this figure also shows that water and bitumen contents are inversely related.

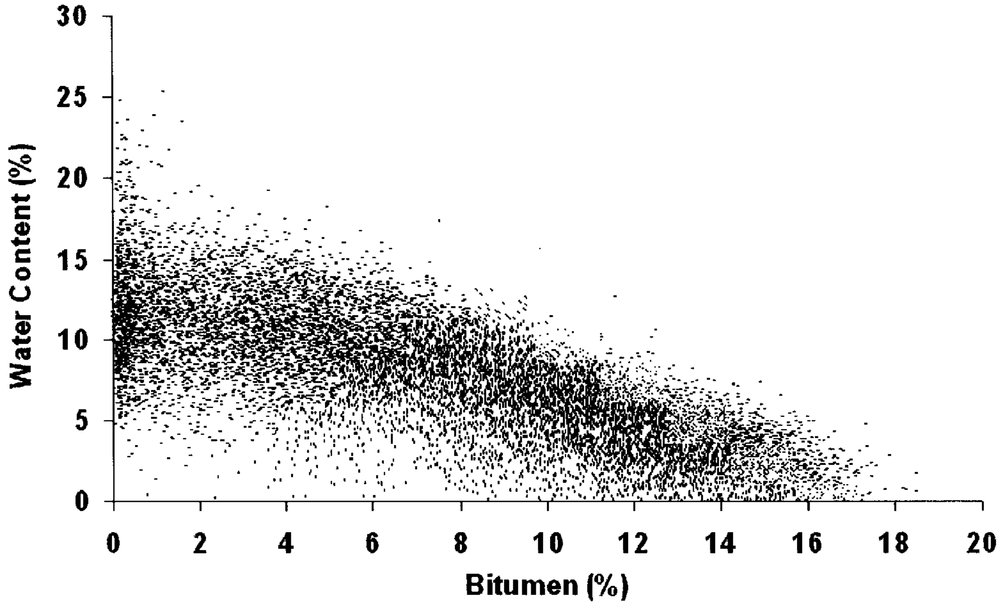


Figure 7-5 Relationship between bitumen content and water content

Although the bitumen content in the McMurray Formation oil sands varies between 0 to 18% by weight and the water content varies between 4 to 15%, the sum of the bitumen and water contents is roughly constant at about 16% of the total weight (Xu, 2005). The mean bitumen content of the McMurray Formation oil sands is approximately 10% by total weight.

Typically, the richer and cleaner oil sands are found in the Lower McMurray member and the leaner oil sands in the upper members. The distribution of oil within the McMurray members is controlled by the porosity of oil bearing sands. Where the sand is clean, the porosity can be as high as 35%, and in such cases the bitumen saturation can be up to 10-18% by weight (O'Donnell, 1988). The upper marine McMurray member is typically less porous than the middle estuarine and lower fluvial McMurray members.

Oil sands with a bitumen content of 6-8% is usually considered as a low-grade (lean), 8-10% is considered an average-grade (medium), while bitumen content above 10% is considered to be a high grade (rich) oil sands ore. Oil sands in Upper McMurray (marine) member are usually lean ores compared to Middle McMurray (estuarine) and Lower McMurray (fluvial) members. From the current research point of view, the difference in the bitumen and water content between the McMurray members can influence the oil sands shear strength and one could expect different diggability conditions in these members.

The amount of water in the oil sands can influence its diggability characteristics, particularly in winter months. Cyr (2004) found that oil sands in the Upper McMurray marine member is associated with higher water content and is susceptible to freezing and frost penetration, which can increase its strength in winter. Mining experience showed that the upper marine benches in the North Mine were difficult to dig in the winter months (Wright, 2005).

As far as the overburden material is concerned, for Holocene and Pleistocene overburden material, the moisture content varies between 11 to 28% and for the Clearwater Formation, the moisture content is 5% dry of the plastic limit (Cameron, 2003).

Gases such as methane and nitrogen can be found dissolved in the oil sands in both the bitumen and water phases. When the oil sands are exposed, the dissolved gases come out of solution and can cause the oil sands to 'puff' and soften (Price, 2005). It has been found that the rich ore often flows out of the bank, possibly aided by gas exsolution, and the resulting material is picked up as a loose pile (Wright, 2005). The amount of gas exsolution and degree of softening of oil sands would, however, depend upon the quantity of dissolved gases and the duration of exposure of oil sands before mining. If the bench is quickly exposed, then gas exsolution may only reduce the oil sands strength and stiffness at the immediate surface and may have a minor influence on oil sands diggablity characteristics. A literature review found that no study has been done to measure the quantity of gas exsolution and its effect on strength of oil sands. The influence of gas exsolution on diggability was not considered in this thesis.

7.3.2 Mineralogy

The oil sands mineralogy is important as it contributes to the abrasiveness and hence, diggability. For example, quartz sand is harder and more abrasive than clay. Minerals such as iron and calcium sometimes occur as cementation between sand particles in the Upper McMurray and increase the strength (Wright, 2005). A study conducted by Cyr (2004) found that the frequency of lump jam events is higher for ore coming from the Upper McMurray member than the other units. Marine ores are usually associated with higher water content. Therefore, when frozen, these ores can be responsible for the lump jam events. One could expect decreasing penetrability in frozen marine ores.

The cementation between the mineral grains can also influence oil sands digging characteristics. The cementation process precipitates minerals in the pore space between the clastic mineral particles binding them together to form hard indurated sediments. Indurated sediments occur within the oil sands as pockets or thin bands of sandstone, ironstone, and siltstone. The presence of these hard and blocky materials of varying thickness within the oil sands units can create difficult digging conditions. The indurated siltstones bands within the oil sands typically have an unconfined compressive strength of 165 to 221 MPa and a tensile strength of 10 to 17.5 MPa. Siltstones present in the

Clearwater overburden can have an unconfined compressive strength of 65 to 93 MPa and a tensile strength of 6.5 to 9.3 MPa (Cameron, 2003).

7.3.3 Density, Porosity and Particle Size Distribution

The density of oil sands is related to its bitumen content. A plot between the bitumen grade and density (estimated based on oil, water and sands assay data), based on data obtained from Price (2005), shows that rich oil sands ore is less dense than the lean ore (Figure 7-6). A typical range of densities, for overburden material and oil sands in Syncrude's mines shows little variation in the density (Table 7-1).

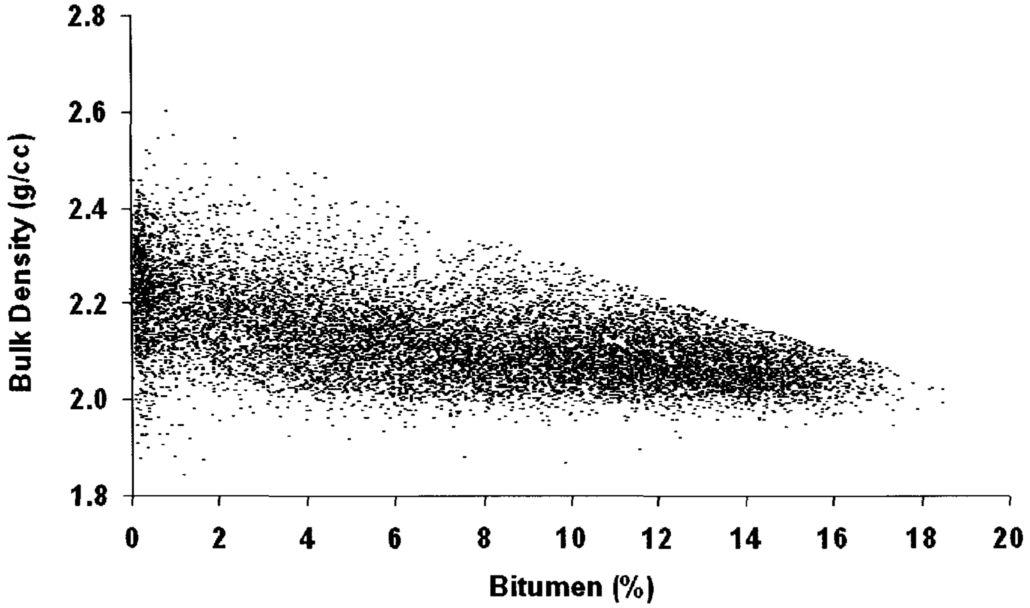


Figure 7-6 Relationship between bitumen grade and bulk density

Table 7-1 Range of densities for overburden and oil sands (Cameron, 2003)

Material	Bulk density (kg/m^3)	
	In situ (bank)	Loose (handled)
Overburden (Holocene, Pleistocene and Clearwater)	1871 – 2182	1500 – 1900
Oil sands (marine, estuarine and transitional ore/reject)	2100 ± 50	1600 – 1850

Properties of frozen soils that affect rippability include the soil type, density, gradation, degree of saturation and temperature (Andersland and Ladanyi, 2004). For a homogeneous soil, the ease of ripping depends upon the soil density; the denser the soil the more difficult to rip. However, in a stratified frozen soil, the soil tends to break along thin seams of sands or gravel. Usually, soils get stronger at lower temperature and their susceptibility to ripping decreases. However, frozen sands or gravels with low water content can be easily ripped even at very low temperatures. Oil sands can be classified as fine-grained sand with a locked structure and has a reasonably high density in comparison to soils with similar sand size particles. However, the presence of stratifications within oil sands causes failures along the weak zones and makes ripping easier (Cyr, 2004).

An important characteristic of oil sands is that the particle size distribution of the mineral solids is a function of the bitumen content. Typically, the bitumen content varies inversely with the fines content (Carrigy and Kramers, 1973). The percentage of finer particles, such as clay, in low-grade ores is high and vice versa. This behaviour can be seen in Figure 7-4. A sample of feed grade oil sands typically contains about 50% to 90% fine quartz sand, 8% to 48% quartz silt and 2% to 8% clay. However, some bands of feed grade oil sands within interburden (reject) areas can have considerably higher clay up to 40% and/or silt up to 55% (Cameron, 2003).

Lean ores, due to higher fines content, have lower porosity and more grain-to-grain contact implying a stronger fabric. Past studies on rippability also show that coarse-grained soils are easier to rip than fine-grained soils (Bell, 2004). For oil sands however, the viscosity (cohesiveness) effect of bitumen in a rich ore may offer additional resistance to digging, which results in a material that is more difficult to dig than lean ore. Therefore, there is no common agreement existing on the influence of bitumen content on oil sands diggability.

7.4 Geological and Geotechnical Data Collection

Syncrude uses a geologic block model for ore reserve estimation, mine planning and engineering. The basis for the block model is the drilling program and its associated assayed values. Exploratory drilling done up to 25 years in advance has a spacing of about 300 m and provides approximate information. Production drilling, which is used for the Five Year Mine Plan, has a denser drill hole spacing to provide more confidence in the geology. The actual spacing during production drilling varies with geologic complexity, but typically follows a 100 m by 150 m grid (O'Donnell and Ostrowski, 1992).

Cores are sent to Syncrude's onsite laboratory where they are frozen and cut in half. Half of the core is used for geological description while the other half is used for OWS (oil, water, sands) analysis. Weight percentages of bitumen, water and solids are determined with any material passing a 44-micron sieve classified as fines. Once the drill holes have been assayed and reported, a block model is created from the geologic database using Surpac mine planning software.

The basic concept in constructing a block model is to divide the entire ore body into smaller blocks and each block contains average values of different properties (block attributes) representing the volume of material within the block. Estimating the attributes for a particular block is accomplished by using geostatistics whereby a weighted average from surrounding drill holes are taken and a value is assigned for the block. Syncrude's block model uses four sub-horizontal surfaces to define the economical mineable region of the deposit corresponding to the top of 6% bitumen (T-6), top of mineable oil sands (TMOS), bottom of mineable oil sands (BMOS) and bottom of 6% bitumen (B-6). The mining region is then divided into blocks with a 50 m by 50 m by 0.5 m spacing (Heyser, 2003) where each block is sub-divided into zones with the properties of each sub-zone being assigned using geostatistics from the calculated assay or the OWS analysis file.

Geology at the North Mine and the Aurora Mine has been classified into several facies that describe precise changes in the mineralogy, texture and deposition. These facies are referred in the block model by means of facies codes. Facies codes are used to track geology within the block model and are subsequently linked to each truck via GPS on the shovel. The geologic source of the ore contained in each truck can be tracked and calculated based on the blocks dumped into it. In the block model, ore is referred as TS1 and TS2, overburden as OB1 and OB2 and the interstitial waste as OTS and OMS.

Geology at a shovel location is determined based on a query of the block model made according to the digging height of a shovel and its elevation. A large number of individual facies are encountered at Syncrude's mines. The degree of variability of these facies in a bench can be very high (Figure 7-7) and therefore, analyzing individual facies is difficult. Therefore, it was decided to simplify the analysis by using composite facies information represented in terms of percent estuarine, marine, fluvial and transitional facies content.

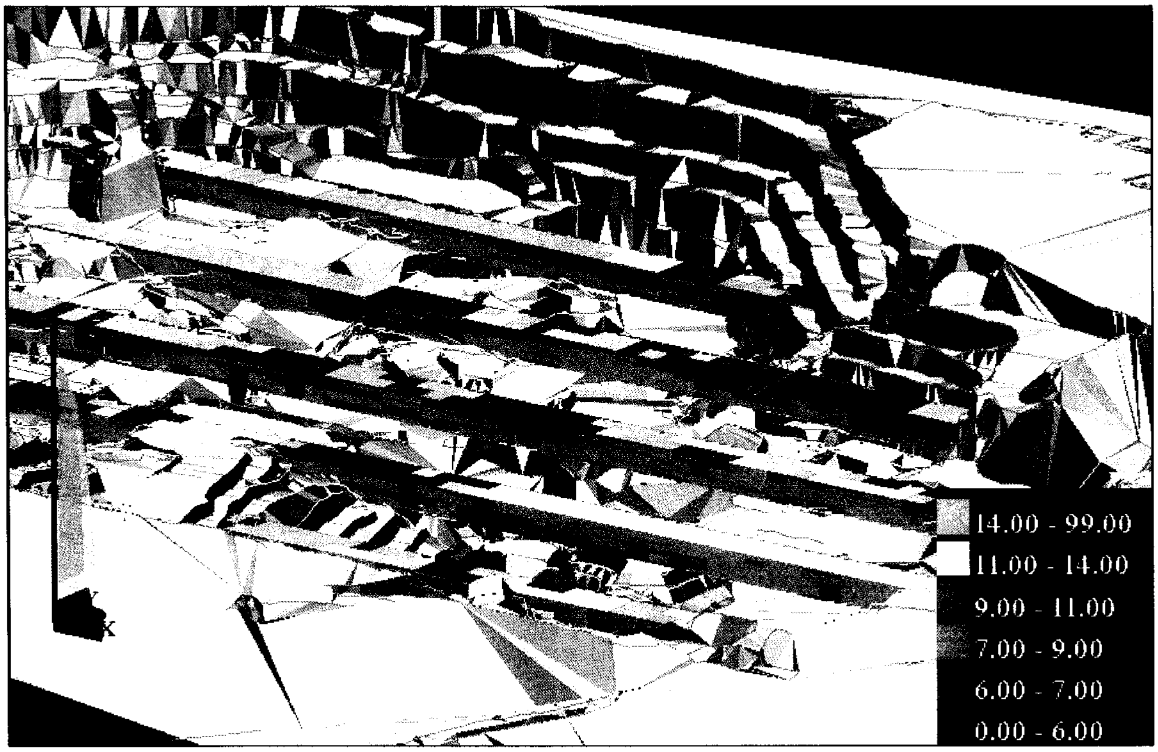


Figure 7-7 Variability in geology in a bench (Price, 2005)

Missing geological information is called an unknown unit in the block model. One reason for the unknown units is whenever a GPS signal becomes poor, the geology of the material being loaded into the truck is assigned as unknown. Also, any error in survey causes discrepancies between the actual and surveyed pits whereby block values become unknown (Cyr, 2004).

During the course of this research, a number of data sources such as Quality Production Database (QPD), Surpac block model and other geological databases were used to gather geological and geotechnical data for individual dig cycles at the shovel locations. Data on equipment (shovel ID, location, elevation, shovel heading), bench elevation, face height, truck payload, origin and destinations of material, ore type (oil sands or overburden), geology (% of estuarine, marine, fluvial, transitional etc.), bitumen (%), and fines (%) are the primary fields of interest within these databases.

Shovel location (northing, easting and elevation) data are routinely acquired using the GPS receiver in the shovel and stored in the QPD database. These data were used in conjunction with the Surpac block model to obtain the geological and geotechnical parameters at the shovel locations. The accuracy of the GPS data is quantified by a validity code and generally a value of less than 3 corresponds to a good GPS signal, whereas a value greater than 5 corresponds to a bad GPS signal. Therefore, the data with validation code of greater than 5 were filtered out and were not included in the analysis. Cyr (2004) found that the error due to GPS precision can result in an average error of no more than a couple blocks in the block model. This magnitude in error when compared to the degree of variation of geology in the mine is not deemed significant and is neglected for this research.

7.5 Influence of Bitumen Content

7.5.1 Effect on Hoist and Crowd Motor Power

In order to assess the influence of bitumen content on diggability, analyses were conducted using shovel performance data combined with QPD data. Logical grouping and selection of data was one important step in conducting analyses. Several data set were searched to identify shifts in which the same shovel (and operating team) was digging two grades of oil sands in similar geology and climatic conditions. In this way, the influences due to the shovel, operator, geology and climate were minimized. It was assumed that the difference in shovel performance, if any, was due to the difference in the bitumen content only. The amount of data that was colleted during this research being huge, logical grouping of data was challenging.

The first analysis used one shift of performance data for a shovel (11-78) operating in the North Mine in the month of June. By considering one shift of data in June, influences of changing temperature and operator were eliminated. Although the shovel dug marine ore throughout the full shift, it dug two different grades of oil sands as shown in Figure 7-8. During the beginning of the shift the shovel was excavating oil sands that had average bitumen content of 9.7% (medium grade) and later in the shift the shovel dug oil sands in a lower bench with 7.2% bitumen content (lean ore). The average fines contents were 19% and 43% respectively. The one-way ANOVA results given in Table 7-2 shows that the difference in two bitumen grades was significant compared to the variability within the data.

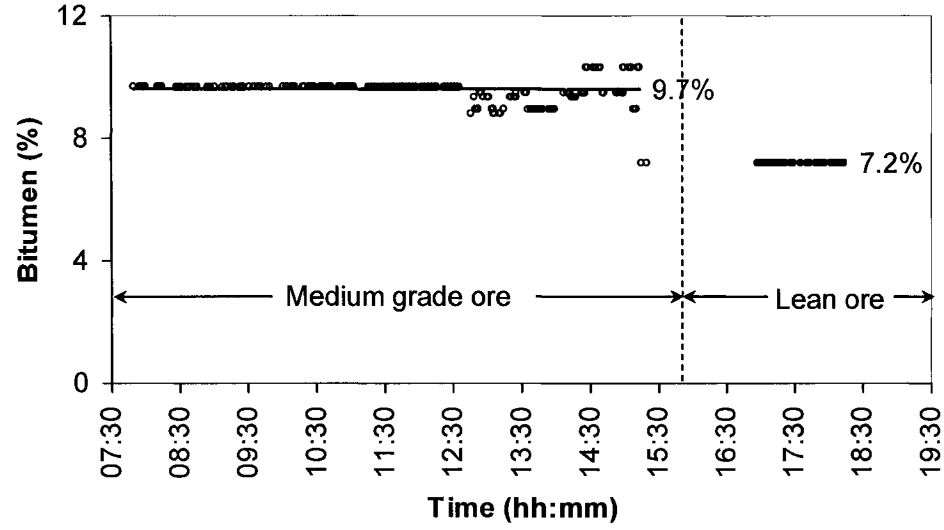


Figure 7-8 Bitumen grade during one shift of operation for the 11-78 shovel (horizontal lines show average bitumen grade)

Table 7-2 Comparison of means (one-way ANOVA) for two different oil sands grades (11-78 shovel)

		Sum of squares	df	Mean square	F	Significance level
Bitumen grade (%)	Between groups	235	1	235.079	2561.9	0.000
	Within groups	29	323	0.092	61	
	Total	264	324			

The hoist and crowd motor powers for the dig cycles identified for the shift are shown in Figure 7-9 and Figure 7-10. The average hoist and crowd motor powers used for digging two different grades of oil sands are also shown. The crowd motor power used for digging the lean ore was slightly higher than the medium grade ore. The hoist motor power used for digging the medium grade ore, however, was significantly higher than for the lean ore (Table 7-3).

