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Analysis of Concrete Removal Technologies in Bridge Rehabilitation

By

James P. Merrigan

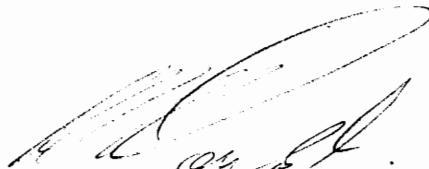
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MASTER OF SCIENCE

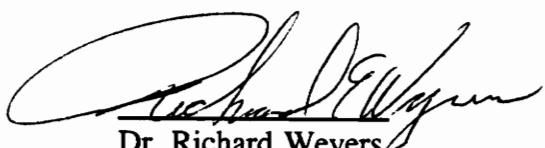
in

Civil Engineering

APPROVED:



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Committee Chairman Dr. M.C. Vorster

(ABSTRACT)

As construction of the nation's interstate highway system nears completion, the emphasis must now be focussed on the rehabilitation of many of the older sections of the system which have undergone damage or deterioration. The efficiency and effectiveness of the concrete removal operation will profoundly affect the outcome of the bridge rehabilitation. Pneumatic breakers, milling machines and hydrodemolition are three concrete removal technologies utilized to remove concrete which has experienced various levels of damage or deterioration.

A general examination of the three technologies is presented in the following five areas: the equipment, the work, production, cost, and quality. The information was primarily obtained through interviews and discussions with persons involved in bridge rehabilitation: contractors, State Highway Agency personnel, and equipment manufacturers and distributors. It is anticipated that the information presented will enable persons involved in the bridge rehabilitation industry to more effectively utilize the technologies discussed.

Acknowledgements

The input and contributions made by the advisory committee greatly aided in the preparation and presentation of this thesis. Dr. Michael Vorster's continual guidance and support throughout my graduate studies and especially as chairman of my advisory committee is evidenced by the quality of this work. Dr. Richard Weyers' knowledge of bridge rehabilitation and concrete deterioration and Dr. Jesus De la Garza's input regarding the format and structure of the work are also appreciated.

The input and effort put forth by Robert Lewis and Tarun Bafna in performing this and related research also greatly contributed to the thesis. I would like to thank my wife, Beth, and my family for their continuing support and encouragement of both my academic and personal pursuits.

Finally, I would like to dedicate this thesis to my father, Larry Merrigan, the Civil Engineer.

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1

Introduction

This thesis presents an examination of concrete removal techniques used in the bridge rehabilitation process. This is accomplished through an analysis of three selected technologies for concrete removal: pneumatic breakers, pavement milling and hydrodemolition. A similar format is used in the evaluation of each method to facilitate a comparison of the areas of interest between the various methods.

The goal of this thesis is to provide persons involved in the bridge repair and rehabilitation industry with a common, unbiased baseline for evaluating the identified methods of concrete removal. It is expected that this evaluation will enable State Highway Agencies (SHAs) and contractors to more efficiently and effectively utilize the methods discussed for bridge rehabilitation work.

The research is being done as a part of the Strategic Highway Research Program (SHRP) research contract C-103 Task 3, "Concrete Removal, Bar Cleaning and Surface Preparation". SHRP is a highly focused, five year research program aimed at attacking practical issues of financial importance in the highway industry.

1.1 Background and Significance of the Problem

In the 1950s the Federal Highway Administration adopted the bare pavement policy to ensure that the nation's major highways would be clear of snow throughout the year. This was accomplished through the application of deicing salts to the roadway to melt the snow. As a result of this liberal salt application there has been an acceleration in the deterioration of concrete bridges.

The chloride ions from the salt permeate the concrete and engage in an electro-chemical reaction with the reinforcing steel. Rust is formed as a by-product of this reaction. The rust takes up approximately six times the volume of the steel, causing tensile stresses to form in the concrete. Cracking occurs in the concrete when the rust induced tensile stresses exceed the tensile strength of the concrete.

At present it is estimated that approximately one third of the nation's half a million bridges are structurally deficient or functionally obsolete. The estimated cost to repair all the damaged bridges is twenty billion dollars and is increasing at an estimated rate of \$500 million a year. This cost includes replacing some bridges as well as rehabilitating those not in need of complete reconstruction.

The traditional method for rehabilitating bridges which have become contaminated or deteriorated by the ingress of chloride ions is to patch the damaged area or to overlay the entire deck with an additional layer of material. Although patching is effective for small areas and overlaying is sufficient as a temporary solution, new methods of bridge rehabilitation must be developed and utilized to effectively repair damaged bridges. This thesis seeks to make a contribution to this endeavor by examining well established and emerging concrete removal technologies.

The primary tool which has been traditionally used in these bridge repair operations is the pneumatic paving breaker. Breakers have been in use since the turn of the century and are a well established and widely accepted construction tool. The primary advantage associated with breakers is the ability to remove small isolated areas of deteriorated concrete from all bridge structural components. However their low production and high dependency on labor make them uneconomical for rehabilitation

projects which require the removal of a large volume of deteriorated or contaminated concrete.

Pavement milling and hydrodemolition are two methods which have been developed for concrete removal on bridge rehabilitation projects. These methods are equipment intensive and capable of attaining very high production rates. However their effectiveness hinges upon them being used in the appropriate situation.

Milling utilizes the impact of numerous cutting teeth mounted on a rotating drum to fracture and remove the concrete. Although this concept has been in practice in the mining industry since the late 1920s, it was not introduced into the road construction industry until the mid 1970s.

Hydrodemolition employs the energy of a highly pressurized water-jet to destroy the concrete bond matrix and thus remove the damaged concrete. The technology was derived from the materials cutting and cleaning industry and although there is some equipment commercially available it is basically still in the developmental stages.

1.2 Research Methodology and Sources of Data

The research began with an investigation of the various methods and equipment used for concrete removal, steel cleaning and surface preparation. From this review it was concluded that pneumatic breakers, milling and hydrodemolition were the technologies most widely utilized for bridge rehabilitation work and therefore represented the area in which improvements would have the greatest potential impact. The remainder of the research and the content of this thesis is dedicated to the examination of these technologies.

As a first step in collecting information on pneumatic breakers and milling machines, a comprehensive literature review was conducted at Virginia Tech's Newman Library in Blacksburg, Virginia. Appropriate subject headings were referenced in scientific and engineering journals to identify articles and publications pertaining to bridge rehabilitation or a particular method of concrete removal being studied. This work built on and expanded a data base of related information developed as part of the SHRP C-103 research.

The major portion of chapter one on hydrodemolition came from a previously prepared thesis entitled "Hydrodemolition for Concrete Removal in Bridge Rehabilitation" by Robert W. Lewis. This work was also done as a part of the SHRP research contract

C-103, task 3. References cited in sections of Lewis' work which appear in this thesis are cited in the bibliography.

The primary source of information for the research for pneumatic breakers and milling machines came from personal discussions and interviews with the people directly involved in the industry: contractors, equipment representatives, and SHA personnel.

Table 1.1 presents a partial list of individuals in these areas who were contacted.

The contractors who use the various methods and equipment provided the majority of the information regarding methods of operation, costs and production rates. They also provided knowledgeable insight into problems associated with the methods and areas of possible improvement. Field visits to jobs in progress provided additional background into operations and procedures for performing bridge rehabilitation work.

Equipment manufacturers and distributors provided information concerning the various models available, the prices of the models and, where applicable, literature was requested. Information was requested and obtained from numerous SHAs both in the U.S. and Canada pertaining to current contract specifications for the concrete removal methods being studied and recommendations for improving these specifications.

Table 1.1 List of Persons Contacted

PERSONNEL CONTACTED

Contractors:

Bob Wingfield/Alan Soltis, Lanford Brothers
Joe Caizzo, BOCA Construction Co.
John Jones, Orders Construction Co.
Al Day, Hill Milling
Mark Polo, Blythe Industries
Pat McKreit, Mid-Atlantic Milling
Dave Reed, Wagman Inc.
Dave Cannon, Swank Assoc. Inc.
Virgil Johnson, Ashbach Constr. Co.
Mike Krissoff, Asphalt Recycling and Reclaiming Assoc.

Equipment:

Roger Lilly, Carter Caterpillar
Jim Patsol, A.E. Finley & Assoc.
Don Durow, Cedarapids Wirtgen
Jay O'Brien, Mitchell Equipment
Jim Reynolds, Dresser/ Karmatsu
Jerry Salemi, Roadtec
Larry Jack, CMI
Dick Lowell, Caterpillar

DOT:

Gary Robeson, WV DOT
Bill Crawford, Nevada DOT
Fred Lucht, Oregon DOT
Stan Penny, Oklahoma DOT

1.3 Outline of the Thesis

The ensuing three chapters will address the selected concrete removal technologies: pneumatic breakers, milling machines, and hydrodemolition, one per chapter. Each chapter, and therefore each method, is discussed in terms of the following five areas:

- 1) The equipment. The first section in each chapter presents a technical description of the equipment being studied. The physical components of the equipment are described as are the principles by which they operate. This section also contains a description of the operating system associated with the method. Support equipment and the number and type of workers required to perform the work are also be discussed.
- 2) The work. The focus of the second section in each chapter is on the characteristics of the work for which the equipment is suited. The scope and complexity of a bridge rehabilitation project varies considerably based primarily on four parameters: The depth of removal, the area of removal, the location of the concrete to be removed and the properties of the material to be removed. These parameters are considered with respect to the advantages and limitations of each method to illustrate how the project environment may affect the ability of a machine to operate at full potential.

- 3) Production. The third section addresses the production rate at which the method is able to remove the material. An instantaneous production rate is first determined based on the maximum rate at which a machine can operate unimpeded. This is followed by an examination of the factors and conditions which will cause a reduction in the instantaneous rate of production either due to limitations of the method or characteristics of the project.
- 4) Costs. The economical aspect of performing concrete removal using each of the methods is examined in the forth section by means of a standardized cost estimating work sheet. The work sheet is broken down into distinct sections which contain inputs for defining the project and determining the estimated cost of performing the work. Each of the parameters is analyzed to illustrate the affect on the estimated cost. A sensitivity analysis comparing the unit cost of the concrete removal operation to the quantity of removal is generated from the work sheet for each method.
- 5) Quality. The fifth and final section of chapters two, three and four considers the issue of managing and controlling quality. Although the concrete removal operation represents only a portion of the bridge rehabilitation process, the quality of the work performed is paramount to the quality of the project as a whole. This section addresses the aspects of the operation in which quality

management is critical, such as removal in the vicinity of the reinforcing steel and the condition of the residual concrete. The role of the specifications in assuring that the necessary quality is achieved and in dictating the terms of measurement and payment is also discussed.

The fifth and concluding chapter of the thesis reviews and summarizes the information developed in the preceding three chapters. The information is graphically presented by means of a matrix which has the three technologies of concrete removal on one axis and the parameters for which each technology is evaluated on the other and a series of figures which depict the primary characteristics of each technology as it relates to the particular parameter being considered. The characteristics of the project which will impact the effectiveness and utilization of a particular technology are also discussed as is the process of matching the technology to a particular project.

2

Pneumatic Breakers as a Concrete Removal Technology

Hand-held breakers are widely used and well established tools for removing contaminated and deteriorated concrete. Their light weight and excellent maneuverability make them ideally suited to remove damaged concrete from small, isolated areas and from vertical and overhead surfaces on all bridge structural elements. This chapter presents an examination of pneumatic breakers through the analysis of five components which comprise the operating environment: the tools, the work, production, cost and quantity.

2.1 Technical Description

This section will provide a basic technical description of the equipment, components and operating parameters associated with concrete removal operations which utilize pneumatic breakers. An understanding of the equipment and equipment components is a first step in developing an appreciation for the technology.

2.1.1 Pneumatic Breakers

Breakers can be powered by a variety of energy sources including: pneumatic pressure, hydraulic pressure, gasoline engine, or electric motor. Table 2.1 illustrates some of the primary advantages and disadvantages of breakers powered by the various energy sources.

Hydraulic breakers use a pressurized fluid to actuate the tool. Although there are small hydraulic breakers, most are larger than is permitted for the selective removal of damaged bridge concrete. Gas and electric breakers are generally heavier than hydraulic or pneumatic breakers of similar productive capacity, due to the fact that the power supply is attached to the instrument. The mechanics of these units are also more complicated than those of hydraulic or pneumatic breakers making them costlier

Table 2.1 Advantages and Disadvantages of Breakers Powered by Various Energy Sources

Energy Sources	Advantages	Disadvantages
Hydraulic	Higher Production Greater Impact Energy	Primarily for Demolition Damage to Residual Conc/Steel Require Hydraulic Compressor
Gas/Electric	Self Contained Suitable to Sites with Limited Access	Greater Weight More Complicated Higher Cost
Pneumatic	Light Weight Durable	Require Air Compressor

to purchase and maintain. These units are however self contained, requiring no additional support equipment and therefore very useful in situations where access is restricted.

This chapter focuses on pneumatic breakers due to the fact that they are more effective and economical than breakers powered by other energy sources when used to remove deteriorated or contaminated concrete from bridge structural elements. Figure 2.1 presents a schematic diagram of a typical pneumatic breaker broken into the following three sections:

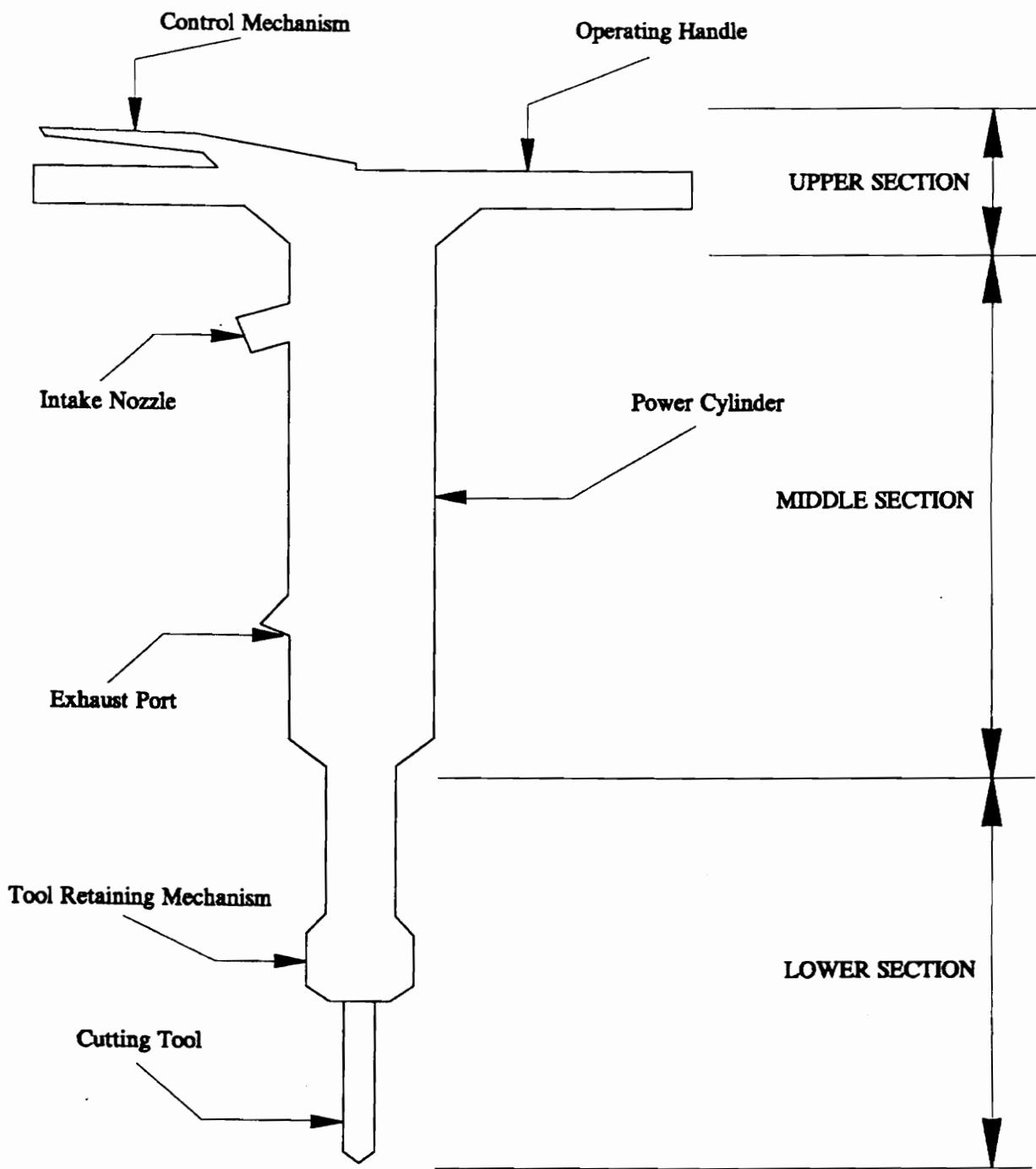


Figure 2.1 Pneumatic Breaker Components

- 1) Upper section. This consists of the operating handle and control mechanism. The handle on most breakers is T-shaped, but D-shaped handles are also used on some of the very small units. Incorporated into the top of one side of the handle is a throttle valve for controlling the amount of air supplied to the breaker. As the operator grips the handle the throttle is opened thus supplying air to the cylinder.
- 2) Middle section. This comprises the power cylinder. Air is supplied to the cylinder in amounts controlled by the operator via the throttle valve. The air is applied to alternating ends of the cylinder causing the piston within the cylinder to reciprocate. The volume of the cylinder determines the volume of air consumed and the power generated by the breaker.
- 3) Lower section. This section of the breaker consists of the tool and tool retaining mechanism. The tool is driven by the piston to deliver repeated impacts on the material to be fractured. Breakers can be fitted with a variety of tools depending on the material to be broken. Either a pointed or wedge shaped tool is typically used for concrete removal in bridge rehabilitation work.

Pneumatic breakers of various sizes are distributed by several manufacturers. They are typically classified by their weight, despite the fact that breakers of a similar weight

do not necessarily generate the same impact force. Figure 2.2 represents the range of weights for which pneumatic breakers are typically available. This ranges from under twenty pounds for small chipping hammers suited for light duty applications to just under 100 pounds for large production breakers. The upper limit governed by the weight which can be handled by the operator with ease and safety.

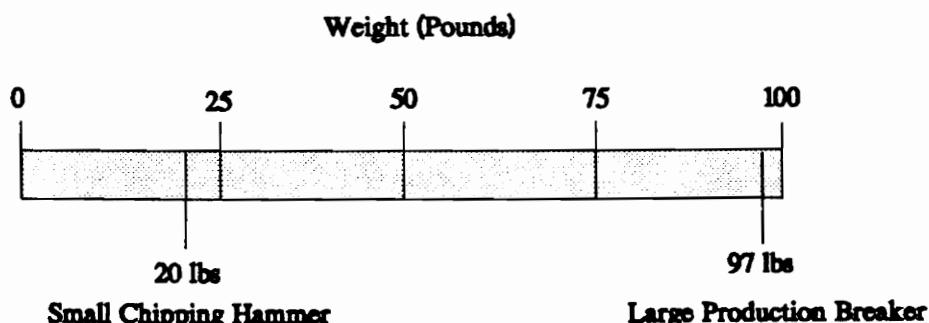


Figure 2.2 Handheld Pneumatic Breaker Weight

The percussive force used by pneumatic breakers to fracture concrete is primarily determined by the energy of the impact and the frequency at which the impacts occur. Figures 2.3 and 2.4 illustrate the range of these values for various types of pneumatic breakers. The impact energy is based on the mass of the piston, the size of the cylinder and the inlet port diameter. Impact energy ranges from approximately fifteen pounds per blow for small tools to over 180 pounds per blow for large tools. The frequency of impact, or blows per minute, range from 900 blows per minute to over 2000 blows per minute depending on the valve design.

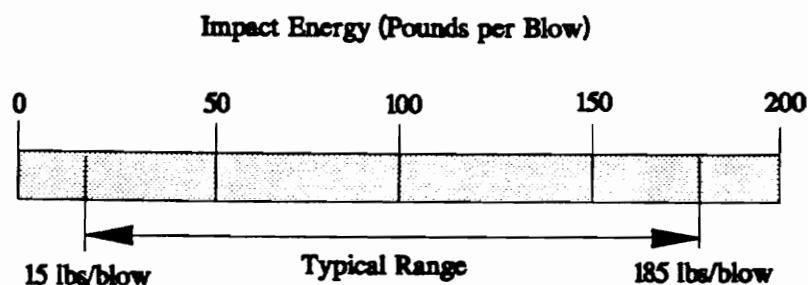


Figure 2.3 Impact Energy for Handheld Pneumatic Breakers

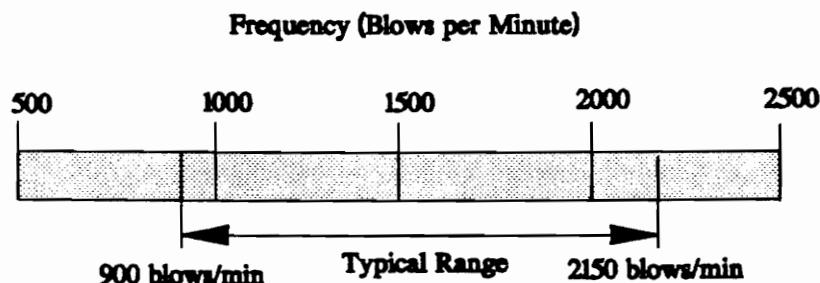


Figure 2.4 Frequency of Blows for Handheld Pneumatic Breakers

Figures 2.5 and 2.6 illustrate the range of values for the air consumption and operating pressure required by a pneumatic breaker. Air consumption can be directly calculated as the cylinder capacity times the strokes per minute. Air consumption generally ranges from approximately 35 cubic feet per minute to just over 70 cubic feet per

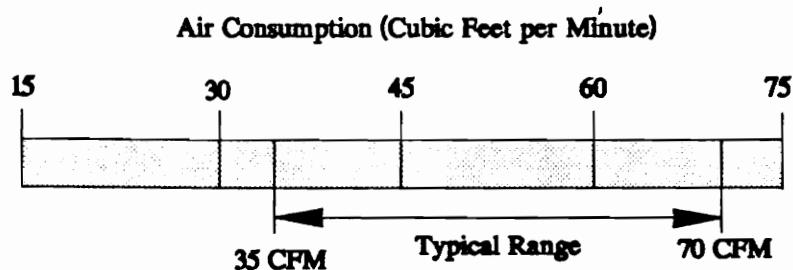


Figure 2.5 Air Consumption for Handheld Pneumatic Breakers

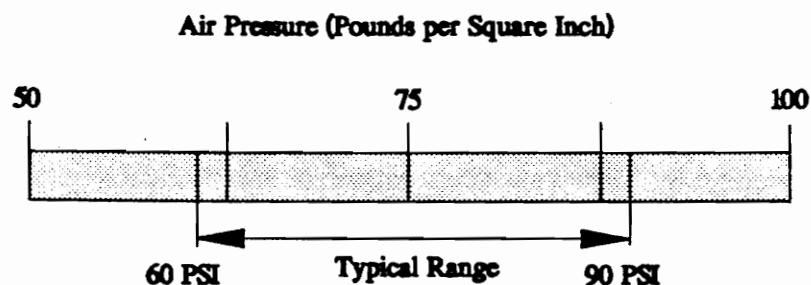


Figure 2.6 Air Pressure Required for Handheld Pneumatic Breakers

minute. The air pressure required by most pneumatic breakers is between sixty and ninety pounds per square inch (PSI).

Figure 2.7 illustrates the relationship between weight, air consumption and impact energy and shows that both the weight and the air consumption must be increased to increase impact energy.

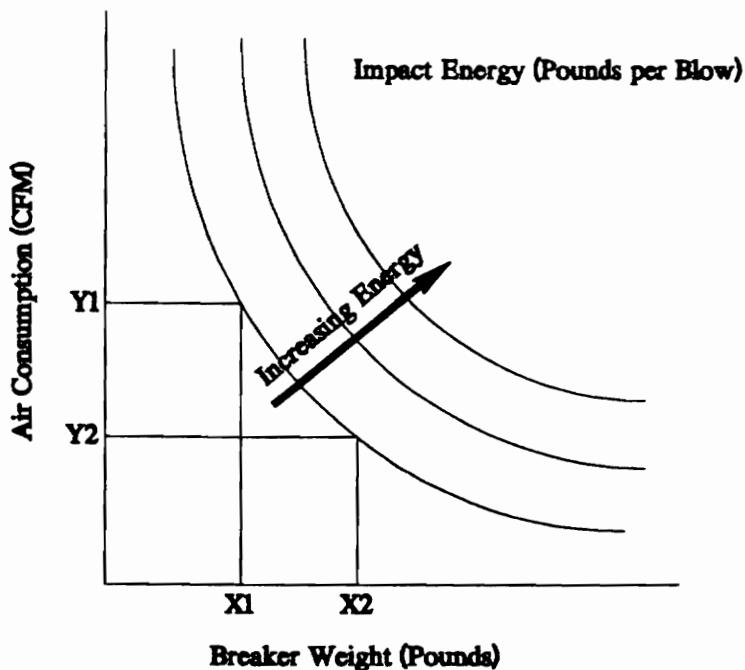


Figure 2.7 Relationship Between Weight, Air Consumption, and Impact Energy

2.1.2 Compressors

A compressor is required to provide the compressed air needed to power the breaker. Most construction jobs utilize portable, wheel mounted, air compressors which are highly mobile and capable of powering several tools simultaneously. The components of a typical unit are a diesel or gasoline engine for powering the unit, the air compressor itself, the regulating system, and the air receiver.

Air compressors can employ either a reciprocating or a rotary action. Rotary compressors use a rotating impeller to force the air through a confined space to increase pressure while reciprocating compressors use a piston and a cylinder arrangement to compress the air.

The regulating system allows the compressor to maintain the discharge pressure at a constant level while meeting the various air consumption requirements of the tools. Most units are equipped with an air receiver which holds the pressurized air prior to discharge to the tools, thus reducing the demand fluctuations on the compressor.

2.1.3 Matching and Air Distribution

The volume and pressure requirements of the compressor can be determined as the aggregate of the demands of all the tools to be used. However, it is important to realize that the maximum air requirements for all the tools will rarely need to be satisfied simultaneously. On the other hand, concrete saws, drills, and air wands can all be powered off of a single compressor and thus there is always a demand for extra capacity.

The air tools will generally not receive the full pressure and quantity of air generated by the compressor due to pressure drops and losses throughout the air distribution system. Hose friction, bends, valves, and air leaks will all reduce the pressure available to the tools.

A single large hose generally transports the air from the compressor. These hoses are connected to manifolds which provide ports for connecting several smaller hoses which will carry the air to the individual tools. Figure 2.8 shows a typical air distribution system in use on a bridge project.



Figure 2.8 Typical Air Distribution System

2.1.4 Operators

A typical crew used for breaker operations consists of a foreman or supervisor, and a gang of laborers. One of the laborers is typically a lead-man while the others are split between skilled or experienced tool operators and inexperienced workers.

The size of the crew required for a specific job will be dependant upon several variables. The primary variable to be considered is the volume of material to be removed as defined by the area and depth of deteriorated concrete. The available working hours and the tempo of the job must also be taken into consideration. The tempo or speed with which a job can be undertaken is influenced by a number of factors including the total working space which can be safely set aside for the crew.

2.2 Work Characteristics

Section 2.1 discussed the components of pneumatic breakers and air compressors and described some of the parameters which must be evaluated when matching air tools to compressors. The crews required and the variables effecting crew productivity were assessed.

