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Techniques for Concrete Removal and Bar Cleaning on Bridge Rehabilitation Projects

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Abstract

The report addresses the partial removal of concrete from decks and other parts of bridge structures. It is intended as a practical guide for state highway agency and contractor personnel who face the challenge of using new and appropriate technologies for concrete removal and bar cleaning on bridge rehabilitation projects. The required removal tasks are classified in terms of the method used to identify the removal area, the size and location of the removal area and the depth of removal.

A variety of concrete removal techniques are analyzed in terms of their ability to perform one or more of the removal tasks. Three technologies are identified as being of particular importance and these are studied in detail: pneumatic breakers, milling and hydrodemolition.

The detailed analysis of the three technologies is done in a uniform format addressing work characteristics, production, cost and quality of product. This permits a comparative analysis of the three technologies and makes it possible to identify their strengths and weaknesses and to make recommendations with regard to the manner in which they can be combined to achieve a desired result.

Executive Summary

This is a practical guide for state highway agency (SHA) and contractor personnel who perform design work, produce contract documents, prepare competitive bids and manage construction operations on bridge rehabilitation projects. It is divided into two main parts.

The first section gives an overview of the deterioration process that describes corrosion-induced deterioration as a two-stage process. The first stage is the ingress of chlorides to reach a critical level at the rebar. The second stage is the production of rust, which expands and creates cracks and spalls in the concrete.

Unless the structure is being demolished, some level of concrete removal and replacement is necessary. The extent of concrete removal will be determined by the type of repair or rehabilitation. The methods of concrete removal will be determined by the extent, location and specification of the concrete removal needs.

There are a number of methods for concrete removal. These range from sandblasting, which is used for surface preparation and rust removal on concrete and/or steel, to sawing, which is used for the full-depth removal of a given area. Three different technologies, one labor-intensive (pneumatic breakers) and two that are capital or equipment intensive (milling and hydrodemolition), are identified as important technologies for use under appropriate conditions. The first portion of the report therefore includes a brief study of the balance between capital study of mechanization and labor-intensive operations. This identifies several contractual and operational changes which must be made if mechanization is to achieve its full potential.

The second section of the report provides a detailed study of the three dominant technologies. This is done in a uniform format addressing work characteristics, productivity, cost and quality of product. It is found that pneumatic breakers, milling and hydrodemolition are in fact not competitors in any given task and that each has both strengths and weaknesses. Pneumatic breakers are extremely flexible in terms of the size and depth of removal tasks to which they are suited; they are also the most expensive of the three technologies. Although milling is the cheapest on a unit area basis, it is the most inflexible as it can only be used to remove concrete above the reinforcing steel on large horizontal surfaces. Hydrodemolition is relatively inexpensive, it is flexible with regard to depth of removal, but is limited to large horizontal surfaces and constrained by the environmental impacts of the resulting waste water.

The second section of the report concludes with comments on how the technologies can be combined to achieve a desired result at minimum cost. This shows that pneumatic breakers are invariably required to perform detail work and that the choice between milling and hydrodemolition depends on the quantity of concrete which must be removed from around, between, and below the reinforcing steel. Combining all three technologies is shown to have substantial potential.

1

Introduction

This report is presented as a practical guide for state highway agency (SHA) and contractor personnel who face the challenge of introducing new and appropriate technologies for concrete removal and bar cleaning on bridge rehabilitation projects. It covers only partial removal of concrete from decks and other parts of bridge structures which may be horizontal, vertical or overhead. The complete removal of all or part of obsolete or deteriorated structures is not covered. This chapter introduces the report by outlining the process of corrosion, describing various concrete removal operations and defining a number of terms used in the balance of the report.

1.1 Chloride Contamination and Deterioration in Concrete

The bare pavement policy introduced in the 1950s mandated that the nation's roads be kept safe for travel in spite of snow and ice. This prompted SHAs to use liberal quantities of sodium and calcium chloride as cheap and efficient deicing agents on both highways and bridges when winter weather threatened the free flow of traffic.

These deicing salts dissolve in the snow and runoff water. The resulting chlorides enter the concrete to contaminate it and create a hostile environment for the reinforcing steel. Decks, piers, beams and all reinforced concrete bridge elements are affected. Unprotected bridge decks show the first signs of deterioration, but increasing problems from runoff onto substructures are being reported.

Bridges in coastal regions are especially exposed to chloride contamination as the marine environment provides a continuous supply of salt, water and oxygen. Chloride induced corrosion of substructures is a major concern in these areas.

The presence of chloride ions in the reinforced concrete promotes the formation of rust on the reinforcing steel. This leads to deterioration of the concrete through cracking, delamination and spalling. Substantial work is required to patch, rehabilitate or replace the deteriorated concrete to keep the bridge in a good service condition.

Maintenance operations invariably require that the concrete contaminated by the ingress of chlorides, cracked, or delaminated by internal stresses, be removed. This is a vital step of almost every bridge repair and rehabilitation project since it dominates the scheduling aspects of the project. It is also expensive because concrete removal has traditionally been a low-production-labor-intensive operation with many factors affecting both productivity and cost.

The need to improve schedule and cost performance has led to the development of numerous alternative technologies for the removal of unwanted concrete and cleaning the exposed reinforcing steel. The implementation of these technologies does, however, necessitate careful thought and some revision to the technical, contractual and construction aspects of the work. This challenge must be met in order that the motoring public may reap the benefits of innovation and not suffer from outmoded, slow and costly construction.

The report is intended to be used for design and construction guidance in implementing these technologies. Both project engineering and construction engineering aspects of the work are addressed so that users may develop a better understanding of the linkage between design and construction.

1.2 Chloride Ion Induced Deterioration in Reinforced Concrete

Steel does not normally corrode when embedded in concrete, despite the presence of water and oxygen. Although concrete is porous, the pores contain a highly alkaline solution of calcium, potassium and sodium hydroxides. These lead to the formation of a "passive" oxide layer on the steel which is so dense that it slows the corrosion process to a virtual standstill.

However, when salt (NaCl) gets into the concrete pores, the chloride ion (Cl^-) permeates down to the steel surface where it breaks down the passive layer and promotes corrosion. The chloride ion is not consumed in the corrosion reaction, which is why simple repair of delaminated concrete will not stop the process, but will lead to the onset of corrosion in adjacent areas.

Chloride contamination and rust formation precede deterioration in reinforced concrete. The four stages in the process, illustrated in figure 1.1, are as follows:

1) Contamination and rust formation through the ingress of chlorides are prerequisites for deterioration in the concrete.

2) Cracking occurs when the rust-induced tensile stresses exceed the tensile strength of the concrete. Cracks may be inclined or parallel to the surface.

3) Delamination occurs when cracks which run parallel to the surface join to create a fracture plane below the surface. The concrete is no longer sound and may spall at a later stage.

4) Spalling occurs when inclined cracks reach the surface and subsequent freeze-thaw cycles, traffic loads or other forces cause the cracked or delaminated concrete to break away from the surface.

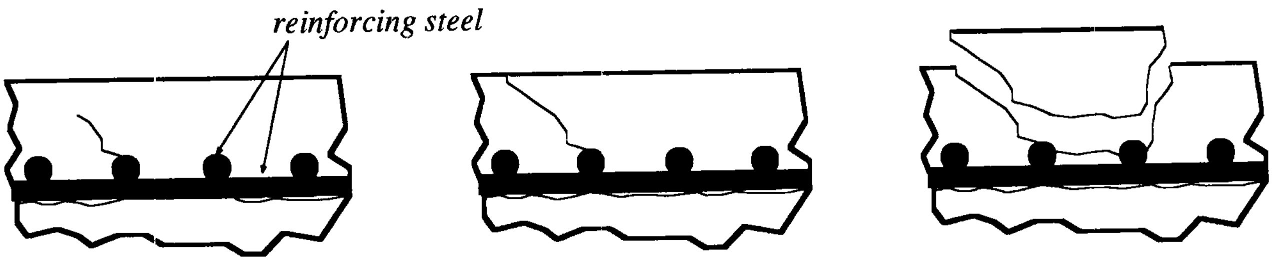
1.3 Obsolescence and Deterioration in Bridges

Reinforced concrete bridges play a vital role in most transportation systems. They are, however, not very robust when compared with other components of the system and they become structurally deficient or functionally obsolete in a relatively short period of time. Some of the reasons for this decline are caused by chloride contamination of the concrete. Others arise because of changes in the demands placed on the bridge and have nothing to do with contamination and deterioration. A distinction between these two factors keeps the question of chloride contamination in perspective and provides a background for section 1.4 (p. 9) which addresses alternatives for reversing the pattern of deterioration.

Obsolescence may be defined as reduced functional and structural adequacy of the bridge compared to the best and most suitable structure that could be constructed at present. It manifests itself in many ways including the following:

- an increase in traffic delays due the old structure's inability to meet current demands,
- reduced safety factors due to increased loads imposed by current traffic demands,
- a lowering of safety standards because the old structure is unable to meet current safety standards.

1. *Contamination*
Contamination and the ingress of chloride is a prerequisite for deterioration.



2. *Cracking*
Cracks may be inclined or parallel to the surface.

3. *Delamination*
Cracks join to create fracture planes.

4. *Spalling*
Sections which are cracked or delaminated break away.

Figure 1.1 Concrete deterioration

Steps to reduce obsolescence could include relatively minor work, such as improving safety barriers, lights and signs to meet new standards; or it could include major work, such as widening or replacing an existing bridge.

Deterioration is very different from obsolescence. It is defined as the reduced structural adequacy of the bridge compared to that which existed when the bridge was new. Deterioration is of concern to the motoring public and the SHA responsible for maintaining a safe and efficient system, and it manifests itself in many forms. Among these manifestations are the following:

- an increase in maintenance expenditures due to increased rates of corrosion and deterioration of the concrete;

- a decrease of safety factors due to excessive steel corrosion, cracking, delamination and spalling structural members;

- a reduction in the ride quality of the deck due to spalling of the surface concrete.

Most of the work performed to reduce deterioration involves maintenance and repair operations where the objective is to restore the old bridge to its prior condition. Removing cracked or delaminated concrete, cleaning the exposed steel and replacing the concrete with a new and perhaps improved material are typical tasks which must be performed to combat deterioration. These operations contrast with reconstruction or enhancement operations to combat obsolescence. While the two operations frequently overlap, it is important to draw some distinction when considering the alternatives available for overcoming structural deficiency and functional obsolescence.

Figure 1.2 outlines the action needed to combat obsolescence and deterioration and to return to acceptable condition.

Little can be done by the maintenance engineer to reverse obsolescence in existing bridges. Growth in traffic volumes, increased loads and enhanced safety standards often require that all or part of the structure be demolished and rebuilt to provide a facility that is able to meet the new demands.

Two alternatives for this work are available:

1) renovation, and
2) reconstruction.

The techniques needed to demolish concrete as a prerequisite for reconstruction or renovation are outside the scope of this report.