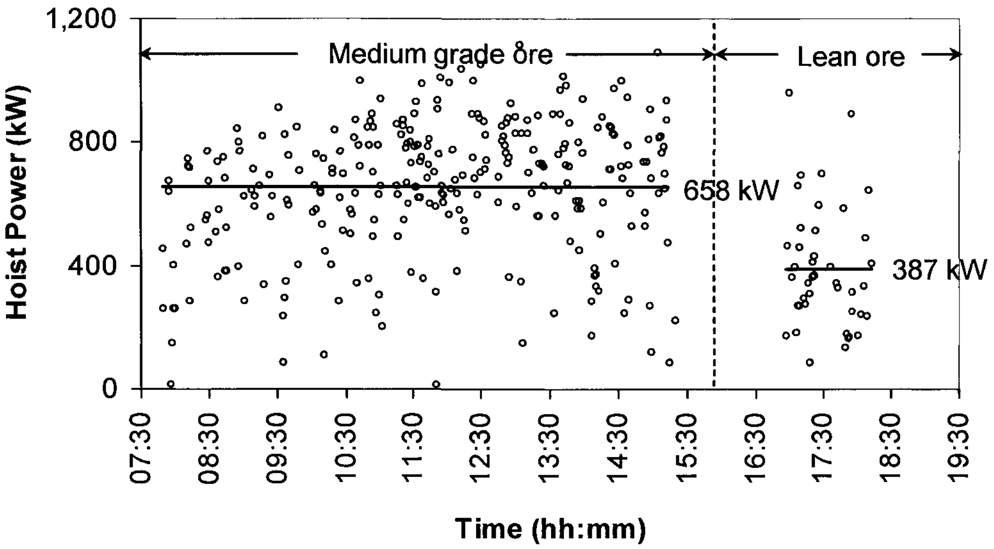


Figure 7-9 Hoist motor power during one shift of operation for the 11-78 shovel (horizontal lines show average hoist power)

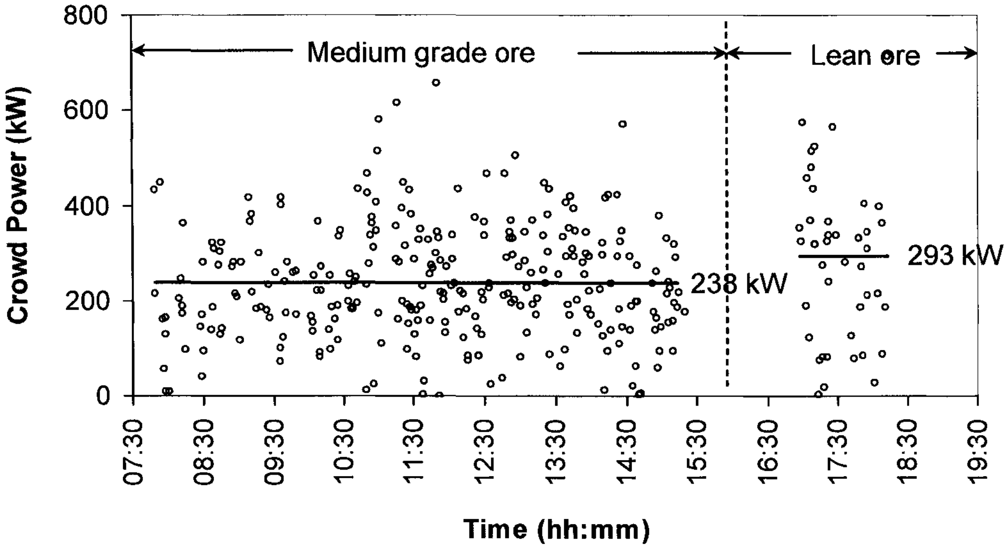


Figure 7-10 Crowd motor power during one shift of operation for the 11-78 shovel (horizontal lines show average crowd power)

Table 7-3 Comparison of means (one-way ANOVA) for hoist and crowd motor powers for digging two different oil sands grades (11-78 shovel)

		Sum of squares	df	Mean square	F	Significance level
Hoist power (kW)	Between groups	3007236	1	3007236	66.414	0.000
	Within groups	14625505	323	45280		
	Total	17632742	324			
Crowd power (kW)	Between groups	640	1	126452	7.704	0.006
	Within groups	25001	323	16412		
	Total	25641	324			

Similar analysis was carried out for another shovel (11-84) operating in the Aurora Mine for one shift of June during which the shovel dug estuarine ore. During the shift, the shovel dug two different grades of oil sands (11% and 8%) on the same bench (Figure 7-11) and the fines contents were similar (14.9% and 13.6%). The one-way ANOVA results given in Table 7-4 shows that the bitumen grades differed significantly. The average hoist and crowd motor powers used for digging the two different oil sands grades are shown in Figure 7-12 and Figure 7-13. These figures show that the shovel used slightly higher crowd motor power in the lean ore and higher hoist motor power in the rich ore. The difference in hoist motor power was significant but the difference in crowd motor power was not significant (Table 7-5).

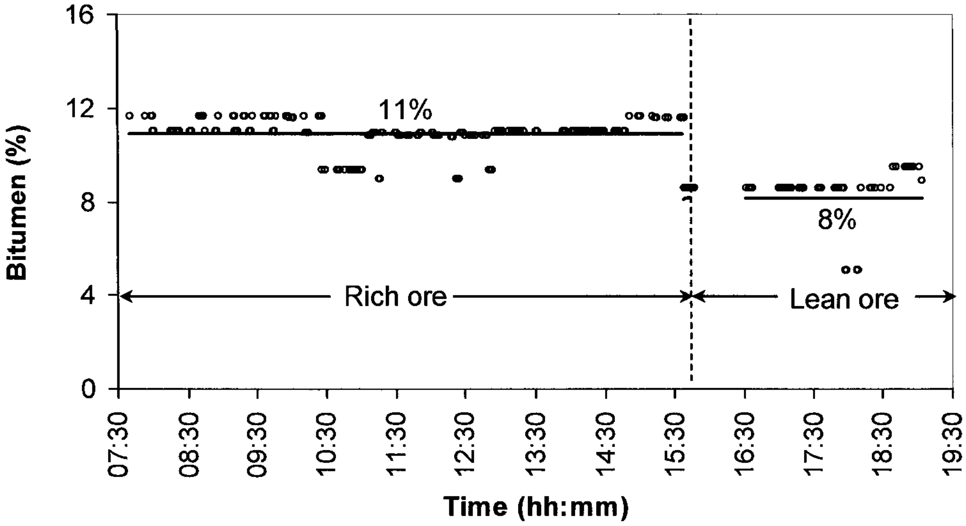


Figure 7-11 Bitumen grade during one shift of operation for the 11-84 shovel (horizontal lines show average bitumen content)

Table 7-4 Comparison of means (One-way ANOVA results) for two different oil sands grades (11-84 shovel)

		Sum of squares	df	Mean square	F	Significance level
Bitumen grade (%)	Between groups	319	1	319.080	507.766	0.000
	Within groups	184	294	.628		
	Total	503	295			

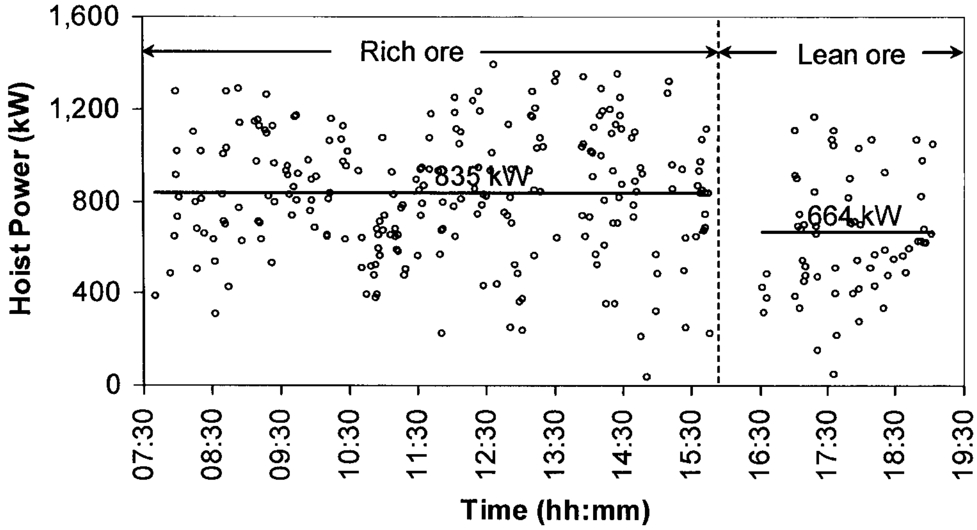


Figure 7-12 Hoist motor power during one shift of operation for the 11-84 shovel (horizontal lines show average hoist power)

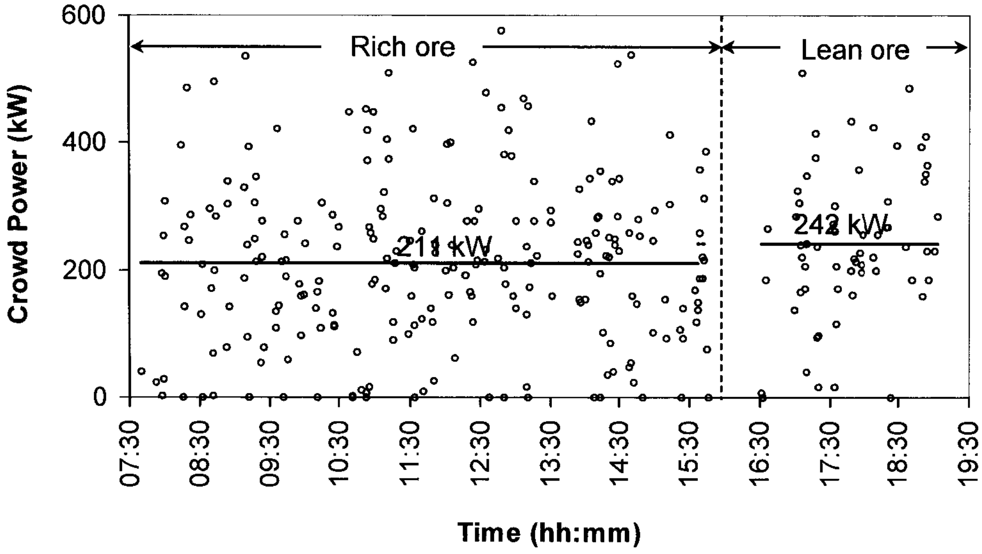


Figure 7-13 Crowd motor power during one shift of operation for the 11-84 shovel (horizontal lines show average crowd power)

Table 7-5 Comparison of means (One-way ANOVA results) for hoist and crowd motor powers for digging two different oil sands grades (11-84 shovel)

		Sum of squares	df	Mean square	F	Significance level
Hoist power (kW)	Between groups	1615530	1	1615530	22.456	0.000
	Within groups	21151269	294	71943		
	Total	22766800	295			
Crowd power (kW)	Between groups	52856	1	52856	3.039	0.082
	Within groups	5112622	294	17389		
	Total	5165478	295			

In another study, the 11-82 shovel dug transition ore in the Aurora Mine in January and February. During these two months the climatic conditions were similar, so similar influence of temperature on diggability was expected. The average powers used in these two months are given in Table 7-6, which shows that the crowd motor power used for digging the medium grade ore (8.2% bitumen) was higher than the rich ore (10.6% bitumen) but the hoist motor power used in the rich ore was higher than the medium grade ore.

Table 7-6 Monthly average values for the 11-82 shovel digging oil sands in winter months

Month	Estuarine (%)	Transition (%)	Bitumen (%)	Dig time (s)	Hoist power (kW)	Crowd power (kW)
January	50.7	49.3	8.2	12	761	232
February	45.1	54.9	10.6	13	804	215

There is a consistent trend seen for the data presented in Figure 7-9 to Figure 7-13 and Table 7-6. In every case, digging in the higher bitumen content oil sands required more hoist motor power and less crowd power compared to the leaner oil sands. As the crowd motor power represents the material penetrability (stiffness), it appears that the lean ore is stiffer than the rich ore. Operators experience also shows that the lean ore remains firm on the face. The higher fines content, higher density and lower porosity of the lean ore can be responsible for its higher resistance to dipper penetration.

As noted in Section 5.2, hoist power is likely a good indicator of digging effort. Interestingly for each data set that was examined, the higher grade oil sands required more hoist motor power.

Further analysis of shovel performance data was conducted to verify the findings presented above. Data from a shovel (11-82) was collected for the months of April to August 2005. This shovel dug rejects in April and rich estuarine ore between May and August. The powers used during different months are given in Table 7-7. As seen before, the hoist motor powers were higher in the rich ores. The crowd motor power used in the rejects (April) was expected to be higher than the rich ores but the opposite was found.

Table 7-7 Monthly average hoist and crowd motor power for the 11-82 shovel digging oil sands in summer months

Month	Estuarine (%)	Bitumen (%)	Dig time (s)	Hoist motor power (kW)	Crowd motor power (kW)
April	99	4.2	13	807	176
May	98	11.6	13	858	241
June	99	11.5	13	849	250
July	97	10.5	13	910	263
August	100	12.4	14	851	237

7.5.2 Effect on Dipper Trajectory and Dig Cycle Time

The difference in penetrability between the lean ore and the rich ore may influence the dipper penetration. In the lean ore, the dipper penetration could be less resulting in a shallow dipper trajectory, which may in turn result in shorter dig cycle times and lower hoist energy. This hypothesis was tested using data from Team 4 operating the 11-82 shovel, which dug oil sands (76% estuarine and 24% transition) with 8.5% bitumen (medium grade) and 35.7% fines in January. The same team on the 11-82 shovel dug oil sands (75% estuarine and 25% transition) with 11.3% bitumen (rich) and 31.1% fines in February. Climatic conditions in both months were similar. The average hoist motor power in the medium grade ore was 697 kW compared to 853 kW in the rich ore. The average crowd motor power was the same for both ore types at 212 kW.

Histograms showing variations in dig cycle times between these two shifts are given in Figure 7-14 and Figure 7-15. The average dig cycle time for both shifts was 12 s. The dig cycle times are more evenly distributed in the rich ore, whereas in the medium grade ore, there are slightly more short (≤10 s) dig cycles (43 % in lean ore versus 38% in rich ore).

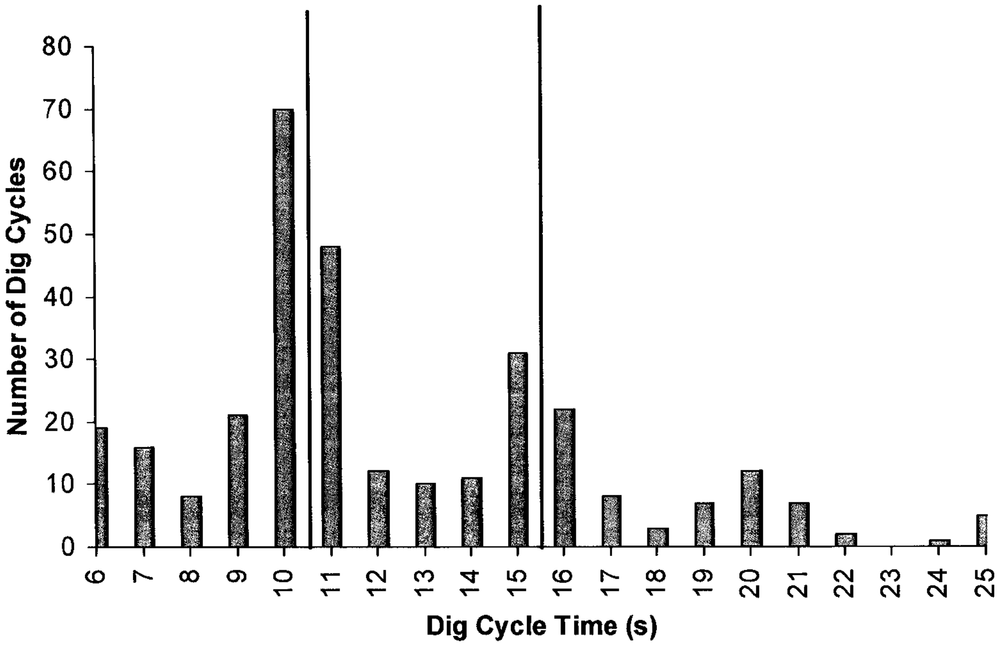


Figure 7-14 Histogram of dig cycle times for 313 dig cycles in one shift of operation of the 11-82 shovel digging medium grade ore in January

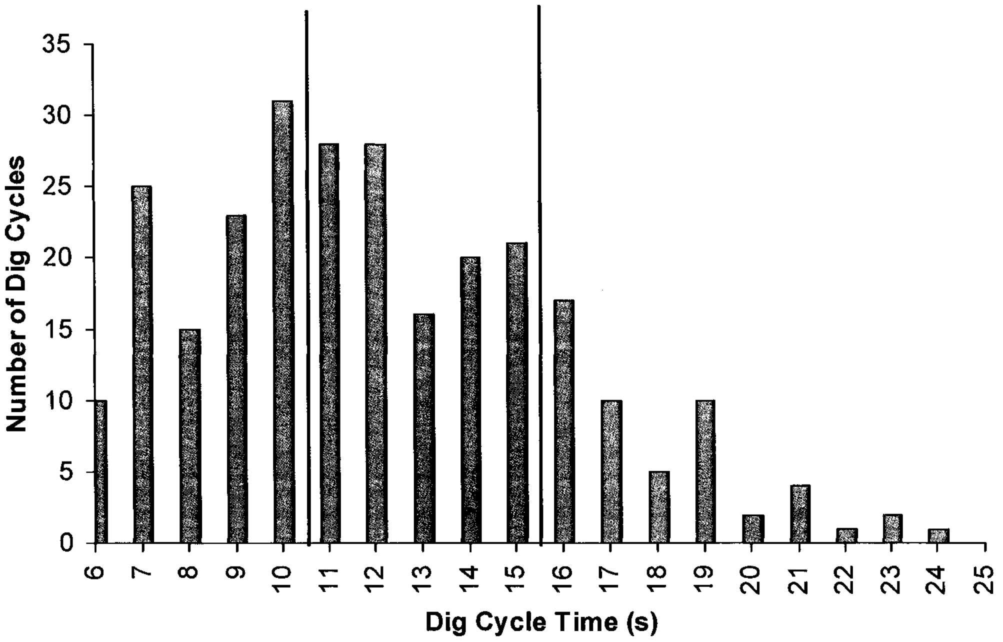


Figure 7-15 Histogram of dig cycle times for 269 dig cycles in one shift of operation of the 11-82 shovel digging rich ore in February

For shallow dipper penetration, one may expect a lower dipper fill factor resulting in more dig cycles to fill a truck. The average number of dig cycles to fill a truck was determined. The calculated number of dig cycles to load a truck was 5.3 in the medium grade ore compared to 5.6 in the rich ore. This indicates that the dipper fill factors were similar in both ores although one may argue that the dipper, on average, takes a shallower cut through the rich ore given the larger number of digs required to fill the truck. However, errors in the QPD data can affect the calculation of dig cycles per truck and this might explain why the values exceed a more typical value of 3 to 4 dig cycles per truck.

Differences in dipper penetration, if they had occurred, should cause different dipper fill factors and possibly different dig cycle times. Since there was essentially no difference in dig cycle times and dipper fill factors for the two ore types, the only reasonable explanation for the significantly higher hoist power needed in the rich ore is that this ore was harder to dig than the medium grade ore.

To further examine the issue of rich ore being more difficult to dig than lean ore, the hoist motor energy used per tonne of oil sands excavated was estimated. The cumulative hoist motor energy for the dig cycles identified for the shift was divided by the cumulative payload of the trucks loaded during the shift to determine the hoist motor energy per tonne of excavated material. It was found that the 11-82 shovel used 132 kJ/tonne in the medium grade ore compared to 181 kJ/tonne in the rich ore. The difference in hoist motor energy again indicates that the rich ore was more difficult to dig.

It may be noted that the average crowd motor powers used in two different ore types were the same (212 kW). In addition, the average crowd motor energy per tonne of excavated oil sands was similar for the two grades of oil sands (40 kJ/tonne and 44 kJ/tonne for medium and rich ores respectively). This confirms that the crowd motor power is insensitive to ground diggability. The hoist motor power represents the effort required to overcome the shearing resistance and gives a measure of material diggability. The hoist motor power for digging the rich ore is higher than the lean ore. Although the lean ore may require higher effort for dipper penetration, once the dipper has penetrated into the bank, the lean ore is easier to dig than the rich ore. It has been observed that oil sands with high bitumen content can cause flow restrictions in haul truck boxes, hopper and chutes (Cameron, 2003). This evidence suggests that the rich ore is more cohesive, which could be a reason for its higher digging resistance.

This is an interesting finding because lean ore being denser and less porous than the rich ore was anticipated to be more difficult to dig. However, the trend found in this study is supported by the laboratory wedge penetration results carried out at Syncrude (Patnayak and Tannant, 2004) where it was found that rich ores require higher cutting forces than lean ores.

In another study, Team 4 on the 11-83 shovel dug lean marine ore with 8% bitumen during one shift in July. The same operating team dug rich estuarine ore with 12.5% bitumen during one shift in February. The average hoist and crowd motor powers in the lean ore were 866 kW and 213 kW respectively. In the rich ore, the average powers used were 913 kW and 246 kW. As consistently seen before, the hoist motor power in the rich ore was higher, but contrary to previous cases, the crowd motor power was higher in the rich ore. This again shows that the crowd motor power is not a good indicator of diggability.

Histograms showing variations in dig cycle times for these two shifts are given in Figure 7-16 and Figure 7-17. The percentage of short dig cycles (≤ 10 s) is 23% in the rich ore compared to 45% in the lean ore. Accepting the notion that lean ore is easier to dig, the dipper travel through a bench face should be faster for a given dig trajectory and this could explain the shorter dig times. However, further analysis of the shovel data using the QPD data showed an average of 4.6 dig cycles to load a truck in the lean grade ore compared to 4.2 dig cycles per truck in the rich ore. This indicates that the dipper fill factor was better in the rich ore. Interpretation of all the data suggests that it is likely that the excavation of the lean ore during the July shift was accomplished with shallower dipper penetration.