This section will focus on the environment in which the work is performed and describe the characteristics which make up an efficient project. An understanding of these characteristics will insure that pneumatic breaker operations achieve their full potential.

2.2.1 Project Type and Location

Breakers are generally utilized to varying degrees on all types of bridge rehabilitation projects. The project type and location for which breakers are most effectively utilized is determined by the location of the concrete to be removed, the location of the bridge, the tempo of the project, the availability and cost of labor and the operating environment. Each of these are discussed in turn.

- 1) Location of removal. Breakers are used as the primary method of concrete removal on projects involving patching, on projects requiring the removal of concrete from bridge structural elements which are not accessible to larger pieces of equipment and on projects where concrete must be removed in small areas from under and around the reinforcing. They are also used in support of large high production, equipment intensive methods on most rehabilitation projects.

- 2) Bridge location. The geographic location of the project will contribute to the efficiency of the breaker operation. They are ideally suited to operate in congested urban areas with high traffic volumes. It is in these areas that their advantages over other methods in terms of setup time and space become apparent. Because of this they are well suited to jobs which require many mobilizations or where the available hours of operation are limited.
- 3) Project Tempo. Many jobs allow that traffic be closed off for only short periods of time due to traffic patterns or safety considerations. Because of their small size and high degree of mobility, breakers are well suited for these projects which have a limited working window. If time is limited or if there is a large quantity of material which is unable to be removed by other methods, breaker production can be increased by adding additional crews.
- 4) Availability and cost of labor. Breakers are a labor intensive method of concrete removal making them sensitive to both the cost and the availability of labor. Urban areas will generally have abundant labor supplies but will also have higher wage rates, whereas rural areas will typically have lower wage rates but laborers may have to be sent to the job site due to an insufficient supply of local labor. The criticality of the labor supply will be largely

dependant upon the size of the job and the number of crews which will be required.

- 5) Operating Environment. The project environment must also be analyzed in terms of the equipment operator. Breaker production and quality is largely dependant on the skill and motivation of the operator. If the working environment which is most conducive to the operator performance can be achieved, then maximum quality and production for the job will be better realized. The primary factors effecting operator performance are weather and safety. Extremes in weather will detract from an operators performance, as will an environment in which an operator feels a threat to their safety.

2.2.2 Type and Extent of Deterioration

Breakers are primarily used to remove small, isolated areas of deteriorated concrete from the bridge deck or other bridge structural members. They are one of the few methods available for removing concrete from vertical and overhead surfaces such as beams, girders, and piers. A smaller 'chipping' hammer is typically used for these applications due to its lighter weight and associated ease in handling. The weight of the tool will, however, work against the operator when working on vertical or

overhead surfaces. A system of scaffolding and lights may be required to gain access and visibility on sub-structural bridge components.

Another major advantage of using breakers on bridge repair jobs is their ability to selectively remove only the damaged concrete. A skilled breaker operator can differentiate between various levels of concrete deterioration by the resistance of the concrete to the breaker. This enables the operator to selectively remove only concrete which is deteriorated and ensures that the quantity of sound material removed is minimized. Quantity variations are, however, not entirely eliminated as the estimated area of deterioration frequently differs from the actual quantity of damaged material which is finally removed.

2.2.3 Preparatory Work and Traffic Control

Visual inspection and sounding are the detection methods typically used to locate deteriorated concrete to be removed by breakers. Sounding of the deck is performed by dragging a chain or a tool equipped with several chains across the deck. The chain will produce a crisp, resonating sound when dragged over sound concrete, whereas a dull, hollow sound will be produced when the chain is dragged across deteriorated concrete. Figure 2.9 illustrates the use of the chain drag method for sounding

concrete. Concrete deterioration in other bridge components is located either by visual inspection or by striking the concrete with a masonry hammer. Deteriorated concrete will produce the same hollow sound when impacted with a masonry hammer as when sounded with a chain.

Once the damaged areas have been located and marked, a vertical saw cut is generally made around the perimeter of the patch area to eliminate tapered edges which tend to chip. The depth of the saw cut should be approximately one inch, but care should be taken not to cut the reinforcing. Saw cuts are not required if the entire deck is to be overlaid.

2.2.4 The Material to be Removed

Breakers are best utilized for removing concrete which is cracked or delaminated as the fracture planes caused by the damage can be used by the operator to increase production. Breakers are, however, not limited to removing only deteriorated concrete, and are often used to remove contaminated or sound concrete in support of other methods.

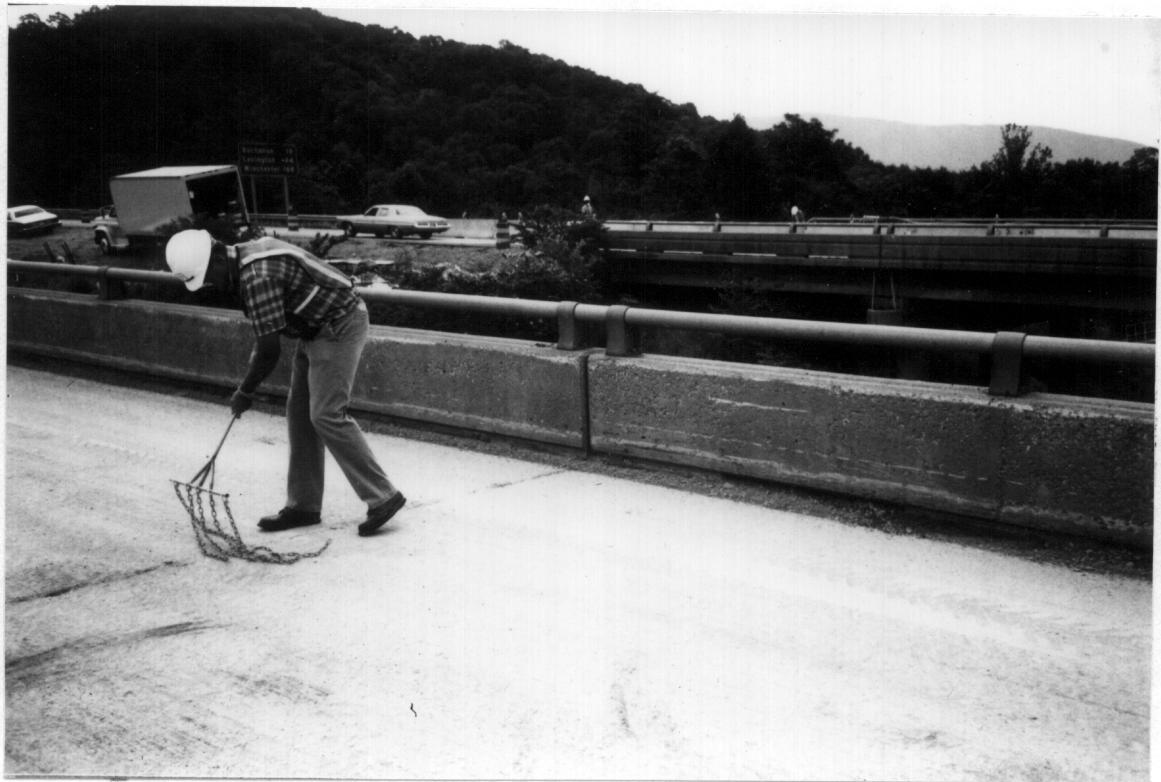


Figure 2.9 Deck Sounding Using Chain Drag Method

The properties of the concrete being removed also affect breaker production and economy. A concrete with very large aggregates or a very dense aggregate mix will offer greater resistance to the cutting mechanism and therefore be more difficult to remove. The result will be lower production and an increase in wear to the breaker components, particularly the cutting tool. Contractors should thus have an idea of the concrete composition for a particular project prior to preparing an estimate.

2.2.5 The Area of Removal

Breakers are typically utilized for the removal of small areas of concrete. This is perhaps the primary factor defining a breaker's ideal work environment. The reason why breakers are most efficient in this environment is based on the tool's geometry and on the economics associated with the use of small versatile tools.

Large equipment intensive methods are generally restricted to removing concrete from bridge decks unless the equipment is greatly modified. These methods are also limited to removing concrete from areas which have definite boundaries and dimensions as dictated by the geometry of the machine. Breakers have no such size limitations and are therefore capable of removing small and irregular sections of pavement. The small size and light weight of breakers also make it possible to work in areas where access is difficult and where maneuverability is limited.

Labor intensive methods such as pneumatic breakers are cost effective for removing low volumes of material. The high initial capital investment required for equipment intensive methods results in a high fixed cost which must be recovered during production. In contrast, labor intensive methods have a very low fixed cost due to the low initial investment required for the equipment. The low production rates generally

associated with labor intensive methods and the high reliance on labor do, however make them uneconomical for removing large quantities of material.

2.2.6 Depth of Removal

For the purposes of this thesis the following system of depth classifications will be utilized:

- 1) Surface preparation and cleaning. This consists of the removal of residue and contamination from the bridge deck surface or from any exposed reinforcing bars to provide an acceptable bond surface for any subsequent overlay or patch material.
- 2) Zone 1 concrete removal. Zone 1 concrete is defined as the concrete which lies outside or above the first layer of reinforcing. The removal task does not involve any interaction with and is not hindered by the reinforcing. Both contaminated and deteriorated concrete can occur in this region.
- 3) Zone 2 concrete removal. Zone 2 is the concrete which lies around and between the reinforcing. The depth of this zone is defined to extend slightly

below the steel to allow for the flow of replacement material into all the voids created.

- 4) Zone 3 concrete removal. Zone 3 concrete is the concrete which lies between the reinforced zones. The quantity of material in this zone is dictated by the size and shape of the structural element.

The abilities of a breaker to work in confined areas are best utilized if concrete must be removed around, between and under the reinforcing steel. The small cutting tool allows the breaker to effectively remove concrete from confined spaces in zone 2 and zone 3 but special caution must be exercised when operating in these areas to avoid damaging the rebar or delaminating the adjacent residual concrete. Production is generally much lower when removing concrete in this region because of the extra time and effort required.

2.2.7 Debris Removal and Cleanup

The debris generated from the breaker operations consists of pieces of concrete and aggregate in a variety of sizes. The larger pieces can be removed by hand and loaded into a wheelbarrow or a loader bucket. The small pieces and dust can then be blown

away using an air wand as illustrated in figure 2.10. The entire surface is generally sandblasted prior to patching or overlaying to clean residual concrete and rust from the reinforcing steel. Disposal of the debris generated from breaker operations is generally not a major concern as it is readily accepted by most materials processing centers or dump sites.



Figure 2.10 Air Wand Blowing Away Small Debris and Dust

2.3 Production Estimating

The first two section of this chapter have discussed the equipment and characteristics which define the work environment. This section will discuss the factors affecting breaker production by first introducing the concept of instantaneous production and

then discussing some of the factors which will modify this to arrive at a realistic production estimate.

2.3.1 Instantaneous Production

The instantaneous production rate is the estimated rate at which the breaker can theoretically remove deteriorated concrete under ideal conditions with no delays or hindrances. The two primary inputs to this estimate are the size and weight of the tool which is to be used and the material which is to be removed.

- 1) Size and weight. Although breakers are generally classified by weight it is actually the impact energy which determines the tools breaking ability. A tool with a greater weight will generally have a larger air cylinder and a piston of greater mass to produce higher impact energy. Weight thus correlates fairly well with impact energy and can be used as a measure of production capacity. The error of this correlation is that not all tools of a similar weight will have the same impact energy due to differences in geometry and construction. Despite this, classification by weight is probably sufficient especially since it is easily measurable and understood.

- 2) Material to be removed. The hardness of the material being removed is an important production parameter with pneumatic breakers just as it is with other concrete removal methods. The concrete properties such as bond strength and aggregate size discussed in section 2.2.4 have a large effect on the production rate.

The area of removal will generally not have a significant effect on individual breaker production rates. Breakers are well suited for jobs with small, non-continuous areas of removal because of their small size and high mobility.

2.3.2 Production Modifiers

There are several factors and conditions which will cause a reduction in the instantaneous rate of production. Primary among these are the level of deterioration, interference from reinforcing steel, operator experience and equipment reliability.

- 1) Level of deterioration. Concrete which is cracked, spalled, or delaminated will offer less resistance to a breaker and will therefore be able to be removed at a faster rate. Chloride contamination does not result in a reduction of a

concrete's strength or resistance to removal and is therefore indistinguishable from non-chloride contaminated concrete.

- 2) Interference from reinforcing steel. The problems associated with performing breaker operations in the vicinity of the reinforcing steel and on bridge structural elements discussed in section 2.2.2 and section 2.2.6 will contribute to a reduction in the instantaneous production rate. The degree to which these factors will affect the production rate can only be determined through the evaluation of a particular project.
- 3) Operator experience. The experience of the equipment operator is an important production parameter which will have a definite effect on the rate of production which will be achieved. Although the workers required to operate the breakers need no special skills or training, the production and quality of the operation are greatly dependant upon the equipment operator. A skilled and motivated operator may be able to remove seven or eight square feet per hour while an unskilled or fatigued operator may only be able to remove two or three square feet per hour as illustrated in figure 2.11.

Not only does operator experience effect production, but the care and attitude of the operator also must be considered. Removing concrete with paving

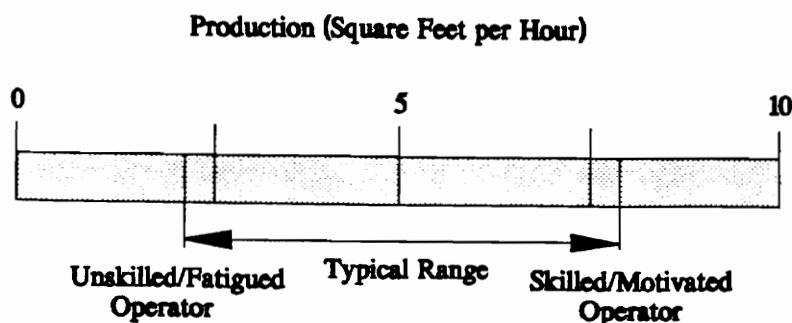


Figure 2.11 Range of Production for Handheld Pneumatic Breakers

breakers is a very non-challenging and tedious task and it is easy for an operator to lose incentive resulting in poor production rates and quality.

- 4) Equipment reliability. Equipment reliability is generally not a significant factor in rehabilitation work utilizing pneumatic breakers. Their relatively simple mechanics and sturdy construction make equipment failures uncommon. Because of their low cost, replacement tools are generally available on the job site should an equipment failure occur.

2.3.3 *Realistic Production*

A realistic production rate can be obtained by reducing the instantaneous production rate as necessary to account for factors which reduce or otherwise effect production. This is the rate at which the work is likely to actually proceed in the field, and is the rate which the contractor should use when estimating the job.

2.4 Economics

This section will continue to develop the quantitative aspects of breaker operations through the development of a cost estimating work sheet as presented in figure 2.12. The parameters listed in the work sheet illustrate the factors which define the cost of breaker operations. Each will be examined in detail to illustrate how they individually and collectively contribute to the final cost. The values used for the inputs to the work sheet represent typical values which may be encountered. They are intended for illustrative purposes only. The section concludes with a sensitivity analysis which illustrates how the unit cost of concrete removal by pneumatic breakers varies with the quantity removed.

Job Specific Parameters:

Total Mobilization Distance	200	miles
Number of Mobilizations	2	mobilizations
Removal Zone: I, II, III, Substruc., Multi.	Multi	zone
Average Depth of Removal	2.50	inches
Area of Removal	20,000	sq. ft.
Number of Breakers	8	breakers
Pneumatic Breaker Size:	30	lbs
Available Working Hours per Shift:	10.00	hours
Number of Shifts per Day:	1	shifts/day

Production Estimate:

Production Estimate:	0.80	cu ft/man hour
	3.84	sq ft/man hour
Crew Production:	30.72	sq ft/crew hour
Hours to Complete Work:	651.04	hours
Days to Complete Work:	65.10	days

Equipment Rental Cost:

Pneumatic Breaker	12	hammers	• \$5	per shift per Breaker
Air Compressor	1	compressor	• \$150	per shift
Van Truck	1	trucks	• \$100	per shift
Industrial Vacuum Truck	0	trucks	• \$110	per shift
Skid Steer Loader	1	loaders	• \$100	per shift
Dump Truck	1	truck	• \$100	per shift
Equipment Rental:			\$510	per day
		x		
			65.10	days
		=		\$33,203

Labor Cost:

Superintendent:	1	super	• \$48.00	per hour
勞工:	10	laborers	• \$20.00	per hour
Truck Driver:	1	drivers	• \$38.00	per hour
Operator:	1	operators	• \$38.00	per hour
Total Labor Cost:			\$324.00	per hour
		x		
			651.04	hours
		=		\$210,938

Mobilization Cost:

Van Truck	\$500	per unit	x	1	unit	=	\$500
Industrial Vacuum Truck	\$500	per unit	x	0	unit	=	\$0
Skid Steer Loader	\$300	per unit	x	1	unit	=	\$300
Dump Truck	\$575	per unit	x	1	unit	=	\$575
Air Compressor & Pneumatic Breakers	\$350	per unit	x	1	unit	=	\$350
Labor	\$20	per unit	x	13	unit	=	\$260
Total Mobilization:							\$1,985

Operating Cost:

Fuel Cost	\$1.50	per gallon	
Industrial Vacuum Truck	0	trucks	• 8 gals/hr
Skid Steer Loader	1	loaders	• 6 gals/hr
Dump Truck	1	truck	• 9 gals/hr
Air Compressor	1	compressor	• 4 gals/hr
 Chisel Bits	 \$4.00	 per sq. yd.	
Miscellaneous Small Tools/Hoses	\$4.00	per sq. yd	
Total Operating Cost:			\$36,332

Total Direct Cost:

\$282,458

Indirect Cost:

Overhead and Administration:	10.00%	of Total Direct Cost	=	\$28,246
Profit:	4.00%	of Total Direct Cost	=	\$12,428
Total Indirect Costs:				\$40,674

Total Price:

\$323,132

Unit Price (per square foot):

\$16.16

Figure 2.12 Pneumatic Breaker Cost Estimating Work Sheet

2.4.1 Job Specific Parameters

A preliminary step to making a cost estimate is to establish the job specific parameters which dictate the time and quantity of resources required. These are listed in the top panel of figure 2.12. The first parameters to be considered are the mobilization distance and the number of mobilizations. Resources and labor continue to accrue costs while in transit and thus a contractor must know the time required and the distance to be covered when mobilizing for a particular project. The mobilization distance is determined by the project location relative to the location of the contractors office or the previous, subsequent, or intermediate jobs which require the use of the resources. The number of mobilizations is often determined by the phasing of the work, traffic patterns or the scheduled sequence of the activities. The work sheet indicates that there are two mobilizations totalling 200 miles.

The second set of job specific parameters: the zone and location, depth, and area of removal, determine the volume of material to be removed and the productivity which can be expected. The affect of these parameters on pneumatic breaker performance was discussed in sections 2.2.1, 2.2.3, 2.2.5 and 2.2.6. If the work includes the removal of concrete from bridge components other than the deck, more extensive planning and procedures are generally involved and lower rates of production can be expected. Substructure removal will generally require the assembly of scaffolding to

access the deteriorated material and involve more extensive debris removal efforts both of which will lower productivity . For this example it was assumed that the removal would be from multiple zones of removal or bridge components. The average depth of removal is 2.5 inches and the estimated area of removal is 20,000 square feet.

The next two items on the work sheet, number of breakers and breaker size, relate to the pneumatic breaker selection. The number of breakers used will be dependant on the area of concrete to be removed and the time constraints imposed on the project. The size of the breaker used will affect the production and therefore the cost of doing the work. The maximum size of the breaker which is permitted to operate on bridge decks is normally specified by the SHA while the removal of substructure concrete necessitates the use of smaller chipping hammers for ease of handling and mobility. A job of this size could possibly employ eight thirty pound breakers as illustrated in the work sheet.

The last two job specific parameters are the working hours per shift and the shifts per day. A single shift of ten hours per day was used in this example. These determine the working hours per day, which can be adjusted by the contractor to insure that the task is completed within the scheduled time while effectively utilizing the resources. The contract may, however, limit the working hours available due to noise ordinances

or traffic control requirements. Working at night is possible with the use of lights and may actually be preferred due to its reduced impact on traffic.

2.4.2 Equipment Production Parameters

A production rate for an individual breaker may be determined as described in section 2.3.3. The estimated rate of production of 0.8 cubic feet per man hour assumed in the example cost estimate can be divided by the depth of removal, 2.5 inches, to determine the production rate per unit of area, 3.84 square feet per man hour in this example. This is multiplied by the number of breakers, eight, to determine a crew production, 30.72 square feet per crew hour, from which the estimated number of hours to complete the work is calculated as 651.04 hours. The number of days required is calculated as 65.10 by imposing the available daily working hours on the total time to complete the work.

Adjustments can be made in the number of breakers, the hours per shift or the shifts per day to ensure that the work will be completed within the scheduled time. The days to complete the work calculation is also important in determining equipment utilization and rental costs.

2.4.3 Equipment Rental Cost

The equipment rental cost is the cost to the contractor to own and maintain a piece of equipment. If the equipment is owned by the contractor then the rental cost is based on the annual equivalent cost distribution of the equipment purchase price less its anticipated salvage value. There are several methods of calculating this, but all generally require an estimate of the anticipated useful life of the equipment and an effective interest rate based on inflation, profit and the cost of capital. This aspect is more important when considering capital intensive technologies such as hydrodemolition and is discussed in greater detail in section 4.4.2.

If the equipment is rented, then the equipment rental cost is simply the price that the contractor must pay for use of the equipment. The rental cost typically includes maintenance and wear.

Most bridge rehabilitation contractors will own many paving breakers and compressors, but may be required to rent some less common tools which may be required. Breaker's low initial cost, minimal maintenance and abundant applications make them an economical investment to a contractor. Contractors will generally supply more breakers to a job than is required so that if one breaks down it can quickly be replaced with minimal delay to the work. For this example four extra

breakers were provided, bringing the total number of breakers to twelve. One compressor is supplied to power the breakers and other air tools.

Support equipment will comprise a van truck to transport personnel and equipment as well as debris removal and hauling equipment. The equipment used to remove the debris will largely depend on the quantity of debris generated. A laborer with a shovel may be adequate for small jobs, whereas a skid steer loader or vacuum truck may be required for larger jobs. A dump truck will generally be required to haul the debris to an appropriate dump site. A skid steer loader and dump truck were provided to handle the debris removal operations in the work sheet example. No additional cost is allocated for debris disposal as it is a common activity to all three technologies. However, additional debris handling procedures will be necessary with hydrodemolition because any contaminants absorbed by the concrete are released when the cement matrix is destroyed by the water-jet. These procedures are discussed in greater detail in section 4.2.3, section 4.2.7, and section 4.5.1.

2.4.4 Labor Cost

The labor cost is the primary expense associated with pneumatic breaker use. The number and type of workers required will depend primarily on the size of the job and

the time schedule to complete the work. In addition to the breaker operators, additional workers will be required to supervise and support the operations. One supervisor is generally required for every eight to ten breaker operators.

Breaker operators are generally classified as common laborers and their wages will be set by local standards. In addition to the workers wages, the contractor must make provisions for taxes, insurance, and workman's compensation when estimating the cost of labor.

The labor required for this example consists of one superintendent, ten laborers, a truck driver and an operator for the loader. The hourly rates reflect the necessary mark-ups for insurance and taxes.

2.4.5 Mobilization Cost

The mobilization cost is the cost which will be incurred by the contractor in getting the required equipment to the job site and removing it at the completion of the work. For this example it is calculated as a lump sum, based on the equipment owning cost, the cost of the labor for the time the equipment is in transit and the fuel and other operating costs consumed in getting the equipment to the job. A contractor will

consider these costs in conjunction with the mobilization distance and number of mobilizations to arrive at the lump sum mobilization cost.

The unit cost for the equipment and labor used on the work sheet represent typical costs for the items considering the number of mobilizations and the mobilization distance.

2.4.6 Operating Cost

The main operating cost items consist of the fuel required to operate the equipment and the wear items for the tools. All other operating and maintenance costs are typically included in the ownership or rental cost estimate. The fuel cost and the equipment fuel consumption rates used in the work sheet are representative values which will vary depending on the actual equipment used.

Pneumatic breakers generally require very little maintenance. Oil must be periodically added for lubrication of the piston and cylinder and the valves. Cutting points and air hoses will also need to be replaced as needed due to wear. Occasionally the valves or ports on a breaker may become clogged with the dust generated by the work. These

can usually be cleared with little trouble by either flushing the tool or by dismantling it and cleaning the components.

2.4.7 Total Direct Cost and Indirect Cost

The sum of the cost elements previously discussed: equipment rental cost, labor cost, mobilization cost, and operating cost comprise the direct cost of performing the work.

The direct costs can be directly attributed to the particular job. In addition to the direct cost the contractor will provide a mark-up for overhead and administration and for profit. These costs are generally calculated as a percentage of the direct costs.

They account for expenses incurred by the contractor in running the business which are difficult to attribute directly to the project. An overhead and administration mark-up of ten percent and a four percent profit are typical values which may be encountered.

The sum of the total direct costs and the indirect costs are equal to the total price which it will cost the contractor to perform the work. This total price can be divided by the estimated area of removal to determine a unit price to perform the work. The unit price is generally what the contractor will include as the bid price for the concrete removal operations utilizing pneumatic breakers.

2.4.8 Sensitivity Analysis

Figure 2.13 presents a graphical representation of the sensitivity of the unit price of concrete removal utilizing breakers to the quantity of removal. The resources required to perform the work were held constant at the levels depicted in the work sheet as the area of removal was varied from 500 to 25,000 square feet.

The curves generated clearly illustrate the fundamental cost-quality relationship of labor intensive methods such as pneumatic breaker operations. The unit price for performing the work remains relatively constant as the quantity of removal increases. Although there is a decrease in the unit price of almost twenty percent as the quantity of removal increases from 500 square feet to 5,000 square feet, the unit price decreases less than three percent over the entire remaining quantity interval. This is because the majority of the costs associated with breaker use are quantity sensitive. They will increase in direct proportion to increases in the quantity of removal, thus maintaining a relatively constant unit price.