1.4 Alternatives for Reversing Deterioration

Many alternatives are available to the maintenance engineer in attempting to combat deterioration and keep the structure in its original condition. These may be grouped into three broad categories:

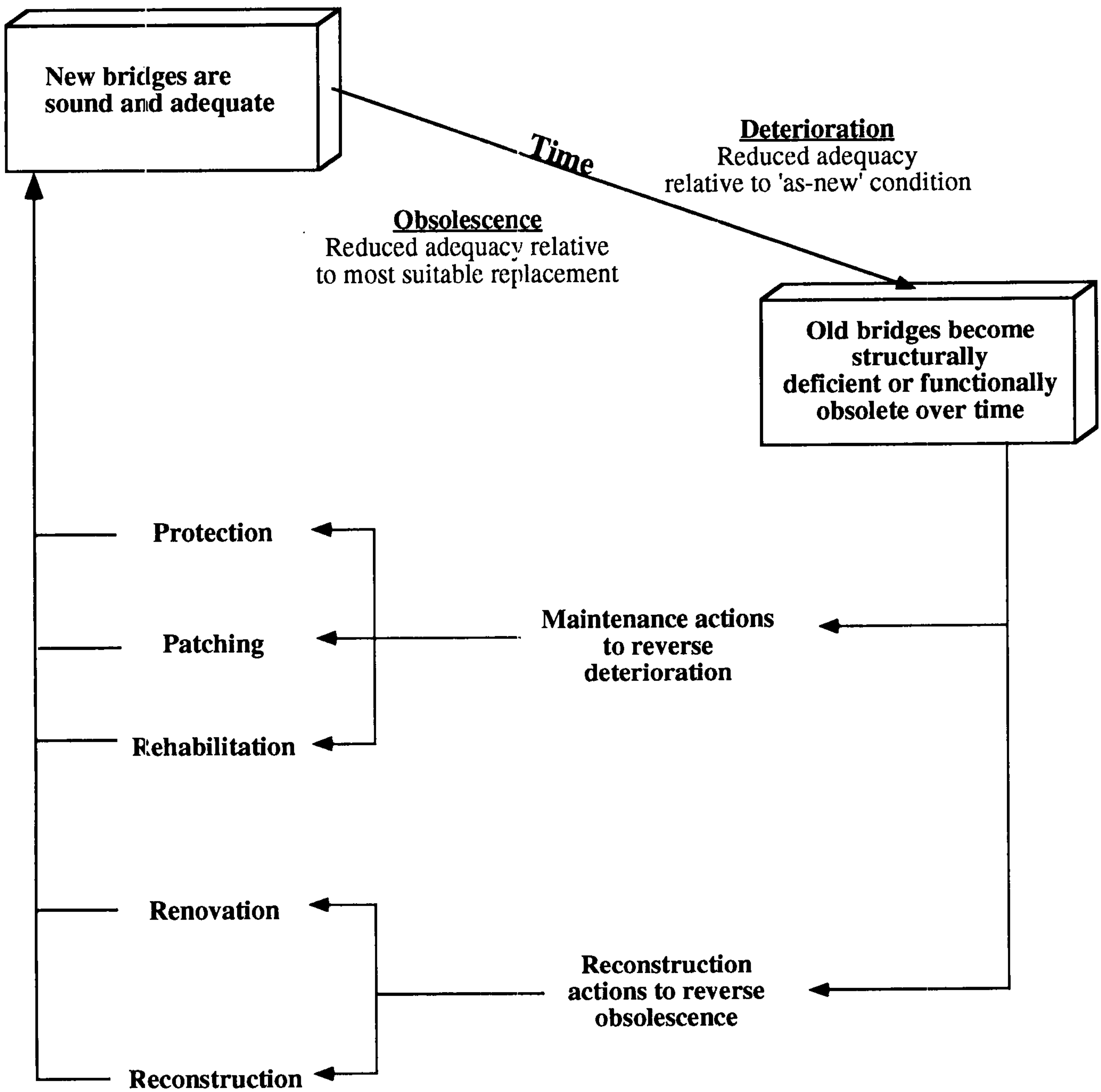


Figure 1.2 Alternatives for reversing deterioration and obsolescence

- Protection,
- patching, and
- rehabilitation.

All these alternatives are maintenance operations. While the work involved is not necessarily minor, it is limited by the fact that it does not involve any change to the original functional characteristics of the bridge.

1.4.1 Protection

Physical barriers such as waterproof overlays or membranes halt or slow the process of deterioration. Electrochemical methods can also be used to remove chlorides or upset the required chemical actions. These alternatives are viable if deterioration has not progressed beyond certain limits.

Protection from chloride ingress is an alternative for new bridges and bridges where chloride contamination has not yet reached critical limits. Under these conditions every effort should be made to use the best technologies available in design, construction and operation to prevent contamination and extend life. Barriers are most effective when introduced during the initial construction but they can also be introduced during maintenance operations as is the case when either membranes or high density concrete is used in deck overlays.

1.4.2 Patching

Patching is defined as the process whereby small localized areas of deterioration in the bridge are repaired by removing the deteriorated concrete, cleaning any corroded reinforcing steel, and replacing the concrete with a substitute material. The objective is to reinstate the original characteristics of the structure as far as possible. There is no expectation of increased life and patching does not enhance the original functional characteristics of the bridge.

Patching is essentially a quick, short-term procedure that may need to be repeated on several occasions. The timing of the work is not fixed and it can be delayed for fairly extensive periods determined only by safety, serviceability and the fact that delayed work costs more than work undertaken at the most opportune time.

1.4.3 Rehabilitation

Rehabilitation is more extensive than patching. Large areas of chloride-contaminated or deteriorated concrete are systematically removed, the corroded steel is cleaned, and the area is repaired with materials similar to those originally used. The objective is to repair the area to a standard at least equal to that found in parts of the structure that are not contaminated. There is an expectation of some increased life but there is no expectation of enhancement to the original functional characteristics of the structure.

The alternatives for reversing deterioration set out in figure 1.2 and the definitions of protection, patching and rehabilitation presented above may give the impression that any project may entail the selection of a single alternative. However, as most projects employ a mix of alternatives to achieve the desired result. This is particularly true insofar as renovation and rehabilitation are concerned. Most projects involve an element of both: renovation to bring the bridge as close to current standards as possible and rehabilitation to systematically remove and repair areas where concrete and steel have been damaged by the ingress of chlorides.

1.5 Summary

This short introductory and technical chapter has sought to provide an insight into the causes of deterioration in reinforced concrete bridges and of the steps needed to reverse or contain the process. A substantial number of terms have been defined and much has been done to develop a conceptual framework for the work which follows. The key points developed are:

- Deterioration follows contamination and takes place in three defined stages: cracking, delamination, and spalling.

- Obsolescence and deterioration are two different forces which work together to render a bridge functionally obsolete and structurally deficient.

- Alternatives available to overcome deterioration fall into three broad categories: protection, patching, and rehabilitation.

- Most projects require use of a blend of alternatives to achieve the desired results. Patching, rehabilitation and renovation all require that concrete removal and bar cleaning tasks be performed.

2

Concrete Removal and Bar Cleaning Tasks and Techniques

Chapter 1 described the process that leads to deterioration and obsolescence in reinforced concrete bridges. It defined SHAs' alternatives for reversing deterioration and obsolescence and argued that most projects require a blend of alternatives to achieve the required results. Concrete removal and bar cleaning tasks were shown to be necessary for alternatives involving patching and rehabilitation.

This chapter reviews four factors which define the nature of concrete removal tasks, discusses quality constraints and gives a brief overview of different methods available to perform the tasks. It provides a starting point to chapter 3 which addresses the economics of the mechanized methods introduced in this chapter.

2.1 Factors That Define the Tasks

Patching, rehabilitation and renovation require that deteriorated and/or contaminated concrete be removed to a specified depth over a given area at a particular location on the structure. These three factors - depth, area and location - and the method used to identify the concrete to be removed, define the nature of the various concrete removal and bar cleaning tasks. Each will be discussed in this chapter.

2.1.1 Method Used to Identify the Concrete to be Removed

Four methods are generally used to identify concrete which must be removed as the first step in either renovating, rehabilitating or patching an existing bridge. The first two, visual inspection and sounding, identify deteriorated concrete and rely on the fact that corrosion has reached the stage where cracking, delamination or spalling are either visible or sufficient to produce a dull sound when the surface is dragged with a metal chain or struck with a masonry hammer. The other two methods, core sampling and half-cell potential measurement, are able to detect contaminated concrete and determine the risk of corrosion in the area of measurement.

The work required to remove deteriorated concrete identified by visual inspection and sounding differs from the work required to remove chloride-contaminated concrete identified by core sampling or half cell potential measurement in two important aspects:

1) The Effort Required. Deteriorated concrete identified by inspection or sounding is relatively easy to remove due to preexisting cracks or delaminations. Contaminated concrete identified by core sampling or half cell potential measurement is more difficult to remove as it may not be structurally damaged in any way.

2) The Area Involved. Visual inspection and sounding identify specific local areas of deterioration whereas core sampling and half cell potential measurements are normally taken as indicators of contamination over a large area. This is discussed in section 2.1.3 (p. 15).

The identification and removal of deteriorated concrete is usually only a stopgap measure. Corrosion will continue in the contaminated concrete. It is only a matter of time before cracks, delaminations and spalls occur in adjacent areas.

2.1.2 Area of Concrete to be Removed

The method used to identify the concrete to be removed influences the area of concrete to be removed in two ways:

1) Visual inspection and sounding identify deterioration in the concrete. The areas are likely to be small and irregular in shape as determined by the actual cracking, delamination and spalling identified. The localized nature of the work limits the alternatives for concrete removal and bar cleaning. The deteriorated concrete is, however, relatively easy to remove because of the existing cracks and fracture planes.

2) Half-cell potential measurements and core sampling can determine chloride content and detect contamination in the concrete. The results are generally seen as reflective

of the overall condition of the structural component. The concrete removal and bar cleaning operations which follow are normally performed in a systematic manner over a large area. Both sound but contaminated concrete and deteriorated concrete will be removed. Thus material that has not been fractured by rust-induced cracking may also be removed.

2.1.3 Location of the Concrete to be Removed

Concrete removal on a bridge deck differs substantially from concrete removal on other structural elements. The flat horizontal surface of a deck provides easy access and permits use of high-production mechanized methods. Clean-up and containment of debris is also easier on the horizontal surface.

Other structural elements have smaller surfaces that frequently are vertical or overhead and difficult to reach. Difficulties with access and debris containment precludes the use of heavy equipment and makes concrete removal less productive and more expensive. The need for scaffolding to provide access for workers and equipment adds to the difficulty and safety hazards involved with the work.

The location of the work influences the area of removal in two ways:

1) Decks present large surface areas that are exposed to chlorides in deicing salts to remove snow in northern climates and sea spray in a marine environment. This, together with exposure to traffic, means that areas of contamination and deterioration are likely to be large with removal operations following a systematic pattern.

2) Other structural elements present small and irregular surface areas that are not uniformly affected by deicing salts and sea spray due to differing patterns of exposure and runoff. Areas of contamination and deterioration are thus likely to be small and irregular in shape.

The extent of concrete removal and bar cleaning operations on a given bridge component can thus vary from large regular areas covering most of the component to small irregular patches in random locations.

2.1.4 Depth of Concrete Removal Required

The depth to which the concrete is removed has a profound effect on the method to be used and the cost of the work. The following classification, as shown in figure 2.1, is used throughout the report.

1) Surface Removal. This is defined as the minimum amount of work needed to remove surface contamination and provide a clean, long-lasting bond between the existing material and the material used to repair or rehabilitate the bridge.

2) Cover Concrete Removal. Cover concrete is defined as the concrete that lies outside or above the first layer of reinforcing steel. The removal task does not involve any interaction with the reinforcement and is not hindered by its presence.

3) Matrix Concrete Removal. Matrix concrete is the concrete which lies around and between the steel reinforcement. The removal tasks are severely hindered by the need to work in confined spaces around, below and between individual bars. Contaminated concrete in this zone is thus extremely difficult to remove. The removal of deteriorated concrete is somewhat easier because of fracture planes caused by cracking and delamination. The depth of the zone is defined to extend a small distance (about 1" or 2.5 cm) below the steel to allow for the flow of replacement material into all the voids created.