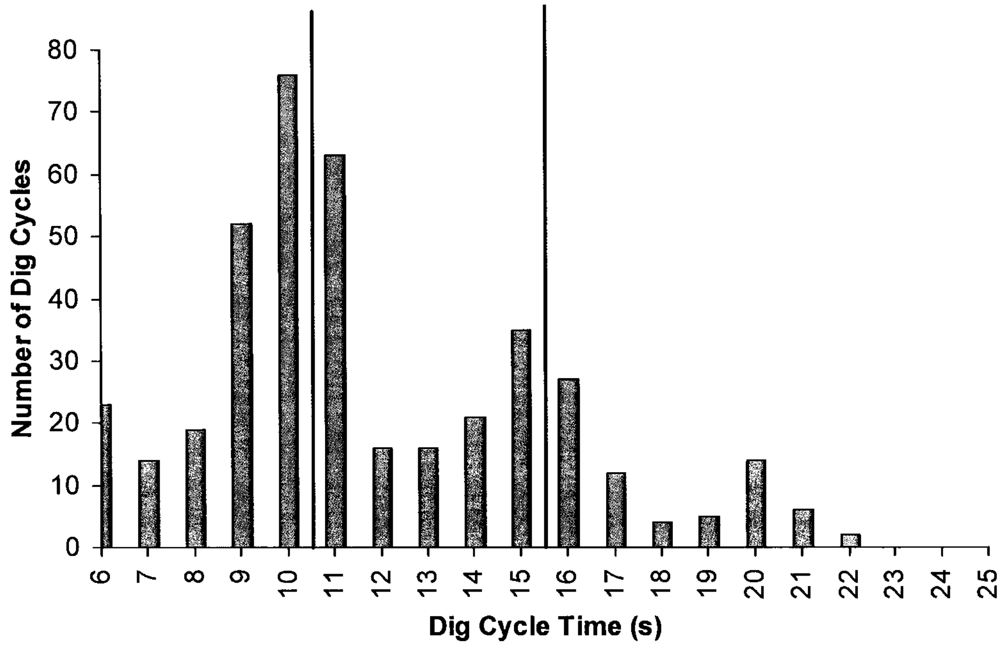


Figure 7-16 Histogram of dig cycle times for 405 dig cycles in one shift of operation of the 11-83 shovel digging lean ore in July

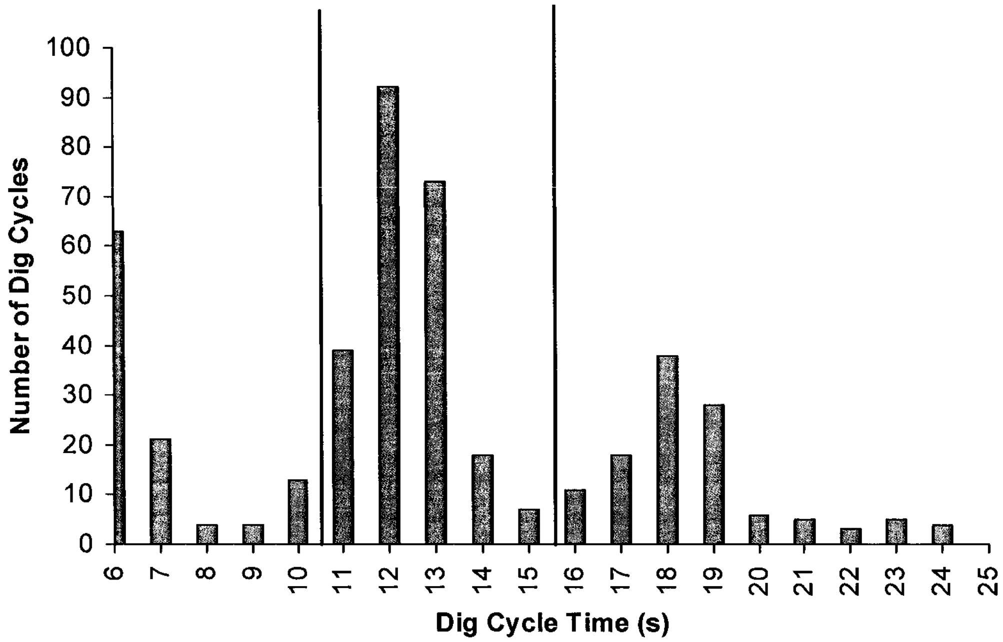


Figure 7-17 Histogram of dig cycle times for 452 dig cycles in one shift of operation of the 11-83 shovel digging rich ore in February

Another way to examine the oil sand diggability is to use the hoist and crowd motor energy used per tonne excavated. These automatically account for different digging depths and dipper fill factors. The shovel used 145 kJ/tonne on the hoist motor and 34 kJ/tonne on the crowd motor in the lean ore compared to 225 kJ/tonne and 61 kJ/tonne in the rich ore. The difference in both hoist and crowd motor energies are significant; the two ore types require different digging effort.

7.6 Marine versus Estuarine Ore

Marine ore usually has lower grade than the estuarine ore and is associated with higher fines and water content. Therefore, different diggability conditions can be expected in these two ore types.

Several data sets were searched to identify shifts in which the same shovel (and operating team) was digging in two different oil sands geology when the bitumen grade and the climatic conditions were similar. In this way, the influences due to the shovel, operator, bitumen grade and climate were minimized. It was found that during January, the 11-80 shovel was operating on two different benches in the North Mine, in which the average bitumen contents were similar but ore types were different. Ore in the upper bench (288 m bench elevation) was mostly marine, with some estuarine ore. In the lower bench (276 m bench elevation) the ore was estuarine. The average hoist and crowd powers used by different operators while digging these two ores are given in Table 7-8 and Table 7-10. For all the operators, the average hoist powers for digging the marine ore were less than the estuarine ore. The average crowd motor powers were, however, higher in the marine ore. The average hoist and crowd motor powers of all four teams were 715 kW and 277 kW in the marine ore. In the estuarine ore, the average hoist and crowd motor powers used were 766 kW and 252 kW respectively. While the differences are not large, they indicate that the penetrability of marine ore was lower than the estuarine ore but the marine ore offered less shearing resistance and was easier to dig once the dipper had penetrated into the ore. The shovel operators have noted more difficult dipper penetration into the upper bench compared to the lower benches, particularly in the winter months.

Table 7-8 Ore type at the shovel locations dug by different teams of operators (11-80 shovel) at 288 m bench elevation during January

Team	Estuarine (%)	Marine (%)	Bitumen (%)
1	32	68	9.6
2	24	76	9.0
3	30	70	9.3
4	10	90	8.9
Average	24	76	9.2

Table 7-9 Average hoist and crowd motor powers for different teams of operators (11-80 shovel) digging marine ore at 288 m bench elevation during January

Team	Dig time (s)	Hoist motor power (kW)			Crowd motor power (kW)		
		Average	95% Confidence interval for mean		Average	95% Confidence interval for mean	
			Upper bound	Lower bound		Upper bound	Lower bound
1	11	690	672	713	284	243	294
2	14	730	713	741	263	237	276
3	12	744	723	761	291	273	303
4	12	696	671	717	278	240	284
Average	12.3	715			277		

Table 7-10 Ore type at the shovel locations dug by different teams of operators (11-80 shovel) at 276 m bench elevation during January

Team	Estuarine (%)	Marine (%)	Bitumen (%)
1	86	14	10.1
2	98	2	11.0
3	100	0	11.3
4	100	0	12.3
Average	96	4	11.2

Table 7-11 Average hoist and crowd motor powers for different teams of operators (11-80 shovel) digging estuarine ore at 276 m bench elevation during January

Team	Dig time (s)	Hoist motor power (kW)			Crowd motor power (kW)		
		Average	95% Confidence interval for mean		Average	95% Confidence interval for mean	
			Upper bound	Lower bound		Upper bound	Lower bound
1	11	714	683	763	249	229	273
2	12	761	738	786	249	230	273
3	12	797	781	869	257	232	283
4	13	794	783	864	253	229	280
Average	12	766			252		

The 11-78 shovel dug marine ore in the North Mine in May and June, while it dug estuarine ore in August. Similarly, the 11-83 shovel dug oil sands with relatively higher percentage of marine ore in July compared to June. The average powers used by these shovels for digging the different ores are given in Table 7-12 and Table 7-13. Consistent with the results presented earlier, these results also show that the average hoist motor powers used for digging marine ores are less than the estuarine ores and the crowd motor powers used for digging marine ores higher. The higher fines content, higher density and lower porosity of the marine ore may be responsible for its lower penetrability. On the other hand, the higher bitumen content associated with the estuarine ores could be responsible for offering higher shearing resistance resulting in higher hoist motor powers.

Table 7-12 Monthly average hoist and crowd motor power for the 11-78 shovel digging marine and estuarine ore

Month	Estuarine (%)	Marine (%)	Bitumen (%)	Dig time (s)	Hoist motor power (kW)	Crowd motor power (kW)
May	5	95	9.4	14	717	240
June	4	96	8.3	14	699	247
August	100	0	9.5	14	738	233

Table 7-13 Monthly average hoist and crowd motor power for the 11-83 shovel digging marine and estuarine ore

Month	Estuarine (%)	Marine (%)	Transition (%)	Bitumen (%)	Dig time (s)	Hoist motor power (kW)	Crowd motor power (kW)
June	17	24	59	7.9	13	857	178
July	15	51	34	7.5	11	804	186

7.7 North Mine versus Aurora Mine Overburden

The geology of the overburden found in North Mine and Aurora Mine are different. In the present mining area, the biggest difference in the overburden is the presence of Clearwater clays at the North Mine. The diggability of overburden was compared for the two mines.

Although P&H 4100 series cable shovels are operating at both mines, the North Mine uses TS model shovels while the Aurora Mine uses BOSS models, except the 11-81 shovel, which is a TS model shovel. As the performance of TS and BOSS model shovels can be different, comparison could be made for similar shovels only. Assuming the performance characteristics of all TS model shovels were similar, digging powers used by the TS model shovels digging overburden in the North Mine and the Aurora Mine were compared.

It was found that 11-78, 11-79 and 11-80 TS model shovels were digging overburden at the North Mine during several months of the year. The average hoist and crowd motor powers used by these three shovels in the North Mine are given in Table 7-14, Table 7-15 and Table 7-16. Results show that the hoist and crowd motor powers used by these shovels while digging overburden were similar. Averaging the three shovels, the hoist and crowd motor powers were about 748 kW and 227 kW respectively.

Table 7-14 Average hoist and crowd motor powers for 11-78 TS shovel digging overburden in the North Mine

Month	Dig time (s)	Hoist motor power (kW)	Crowd motor power (kW)
February	12	755	233
March	12	760	225
Average	12	758	229

Table 7-15 Average hoist and crowd motor powers for 11-79 TS shovel digging overburden in the North Mine

Month	Dig time (s)	Hoist motor power (kW)	Crowd motor power (kW)
January	12	745	246
February	12	721	239
March	13	756	223
June	12	731	225
July	13	724	219
August	13	712	212
Average	12.5	732	227

Table 7-16 Average hoist and crowd motor powers for 11-80 TS shovel digging overburden in the North Mine

Month	Dig time (s)	Hoist motor power (kW)	Crowd motor power (kW)
May	13	752	210
June	12	749	239
July	12	765	241
August	13	753	216
Average	12.5	755	227

Similarly, the 11-81 TS model shovel dug overburden in the Aurora Mine during several months and the powers used are given in Table 7-17. The average hoist motor power while digging overburden in the Aurora Mine was 655 kW. Digging at North Mine required 15% more average hoist motor power than the Aurora Mine indicating more difficult digging conditions. These results are consistent with the fact that the North Mine overburden contains Clearwater clays which are known to be difficult to dig.

Table 7-17 Average hoist and crowd motor powers for 11-81 TS shovel digging overburden in the Aurora Mine

Month	Dig time (s)	Hoist motor power (kW)	Crowd motor power (kW)
January	11	685	271
February	10	673	267
March	10	656	268
May	11	663	300
July	10	598	278
Average	10.4	655	277

The average crowd motor power in the Aurora Mine (277 kW) is higher than the average from North Mine (227 kW). This indicates that the penetrability of the overburden material in the Aurora Mine is lower than the North Mine overburden. No specific reason could be found for why Aurora Mine overburden is easier to dig but harder to penetrate. The overburden in the Aurora Mine is more sandy and abrasive because it does not include Clearwater clay and this could be a possible reason for its lower penetrability.

7.8 Summary

The oil sands diggability is related to the geology and bitumen content of the oil sands. The shovel hoist motor power used for digging rich ore was consistently higher than for the lean ore, which indicates that the rich ore is more difficult to dig compared to the lean ore. From examination of crowd powers, it appears that the penetrability of lean ore is lower, but once the dipper has penetrated into the bank, the lean ore is easier to dig than the rich ore.

A comparison of shovel performance in marine and estuarine ores showed that the estuarine ore was more difficult to dig. In contrast, the crowd motor powers used in the estuarine ore were lower indicating easier penetrability of this ore. The higher bitumen content associated with the rich ore (and estuarine ores) may be a possible reason for its higher hoist power requirements. The higher bitumen content could be responsible for offering higher shearing resistance resulting in more digging resistance.

The overburden digging at the North Mine was more difficult (took more hoist power) than at the Aurora Mine. The absence of Clearwater clay units in the Aurora Mine is a likely reason for its easier digging condition.

CHAPTER 8 INFLUENCE OF TEMPERATURE

8.1 Climate of Fort McMurray

The climate of Fort McMurray is indicative of a sub-arctic environment characterized by short, hot summers and long, cold, dry winters. The mean annual temperature at the Fort McMurray airport is approximately 0.7 °C with extremes of up to 37°C and –50.6°C (Environment Canada, 2005). Table 8-1 shows the monthly temperature, precipitation and wind values collected over a 30-year period from 1971-2000. As Syncrude's mining operations are located approximately 45 km north and at a lower elevation than the Environment Canada station, its climate is slightly different. Comparing Syncrude's Mildred Lake weather station to Environment Canada's station located at the Fort McMurray airport, Cyr (2004) found that the annual mean temperature at Syncrude is about 1 °C warmer than the Fort McMurray airport.

Table 8-1 Fort McMurray monthly climatic means (after Environment Canada, 2005)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature													
Daily Average (°C)	-18.83	-13.7	-6.5	3.4	10.4	14.7	16.8	15.3	9.4	2.8	-8.5	-16.5	0.7
Daily Maximum (°C)	-13.61	-7.6	0.3	10	17.4	21.4	23.2	21.9	15.4	7.8	-4.2	-11.6	6.7
Daily Minimum (°C)	-24.01	-19.8	-13.2	-3.3	3.3	7.9	10.2	8.6	3.3	-2.2	-12.8	-21.4	-5.3
Extreme Maximum (°C)	13.1	15	18.9	30.2	34.8	36.1	35.6	37	32.4	28.6	18.9	10.7	
Extreme Minimum (°C)	-50	-50.6	-44.4	-34.4	-13.3	-4.4	-3.3	-2.9	-15.6	-24.5	-37.8	-47.2	
Precipitation													
Rainfall (mm)	0.46	0.8	1.6	9.3	34.2	74.8	81.3	72.6	45	18.8	2.4	1.1	342.2
Snowfall (cm)	27.03	20.6	20.4	14.5	2.9	0	0	0	2.4	13.1	29	25.9	155.8
Precipitation (mm)	19.28	15	16.1	21.7	36.9	74.8	81.3	72.7	46.8	29.6	22.2	19.3	455.5
Average Snow Depth (cm)	27.86	31	26	6	0	0	0	0	0	1	9	20	10
Extreme Daily Rainfall (mm)	6.4	4.8	8.4	15.4	38.4	50	52.5	94.5	60.5	29.4	15.2	8.4	
Extreme Daily Snowfall (cm)	16.3	15.2	29.7	26.2	15.2	0.3	0	0.2	27.9	17.2	18	22.6	
Extreme Daily Precipitation (mm)	16	13.2	29.7	26.8	39.4	50	52.5	94.5	60.5	29.4	15.7	22.6	
Extreme Snow Depth (cm)	68	67	66	53	12	0	1	0	15	18	41	53	
Wind													
Speed (km/h)	8.37	9.1	9.6	10.9	10.8	9.7	9	8.7	9.7	10.5	9	8.6	9.5
Most Frequent Direction	E	E	E	E	E	E	SW	SW	E	E	E	E	E
Maximum Hourly Speed (km/h)	67	56	54	54	63	48	72	50	51	63	60	52	
Direction of Maximum Hourly Speed	SW	W	SW	NW	W	W	W	W	W	W	W	W	W

8.2 Impact of Climate on Oil Sands Strength and Equipment Operation

The wide range of temperatures experienced in Fort McMurray region causes significant variations in oil sands properties between summer and winter months. This results in varying problems in the operation of mining equipment, both in summer and winter months. In the summer, the oil sands become soft and shovels can sink into the bench in rich ores. During digging, the shovel develops a rocking motion that preferentially softens the underfoot near the ends of the track-ground contact. With increasing duty cycles, this softened zone progresses toward the mid-point of the track creating a crowning effect. Given a sufficient number of duty cycles, this softened zone encompasses the entire shovel footprint and causes the oil sands to fail in shear and the shovel sinks. The cyclic motion is also responsible for creating cracks on shovel side frames. Similar cyclic motion also causes cracks on the haul truck body.

In the winter the oil sands is stiffer, thus underfoot conditions are of less concern, but other issues such as hard digging conditions arise. Long and cold winters resulting in frozen oil sands and frost penetration can cause increased abrasiveness and offer greater penetration resistance and in turn affect overall efficiency of the shovel.

The mechanical properties of frozen soils are influenced by the grain size distribution, the mineral content, the density, the frozen and unfrozen water contents, and the presence of ice lenses and layering (Bell, 2004). Once the soil is frozen, it becomes relatively impervious and develops high strength. A study conducted by Andersland and Ladanyi (1994) on strength of Ottawa sands showed that when frozen, the sand can have a compressive strength of about 11.5 MPa, which is approximately 8.5 times higher than its unfrozen strength. Increased strength of frozen ground results from a combination of cohesion, frictional resistance, dilatancy and interaction between the soil skeleton and the ice matrix. Because of the bond that exists between water and clay particles a significant portion of the natural moisture content in a clay soil remains unfrozen even at temperatures as low as -25°C. Nevertheless, the compressive strength of clay soil increases significantly at colder temperature (Figure 8-1). Frozen sand, in which all the water is more or less frozen, exhibits a brittle type of failure at low strains.

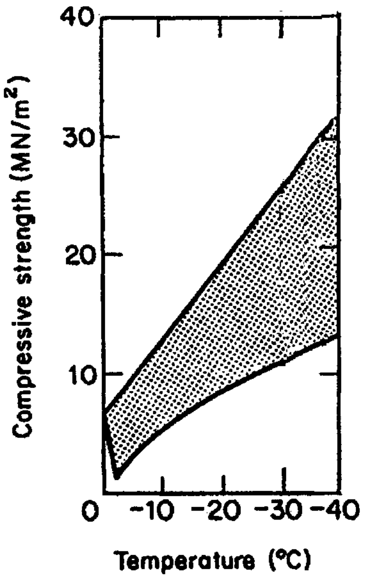


Figure 8-1 Compressive strength of frozen sand and clay (after Bell, 2004)

Laboratory testing on oil sands samples to determine strength parameters have been reported by Kosar (1989), Plewes (1987), Agar (1984), Agar et. al. (1986), Lord and Cameron (1985), and Chalaturnik (2004). Kosar (1989) reported the following shear strength parameters for oil sand:

For mean stress > 4 MPa: $c' = 500$ kPa and $\phi' = 30°$

For mean stress < 4 MPa: $c' = 0$ kPa and $\phi' = 59°$.

The peak insitu shear strength parameters of oil sands are 54° angle of internal friction and 100 kPa cohesion (Cameron, 2003). A literature review highlighted the lack of research or understanding of the properties of frozen oil sands. There appears to be no published test data available on the strength of undisturbed oil sands at freezing temperatures. However, there is clear evidence of higher oil sands strength when frozen. The firm haul road conditions during the winter is one example.

O&K wedge penetration tests on unconfined cylindrical specimens of oil sands were performed at Syncrude in a temperature range of -40°C to +20°C (Patnayak and Tannant, 2004). Samples sizes were 150 mm in diameter and 150 mm in height, and included rich oil sands (10-12% bitumen) and lean oil sands (6-9% bitumen). The tests were carried out at a high loading rate (2.6 m/s) to represent the cutting speed of a bucket wheel excavator. The test results are shown in Figure 8-2. The study found that the cutting resistance of oil sands is a function of water content, bitumen content and temperature. Interestingly, the rich oil sands was found to be more difficult to cut than the lean oil sands with a peak cutting force of about 38 kN compared to 30 kN for the lean ore. It was also found that that the cutting resistance of oil sands increases with increasing water content. Figure 8-2 shows that the maximum cutting force occurs at about -15°C. The study indicated that as the oil sands is cooled down to -15°C, the bitumen in the oil sands increased the cutting force. Below this temperature, oil sands become more brittle and the cutting force decreases. The test results were also linked to predicted bucket wheel excavator performance. The study concluded that cutting force required at -15°C is about 9 to 12 times higher compared to the cutting force at 20°C. In terms of machine power, the power requirement increases by a factor of 2.

While it is expected that the actual cutting resistance during excavation of in situ oil sands could be different than the wedge test results due to the loss of locked structure upon remoulding, however, the trend of increasing oil sands cutting forces due to decreasing temperature appear to be correct. This is also in agreement to the operator's feedback that oil sands become stiff and dipper penetration becomes difficult in winter months.