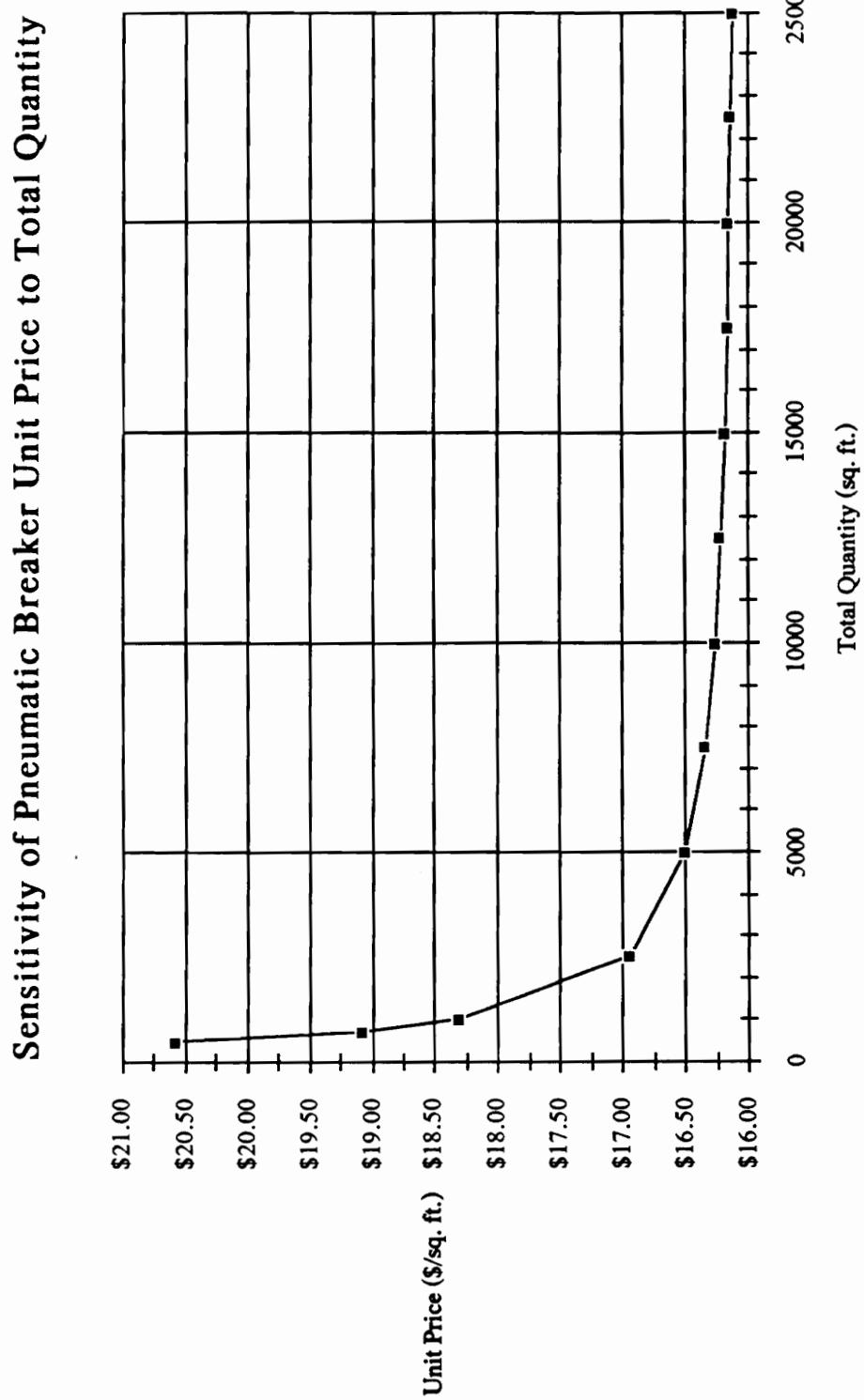


Figure 2.13 Sensitivity Analysis of Pneumatic Breaker Price

2.5 Managing and Controlling Quality

The first two sections of this chapter described the equipment and operating environment associated with pneumatic breaker operations. Section three and four continued by examining the quantitative issues of production and cost. This fifth and final section will address the issues of quality and quality control.

2.5.1 *Quality Requirements*

For a breaker operation to achieve the desired level of quality, parameters which contribute to the success of the project must be established and maintained. Four quality concerns are imperative to the success of the breaker operation in particular and the project as a whole. These are:

- 1) Complete removal of deteriorated concrete. It is essential that the breaker operations remove the concrete from the necessary depth and area to ensure that all deteriorated concrete is removed. Because a properly skilled breaker operator is capable of selectively removing only the deteriorated concrete, the actual quantity of concrete removed may vary from the estimated quantity of

removal in the case that the amount of deteriorated concrete was over or under estimated.

The emphasis of the removal operations should be to ensure that all the deteriorated concrete is removed regardless of how closely it corresponds to the area and estimated depth delineated for removal.

- 2) Damage to reinforcing steel. Another quality concern associated with breaker operations is the possibility of damaging the reinforcing steel. The percussive force used by the breaker to fracture the concrete often errantly damages the steel reinforcing or the bond between the concrete and the steel.

If the cross sectional area of the reinforcing bar is substantially reduced, either due to gouging caused by the breaker or by corrosion, then the entire damaged section of the bar should be removed and replaced. Also, if the concrete from around the reinforcing bar is removed, exposing the steel, then the concrete should be removed to a specified depth below the steel. This ensures that there is sufficient surface area on the steel to form a bond and there is adequate space below the rebar for the coarse aggregate in the patch material.

- 3) Surface characteristics. The surface produced by the work must have the necessary characteristics for it to effectively bond with the replacement material. The breaker operations produce a rough, textured surface that is very uneven and irregular. This texture bonds well with patch or overlay material but it is not suitable to be opened to traffic prior to resurfacing.
- 4) Environmental concerns. Effects of the breaker operations must be monitored to ensure minimal impact on the surrounding environment. The primary environmental issues of concern are dust and noise created both from the breaker operations and from the subsequent debris removal process. These may pose a health threat to the workers and a safety threat to passing motorists.

The best way to reduce the noise level is to allow the exhaust air to escape into an expansion chamber before being exhausted into the atmosphere. However, this may result in a decrease in breaker power due to increased back pressure in the power cylinder.

Occupational safety issues arising from the operation of vibratory equipment are discussed in section 2.5.3.

2.5.2 Residual Concrete

The potential for damaging the concrete which is to remain is a problem associated with all methods of concrete removal which utilize an impact force to fracture the damaged material. The impact force which is used to fracture the damaged concrete may produce a "bruised layer" of microcracks in the top 1/4 to 1/2 inch of the residual concrete. These microcracks accelerate the deterioration of the residual concrete and weaken the strength of the bond with the overlay or patch material. The factors which determine the extent of cracking are the force generated by the hammer, the quality of the residual concrete and the effort exerted by the breaker operator.(Hindo, 1987)

In an effort to minimize the extent of micro-cracking, SHAs often limit the allowable weight of pneumatic breakers which are used to remove concrete from bridge decks. Although these lighter breakers will typically have a lower impact energy, they will also have lower production rates. A balance must be made between an acceptable production rate and the possibility of damaging the residual concrete. Contractors and SHA personnel should be made aware of the causes and consequences of micro-cracking so that steps may be taken to locate and minimize areas of potential damage.

SHAs often specify that breakers be operated at an angle between 45 and 60 degrees to the removal surface in an effort to reduce the chances of the impact damaging the

residual concrete. This directs the breaker's impact force in a non-vertical plane which will minimize the number of cracks propagated into the residual concrete. The angled direction of impact also aids in breaking the concrete into pieces for removal and reduces the chances of a 'pop through', where the breaker accidentally removes the concrete all the way through the deck.

2.5.3 Occupational Safety

There is a possibility of health problems associated with the operation of vibratory hand tools such as paving breakers. These problems are known as cumulative trauma disorders and are caused by repeated, long-term exposure to hand, wrist and finger activities. The disorder associated with pneumatic paving breaker operation is called carpal tunnel syndrome or white finger. With carpal tunnel syndrome the tendons which pass through a narrow wrist passage become swollen, causing numbness in the fingers and hands of the worker. Initially the symptoms are temporary, but permanent damage may result if corrective measures are not taken.

2.5.4 Specifications

The primary function of the specifications is to stipulate the standard of quality which must be achieved by the various aspects of the work. The quality of the concrete removal operations which utilize pneumatic paving breakers is a function of the breaker operator, the inspector and the specifications.

- 1) The operator. Breaker work is inherently dependant on the skill and effort put forth by the operator. The maximum quality of the product will be more fully realized if the conditions which will promote optimal operator effectiveness are specified. These conditions are primarily associated with the working environment and safety issues.

Traffic barricades as well as safety goggles and earplugs are safety measures which improve an operators performance and therefore the quality of the work. If the work space becomes overcrowded the effort required to stay clear of other equipment and workers will detract from the workers concrete removal efforts. The optimal number of workers on the bridge deck will ensure that the work gets done in an efficient manner without overcrowding the work space.

- 2) The inspector. The second area of contribution to quality and quality control for a breaker operation is the inspector. The inspector is involved in the quality of a job in all phases. In the initial stages of the concrete removal operations, the inspector is responsible for sounding the deck and marking the areas which will require removal. This enables the inspector to determine the level of concrete quality which is acceptable. The inspector should continually monitor the work throughout the removal operations to ensure that the required level of soundness is achieved. The inspector must also ensure that further damage is not caused to the bridge deck in the form of excessive cracking in the residual concrete or gouging of the reinforcing.
- 3) The specifications. The specifications can affect the quality of the work with regards to equipment which is be used. Specifications usually limit the weight of breakers which can be used and contain a section describing the essential procedures which must be followed to ensure that the work is of acceptable quality.

Specifications will reduce the risk to all parties involved in performing the work by clearly stating what is required and what is expected. The primary risk associated with removing concrete with pneumatic breakers is the possibility of quantity variations. This risk will be substantially reduced if

every effort is made to accurately determine the extent of deterioration prior to commencing work. However this is often difficult to accurately establish especially if the deck has been previously overlaid or if the breaker work is to follow another concrete removal method.

The final sections of the specification should describe the method of measurement and the basis of payment. This is typically by the square yard of the various classes of removal. The measurement should be made by the inspector following the concrete removal. The payment should be for the removal and disposal of all unsound and contaminated concrete and for the removal and replacement of reinforcing not otherwise specified to be removed.

3

Milling as a Concrete Removal Technology

Milling is a capital intensive method of concrete removal employing high production machines to strip contaminated and deteriorated concrete from above the reinforcing steel. Milling machines are ideally suited to bridge deck rehabilitation projects requiring the removing of large volumes of concrete from above the reinforcing steel. Their inability to remove deteriorated concrete from below the reinforcing steel or from inaccessible areas such as at joint faces, drains or around other obstacles means that methods such as pneumatic breakers are invariably required to support the operations and complete the detail work.

3.1 Technical Description

This section presents an examination of the components which comprise a milling machine and describes their function in relation to the concrete removal operation.

Figure 3.1 highlights the key components of a typical machine discussed in the section which follows.

3.1.1 *Cutting Mandrel*

The cutting mandrel is a cylindrical metal drum mounted horizontally on the underside of the milling machine. It carries the cutting teeth used to break the pavement. Its width, which varies from a few inches on very small machines to over 12 feet on the largest machines, dictates the width of the material cut. Figure 3.2 illustrates the range of available mandrel widths and the typical sizes which are used for bridge deck rehabilitation work.

Cutting mandrels also vary in diameter, ranging from about eight inches to over four feet. The smaller mandrels generally rotate faster, using speed to cut the pavement, whereas larger mandrels tend to rotate more slowly, using the weight and horsepower of the machine to break the pavement.

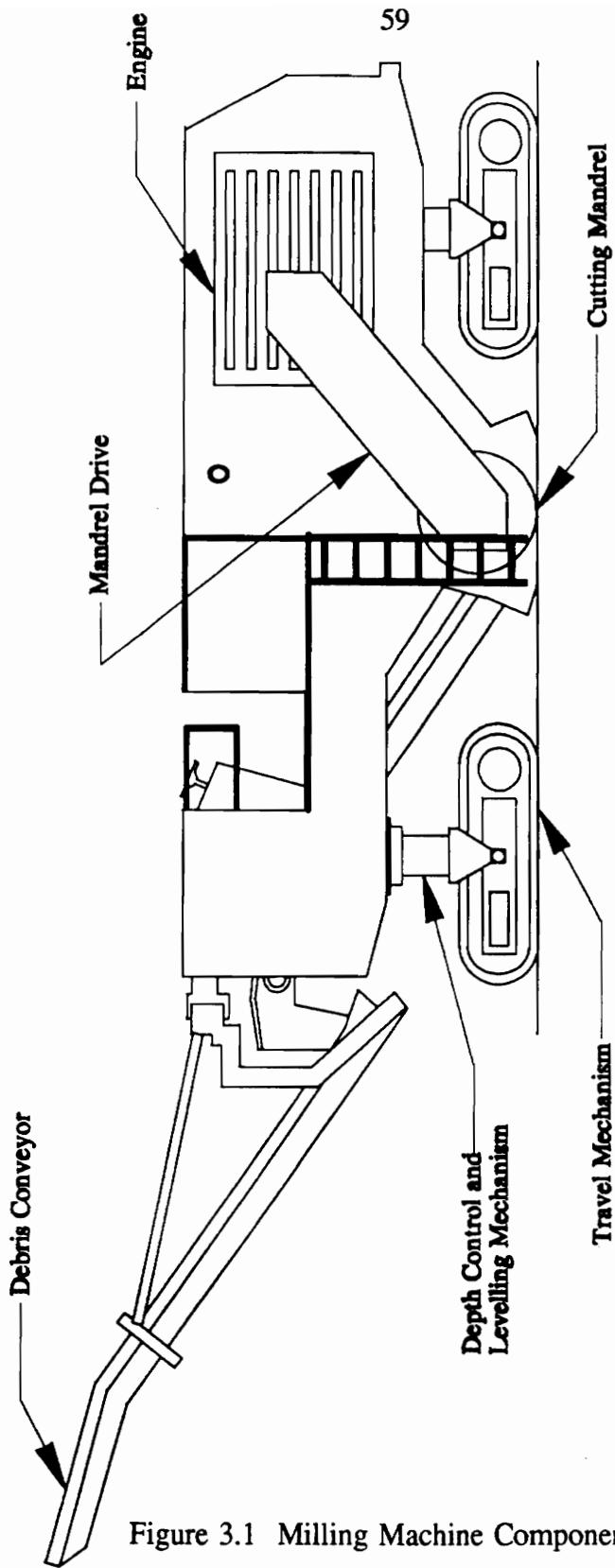


Figure 3.1 Milling Machine Components

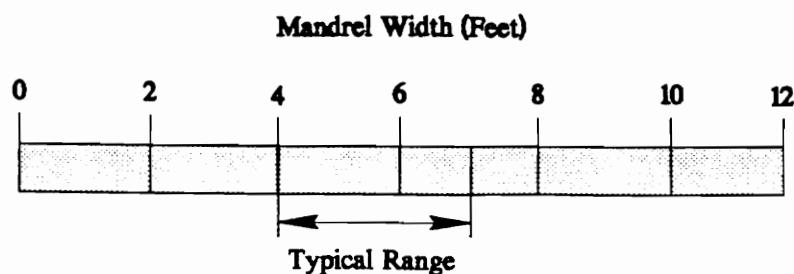


Figure 3.2 Range of Available Mandrel Widths

Carbide-tungsten tipped cutting teeth as illustrated in Figure 3.3 are used to break the pavement. The teeth are usually slightly over three inches long. About one half of this length is made up of the mounting shaft while the other half comprises the conical shaped holder and carbide-tungsten tip.

The teeth are secured to the cutting mandrel through blocks which are either bolted or welded to the mandrel. A typical mounting block is illustrated in Figure 3.4. The mounting block is designed to hold the mounting shaft in a manner which makes changing teeth as simple and fast as possible. Changing teeth once a day is typical for bridge work, but the frequency with which teeth will need to be replaced depends upon amount of work done and the hardness of the material being removed.

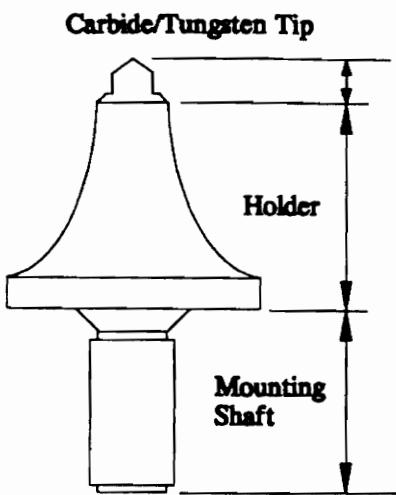


Figure 3.3 Carbide-Tungsten Tipped Cutting Teeth

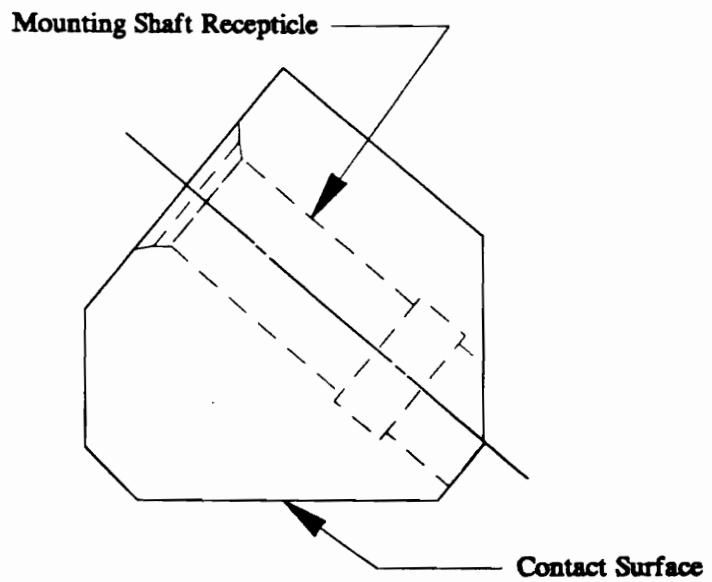


Figure 3.4 Mounting Block

The configuration of the teeth on the mandrel plays an important role in the operation of a milling machine. The teeth are mounted on the cutting mandrel in a spiral which runs inward from the sides. This directs the cut material towards the center where it may be either loaded onto a conveyor for removal or left to be removed by other methods.

The spiral usually wraps the drum between one and three times with teeth staggered to strike the pavement at half inch intervals. The teeth are mounted at a slightly skewed angle so that they rotate as they travel through the pavement to wear evenly for maximum life.

3.1.2 Mandrel Drive

The mandrel drive transfers power from the engine to the mandrel. Large machines favor mechanical drives employing belts or chains while smaller machines generally use a hydraulic drive system.

The hydraulic system has the advantage of allowing the mandrel speed to be adjusted to the desired level while maintaining the optimum engine speed. Most of the smaller machines are driven by a single hydrostatic unit located external to the mandrel, but a

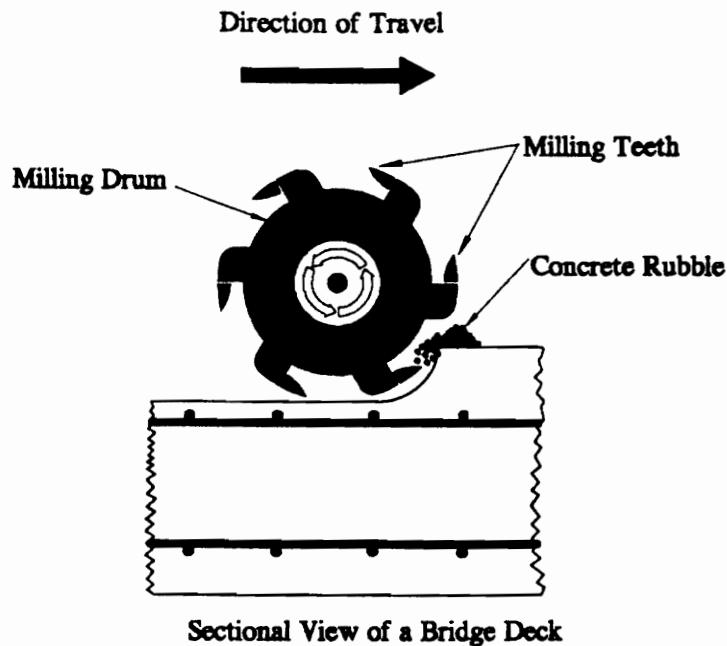


Figure 3.5 Cutting Action of a Milling Machine

few use two hydrostatic units located inside the drum. The dual units provide an even distribution of power and minimize obstructions which limit the ability to cut flush to a vertical boundary such as a curb or a retaining wall.

Mechanical drive systems deliver power to the mandrel more efficiently. Belt systems tend to be less costly to maintain than chains and reduce possible machine damage by isolating the drive train from shocks generated by the mandrel.

The drive system rotates the mandrel in a direction opposite to direction of travel of the machine as illustrated in figure 3.5. This causes the cutting teeth to strike the

pavement forward and up in order to fracture the concrete in tension. This is not only more efficient but, it also reduces cracking and other damage to the substrate concrete.

3.1.3 Depth Control and Leveling

Depth control is achieved either by adjusting the height of the machine as a whole or by adjusting the height of the cutting mandrel relative to the machine. When the whole machine is adjusted, the drive tracks or tires are attached to the machine through adjustable hydraulic cylinders, while the cutting mandrel is fixed directly to the machine frame.

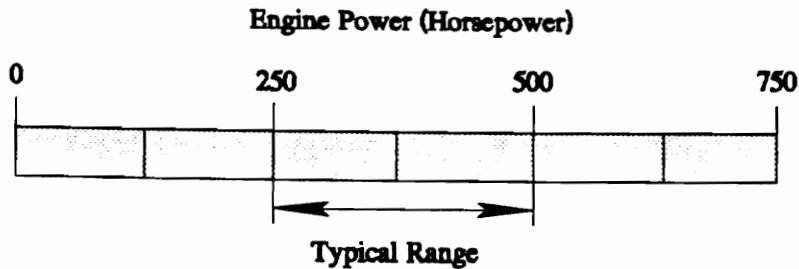
The mandrel is connected to the frame through adjustable hydraulic cylinders when depth control is achieved by moving the mandrel relative to the machine. This provides quick response to depth adjustments.

Most machines have the option of adjusting the depth of the cut either manually or automatically. Automatic depth control systems work through elevation sensors which can be operated off of a reference wheel, an averaging ski, or a string line. The accuracy of the depth control is generally limited by the maximum aggregate size.

Level and cross fall are achieved by raising either the machine or the ends of the cutting mandrel to the required height.

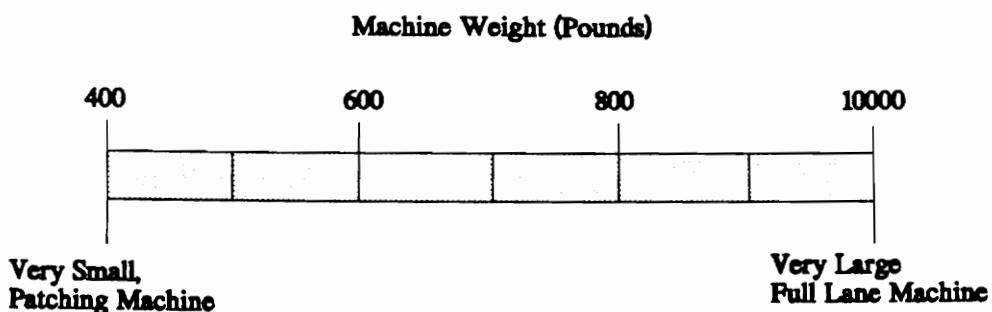
3.1.4 Engine

Milling machines are powered by diesel engines ranging in power from 24 horsepower for the smallest machine to 750 horsepower for the largest machines. As illustrated in Figure 3.6, the typical range for bridge deck work varies between 250 and 500 horsepower. Most of the machine components are powered by hydraulic pumps operated off of the engine. Some of the very large machines are equipped with two engines, one to power the cutting mandrel exclusively, and the other to power the hydraulic system. These machines may have a combined power of up to 1000 horsepower.



3.6 Power Range for Milling Machines

Weight correlates closely with power and is important when evaluating a milling machine. Figure 3.7 illustrates the range of weights for milling machines. Machine weights range from under 4000 pounds for the smallest machines, to over 100,000 pounds for the largest. A heavier machine is able to exert a greater downward force to keep the machine in the cut and increase production. Although a heavier machine is generally capable of working more efficiently, many bridges have weight restrictions which must be taken into account when selecting a machine.



3.7 Weight Range for Milling Machines

3.1.5 Travel Mechanism

Milling machines run on either tracks or tires which are independently powered by a hydrostatic motor. This allows the machine speed to be adjusted without effecting the engine speed. Tires are used on most small machines and some mid sized machines.

They have the advantage of greater maneuverability, less damage to the bridge deck, and greater dampening of vibrations.

Mid and large size machines are usually equipped with tracks. The primary advantages of tracks stem from their ability to carry heavier loads and exert increased traction. Tracks also distribute a machine's weight over a larger area and thus reduce the possibility of exceeding point load limits on the bridge. Some machines have three tracks for increased maneuverability, while others have four to give greater stability.

Machines usually have separate speed ranges for operating and travelling. Figure 3.8 illustrates the ranges for both the operating speed and the traveling speed. Operating speeds range from 33 feet per minute to 150 feet per minute but will largely be determined by the material being milled. Travelling speeds are generally in the four to five miles per hour range but can be as high as 24 miles per hour.

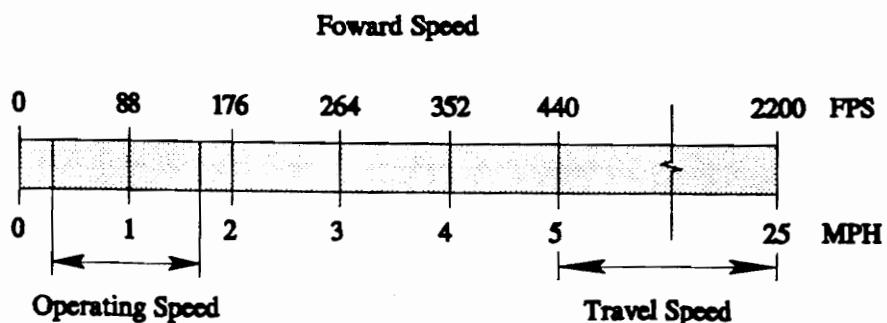


Figure 3.8 Speed Ranges

3.1.6 Debris Conveyor

Most larger machines are equipped with a hydraulically controlled conveyor system for the removal of debris. Conveyors either discharge to the front of the machine or to the rear. The rear loading provides greater visibility for the operator due to reduced dust and reduced forward obstruction.

Front discharging conveyors make it possible for the trucks receiving the milled material to travel in the same direction as the milling machine and traffic. This decreases the amount of time required to switch trucks and thus makes the operation more efficient. Also, any material which falls off the truck or conveyor is recycled by the milling machine, leaving a cleaner finished surface.

Conveyors, whether front loading or rear loading, generally have the capability to swing from side to side to facilitate loading the material into a truck travelling alongside. Although conveyors are very efficient on large highway milling projects, they are frequently not used on bridge rehabilitation jobs because they restrict maneuverability.

3.2 Work Characteristics

This section will discuss the nature of the projects and the work tasks suited to the use of milling machines. The factors which cause the operations to be productive and the factors which limit them from achieving their full potential are analyzed through the examination of seven parameters which define the characteristics of the work.

3.2.1 Project Type and Location

The ideal work environment for high production milling machines is provided by one large or several smaller but consecutive bridges where the entire deck surface must be removed to a specified depth above the reinforcing steel. By milling a large area at once, greater equipment utilization and reduced mobilization costs are achieved.

Milling machines are not designed for and not economical when used on small areas requiring intermittent operation and substantial maneuverability.

The location of a bridge is important because mobilization costs are high if the distance between work sites is large. Reduced travel distances will result in lower mobilization costs and will also allow the contractor to react more quickly to schedule changes.

Urban job sites often have several limitations. Bridges are usually quite small and access is often limited. Operating hours are often restricted and work may only be permitted at night. Rural job sites generally have better access and fewer limitations on operating hours but may be more costly in terms of mobilization.

3.2.2 Type and Extent of Damage

Milling machines are only able to remove concrete from above the top mat of reinforcing. If contamination or deterioration is limited to concrete above the top mat of reinforcing, zone 1, or if milling is being performed only as preparation for an overlay, a milling machine will be ideally suited to perform the work. However if the

area of removal extends into zone 2 or deeper, additional or alternative methods of concrete removal will be required.