4) Core Concrete Removal. Core concrete forms the core of the structural element and lies between the reinforced zones. The removal task is inhibited by the reinforcing steel that was exposed during the removal of the matrix concrete. Conventional cutting, grinding and sawing techniques cannot be used. The quantity of material in this zone is dictated by the size and shape of the structural element. Thin deck sections contain little core concrete material, while piers and pile caps may contain a fairly substantial quantity. The volume of material to be removed is limited by the extent of chloride contamination.

5) Bar Cleaning. Bar cleaning operations are aimed at removing rust and chlorides to provide a fresh surface for bonding with the repair material. The minimum amount of material needed to achieve the required quality must be removed.

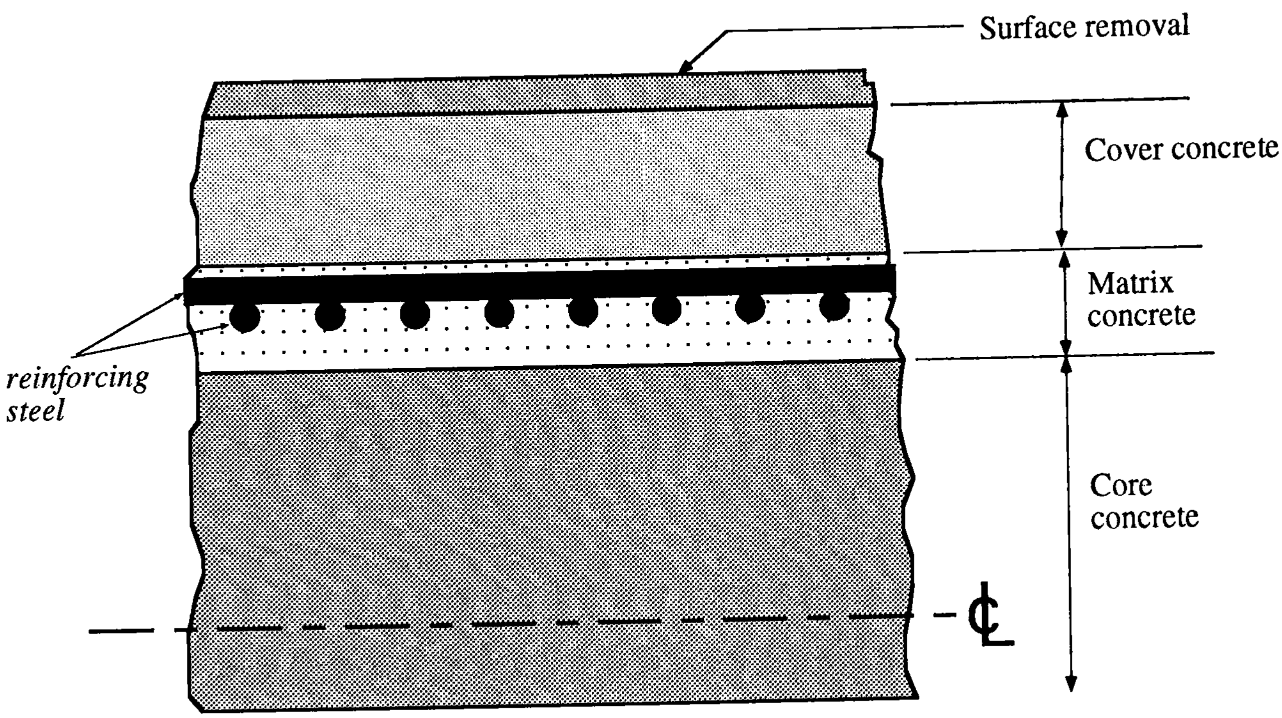


Figure 2.1 Depth classification for concrete removal

2.2 Quality Constraints

The concrete removal and bar cleaning tasks performed to renovate, rehabilitate or patch an existing reinforced concrete bridge are very different from the tasks performed simply to demolish the structure. This stems from the fact that removal tasks must meet three quality constraints which do not apply to demolition.

2.2.1 Selectivity

Removal tasks must be performed selectively on parts of the bridge. Only the contaminated or deteriorated concrete and rusted reinforcing steel marked for removal must be removed. Removal in excess of the required minimum is expensive in terms of both removal and replacement cost and contributes nothing to the quality of the completed product.

2.2.2 Residual Damage

Removal tasks must be performed in a manner that ensures that the remaining concrete and reinforcing steel retains its structural integrity. Equipment used to perform the work must not overload the structure. Any impact forces used to remove damaged concrete should be applied in a manner that minimizes cracking in the residual concrete and damage to the bond between the remaining concrete and steel. Methods to remove rust and chlorides from the steel should also minimize damage and loss to the remaining steel.

2.2.3 Bond Quality

Removal tasks are only part of the repair process. Any new material needed to patch overlay or replace the damaged material will need to bond effectively with the remaining concrete and steel. Remaining surfaces must be clean and sufficiently textured to provide the required bond.

The quality constraints, selectivity, residual damage and bond quality make removal a more demanding and expensive task than demolition. They also preclude the use of many high impact, high-production techniques developed for concrete demolition and limit suitable techniques to those that comply with the constraints.

2.3 Methods for Performing the Tasks

This section gives a brief overview of the methods that are available for concrete removal and bar cleaning operations on bridge repair and rehabilitation projects.

The methods are classified according to the four removal depth categories defined in section 2.1.4 (p. 16) as this is the most readily apparent and easily defined aspect of the work to be performed.

2.3.1 Methods for Surface Removal

It is frequently necessary to remove surface contaminants such as oil, rubber and rust from the work area in order to provide a sound, long-lasting bond between the existing structure and the new materials used to repair or rehabilitate the bridge. The objective is to clean rather than to remove material. The following four methods are frequently used:

1) Scrabbling. A scrabbler uses pneumatically driven bits to impact the surface to remove concrete to a depth of between 1/32" and 1/4" (1 mm and 6 mm). Scrabblers vary in size from large, self-propelled machines that can only work on large horizontal surfaces to small, hand-held tools for use in restricted, vertical or irregular surfaces. Vacuum collection systems are frequently used to collect the concrete debris.

2) Planing. A plane or diamond grinder removes concrete by abrasion. Numerous diamond tipped concrete saw blades are mounted close to one another on a horizontal spindle which is rotated to cut and remove up to 1/2" (12 mm) of concrete in a single pass. The process requires water to cool the blades and the resulting slurry of concrete particles can be vacuumed up for collection and disposal.

3) Sandblasting. Sandblasters use compressed air to propel sand particles at high velocity. The impact of the particles produces a very abrasive action which cleans and roughens the exposed concrete or steel. The size and capacity of the equipment varies substantially. Small, hand-held tools are used on vertical or irregular surfaces. Vacuum systems are used to recover the sand and resulting debris.

4) Shot Blasting. Shot blasters use a rotating paddle wheel to propel steel shot against the concrete surface at high velocities. The impact is capable of removing concrete to depths up to 1/2" (12 mm). The roughness of the substrate concrete is controlled by the selection of different shot sizes. Machines vary in size, but the fact that a collection chamber must be used to control the rebounding shot limits their use to horizontal surfaces. A vacuum system is used to pick up the concrete debris and steel shot which are separated so that the shot can be reused.

2.3.2 Methods for Removing Cover Concrete

The removal of cover concrete over a relatively wide area is frequently necessary in bridge rehabilitation projects. The work involves removal to a depth less than the cover depth of the steel and thus no work between, around or under the reinforcing mat is included in the task.

Scrabbling, planing, sandblasting and shot blasting all can be used in repeated passes to achieve the required depth. This is an inefficient use of these methods, and the only really effective way of doing the work when large areas are involved is by using a concrete milling machine. A milling machine removes concrete by the impact of numerous tungsten-tipped teeth mounted on a rotating drum or mandrel as shown in figure 2.2.

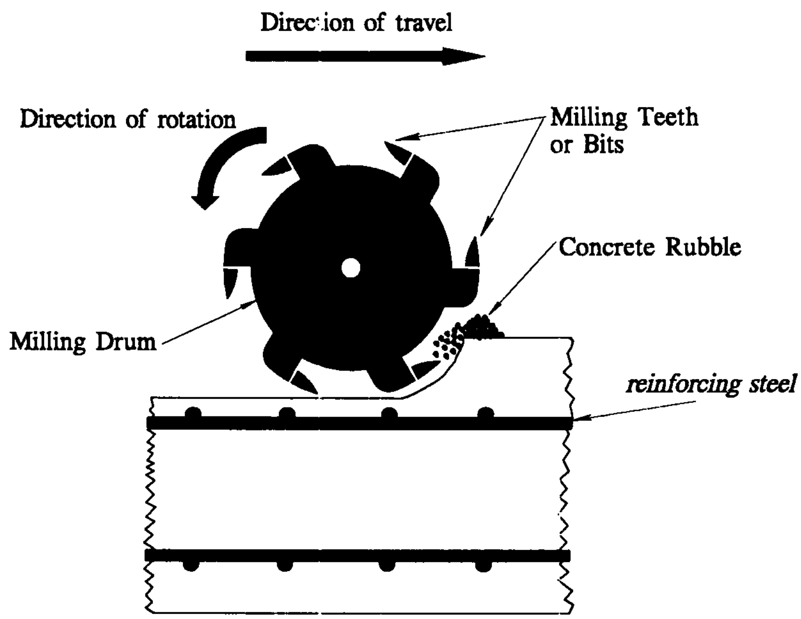


Figure 2.2 Action of a milling machine on a bridge deck

Milling machines can achieve very high levels of production but they can only be used on horizontal surfaces such as bridge decks. They are also only capable of removing concrete above the reinforcing steel and severe damage can occur when milling teeth cut or snag the reinforcement. Despite these limitations the use of milling for the removal of cover concrete is an emerging technology suited to the large volume of high-production work which must be performed for infrastructure maintenance in the next decade. It is discussed in detail in chapter 5 (p. 53) of this report.

Hydrodemolition can also be used as a high-production, equipment-intensive method for the removal of cover concrete. It is, however, more frequently used to remove cover and matrix concrete simultaneously and is discussed in section 2.3.3 (p. 21).

Hand-held pneumatic breakers are frequently used to remove cover concrete when the areas involved are inaccessible to a milling machine or too small to be milled. As with hydrodemolition, hand held breakers are primarily used for matrix concrete removal and are discussed in section 2.3.3 (p. 21).

2.3.3 Methods for Removing Matrix Concrete

It is necessary to remove matrix concrete when contamination, spalling and delamination have progressed into the concrete layer that surrounds and encases the reinforcing mat. The work involved is awkward as it must be performed between, around and under the steel without damaging the steel, cracking the substrate concrete, or destroying the bond between steel and concrete in areas where the concrete is not to be removed. There are basically two methods available: pneumatic breakers, and hydrodemolition. Both of these techniques may be used to remove cover and matrix concrete in a single operation or may be used to remove only matrix concrete after a more specialized and high-production method, such as milling, has been used to remove the cover concrete.

1) Pneumatic Breakers. The pneumatic breaker (frequently known as a jack-hammer but properly known as a paving breaker) is currently the most prevalent method for concrete removal in bridge rehabilitation work. The breaker is hand held and powered by compressed air to deliver a series of high frequency blows which fracture the concrete in a small, easily controlled area. The production of pneumatic breakers depends on two factors; the size of the breaker and the skill of the operator.