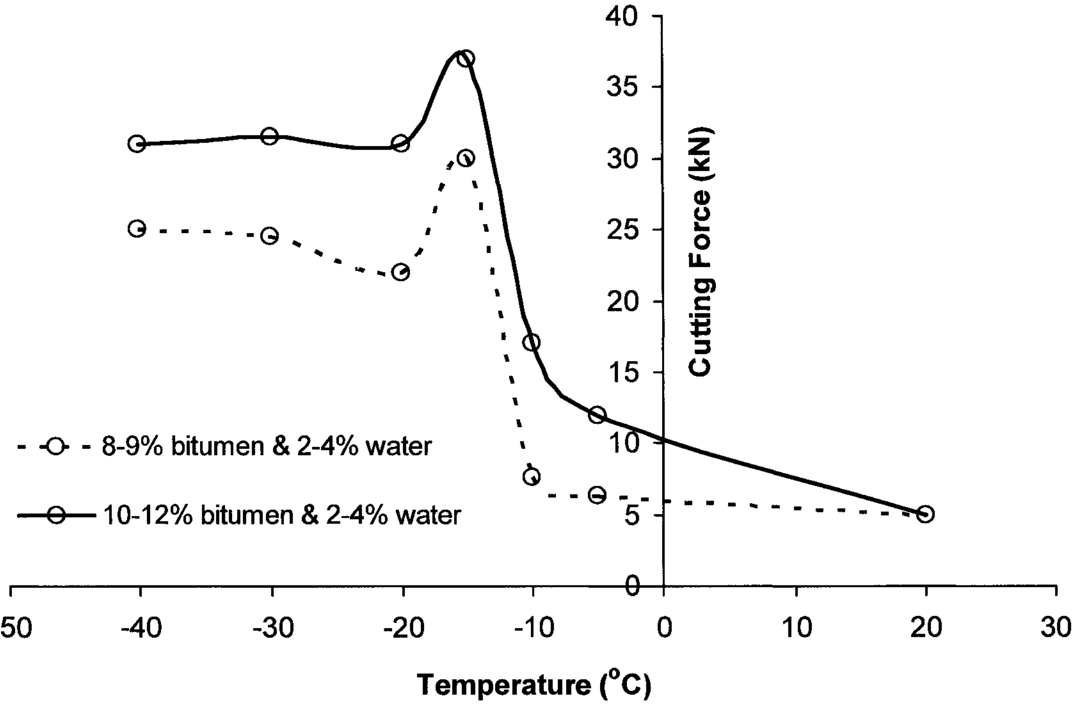


Figure 8-2 Wedge penetration test results on oil sands samples at different temperatures (after Patnayak and Tannant, 2004)

In addition to the bitumen content (%) and water content (%), the change in bitumen viscosity as a function of temperature can also cause variation in oil sands diggability. Figure 8-3 shows that bitumen viscosity can increase significantly with decreasing temperature which can contribute to higher digging resistance at colder temperatures. It has been observed that during winter months, oil sands tend to stick and hang up in the dipper. This is clear evidence of increasing bitumen viscosity at cold temperatures.

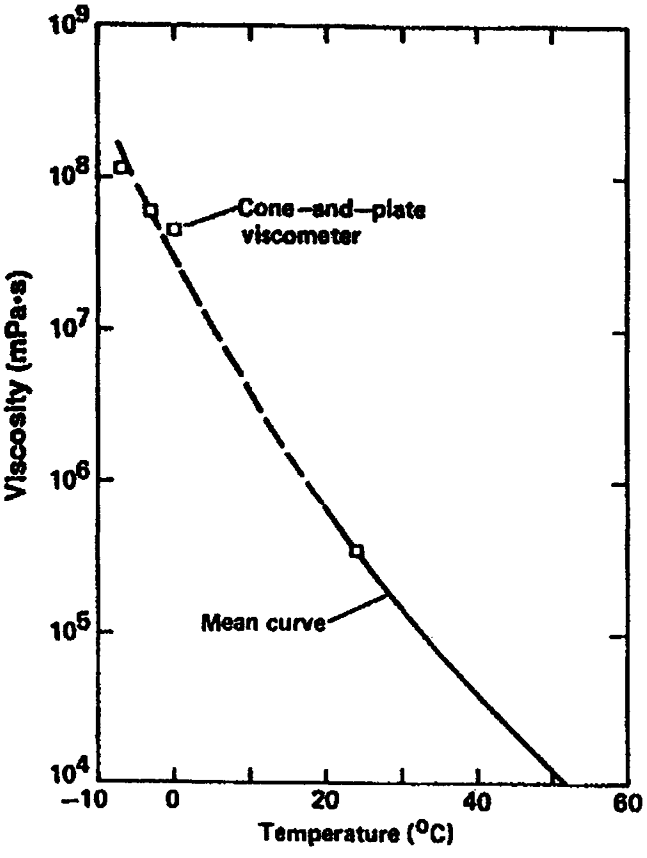


Figure 8-3 Variation of mean viscosity of Athabasca bitumen with temperature (after Xu, 2005)

Cold temperatures can create a frozen crust on top of the bench and the bench faces if the benches are left exposed to cold temperatures before mining. If the depth of frozen oil sands is large enough it may influence the digging resistance. The process of freezing in a soil matrix involves temperature effects, phase change and volume expansion of water. As cool air moves over the surface, in order to maintain temperature balance heat flows from depth to the cold surface until the surface reaches 0°C. When the soil temperature reaches 0°C, the water in the voids liberate heat as it undergoes phase change. This liberated heat is conducted to the surface and a frost front progresses into the soil. At the surface, the frost front propagates quickly due to the high temperature gradients, but slows down considerably as it goes deeper because of decreasing temperature gradient with depth.

A study performed by Cyr (2004) and Cyr et al. (2004) on generation of frozen lumps at Syncrude's North Mine using a simplified, linear, one-dimensional frost penetration model indicated that the depth of frost penetration is a function of temperature conditions, duration of exposure and thickness of snow cover above the benches. The study showed that the frost depth increases as the exposure time increases. It was found that when benches are exposed for about 14 days, winter weather can cause about 1.2 m of frozen oil sands. To minimize the occurrence of frozen ground, the study recommended that mining in the winter should be limited to active areas with as little interruptions as possible.

Typically the lower elevation benches are exposed to cold temperature for a relatively shorter than the top benches. For three to five months of winter exposure, a frost penetration of up to 4 m can be expected in undisturbed oil sands and overburden benches. In loose stockpiles, oil sands and unconsolidated fills, up to 2 m of frost penetration can be expected during winter months (Cameron, 2003).

The depth of snow cover above the face is also important because snow acts as an insulator and prevents heat loss. A study was conducted at Suncor's Fort McMurray operation during the winter of 1996/1997 to determine the effect of snow cover depth on winter mining (Cyr, 2004). The study found that frost penetration can be reduced by placing at least 0.6 m of snow on top of ore benches by early winter, thus facilitating easier mining of these benches in late winter.

8.3 Shovel Performance in Frozen versus Unfrozen Material

A bench could be difficult to dig if left unmined for more than a few weeks during the winter but the same bench could become easy to dig when the frozen material covering the face is mined out. While some areas may be left exposed and untouched for several weeks or months, the majority of the mining activity focuses on particular areas for prolonged periods thus reducing the actual degree-days the bench is exposed to cold weather and therefore, the impact of freezing may not be significant on diggability.

Nevertheless, to assess the impact of temperature on diggability, data specific to the days and locations where the ground was frozen were analyzed.

The daily mean temperature data required for this study were collected from Environment Canada's website (Environment Canada, 2005). Bench exposure times were estimated from the known mining sequence. There were no data available on snow cover depth at the specific shovel locations, thus snow cover is ignored.

An example of the analysis is illustrated in Figure 8-4 and Figure 8-5. Figure 8-4 shows the mining sequence of the 11-85 shovel during two weeks of operation in February. The shovel was excavating uniform rich (13% bitumen) estuarine ore. From the sequence of mining it was found that the materials excavated on February 2, 3, 14 and 15 were left unmined and exposed to cold weather for about 14 days. Therefore, the oil sands at those specific locations were expected to be sufficiently frozen to create a more difficult digging condition. The exact number of days of exposure was, however, unknown. The daily average hoist powers for the two-week period along with the mean daily temperatures are shown in Figure 8-5. It can be seen that the hoist powers at the identified frozen locations are not significantly higher than the other locations. The mean temperature, as shown in Figure 8-5, on the previous days (February 1 and 12) was above 0°C and might have caused some softening of the ground. However, the degree of softening is expected to be little in such a short time.

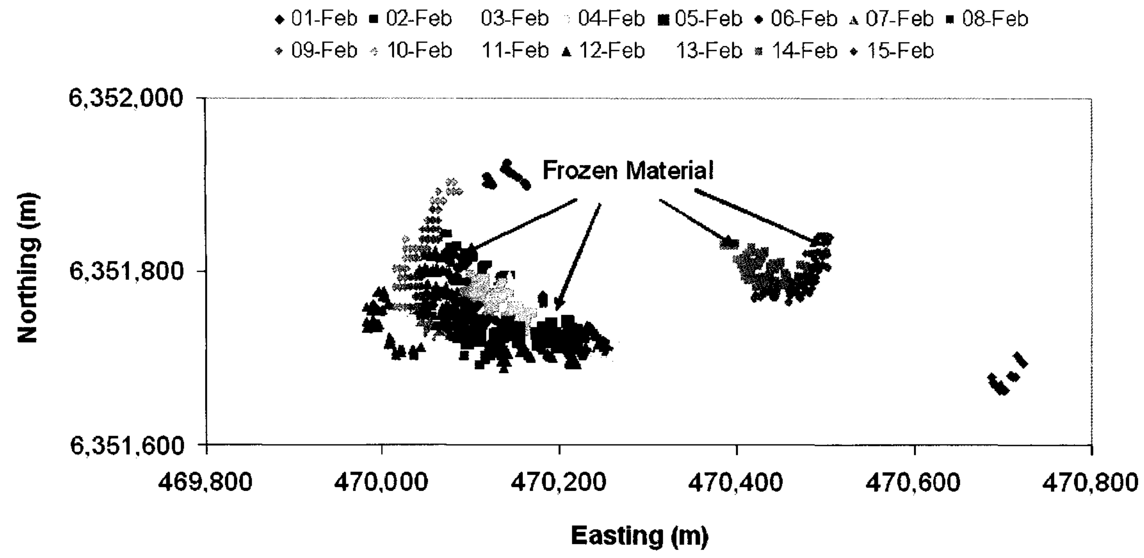


Figure 8-4 Sequence of mining for two weeks of operation (11-85 shovel)

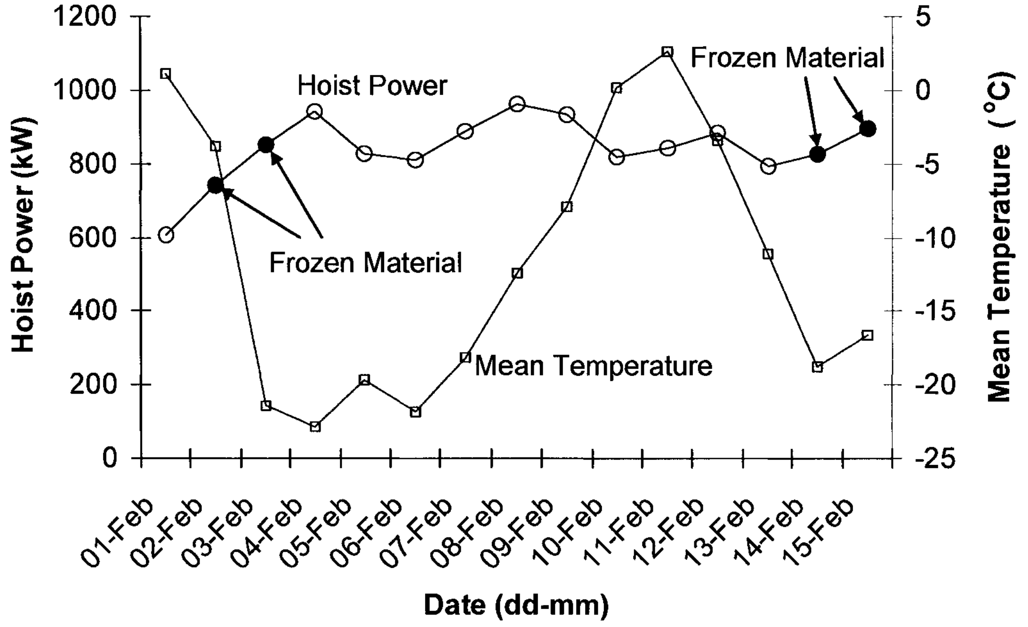


Figure 8-5 Variation of hoist power during two weeks of operation (11-85 shovel)

By analyzing the operator's team schedules, it was found that Teams 1 and 2 were working at the identified frozen locations. The average hoist and crowd motor powers required by Teams 1 and 2 while operating at these locations were determined and compared with the average hoist and crowd motor powers of these two teams for the month of February in Table 8-2 and Table 8-3. The hoist and crowd powers at the frozen locations are somewhat higher than the monthly average. This indicates that cold weather and frozen oil sands may have a localized impact on oil sands diggability.

Table 8-2 Hoist and crowd motor power at the identified frozen locations

Team	Hoist motor power (kW)				Crowd motor power (kW)			
	Average	95% Confidence interval for mean		Median	Average	95% Confidence interval for mean		Median
		Upper bound	Lower bound			Upper bound	Lower bound	
1	913	860	965	903	251	216	286	251
2	796	699	894	791	240	226	253	238

Table 8-3 Hoist and crowd motor power for the entire month of February

Team	Hoist motor power (kW)				Crowd motor power (kW)			
	Average	95% Confidence interval for mean		Median	Average	95% Confidence interval for mean		Median
		Upper bound	Lower bound			Upper bound	Lower bound	
1	849	762	932	869	246	196	281	240
2	708	659	857	729	239	194	277	245

It may be noted that the difference in crowd powers between the frozen and unfrozen locations was smaller than the difference in hoist motor powers. It appears that there was no major change in oil sands penetrability due to freezing. Since the shovel dug rich estuarine ore, the low water content associated with the ore could be one of the possible reasons for insignificant increase of crowd motor power when digging at the frozen locations. The higher difference in the hoist motor powers suggests that cold weather had a greater impact on increasing the oil sands resistance to shearing, which could be due to increasing bitumen viscosity at colder temperatures.

It was found that the 11-79 shovel dug overburden during several summer and winter months. The average hoist motor power and crowd motor power during various months of shovel operations are given in Table 8-4. January, February and March represent colder periods of the year compared to June, July and August. Comparing the hoist and crowd motor powers for various months, it can be seen that there is no substantial difference in the hoist motor power between these months. For the winter months the average hoist and crowd motor powers were 741 kW and 236 kW respectively, which are only marginally higher than values for the summer months (722 kW and 219 kW). This indicates that winter mining conditions may only have a minor influence on material diggability.

Table 8-4 Monthly averages of hoist and crowd motor powers for the 11-79 shovel digging similar overburden in the North Mine

Month	Dig time (s)	Hoist motor power (kW)	Crowd motor power (kW)
January	12	745	246
February	12	721	239
March	13	756	223
June	12	731	225
July	13	724	219
August	13	712	212

The 11-82 shovel dug estuarine oil sands during various months except in February when it dug transition ore. The average hoist motor power and crowd motor power during various months of shovel operations are given in Table 8-5. This table shows no significant difference between the hoist (and crowd) motor powers between these months. The estuarine ore usually has low water content and relatively high bitumen content. This could be a possible reason that temperature had little influence on diggability of estuarine ore.

Table 8-5 Monthly average hoist and crowd motor power for the 11-82 shovel digging estuarine oil sands

Month	Bitumen (%)	Dig time (s)	Hoist motor power (kW)	Crowd motor power (kW)
February*	10.6	13	804	215
March	10.4	13	824	241
May	11.6	13	858	241
June	11.5	13	849	250
July	10.5	13	910	263
August	12.4	14	851	237

* Transition ore

While evaluating the climatic influence on marine ore, it was found that none of the shovels excavated similar marine ore during summer and winter months. Therefore, it was not possible to compare the temperature influence for the same shovel. However, it was found that the 11-78 shovel dug marine ore in the summer months, while the 11-80 shovel dug similar marine ore in the winter months. Both were TS model shovels and were operating in the North Mine. Therefore, their performance can be assumed to be similar. The analysis results are given in Table 8-6 and Table 8-7. Results show that both hoist and crowd motor powers are higher in the winter months compared to the summer months. This indicates that temperature had a greater influence on the diggability of marine ore. The marine ore usually has high water content. This can be one of the possible reasons for the increasing digging powers in winter months for the marine ore. The feedback from the shovel operators agreed with the results found in this analysis.

Table 8-6 Monthly average hoist and crowd motor power for the 11-80 shovel digging marine oil sands

Month	Bitumen (%)	Dig time (s)	Hoist motor power (kW)	Crowd motor power (kW)
January	9.5	13	744	261
February	9.6	14	807	253
March	10.2	14	798	255

Table 8-7 Monthly average hoist and crowd motor power for the 11-78 shovel digging marine oil sands

Month	Bitumen (%)	Dig time (s)	Hoist motor power (kW)	Crowd motor power (kW)
June	8.3	14	692	247
July	7.8	14	682	233

8.4 Summary

Winter weather was expected to have a significant influence on oil sands diggability. However, cold temperatures were found to only have a minor and localized influence on oil sands diggability characteristics. Both shovel hoist and crowd motor power requirements were found to increase when digging in the winter with a bigger effect found for the marine ore compared to the estuarine ore. The extent of the influence would depend upon the temperature conditions and the duration of bench exposure.

CHAPTER 9 INFLUENCE OF SHOVEL TYPE AND TOOTH ADAPTERS

The performance of a shovel can be influenced by the type of shovel and its components, especially the dipper and the tooth configuration. Syncrude operates two different varieties of P&H 4100 shovels: TS and BOSS models. These two models differ slightly in their electrical motor capacities, so their performance while digging similar material can be different. Similarly, two different types of tooth adapters are used at Syncrude: inline and down-pitch adapters. The main difference between them is the different angle the teeth make with the bottom of the dipper. The teeth angle can have an influence on the dipper's ability to penetrate into the bank, which can influence the shovel performance.

9.1 Inline versus Down-pitch Tooth Adapter

Teeth are attached to the dipper by means of an adapter (Figure 9-1). An inline adapter inclines the teeth 2° downward from the base of the dipper. Most of the adapters used on the shovels at Syncrude are inline adapters. Recently, a different type of adapter, referred as the down-pitch adapter, is being used on some of the shovels. A down-pitch adapter inclines the teeth 5° downward.

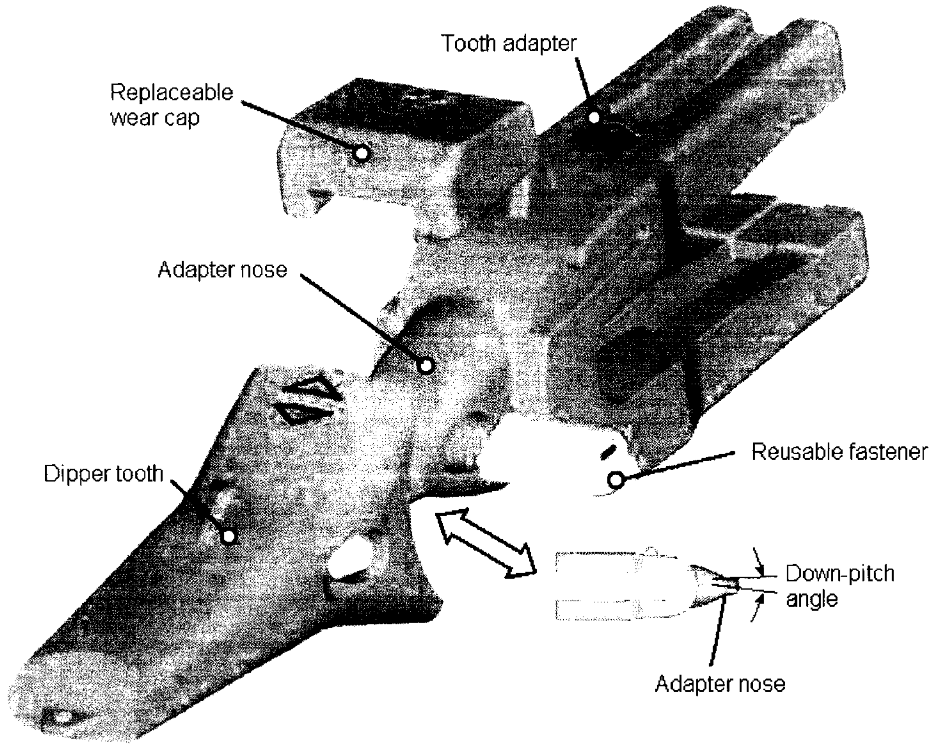


Figure 9-1 Tooth adapter configuration (Hensley Industries Inc., 2006)

An attempt was made to evaluate the influence of these two types of adapters on the digging power and energy. To properly assess the influence of teeth adapters on digging energy, the influence of other variables such as the operator, temperature, geology, and material type must be minimized.

After search through several datasets, it was found that part way through one shift in June, the inline tooth adapter was replaced with a down-pitch tooth adapter on the 11-78 shovel. During the shift, the shovel was digging uniform marine ore with 9.3% average bitumen content and 19.1% fines. The performance data were analyzed for the shift and the average powers used by the shovel with the two adapter types are given in Figure 9-2 and Figure 9-3. The average value of powers indicated that the tooth angle can influence the digging power. The shovel used lower crowd motor power and higher hoist motor power with the down-pitch adapter. Comparison of mean hoist motor and crowd motor powers for two adapter types, however, indicated that the power consumptions are not significantly different (Table 9-1).