Milling machines are unable to differentiate between concrete which is contaminated and that which is deteriorated and should therefore be precluded from situations where this distinction is necessary. The wide cutting drum and the continuous action of the cutter restricts the machine from selectively removing damaged concrete. However, a highly deteriorated concrete which is cracked or crumbled will offer less resistance to the cutting mechanism and will allow the machine to attain higher rates of production.

3.2.3 Preparatory Work and Traffic Control Requirements

Prior to commencing milling work, the area to be milled, typically one lane or half the width of the bridge is closed to traffic. This may be accomplished through temporary means such as cones or barrels if the traffic volumes are low or if the bridge is to be closed for a short time. High speed roads with high traffic volumes generally require that concrete barriers be installed to provide added safety to both the motorists and the crews employed on the milling operations.

Sounding and marking the deck prior to milling is generally not necessary because milling typically removes concrete over the entire deck area. However, the depth to the top mat of reinforcing should be determined in several locations on the bridge deck prior to commencing milling work to avoid the damages which may result if a machine catches the rebar. Although the depth to the reinforcing generally varies less than one half of an inch, the expense in time and effort required to determine the rebar cover is much less than the cost which will be incurred if a bar is pulled up. The depth to the reinforcing can be fairly accurately measured with a commercially available pacometer which electronically senses the location and depth of the reinforcing steel.

3.2.4 The Material to be Removed

In order for the depth of removal to be accurately monitored, any previously placed asphalt overlay must be removed prior to the concrete removal operation. Milling machines are ideally suited to remove most overlay materials, but an allowance must be made for the additional time which will be required for the overlay removal.

The properties of the concrete to be removed from the bridge deck will effect the milling machines efficiency and production. The primary components of the concrete

which will have an effect on the operation are the bonding strength of the cement and the size and hardness of the aggregate.

It is generally much easier for a milling machine to break the bond between the cement and the aggregate than to fracture the aggregate. However this will be difficult if the aggregate mix is very dense if the cement has a very high bonding strength.

Aggregate hardness also affects production and contractors must make allowances for this by lowering estimated production and increasing maintenance downtime in areas which have typically had hard aggregates.

3.2.5 The Area of Removal

The area to be removed is the primary factor effecting milling machine efficiency and productivity as it determines the extent to which the machine can be operated at optimum capacity. Continuous uninterrupted operation enables the machine to reach high production rates and achieve lower unit costs. It also permits a greater number of hours in operation and thus the contractor is able to recover the owning costs of the machine in a more efficient and timely manner. This is of great importance with capital intensive methods where owning and capital recovery costs play a major role.

Continuous, uninterrupted operations are difficult to achieve and maintain on bridge work. The area to be removed is limited by the size of the bridge, the extent of the contamination and the phasing of the work. These limitations can be mitigated if several bridges in the same area are milled in sequence so that the contractor is able to improve equipment utilization, production and unit costs.

3.2.6 The Depth of Removal

The depth of concrete above the top mat of reinforcing and the depth of contaminated or deteriorated concrete requiring removal are important project parameters which effect the utilization of a milling machine. The depth to the reinforcing bars determines the maximum depth to which the milling machine may operate. There will be a reduced potential of damaging both the machine and the bridge if this is fairly substantial and uniform. If the concrete requiring removal extends beyond zone 1 or is in areas inaccessible to the milling machine, then additional concrete removal methods will be required.

3.2.7 Obstructions

Reinforcing bars and other built-in steel components frequently interrupt the milling operation and preclude the machine from achieving its full potential. Increased caution must be taken when the depth of reinforcing varies and thus the quality of the original deck construction thus plays a major role in determining the efficiency of any subsequent milling operation. The machine size and drum width should be selected to provide the maneuverability needed to avoid obstructions.

3.3 Production Estimating

Estimating the production which can be achieved by a milling machine is a difficult task because it is dependent on a large number of variables which are difficult to predict accurately. This section addresses the production estimating process for bridge milling operations as illustrated in figure 3.9.

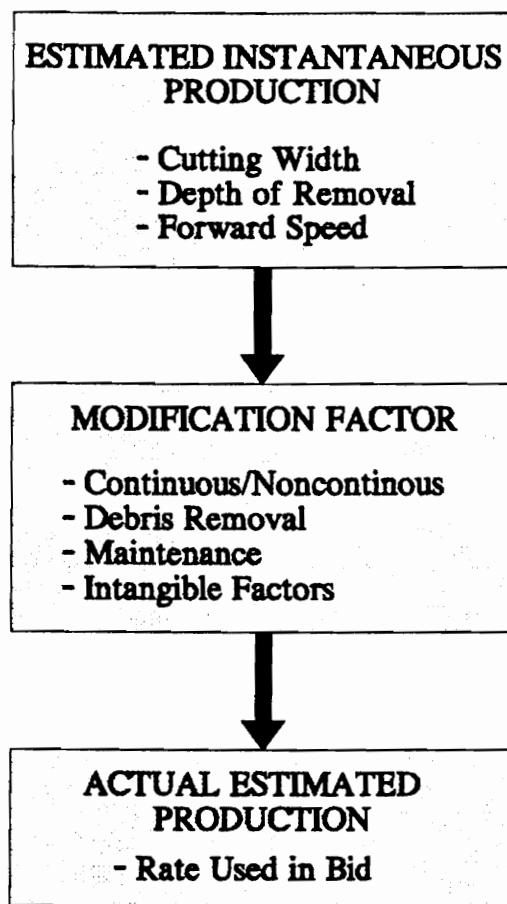


Figure 3.9 Factors Affecting Milling Machine Production

3.3.1 Instantaneous Production

The first production figure to be calculated is an ideal or instantaneous production rate. It is the maximum rate of production which can be attained under ideal operating conditions. The ideal production may be realized for short periods of time, but it will rarely if ever be realized throughout the duration of the project.

The instantaneous production is determined by the machine cutting width, the cutting depth and the anticipated operating speed. The cutting width is determined by the width of the cutting mandrel and determines how many passes will be required to mill the area of the deck which is available for work.

The cutting depth is determined by the extent of damage and the location of the reinforcing steel and will impact production by increasing the volume of material which must be removed and because of the possible interference with the reinforcing steel. A greater volume of material will require a greater effort by the machine and will thus result in a lower rate of production. On jobs which require that the concrete be removed to very close to the reinforcing, the machine will have to be operated much more slowly to be certain that the reinforcing bars are not damaged or pulled up by the machine.

The operating speed of the machine will be set by the operator based on the weight and power of the machine, the hardness of the material being removed and the depth of removal.

3.3.2 *Modification Factor*

A modification factor is used to scale down or modify the instantaneous production so that it more accurately reflects the production which will actually be achieved. It is a highly subjective number based on many inputs, both tangible and intangible. The factor may range from 0.3 for a job which expected to progress very slowly, to 0.8 to a fairly simple job with no anticipated delays.

Continuity of operation is a primary parameter effecting the modification factor. If the removal is continuous then the factor will be high but if the removal is non-continuous as in patching and other work requiring the removal of small areas then the actual production can be expected to be substantially lower than the ideal production.

The time required to remove the milled debris will also cause a reduction in the modification factor. Many machines are equipped with debris removal conveyors which load the milled material directly into a vehicle for transport away from the job site. If a milling machine is not equipped with a conveyor or if the contractor opts not to use one to gain maneuverability then the material will need to be removed by loader in a separate operation which delays production. A mechanical broom or industrial vacuum truck may be required to remove any material not picked up by the conveyor or shovel.

Downtime for maintenance on the milling machine will also contribute to the modification factor. Routine maintenance can be expected to reduce production by between ten and twenty percent. This maintenance will include such items as changing the teeth, oil, lubrication, filters, and hoses.

Intangible factors which affect production include the relationship of the milling contractor with the prime contractor and the SHA engineer or inspector. Positive relations will invariably enable problems to be resolved quickly with minimal effect on productivity or delay to the project. However if the relations are poor then production may be reduced.

3.3.3 Realistic Production

The realistic production is the production which can be expected to be achieved throughout the duration of the project. It is equal to the product of the instantaneous production and the modification factor. The rate will be used by the contractor in preparing the bid and scheduling the work.

3.4 Economics of Milling Operations

Figure 3.10 presents a work sheet for estimating the cost of removing contaminated or deteriorated bridge deck concrete with a milling machine. The seven sections of the work sheet represent distinct areas which will contribute to the cost of milling. This work sheet illustrates many of the parameters which affect the economics of milling and can be used to calculate the cost of the work under a given set of circumstances. The values used in the work sheet represent a hypothetical situation which has been developed for illustrative purposes. Resources and parameters contained on this work sheet which are also on the work sheets developed for pneumatic breakers and hydrodemolition have the same value where practical to facilitate a comparison between methods.

3.4.1 Job Specific Parameters

The job specific parameters define critical aspects of the job which a contractor must quantify in order to make a reasonable estimate. They define the area of concrete to be removed and give an indication of whether or not the work will be continuous, enabling the contractor to determine how fully the equipment will be utilized.

Job Specific Parameters:

Area of Removal:	20,000	sq. ft.
Depth of Removal:	1.00	inches
Type of Work (Patching / Entire Surface)	Entire Surface	
Number of Mobilizations:	2	
Total Mobilization Distance:	200	miles
Hours per Shift:	10.00	hours
Shifts per Day:	1	shifts/day
Overlay Removal (Yes / No)	Yes	

Equipment Production Parameters:

Cutting Mandrel Width:	6.50	feet
Operating Speed:	5.00	ft/min
Ideal Production:	32.50	sq ft/min
Modification Factor:	0.50	
Actual Production:	16.25	sq ft/min
Time to Complete Work:	20.51	hours
Time to Complete Work:	2.05	days

Equipment Rental Cost:

Equipment Purchase Price:	(\$350,000)	
Salvage Value:	\$0	
Equipment Life:	8	years
Interest Rate Applied:	24.00%	
Cost of Money:	12.00%	
Profit:	7.00%	
Inflation:	5.00%	
Annual Equipment Cost:	\$102,303	per year
Working Days per Year:	200	days per year
Daily Equipment Rental Cost:	\$512	per day
 Equipment Rental:	 \$512 per day	 x 2.05 days = \$1,049

Labor Cost:

Foreman	\$48.00	per hour
Hours per Shift:	10.00	
Number of Shifts:	1	
Foreman Cost:	\$528.00	per day
 Operator	 \$38.00	 per hour
Hours per Shift:	10.00	
Number of Shifts:	1	
Operator Cost:	\$418.00	per day
 Groundsman	 \$20.00	 per hour
Number of Groundsmen	1	
Hours per Shift:	10	
Number of Shifts:	1	
Groundsman Cost:	\$220.00	per day
 Personnel Per Diem:	 \$0.00	 per day
Number of Personnel:	0	
Lodging:	\$0.00	per day
Total Living Expenses:	\$0.00	per day
 Total Labor Cost:	 \$1,166.00 per day	 x 2.05 days = \$2,392

Mobilization Cost:

Days In Mobilization:	0.80	days
Equipment Rental Cost:	\$512	per day
Daily Labor Cost:	\$748	per day
 Total Mobilization:	 \$1,260 per day	 x 0.80 days = \$1,008

Operating Cost:

Fuel	\$20.00	per hour
Oil, Lube, Filters	\$7.00	per hour
Tooth	\$30.00	per hour
Cutting Mandrel	\$8.00	per hour
Conveyor	\$4.50	per hour
Hydraulics	\$9.00	per hour
Drum Drive	\$3.00	per hour
Bearings	\$10.00	per hour
Miscellaneous	\$8.00	per hour
Total:	\$99.50	per hour
 Equipment Operating Cost:	 \$99.50 per hour	 x 20.51 hours = \$2,041

Total Direct Cost:

\$6,490

Indirect Cost:

Overhead and Administration:	10.00%	of Total Direct Cost = \$649
Profit:	4.00%	of Total Direct Cost = \$260
 Total Indirect Costs:	 \$909	

Total Price:

\$7,398

Unit Price (per square foot):

\$0.37

Figure 3.10 Milling Cost Estimating Work Sheet

The area and depth of removal will be determined by the State Highway Agency (SHA) based on the condition of the concrete deterioration and the extent to which the bridge is being rehabilitated. This is illustrated in the work sheet where the entire surface, comprising an area of 20,000 square feet, is to be milled to a depth of one inch.

Bridge milling is usually phased to allow a portion of the bridge to remain open at all times. During the idle time between phases a milling contractor will generally schedule the equipment for other jobs, thus resulting in the need to remobilize the equipment for each phase of a job. Mobilization costs are an important component of a project's costs, therefore knowing the number of mobilizations and the mobilization distance is necessary before a contractor can prepare an estimate. The work sheet presents the case in which there are two mobilizations totalling 200 miles.

The final job specific parameter to be considered is the hours per day that a contractor is able to work on a project as determined by the hours per shift and the shifts per day. In the case illustrated in the work sheet, there is one ten hour shift per day. Contracts often limit the hours in which work may be performed in an effort to accommodate traffic patterns or other project specific conditions.

3.4.2 Equipment Production Parameters

The estimated equipment production is determined as presented in the previous section with a combination of equipment components and abilities and job specific parameters. The time required to complete the work is calculated from the production rate and the computed hours available per day. In the case presented in the work sheet, the machine has a 6.5 foot wide cutting mandrel and is expected to progress at 5 feet per minute, thus realizing an ideal production of 32.5 square feet per minute. However this is reduced by a modification factor of 0.5, resulting in an actual estimated production of 16.25 square feet per minute. At this rate it will take 20.51 hours or 2.05 working days to mill the specified area.

3.4.3 Equipment Rental Cost

The equipment rental cost corresponds to the cost to the contractor to own the milling machine. It can be considered a fixed cost since it is not quantity sensitive. It is based on an annual equivalent cost distribution of the equipment purchase price less its salvage value, an estimated equipment life and an interest rate which is determined by the cost of money, inflation and profit. This process and the equations used are described in greater detail in section 4.4.3.

The annual cost represents the cost to the contractor to own the piece of equipment for a one year period. For a piece of equipment to be an economically justified investment it must recover its annual owning cost through production. Therefore it is to the contractors benefit to utilize the equipment as fully as possible to recover these owning costs and to offer the services at a competitive unit cost. By estimating the days per year that the equipment will be used, a daily equipment owning cost can be calculated.

A milling machine costing \$350,000 with no expected salvage value and an expected useful life of eight years will have an annual cost of slightly over \$100,000 using an applied interest rate of 24%, calculated as the sum of the rates allocated for the cost of money, profit on the equipment and inflation. If the machine is expected to be operated 200 days per year, then the daily equipment rental cost is \$512 per day.

3.4.4 Labor Cost

The next major cost component of a contractors bid is the labor cost. The primary factors effecting the labor cost are the labor rate, crew size and the hours worked per day. Milling crews generally consist of a foreman, a machine operator, and one or more laborers. The wage rate for these workers is based on the prevailing wage rate

for the region at the time of the work. An allowance for personal expenses and lodging should be included if crews are required to work away from their normal base of operations.

The case presented in the work sheet utilizes a three man crew consisting of a foreman, a machine operator, and a groundsman. The total cost per day for this crew is \$1166, with no allowances made for personal expenses.

3.4.5 Mobilization Cost

The number of mobilizations and mobilization distance will determine how much time will be spent in transit. The daily equipment owning or rental cost and the daily labor cost can then be applied to the time in transit to determine the mobilization cost. The key to this cost is that equipment and labor costs must be recovered regardless of whether they are working or in transit.

Given the mobilization distance, the number of mobilizations and an estimated daily travel distance of 250 miles, the days in mobilization can be calculated as 0.8 days. When this is multiplied by the daily equipment and labor cost, the total mobilization cost can be calculated as just over \$1000.

3.4.6 Operating Cost

Operating costs are those costs which are incurred by the equipment only while it is working. These costs are proportional to the time a machine is in operation and include items such as fuel oil, lubrication, and wear parts such as cutting teeth. All of these operating costs are calculated on a per hour basis and multiplied by the estimated hours which the equipment is to be in operation to determine the total operating cost.

The primary operating costs in the work sheet are fuel and replacement teeth, which are \$20 per hour and \$30 per hour respectively. The total operating cost, \$2041, is calculated as the total hourly operating cost, \$99.50 per hour, times the previously calculated time to complete the work, 20.51 hours.

3.4.7 Direct Cost, Indirect Cost, and Profit

Equipment owning cost, labor cost, mobilization cost and operating cost are all direct costs. which can be directly attributed to a project. The total direct cost for the cost estimating work sheet is \$6490.

The contractor will incur other costs for management and administration which are difficult to attribute directly to the project. To account for these indirect costs a contractor must add a mark-up, usually expressed as a percentage of the direct cost to determine the total cost. A mark-up will also be included to provide for a profit. The amount of the profit markup is related to the size of the project, the perceived risks, and the degree of competition. For this example, mark-ups of 10% for overhead and administration and 4% for profit were used.

The direct cost and the additional markups comprise the total estimated price to remove the concrete by milling which is equal to \$7398 in this example. A unit price for doing the work can be calculated by dividing the total price by the area of removal. The unit price for milling 20,000 square feet of concrete as calculated in the work sheet is less than \$0.37 per square foot.

3.4.9 Sensitivity Analysis

Figure 3.11 presents a sensitivity analysis based on the cost estimating spreadsheet. It illustrates how the unit price of performing the work varies with the quantity of material removed. To maintain consistency, changes were made in the area of removal only, all other job specific and production parameters were held constant.

Although the equipment, labor and operating cost all retained a constant daily or hourly cost, the increase in the time to perform the work caused increases in the total cost for these components.

At low quantities of removal, an increase in quantity results in sharp reductions to the unit cost. This is because increases in quantity allow the fixed cost, which dominate the price of performing the work at this point, to be more evenly distributed. Between 500 square feet of removal and 5,000 square feet of removal the unit cost drops almost 80 percent from \$2.61 per square foot to \$0.54 per square foot. At high volumes of removal, the fixed costs no longer contribute significantly to the unit price. The variable costs increase in proportion to the quantity and therefore the unit price remains relatively constant.

3.5 Managing and Controlling Quality

Quality is defined as the degree to which the work satisfies the intended need or purpose. For the quality to be properly assessed, the intended need or purpose must first be clearly understood. Specifications typically describe the quality requirements for the project as a whole as well as the standards to be met by intermediate tasks

Sensitivity of Milling Unit Price to Total Quantity

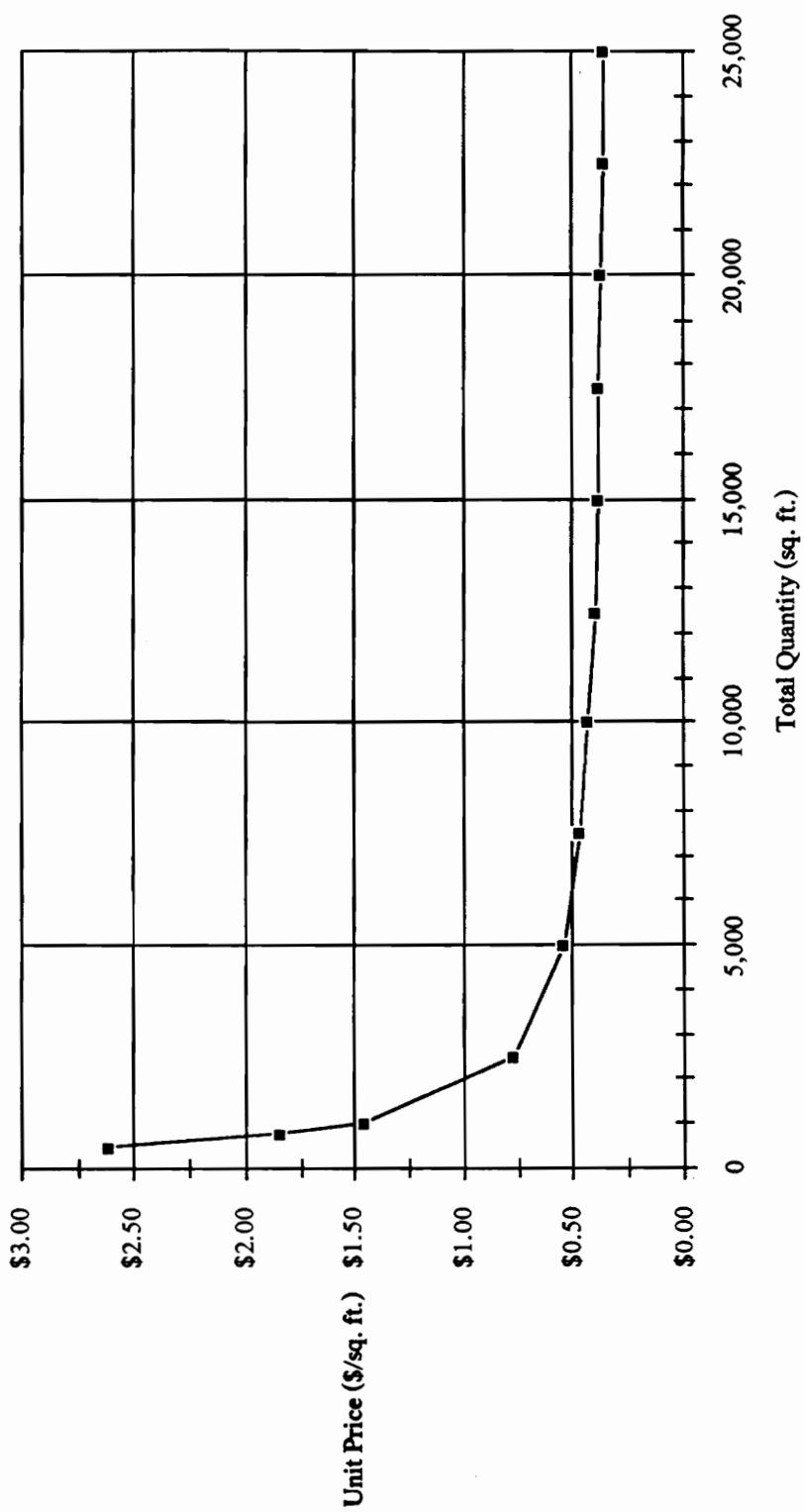


Figure 3.11 Sensitivity Analysis of Milling Price

such as milling. The section which follows examines the issue of quality by addressing the issues of quality requirements, residual cracking and specifications.

3.5.1 Quality Requirements

Specific requirements must be established and maintained to ensure that the quality is of an acceptable level. This section addresses five issues concerning requirements which will ensure that the desired quality is achieved.

- 1) Inspector. The inspector, as representative of the project engineer, has the responsibility of monitoring the quality of the intermediate tasks and to locating any potential problems which may effect the final project. The inspector must also ensure that the contractor complies with the contract, the specifications and the drawings and thus he or she has front line responsibility for resolving any disputes concerning the interpretation of the contract documents.

The conformity of the milling operations to the depth and cross slope requirements as specified in the contract plans or specifications must also be monitored. While deviations from the specified depth and cross slope will

have little effect on the milling operations, they may cause quantity and cost overruns in the subsequent overlay operations.

- 2) Machine size. A machine which is not the proper size to perform the work can result in a product of inferior quality. A machine which is too small will not have the necessary production to be economical. An underpowered machine may also damage the residual concrete if the machine is pushed beyond its capabilities when removing the concrete to the required depth and area.

A machine which is too large will not have the control or maneuverability required for bridge milling work. Additionally, the weight and vibrations of a large machine can easily damage the remaining deck or structural components of the bridge.

Appropriate precautions must be taken to insure that the bridge structure is not loaded beyond its capacity. Any weakening of the bridge due to a reduction in depth and the relocation of the neutral axis caused by removing surface concrete should be taken into account when evaluating the structural capacity of the bridge.

- 3) Surface texture. The milling process leaves the residual concrete with a rough textured finish which may be either opened to traffic immediately or covered with an overlay material. The texture of the finish produced by a milling machine is dependent on the tooth configuration, the mandrel rotation speed and the rate at which the machine progresses. The grid pattern produced by milling allows the overlay material to interlock with the milled surface, forming a tight bond.
- 4) Reinforcing. Great caution must be exercised when operating a milling machine in the vicinity of the top mat reinforcing steel. On projects which require that the milling operation remove the concrete to a depth which approaches the cover over the reinforcing bars, the machine should proceed very slowly and under close control of the machine operator and groundsman. Because the cover over the reinforcing bars is not always uniform, the machine may occasionally catch a bar and pull it up out of the concrete. This frequently damages the machine by breaking teeth and holders, and can cause extensive damage to the deck.

Milling to this depth is a very costly, time consuming and risky operation. It is frequently more cost effective to utilize the milling machines to remove the concrete to a reasonable depth above the reinforcing, and to use other methods

such as pneumatic breakers or hydrodemolition to remove any remaining damaged concrete.

- 5) Environmental concerns. The dust generated by the milling and debris removal operations can obstruct the vision of both the machine operator and the passing motorist. It should thus be monitored and maintained at acceptable levels so as not to endanger traffic or impact the surrounding environment. Most machines are equipped with water systems which aid in the suppression of dust.

Equipment noise should also be monitored, especially if the work is being performed in densely populated urban areas. Water run-off is generally not a problem, but appropriate containment measures should be taken if run-off is likely to impede traffic or pollute the environment.

3.5.2 Residual Concrete

Studies have shown that impact methods of concrete removal such as milling may produce a bruise layer of concrete with small cracks extending between one half and three quarters of an inch into the residual concrete. These cracks reduce the strength

of the concrete, lower the bond between concrete and steel and reduce the bond between the existing structure and any overlay material.(Hindo, 1987)

Milling machines reduce the potential of microcrack formation by having the cutting mandrel rotate upward and into the cut as discussed in section 3.1.2 and illustrated in figure 3.5. This directs the angle of impact away from the concrete which is to be removed and not downward into the residual concrete. However contractors and inspectors should be aware of this problem and take steps to minimize it when possible. The best way to minimize the potential for microcrack formation is to keep the cutting head on the milling machine well maintained and to be certain that the machine does not progress at too rapid of a rate.

3.5.3 Specification

A specification is a written technical description detailing the methods, materials, and equipment required to perform a specific task to the prescribed standard of quality. Most SHA Road and Bridge Specifications do not contain any information concerning bridge milling operations, and those that do mention it are generally quite vague. Appendix A contains a sample specification for concrete milling for bridge rehabilitation projects. This specification is largely based on a guideline specification

for cold planing asphalt pavement presented by the Asphalt Recycling and Reclaiming Association (ARRA), with alterations to make it applicable to concrete bridge decks.

The primary purpose of the specification is to describe the quality which must be achieved by the milling operations. This is accomplished through equipment standards, operating procedures, risk apportionment and measurement and payment terms.

Equipment standards are specified to ensure that the equipment used is able to produce a product of acceptable quality. This is especially critical with methods such as milling in which the quality is primarily dictated by the equipment. Specifications will also contain a section describing the procedures for performing the work. This insures a consistency in operations which will aid in establishing standards of quality. However the degree to which these standards have been met is largely left to the discretion of the engineer.

Inconsistencies in the depth to the reinforcing steel can be considered as unforeseen subsurface conditions. Therefore, it is the responsibility of the SHA to determine this measurement prior to commencement of the milling operations either with a pacometer as discussed in section 3.2.3 or through as-built drawings or maintenance records.

Changes may be made to the depth of removal as the work progresses in response to actual conditions encountered.