   Breakers are sized according to their weight. This can vary from 8 to over 120 pounds (4 to 55 kg). Heavier breakers are more productive because they are able to impart more energy with each blow. They are also more destructive. SHAs typically limit the weight of breakers that can be used for selective concrete removal to less than 45 pounds (20 kg) to minimize residual cracking and preserve the bond between the residual concrete and the repair concrete in areas that are not removed. The angle of attack measured from the breaker's axis to the concrete surface is also frequently limited to 45 degrees for the same reasons. The skill of the operator is important with regard to both the quantity and quality of the work performed. This factor must not be overlooked when assessing the viability of the method.

   Pneumatic breakers play a major role in the removal of concrete for all types of bridge rehabilitation projects. They are thus discussed in detail in chapter 4 (p. 35).

2) Hydrodemolition. Hydrodemolition is a high-production capital intensive method for concrete removal. An extremely high pressure (12,000 - 35,000 psi: 80 - 240 MPa) water jet is used to destroy the cement matrix of the concrete and liberate the aggregate. The equipment needed to generate the pressure and focus the water jet on the concrete to be removed is expensive and complex. The results under the right conditions can be impressive.

The majority of hydrodemolition work involves the removal of matrix concrete on bridge decks. The equipment can, however, be calibrated to remove concrete to almost any depth and the nature of the process is such that there is an element of self adjustment in depth depending on the soundness of the material encountered. Hydrodemolition can be used on inclined, vertical and overhead surfaces but cost effectiveness is reduced by the inordinate cost of the specialized equipment needed to safely direct the jet and contain the debris when working on other than horizontal surfaces.

Hydrodemolition is an emerging technology suited to all phases of concrete removal. It is discussed in detail in chapter 6 (p. 71).

2.3.4 Core Concrete Removal

Core concrete removal necessitates the removal of concrete at the core of the structural element in a manner which respects the three quality constraints of selectivity, residual damage and bond quality detailed in section 2.2 (p. 17). Pneumatic breakers and hydrodemolition are the only two techniques available if the surrounding mats of reinforcing steel are to be left intact. Both of these methods, however, suffer serious losses in productivity due to the difficulty of reaching the material. There also is no efficient way to remove substantial quantities of core concrete while leaving the reinforcing steel in place.

Core concrete material can be more efficiently removed if the reinforcing steel is cut. This will of course require that it be replaced at a later stage but it does permit the use of two technologies frequently used for full-depth removal. These are:

1) Sawing. Concrete saws use industrial-diamond-coated circular blades to cut concrete and steel. They range in size from 4 to 48 inches (100 mm - 1.2 m), may be hand held or mounted on self-propelled carriages, and can be powered by a variety of sources. Water is sprayed onto the blade and into the cut to cool the blade and reduce friction between the blade and cut sidewall. Sawing is a low-cost, versatile technique for performing a number of tasks including: cutting the perimeter of an area where pneumatic breakers are to be used for removing concrete; cutting to full depth in slabs and decks so that sections may be removed; and cutting joints in new concrete.

2) Lancing. The thermal lance employs intense heat (12,000°F: 6,700°C) to melt concrete and steel. The heat is generated by an oxygen-iron reaction with various sources such as iron rods, powdered iron and powdered iron and aluminum mixtures

available to support the process. A thermal lance is typically used to cut thick (up to 4": 100 mm) concrete. It is most effective when the molten slag is free to flow away from the cut area. The major concern when using a thermal lance is safety and the effect of the high temperatures on the concrete that remains.

Demolition techniques fall outside the scope of this report in that they focus on the removal of the whole structure or structural element and do not satisfy the three quality constraints detailed in section 2.2 (p. 17).

2.3.5 Bar Cleaning

Bar cleaning necessitates the removal of rust, chlorides and other unwanted material from the exposed reinforcing steel. The work follows the removal of matrix concrete and is extremely important as all the chloride contaminated rust and cement paste must be removed to stop corrosion from continuing in the backfilled concrete. Three methods are frequently used. These are:

1) Sandblasting. The abrasive impact of sand particles under compressed air is an effective method for cleaning exposed steel because it is able to remove cement deposits and rust to leave a bare metal finish.

2) Wire Brushing. Powered rotary wire bristle brushes can be used to clean exposed rebar. Brushes are pneumatically or hydraulically driven and usually mounted on a small utility construction vehicle. Access to hidden and difficult-to-reach surfaces is restricted.

3) Hydrodemolition. Sand arising from the hydrodemolition process is propelled by the high pressure water to create an abrasive fluid able to clean rebar as an adjunct or parallel operation to the removal of matrix or core concrete by hydrodemolition.

2.4 Summary

This chapter has provided a brief review of concrete removal and bar cleaning tasks and technologies. Four different depths for concrete removal have been defined and three quality constraints have been identified. A number of methods for performing the tasks have been discussed. The main findings are:

1) Pneumatic breakers are widely used as the primary means of performing a number of tasks. They are thus worthy of further study in chapter 4 (p. 35).

2) Milling is the primary means of surface removal and cover concrete removal over large areas. There is a substantial demand for the performance of these tasks and the technology is thus studied further in chapter 5 (p. 53).

3) Hydrodemolition is the primary means for removing cover and matrix concrete on large horizontal surfaces. This work is also an important component of the bridge rehabilitation process and thus chapter 6 (p. 71) is devoted to a study of hydrodemolition.

Two other important points made in the chapter need to be summarized:

1) Bar Cleaning. Bar cleaning removes rust and chlorides from exposed steel so as to inhibit further corrosion and improve the bond between the steel and the replacement material. Wire brushing can be used but the work is normally done by sandblasting as a self-standing operation or as part of an overall cleanup and bond improvement process performed immediately prior to placing the replacement concrete. The abrasive action of sand particles liberated in the hydrodemolition process plays an important part in bar cleaning when this technology is used. It must be emphasized that all of the chloride-contaminated rust and cement paste must be removed from the exposed rebars or corrosion will continue in the repaired area.

2) Quality Constraints. The three quality constraints of selectivity, residual damage and bond quality discussed in section 2.2 (p. 17) must be met under all conditions. No removal technology can be used if it does not satisfy the constraints.

Two of the chosen technologies, milling and hydrodemolition are equipment- or capital-intensive. Their effective use necessitates an understanding of the issues discussed in chapter 3, which focuses on the economics of mechanization and equipment-intensive operations.

3

Mechanization and Equipment-Intensive Operations

Chapter 2 provided an understanding of concrete removal and bar cleaning tasks and reviewed the technologies available to perform the work. Three technologies, pneumatic breakers, milling and hydrodemolition, were identified for further study in chapters 4, 5, and 6.

Two of these technologies, milling and hydrodemolition, present radical departures from the traditional labor-intensive approach of using pneumatic breakers to remove deteriorated and contaminated concrete on bridge rehabilitation projects. Their implementation will improve cost effectiveness and depends on an understanding of the factors which lead to success in mechanization and equipment-intensive operations. This chapter addresses the economic, contractual and operational requirements of mechanization and capital intensive operations.

3.1 Labor-Intensive Methods

Labor-intensive methods are less complex from a technical point of view. They are likely to be tried, tested and accepted by owner and contractor. The technical risks involved when using a labor-intensive method, such as pneumatic breakers, for removing deteriorated concrete are minor. Everyone knows that the method will work and that the required quality constraints will be met if the work is done with reasonably qualified operators. Specifications have been developed with this method in mind and inspectors have substantial experience in accepting or rejecting the work.

The low technical risk associated with labor-intensive methods is matched by low and easily managed risks from a scheduling and works planning point of view. Labor is a versatile resource which can be deployed on many operations and thus the need for careful planning to ensure continuity in the performance of a given task is not critical. This is important when working in congested areas, when access to the job site is difficult, and when the extent of deteriorated concrete is not well known. Under these conditions the versatility of a labor-intensive operation is important and can play a significant part in achieving satisfactory results.

The flexibility of labor-intensive operations is again important when considering economic risk. No major capital investments requiring monthly interest and redemption payments are involved. Most of the contractor's costs will vary in direct proportion to the quantity of work done. This is well suited to the method of payment used in unit price contracts where the value of work is also proportional to quantity. Risk in patching or rehabilitation contracts where the quantity of concrete removal and bar cleaning is not well known is thus substantially reduced by using labor-intensive methods.

The three areas outlined above, technical risk, flexibility in planning, and the economic risk associated with variations in quantity, favor the use of labor-intensive methods which would certainly be used if all things were equal. This is, however, seldom the case because concrete removal tasks require substantial amounts of energy and are expensive, slow, and physically demanding if technology and mechanization are not used to advantage.

3.2 Capital-Intensive Methods

Capital-intensive methods such as hydrodemolition and milling rely on the use of large sophisticated machines to apply the energy needed to remove deteriorated concrete. The production attainable on a given area of bridge deck in a given period can be very high. This reduces construction time and results in shorter delays to the traveling public. Economies of scale are possible and, under proper conditions, mechanization is extremely cost-effective. The machines are less physically demanding to operate than hand tools such as pneumatic breakers, and safety is improved by virtue of the fact that fewer people are employed in the hazardous work zones associated with bridge repair and rehabilitation projects.

These factors, and particularly the fact that construction periods can be reduced, count heavily in favor of mechanized methods. There are, however, significant risks for the contractor. The first of these is a technical risk caused by the fact that mechanized methods such as hydrodemolition have only recently won general acceptance. This means that the technology has yet to mature with regard to the mechanical reliability of the equipment and the operational techniques used in different applications. It also means that specifications suited to mechanized methods are not as yet generally available and that inspectors have little background to draw on when accepting or rejecting the work.

The second major risk relates to flexibility of operational planning. The equipment used in mechanized operations is specialized and not suited for use on any other type of work. This means that the work must be carefully planned and sequenced if the equipment is to be kept productively employed and if targets are to be met. This is frequently very difficult on bridge repair and rehabilitation projects where traffic control and construction phasing can cause equipment to stand idle for substantial periods with average production rates being significantly lower than the maximum that can be achieved.

The substantial investment required for mechanization introduces a significant economic risk. Capital costs are proportional to the time taken to complete a task and not the amount of work done. Continuity of operations and productivity thus become extremely important as does the quantity of work that must be done with a particular machine on a particular contract. This causes mechanization to be a high-risk choice in contracts where the quantity of deteriorated concrete to be removed is not well known and where variations are expected.

3.3 Contractual Requirements for Mechanization

The contract and the manner in which it allocates risk between the SHA and the contractor establishes the framework within which the contractor makes the decisions needed to perform the work at a reasonable balance between risk and reward. The SHA sets the contractual requirements and it is thus in a position to create a contractual environment which either enables or inhibits mechanization from achieving its full potential. Aspects which merit attention include: funding levels, continuity of the work, size and scope of the projects, project location, traffic control, quality standards and inspections.

3.3.1 Funding and Continuity of Work

The timing of maintenance operations can be delayed or accelerated over a fairly wide range depending on the availability of funds and other macroeconomic issues. This results in a situation where the volume of work let on contract fluctuates substantially from year to year. It is thus all but impossible for SHAs and contractors to manage resources in an economical manner over an extended planning horizon. Fluctuations in work load have a particularly adverse effect on the confidence needed to make major capital investments in equipment and much can be done to promote the use of mechanized methods by providing competitive contractors with a steady stream of work.

3.3.2 Size and Scope of Projects

The size and scope of projects have an effect on the selection of the appropriate method for concrete removal and bar cleaning. Most large projects include demolition tasks, such as the removal of existing sidewalks and barriers, as well as concrete removal tasks for rehabilitation and patching. The size, scope and pace of the concrete removal work itself is thus a better determinant of the appropriate method. The following examples show the range of options available:

- If the project requires that all contaminated and deteriorated concrete be removed over the full width and length of the deck, and if this work dictates the critical path of the project, then a high-production mechanized method such as hydrodemolition should be used.