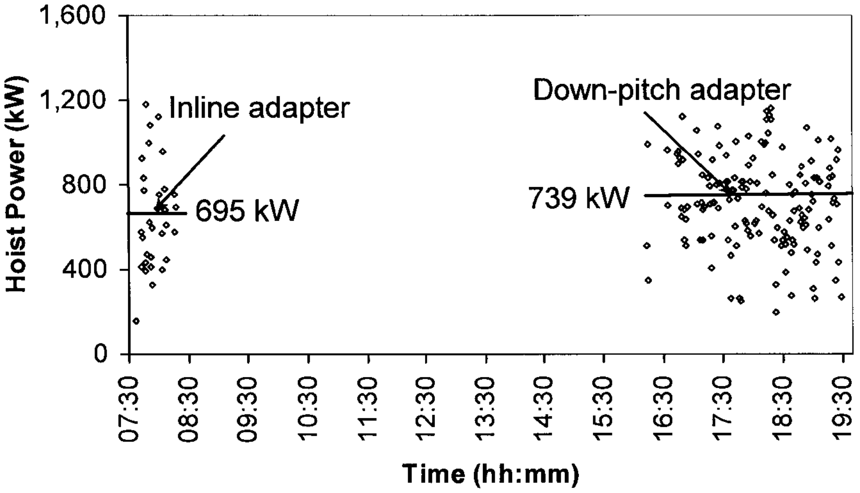


Figure 9-2 Hoist motor powers for inline and down-pitch adapters during one shift of the 11-78 shovel operation (horizontal lines show average hoist powers)

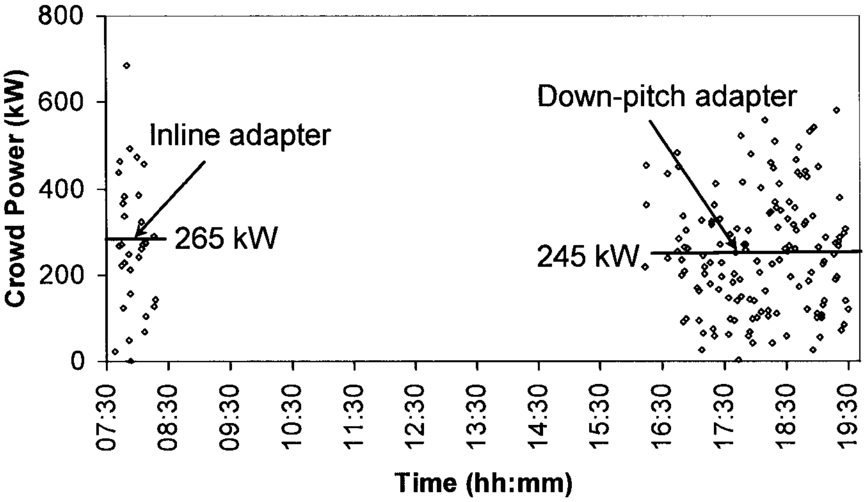


Figure 9-3 Crowd motor powers for inline and down-pitch adapters during one shift of the 11-78 shovel operation (horizontal lines show average crowd powers)

Table 9-1 One-way ANOVA results for two adapter types

		Sum of squares	df	Mean Square	F	Significance level
Hoist motor power (kW)	Between groups	130946	1	130946	2.760	0.098
	Within groups	8160626	172	47445		
	Total	829157	173			
Crowd motor power (kW)	Between groups	9703	1	9703	0.517	0.473
	Within groups	3267467	174	18778		
	Total	3277172	175			

To further verify the results, 11-78 shovel performance data were analyzed based on team schedules for various shifts. Teams 1 and 2 were digging similar marine ore with about 8.5% bitumen before and after the adapter change was made. Four shifts of performance data were analyzed that represented the performance of these two teams with inline and down-pitch adapters. The average powers used by Teams 1 and 2 with different adapter types are given in Table 9-2 and Table 9-3. The average values show that both teams used lower crowd motor powers and higher hoist motor powers with the down-pitch adapter. Comparison of the means, however, indicates that the powers used with two different adapter types were not significantly different (Table 9-4 and Table 9-5). A comparison could not be made for Teams 3 and 4 on this shovel because they were not digging similar material before and after the adapter change was made.

Table 9-2 Average hoist motor powers used with inline and down-pitch adapters while digging 8.5% bitumen marine ore with 11-78 shovel

Operator	Inline adapter			Down-pitch adapter		
	Average	95% Confidence interval for mean		Average	95% Confidence interval for mean	
		Upper bound	Lower bound		Upper bound	Lower bound
Team 1	686	698	660	693	698	666
Team 2	725	749	714	785	775	740

Table 9-3 Average crowd motor powers used with inline and down-pitch adapters while digging 8.5% bitumen marine ore with 11-78 shovel

Operator	Inline adapter			Down-pitch adapter		
	Average	95% Confidence interval for mean		Average	95% Confidence interval for mean	
		Upper bound	Lower bound		Upper bound	Lower bound
Team 1	239	264	230	234	224	247
Team 2	302	328	300	249	253	232

Table 9-4 Comparison of means of two adapter types for Team 1

		Sum of squares	df	Mean square	F	Significance level
Hoist motor power (kW)	Between groups	10309.229	1	10309	0.239	0.625
	Within groups	43862122	1015	43214		
	Total	43872432	1016			
Crowd motor power (kW)	Between groups	24089.996	1	24090	1.475	0.225
	Within groups	16582126	1015	16337		
	Total	16606216	1016			

Table 9-5 Comparison of means of two adapter types for Team 2

		Sum of squares	df	Mean square	F	Significance level
Hoist motor power (kW)	Between groups	164305	1	164305	4.202	0.041
	Within groups	38471398	984	39097		
	Total	38635703	985			
Crowd motor power (kW)	Between groups	1337556	1	1337556	82.809	0.000
	Within groups	15893960	984	16152		
	Total	17231517	985			

Although there were no significant difference between the digging powers used with two adapter types, by comparing the average values a consistent trend can be seen in the data set presented in Figure 9-2, Figure 9-3 and Table 9-2. In every case, digging with down-pitch adapter required more hoist motor power and less crowd motor power compared to the inline adapter. As the tooth angle changes, the ability of the teeth to penetrate into the face also changes. In a uniform material, with the same amount of applied thrust, the extent of dipper penetration could differ for different teeth configurations. A tooth configuration that is favourable to penetration would penetrate more into the bank with low crowding effort. Easier crowding would allow for deeper dipper penetration possibly resulting in a greater fill factor, which can increase the required hoist motor power. As digging with the down-pitch adapter required more hoist power and less crowd power compared to the inline adapter, it appears that the down-pitch adapter facilitates easier penetration by the crowding action. The results were also supported by the feedback from the operators (Hoskins, 2005).

To verify the influence on dipper fill factor, the average number of dig cycles used by each team for loading a truck was calculated. The results given in Table 9-6 show that fewer dig cycles were used by both teams for loading a truck with the down-pitch adapter. From this it appears that the dipper fill factor was better with the down-pitch adapter than the inline adapter.

Table 9-6 Average hoist and crowd motor powers used with inline and down-pitch adapters (11-78 shovel)

Operator	Number of dig cycles / truck		Hoist motor energy / tonne (kJ/tonne)		Crowd motor energy / tonne (kJ/tonne)	
	Inline adapter	Down-pitch adapter	Inline adapter	Down-pitch adapter	Inline adapter	Down-pitch adapter
Team 1	3.9	3.7	153	147	53	50
Team 2	4.2	3.5	195	139	82	44

The average hoist and crowd motor energies used per tonne of material excavated were determined (Table 9-6). It was found that although the hoist motor power consumption per dig cycle was higher, the shovel used less hoist and crowd motor energy per tonne of material excavated with the down-pitch adapter compared to the inline adapter. From the results presented here it appears that the down-pitch adapter is a better choice than the inline adapter.

9.2 P&H 4100 BOSS versus P&H 4100 TS Shovel

Syncrude operates two different types of P&H 4100 shovels: TS and BOSS models. The motors in the BOSS model have slightly different capacity electrical motors. The motors in the BOSS model are of higher capacity than the TS model. Therefore, differences in energy and power consumption may be anticipated for these two shovel models. An attempt was made to compare the performance of these two shovel types while they were digging similar material.

The geology in the North Mine and the Aurora Mine are different and can influence the shovel performance. Therefore, a comparison between shovel types operating in different mines may not give any meaningful results. Therefore, the performance of TS and BOSS shovels working in the same mine were analyzed. All the shovels operating in the North Mine were TS models, so a comparison could not be made between shovel types at this mine. In the Aurora Mine, however, the 11-81 shovel was TS and others (11-82 to 11-85) were BOSS model shovels, which allowed for comparison between shovel types.

After searching through the huge datasets, it was found that the 11-81 TS shovel was digging overburden for most of the year. Amongst the BOSS models shovels, 11-84 was the only shovel that dug overburden during the year. Therefore, a comparison was possible between the 11-81 shovel and the 11-84 shovel only.

The average hoist and crowd motor powers used by these two shovels, while digging overburden, for three different months are given in Table 9-7 and Table 9-8. The results show that the hoist motor powers used by the BOSS shovel were higher than the TS shovel. Because the BOSS shovel has slightly higher capacity motors, this could be one of the reasons for its higher power consumption. The crowd motor power for the BOSS shovel was significantly lower than for the TS shovel. Although the reasons for the differences in crowd motor powers are not clear, the results show that the power consumption can be influenced by the shovel type while digging similar material.

Hoist and crowd motor energies used per tonne of material excavated were also determined and are given in Table 9-7 and Table 9-8. It appears that the two shovel types dig differently. The BOSS shovel used about 16% higher hoist motor energy per tonne than the TS shovel. The relative ratios of crowd and hoist motor powers are quite different and the total energy per tonne of material excavated is also different for the two shovels.

Table 9-7 Average hoist and crowd motor powers for the 11-81 TS shovel digging overburden in the Aurora Mine

Month	Dig time (s)	Hoist motor power (kW)	Crowd motor power (kW)	Hoist motor energy / tonne (kJ/tonne)	Crowd motor energy / tonne (kJ/tonne)	Total* energy / tonne (kJ/tonne)
January	11	685	271	86.9	32.7	206.5
February	10	673	267	86.2	34.2	206.6
March	10	656	268	89.1	36.2	214.4
Average	10.3	671	269	87.4	34.4	209.2

*For two hoist motors and one crowd motor

Table 9-8 Average hoist and crowd motor powers for the 11-84 BOSS shovel digging overburden in the Aurora Mine

Month	Dig time (s)	Hoist motor power (kW)	Crowd motor power (kW)	Hoist motor energy / tonne (kJ/tonne)	Crowd motor energy / tonne (kJ/tonne)	Total* energy / tonne (kJ/tonne)
January	11	775	165	102.3	22.3	226.9
February	10	823	148	98.4	17.6	214.4
March	11	731	153	104.8	21.9	231.5
Average	10.7	776	155	101.8	20.6	224.2

*For two hoist motors and one crowd motor

Because the shovel performance can be significantly influenced by the operating practice and the operating teams were different in these shovels, the results given in Table 9-7 and Table 9-8 can be biased by the operator's variability. Therefore, for comparing performance of different shovel types, a comparison would be more appropriate when the same teams operate different shovel types. More studies are required to arrive at a definite conclusion.

CHAPTER 10 CONCLUSIONS AND RECOMMENDATIONS

This thesis presents performance data obtained from P&H 4100 TS and P&H 4100 BOSS electric mining shovels operating at Syncrude's North and Aurora mines. The study was attempted to assess influence of various factors on shovel performance and material diggability while excavating in situ oil sands and overburden. The objectives of the thesis were to:

- Collect, synthesize and interpret cable electric shovel performance data to develop a dig cycle identification algorithm.
- Determine key performance indicators that can be related to digging effort and other operational parameters using data that are routinely collected by on-board shovel monitoring equipment.
- Determine the influence of ore type (rich versus lean grade oil sands; marine versus estuarine), overburden type and climate (cold temperature) on diggability.
- Determine the influence of operator's digging technique on shovel performance.
- Compare performance of shovel type (TS versus BOSS) and dipper tooth adapter (inline versus down-pitch) while digging similar material.

One year of shovel performance data along with the geological, geotechnical, and climatic data were analyzed. The data came from eight different electric shovels. Given that performance data were collected at one-second time intervals, the quantity of data handled was huge. During this research more than 2,000,000 dig cycles were analyzed. The approach adopted in this research was to use current and voltage data collected from hoist and crowd motors and to calculate the energy and/or power associated with the motors during digging.

10.1 Conclusions

Identification of the dig cycle was an essential step in analyzing shovel performance. Analysis of performance data along with digital video records of operating shovels indicated that hoist and crowd motor voltages and currents can be used to identify the beginning and the end of individual dig cycles. In practice, digging involves complex actions, so swing data are not useful for isolating the dig cycles from other shovel activities.

Performance indicators such as dig cycle time, hoist motor energy and power, and crowd motor energy and power were determined using data from different shovels. The dig cycle time can be used as an indicator of digging trajectory. By averaging the hoist (or crowd) motor powers over a number of dig cycles, the average power is less sensitive to digging trajectory.

The diggability of ground is a function of the shearing resistance offered by the soil, especially when digging in situ material. Therefore, the hoist motor power is a useful key performance indicator for assessing digging resistance. The average hoist motor power of several dig cycles (such as 100 dig cycles, shift or month) can be used as key performance indicator but the hoist motor power for an individual dig cycle is not a good performance indicator. Crowd action provides the thrust required for dipper penetration and is not a good indicator of diggability for shovels operating in oil sands. When digging a steep bench face little or no crowd may be required.

Hoist motor energy consumption per tonne of material excavated and the number of dig cycles required for loading a truck can be useful key performance indicators for assessing operator performance and productivity. Low energy usage and less dig cycles to load a truck could indicate better operator performance while digging uniform material. However, for diggability assessment, low energy usage and smaller number of dig cycles to load a truck may indicate easy digging conditions.

Oil sands diggability characteristics depend upon the geology, ore type and climatic conditions. By comparing the hoist motor powers used for digging estuarine and marine ore, it was found that the estuarine ore was more difficult to dig. Similarly, the rich ore was found more difficult to dig than the lean ore. The higher bitumen contents associated with the rich and estuarine ores could be responsible for offering higher digging resistance resulting in higher hoist powers. This is an interesting finding because lean ore being denser and less porous than the rich ore was anticipated to be more difficult to dig.

The crowd motor powers used in the lean and marine ores were higher than the rich and estuarine ores. The higher fines content, higher density and lower porosity of the lean and marine ores may be responsible for the lower penetrability.

Winter weather was expected to have a significant influence on oil sands diggability. But the study found that the cold weather only has a minor and localized influence on oil sands diggability characteristics. The extent of influence depends upon the ore type, temperature conditions and the duration of bench exposure. The study found that the freezing conditions can have a greater influence on the diggability of marine ore than the estuarine ore, possibly due to the higher water content of the marine ore.

Shovel type and dipper teeth configuration can influence the power draw on electrical motors while digging. It appears that the two shovel types dig differently. The BOSS shovel used about 16% higher hoist motor energy per tonne than the TS shovel. The relative ratios of crowd and hoist powers are quite different but the total energy per tonne of material excavated is the same for both shovels as expected. The shovel used less hoist and crowd motor energy per tonne of material excavated with the down-pitch adapter compared to the inline adapter.

Analysis of performance data along with operator team schedules showed that the performance of a shovel can be significantly influenced by the team's digging technique while digging uniform material. The study found that the average digging power per shift for a given operator could vary as much as 25% versus the average for all operators. One P&H 4100 series shovel (with two hoist motors and one crowd motor) can consume about 2 MJ of electrical energy in one second of actual digging. Assuming the average dig cycle time is about 12 s, the average number of trucks loaded by each shovel during a shift is about 100 and each truck takes about 3 to 4 shovel dig cycles to fill in, the total electrical energy consumed by each shovel would be about 6,132 GJ/year (i.e., approximately 1700 MW-h per year). The fact that each MW-h of electric energy costs about $60, the cost of digging energy for the eleven P&H shovels operating in Syncrude is a little over one million dollars per year. Considering the variation of energy usage among the operators, if the operators' performance is improved by 25%, it could save about $280,000/year on energy cost alone. A better operating practice would also result in significant savings on maintenance costs.

10.2 Recommendations

Currently shovel performance data are being collected by Syncrude at one-second time intervals. Considering the duration of dig cycle can be as short as 6 s, the estimated energy and powers using the MDSP data can, therefore, be inaccurate. If possible, collection of performance data at higher frequency is recommended. High resolution data together with the implementation of the dig cycle identification algorithm developed in this research could permit real-time shovel performance analysis. It should be possible to develop a software tool which enables operators to assess their performance in real time using calculated performance indicators. Only the performance indicators need to be stored thus minimizing data storage requirements.

The payload and truck status data in the QPD system can be erroneous. These data are very useful for assessing shovel performance and productivity. Any effort to improve data collection procedures and the resulting data reliability would enable more accurate calculation of number of dig cycles/truck and energy consumption per tonne of material excavated.

At the onset of this research, development of a means to determine a oil sands diggability index was an objective. As the research progressed the emphasis shifted to developing a methodology for determining key shovel performance indicators. By further monitoring the performance of shovels in a range of digging environments, it may be possible to develop a diggability index for oil sands excavation based on shovel performance indicators, such as hoist motor energy or power. However, there appears to be much more benefit in refining and using the shovel performance indicators as they provide important insight into how geology, equipment and operators affect the digging efficiency.

The study found that the variation of energy usage within the operating teams can be significant. Therefore, the results of this study should be used for team training to achieve optimum digging practice.

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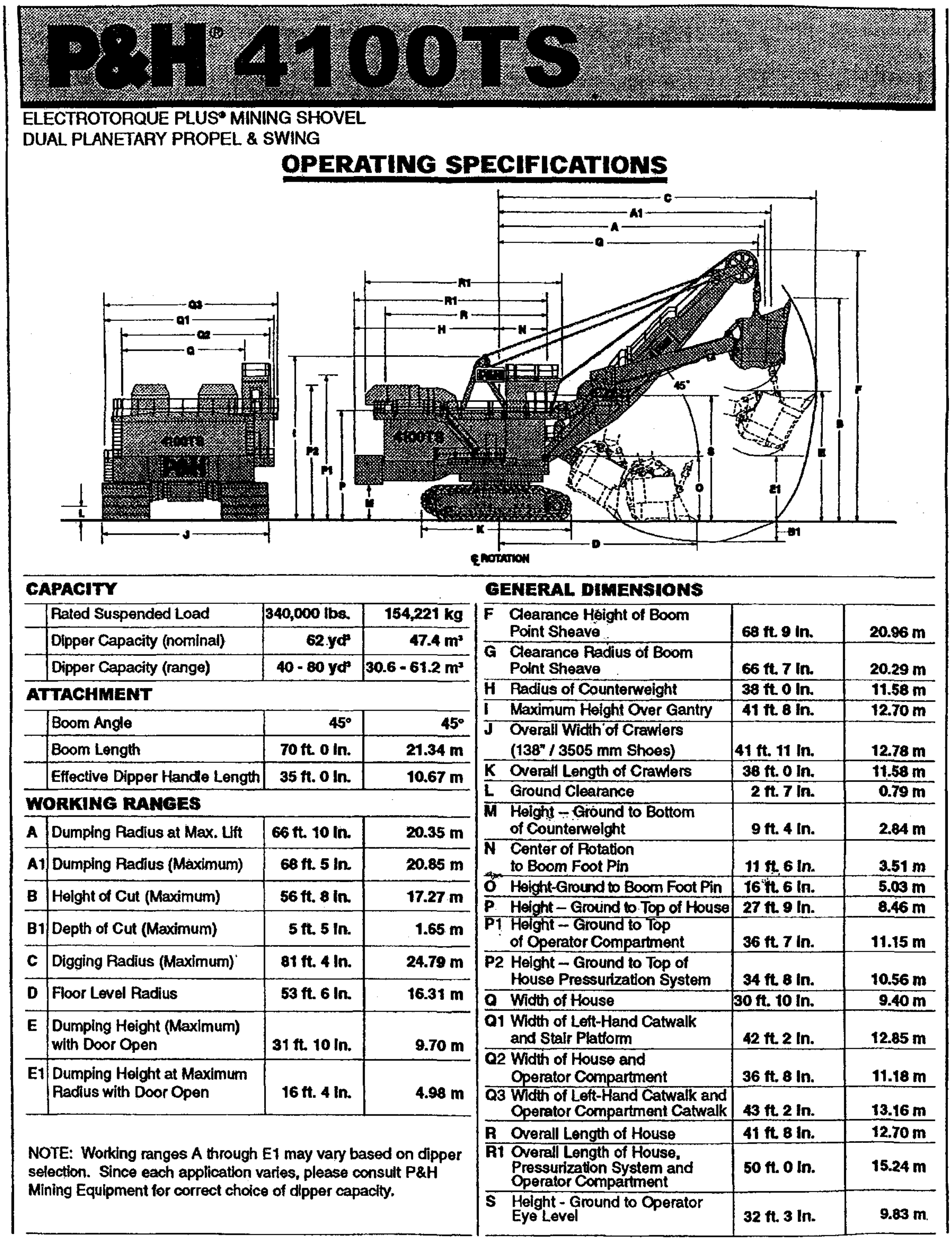
APPENDIX A – OPERATING SPECIFICATIONS OF P&H 4100 TS AND P&H 4100 BOSS SHOVELS



P&H® 4100TS

ELECTROTORQUE PLUS® MINING SHOVEL
DUAL PLANETARY PROPEL & SWING

OPERATING SPECIFICATIONS

CAPACITY

	Rated Suspended Load	340,000 lbs.	154,221 kg
	Dipper Capacity (nominal)	62 yd^3	47.4 m^3
	Dipper Capacity (range)	40 - 80 yd^3	30.6 - 61.2 m^3

ATTACHMENT

	Boom Angle	45°	45°
	Boom Length	70 ft. 0 in.	21.34 m
	Effective Dipper Handle Length	35 ft. 0 in.	10.67 m

WORKING RANGES

A	Dumping Radius at Max. Lift	66 ft. 10 in.	20.35 m
A1	Dumping Radius (Maximum)	68 ft. 5 in.	20.85 m
B	Height of Cut (Maximum)	56 ft. 8 in.	17.27 m
B1	Depth of Cut (Maximum)	5 ft. 5 in.	1.65 m
C	Digging Radius (Maximum)	81 ft. 4 in.	24.79 m
D	Floor Level Radius	53 ft. 6 in.	16.31 m
E	Dumping Height (Maximum) with Door Open	31 ft. 10 in.	9.70 m
E1	Dumping Height at Maximum Radius with Door Open	16 ft. 4 in.	4.98 m

NOTE: Working ranges A through E1 may vary based on dipper selection. Since each application varies, please consult P&H Mining Equipment for correct choice of dipper capacity.