Work may need to be redone either to meet the depth requirement specified by the contract or to produce an acceptable pattern or texture on the milled surface. Care should be taken when increasing the depth of removal not to strike any reinforcing bars.

By specifically stating what is required concerning the equipment and the work procedures, the specifications perform the function of apportioning risk. A specification should clearly state what is required of the milling contractor while avoiding job specific phrasing which would limit it from being applicable on a universal basis.

The specifications will define the method of measurement and the basis of payment. By specifying the method of measurement as the area of removal for a specified depth or class of removal, the risk of quantity variations is reduced. The basis of payment must define what is to be included in the unit price for the milling work.

4

Hydrodemolition as a Concrete Removal Technology

This chapter examines hydrodemolition as a technology for removing concrete as a part of the bridge rehabilitation process. Hydrodemolition is a capital intensive technology which utilizes the energy of a high pressure water jet to destroy the cement matrix and thus remove the concrete. It is capable of attaining a high rate of production while selectively removing deteriorated or contaminated concrete to the desired depth from flat horizontal surfaces. It is effective in cleaning the reinforcing steel and preparing the surface for a subsequent overlay.

4.1 Technical Description

Hydrodemolition in its simplest terms involves the pressurization of water and the controlled delivery of a water-jet. To accomplish this requires a sophisticated equipment system consisting of two distinct components: a power unit and a demolishing unit. This section examines the hydrodemolition system first by discussing the equipment and components and then by addressing the system and the calibration process.

4.1.1 Power Unit

Figure 4.1 shows a typical power unit used to provide the high pressure water required for hydrodemolition. It is comprised of a drive engine, a high pressure pump, water filters, water reservoir tank and other ancillary equipment. The power unit is housed in a large metal container on a flatbed tractor trailer.

The water supplied to the power unit is passed through a series of filters before storage in the reservoir tank. The filters remove solids from the water to prevent excessive wear on the high pressure system.

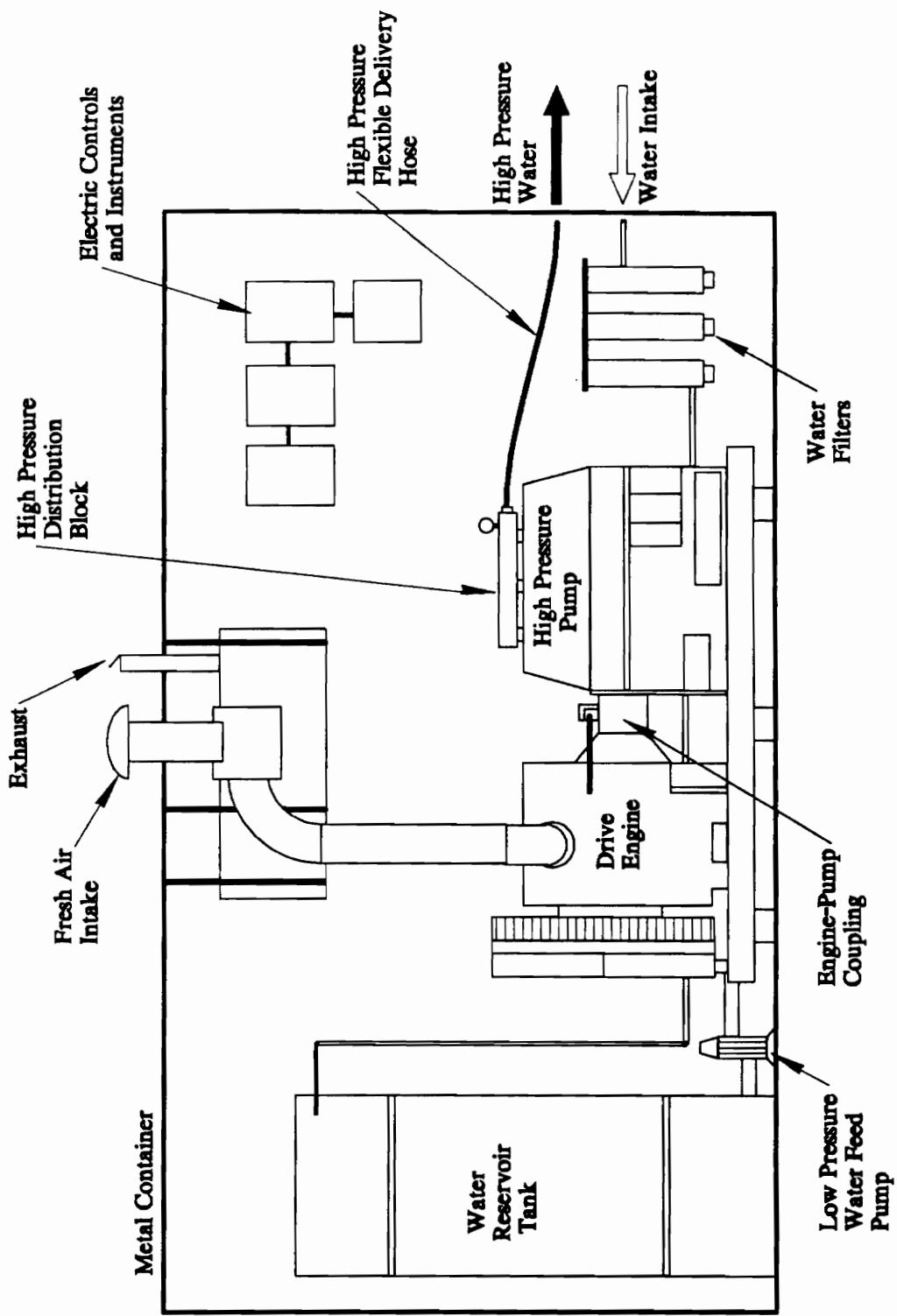


Figure 4.1 Hydrodemolition Power Unit

The high pressure pump is driven by a 300 to 500 horsepower diesel engine. The engine size varies depending upon the specific system make and the capacity of the pump. Two different types of high pressure pumps may be used. A plunger or piston type pump is able to pressurize the water to between 12,000 to 20,000 psi at a flow rate of 20 to 70 gpm. An intensifier pump is capable of pressuring small flows of water to ultra high pressures. One hydrodemolition system currently uses intensifier pumps which deliver water at 35,000 psi and 13 gpm.

Hydrodemolition systems may utilize one or two power units. Using two power units running in tandem doubles the flow rate, roughly doubling the productive capacity of the hydrodemolition system.

4.1.2 Demolishing Unit for Bridge Decks

The demolishing unit used for bridge decks is a microprocessor controlled, wheeled vehicle as illustrated in figure 4.2. A water delivery nozzle is attached to a trolley which traverses back and forth along a cross-feed beam at a programmed rate. The nozzle is rotated or oscillated at a constant programmed frequency. At the end of the trolley's programmed cycle the entire demolishing unit advances or indexes forward a set distance. Microprocessor controls dictate all movements of the nozzle, the nozzle

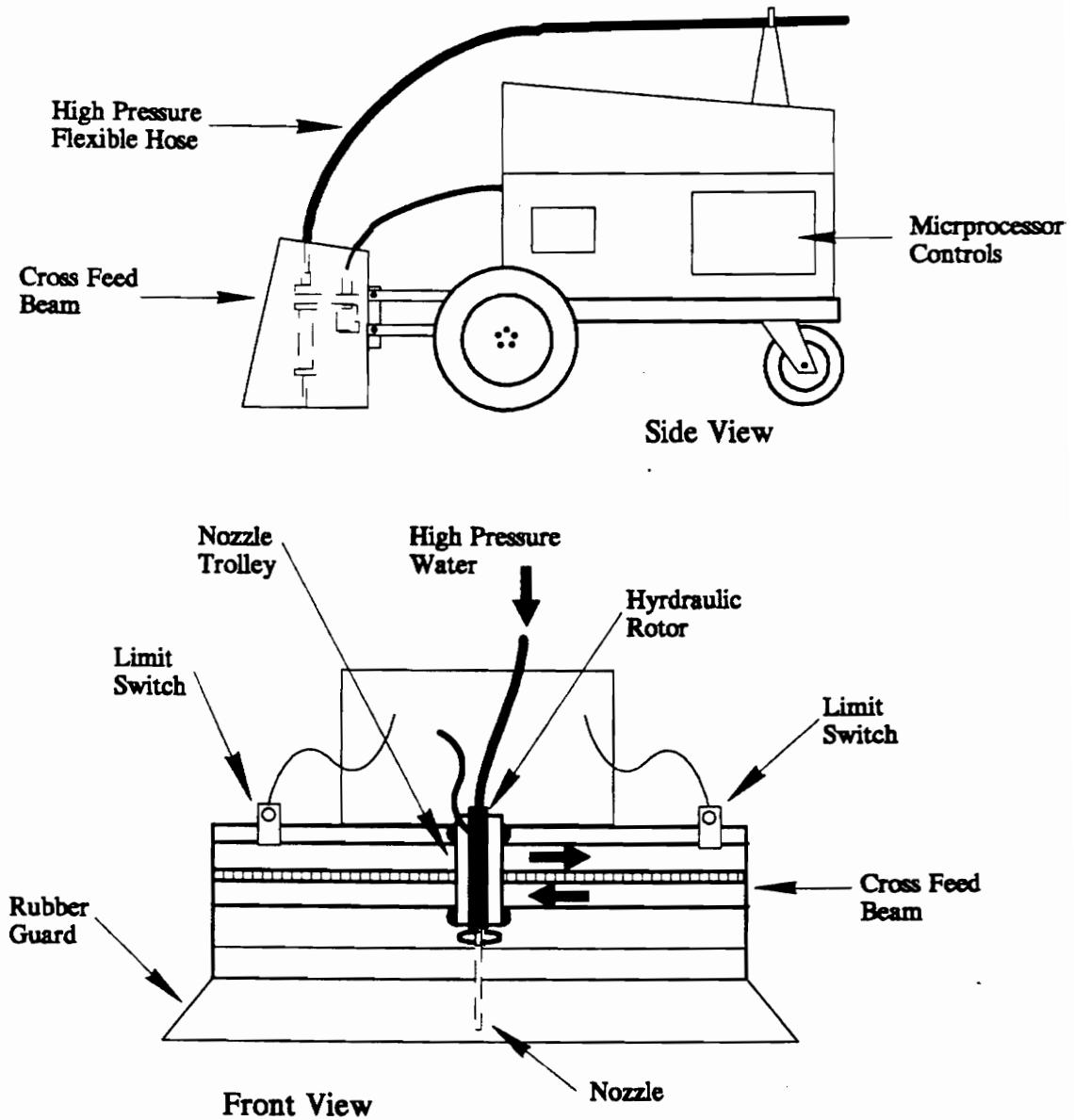


Figure 4.2 Hydrodemolition Demolishing Unit

trolley, and the demolishing unit to ensure precise control over the fluid dynamic properties of the water-jet and to provide consistent quality.

Limit switches located at opposing ends of the cross-beam can be adjusted within the length of the beam to produce a cut of desired width, enabling the unit to remove various sizes of rectangular areas.

High pressure water is delivered from the power unit(s) to the nozzle by high pressure flexible hosing. The flexible hosing consists essentially of a hose within a hose. The inner hose carries the high pressure water while the outer hose serves to shield the inner hose from cuts and acts as a safety containment should the inner hose burst. The system is also designed with an emergency water shut off valve which automatically activates should a hose lose pressure or rupture.

4.1.3 Equipment for Vertical and Overhead Surfaces

The demolishing unit is the predominant piece of equipment used in hydrodemolition on bridge decks. Some makes of equipment have special attachments which enable the cross-beam to be held upright or overhead for concrete removal on vertical and overhead surfaces. This type of equipment is not used frequently on bridges because

the substructure elements have small, irregular surface areas which are difficult to access.

Manufacturers do make a hand-held wand for concrete "dental work". These operate at lower pressures and flow rates and require a person to hold the wand and direct the water-jet over the concrete surface. The loss of microprocessor control over the water-jet's movement causes the quality to vary and safety considerations make hand held water-jets all but impossible to use.

Some experimental equipment exists for special application concrete removal work such as columns and tunnels. This type of equipment is generally produced by a manufacturer for a specific job and is typically not owned by hydrodemolition contractors. The economics of producing such specialized equipment usually require that the specific job absorb the entire cost of developing the piece of equipment.

4.1.4 Operating System

The equipment required to perform hydrodemolition work consists of a trailer containing the power unit, the demolition unit itself, and equipment needed for debris

removal and cleanup. If there is not a water source available, a water supply truck will also be required.

A hydrodemolition subcontractor typically provides the hydrodemolition equipment and operators required to perform the concrete removal work. All other ancillary equipment and personnel required for debris cleanup, water supply, water runoff control and debris containment are generally supplied by the general contractor.

The operating parameters for the hydrodemolition system are established through a process of estimating and testing. The summary of the process is outlined in figure 4.3 which shows that the contractor initially sets the equipment operating parameters based on job parameters, concrete parameters and past experience.

A trial area of sound concrete is hydrodemolished using these estimated operating parameters. After evaluating the results of the trial area the system parameters are adjusted until the desired mean removal depth is achieved. The system is then tested on an area of deteriorated concrete and the operating parameters recalibrated until the concrete is removed to the desired level of soundness.

The microprocessor control ensures constant, repeatable results. However, if the concrete material or job parameters change then the equipment must be recalibrated.

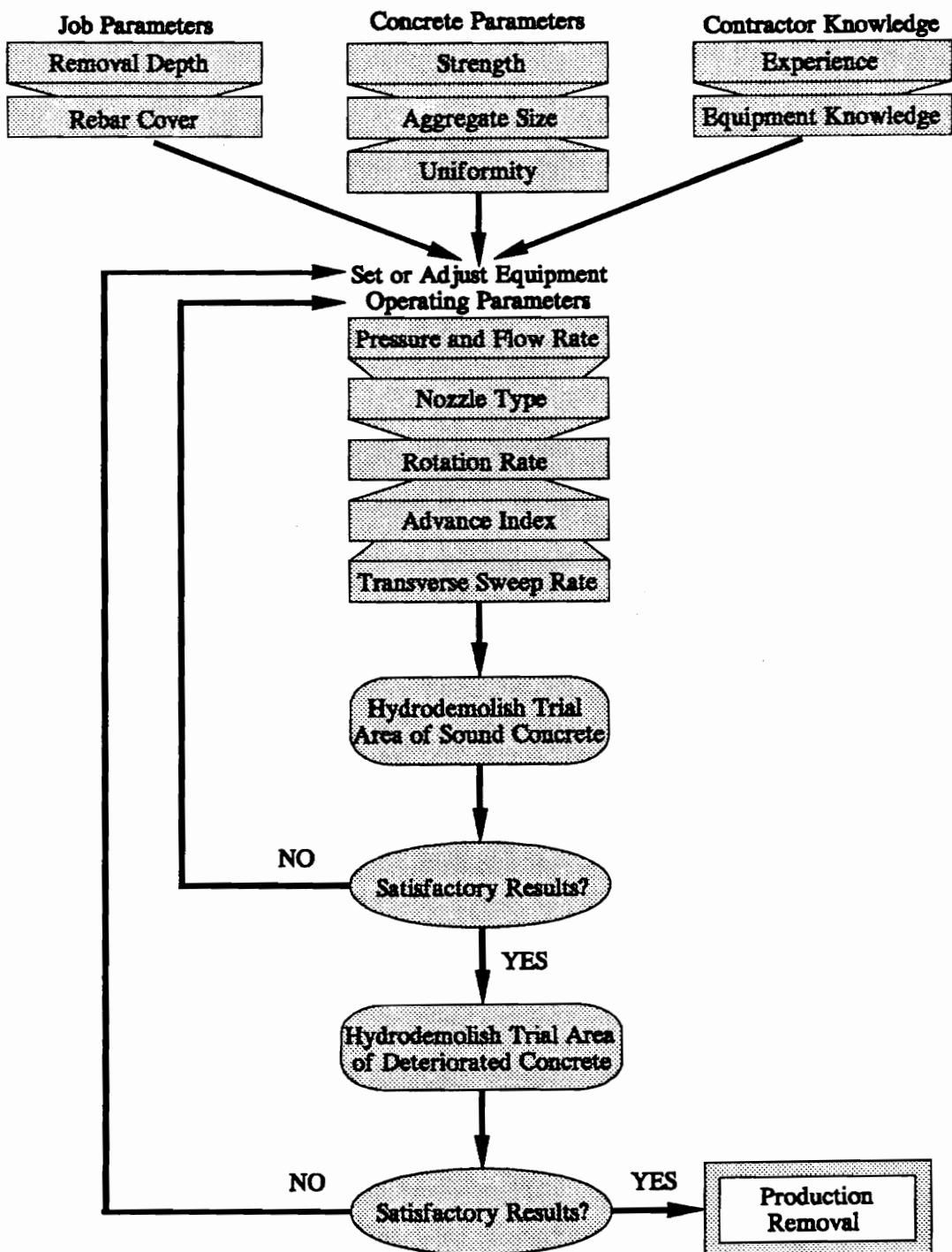


Figure 4.3 Summary of Hydrodemolition Calibrating Process

4.2 Work Characteristics

This section addresses the work environment and the associated operating procedures which will enable hydrodemolition to be performed at maximum efficiency and effectiveness.

Hydrodemolition is primarily applicable to projects which require the extensive removal of deteriorated or contaminated concrete to a desired depth or level of soundness over a large continuous area.

4.2.1 Project Type and Location

Hydrodemolition is constrained by design to removing concrete from flat level surfaces and from areas of a constant width as dictated by the limit switch settings discussed in section 4.1.2. Bridge decks which have been determined to contain large quantities of contaminated or deteriorated concrete are ideally suited to take advantage of hydrodemolition's ability to remove concrete from around and below the reinforcing while operating within the restraints imposed by the equipment geometry and operations.

The high capital costs and the high degree of mechanization involved make hydrodemolition most favorable if operated on projects which will enable it to be operated uninterrupted.

Access to the site should be such that a sizable portion of the deck is available to allow the hydrodemolition equipment to perform the necessary work with as few set ups as possible.

Hydrodemolition will require that a portion of the bridge be completely closed to traffic for an extended period of time. Although the high productivity associated with hydrodemolition enables the concrete removal to be performed quickly, the surface produced is not suitable to be re-opened prior to resurfacing, which may not occur for several days.

The specialized nature of owning and operating hydrodemolition equipment means that it is frequently more economical for the work to be done by specialty subcontractors. They are better able to achieve the number of hours required to recover the high initial investment and able to meet the specialized maintenance demands of the equipment.

4.2.2 Type and Extent of Deterioration

Hydrodemolition equipment can be calibrated to remove sound, chloride contaminated or deteriorated concrete to the depth necessary to achieve an acceptable level of contamination in the residual concrete. Selective removal is achieved by applying a constant amount of energy to the concrete in a manner which causes all material with less than the required strength to be removed regardless of depth.

4.2.3 Preparation Work and Traffic Control

Identification methods such as half cell potential measurement and core sampling are able to detect the chloride content in concrete and typically result in projects requiring the removal of concrete over the entire area of the bridge deck. Although the resultant concrete removal operations are quite exhaustive, the process eliminates any variability associated with the detection of unsound concrete.

The work area may be cordoned off with either concrete barriers or traffic barrels, depending on the extent of the rehabilitation and the traffic conditions. A primary concern related to the method of traffic control is the containment of the water and paste like slurry which may flow into adjacent lanes open to traffic.

If concrete barriers are used to cordon off the work area then a silicon caulk can be used to form a seal between the bottom of the barriers and the bridge deck thus preventing the runoff water from flowing into adjacent lanes of traffic. Hay bales are often used to filter the debris and suspended solids out of the runoff when traffic barrels are used as the method of traffic control.

In either case, it is not possible to completely prevent water from running into adjacent open traffic lanes. Construction warning signs which inform the motorists that unexpected wet pavement lies ahead should be used to provide additional safety. Runoff control is discussed in more detail in section 4.5.1.

4.2.4 The Material to be Removed

The strength, uniformity of strength and aggregate size of the concrete will determine how effectively a hydrodemolition system is able to remove the material. These material properties also determine the resultant surface profile obtained from hydrodemolition. Each of these properties must be evaluated to establish the optimum fluid dynamic operating parameters and the expected results of hydrodemolition.

- 1) Strength of material. Hydrodemolition removes concrete by applying a water-jet of greater energy than can be absorbed by the material being removed, as discussed in section 4.2.2. The strength of the concrete will therefore determine how much energy it is capable of absorbing and the associated water-jet energy required to remove it.
- 2) Uniformity of strength. A hydrodemolition system is calibrated to remove concrete of a uniform strength to a specified depth. Any deviation in the strength of the concrete encountered will result in an inconsistent depth of removal. A lower strength concrete will be removed to a greater depth and a higher strength concrete will not be removed to as great a depth.
- 4) Aggregate size. The concrete aggregate will primarily effect the hydrodemolition operation by determining the texture of the resultant surface. Hydrodemolition removes concrete by destruction of the cement matrix, it does not split or cut the aggregate. The resulting surface profile has a texture as determined by the maximum aggregate size as illustrated in figure 4.4.

Surface Profile of Hydrodemolished Concrete

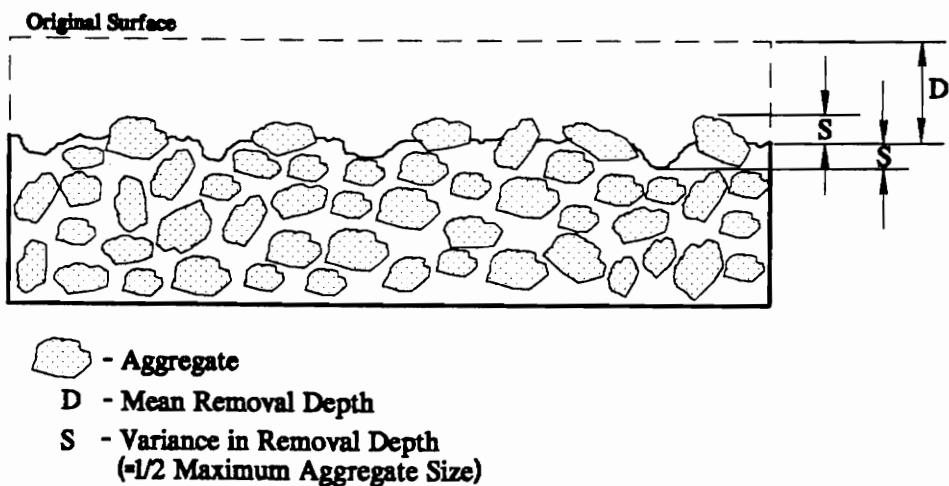


Figure 4.4 Mean Depth of Removal as a Function of Aggregate Size

4.2.5 The Area of Removal

Economic recovery of the high owning and operating costs associated with hydrodemolition will not be able to be realized unless the equipment is able to be operated over a large and continuous area, as discussed in section 4.2.1.

The area which may be removed by hydrodemolition is physically limited by the machine geometry and method of operation. As discussed in section 4.1.2, the cross-beam width and limit switch settings will determine the width of the cut, and therefore the number of passes which will be required.

4.2.6 Depth of Removal

The mean depth of removal is determined by the energy of the water-jet, the previously set system parameters and the strength of the material being removed. The energy delivered by the water-jet depends on three factors. These are:

- 1) Distance from nozzle to point of impact. The water-jet will realize maximum impact energy at a prescribed distance from the nozzle. If the distance is reduced, the build up of water at the impact surface will cause a reduction in the impact energy. If the distance is increased the water-jet will experience a reduction in energy due to loss of stability, decreased velocity and greater dispersion.
- 2) Angle of impingement. The angle the water-jet impinges the concrete affects the depth of concrete removal as illustrated in figure 4.5 (Thiruvengadam, et al., 1983). Examination of this figure reveals that there is an optimum angle of impingement which is dependent upon the other water-jet fluid dynamic parameters and the properties of the concrete being removed.

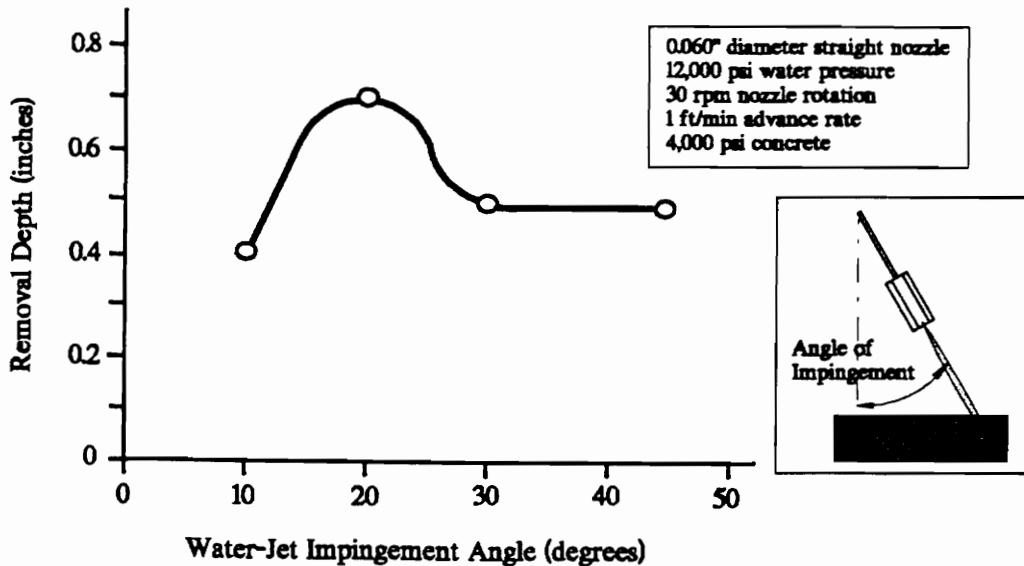


Figure 4.5 Affect of Impingement Angle on Removal Depth (Thiruvengadam, et al., 1983)

- 3) Time of impingement. The duration that the water-jet impinges a unit area of concrete is important in determining the concrete removal depth. Figure 4.6 shows the concrete removal depth as a function of the time of impingement (Thiruvengadam, et al., 1983). Examination of figure 4.6 reveals that increasing the time of impingement of a water-jet increases the depth of removal. There is however, a point at which increases in the time of impingement do not appreciably increase the removal depth.

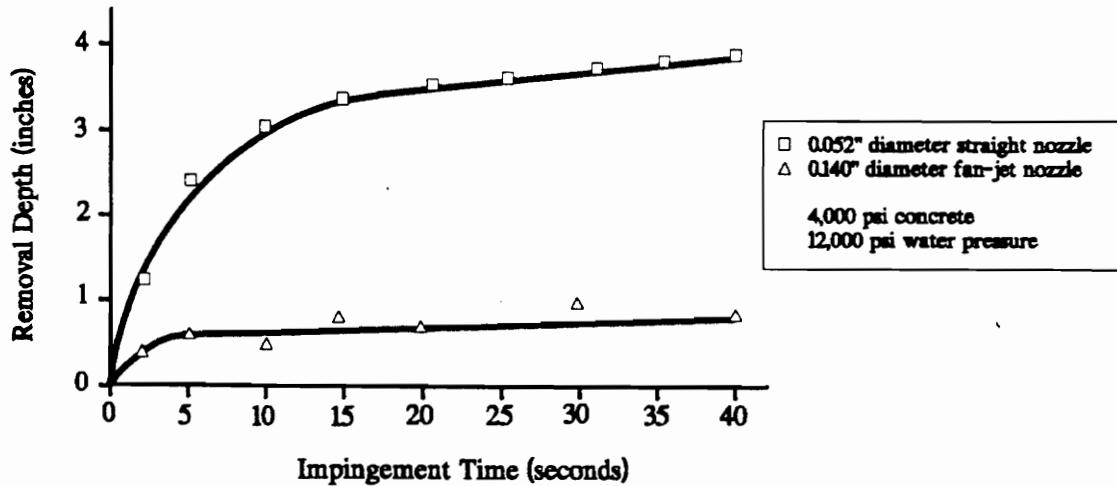


Figure 4.6 Affect of Impingement Time on Removal Depth (Thiruvengadam, et al., 1983)

4.2.7 Debris Removal and Clean-up

The demolished concrete and other waste products arising from hydrodemolition form a combination of rubble, slurry and runoff water. Cleanup is accomplished by vacuuming or manual shoveling the coarse particles and flushing the slurry and fine particles away with fresh water.