- If the project requires that sidewalks and handrails be demolished and new barriers be installed to bring the bridge up to current standards, and that localized areas of deterioration be repaired as a parallel operation, then a low-pace flexible method based on the use of pneumatic breakers should be employed to ensure that the main critical path activity can proceed unhindered.

An understanding of the concept illustrated in these examples and a realization that concrete removal is never more than part of the total process is important to SHAs and contractors in specifying and selecting appropriate mechanized methods.

3.3.3 Project Location and Traffic Control

Rehabilitation projects require that sections of the bridge be closed and that regular traffic patterns be disturbed. This causes distress to the motoring public and increases the risk of accidents. This is particularly true when projects are located in heavily trafficked urban areas and when procedures needed to control traffic and ensure safe flows become complex and expensive.

Mechanization affects both the area which must be closed to traffic and the total amount of time required to perform the work.

1) The Area. Mechanized methods require that substantial portions of the structure, particularly the deck, be closed to traffic and made available to both production and support equipment. The benefits of mechanization cannot be achieved if this is impossible. More expensive, labor-intensive methods become viable if working space is not available in a manner which ensures continuous operations.

2) Time Available. Mechanized methods are able to achieve high productions under the right circumstances. They are thus suited to projects where traffic and weather requirements dictate a high pace of work. Labor-intensive methods become more attractive when the tempo of work is not high and when traffic control requirements are such that continuous operations cannot be maintained.

3.3.4 Scheduling and Continuity

The high fixed costs associated with owning the equipment needed to remove concrete using high-production mechanized methods means that contractors face very high risks if construction schedules are delayed or if work cannot be performed continuously.

Rehabilitation projects are particularly difficult to manage in regard to these two factors because of the traffic control problems discussed in section 3.3.3 (p. 28) and because so many unforeseen factors become known as work proceeds.

Successful use of mechanized methods requires that contractors and SHA project managers work together to schedule work and resolve variations. Contract conditions that require that the contractor assume all schedule risk regardless of changes in access and working hours will inhibit the use of mechanized methods.

3.3.5 Quantity Variations

The sensitivity of capital-intensive methods to changes in the quantity of work performed means that mechanization is a very high risk choice in contracts where the quantity of concrete to be removed is not well known.

As with scheduling and continuity, the risk of quantity variations does not lie with the contractor and the classic unit price methodology should be amended to share the risk between contractor and SHA in a more equitable manner, including the following amendments:

1) the provision of monthly or weekly pay items to cover fixed costs.

2) clear provisions for change in unit rate with change in quantity.

3.3.6 Quality Standards and Inspections

Labor-intensive methods produce quality of a different type than that produced by mechanized methods. Pneumatic breakers and saws in the hands of skilled operators can produce work which follows lines, levels and tolerances precisely. Mechanized methods such as hydrodemolition cannot do this. Much is lost if, for instance, the specification requires that peaks behind the rebar be removed to produce a smooth surface; in such a case, both hydrodemolition and pneumatic breakers would have to be used at a substantial increase in cost.

Tolerances and inspection expectations must be changed if mechanized methods are to achieve their full potential functionality. Designs and specifications must be based on realistic quality standards at levels which can be met by mechanized methods.

3.4 Operational Requirements for Mechanization

The organization and management of the work lies with the contractor, and the skill with which he/she manages the various operations has a profound effect on a given method for concrete removal and bar cleaning. Mechanized methods employing specialized equipment are less flexible than labor-intensive methods. They therefore place a high demand on the contractor's ability to manage the work and create an environment in which the methods can achieve their full potential. Old approaches which rely on improvisation and on-the-spot reallocation of labor will simply not suffice when faced with the challenge of using new technologies such as milling and hydrodemolition.

This section presents four issues which need to be addressed by contractors at a strategic level if mechanization is to be successful. These are works planning, specialization and subcontracting, manufacturer relationships and owner relationships.

3.4.1 Works Planning

Mechanized methods have the potential of achieving very high rates of production. These can, however, only be achieved if the work is planned in detail and if all the required resources are available. This planning must be done within the confines of the project location and traffic control constraints and must provide for continuity of work as discussed in section 3.3.4 (p. 29).

Works planning must include all the repair and maintenance operations needed to ensure high levels of reliability and availability in the equipment used. Spare parts, consumables such as fuel and oil and wear items such as cutting teeth and nozzles must be kept in stock and skilled personnel must be available. This is particularly true in concrete removal operations where the equipment works at high levels of stress in an abrasive environment.

3.4.2 Specialization and Subcontracting

Most bridge rehabilitation projects involve a mix of tasks which range from the removal and replacement of bearings to deck rehabilitation and the replacement of signs and lights. This mix of work is usually done by multi-skilled crews who switch from one task to another as required by the status of the project. This flexibility is not possible when using milling or hydrodemolition equipment and specialized crews or subcontractors are therefore frequently employed to perform the concrete removal tasks in one or more periods of intense activity.

Specialized crews or subcontractors improve the utilization of the equipment. In addition, operating and mechanical maintenance skills are retained within the specialized unit resulting in higher availability. Contractors must develop the skills needed to manage specialized crews and subcontractors. Poor works planning and stop-start operations will negate the advantages and result in high mobilization costs as crews and equipment are moved on and off the project.

3.4.3 Manufacturer Relationships

Milling and hydrodemolition have been identified as two emerging technologies capable of improving concrete removing and bar cleaning operations. The fact that they are emerging rather than established technologies means that developmental work is still required to improve the operational characteristics and reliability of the equipment used.

Contractors who wish to implement milling and particularly hydrodemolition technology should improve communication and liaison between themselves and manufacturers to expedite the full commercialization of these technologies. Manufacturers should be encouraged to participate in the process and continue to work with contractors as suppliers and operators of equipment rather than vendors. A change in traditional commercial relationships is needed and contractors should encourage the manufacturers' involvement in field operations.

3.4.4 SHA/Contractor Relationships

The successful implementation of new and innovative technologies in construction requires a special relationship between SHA and contractor. Traditional contract forms as referenced by lump sum or unit price contracts are based on the assumption that the nature of the work is fully known and that the methods used are tried and tested. Neither of these are true for most bridge rehabilitation projects and thus traditional contract forms frequently give rise to variation and dispute.

3.5 Summary

This chapter reviewed a number of issues relating to the economic, contractual and operational aspects of mechanization. A distinction was made between labor-intensive and capital-intensive methods with regard to various categories of risk to show that the economic advantages of mechanization can be attained when planning is done well and when the quantity of work is well known.

Discussion and contractual aspects focused on seven issues which are under the control of the SHA. These are summarized in table 3.1 (p. 33) with emphasis placed on the action which SHAs can take to promote the implementation of mechanized methods.

The operational aspects discussed are summarized under the four headings of table 3.2 (p. 34). These are largely under the control of the contractor and show what the construction industry can do to enhance the success of mechanization.

This chapter is the last of three chapters about the technical environment within which concrete removal and bar cleaning operations take place. It thus provides an introduction to the main body of the report which focuses on the three specific technologies used to remove contaminated and/or deteriorated concrete identified in chapter 2. These are:

Table 3.1 Contractual aspects

Funding and Continuity of Work Well-planned and funded rehabilitation programs that provide a continuity of work will provide an incentive for contractors to invest in mechanized methods and will result in the most economical technical solution. Size and Scope The award of large contracts that seek to achieve the economies attainable through rehabilitation and renovation will encourage contractors to improve efficiency through the use of mechanized methods. Location and Traffic Control Mechanization is extremely effective to shorten construction time in heavily trafficked urban areas if the required work area can be provided by proper traffic control. Scheduling and Continuity Contractors will accept the risks associated with mechanized methods more readily if they believe the work can be scheduled with confidence and performed in a manner which provides continuity in the use of capital-intensive resources. Quantity Variations Measurement and payment clauses which acknowledge the fact that the costs associated with mechanized methods are largely fixed and not proportional to the quantity of work done will reduce the contractor's risk and encourage the use of mechanized methods. Quality Standards and Inspections Mechanization will be encouraged by specifications that set realistic quality standards and levels that can be met by the proper use of high-production mechanized methods and inspection standards which recognize the limitations of these methods.

Table 3.2 Operational aspects

Works Planning

Specialized high production equipment is only effective in a well-planned and ordered work environment. Detailed planning of operations and mechanical support systems will improve the cost effectiveness of mechanized methods.

Specialization and Subcontracting

Mechanized methods for concrete removal and bar cleaning can be more effectively implemented by specialized contractors or subcontractors who can develop the required expertise and maintain the required work load. Contractors must develop the skills needed to use specialized crews and/or subcontractors effectively.

Manufacturer Relationships

The development of specialized equipment is made more efficient by improving liaison and communication between equipment manufacturer and user and by moving away from the traditional commercial relationship.

Other Relationships

Innovative contract forms which recognize the risks inherent in using a new and capital-intensive technology will result in more equitable contractual arrangements and promote the implementation of the technology.

1) Pneumatic Breakers,
2) Milling Machines, and
3) Hydrodemolition.

The technologies are discussed in turn in chapters 4, 5 and 6. Each chapter provides a technical description of the equipment involved, reviews the work characteristics, production and economics of the method, and provides some comment on managing and controlling quality. The uniform approach creates a basis for chapter 7 which compares the technologies, discusses what can be done if they are used in combination and sets selection criteria.

4

Hand-Held Pneumatic Breakers

Hand-held pneumatic breakers are widely used and well-established tools for removing contaminated and deteriorated concrete. Their light weight and excellent maneuverability are suited to remove damaged concrete from small, isolated areas and from vertical and overhead surfaces on all bridge structural elements. They can be used on cracked, spalled, or delaminated concrete, and on chloride-contaminated concrete when the depth of removal is known from the evaluation of the structure and indicated on the plans. This chapter presents an examination of pneumatic breakers by providing a technical description of the equipment, reviewing the characteristics of the work done and analyzing production, cost and quality.

4.1 Technical Description

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

4.1.1 Pneumatic Breakers

Breakers can be powered by a variety of energy sources including pneumatic pressure, hydraulic pressure, gasoline engine, or electric motor. Table 4.1 summarizes some of the primary advantages and disadvantages of breakers powered by the various energy sources.

Table 4.1 Advantages and disadvantages of breakers powered by various energy sources

Energy Sources	Advantages	Disadvantages
Hydraulic	Higher production Greater impact energy Require hydraulic compressor	Primarily for demolition Damage to residual concrete/steel
Gas/Electric	Self-contained Suitable to sites with limited access	Greater weight More complicated Higher cost
Pneumatic	Light weight Durable	Require air compressor

Hydraulic breakers use a pressurized fluid to actuate the tool. Although there are small hydraulic breakers, most are too large for the selective removal of damaged bridge concrete.

Gas and electric breakers are generally heavier than hydraulic or pneumatic breakers of similar productive capacity, because the power supply is attached to the instrument. The mechanics of these units also are more complicated than those of hydraulic or pneumatic breakers, making them costlier to purchase and maintain. These units are, however, self-contained. They require no additional support equipment and are therefore very useful in situations where access is restricted.

This chapter focuses on pneumatic breakers because 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 4.1 presents a schematic diagram of a typical pneumatic breaker to show the main components and sections.

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. Available weights range from under 20 pounds (9 kg) for small chipping hammers suited for light duty applications to just under 100 pounds (45 kg) for large production breakers. Small chipping hammers are limited to less than 45 pounds (20 kg) so that they may be safely used on vertical or overhead surfaces. The upper weight limit for large production breakers is governed by the quality requirements of the job and the weight which can be handled by the operator with ease and safety on horizontal surfaces.