GENERAL DIMENSIONS

F	Clearance Height of Boom Point Sheave	68 ft. 9 in.	20.96 m
G	Clearance Radius of Boom Point Sheave	66 ft. 7 in.	20.29 m
H	Radius of Counterweight	38 ft. 0 in.	11.58 m
I	Maximum Height Over Gantry	41 ft. 8 in.	12.70 m
J	Overall Width of Crawlers (138" / 3505 mm Shoes)	41 ft. 11 in.	12.78 m
K	Overall Length of Crawlers	38 ft. 0 in.	11.58 m
L	Ground Clearance	2 ft. 7 in.	0.79 m
M	Height – Ground to Bottom of Counterweight	9 ft. 4 in.	2.84 m
N	Center of Rotation to Boom Foot Pin	11 ft. 6 in.	3.51 m
O	Height-Ground to Boom Foot Pin	16 ft. 6 in.	5.03 m
P	Height – Ground to Top of House	27 ft. 9 in.	8.46 m
P1	Height – Ground to Top of Operator Compartment	36 ft. 7 in.	11.15 m
P2	Height – Ground to Top of House Pressurization System	34 ft. 8 in.	10.56 m
Q	Width of House	30 ft. 10 in.	9.40 m
Q1	Width of Left-Hand Catwalk and Stair Platform	42 ft. 2 in.	12.85 m
Q2	Width of House and Operator Compartment	36 ft. 8 in.	11.18 m
Q3	Width of Left-Hand Catwalk and Operator Compartment Catwalk	43 ft. 2 in.	13.16 m
R	Overall Length of House	41 ft. 8 in.	12.70 m
R1	Overall Length of House, Pressurization System and Operator Compartment	50 ft. 0 in.	15.24 m
S	Height - Ground to Operator Eye Level	32 ft. 3 in.	9.83 m

MAIN MACHINE SPECIFICATIONS

INCOMING SUPPLY REQUIREMENTS

Supply Voltage	**4160, 7200 or 13,800 Volts 3-Phase, 60 Hz.**	**5000, 6000, 6600 or 11,000 Volts 3-Phase, 50 Hz.**
Supply Transformer		**(Minimum) 3000 KVA**
Minimum Short Circuit VA Available at Shovel		**25 MVA**

ELECTRICAL COLLECTOR SYSTEM

High Voltage	**Deck Mounted, 15,000 Volts**
Low Voltage	**Deck Mounted**

HIGH VOLTAGE SWITCHGEAR

High-Voltage Load Break Air Disconnect	**Incoming Power to Upper Equipment**
High-Voltage Load Break Air Disconnect	**Incoming Power to Main Transformer**
High-Voltage Vacuum Contactor	**Primary Side of Main Transformer**
High-Voltage Load Break Air Disconnect	**Incoming Power to Lower of Machine**

TRANSFORMERS

Main Armature Transformer	**2500 KVA**
Auxiliaries - Field Transformer	**350 KVA**
Relays / Lighting Supply Winding	**45 KVA**

ELECTRICAL CONTROL

P&H Electrotorque-Plus® System, Digital Control with Thyristor Convertors and Static Synchronous Reactive Power Compensation.

Programmable Logic Controller for sequencing, lube and limits control.

Touch-Screen MMI in Operator's Cab for Fault Read-Out, Limits Setting, Machine, System and Lube Status and PLC I/O Status.

GUI in Electronics Room: Same as MMI plus Lube Setting, Motor Temperature Trending and Daily Fault Logging.

ELECTRICAL PROTECTION

Primary Lightning Arrestors	**Line-To-Line Line-To-Ground**
Main Armature Transformer	**Thermal and *Instantaneous Overload,* High Voltage Current-Limiting Fuses**
Auxiliaries-Field Transformer	**High Voltage Current Limiting Fuses**
Auxiliary Supplies	**Thermal and Short-Circuit Protection for all Auxiliary Motors *Branch Circuit Protection***
Armature Supply	**Thermal and Instantaneous Overload Diverter Circuit (Electronic Over-Current Protection)**
Field Supply	**Circuit Breakers**
DC Motors	**Thermal Monitoring of Armature, Field and Bearing Temperatures**

DC ELECTROTORQUE® STATIC POWER CONVERSION

	Hoist^2/Propel	Swing	Crowd/Propel
Continuous Armature Converter Rating @ 600 VDC^1	**2 x 1320 KW**	**1320 KW**	**1320 KW**
15 Sec. Armature Converter Current Rating	**3100 Amp.**	**3100 Amp.**	**3100 Amp.**
Continuous Field	**150 Amp.**	**150 Amp.**	**150 Amp.**

1. Based on outside ambient temperature of 50°C or 122°F
2. Cascaded hoist convertors

STANDARD AUTOMATIC REACTIVE POWER COMPENSATION*

	60 Hz. (7-step)	50 Hz. (6-step)
Switched Steps	**+4725 KVAR Total**	**+4500 KVAR Total**

*Nominal rating at rated capacitor voltage (600 VAC).

MAIN MACHINERY HOUSE
P&H DC FAST-RESPONSE MOTORS*

Hoist Motor (Two K-1690 units used)	H.P. @ 550 Volts D.C. (Continuous)	**Total 2380**
	Peak H.P. Developed	**3400**
	Motor Ventilation	**Blown**
Swing Motor (Two K-558A units used in series)	H.P. @ 550 Volts D.C. (Continuous)	**1000**
	Peak H.P. Developed	**1662**
	Motor Ventilation	**Blown**
Crowd Motor (One K-700 unit used)	H.P. @ 550 Volts D.C. (Continuous)	**720**
	Peak H.P. Developed	**975**
	Motor Ventilation	**Blown**
Propel Motor (Two K-558B units used)	H.P. @ 550 Volts D.C. (Continuous)	**960**
	Peak H.P. Developed	**1441**
	Motor Ventilation	**Blown**

*Specifically designed for Electrotorque® system.

AUXILIARY MOTORS*

Dipper Trip (Two used)	**Each 10 H.P.**
Hoist Motor Blowers (Two used)	**Each 20 H.P.**
Crowd Motor Blower	**15 H.P.**
Propel Motor Blowers (Two used)	**Each 7.5 H.P.**
Swing Motor Blowers (Two used)	**Each 7.5 H.P.**
Converter Blowers (Two used)	**Each 2 H.P.**
RPC Blowers (Three used)	**Each 2 H.P.**
Control Cabinet Blower	**0.33 H.P.**
Machinery Cab Blowers (Two used)	**Each 30 H.P.**
Fresh Air Blower (Operator's Compartment and Electronics Room)**	**0.75 H.P.**
Upper Lube Pump Motor, Hoist	**1 H.P.**
Air Compressor Motor	**30 H.P.**

* Horsepower shown are for 60Hz operation -- may vary for 50 Hz. operation.
** Fresh air blower supplied only if air conditioning unit is not installed.

OPERATING STATION

Hoist / Propel - Swing Controller	**Right Joystick**
Crowd / Propel - Horn and Dipper Trip	**Left Joystick**
Propel Steering	**Independent Crawler Control, Joysticks**
◆ Dig -- Propel Mode Transfer ◆ Brake Set -- Hoist, Crowd, Swing ◆ Brake Release -- Hoist, Crowd, Swing ◆ All Brakes Set ◆ System Status - Visual	**Push-Button Panel with Status Lights Directly Interfaced to PLC via Communication Link**
System Status - Alarms	**Audible Alarms with Distinct Tones**
Man-Machine Interface with touch screen for fault read-out, shovel and system status and limit setting.	
Console Illumination (Dimmable)	**Panel Lights**
Operator's Seat, Joysticks and Footrest	**Adjustable**

CABLE DATA

	Type	Size	Length
Hoist (2 required)	**14**	**2.75" 70 mm**	***380' 115.8 m**
Boom Suspension (4 required)	**18**	**4.38" 111 mm**	****63' 2" 19.25 m**
Dipper Trip - Electric	**18**	**0.75" 19 mm**	**70' 21.34 m**

* With ferrule beckets ** 45° boom angle

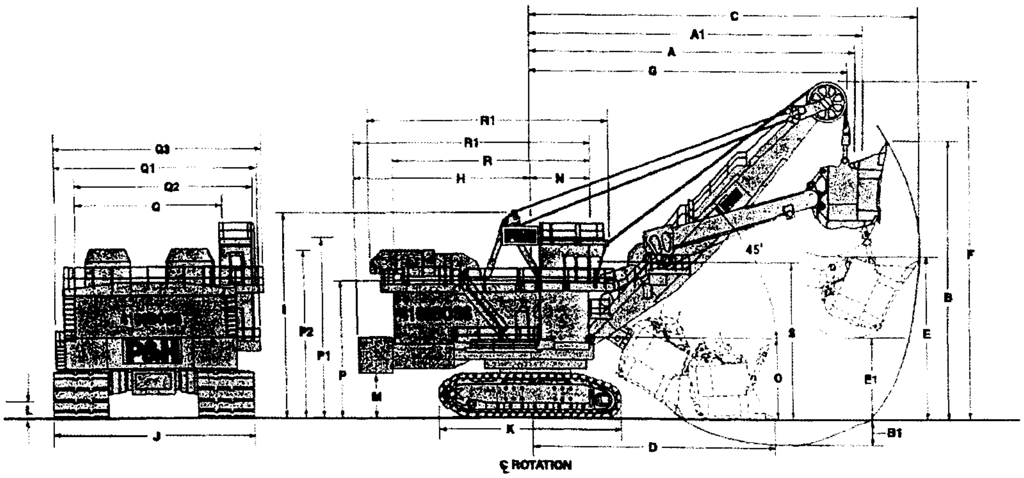
LUBRICATION SYSTEM

Type	**Centralized, Dual Line, Programmable From GUI**
Grease Reservoir	**138 gallon / 522 liter**
Open Gear Lube Reservoir	**138 gallon / 522 liter**

P&H 4100BOSS

ELECTROTORQUE PLUS® MINING SHOVEL
DUAL PLANETARY PROPEL & SWING

OPERATING SPECIFICATIONS



CAPACITY

Rated Suspended Load	345,000 lbs.	154,221 kg
Dipper Capacity (nominal)	62 yd³	47.4 m³
Dipper Capacity (range)	40 - 80 yd³	30.6 - 61.2 m³

ATTACHMENT

Boom Angle	45°	45°
Boom Length	70 ft. 0 in.	21.34 m
Effective Dipper Handle Length	35 ft. 0 in.	10.67 m

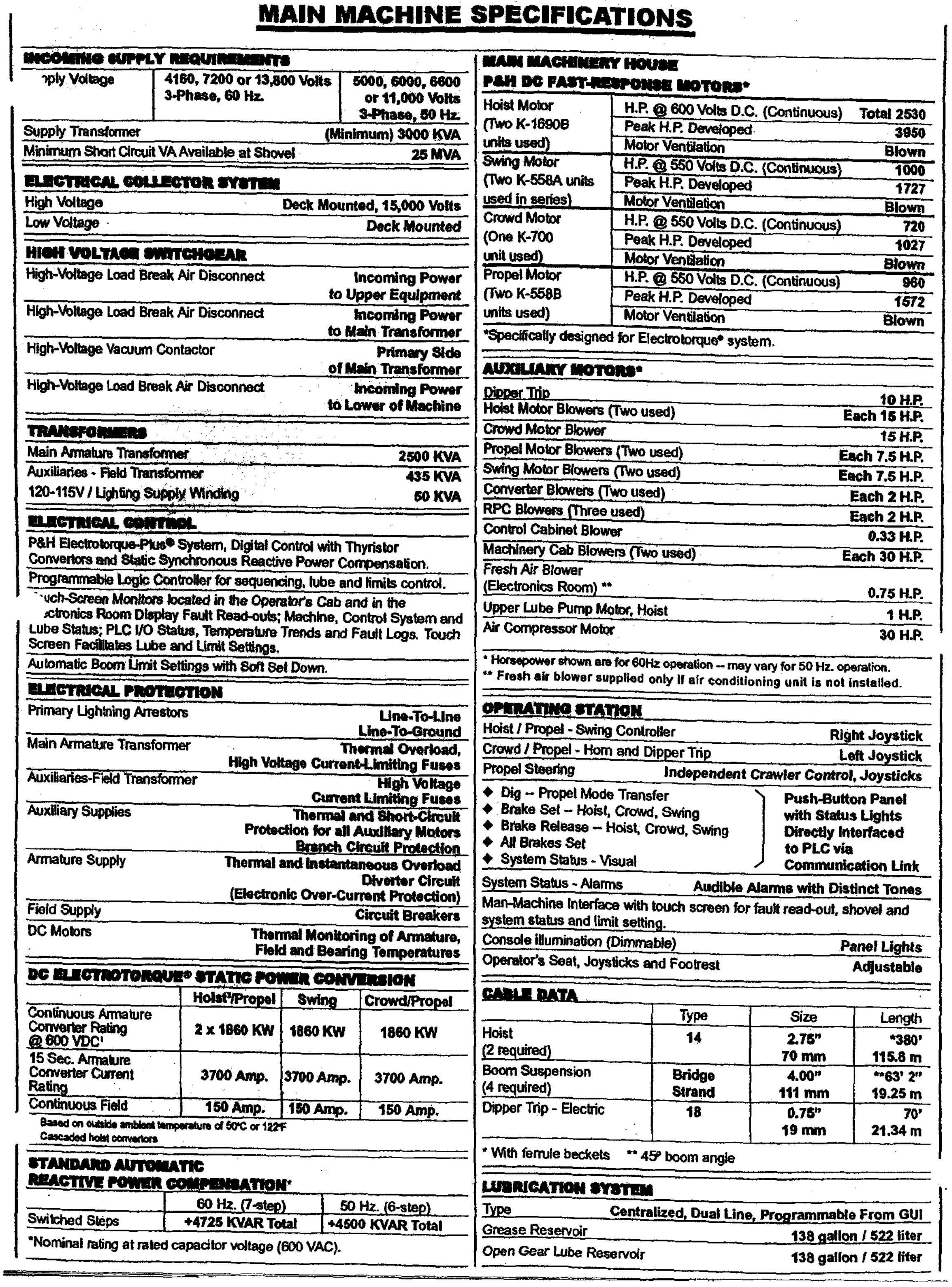
WORKING RANGES

A	Dumping Radius at Max. Lift	66 ft. 10 in.	20.35 m
A1	Dumping Radius (Maximum)	68 ft. 5 in.	20.85 m
B	Height of Cut (Maximum)	56 ft. 8 in.	17.27 m
B1	Depth of Cut (Maximum)	5 ft. 5 in.	1.65 m
C	Digging Radius (Maximum)	81 ft. 4 in.	24.79 m
D	Floor Level Radius	53 ft. 6 in.	16.31 m
E	Dumping Height (Maximum) with Door Open	31 ft. 10 in.	9.70 m
E1	Dumping Height at Maximum Radius with Door Open	16 ft. 4 in.	4.98 m

NOTE: Working ranges A through E1 may vary based on dipper selection. Since each application varies, please consult P&H Mining Equipment for correct choice of dipper capacity.

GENERAL DIMENSIONS

F	Clearance Height of Boom Point Sheave	68 ft. 9 in.	20.96 m
G	Clearance Radius of Boom Point Sheave	66 ft. 7 in.	20.29 m
H	Radius of Counterweight	38 ft. 0 in.	11.58 m
I	Maximum Height Over Gantry	41 ft. 8 in.	12.70 m
J	Overall Width of Crawlers (138" / 3505 mm Shoes)	41 ft. 11 in.	12.78 m
K	Overall Length of Crawlers	38 ft. 0 in.	11.58 m
L	Ground Clearance	2 ft. 7 in.	0.79 m
M	Height – Ground to Bottom of Counterweight	9 ft. 4 in.	2.84 m
N	Center of Rotation to Boom Foot Pin	11 ft. 6 in.	3.51 m
O	Height-Ground to Boom Foot Pin	16 ft. 6 in.	5.03 m
P	Height – Ground to Top of House	27 ft. 9 in.	8.46 m
P1	Height – Ground to Top of Operator Compartment	36 ft. 7 in.	11.15 m
P2	Height – Ground to Top of House Pressurization System	34 ft. 8 in.	10.56 m
Q	Width of House	30 ft. 10 in.	9.40 m
Q1	Width of Left-Hand Catwalk and Stair Platform	42 ft. 2 in.	12.85 m
Q2	Width of House and Operator Compartment	36 ft. 8 in.	11.18 m
Q3	Width of Left-Hand Catwalk and Operator Compartment Catwalk	43 ft. 2 in.	13.16 m
R	Overall Length of House	41 ft. 8 in.	12.70 m
R1	Overall Length of House, Pressurization System and Operator Compartment	50 ft. 0 in.	15.24 m
S	Height - Ground to Operator Eye Level	32 ft. 3 in.	9.83 m



MAIN MACHINE SPECIFICATIONS

INCOMING SUPPLY REQUIREMENTS

pply Voltage	**4160, 7200 or 13,800 Volts 3-Phase, 60 Hz.**	**5000, 6000, 6600 or 11,000 Volts 3-Phase, 50 Hz.**
Supply Transformer		**(Minimum) 3000 KVA**
Minimum Short Circuit VA Available at Shovel		**25 MVA**

ELECTRICAL COLLECTOR SYSTEM

High Voltage	**Deck Mounted, 15,000 Volts**
Low Voltage	***Deck Mounted***

HIGH VOLTAGE SWITCHGEAR

High-Voltage Load Break Air Disconnect	**Incoming Power *to Upper Equipment***
High-Voltage Load Break Air Disconnect	**Incoming Power to Main Transformer**
High-Voltage Vacuum Contactor	**Primary Side of Main Transformer**
High-Voltage Load Break Air Disconnect	**Incoming Power to Lower of Machine**

TRANSFORMERS

Main Armature Transformer	**2500 KVA**
Auxiliaries - Field Transformer	**435 KVA**
120-115V / Lighting Supply Winding	**50 KVA**

ELECTRICAL CONTROL

P&H Electrotorque-Plus® System, Digital Control with Thyristor Convertors and Static Synchronous Reactive Power Compensation.

Programmable Logic Controller for sequencing, lube and limits control.

uch-Screen Monitors located in the Operator's Cab and in the ctronics Room Display Fault Read-outs; Machine, Control System and Lube Status; PLC I/O Status, Temperature Trends and Fault Logs. Touch Screen Facilitates Lube and Limit Settings.

Automatic Boom Limit Settings with Soft Set Down.

ELECTRICAL PROTECTION

Primary Lightning Arrestors	**Line-To-Line Line-To-Ground**
Main Armature Transformer	**Thermal Overload, High Voltage Current-Limiting Fuses**
Auxiliaries-Field Transformer	**High Voltage Current Limiting Fuses**
Auxiliary Supplies	**Thermal and Short-Circuit Protection for all Auxiliary Motors Branch Circuit Protection**
Armature Supply	**Thermal and Instantaneous Overload Diverter Circuit (Electronic Over-Current Protection)**
Field Supply	**Circuit Breakers**
DC Motors	**Thermal Monitoring of Armature, Field and Bearing Temperatures**

DC ELECTROTORQUE® STATIC POWER CONVERSION

	Hoist[2]/Propel	Swing	Crowd/Propel
Continuous Armature Converter Rating @ 600 VDC[1]	**2 x 1860 KW**	**1860 KW**	**1860 KW**
15 Sec. Armature Converter Current Rating	**3700 Amp.**	**3700 Amp.**	**3700 Amp.**
Continuous Field	**150 Amp.**	**150 Amp.**	**150 Amp.**

Based on outside ambient temperature of 50°C or 122°F

Cascaded hoist convertors

STANDARD AUTOMATIC REACTIVE POWER COMPENSATION*

	60 Hz. (7-step)	50 Hz. (6-step)
Switched Steps	**+4725 KVAR Total**	**+4500 KVAR Total**

*Nominal rating at rated capacitor voltage (600 VAC).

MAIN MACHINERY HOUSE

P&H DC FAST-RESPONSE MOTORS*

Hoist Motor (Two K-1690B units used)	H.P. @ 600 Volts D.C. (Continuous)	**Total 2530**
	Peak H.P. Developed	**3950**
	Motor Ventilation	**Blown**
Swing Motor (Two K-558A units used in series)	H.P. @ 550 Volts D.C. (Continuous)	**1000**
	Peak H.P. Developed	**1727**
	Motor Ventilation	**Blown**
Crowd Motor (One K-700 unit used)	H.P. @ 550 Volts D.C. (Continuous)	**720**
	Peak H.P. Developed	**1027**
	Motor Ventilation	**Blown**
Propel Motor (Two K-558B units used)	H.P. @ 550 Volts D.C. (Continuous)	**960**
	Peak H.P. Developed	**1572**
	Motor Ventilation	**Blown**

*Specifically designed for Electrotorque® system.

AUXILIARY MOTORS*

Dipper Trip	**10 H.P.**
Hoist Motor Blowers (Two used)	**Each 15 H.P.**
Crowd Motor Blower	**15 H.P.**
Propel Motor Blowers (Two used)	**Each 7.5 H.P.**
Swing Motor Blowers (Two used)	**Each 7.5 H.P.**
Converter Blowers (Two used)	**Each 2 H.P.**
RPC Blowers (Three used)	**Each 2 H.P.**
Control Cabinet Blower	**0.33 H.P.**
Machinery Cab Blowers (Two used)	**Each 30 H.P.**
Fresh Air Blower (Electronics Room) **	**0.75 H.P.**
Upper Lube Pump Motor, Hoist	**1 H.P.**
Air Compressor Motor	**30 H.P.**

* Horsepower shown are for 60Hz operation -- may vary for 50 Hz. operation.