The slurry should not be allowed to dry on the prepared surface as the paste rehydrates and adheres to the deck. If rehydration of the paste occurs then the deck

must be thoroughly water blasted or sand blasted to provide a clean, bondable surface. The requirement to provide a good bonding surface for patches or overlays means that water or sand blasting operations must be performed or repeated no more than twenty-four hours prior to the overlay placement.

An industrial vacuum truck is often used to clean the hydrodemolition waste.

Vacuuming takes place forty to fifty feet behind the advance of the demolishing unit using a hand held vacuum nozzle. The vacuumed area is frequently flushed with fresh water and revacuumed before the required level of cleanliness is reached.

Confined working areas do however limit the use of vacuum trucks due to three factors. These are:

- 1) Access. The vacuum trucks, which are roughly the size of normal highway dump trucks, must be able to enter and exit the work area to dump the waste.
- 2) Hose length. The hose length on a vacuum truck generally does not extend beyond approximately one hundred feet, limiting the area which may be serviced.

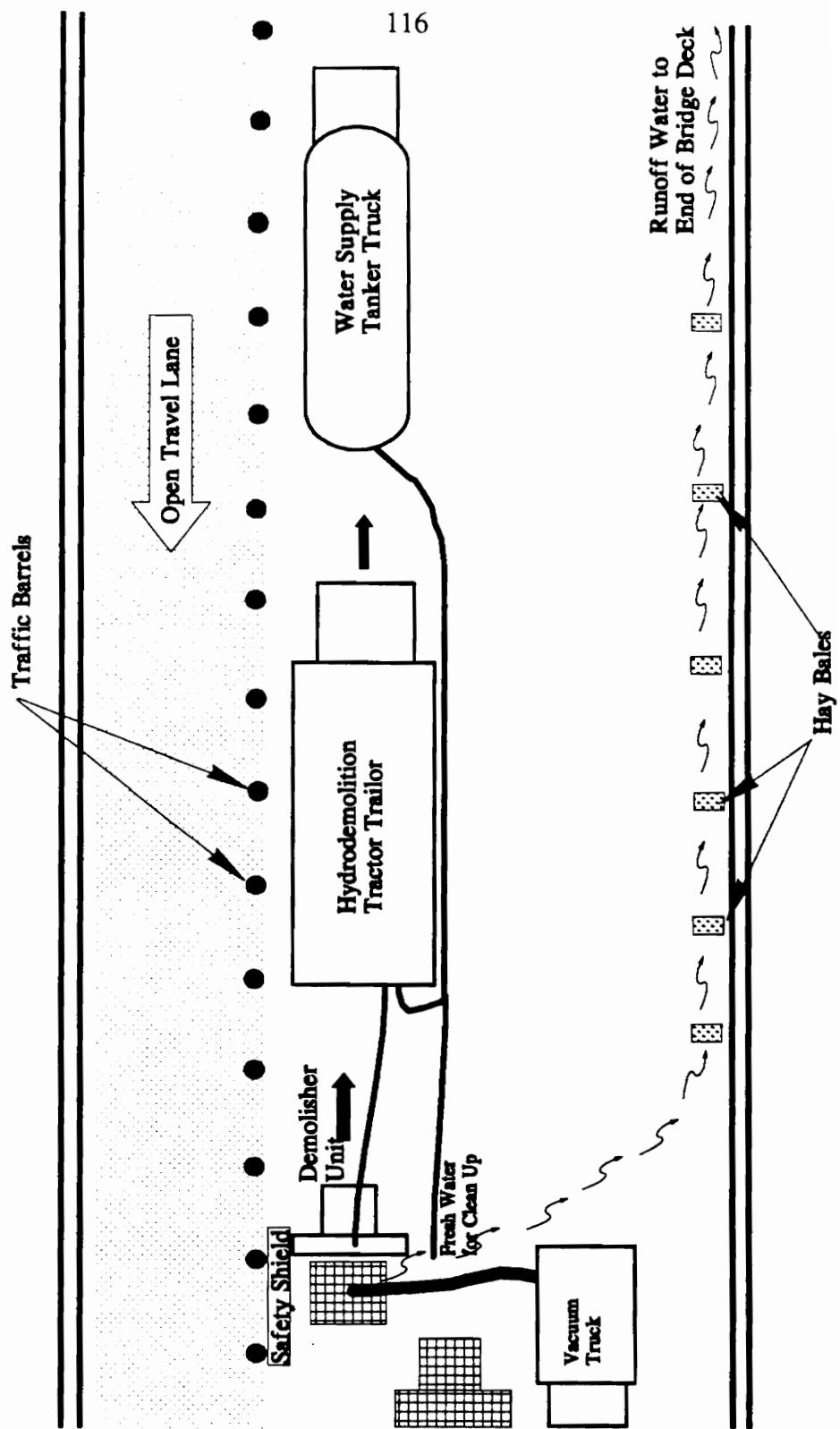


Figure 4.7 Hydrodemolition Setup Utilizing a Vacuum Truck

- 3) Travel. The vacuum truck can not be allowed to ride upon a hydrodemolished surface with exposed, unsupported reinforcing steel.

Thus, using an industrial vacuum truck generally requires a two lane wide work space. Figure 4.7 shows a typical hydrodemolition system set up utilizing an industrial vacuum. While the use of an industrial vacuum reduces the volume of water runoff it does not eliminate the need for water runoff control.

Another method of hydrodemolition cleanup involves hand shoveling the rubble and flushing the deck with clean water. This method is more labor intensive and requires controlling a larger volume of runoff water than vacuuming but is better suited to confined work spaces where large equipment can not be used. Figure 4.8 shows a typical hydrodemolition system setup utilizing a manual cleanup operation.

In addition to the runoff control and debris filter methods discussed in section 4.2.3, the deck drains are often plugged to allow the water to run down the bridge deck in an effort to settle the cement and fine aggregate particles out of suspension. Sand bags may be used to direct the flow of the runoff and hay bales or pea gravel dikes are often used to filter the suspended solids out of runoff water. Environmental considerations associated with hydrodemolition runoff are discussed in section 4.5.1.

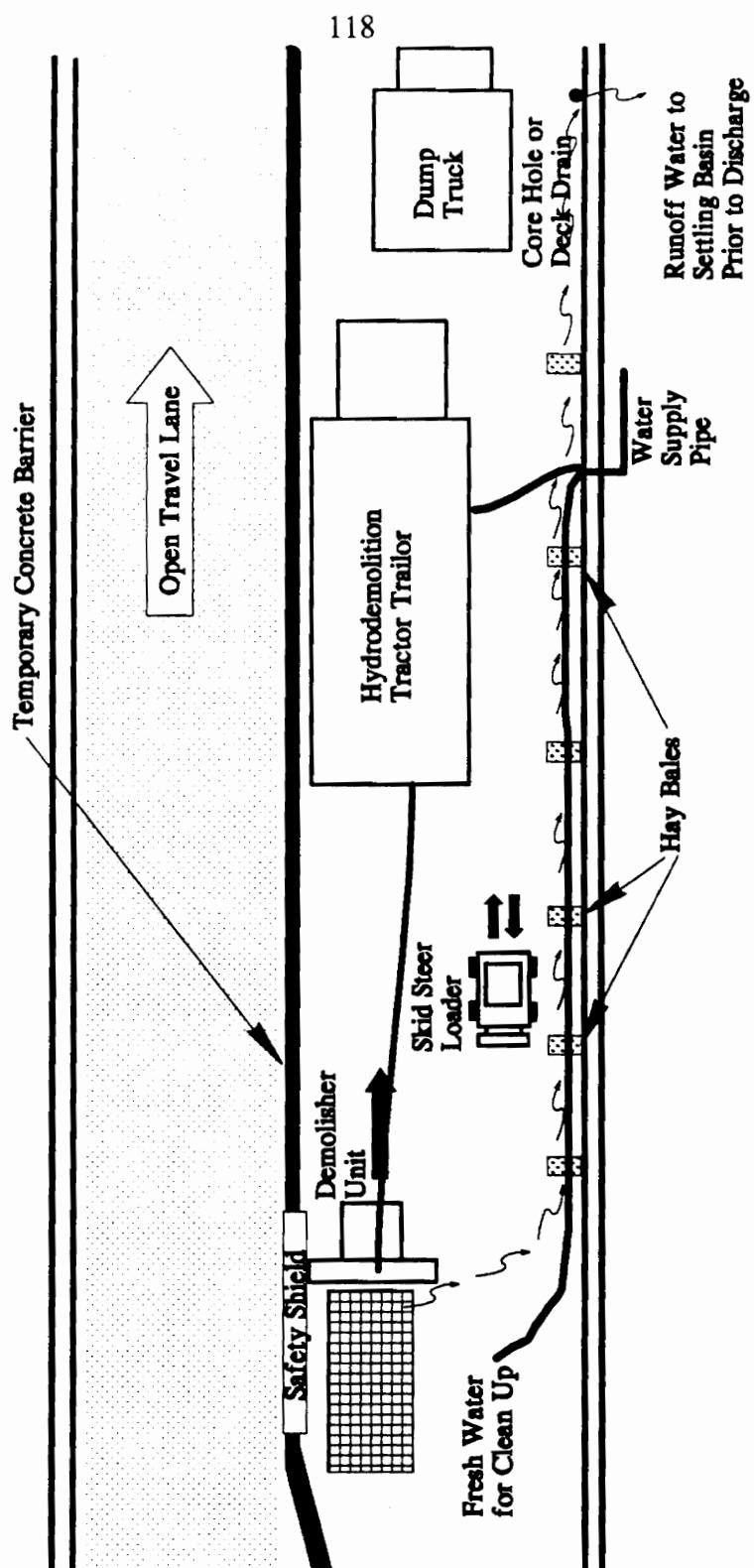


Figure 4.8 Hydrodemolition Setup Utilizing Manual Cleanup

4.3 Production Estimating

Production estimates are considered highly guarded, proprietary information by hydrodemolition contractors. This is because contractors must use their own experience to refine rough estimating guides provided by manufacturers in order to develop a more accurate means of estimating productivity. Hydrodemolition contractors feel that refined estimating methods provide an important competitive advantage and thus they are unwilling to discuss any information. In addition, many hydrodemolition contractors modify their equipment to improve performance and any competitive advantage in this area is also not openly shared.

The parameters which must be considered and the process used in arriving at the hourly production estimate are summarized in figure 4.9.

4.3.1 Instantaneous Production

Instantaneous production is the quantity of concrete removed for each unit of time the water-jet spends actually impacting the concrete. This is a function of equipment parameters, concrete properties and job parameters.

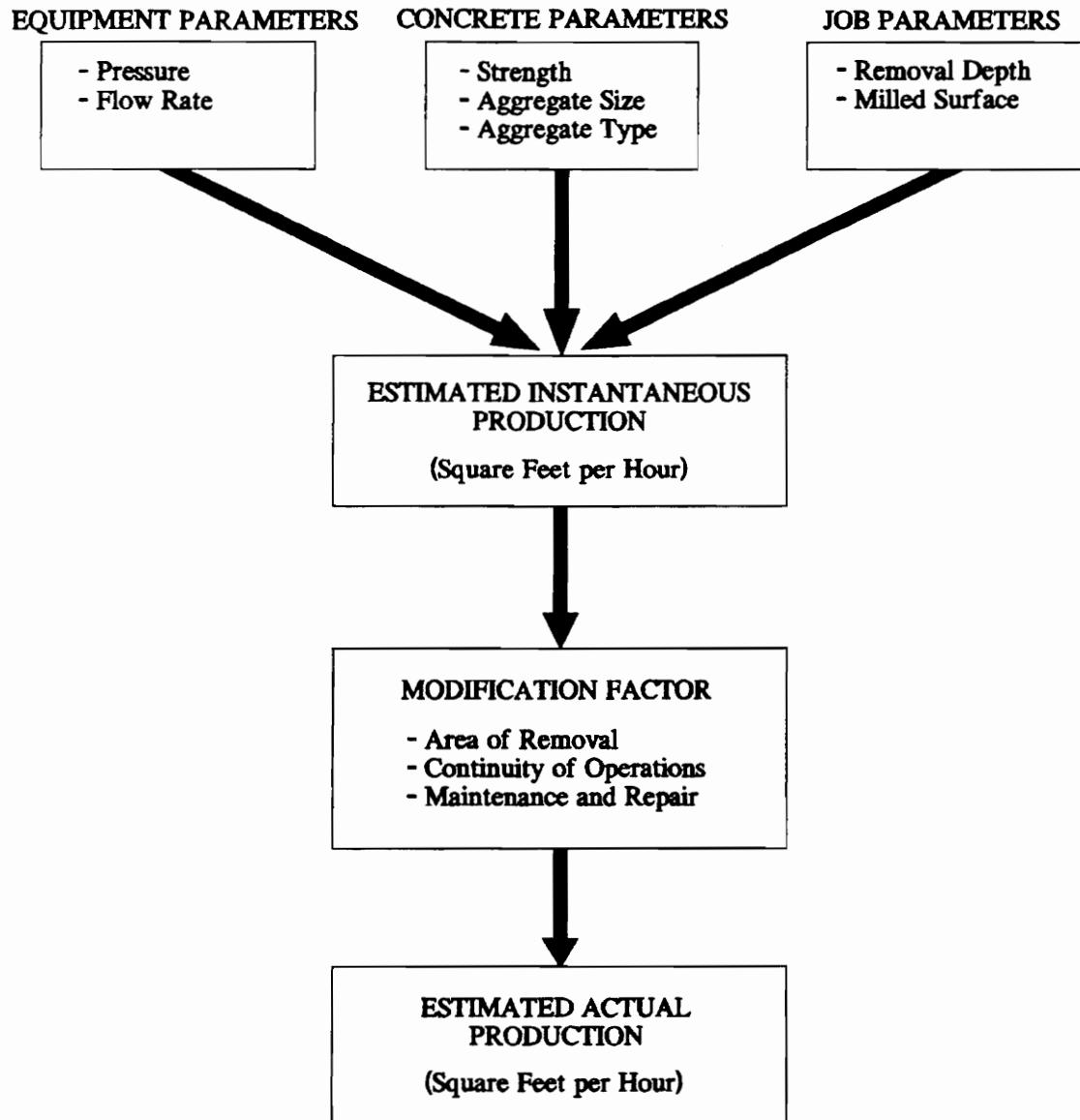


Figure 4.9 Hydrodemolition Productivity Estimating Process

- 1) Equipment parameters. The primary equipment parameter effecting the instantaneous production of a hydrodemolition system is the power of the water-jet measured in terms of both the pressure and the flow rate of the water.
- 2) Concrete properties. The concrete's strength, aggregate size and aggregate type all influence hydrodemolition's instantaneous productivity. The stronger the concrete the lower the instantaneous productivity. The aggregate type is significant because it affects the cement-to-aggregate bond strength.
- 3) Job parameters. The required removal depth is the main job parameter which influences instantaneous production. The depth related factors which contribute to hydrodemolition production were discussed in section 4.2.6. If the concrete above the top mat of reinforcing is first removed by milling as discussed in chapter 3, then the loss in production due to the depth of removal can be reduced.

Figure 4.10 shows the range of hydrodemolition systems' instantaneous productivity. These productivity rates are based on the hydrodemolition equipment manufacturer's productivity estimating guidelines for "typical" 4,000 psi concrete and a removal depth of up to three inches.

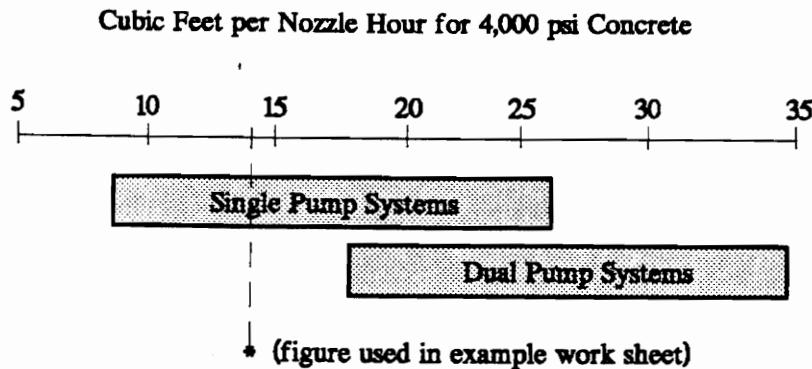


Figure 4.10 Range of Hydrodemolition Equipment Instantaneous Productivity

4.3.2 Modification Factors

Modification factors are used to scale down the instantaneous production to reflect specific job characteristics. The primary parameters which will contribute to the modification factor are the area of removal, the continuity of operations and equipment down time for maintenance and repair. The ability to accurately select this production modification factor is dependent upon the hydrodemolition contractor's experience.

The modification factor ranges from 0.40 to 1.00. A modification factor of 0.80 to 1.00 is typically applied for a job where operations are able to proceed uninterrupted over a large continuous area. A modification factor of 0.40 to 0.80 is typically applied to jobs which involve removing concrete from small non-continuous areas.

Downtime for maintenance and repair will further reduce the instantaneous production from between five and fifteen percent, depending on the particular hydrodemolition equipment.

4.3.3 Realistic Production

A realistic rate of production can be calculated by applying the modification factor to the instantaneous production. The realistic production is an estimate of the average rate at which the hydrodemolition equipment will actually remove the concrete over the entire bridge deck and is the production rate which the contractor will use in developing a bid.

4.4 Economics of Hydrodemolition Operations

This section examines the economics of hydrodemolition for concrete removal in bridge deck rehabilitation work by use of a hydrodemolition cost estimating work sheet as presented in figure 4.11. The work sheet presented in this section is similar to the work sheet presented in chapter two for pneumatic breakers and chapter three for milling machines. Although the work performed by the three methods of concrete

removal vary in scope and complexity, work sheet values common to all three methods were held constant, where practical, to provide a common basis of comparison. The economics of hydrodemolition for concrete removal from other bridge components (piers, abutments, etc.) is not discussed because of the very limited experience to date with applications of hydrodemolition to substructure concrete removal work.

4.4.1 Job Specific Parameters

The first section of the hydrodemolition cost estimating work sheet contains basic information about the job. These items are very job specific and require that each be evaluated for the particular job at hand.

The first two items are the mobilization distance and the number of mobilizations. This figure is highly variable and can only be evaluated by the hydrodemolition contractor as it is dependent upon the location of equipment and personnel.

Bridge deck rehabilitation work is often phased to keep a portion of the bridge open to traffic at all times. This requires the equipment to be mobilized more than once for a job. The contractor will typically consider each phase of a job as a separate, distinct

Job Specific Parameters:

125

Total Mobilization Distance	200	miles
Number of Mobilizations	2	
Depth of Removal	2.50	inches
Total Square Feet of Removal	20,000	sq ft
Type of Work (Patching or Entire Surface)	Entire Surface	
Available Working Hours per Shift	10.00	hours
Number of Shifts per Day	1	shifts/day

Equipment Production Parameters:

Instantaneous Production (cubic foot)	14.00	cubic ft/hr
Instantaneous Production (square foot)	67.20	sq ft/hr per nozzle hour
Production Modification Factor	0.60	
Hourly Production Estimate	40.32	sq ft/hr
Nozzle Hours to Complete Work	297.62	nozzle hours
Hours to Complete Work	496.03	hours
Days to Complete Work	49.60	days

Equipment Rental Cost:

Equipment Purchase Price	(\$440,000)	
Salvage Value	\$0	
Equipment Life:	5	years
Interest Rate Applied	24.00%	
Cost of Money:	12.00%	
Profit:	7.00%	
Inflation:	5.00%	
Annual Equipment Cost	\$160,269	per year
Working Days per Year:	225	days per year
Daily Equipment Rental Cost:	\$712	per day
Equipment Rental:	\$712	per day
	x	
		49.60 days =
		\$35,333

Labor Cost:

Operator/Mechanic:	\$48.00	per hour
Hours per Shift:	10.00	
Number of Shifts:	1	
Operator/Mechanic Cost:	\$528.00	per day
Assistant:	\$20.00	per hour
Hours per Shift:	10	
Number of Shifts:	1	
Assistant Cost:	\$220.00	per day
Personnel Per Diem:	\$0.00	per day
Number of Personnel:	2	
Lodging:	\$0.00	per day
Total Living Expenses:	\$0.00	per day
Total Labor Cost:	\$748.00	per day
	x	
		49.60 days =
		\$37,103

Mobilization Cost:

Mileage Cost:	\$4.00	per mile	x	200 miles	=	\$800
Equipment Rental Cost:	\$712	per day	x	0.80 days	=	\$570
Labor Cost	\$748	per day	x	0.80 days	=	\$598
Total Mobilization:						\$1,968

Operating Cost:

Fuel:	\$15.00	per nozzle hour
Oil, Lube & Filters:	\$1.50	per nozzle hour
Water Filter:	\$40.00	per nozzle hour
Pump:	\$7.00	per nozzle hour
Diesel Engine:	\$1.50	per nozzle hour
Pistons & Cylinders:	\$9.00	per nozzle hour
Hoses:	\$2.00	per nozzle hour
Nozzles:	\$10.00	per nozzle hour
Demolishing Unit:	\$2.00	per nozzle hour
Miscellaneous Items:	\$1.00	per nozzle hour
Total:	\$89.00	per nozzle hour
Equipment Operating Cost:	\$89.00	/nozzle hour X
		297.62 nozzle hours =
		\$26,488

Total Direct Cost:

\$100,892

Indirect Cost:

Overhead and Administration:	10.00%	of Total Direct Cost =	\$10,089
Profit:	4.00%	of Total Direct Cost =	\$4,036
Total Indirect Costs:			\$14,125

Total Price:

\$115,017

Unit Price (per square foot):

\$5.75

Figure 4.11 Hydrodemolition Cost Estimating Work Sheet

job in itself. This allows the equipment to work elsewhere during the time between the phasing of the work. The work sheet illustrates an example in which there are two mobilizations which total two hundred miles.

The third item is the specified depth of concrete removal. The primary advantage associated with using hydrodemolition is the ability to remove concrete from below and between the reinforcing. The factors which affect the operations in this area have been discussed in section 4.2.6. The work sheet specifies that the concrete is to be removed to a depth of 2.5 inches.

The fourth item is the total area of removal required to complete the job. This parameter is dependent upon the size of the deck, the condition of the deck and the SHA's decision of how to rehabilitate the deck. It is difficult to accurately estimate the total quantity of removal if the rehabilitation is to be a patching type operation. The capital intensive nature of hydrodemolition makes it highly sensitive to quantity fluctuations and it is thus important that both the SHA and the contractor estimate this parameter as accurately as possible. This example assumes an area of removal of 20,000 square feet.

The fifth item describes the type of concrete removal work which is required (patching or entire surface). This is also determined by the SHA's decision regarding how to

rehabilitate the bridge deck. Hydrodemolition is most economical for and most commonly used for projects which require the entire surface to be removed as is the case in the example presented in the work sheet.

The final two items are the available hours per shift and the shifts per day that the hydrodemolition equipment can be operated. These are dependent upon the contractor's access to the deck as well as the imposed time constraints of the job as dictated by the SHA's decisions regarding traffic control and the contract duration. One shift of ten hours per day is assumed in the example presented in the work sheet.

4.4.2 Equipment Production Parameters

The estimated instantaneous production and the modification factor as determined in section 4.3 can be used to determine the estimated hourly production and the time to complete the work. The area of removal, 20,000 square feet, can be divided by the instantaneous production, 67.20 square feet per nozzle hour, to determine the nozzle hours to complete the work, 297.62 nozzle hours. By reducing the instantaneous production by the modification factor of 0.6, the hourly production estimate can be calculated as 40.32 square feet per hour. The hours to complete the work is calculated as 496.03 hours by dividing the area of removal by the estimated hourly production.

By imposing the hours per shift and the shifts per day restraint on the hours to complete the work, the days to complete the work can be determined as 49.60.

4.4.3 Equipment Rental Cost

The third section of the work sheet calculates the hydrodemolition equipment rental cost based on an annual equivalent cost distribution of the purchase price less an anticipated salvage value as calculated by the formula presented in Appendix 2. This is the same method that was used to calculate the annual cost distribution of a milling machine in chapter three and is a generally accepted method for calculating depreciation of capital intensive investments.

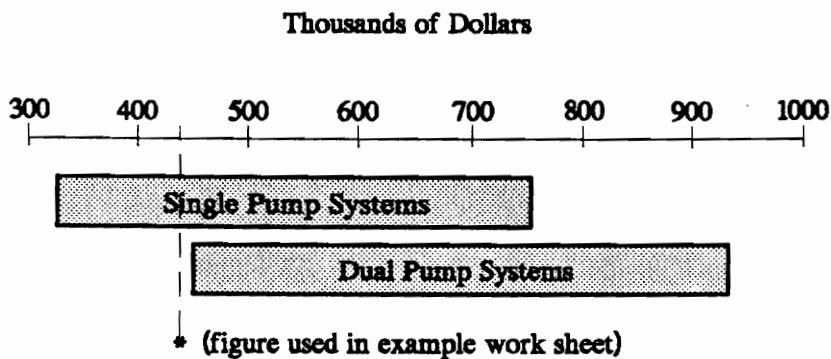


Figure 4.12 Range of Hydrodemolition Equipment Purchase Price

The first item in this section is the hydrodemolition equipment purchase price. Figure 4.12 shows the range of purchase prices for hydrodemolition systems. A purchase price of \$440,000 was used for the work sheet.

The second item in this section is the equipment's salvage value. The salvage value of a piece of construction equipment is a function of its demand, its standardization, and its condition. Because of the rapid rate of technological advancement it is not unreasonable to assume the salvage value to be zero for hydrodemolition equipment due to obsolescence. However, a small salvage value may reasonably be expected from some components of the hydrodemolition system.

The third item in this section is the expected life of the equipment which is generally around five years depending on how heavily a contractor uses the equipment and the mechanical reliability of the particular make of equipment.

The fourth item is the minimum attractive rate of return (MARR) for the capital investment in the equipment. The three major components of the MARR are: the capital lending rate; a profit on investment; and the rate of inflation. These three rates were estimated as twelve percent, seven percent and five percent in the work sheet.

Item eight is the annual equivalent cost of owning the equipment calculated as \$160,269. This cost is incurred by a contractor regardless as to whether the equipment is idle or operating, therefore it is to the contractors advantage to utilize the equipment as fully as possible.

The ninth item is the number of working days per year that the equipment is expected to work. Hydrodemolition contractors frequently do not expect to work during the months of December, January and February due to inclement weather conditions. In addition, a few days are set aside to account for equipment downtime. Contractors generally expect to operate their equipment 200 to 250 days per year, 225 working days per year was used in the work sheet.