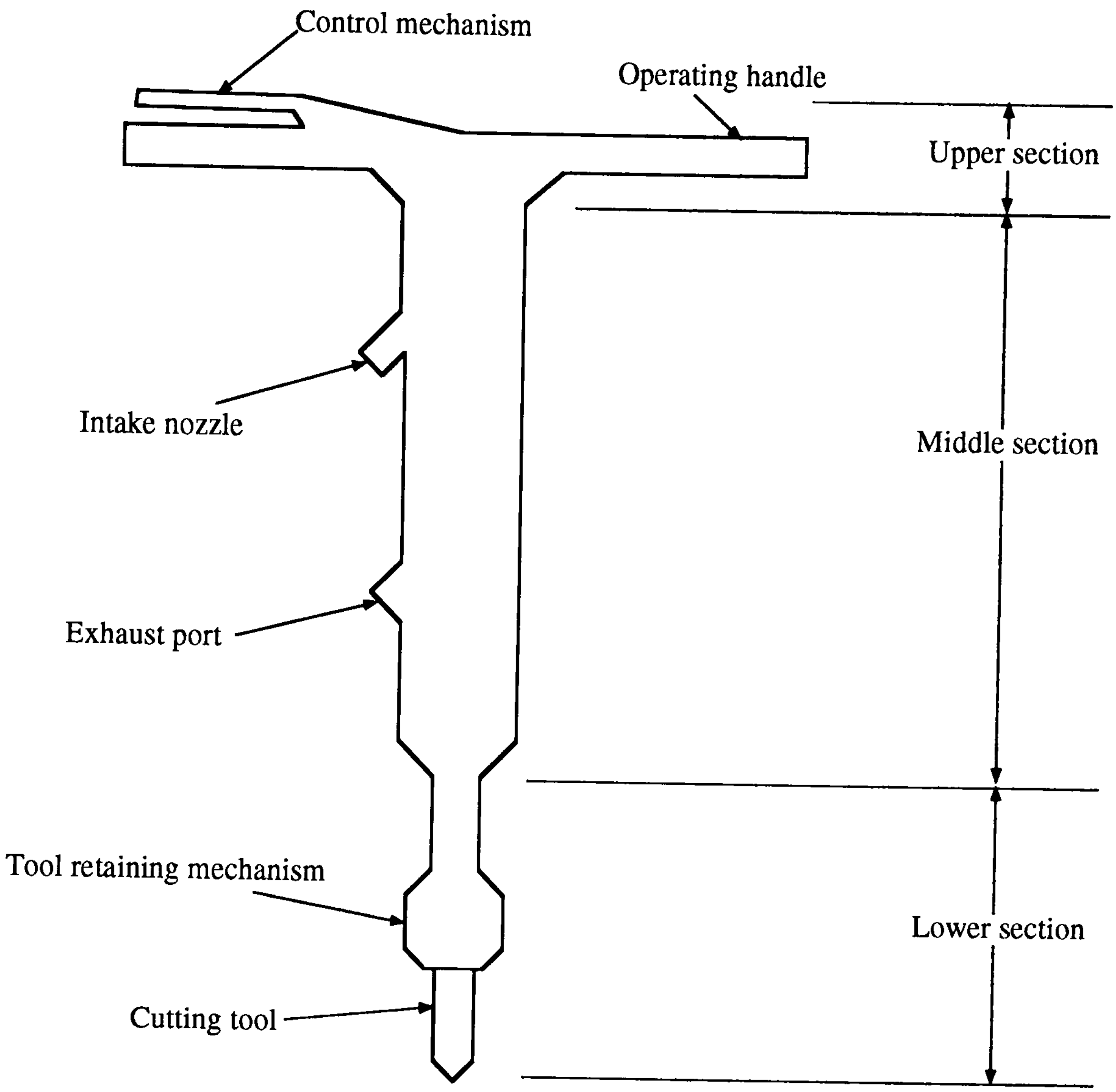


Figure 4.1 Pneumatic breaker components

The percussive force used by pneumatic breakers to fracture concrete is primarily determined by the impact energy and the frequency at which the impacts occur. 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 15 pounds (7 kg) per blow for small tools to over 180 pounds (82 kg) 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.

The air consumption of a pneumatic hammer 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 minute (1 m^3/min to 2 m^3/min). The air pressure required by most pneumatic breakers is between 60 and 90 pounds per square inch (420 kPa to 620 kPa).

4.1.2 Cutting Tools

Various cutting tools are available for use with hand-held pneumatic breakers. The shank end, which is inserted into the tool-retaining mechanism, is common to all. The cutting or working end can vary from a broad spadelike blade to a sharp well-honed point. The vast majority of concrete removal work is done with a pointed tool, although a relatively narrow (3"-4": 75 mm - 100 mm) blade-type tool is sometimes used to remove cracked and deteriorated concrete. Proper maintenance of the cutting tool is important to the productivity and quality of the work.

4.1.3 Compressors and Distribution

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.

The volume and pressure requirements of the compressor can be determined as the aggregate of the demands of all the tools to be used. It is important to realize that the maximum air requirements for all the tools will rarely be needed. Thus a single compressor can supply air to tools whose aggregate total demand exceeds compressor capacity by up to 20%.

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

4.2 Primary Applications

Section 4.1 (p. 35) 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.

This section will focus on the primary applications for hand-held pneumatic breakers 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.

4.2.1 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 pace of the project, and the availability of labor. Each of these is discussed in turn.

- 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 that are not accessible to larger pieces of equipment, and on projects where concrete must be removed in small areas from between, around, and below the reinforcing. They are also used in support of large, high-production, equipment-intensive methods on most rehabilitation projects.

- Bridge Location. Breakers are ideally suited to operate in congested urban areas with high traffic volumes. In these areas their advantages over other methods in terms of setup time and space become apparent. Thus they are well suited to jobs which require many mobilizations or where the available hours of operation are limited.

- Project Pace. Many jobs allow traffic to 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 to projects that have a limited working window. If time is limited or if there is a large quantity of material that cannot be removed by other methods, breaker production can be increased by adding additional crews.

- Availability of Labor. Breakers are a labor-intensive method of concrete removal, sensitive to both the cost and the availability of labor. Urban areas will generally have an abundant labor supply but also will have higher wage rates. Rural areas will typically have lower wage rates, but laborers may have to be sent to the job site because of 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 required.

4.2.2 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 weighing less than 45 pounds (20 kg) is typically used for these applications. 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 when working on bridge substructure components and nets or other safety devices may be required to contain debris.

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 eliminated as the actual area of deterioration frequently differs from the quantity originally estimated.

4.2.3 Preparatory Work

Visual inspection and sounding during project planning and immediately prior to actual removal are used to locate deteriorated concrete. Sounding is done by using a masonry hammer or by dragging a chain or a tool equipped with several chains across the deck. The damaged area is marked and a vertical saw cut is generally made around the perimeter of the patch area to eliminate tapered edges. The need for the saw cut and its depth is determined by the need to produce a firm edge for subsequent patching operations. No cutting is needed when the material removed forms part of a total deck overlay.

4.2.4 The Material to be Removed

Breakers are best utilized for removing concrete that 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. They are also frequently used in support of other methods such as milling or hydrodemolition.

The properties of the concrete being removed and the characteristics of the individual type of breaker affect production and economy. No definitive data is available because different combinations of impact energy and frequency of impact produce different results on concrete with a given strength or aggregate type.

4.2.5 The Area of Removal

Breakers are typically used to removed small areas of concrete. The small size of the removal area is perhaps the primary factor defining a breaker's ideal work environment. The tool's geometry and the economics associated with the use of small versatile tools make breakers most efficient in such an environment.

Large-equipment-intensive methods are generally restricted to removing concrete from bridge decks unless the equipment is greatly modified. These methods also are 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.

4.2.6 Depth of Removal

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 matrix or core concrete.

Special caution must be exercised when operating in these areas to avoid damaging the rebar or fracturing the adjacent residual concrete. Production is generally much lower when removing concrete in these regions because of the extra time and effort required.

4.2.7 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 with an air wand. 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 because the debris is readily accepted by most materials processing centers or dump sites.

4.3 Production Estimating

The first two sections of this chapter have discussed the equipment and the characteristics which define the work environment. This section will discuss the factors affecting breaker production by first discussing theoretical production and then discussing some of the factors used to arrive at a modified production estimate.

4.3.1 Theoretical Production Rate

The theoretical production rate is the estimated rate at which the breaker can 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. A tool with a greater weight will generally have a larger air cylinder and a piston of greater mass to produce higher impact energy. Not all tools of a similar weight will perform similarly due to differences in geometry and construction.

4.3.2 Modified Production Rate

There are several factors and conditions that reduce the theoretical rate of production. Primary among these are the location, depth and nature of the concrete to be removed, the level of deterioration in the concrete, interference from reinforcing steel, operator experience and equipment reliability. 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.

The relationship between these factors and the theoretical production is not clear and certainly not linear. Figure 4.2 provides some guidance where

- the upper bound is achievable when shallow horizontal areas of relatively weak or deteriorated cover concrete are removed by experienced operators;
- the lower bound is achieved when solid contaminated matrix or core concrete is to be removed in awkward locations with less proficient operators.

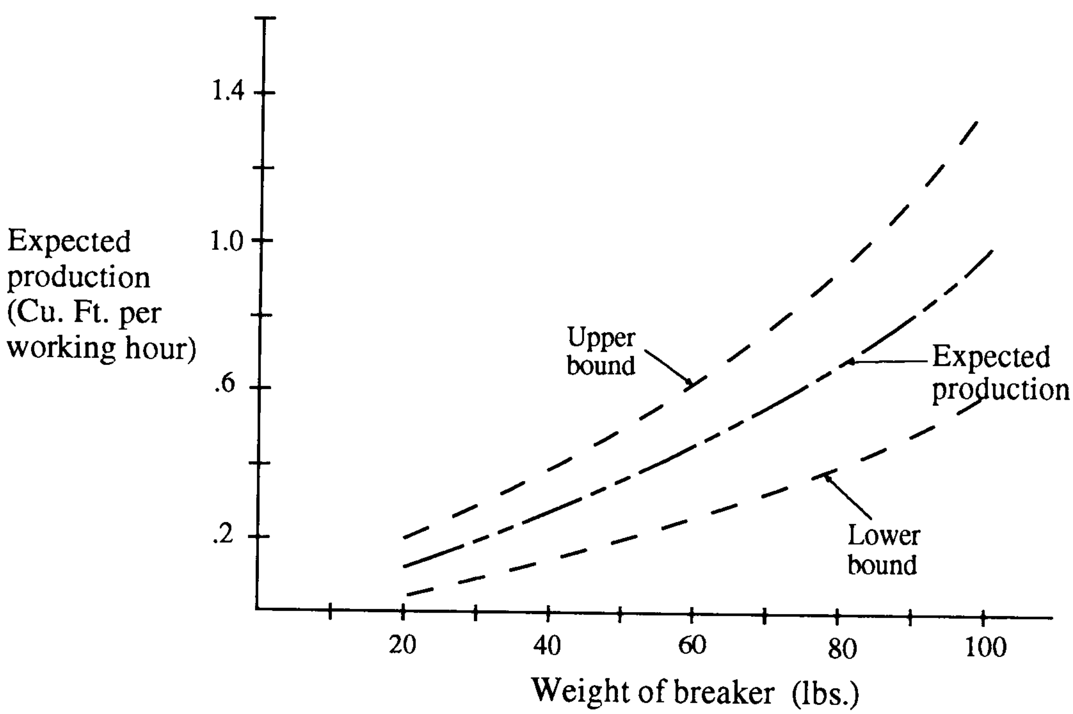


Figure 4.2 Pneumatic breaker rate of production
(See appendix B for metric equivalents.)