** Fresh air blower supplied only if air conditioning unit is not installed.

OPERATING STATION

Hoist / Propel - Swing Controller	**Right Joystick**
Crowd / Propel - Horn and Dipper Trip	**Left Joystick**
Propel Steering	***Independent Crawler Control, Joysticks***
◆ Dig -- Propel Mode Transfer ◆ Brake Set -- Hoist, Crowd, Swing ◆ Brake Release -- Hoist, Crowd, Swing ◆ All Brakes Set ◆ System Status - Visual	**Push-Button Panel with Status Lights Directly Interfaced to PLC via Communication Link**
System Status - Alarms	**Audible Alarms with Distinct Tones**

Man-Machine Interface with touch screen for fault read-out, shovel and system status and limit setting.

Console illumination (Dimmable)	**Panel Lights**
Operator's Seat, Joysticks and Footrest	**Adjustable**

CABLE DATA

	Type	Size	Length
Hoist (2 required)	**14**	**2.75" 70 mm**	***380' 115.8 m**
Boom Suspension (4 required)	**Bridge Strand**	**4.00" 111 mm**	****63' 2" 19.25 m**
Dipper Trip - Electric	**18**	**0.75" 19 mm**	**70' 21.34 m**

* With ferrule beckets ** 45° boom angle

LUBRICATION SYSTEM

Type	**Centralized, Dual Line, Programmable From GUI**
Grease Reservoir	**138 gallon / 522 liter**
Open Gear Lube Reservoir	**138 gallon / 522 liter**

APPENDIX B - PAST EMPIRICAL DIGGABILITY STUDIES

Empirical diggability assessment methods use field observations and/or laboratory measurements of the material physical characteristics. Various empirical diggability studies are reviewed and their usefulness to oil sands mining is discussed.

Rockmass Classification Systems

Rock mass classification systems and measurements of rock physical properties have been used in the past to develop various empirical diggability classification systems. Quantifiable ratings are assigned to ground parameters depending on their degree of influence on diggability. Individual parameter ratings are combined and the resultant index reflects the ground diggability. Empirical diggability assessment methods based on field observations and/or laboratory measurements of the material physical characteristics are reviewed by Hadjigeorgiou and Scoble (1988), Hadjigeorgiou and Poulin (1998) and Patnayak and Tannant (2004). The different diggability classification systems that have been developed are summarized in Table B-1. Most of them are site specific. Unlike rock, the diggability of oil sands would be controlled by various other parameters such as depositional environment, water content, bitumen content, density, particle size distribution, indurated sediments, temperature, depth of frost penetration, etc. Therefore, the classification systems listed in Table B-1 cannot be used for oil sands excavation.

Table B-1 Diggability based on geotechnical parameters (modified from Hadjigeorgiou and Poulin, 1998)

	Franklin et al.	Weaver	Read et al.	Kirsten	Scoble & Muftuoglou	Singh et al.	Smith	Scoble et al.	Karpuz	Hadjigeorgiou & Poulin
Uniaxial compressive strength	√	√		√	√		√		√	
Point load strength	√		√		√	√		√		√
Schmidt hammer									√	
Tensile strength						√				
Number of joint sets				√						
RQD				√						
Volumetric joint count				√				√		√
Joint roughness				√						
Joint alteration				√						
Joint orientation		√	√	√			√	√		
Bedding spacing					√					
Joint spacing	√	√	√	√	√	√	√		√	
Joint continuity		√	√				√			
Joint gouge		√	√				√			
Weathering	√	√	√		√	√		√	√	√
Seismic velocity		√	√			√			√	
Abrasivity						√				
Relative ground structure										√

O&K Wedge Penetration Test

The O&K wedge penetration test was originally developed by the Lubeck Works of Orienstein and Koppel to determine cutting resistance of a bucket knife or tooth in the laboratory (Bolukbasi et al., 1991a). The wedge penetration test is carried out on 150 mm cubic specimens or on cylindrical specimens having 150 mm diameter and height. The wedge, which is 65 mm long with a 34° apex angle, is placed centrally on the specimen and loaded until the specimen splits. Three ways for calculating the cutting resistance have been used. The length of the cutting edge, the depth of the cut, and the area of the cut are measured and the cutting resistance is calculated as the breaking force per length of cutting edge, or per depth of cut, or per area of cut.

Many researchers have used this test to develop ground diggability classification systems for bucket wheel excavators (Krzanowski, 1984; Krzanowski and Golosinski, 1987; Wade and Clark, 1989; Bolukbasi et al., 1991b). The published diggability classification systems are summarized in Table B-2. The classification systems based on wedge tests are site specific (usually coal and other soft rock overburden materials) and were developed primarily for design of bucket wheel excavators. Therefore, the classification systems listed in Table B-2 should not be used for shovel excavation in oil sands mining.

O&K wedge penetration tests on unconfined cylindrical specimens of oil sands at Syncrude have been reported (Patnayak and Tannant, 2004). Samples sizes were 150 mm in diameter and 150 mm in height. Tests carried out on such small size unconfined specimens will have end effects and therefore, the test results could be misleading. The oil sands sample may fail in a manner that is not truly representative of actual failure mechanisms during digging. Therefore, results based on extrapolation of laboratory wedge penetration test data may not be suitable for actual mining operations.

Table B-2 Diggability based on O&K wedge penetration test (after Bolukbasi et al., 1991a)

Class	Author	Ground type	CR* (MPa)	Author	Ground type	CR* (MPa)
Easy	Kozlowski (1980)	-	0.00-0.17	O'Regan et al. (1987)	Overburden	0.15-0.45
Diggable			0.17-0.36			0.45-0.60
Hard			0.36-0.54			0.60-0.75
Marginal			0.54-0.80			0.75-1.00
Undiggable			0.80			>1.00
Easy	Weise (1981)	Coal	-	Rodenberg (1987)	Coal & Overburden	-
Diggable			0.00-1.00			1.10
Hard			1.00-1.50			1.10-2.30
Marginal			1.50-2.40			-
Undiggable			>2.40			2.30
Easy	Krzanowski & Golosinski (1987)	Overburden	0.00-0.27	Wade & Clark (1989)	Coal	0.00-0.60
Diggable			0.27-0.90			0.60-1.10
Hard			0.90-1.85			1.10-1.40
Marginal			-			1.40-1.80
Undiggable			>1.85			>1.80

* Cutting resistance from O&K wedge tests using breaking force per area of cut

Soil Rippability Studies

Seismic measurement techniques have been used in the past for determining ground rippability. Tart (1983) reported that frozen gravel deposits are usually rippable when seismic velocities are under about 2,100 m/s. Rippability charts have been developed based on field seismic velocity measurements for a variety of materials such as topsoil, clay, glacial till, igneous rocks, sedimentary rocks, metamorphic rocks, minerals and ores (Caterpillar, 2002). These charts are useful as an indicator of ripping ability and productivity of different rippers. A rippability chart for a D11 dozer shows that for a sedimentary deposit, ripping is possible if the seismic velocity is below 2,900 m/s and marginal if between 2,900 m/s and 3,500 m/s (Figure B-1). These charts although are useful for soil ripping, cannot be used for shovel excavation in oil sands mining.

Measurements of p-wave velocity by Pullin et al. (1987) at Gregoire Lake indicate that the McMurray Formation has a seismic velocity of about 2,400 m/s at in situ conditions. P-wave measurements by Lines et al. (1990) on oil sands cores at 25°C showed that the seismic velocity in oil sands is approximately 2,800 m/s. Comparing these values in

Figure B-1, it appears that ripping could be effective in oil sands. However, ripping is mainly done in the winter, when the ground is relatively harder and thus p-wave velocities are expected to be higher. Therefore, the rippability of the oil sands could be classified as marginal in winter months.

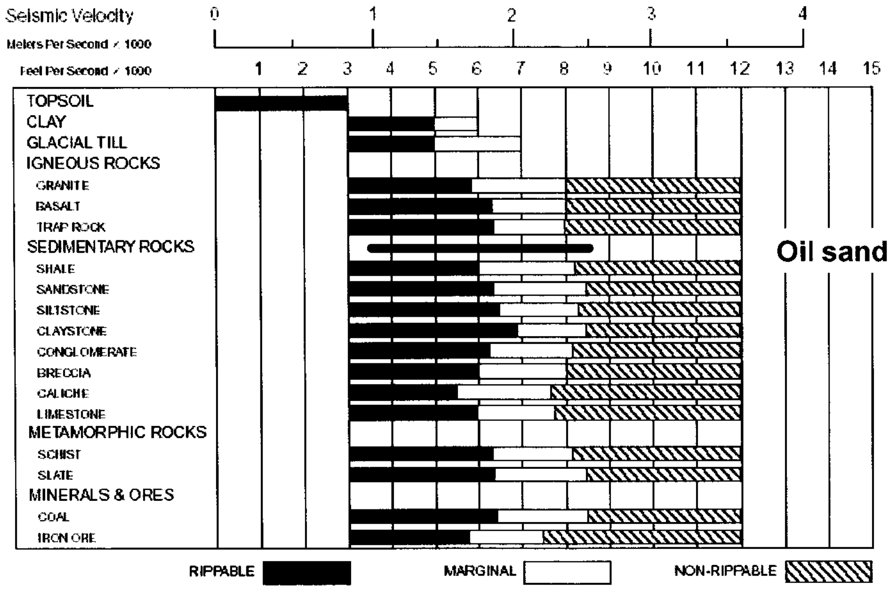


Figure B-1 D11R rippability chart (modified from Caterpillar, 2002)

Attempts have been made to evaluate the performance of other excavating equipment in terms of seismic velocity (Figure B-2). It appears that most earth moving equipment operates most effectively when the seismic velocity of the ground is less than 1000 m/s and will not function above 1800 m/s.

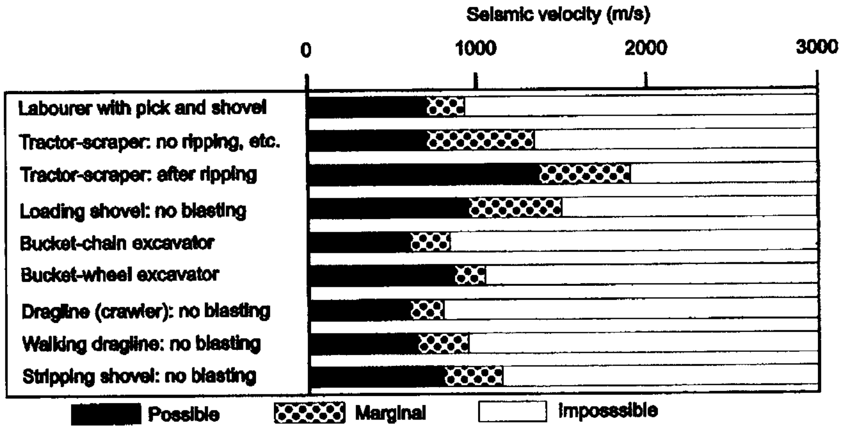


Figure B-2 Diggability chart (after Bell, 2004)