The tenth item is the daily equipment rental rate. It is calculated as \$712 per day by dividing the annual equipment cost, by the number of working days per year. This equipment rental rate accounts only for the cost of owning the equipment and does not include the operating or maintenance costs.

The product of the daily equipment rental rate, \$712, and the number of days to complete the job, 49.6 days, is the total equipment rental cost to complete the job, calculated as \$35,333 in the work sheet.

4.4.4 Labor Cost

The forth section of the hydrodemolition cost estimating work sheet calculates the labor costs incurred in operating and maintaining the hydrodemolition equipment.

Hydrodemolition contractors typically use a two man crew to transport, operate and maintain the equipment. One of crew members is a highly skilled operator who knows how to operate, calibrate, repair and maintain the hydrodemolition equipment. The second crew member assists the operator with the operation and maintenance of the hydrodemolition equipment.

The work sheet uses the labor rates of \$48 per hour for the operator and \$20 per hour for the assistant. These rates are inclusive of all costs incurred by the employer such as payroll taxes, insurance, etc. In addition a contractor may make an allowance for personal expenses to cover room and board if the work takes place away from the contractors base. No expenses were provided for in this example. The total daily expense, \$748, can be multiplied by the days to complete the work, 49.6, to determine the total labor cost, \$37,103.

4.4.5 Mobilization Cost

The fifth section of the hydrodemolition cost estimating work sheet calculates the mobilization cost of the hydrodemolition equipment and associated labor.

A cost per mile rate, estimated by the contractor based on the resources required and the distance to be traveled, is multiplied by the total number of miles the hydrodemolition equipment must be transported. This cost is estimated as \$4.00 per mile and includes all the expenses associated with owning and operating the tractor-trailer which hauls and houses the hydrodemolition equipment.

The daily equipment rental charge, \$712, and the daily labor charge, \$850, is multiplied by the days in transit, 0.8 days, to determine the mobilization cost for these resources. The days in transit is determined dividing the total mobilization distance by 500, which is the estimated daily travel distance. The sum of the cost per mile and the daily equipment and labor cost constitute the total mobilization cost for the job, \$1968.

4.4.6 Maintenance and Operating Cost

The sixth section of the hydrodemolition cost estimating work sheet calculates the equipment maintenance and operating costs. Maintenance and operational costs are incurred on a nozzle hour basis for hydrodemolition equipment. The only cost incurred while the equipment is idling is the diesel engine fuel consumption. This idle time fuel cost is generally included in the nozzle hour fuel cost to simplify the calculations.

The ten items in the operating cost section list the wear items and the spare parts in a hydrodemolition equipment system. The cost figures shown are typical values which can be expected for a single pump system. Use of a dual pump system requires that the cost figures for the first six items be doubled. Operating costs range from \$75 to \$95 per nozzle hour for a single pump system and \$140 to \$175 per nozzle hour for a double pump system.

The total operating costs to complete the job is calculated as \$26,488, by multiplying the total operating cost per nozzle hour, \$89.00, by the number of nozzles hours to complete the work, 297.62 nozzle hours.

4.4.7 Indirect Cost

The final section of the work sheet calculates the indirect cost of performing the work.

The overhead and administration cost is calculated as a percentage of the job's total direct cost. A ten percent rate for overhead and administration is used for the work sheet example.

The hydrodemolition contractor adds a final percentage for profit. The percentage for profit typically ranges from four to eight percent. A profit of four percent is used in the work sheet. If the hydrodemolition contractor feels that the job entails considerable risk (ie.. a potential for significant quantity variations) then a larger percentage for profit and risk will be applied. Factors which a contractor considers when evaluating the risk associated with a job are: potential for quantity variations; the previous relationship with the general contractor; and the previous relationship with the SHA.

The total indirect cost \$14,125 is equal to the sum of the overhead and administration cost and the percentage for profit.

4.4.8 Hydrodemolition Total Price & Unit Price

The last two items on the hydrodemolition cost estimating work sheet are the total price and the unit price. The hydrodemolition total price is simply the sum of all direct and indirect costs. The unit price is the total price divided by the total area to be removed. This is the unit price for the hydrodemolition portion of the work, it does not include related costs such as clean up, water supply, run off control, and waste water treatment. The total cost for the example hydrodemolition project is \$115,017 which computes to a unit cost of \$5.75 per square foot.

4.4.10 Hydrodemolition Unit Price Sensitivity

The sensitivity of hydrodemolition's unit price to the total quantity of work is shown in figure 4.13. The curve was generated by varying the total square feet of removal in the hydrodemolition cost estimating work sheet. No other input values were altered. The increases in the area of removal resulted in a greater amount of time to complete the work which correspondingly increased the cost of the various work sheet components.

Sensitivity of Hydrodemolition Unit Price to Total Quantity

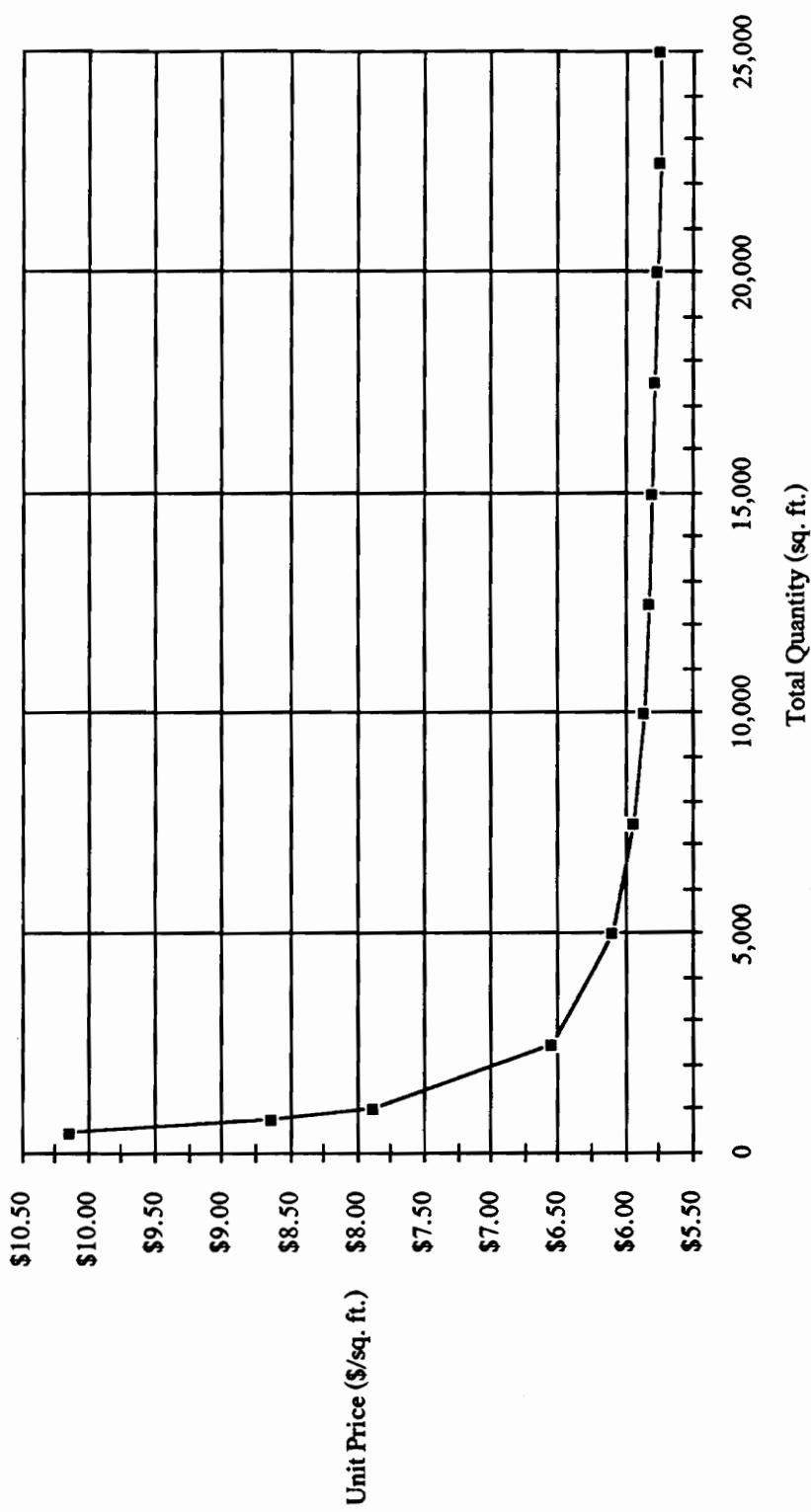


Figure 4.13 Sensitivity of Hydrodemolition Unit Price to Total Quantity

The sensitivity analysis illustrates the basic cost-quantity relationship of capital intensive methods. At low quantities of removal the cost to perform the work is very high as the high owning and operating costs are not able to be economically recovered. As the quantity of removal increases, the costs are able to be more evenly distributed, resulting in a reduced cost to perform the work.

4.5 Managing and Controlling Quality

An understanding of the issues relative to managing and controlling the quality of hydrodemolition operations is necessary to ensure effective utilization of the technology. The primary issues which are addressed in this section are quality requirements, residual cracking and specifications.

4.5.1 Quality Requirements

The primary quality concern associated with concrete removal by hydrodemolition is ensuring that the machine is correctly calibrated to remove the concrete to the specified depth or level of soundness. The opposite of hydrodemolition's inherent

advantage of selective removal, discussed in section 4.2.6, occurs when there is a high strength concrete or other material on top of or within an area of lower strength concrete. This condition, shown in figure 4.14, typically is encountered when rehabilitating a bridge deck that has been previously patched.

If the hydrodemolition system is calibrated to remove the high strength concrete then excessive amounts of original low strength material may be removed from around the perimeter or underneath the high strength material. Absolute, precise depth control is not possible when the concrete's strength is non-homogeneous.

Existing patches which have a lower strength than the original deck concrete do not present the same problem as higher strength patches. Cold patches or bituminous concrete patches in a bridge deck are easily removed by hydrodemolition.

However, there may be problems if an unanticipated area of low strength or extensively deteriorated concrete is encountered. The hydrodemolition system, calibrated for a higher strength material will remove the concrete to a greater depth than desired, possibly all the way through the deck.

The best way to handle this problem is to anticipate its occurrence by carefully inspecting the underside of the bridge deck. Anticipating this situation enables the

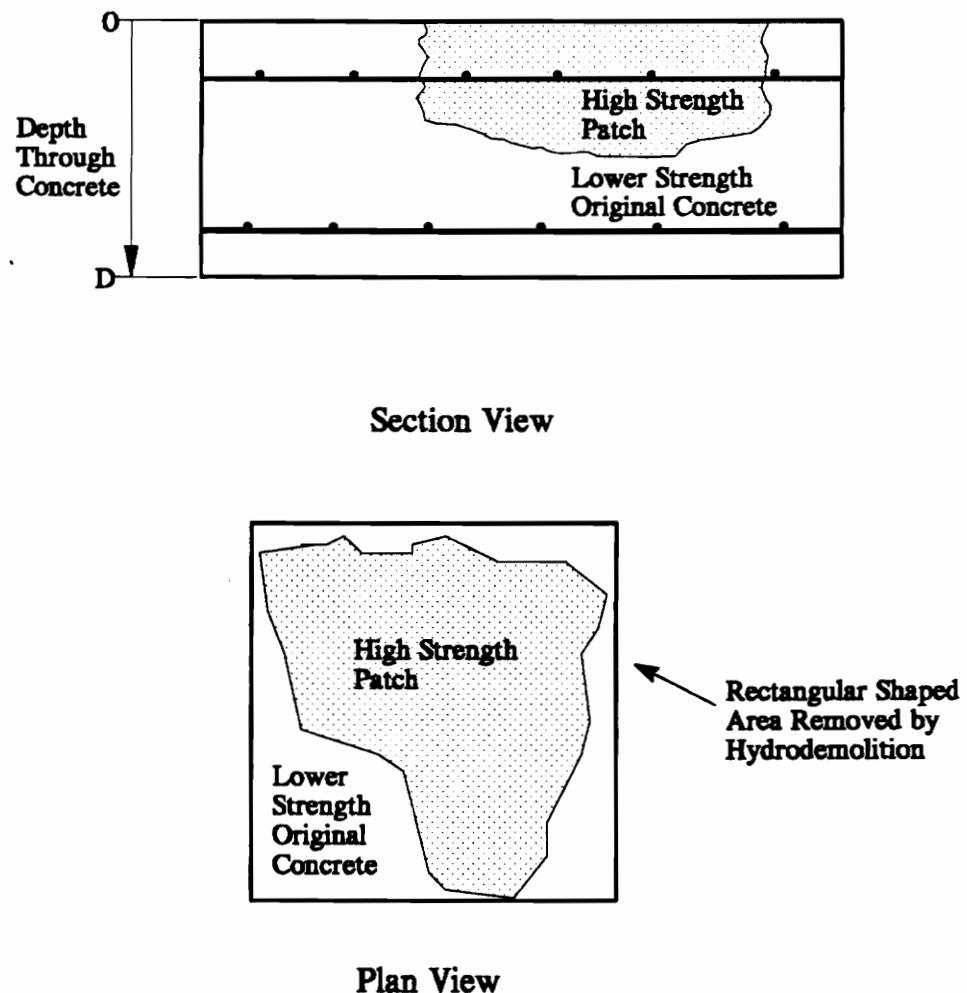


Figure 4.14 High Strength Patch in a Bridge Deck

contractor to provide a means for catching the debris and protecting the area under the bridge prior to the removal by hydrodemolition.

Hydrodemolition is capable of removing concrete from around and below reinforcing steel bars without causing damage to the bars or damaging the concrete-to-steel bond. However, problems with rebar shadowing can occur because the reinforcing steel bars shield the concrete directly beneath them from impingement by the water-jet. Figure 4.15 illustrates what happens as the hydrodemolition nozzle advances across a steel reinforcing bar. The shaded triangular area directly below the steel bar is shielded from impingement by the water-jet. If the mean removal depth is below the water-jet's intersection point, then the unimpingable area will be removed by the scouring action of the loose aggregate. If the mean removal depth is above the water-jet intersection point then the unimpingable area will not be removed and a rebar shadow will remain.

Hydrodemolition's ability to remove concrete from directly below reinforcing steel bars is a function of the bar size, the maximum aggregate size, the water-jet angle of impingement and the chosen mean removal depth. Larger steel bars move the water-jet intersection point deeper and create larger unimpingable areas. To avoid rebar shadowing the mean removal depth should be set so that it is below the water-jet

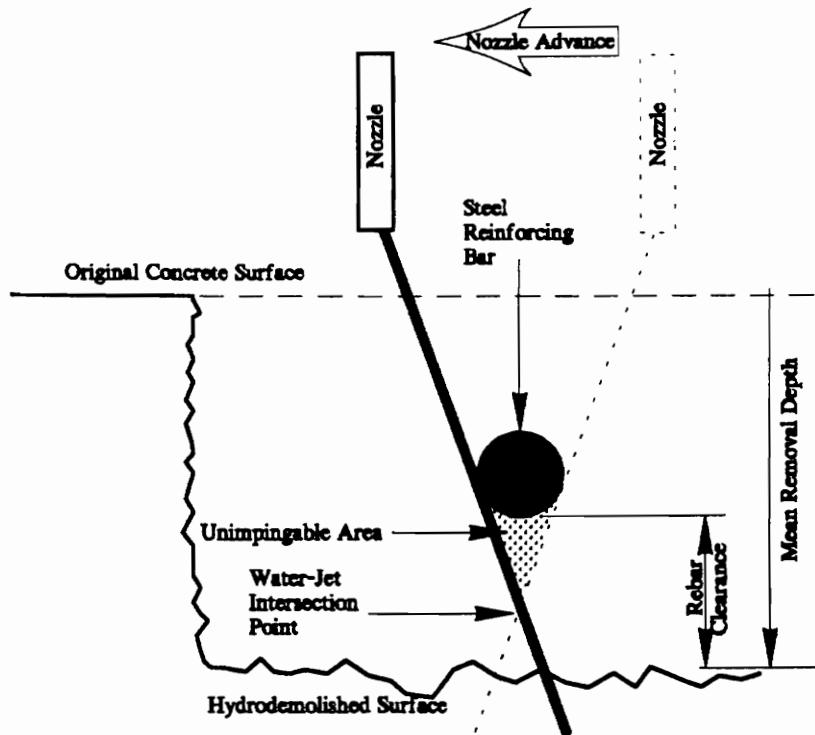


Figure 4.15 Nozzle Advance and Rebar Shadow

intersection point and the rebar clearance is at least equal to the maximum aggregate size.

Hydrodemolition cleans the reinforcing steel bars as it removes concrete from around them. The swirling action of the high velocity water and the fine aggregate particles from the demolished concrete act to provide a wet sandblast. This effectively removes rust deposits and bonded cement from the reinforcing steel bars.

Careful planning is required to effectively control the large volume of water generated by the removal operation. The planning must consider such items as the deck's geometry, equipment access and maintenance of traffic.

The contents and chemical nature of the runoff water which is discharged into the environment is also a concern with hydrodemolition. Discharging the runoff water into the environment typically requires approval from an environmental agency which may require a detailed environmental impact report. Treatment methods have included building settling ponds, buffering with acid and additional filtering prior to discharge into the environment.

Currently, there is not a standard policy or regulation for the discharge of hydrodemolition runoff water into the environment. A standard water runoff treatment process which is widely accepted by the various environmental agencies would promote the use of hydrodemolition.

Disposing of the rubble produced by hydrodemolition is not usually a problem. Most disposal sites readily accept it. The vacuumed up rubble and slurry may be used as base material for rural roads. The material has been found to be excellent for this purpose because the cement slurry rehydrates and provides a cohesive element to a gravel road or drive.

4.5.2 Residual Concrete

Microscopic examination of concrete samples reveals that hydrodemolition does not induce micro-cracks in the prepared concrete surface (Hindo, 1987). Bond failure of a hydrodemolished surface generally occurs at the concrete-to-concrete bond interface as opposed to in a bruised layer as is the case with impact methods which are more likely to produce micro-cracks and the bond strength of the hydrodemolished surface is roughly twice that of a surface prepared with impact methods (Ingvarsson, 1988, Hindo, 1987, Silfwerbrand, 1989, Tayabji, 1986).

4.5.3 Specifications

A specification has two purposes: the first is to convey the engineer's thoughts and visions of the project; and the second is to provide a definite document on which a legal contract is based and executed (Ayers, 1984). To convey the engineer's thoughts and visions of the work a specification must describe the desired work's quality, dimensions and results. The legal aspect of a specification establishes the obligations and rights of the parties to the contract. The owner and engineer are obligated to clearly define what is required, the means for enforcing the requirements, the method of measurement for the work and the method of payment for the work. The contractor

is obligated to comply with the requirements of the contract and perform the work in accordance with the specifications. It is the right of both parties to assume the other will fulfill their obligations (Goldbloom, 1989).

A prevalent problem with hydrodemolition specifications is the use of method specifications which specify the operating parameters of the hydrodemolition equipment. These specifications tend to favor particular makes of hydrodemolition equipment while excluding others, regardless of ability to produce a product of acceptable quality. Hydrodemolition specifications should be performance specifications which address only the aspects of the work which are necessary and critical to achieving the desired quality for the final product.

Every bridge rehabilitation job must be evaluated on an individual basis to determine if hydrodemolition is capable of effectively performing the concrete removal. As discussed in section 4.5.1, hydrodemolition is not capable of selectively removing high strength patches or overlays in a bridge deck. The SHA engineer must be aware of the existence of high strength patches in a deck so that provisions can be made in the plans and specifications for their removal by alternative methods. The contractor is also responsible for evaluating the bridge deck before bidding the job to determine if hydrodemolition is appropriate in accordance with the specifications.

The method of payment used in a bridge rehabilitation contract can influence the performance of the work and the job's total cost. In rehabilitation work involving entire surface removal, quantity overruns often cause large job cost overruns for the SHAs. The cost overruns occur on jobs in which hydrodemolition removes a greater volume of concrete than estimated. The cost increase is not manifested in the hydrodemolition bid item because it is bid on a square foot basis, but rather in the bridge deck overlay item which is generally bid by volume.

The bridge deck overlay bid item generally includes the cost of the construction methods such as placing and finishing as well as the cost of the material. Although the additional cost in material is justified by an increase in volume, there is no substantial increase in the time or resources required for the placement or finishing of the material. However, because the construction methods are included in the unit price for bridge deck overlay, their price will go up relative to the increase in the volume of the overlay material.

This can be avoided by having the overlay material and the construction methods as two separate pay items. The overlay material can be bid and paid for by the volume of material while the construction methods pay item, which includes the placing and finishing of the material, will be paid for by the area. In this way increases in the

volume of material removed will result in increases in the quantity and cost of the overlay material only.

A similar problem is often encountered on patching jobs in which SHAs use a single pay item for patching work. The single pay item is usually specified as cubic yards of replacement concrete or bags of cement used to fill the patches. The cost of all concrete removal, surface preparation and placement of the patching material must be combined into this single unit price. The discrepancy occurs because the increase in cost received by the contractor for quantity overruns is generally not proportional to the increase in price to perform the work. The opposite situation occurs when there is a quantity underrun. To avoid this potential conflict it is best to separate the concrete removal and the placement of new concrete into two distinct pay items.

5

Conclusion

This final and concluding chapter begins by reviewing and summarizing the three technologies: pneumatic breakers, milling machines, and hydrodemolition. Following this, the characteristics of the project which will affect the utilization of each technology will be examined. Once the technologies have been reviewed and the project characteristics analyzed, the process for matching the technology to the project is addressed, for the selection process will have a significant impact on the outcome of the project.

The matrix presented in figure 5.1 represents the format used to evaluate the technologies. The parameters which define the technology make up the column headings while the three technologies are on the rows of the matrix.

	TECHNICAL DESCRIPTION	WORK CHARACTERISTICS	PRODUCTION ESTIMATING	ECONOMICS OF OPERATION	MANAGING QUALITY
PNEUMATIC BREAKERS					
MILLING MACHINES					
HYDRODEMOLITION					

Figure 5.1 Technology Evaluation Matrix

Chapters two, three and four presented the information along each row of the matrix by analyzing a particular method in terms of the five parameters. This chapter analyzes the information vertically to compare the strengths and weaknesses of each technology in terms of the given parameters.

5.1 The Technologies

This section summarizes the information presented in the previous three chapters. To accomplish this, the matrix is broken down into five separate sheets, one for each of the parameters. The primary characteristics of each technology as it relates to the parameter being considered are discussed.

5.1.1 Technical Description

The nature and sophistication of the three technologies varies from very basic and simple to very complex and sophisticated.

Pneumatic breakers require little capital investment but are highly labor intensive. The equipment consists of small hand held instruments which are powered by pressurized air supplied by a compressor. The reciprocating action of the piston causes the cutting tool to deliver repeated high impact blows which fracture the material to be removed.

Pneumatic breakers are a basic construction tool. Their low cost and abundant applications make them an economical investment for a contractor. Their durable construction and simple mechanics result in minimal required maintenance.

Milling and hydrodemolition are, by contrast, capital and equipment intensive technologies. Milling is a very simple process which relies on the weight and power of a large machine to remove concrete by repeated impacts of multiple cutting teeth mounted on a rotating cutting mandrel.

The limited number of applications for which milling machines can be used and their very high purchase price and maintenance cost has limited their appearance in the market.

Hydrodemolition is a highly sophisticated concrete removal technology which utilizes a computer calibrated high pressure water-jet to destroy the cement matrix and thus remove the concrete. The system is composed of two components: the power unit and the demolishing unit. The power unit is used to pressurize the water and is generally housed in a large trailer. The demolition unit is a wheel mounted device which contains the equipment required to apply the high pressure water to the deck. A microprocessor located in this unit controls the operating parameters of the water-jet. Hydrodemolition equipment is still in the evolutionary stages and accordingly requires intensive maintenance and often times modification.

The workers required to operate pneumatic breakers will have a direct impact on the operations as they control the force applied and the positioning of the tool. Workers

TECHNICAL DESCRIPTION

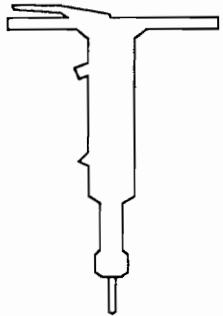
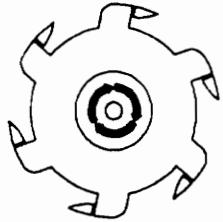
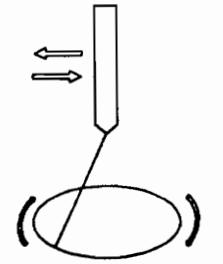
PNEUMATIC BREAKERS	<p>Pneumatic breakers are small inexpensive, hand-held tools which utilize the percussive force generated by high frequency impacts of a cutting tool to fracture concrete. A compressor is required to supply the pressurized air to power the tool.</p> 
MILLING MACHINES	<p>Milling is a capital intensive process which relies on the weight and power of a large machine to remove concrete by repeated impacts of numerous teeth mounted on a rotating drum.</p> 
HYDRODEMOLITION	<p>Hydrodemolition is a large capital intensive method which utilizes the force of a computer calibrated high pressure water-jet to destroy the cement matrix and thus remove the concrete. The equipment comprises a power unit and a demolition unit.</p> 

Figure 5.2 Technical Description Summary

which operate milling and hydrodemolition equipment have minimal impact on the operations due to the highly mechanized nature of the equipment.

Figure 5.2 summarizes the technical description of each technology.

5.1.2 Work Characteristics

The work characteristics define the strengths of a particular technology in terms of the work it is able to perform most efficiently. This is generally dictated by the design of the equipment and the method by which it removes the damaged concrete.

The small size and excellent maneuverability of pneumatic breakers make them ideally suited for removing small areas of damaged concrete from zone 2 and zone 3 which consists of areas under, around and between the reinforcing and from vertical and overhead surfaces on all bridge structural elements. Because of this, they are commonly used in conjunction with other high production methods which are unable to effectively remove concrete from these areas. A skilled pneumatic breaker operator is able to selectively remove concrete to the desired level of deterioration.

The large contact area of the cutting mandrel limits milling machines to removing concrete from above the reinforcing steel, zone 1, on flat, horizontal surfaces.

Obstructions such as joint faces and utility boxes which may interfere with a milling machine's cutting mechanism pose a serious threat to operations as do reinforcing bars which may be struck or pulled up by the machine's cutting mechanism. Milling is often used to remove the surface layer of concrete in preparation for hydrodemolition.

The absence of physical contact between the machine's cutting mechanism and the material to be removed enables hydrodemolition to remove concrete from below and around the reinforcing in zone 2 and zone 3 over a large area. However the equipment is restricted to removing concrete from rectangularly shaped areas as dictated by the limit switch settings. A standard hydrodemolition unit is also unable to remove concrete from non-horizontal surfaces.

Both milling and hydrodemolition require that a large portion of the bridge be closed for an extended period of time to facilitate the access and setup requirements of the equipment. Pneumatic breakers on the other hand require minimal access to the site or set up space.