4.4 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 4.3. The parameters listed in the work sheet illustrate the factors that 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 and are intended for illustrative purposes only. Although they are of the right order of magnitude, they must be adjusted to allow for local costs and the factors discussed in sections 4.2 (p. 39) and 4.3 (p. 42). The section concludes with a sensitivity analysis that illustrates how the unit cost of concrete removal by pneumatic breakers varies with the total quantity removed on a given job.

4.4.1 Job-Specific Parameters

A preliminary step to making a cost estimate is to establish the job-specific parameters that dictate the time and quantity of resources required. These are listed in the top panel of figure 4.3. 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 contractor's 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 (320 km).

The second set of job-specific parameters, the depth and area of removal, determine the volume of material to be removed and the productivity to be expected. 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. The average depth assumed is 2.5 inches (64 mm) and the estimated area of removal is 20,000 square feet (1860 m^2).

Job Specific Parameters:	Total Mobilization Distance	200	miles
	Number of Mobilizations	2	mob's
	Removal: Cover & Matrix	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: Estimates	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

DIRECT COSTS

Mobilization:	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 Breaker	$350	per unit x	1	unit =	$350
	Labor	$20	per unit x	13	unit =	$260
	Total Mobilization:					**$1,985**

Equipment Rental:	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	day	**$33,203**

Equipment Operation:	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**

Labor:	Superintendent:	1	super @	$48.00	per hour	
	Laborer:	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	hrs =	**$210,938**

TOTAL DIRECT COST: **$282,458**

INDIRECT COSTS:

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 4.3 Pneumatic breaker cost estimating worksheet (See appendix B for metric equivalents.)

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 depend on the area of concrete to be removed and the time constraints imposed on the project. The size of the breakers will affect the production and therefore the cost of doing the work.

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.

4.4.2 Equipment Production Parameters

A production rate for an individual breaker may be determined as described in section 4.3 (p. 42). The estimated rate of production of 0.8 cubic feet per person-hour assumed in the example cost estimate can be divided by the depth of removal, (0.023 m^3) to determine the production rate per unit of area, 3.84 square feet (0.36 m^2) per person-hour in this example. This is multiplied by the number of breakers, 8, to determine a crew production, 30.72 square feet (2.86 m^2) 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 calculation of days to complete the work is also important in determining equipment utilization and rental costs.

4.4.3 Mobilization Cost

Mobilization costs are 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 cost of owning equipment, 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.

4.4.4 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. 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.

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 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 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 loader and dump truck were provided to handle the debris removal operations in the worksheet example.

4.4.5 Equipment 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 that will vary depending on the actual equipment used.

4.4.6 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.

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 markups for insurance and taxes. The rates shown must clearly be adjusted for local conditions.

4.4.7 Total Direct Cost and Indirect Cost

The sum of the cost elements previously discussed (mobilization, equipment rental cost, equipment operating cost, and labor cost) comprise the direct cost of performing the work. In addition to the direct cost the contractor will provide a markup for overhead administration and profit. These costs are generally calculated as a percentage of the direct costs. The assumed overhead and administration markup of ten percent, and four percent for profit, are typical values.

The sum of the total direct costs and the indirect costs is equal to the total price the contractor will bid 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.

4.4.8 Sensitivity Analysis

Figure 4.4 presents a sensitivity analysis for the unit price of concrete removal utilizing breakers. It shows how the unit price varies with the quantity of material removed. The total mobilization cost, production estimate and unit resource costs were held constant at the levels depicted in the worksheet (p. 45) as the area of removal was varied from 500 to 25,000 square feet (46 to 2320 m^2).

The curve illustrates the fundamental cost-quantity relationship of labor-intensive methods such as pneumatic breaker operations. This shows a decrease in the unit cost of almost 20% the quantity of removal increases from 500 square feet to 5,000 square feet (46 to 460 m^2), followed by a decrease of less than 3% over the entire remaining quantity interval. Unit cost is thus seen to be relatively insensitive to change in quantity once the fixed costs (mobilization) have been distributed.

4.5 Managing and Controlling Quality

The first two sections of this chapter described the equipment and operating environment associated with pneumatic breaker operations. Sections three and four continued by

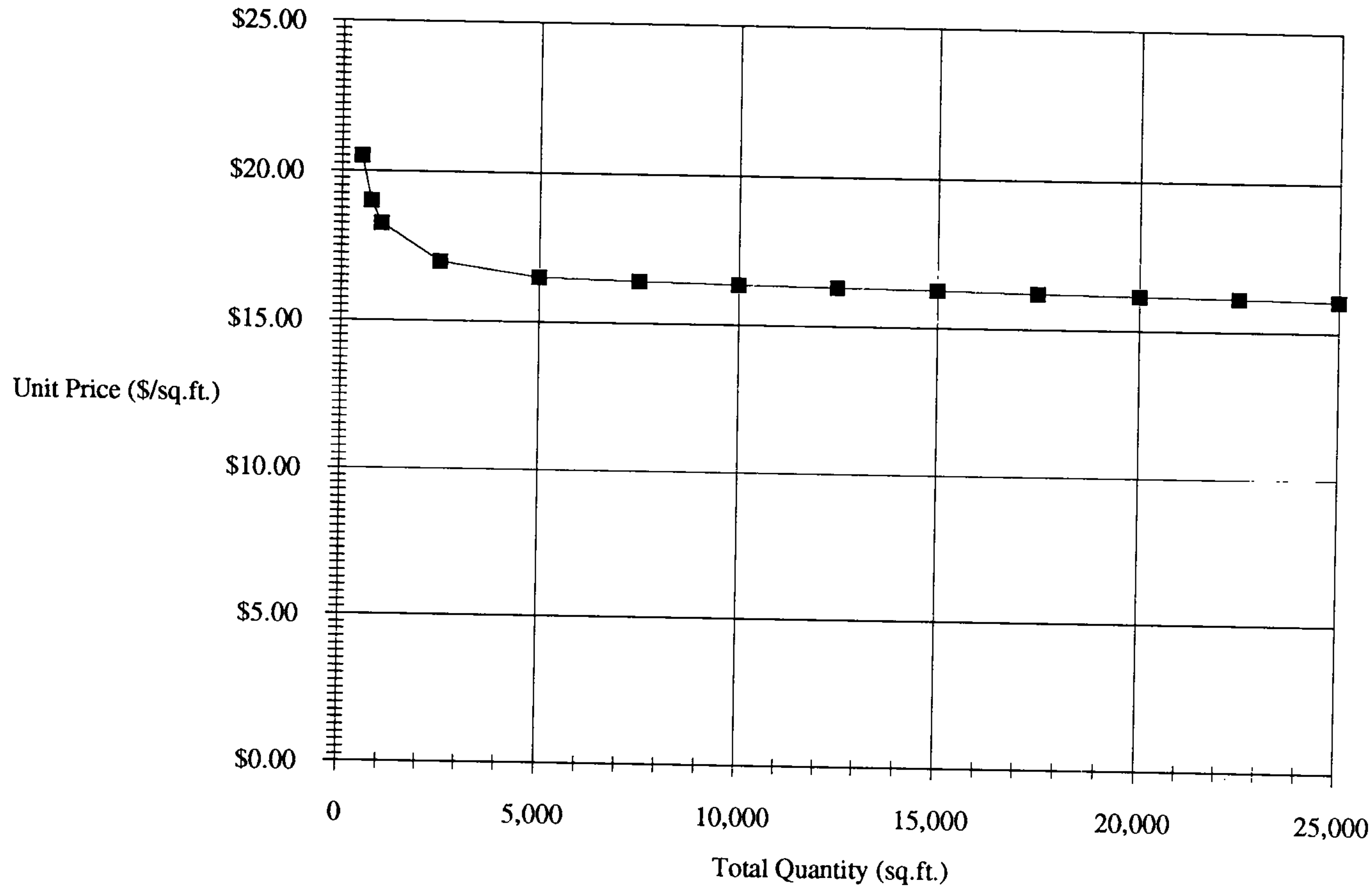


Figure 4.4 Sensitivity analysis of pneumatic breaker unit price to total quantity based on costs given in figure 4.3
(See appendix A for metric equivalents.)

examining the quantitative issues of production and cost. This fifth and final section will address the issues of quality and quality control.

Parameters for the success of the project must be established and maintained to ensure that breaker operations achieve the desired level of quality. Five quality concerns are imperative to success:

1) <u>Complete removal of deteriorated concrete</u>. 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 such a case, the amount of deteriorated concrete may have been over- or underestimated.

   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) <u>Damage to Residual Concrete</u>. The impact forces used to fracture and remove the deteriorated or contaminated concrete may produce microcracks in and immediately below the surface of the residual concrete. These cracks accelerate the deterioration of the residual concrete and weaken the bond between the residual material and the overlay or patch material.

   The extent of microcracking is determined by the magnitude and direction of the impact force. To control the situation, SHAs limit the weight of breakers used to remove concrete from bridge decks to 35 pounds (16 kg) and specify that the impact angle must be between 45 and 60 degrees to the impact surface. Adherence to these limits is important.

3) <u>Damage to reinforcing steel</u>. 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 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. If the concrete is removed around the steel, then the work should continue for and additional distance to ensure 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. All steel surfaces must be clean and free of chloride contaminated rust and cement paste. This is normally achieved by wire brushing or sand blasting as described in section 2.3.5 (p. 23).

4) 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.

5) 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, noise and flying debris created both from the breaker operations and from the subsequent debris removal process.

Safety standards require that operators wear steel-toed boots, hard hats, ear protectors and goggles. Passing traffic and the public must be protected by the provision of all necessary barricades and screens. Noise suppression devices on the compressors and the breakers themselves should also be used to maintain acceptable safe noise levels.

5

Milling

Milling is a capital-intensive method of concrete removal that uses 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 removal 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.

5.1 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 5.1 highlights the key components of a typical machine.

5.1.1 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 (3.6 m) on the largest machines, dictates the width of the material cut.