APPENDIX C – PROGRAM TO IDENTIFY DIG CYCLES AND ESTIMATE PERFORMANCE INDICATORS

```
Option Explicit

Public Sub runMe()
 fillData
 findDigCycles
 calculateDigParameters
End Sub

Private Sub fillData()
 Dim FilledDataSheet As Worksheet, inputDataSheet As Worksheet
 Dim i As Long, j As Long, k As Long, numDataPoints As Long, missingRows As
Integer
 Dim x, y As Variant
 Dim m As Variant
 Dim heading1 As String, heading2 As String, heading3 As String, heading4 As String,
heading5 As String
 Dim hoistEnergy, crowdEnergy, hoistPower, crowdPower, varHoistPower,
varCrowdPower
 Dim varTime As Date
 Dim varScaledHoistArmatureCurrent As Double
 Dim varScaledHoistArmatureVolt As Double, varScaledCrowdArmatureCurrent As
Double, varScaledCrowdArmatureVolt As Double
 Dim varScaledHoistArmatureCurrentNext As Double,
varScaledHoistArmatureVoltNext As Double
 Dim varScaledHoistFieldCurrentNext As Double,
varScaledCrowdArmatureCurrentNext As Double
 Dim varScaledCrowdArmatureVoltNext As Double
 Dim varScaledHoistFieldCurrent As Double, varScaledSwingArmatureCurrent As
Double
 Dim varScaledSwingArmatureVolt As Double, varSwingArmatureCurrent As Double
 Dim varSwingFieldCurrent As Double, varScaledCrowdFieldCurrent As Double

 Set inputDataSheet = Sheets("Interpolated 10 Sens")
 On Error Resume Next
 Set FilledDataSheet = Worksheets("Filled Data")
 If Err.Number <> 0 Then
   Err.Clear
   Set FilledDataSheet = Sheets.Add(after:=inputDataSheet)
   FilledDataSheet.Name = "Filled Data"
 End If
 FilledDataSheet.Range("A:IV").ClearContents
 On Error GoTo 0
```

```
With inputDataSheet.Range("A1:K1")
  .Font.Bold = True
  .Interior.ColorIndex = 36
  .WrapText = True
  .HorizontalAlignment = xlHAlignCenter
  .VerticalAlignment = xlVAlignCenter
End With

j = inputDataSheet.Range("A1:K1").Count
With inputDataSheet.Range("A1:K1")
  For i = 1 To j
    FilledDataSheet.Cells(1, i) = .Cells(i)
  Next i
End With

FilledDataSheet.Columns(1).NumberFormat = "dd-mmm-yyyy hh:mm:ss"

i = 2

varTime = inputDataSheet.Cells(i, 1)
varScaledHoistArmatureCurrent = inputDataSheet.Cells(i, 2)
varScaledHoistArmatureVolt = inputDataSheet.Cells(i, 3)
varScaledHoistFieldCurrent = inputDataSheet.Cells(i, 4)
varScaledSwingArmatureCurrent = inputDataSheet.Cells(i, 5)
varScaledSwingArmatureVolt = inputDataSheet.Cells(i, 6)
varSwingArmatureCurrent = inputDataSheet.Cells(i, 7)
varSwingFieldCurrent = inputDataSheet.Cells(i, 8)
varScaledCrowdArmatureCurrent = inputDataSheet.Cells(i, 9)
varScaledCrowdArmatureVolt = inputDataSheet.Cells(i, 10)
varScaledCrowdFieldCurrent = inputDataSheet.Cells(i, 11)

j = 2

FilledDataSheet.Cells(j, 1) = varTime
FilledDataSheet.Cells(j, 2) = varScaledHoistArmatureCurrent
FilledDataSheet.Cells(j, 3) = varScaledHoistArmatureVolt
FilledDataSheet.Cells(j, 4) = varScaledHoistFieldCurrent
FilledDataSheet.Cells(j, 5) = varScaledSwingArmatureCurrent
FilledDataSheet.Cells(j, 6) = varScaledSwingArmatureVolt
FilledDataSheet.Cells(j, 7) = varSwingArmatureCurrent
FilledDataSheet.Cells(j, 8) = varSwingFieldCurrent
FilledDataSheet.Cells(j, 9) = varScaledCrowdArmatureCurrent
FilledDataSheet.Cells(j, 10) = varScaledCrowdArmatureVolt
FilledDataSheet.Cells(j, 11) = varScaledCrowdFieldCurrent

j = j + 1
```

```
i = i + 1

Do While ((IsEmpty(inputDataSheet.Cells(i + 1, 1)) = False))

 'm is time interval between two readings

 m = Second(inputDataSheet.Cells(i, 1) - inputDataSheet.Cells(i - 1, 1))

 If (m = 1) Then

  varTime = inputDataSheet.Cells(i, 1)
  varScaledHoistArmatureCurrent = inputDataSheet.Cells(i, 2)
  varScaledHoistArmatureVolt = inputDataSheet.Cells(i, 3)
  varScaledHoistFieldCurrent = inputDataSheet.Cells(i, 4)
  varScaledSwingArmatureCurrent = inputDataSheet.Cells(i, 5)
  varScaledSwingArmatureVolt = inputDataSheet.Cells(i, 6)
  varSwingArmatureCurrent = inputDataSheet.Cells(i, 7)
  varSwingFieldCurrent = inputDataSheet.Cells(i, 8)
  varScaledCrowdArmatureCurrent = inputDataSheet.Cells(i, 9)
  varScaledCrowdArmatureVolt = inputDataSheet.Cells(i, 10)
  varScaledCrowdFieldCurrent = inputDataSheet.Cells(i, 11)

  FilledDataSheet.Cells(j, 1) = varTime
  FilledDataSheet.Cells(j, 2) = varScaledHoistArmatureCurrent
  FilledDataSheet.Cells(j, 3) = varScaledHoistArmatureVolt
  FilledDataSheet.Cells(j, 4) = varScaledHoistFieldCurrent
  FilledDataSheet.Cells(j, 5) = varScaledSwingArmatureCurrent
  FilledDataSheet.Cells(j, 6) = varScaledSwingArmatureVolt
  FilledDataSheet.Cells(j, 7) = varSwingArmatureCurrent
  FilledDataSheet.Cells(j, 8) = varSwingFieldCurrent
  FilledDataSheet.Cells(j, 9) = varScaledCrowdArmatureCurrent
  FilledDataSheet.Cells(j, 10) = varScaledCrowdArmatureVolt
  FilledDataSheet.Cells(j, 11) = varScaledCrowdFieldCurrent

  j = j + 1

 Else

  missingRows = m - 1

  For k = 1 To missingRows

   varTime = DateAdd("s", 1, varTime)
```

```
 varScaledHoistArmatureCurrent = inputDataSheet.Cells(i - 1, 2)
 varScaledHoistArmatureVolt = inputDataSheet.Cells(i - 1, 3)
 varScaledHoistFieldCurrent = inputDataSheet.Cells(i - 1, 4)
 varScaledSwingArmatureCurrent = inputDataSheet.Cells(i - 1, 5)
 varScaledSwingArmatureVolt = inputDataSheet.Cells(i - 1, 6)
 varSwingArmatureCurrent = inputDataSheet.Cells(i - 1, 7)
 varSwingFieldCurrent = inputDataSheet.Cells(i - 1, 8)
 varScaledCrowdArmatureCurrent = inputDataSheet.Cells(i - 1, 9)
 varScaledCrowdArmatureVolt = inputDataSheet.Cells(i - 1, 10)
 varScaledCrowdFieldCurrent = inputDataSheet.Cells(i - 1, 11)

 FilledDataSheet.Cells(j, 1) = varTime
 FilledDataSheet.Cells(j, 2) = varScaledHoistArmatureCurrent
 FilledDataSheet.Cells(j, 3) = varScaledHoistArmatureVolt
 FilledDataSheet.Cells(j, 4) = varScaledHoistFieldCurrent
 FilledDataSheet.Cells(j, 5) = varScaledSwingArmatureCurrent
 FilledDataSheet.Cells(j, 6) = varScaledSwingArmatureVolt
 FilledDataSheet.Cells(j, 7) = varSwingArmatureCurrent
 FilledDataSheet.Cells(j, 8) = varSwingFieldCurrent
 FilledDataSheet.Cells(j, 9) = varScaledCrowdArmatureCurrent
 FilledDataSheet.Cells(j, 10) = varScaledCrowdArmatureVolt
 FilledDataSheet.Cells(j, 11) = varScaledCrowdFieldCurrent

 j = j + 1

Next k

varTime = inputDataSheet.Cells(i, 1)
varScaledHoistArmatureCurrent = inputDataSheet.Cells(i, 2)
varScaledHoistArmatureVolt = inputDataSheet.Cells(i, 3)
varScaledHoistFieldCurrent = inputDataSheet.Cells(i, 4)
varScaledSwingArmatureCurrent = inputDataSheet.Cells(i, 5)
varScaledSwingArmatureVolt = inputDataSheet.Cells(i, 6)
varSwingArmatureCurrent = inputDataSheet.Cells(i, 7)
varSwingFieldCurrent = inputDataSheet.Cells(i, 8)
varScaledCrowdArmatureCurrent = inputDataSheet.Cells(i, 9)
varScaledCrowdArmatureVolt = inputDataSheet.Cells(i, 10)
varScaledCrowdFieldCurrent = inputDataSheet.Cells(i, 11)

FilledDataSheet.Cells(j, 1) = varTime
FilledDataSheet.Cells(j, 2) = varScaledHoistArmatureCurrent
FilledDataSheet.Cells(j, 3) = varScaledHoistArmatureVolt
FilledDataSheet.Cells(j, 4) = varScaledHoistFieldCurrent
FilledDataSheet.Cells(j, 5) = varScaledSwingArmatureCurrent
FilledDataSheet.Cells(j, 6) = varScaledSwingArmatureVolt
FilledDataSheet.Cells(j, 7) = varSwingArmatureCurrent
```

```
   FilledDataSheet.Cells(j, 8) = varSwingFieldCurrent
   FilledDataSheet.Cells(j, 9) = varScaledCrowdArmatureCurrent
   FilledDataSheet.Cells(j, 10) = varScaledCrowdArmatureVolt
   FilledDataSheet.Cells(j, 11) = varScaledCrowdFieldCurrent

   j = j + 1

  End If

  i = i + 1
 Loop

 FilledDataSheet.Rows(1).Font.Bold = True
 FilledDataSheet.Columns("A:K").AutoFit

End Sub

Private Sub findDigCycles() 'Module to find DIG Cycle

 Dim DigCyclesSheet As Worksheet, FilledDataSheet As Worksheet, inputDataSheet As
Worksheet
 Dim i As Long, j As Long, k As Long, numDataPoints As Long, missingRows As
Integer
 Dim x, y As Variant
 Dim m As Variant
 Dim heading1 As String, heading2 As String, heading3 As String, heading4 As String,
heading5 As String
 Dim hoistEnergy As Double, crowdEnergy As Double, hoistPower As Double,
crowdPower As Double
 Dim varHoistPower As Double, varCrowdPower As Double
 Dim varTime As Date
 Dim varScaledHoistArmatureCurrent As Double, varScaledHoistFieldCurrent As
Double
 Dim varScaledHoistArmatureVolt As Double, varScaledCrowdArmatureCurrent As
Double
 Dim varScaledCrowdArmatureVolt As Double
 Dim varScaledHoistArmatureCurrentNext As Double,
varScaledHoistArmatureVoltNext As Double
 Dim varScaledHoistFieldCurrentNext As Double,
varScaledCrowdArmatureCurrentNext As Double
 Dim varScaledCrowdArmatureVoltNext As Double
 Dim varTimeNext As Date

 Set inputDataSheet = Worksheets("Interpolated 10 Sens")
 Set FilledDataSheet = Sheets("Filled Data")
```

```
On Error Resume Next
Set DigCyclesSheet = Worksheets("Dig Cycles")
If Err.Number <> 0 Then
  Err.Clear
  Set DigCyclesSheet = Sheets.Add(after:=FilledDataSheet)
  DigCyclesSheet.Name = "Dig Cycles"
End If
DigCyclesSheet.Range("A:IV").ClearContents
On Error GoTo 0

DigCyclesSheet.Columns(1).NumberFormat = "dd-mmm-yyyy hh:mm:ss"

i = 1

heading1 = FilledDataSheet.Cells(i, 1)
heading2 = FilledDataSheet.Cells(i, 2)
heading3 = FilledDataSheet.Cells(i, 3)
heading4 = FilledDataSheet.Cells(i, 9)
heading5 = FilledDataSheet.Cells(i, 10)

j = 1

DigCyclesSheet.Cells(j, 1) = heading1
DigCyclesSheet.Cells(j, 2) = heading2
DigCyclesSheet.Cells(j, 3) = heading3
DigCyclesSheet.Cells(j, 4) = heading4
DigCyclesSheet.Cells(j, 5) = heading5

i = i + 1

varTime = FilledDataSheet.Cells(i, 1)
varScaledHoistArmatureCurrent = FilledDataSheet.Cells(i, 2)
varScaledHoistArmatureVolt = FilledDataSheet.Cells(i, 3)
varScaledHoistFieldCurrent = FilledDataSheet.Cells(i, 4)
varScaledCrowdArmatureCurrent = FilledDataSheet.Cells(i, 9)
varScaledCrowdArmatureVolt = FilledDataSheet.Cells(i, 10)

varScaledHoistArmatureCurrentNext = FilledDataSheet.Cells(i + 1, 2)
varScaledHoistArmatureVoltNext = FilledDataSheet.Cells(i + 1, 3)
varScaledHoistFieldCurrentNext = FilledDataSheet.Cells(i + 1, 4)
varScaledCrowdArmatureCurrentNext = FilledDataSheet.Cells(i + 1, 9)
varScaledCrowdArmatureVoltNext = FilledDataSheet.Cells(i + 1, 10)

j = j + 1

Do While (IsEmpty(FilledDataSheet.Cells(i + 1, 1)) = False)
```

```
 If (varScaledHoistFieldCurrent > 10) Then

 'Check hoist armature volt to find begin dig

  If (varScaledHoistArmatureVolt <= -200 _
     And (varScaledHoistArmatureVoltNext - varScaledHoistArmatureVolt > 200) _
     And (varScaledHoistArmatureCurrentNext > 0) _
     And (varScaledHoistArmatureCurrent <= 1000 _
     Or varScaledHoistArmatureCurrentNext <= 1000)) Then    'changes made after
Jeremy's explanation: And (varScaledHoistArmatureCurrent > 0)

   'Check hoist armature current to find end dig

      k = 1

   While (k = 1 And IsEmpty(inputDataSheet.Cells(i + 1, 1)) = False And _
        (varScaledHoistArmatureCurrentNext >= 200 And k <> 0) _
        Or (varScaledHoistArmatureCurrentNext >= varScaledHoistArmatureCurrent
And k <> 0) _
        Or (varScaledHoistArmatureCurrentNext > 2600 And k <> 0) _
        Or (varScaledHoistArmatureCurrentNext > 1500 And
varScaledCrowdArmatureVoltNext > -150 And _
           varScaledCrowdArmatureCurrentNext > 900 And k <> 0) _
        Or (FilledDataSheet.Cells(i + 2, 2) > varScaledHoistArmatureCurrent And k <>
0) _
        Or (FilledDataSheet.Cells(i + 3, 2) > varScaledHoistArmatureCurrent And k <>
0) _
        Or (FilledDataSheet.Cells(i + 4, 2) > varScaledHoistArmatureCurrent And k <>
0) _
        Or (FilledDataSheet.Cells(i + 5, 2) > varScaledHoistArmatureCurrent And k <>
0) _
        Or (FilledDataSheet.Cells(i + 6, 2) > varScaledHoistArmatureCurrent And k <>
0) _
        Or (FilledDataSheet.Cells(i + 2, 2) > 2000 And
varScaledCrowdArmatureVoltNext > -150 And _
           varScaledCrowdArmatureCurrentNext > 900 And k <> 0) _
        Or (FilledDataSheet.Cells(i + 3, 2) > 2000 And
varScaledCrowdArmatureVoltNext > -150 And _
           varScaledCrowdArmatureCurrentNext > 900 And k <> 0) _
        Or (FilledDataSheet.Cells(i + 4, 2) > 2000 And
varScaledCrowdArmatureVoltNext > -150 And _
           varScaledCrowdArmatureCurrentNext > 900 And k <> 0) _
        Or (FilledDataSheet.Cells(i + 5, 2) > 2000 And
varScaledCrowdArmatureVoltNext > -150 And _
           varScaledCrowdArmatureCurrentNext > 900 And k <> 0) _
```

```
        Or (FilledDataSheet.Cells(i + 6, 2) > 2000 And
varScaledCrowdArmatureVoltNext > -150 And _
          varScaledCrowdArmatureCurrentNext > 900 And k <> 0) _
        Or (varScaledHoistFieldCurrentNext - varScaledHoistFieldCurrent > 50))

      DigCyclesSheet.Cells(j, 1) = varTime
      DigCyclesSheet.Cells(j, 2) = varScaledHoistArmatureCurrent
      DigCyclesSheet.Cells(j, 3) = varScaledHoistArmatureVolt
      DigCyclesSheet.Cells(j, 4) = varScaledCrowdArmatureCurrent
      DigCyclesSheet.Cells(j, 5) = varScaledCrowdArmatureVolt

      j = j + 1

      i = i + 1

      varTime = FilledDataSheet.Cells(i, 1)
      varScaledHoistArmatureCurrent = FilledDataSheet.Cells(i, 2)
      varScaledHoistArmatureVolt = FilledDataSheet.Cells(i, 3)
      varScaledHoistFieldCurrent = FilledDataSheet.Cells(i, 4)
      varScaledCrowdArmatureCurrent = FilledDataSheet.Cells(i, 9)
      varScaledCrowdArmatureVolt = FilledDataSheet.Cells(i, 10)

      varTimeNext = FilledDataSheet.Cells(i + 1, 1)
      varScaledHoistArmatureCurrentNext = FilledDataSheet.Cells(i + 1, 2)
      varScaledHoistArmatureVoltNext = FilledDataSheet.Cells(i + 1, 3)
      varScaledHoistFieldCurrentNext = FilledDataSheet.Cells(i + 1, 4)
      varScaledCrowdArmatureCurrentNext = FilledDataSheet.Cells(i + 1, 9)
      varScaledCrowdArmatureVoltNext = FilledDataSheet.Cells(i + 1, 10)

      k = k + 1

        If ((k > 5 And varScaledHoistArmatureVoltNext < 15) Or _
        (k > 5 And varScaledHoistArmatureCurrentNext < 500) Or _
        (k > 10 And varScaledHoistArmatureCurrent < 1000) Or _
        (varScaledHoistArmatureCurrent < 0) Or _
        (varScaledHoistArmatureCurrentNext < 0)) Then 'changes made after Jeremy's
explanation
       k = 0
      End If
     Wend

     DigCyclesSheet.Cells(j, 1) = varTimeNext
     DigCyclesSheet.Cells(j, 2) = varScaledHoistArmatureCurrentNext
     DigCyclesSheet.Cells(j, 3) = varScaledHoistArmatureVoltNext
     DigCyclesSheet.Cells(j, 4) = varScaledCrowdArmatureCurrentNext
     DigCyclesSheet.Cells(j, 5) = varScaledCrowdArmatureVoltNext
```

```
        Else
          varScaledHoistArmatureCurrent = 0
          varScaledHoistArmatureVolt = 0
          varScaledCrowdArmatureCurrent = 0
          varScaledCrowdArmatureVolt = 0
        End If

      Else
        varScaledHoistArmatureCurrent = 0
        varScaledHoistArmatureVolt = 0
        varScaledCrowdArmatureCurrent = 0
        varScaledCrowdArmatureVolt = 0

      End If

      DigCyclesSheet.Cells(j, 1) = varTime
      DigCyclesSheet.Cells(j, 2) = varScaledHoistArmatureCurrent
      DigCyclesSheet.Cells(j, 3) = varScaledHoistArmatureVolt
      DigCyclesSheet.Cells(j, 4) = varScaledCrowdArmatureCurrent
      DigCyclesSheet.Cells(j, 5) = varScaledCrowdArmatureVolt
      j = j + 1

      i = i + 1
      varTime = FilledDataSheet.Cells(i, 1)
      varScaledHoistArmatureCurrent = FilledDataSheet.Cells(i, 2)
      varScaledHoistArmatureVolt = FilledDataSheet.Cells(i, 3)
      varScaledHoistFieldCurrent = FilledDataSheet.Cells(i, 4)
      varScaledCrowdArmatureCurrent = FilledDataSheet.Cells(i, 9)
      varScaledCrowdArmatureVolt = FilledDataSheet.Cells(i, 10)

      varTimeNext = FilledDataSheet.Cells(i + 1, 1)
      varScaledHoistArmatureCurrentNext = FilledDataSheet.Cells(i + 1, 2)
      varScaledHoistArmatureVoltNext = FilledDataSheet.Cells(i + 1, 3)
      varScaledHoistFieldCurrentNext = FilledDataSheet.Cells(i + 1, 4)
      varScaledCrowdArmatureCurrentNext = FilledDataSheet.Cells(i + 1, 9)
      varScaledCrowdArmatureVoltNext = FilledDataSheet.Cells(i + 1, 10)
    Loop

  With DigCyclesSheet.Range("A1:E1")
    .Font.Bold = True
    .Interior.ColorIndex = 36
    .WrapText = True
    .HorizontalAlignment = xlHAlignCenter
    .VerticalAlignment = xlVAlignCenter
  End With
```

```
DigCyclesSheet.Columns("A:E").AutoFit

End Sub

Private Sub calculateDigParameters() 'Module to calculate Digging Parameters (cycle
time, energy, power)
  Dim DigCyclesSheet As Worksheet, FilledDataSheet As Worksheet,
DigCycleAnalysisSheet As Worksheet
  Dim i As Long, j As Long, k As Long, numDataPoints As Long, missingRows As
Integer
  Dim x, y As Variant
  Dim m As Variant
  Dim heading1 As String, heading2 As String, heading3 As String, heading4 As String,
heading5 As String
  Dim hoistEnergy As Double, crowdEnergy As Double, hoistPower As Double,
crowdPower As Double
  Dim varHoistPower As Double, varCrowdPower As Double
  Dim beginCycleTime As Date, endCycleTime As Date
  Dim hoistArmatureCurrentMax As Double, hoistArmatureVoltageMax As Double,
tTime As Double
  Dim varTime As Date
  Dim varScaledHoistArmatureCurrent As Double, varScaledHoistFieldCurrent As
Double
  Dim varScaledHoistArmatureVolt As Double, varScaledCrowdArmatureCurrent As
Double, varScaledCrowdArmatureVolt As Double
  Dim varScaledHoistArmatureCurrentNext As Double,
varScaledHoistArmatureVoltNext As Double
  Dim varScaledHoistFieldCurrentNext As Double,
varScaledCrowdArmatureCurrentNext As Double
  Dim varScaledCrowdArmatureVoltNext As Double
  Dim varTimeNext As Date

  Dim tempVarScaledHoistArmatureCurrent As Double,
tempVarScaledHoistArmatureVolt As Double
  Dim tempVarScaledCrowdArmatureCurrent As Double,
tempVarScaledHoistArmatureCurrentNext As Double
  Dim tempVarScaledCrowdArmatureVolt As Double,
tempVarScaledHoistArmatureVoltNext As Double
  Dim tempVarScaledCrowdArmatureCurrentNext As Double,
tempVarScaledCrowdArmatureVoltNext As Double
  Dim varHoistPowerNext As Double, varCrowdPowerNext As Double,
hoistArmatureVoltMax As Double
  Dim digCycleTime As Double

  Set DigCyclesSheet = Worksheets("Dig Cycles")
  On Error Resume Next
```

```
Set DigCycleAnalysisSheet = Worksheets("Dig Cycle Analysis")
If Err.Number <> 0 Then
  Err.Clear
  Set DigCycleAnalysisSheet = Sheets.Add(after:=Sheets("Dig Cycles"))

  DigCycleAnalysisSheet.Name = "Dig Cycle Analysis"
End If
On Error GoTo 0
DigCycleAnalysisSheet.Range("A:IV").Clear

i = 1
j = 1

DigCycleAnalysisSheet.Cells(j, 2) = "DIG CYCLE TIME"
DigCycleAnalysisSheet.Cells(j, 3) = "HOIST ENERGY"
DigCycleAnalysisSheet.Cells(j, 4) = "HOIST POWER"
DigCycleAnalysisSheet.Cells(j, 5) = "CROWD ENERGY"
DigCycleAnalysisSheet.Cells(j, 6) = "CROWD POWER"

j = j + 1

i = i + 1

Do While (IsEmpty(DigCyclesSheet.Cells(i + 1, 1)) = False)

  varTime = DigCyclesSheet.Cells(i, 1)
  varScaledHoistArmatureCurrent = DigCyclesSheet.Cells(i, 2)
  varScaledHoistArmatureVolt = DigCyclesSheet.Cells(i, 3)
  varScaledCrowdArmatureCurrent = DigCyclesSheet.Cells(i, 4)
  varScaledCrowdArmatureVolt = DigCyclesSheet.Cells(i, 5)

  varTimeNext = DigCyclesSheet.Cells(i + 1, 1)
  varScaledHoistArmatureCurrentNext = DigCyclesSheet.Cells(i + 1, 2)
  varScaledHoistArmatureVoltNext = DigCyclesSheet.Cells(i + 1, 3)
  varScaledCrowdArmatureCurrentNext = DigCyclesSheet.Cells(i + 1, 4)
  varScaledCrowdArmatureVoltNext = DigCyclesSheet.Cells(i + 1, 5)

varScaledHoistArmatureCurrentNext = 0) Then
  If (varScaledHoistArmatureCurrentNext = 0) Then

        'While (varScaledHoistArmatureCurrent = 0 And
varScaledHoistArmatureCurrentNext = 0)
     While (varScaledHoistArmatureCurrentNext = 0 And
IsEmpty(DigCyclesSheet.Cells(i + 1, 1)) = False)

     i = i + 1
```

```
      varTime = DigCyclesSheet.Cells(i, 1)
      varScaledHoistArmatureCurrent = DigCyclesSheet.Cells(i, 2)
      varScaledHoistArmatureVolt = DigCyclesSheet.Cells(i, 3)
      varScaledCrowdArmatureCurrent = DigCyclesSheet.Cells(i, 4)
      varScaledCrowdArmatureVolt = DigCyclesSheet.Cells(i, 5)

      varTimeNext = DigCyclesSheet.Cells(i + 1, 1)
      varScaledHoistArmatureCurrentNext = DigCyclesSheet.Cells(i + 1, 2)
      varScaledHoistArmatureVoltNext = DigCyclesSheet.Cells(i + 1, 3)
      varScaledCrowdArmatureCurrentNext = DigCyclesSheet.Cells(i + 1, 4)
      varScaledCrowdArmatureVoltNext = DigCyclesSheet.Cells(i + 1, 5)

     Wend

   End If

   If (varScaledHoistArmatureCurrent = 0 And varScaledHoistArmatureCurrentNext <>
0) Then
     beginCycleTime = varTimeNext

     hoistEnergy = 0
     crowdEnergy = 0

     hoistArmatureCurrentMax = DigCyclesSheet.Cells(i + 2, 2)
     hoistArmatureVoltageMax = DigCyclesSheet.Cells(i + 2, 3)

     While (varScaledHoistArmatureCurrentNext <> 0 And
IsEmpty(DigCyclesSheet.Cells(i + 1, 1)) = False)
       i = i + 1

       varTime = DigCyclesSheet.Cells(i, 1)
       varScaledHoistArmatureCurrent = DigCyclesSheet.Cells(i, 2)
       varScaledHoistArmatureVolt = DigCyclesSheet.Cells(i, 3)
       varScaledCrowdArmatureCurrent = DigCyclesSheet.Cells(i, 4)
       varScaledCrowdArmatureVolt = DigCyclesSheet.Cells(i, 5)

       If (varScaledHoistArmatureCurrent < 0) Then
         tempVarScaledHoistArmatureCurrent = 0
       Else
         tempVarScaledHoistArmatureCurrent = varScaledHoistArmatureCurrent
       End If

       If (varScaledHoistArmatureVolt < 0) Then
         tempVarScaledHoistArmatureVolt = 0
       Else
```

```
 tempVarScaledHoistArmatureVolt = varScaledHoistArmatureVolt
End If

If (varScaledCrowdArmatureCurrent < 0) Then
 tempVarScaledCrowdArmatureCurrent = 0
Else
 tempVarScaledCrowdArmatureCurrent = varScaledCrowdArmatureCurrent
End If

If (varScaledCrowdArmatureVolt < 0) Then
 tempVarScaledCrowdArmatureVolt = 0
Else
 tempVarScaledCrowdArmatureVolt = varScaledCrowdArmatureVolt
End If

varHoistPower = tempVarScaledHoistArmatureCurrent *
tempVarScaledHoistArmatureVolt
varCrowdPower = tempVarScaledCrowdArmatureCurrent *
tempVarScaledCrowdArmatureVolt

varTimeNext = DigCyclesSheet.Cells(i + 1, 1)
varScaledHoistArmatureCurrentNext = DigCyclesSheet.Cells(i + 1, 2)
varScaledHoistArmatureVoltNext = DigCyclesSheet.Cells(i + 1, 3)
varScaledCrowdArmatureCurrentNext = DigCyclesSheet.Cells(i + 1, 4)
varScaledCrowdArmatureVoltNext = DigCyclesSheet.Cells(i + 1, 5)

If (varScaledHoistArmatureCurrentNext < 0) Then
 tempVarScaledHoistArmatureCurrentNext = 0
Else
 tempVarScaledHoistArmatureCurrentNext = varScaledHoistArmatureCurrentNext
End If

If (varScaledHoistArmatureVoltNext < 0) Then
 tempVarScaledHoistArmatureVoltNext = 0
Else
 tempVarScaledHoistArmatureVoltNext = varScaledHoistArmatureVoltNext
End If

If (varScaledCrowdArmatureCurrentNext < 0) Then
 tempVarScaledCrowdArmatureCurrentNext = 0
Else
 tempVarScaledCrowdArmatureCurrentNext =
varScaledCrowdArmatureCurrentNext
End If

If (varScaledCrowdArmatureVoltNext < 0) Then
```

```
          tempVarScaledCrowdArmatureVoltNext = 0
        Else
          tempVarScaledCrowdArmatureVoltNext = varScaledCrowdArmatureVoltNext
        End If

        varHoistPowerNext = tempVarScaledHoistArmatureCurrentNext *
tempVarScaledHoistArmatureVoltNext
        varCrowdPowerNext = tempVarScaledCrowdArmatureCurrentNext *
tempVarScaledCrowdArmatureVoltNext

        If (varScaledHoistArmatureCurrentNext <> 0) Then
          tTime = DateDiff("S", varTime, varTimeNext)
          hoistEnergy = hoistEnergy + 0.5 * (tTime) * (varHoistPowerNext +
varHoistPower)
          crowdEnergy = crowdEnergy + 0.5 * (tTime) * (varCrowdPowerNext +
varCrowdPower)
        End If

        If (varScaledHoistArmatureCurrentNext > hoistArmatureCurrentMax) Then
          hoistArmatureCurrentMax = varScaledHoistArmatureCurrentNext
        End If

        If (varScaledHoistArmatureVoltNext > hoistArmatureVoltMax) Then
          hoistArmatureVoltMax = varScaledHoistArmatureVoltNext
        End If

      Wend

      endCycleTime = varTime

      digCycleTime = Second(endCycleTime - beginCycleTime)

      If (digCycleTime >= 6 And digCycleTime <= 25 And hoistArmatureVoltMax > 0
      And hoistArmatureCurrentMax > 1500) Then
        hoistPower = hoistEnergy / digCycleTime
        crowdPower = crowdEnergy / digCycleTime

        DigCycleAnalysisSheet.Cells(j, 1) = beginCycleTime
        DigCycleAnalysisSheet.Cells(j, 2) = digCycleTime
        DigCycleAnalysisSheet.Cells(j, 3) = hoistEnergy
        DigCycleAnalysisSheet.Cells(j, 4) = hoistPower
        DigCycleAnalysisSheet.Cells(j, 5) = crowdEnergy
        DigCycleAnalysisSheet.Cells(j, 6) = crowdPower

      j = j + 1
      End If
```

```
    digCycleTime = 0#
    hoistEnergy = 0#
    hoistPower = 0#
    crowdEnergy = 0#
    crowdPower = 0#
  End If
  i = i + 1
Loop

End Sub
```