Continuity of operations is essential for both milling and hydrodemolition to achieve maximum utilization. The degree to which operations can proceed unimpeded is

WORK CHARACTERISTICS

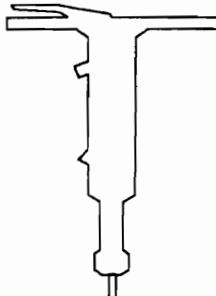
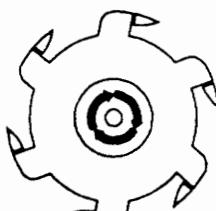
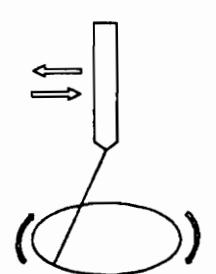
PNEUMATIC BREAKERS	<p>Pneumatic breakers are best utilized for removing small, scattered patches of zone 2 or zone 3 concrete from horizontal, vertical and overhead surfaces on all bridge structural elements. A skilled operator is able to differentiate between concrete of varying degrees of deterioration.</p>	
MILLING MACHINES	<p>Milling is confined to removing zone 1 concrete from flat horizontal surfaces. It is best utilized if there is a large continuous area requiring removal to a uniform depth. Obstruction and inconsistent rebar cover will severely interfere with operations.</p>	
HYDRODEMOLITION	<p>Hydrodemolition is most effective for removing zone 2 or zone 3 concrete from large continuous areas. It is able to selectively remove concrete of less strength than the breaking energy imparted by the water-jet.</p>	

Figure 5.3 Work Characteristics Summary

primarily determined by the area of removal, the available access and obstructions which may interfere with progress.

These characteristics are summarized in figure 5.3.

5.1.3 Production

Productivity is determined by the equipment itself and the environment in which it operates. Levels of productivity range from under 10 square feet per hour for pneumatic breakers to over 500 square feet per hour for milling machines.

Hydrodemolition falls somewhere between these two at between 25 and 50 square feet per hour. However it is not appropriate to compare the production rates of the three technologies since each is designed to operate under separate conditions.

The skill and motivation of a pneumatic breaker operator play a significant role in the rate of production, which is otherwise determined by the weight and power of the equipment. The productivity of pneumatic breakers is inherently very low due to the restricted environment in which they are typically operated and because the cutting mechanism is limited to a single impacting tool. Removing concrete from areas of difficult access and from around and between reinforcing bars requires that the

operator exercise a great deal of caution and involves frequent repositioning of the tool.

Milling machine production is determined by the width of the cutting mandrel and the speed at which the machine can be safely operated which is a function of the machine's weight and power and the hardness of the material being removed. Milling machines are generally capable of attaining very high rates of production due to the continuous action of the cutting mechanism, the large number of cutting tools which are used to fracture the concrete and the large, continuous, obstruction free areas for which they are typically utilized.

The production rate for hydrodemolition operations is determined by the rate at which the water-jet is able to remove the concrete and the ability of the equipment to operate uninterrupted. The rate at which the concrete is able to be removed is affected by the strength of the concrete being removed and the energy of the water-jet.

This information is summarized in figure 5.4.

PRODUCTION ESTIMATING

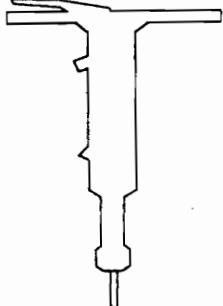
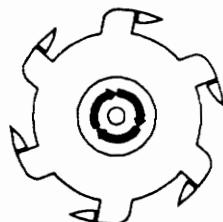
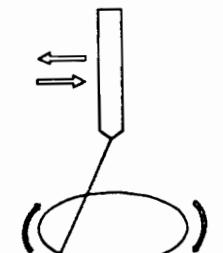
PNEUMATIC BREAKERS	<p>Breaker productivity is primarily determined by three components: the weight and associated power of the equipment, the skill and motivation of the operator and the degree of rebar interference.</p> 
MILLING MACHINES	<p>The machine characteristics of power, weight, drum width and operating speed and the ability of the machine to be operated continuously are the primary determinants of a milling machine's productivity.</p> 
HYDRODEMOLITION	<p>Hydrodemolition's production capacity is determined by the breaking energy of the water-jet, the strength of the material being removed, and the ability to be operated continuously.</p> 

Figure 5.4 Production Estimating Summary

5.1.4 Economics

The cost of concrete removal for the various methods can be analyzed in terms of the magnitude of the cost and the variability of the cost to the quantity of material removed.

Figure 5.5 presents a sensitivity analysis of the unit cost of performing the concrete removal operations with the three technologies as a function of the area of removal. It is simply a compilation of the sensitivity analyses generated in the previous three chapters.

The magnitude of the cost is determined by the rate at which the method is able to perform the work. The low rate of production associated with pneumatic breakers does not allow for an economical distribution of costs, thus resulting in a high unit cost. Milling machines and hydrodemolition however, are designed for and generally operated in conditions which allow them to achieve very high production rates. This provides for a more economical distribution of the costs, thus resulting in a lower unit cost.

The degree to which the unit cost of removal is sensitive to the area of concrete removed is dependent on the nature of the cost components. The primary cost

Sensitivity of Unit Price to Total Quantity

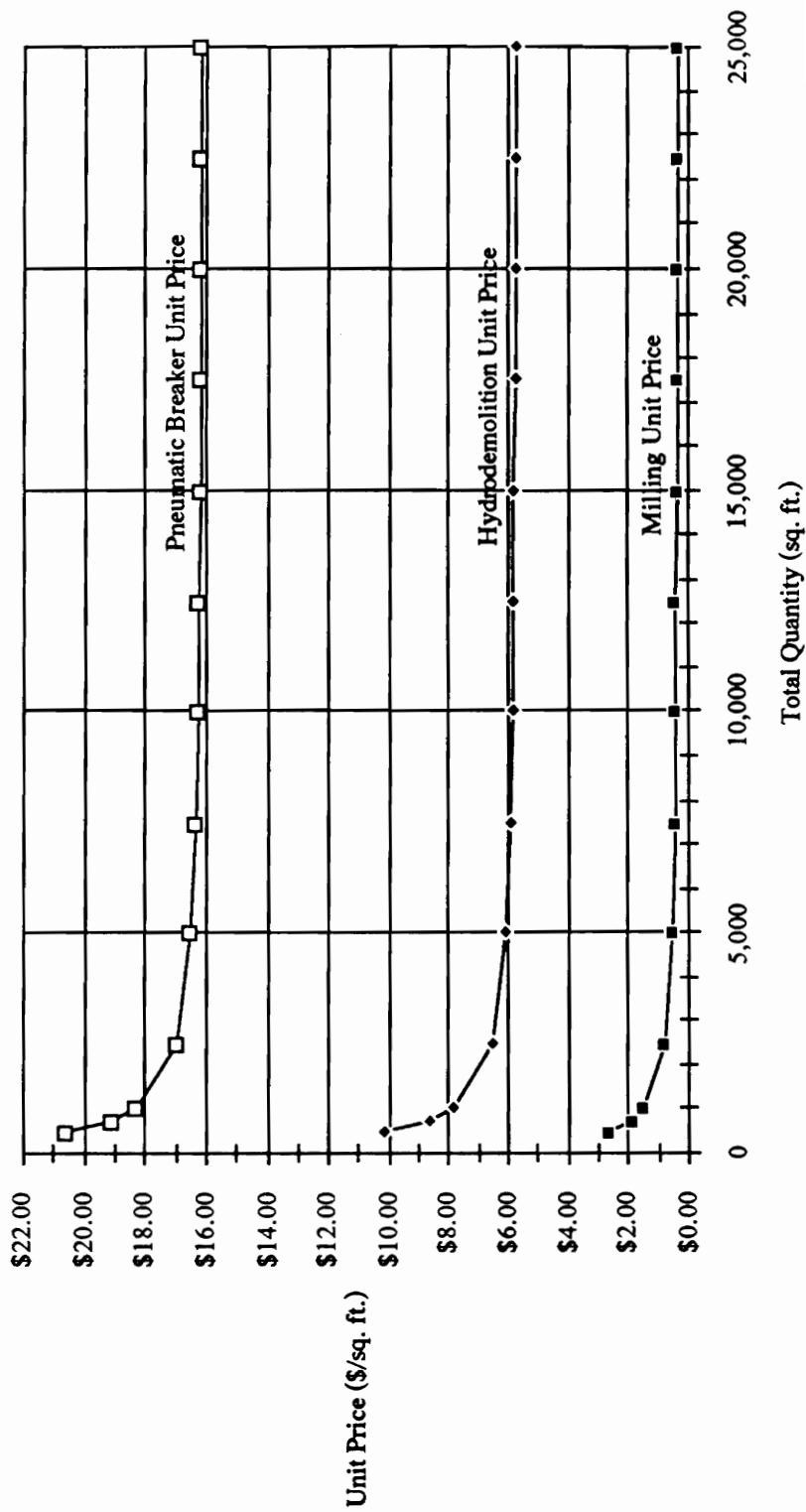


Figure 5.5 Sensitivity Analysis for the Three Technologies

ECONOMICS OF OPERATIONS

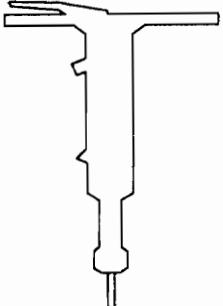
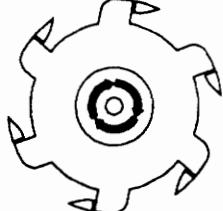
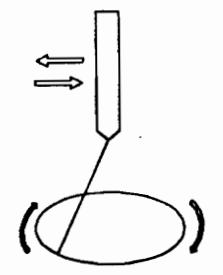
PNEUMATIC BREAKERS	<p>The primary cost component of pneumatic breaker operations is labor. The unit cost will remain relatively constant in response to variations in the quantity of removal because of the variable nature of the labor cost. The low production rate associated with pneumatic breakers results in a high unit cost.</p>	
MILLING MACHINES	<p>The unit cost of milling is determined by the area of removal, the depth of removal and the continuity of operations. The unit cost will decrease sharply with increases in quantity as fixed cost become more widely distributed.</p>	
HYDRODEMOLITION	<p>The cost of hydrodemolition will be affected by the area of removal, the continuity of operations and the hardness of the material being removed. It is more economical when used to remove large quantities of material due to the sensitivity of the unit cost to quantity.</p>	

Figure 5.6 Economics of Operations Summary

component of pneumatic breakers is the labor cost, a variable cost, which changes in direct proportion to quantity. The cost-quantity ratio thus remains relatively constant, resulting in a relatively constant unit cost.

The high capital cost associated with milling and hydrodemolition is a fixed cost which must be recovered regardless of the quantity of removal. These methods therefore are much more economical when used for removing large quantities of material as the fixed cost is able to be more widely distributed. The reduction of the unit price for hydrodemolition decreases only a little over ten percent with an increase in quantity from 5,000 square feet to 25,000 square feet, and the unit price of milling drops only slightly over two percent over this same interval, whereas the unit price of pneumatic breakers drops thirty three percent over this interval.

Figure 5.6 further summarizes the economic aspects of the three technologies.

5.1.5 Managing and Controlling Quality

A problem common to concrete removal methods, such as pneumatic breakers and milling machines, which utilize an impact force to fracture the material is the possibility of producing damaging microcracks in the residual concrete.

This problem is minimized with breaker operations by limiting the weight of the equipment which may be used and by specifying that the breaker be operated at an angle.

Milling machines use an upward cutting action so as not to direct the impact into the material which is to remain in an effort to reduce the possibility of microcrack formation. A well maintained cutting head and the proper operating speed will also reduce the possibility of the machine damaging the residual concrete.

Milling machines are also at a risk of damaging the bridge and the machine by pulling up reinforcing bars. This risk can be reduced if the depth to the reinforcing is determined in several locations over the bridge deck prior to milling operations.

A hydrodemolition machine is not able to properly remove concrete which is of a different strength than that for which the machine is calibrated. The water-jet will not have sufficient energy to remove material which is of a higher strength than the equipment is calibrated and a low strength material may be removed to a greater depth than desired, possibly even all the way through the bridge deck. Also, the large amount of runoff generated by hydrodemolition is an environmental and safety concern which must be addressed.

MANAGING QUALITY

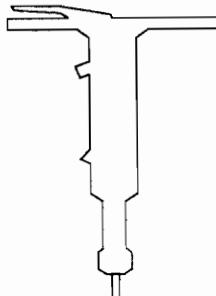
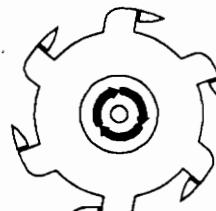
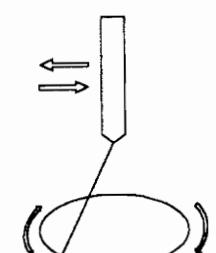
PNEUMATIC BREAKERS	<p>The primary quality concern associated with pneumatic breakers is the condition of the residual concrete and exposed steel. A concerted effort must also be made to accurately estimate the quantity of material which will require removal in an effort to reduce quantity variations.</p>	
MILLING MACHINES	<p>Accurate determination of the depth of material above the reinforcing must be made to avoid the damage associated with striking or pulling up a reinforcing bar. The condition of the residual concrete with regards to microcracking must also be monitored.</p>	
HYDRODEMOLITION	<p>The quality associated with concrete removal utilizing hydrodemolition is dependent on the machine being correctly calibrated and the proper assessment of the strength and condition of the material being removed. Environmental concerns associated with runoff control must also be addressed.</p>	

Figure 5.7 Quality Management and Control Summary

Potential damage to the integrity of the bridge structure must be assessed due to changes in the magnitude and pattern of the applied loads and a possible relocation of the neutral axis.

Quality variations which may occur in the concrete removal operation or the subsequent patching or overlay operation are a concern with all three methods. An accurate assessment of the condition of the concrete prior to commencing work will reduce the possibility of the quantity of removal deviating from that which was estimated.

A summary of the quality management and control issues is presented in figure 5.7.

5.2 The Project

Once an understanding of the technology has been established, the individual project for which the technology is to be applied must be examined. The characteristics of the bridge rehabilitation project as determined by the type and extent of damage and the location of the damage on the bridge structure will determine which method or methods are best capable of performing the work.

The type of damage may be contamination or deterioration. Contamination occurs when chloride ions from deicing salts or sea spray permeate the concrete. Although contamination itself does not weaken the structure, if left untreated it may promote subsequent deterioration. Deterioration occurs as a result of a chemical reaction

involving the chloride ions and the reinforcing steel in which rust is formed as a by product. Deterioration can be in the form of cracking, delamination or spalling.

The extent of damage is measured by how large of an area is affected and how deep the damage extends and will determine how extensive the rehabilitation must be and what method is best suited to perform the work.

- 1) Small areas. Small, isolated areas of damage are generally characterized by visible cracking or spalling of concrete within the damaged area. The emphasis of the repair operation is to completely remove the deteriorated concrete with minimal damage to the steel reinforcing or residual concrete and to restore the area to its original functional characteristics.
- 2) Large areas. Projects which are characterized by a high degree of contamination as detected by half cell potential measurements or core sampling typically involve the extensive removal of large areas of damaged concrete.

This type of removal is most efficiently achieved with high production equipment.

- 3) Depth of removal. The primary consideration associated with the depth of removal is the possible interference with the reinforcing steel. Concrete which must be removed from under, around and between the reinforcing will generally require a much greater effort and will correspondingly affect the production and cost of performing the work.

The location of the damage on the bridge structure is an important characteristic which must also be evaluated. Bridge rehabilitation operations which require removal from substructure elements are fundamentally different from those which are limited to the flat horizontal surfaces of the bridge deck. A bridge deck is able to accommodate mechanized methods of concrete removal which are capable of attaining high rates of production. Substructure elements generally consist of small isolated areas which are often on vertical or overhead surfaces and are difficult to access thus requiring a removal method with the flexibility to operate in these conditions.

5.3 Matching the Technology and the Project

A great deal of judgement and experience is required to select the appropriate technology to perform the concrete removal operations as defined by the project characteristics. Examination of the three methods: pneumatic breakers, milling machines, and hydrodemolition reveals that each is applicable to a unique primary application and thus they should not be evaluated as competitors for a given project. Most projects will in fact use a combination of the technologies to arrive at the most cost effective solution. Figure 5.8 lists the possible combinations of the three technologies.

	COMBINATION #1	COMBINATION #2	COMBINATION #3	COMBINATION #4
PNEUMATIC BREAKERS	X	X	X	X
MILLING MACHINES		X		X
HYDRODEMOLITION			X	X

Figure 5.8 Possible Combinations of the Three Technologies

5.3.1 Combination One

Pneumatic breakers are generally used to varying degrees on all bridge rehabilitation projects due to their unique ability to remove contaminated or deteriorated concrete from small isolated areas and from vertical and overhead surfaces. The bridge rehabilitation project at the I-81 overpass at exit 37 in Christiansburg, Virginia utilizes pneumatic breakers to remove areas of damaged concrete from both northbound and southbound lanes of traffic.

Prior to the removal operations the areas of damaged concrete were determined by visual inspection and by the chain drag method. It was determined that the damage to the concrete was only in small, localized areas which would be most effectively removed by pneumatic breakers. A vertical saw cut was made around the removal areas to provide a suitable interface which would resist chipping.

Pneumatic breakers were then used to remove the damaged concrete from the delineated areas including around the reinforcing steel and on structural elements. A skilled breaker operator is able to selectively remove the deteriorated concrete based on the level of resistance and the associated ease of removal. This reduces the chances of removing excessive amounts of concrete and ensures that all the damaged concrete is removed. However, special caution must be exercised when using

pneumatic breakers to avoid damaging the residual concrete, gouging the reinforcing steel or creating additional delamination of the concrete to steel bond.

Following the pneumatic breaker operations, the areas of removal are sandblasted to free any loose material and filled with replacement material to match the grade of the existing surface.

5.3.2 Combination Two

The rehabilitation of I-84 at the Taconic State Parkway overpass in New York State provides an example of a project in which milling machines and pneumatic breakers were used in conjunction. In the evaluation of the bridge it was determined that the levels of contamination and deterioration had advanced to the point that to successfully rehabilitated the bridge the entire deck surface would need to be removed and replaced.

This was most effectively and efficiently accomplished by utilizing the low unit cost and high productivity associated with milling machines to initially remove the top 1/2 inch of the entire deck surface. The large area of removal, over 30,000 square feet, allowed for a high degree of continuity in the operations which enabled the machine to

attain high levels of production and to economically recover owning costs. The relatively shallow depth of removal reduced the possibility of interference with the reinforcing steel.

Following the initial entire deck removal, half cell potential measurements were taken to determine areas which would require further removal. These areas were then milled an additional 1 to 1.5 inches as necessary to be within 1/2 inch of the reinforcing. This work was performed as a separate bid item, concrete removal necessary for rebar exposure. The cost and production of milling in these areas is much higher than for entire deck removal due to the greater depth of removal, the proximity to the reinforcing and the smaller non-continuous areas.

Pneumatic breakers were used to further remove the damaged concrete from around, between and below the reinforcing under the same bid item as the localized milling operations. Following the concrete removal, the entire bridge deck area was sand blasted and air blown to remove any remaining rust or concrete residue. The localized areas of removal were then filled to the level of the milled surface and finally the entire deck was overlaid with a latex modified concrete.

This situation typifies the circumstances in which these technologies are most effectively utilized, milling machines for large, continuous areas requiring uniform removal, and pneumatic breakers for small localized areas and around reinforcing.

5.3.3 Combination Three

The bridge rehabilitation project at the I-84/Route 8 interchange in Waterbury, Connecticut is an example of a project which is utilizing hydrodemolition and pneumatic breakers to remove damaged concrete. The project consists of the rehabilitation of twenty five bridges, twenty of which require hydrodemolition, with the other five requiring full deck replacement.

Hydrodemolition is the primary means being utilized to remove concrete to a minimum depth of one inch below the reinforcing from areas greater than ten square feet. Pneumatic breakers are being used to remove concrete from areas less than ten square feet, in areas inaccessible to the hydrodemolition equipment or to remove deteriorated concrete to 1/4 inch above the top mat of reinforcing prior to hydrodemolition. The non-impact method utilized by hydrodemolition to remove concrete is less likely to produce damaging micro-cracks in the residual concrete and

will thus result in a longer lasting rehabilitation with reduced possibility of reoccurring damage.

The large number of bridges requiring hydrodemolition and the fact that hydrodemolition operations were often performed around the clock in multiple shifts enabled the equipment to achieve the production rates necessary to economically recover their high initial capital investment. The ability of hydrodemolition to rapidly remove concrete from around the reinforcing without damaging the steel or the residual concrete ensures a high quality and consistent product and minimizes the time, cost and variability associated with performing the work manually.

Containing the large volume of slurry produced by the hydrodemolition operation was a major concern with this project because the work was performed over and adjacent to open lanes of traffic. Prior to hydrodemolition, the deck joints were sealed with caulk to prevent the runoff from draining onto traffic under the work area. A vacuum truck, operated immediately behind the hydrodemolition equipment, removed the major portion of the water generated by the operation. Concrete barriers, hay bales and settling basins were used to further direct, filter and contain the runoff.

5.3.4 Combination Four

The second of two phases of rehabilitation of the Rouge River Bridge on I-75 outside of Detroit, Michigan used a combination of milling, hydrodemolition and pneumatic breakers to remove damaged concrete from the 52 foot wide, 8627 foot long bridge.

As a first step in the concrete removal operations, the top two inches of the deck surface was removed by milling. The operations required four days to complete. The large continuous area enabled the operations to proceed unimpeded thus maximizing productivity and minimizing costs. By milling the deck prior to hydrodemolition, a large volume of material was able to be removed at a substantially lower cost than would be incurred with other methods.

Following the milling operation, the entire deck was hydrodemolished. It is important to note that the specification requiring a one inch clearance around exposed reinforcing was relaxed for this project due to the reduced likelihood of microcrack formation and delamination associated with hydrodemolition. This reduced the quantity of material removed and minimized the amount of pneumatic breaker work required. The hydrodemolition effectively cleaned the exposed reinforcing steel and produced a textured surface with excellent bonding potential. Hydrodemolition is most effectively

utilized if the entire deck surface is removed to a depth which requires the removal of concrete from around the reinforcing.

The major area in which pneumatic breakers were utilized was to remove damaged concrete from around previously placed high strength patches. Hydrodemolition equipment is unable to properly remove material of a higher strength than the equipment is initially calibrated to remove. Following the concrete removal operations the entire deck was water washed to remove any remaining residue and then overlaid with latex modified concrete.

5.4 Conclusion

This thesis has examined the concrete removal technologies of pneumatic breakers, milling machines and hydrodemolition as they pertain to bridge rehabilitation. Each method was analyzed in terms of five parameters: technical description, work characteristics, production estimating, economics of operations, and managing and controlling quality, which collectively describe the technology and the environment in which it is most effectively utilized.

Chapters two, three and four presented a general examination of each technology in terms of the five parameters. This final chapter has summarized this information and presented an examination of the primary characteristics of a project which will determine which method or methods are best able to perform the concrete removal operations. Finally, the process of matching the technology to the project was briefly discussed.

It is anticipated that this information will assist persons involved in the bridge rehabilitation industry in defining and executing concrete removal operations by addressing the factors which will promote or hinder the effectiveness and efficiency of the three identified methods.

APPENDIX 1

Guideline Specifications for Bridge Deck Milling

A. Description

The work shall consist of removal of portland cement concrete pavement from the bridge deck by milling in accordance with these specifications and in reasonably close conformity with the lines, grades and cross-sections shown on the plans or as designated by the engineer.

B. Equipment

The equipment for removing the portland cement concrete pavement shall be a commercially designed and manufactured machine capable of performing the work in a manner satisfactory to the engineer.

The machine shall be power-operated and self-propelled, and shall have sufficient power, traction and stability to remove a thickness of concrete surface to a specified depth, and provide a uniform profile and cross slope. The machine shall be capable of accurately and automatically establishing profile grades (within $\pm 1/8$ inch) along each edge of the machine by referencing from the existing pavement by means of a ski or machine shoe, or from an independent grade line. The machine shall have an automatic system for controlling grade elevation and cross slope. The machine shall be equipped with a means to effectively control dust generated by the cutting operation.

C. Classification

Milling - Class I shall consist of milling the existing surface to the extent necessary to remove surface irregularities and to provide the desired texture and pattern required to create an effective bond with a subsequent overlay.

Milling - Class II shall consist of milling the existing surface only in the areas delineated by on the plan or by the engineer. These areas may not be continuous.

Milling - Class III shall consist of milling the existing surface to a uniform depth over the entire area of the bridge deck as directed by the engineer or as shown on the plans.

Milling - Class IV shall consist of milling the existing surface to a variable depth over the entire area of the deck as directed by the engineer or shown on the plans.

D. Procedures

The surface resulting from the milling operation shall be in accordance with the plan and specification grades, and shall be characterized by uniform, discontinuous longitudinal striations or other uniform pattern.

If, in the opinion of the engineer, the milling operation is substantially cracking or otherwise causing damage to the residual concrete, the operation shall be halted until the cause of the damage can be determined and corrected.

Removal of overlay material shall be performed in such a manner that underlying concrete will be prepared to receive any required subsequent treatment.

Before opening the milled surface to traffic , all loose material shall be removed from the milled surface and the surface swept clean with a power broom or other equipment approved by the engineer.

If the road is to remain open to traffic, longitudinal, vertical drop offs in excess of two inches at a lane line or center line shall not be left overnight.

Transverse faces existing at the end of a work period shall be tapered in a manner approved by the engineer to avoid a hazard to traffic.

Concrete that cannot be removed by milling equipment because of physical or geometric constraints shall be removed by other methods acceptable to the engineer.

If independent grade reference is required, it shall be designated in the plans and contract documents, and elevations shall be provided by the engineer. Milled material shall be disposed of as indicated on the plans or at the direction of the engineer.

E. Method of Measurement

Class I, Class II, Class III, and Class IV Milling shall be measured in square yards for the appropriate areas which have been prepared.

F. Basis of Payment

Accepted quantities shall be paid for at the contract unit price per square yard for the specified class of milling, and shall be full compensation for furnishing all labor, materials equipment, tools, and incidentals necessary to complete the work specified. Hauling the milled material may be incidental to the price for milling, if so indicated on the plans or in the special provisions, or may be a separate bid item and shall be paid at the contract unit price per square yard or per ton.

APPENDIX 2

Calculation of Annual Cost of Owning Equipment

Annual Equivalent Cost = Purchase Price x $(A/P)_n^i$ - Salvage Value x $(A/F)_n^i$

Where:
$$(A/P)_n^i = \frac{i(1+i)^n}{1+i^n - 1}$$

$$(A/F)_n^i = \frac{i}{(1+i)^n - 1}$$

n = Life of Equipment in Years

i = Interest Rate Applied

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Vita

James P. Merrigan, son of Lawrence James and Ann Marie Merrigan, was born on January 25, 1966 in Washington, D.C.. He grew up in the Northern Virginia area and graduated from West Springfield High School in 1984. After graduating with a Bachelor of Science in Civil Engineering at Virginia Polytechnic Institute and State University in May of 1989, he entered the graduate program in the Construction Engineering and Management Division of Civil Engineering at Va. Tech. On August 11, 1990, during his graduate studies, James married Beth Cusick who was pursuing a Masters of Business Administration at Va. Tech.

During his undergraduate studies, James was involved in the Cooperative Education Program at Virginia Tech, through which he worked several quarters with Dewberry and Davis, a large land development consulting firm. He also worked with a local land development consulting firm part-time during his senior year of undergraduate studies and full-time during the interim before beginning graduate studies. He plans to pursue a career in construction management following an extended hiatus in which he intends to hike the Appalachian Trail.

A handwritten signature in black ink that reads "James P. Merrigan". The signature is fluid and cursive, with "James" on the first line and "P. Merrigan" on the second line.