Cutting mandrels also vary in diameter, ranging from about 8 inches (200 mm) to over 4 feet (1.25 m). The smaller mandrels generally rotate faster, using speed to cut the pavement,

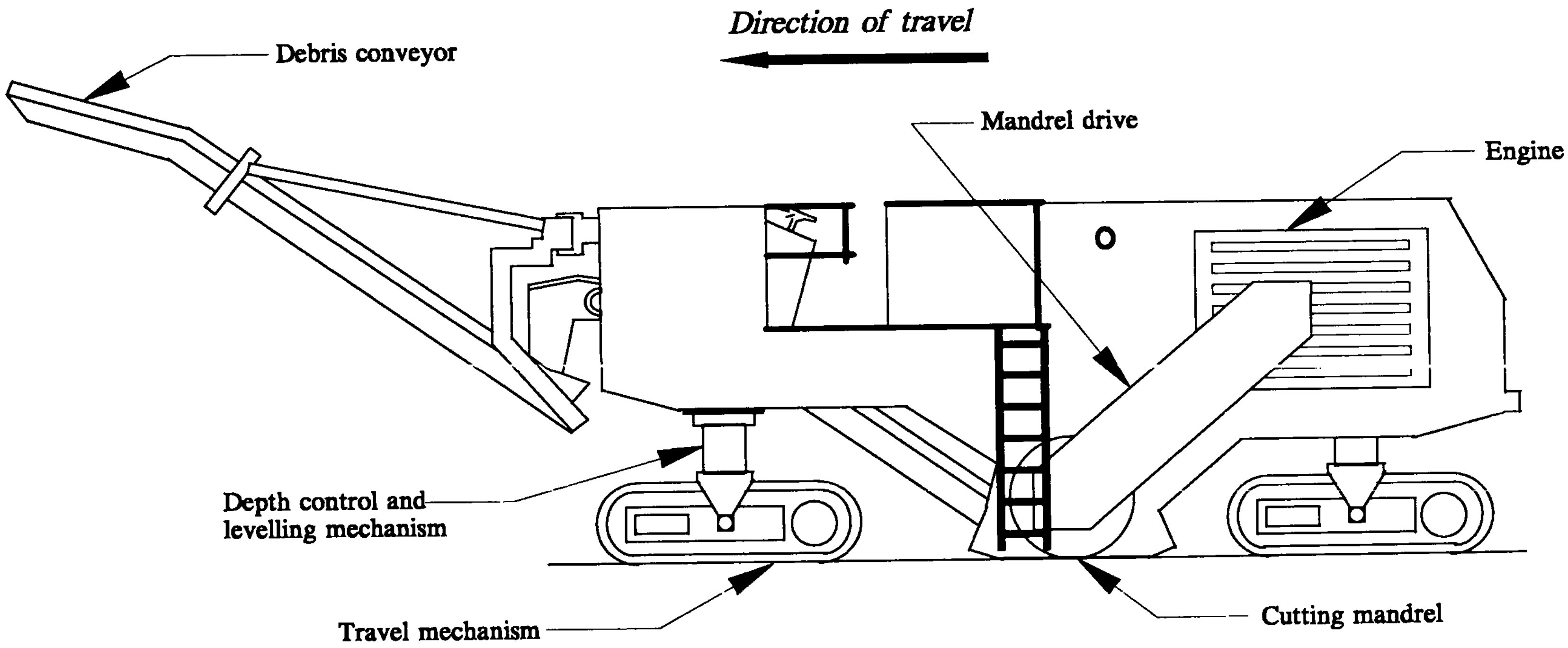


Figure 5.1 Milling machine components

whereas larger mandrels tend to rotate more slowly, using the weight and horsepower of the machine to break the pavement.

Carbide-tungsten tipped cutting teeth as illustrated in figure 5.2 are used to break the pavement. The teeth are usually slightly over 3 inches (76 mm) 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. Tip life varies from as low as 4 operating hours to a maximum of 24 operating hours.

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 5.3. 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.

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 (12 mm) 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.

The mandrel drive system rotates the mandrel in a direction opposite to direction of travel of the machine as illustrated in figure 5.4. 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.

5.1.2 Depth Control and Leveling

A depth control mechanism is needed to control the depth of cut as required by the demands of the job. Milling machines are limited to the removal of cover concrete, and thus the depth of steel limits the maximum depth of cut. Large, heavy machines may be able to achieve this in one pass; lighter, less-powerful machines require several passes.

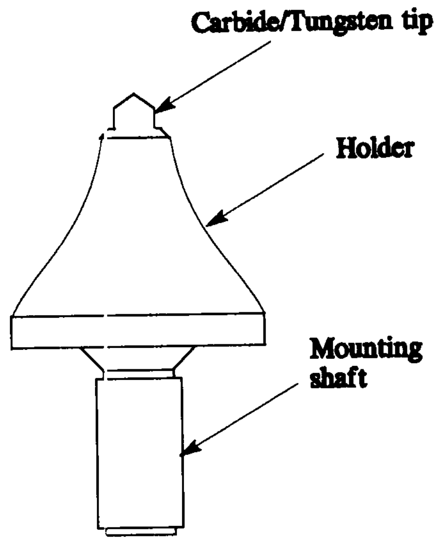


Figure 5.2 Carbide-tungsten-tipped cutting teeth

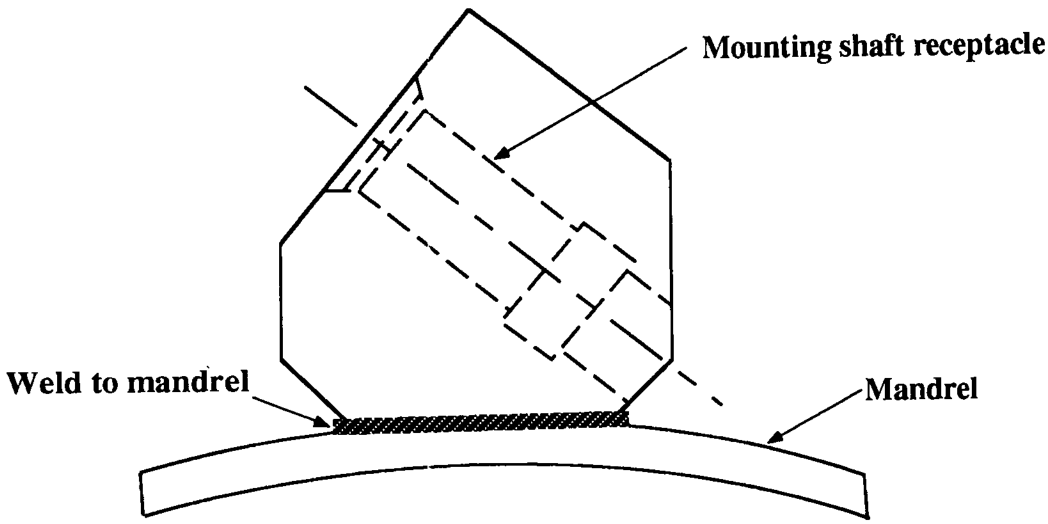


Figure 5.3 Mounting block

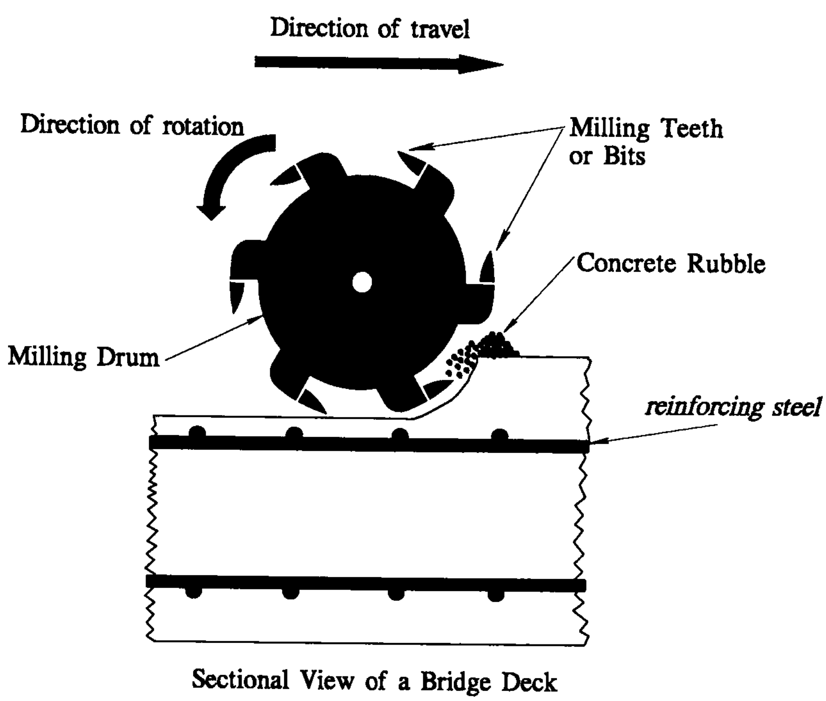


Figure 5.4 Cutting action of a milling machine

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.

If depth is controlled by moving the mandrel, the mandrel is attached to the frame by adjustable hydraulic cylinders. 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 in 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.

5.1.3 Power, Weight and Cutting Speed

Milling machines are powered by diesel engines ranging in power from 24 horsepower (18 kw) for the smallest machine to 750 horsepower (560 kw) for the largest machines. The typical range for bridge deck work varies between 250 and 500 horsepower (180 kw and 375 kw).

Weight correlates closely with power and is important when evaluating a milling machine. Machine weights range from under 4000 pounds (1800 kg) for the smallest machines, to over 100,000 pounds (45 t) 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. Some SHAs have, and many are considering, a 42,000 lb. (19 t) limit on the weight of the milling machines for bridge deck work.

Milling machines run on either tracks or tires that 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.

Machines usually have separate speed ranges for operating and traveling. Operating speeds range from 33 feet per minute to 150 feet per minute (10 to 45 m/min) but will largely be determined by the material being milled. Travelling speeds are generally 4 to 5 miles per hour (6 to 8 km/hr) but can be as high as 24 miles per hour (40 km/hr).

The relationship between the weight of the machine, mandrel width, operating speed and optimum cutting depth is determined by the manufacturer and set out in the specifications for the machine.

5.1.4 Debris Conveyor

Most larger machines are equipped with a hydraulically controlled conveyor system for the removal of debris. Conveyers 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.

5.2 Primary Applications

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

5.2.1 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 be permitted only at night. Rural job sites generally have better access and fewer limitations on operating hours but may be more costly in terms of mobilization.

5.2.2 Type and Extent of Deterioration

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, or if milling is being performed only as preparation for an overlay, a milling machine will be ideally suited to perform the work. If the required depth of removal extends below the top of the reinforcing steel, then additional or alternative methods of concrete removal such as pneumatic breakers or hydrodemolition will be required.

The wide cutting drum and the continuous action of the cutter restricts the machine from selectively removing damaged concrete. 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.

5.2.3 Preparatory Work

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 at random locations over each span of the bridge deck before milling begins. Although the depth to the reinforcement generally varies less than 1 inch (25 mm) from the average cover depth, the expense in time and effort required to determine the rebar cover is much less than the cost incurred if a bar is pulled up. The depth to the reinforcement can be fairly accurately measured with a commercially available pachometer which electronically senses the location and depth of the reinforcing steel.

5.2.4 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 required for the overlay removal.

The properties of the concrete to be removed from the bridge deck will effect the milling machine's efficiency and production. The primary components of the concrete that affect the operation are the size and hardness of the aggregate.

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

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

5.2.5 The Area of Removal

The area to be removed is the primary factor affecting milling machine efficiency and productivity because 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 costs of owning 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.

5.2.6 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. If the concrete requiring removal extends beyond this depth or is in areas inaccessible to the milling machine, then additional concrete removal methods will be required.

5.2.7 Obstructions

The quality of the original deck construction plays a major role in determining the efficiency of any subsequent milling operation. 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 reinforcement varies. The machine size and drum width should be selected to provide the maneuverability needed to avoid obstructions. Some areas cannot be reached because joints, drains, drain covers and the like obstruct the milling process, and such areas must be removed using pneumatic breakers in a secondary operation.

5.3 Production Estimation

Estimating the production of a milling machine is a difficult task because it depends on a large number of variables that are difficult to predict accurately.

5.3.1 Theoretical Production Rate

The first production figure to be calculated is the theoretical production rate. This is the maximum rate of production that can be attained for short periods of time under ideal operating conditions.

The theoretical production rate is determined by the machine power, weight, depth and anticipated operating speed. The cutting width is determined by the width of the cutting mandrel and determines how many passes will be required.

The cutting depth is determined by the extent of damage and the location of the reinforcement steel. This affects production and, if the concrete must be removed to a depth very close to the reinforcement, the machine must operate slowly to be certain that the reinforcement bars are not damaged or pulled up by the machine.

The operating speed varies between 10 and 25 feet/minute (3 and 8 m/min) and 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.

5.3.2 Modified Production Rate

A modification factor is used to scale down or modify the theoretical production rate 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. 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 in order 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 also will 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.

5.4 Economics

Figure 5.5 presents a worksheet for estimating the cost of removing contaminated or deteriorated bridge deck concrete with a milling machine. The seven sections of the worksheet represent distinct areas that contribute to the cost of milling. This worksheet illustrates many of the parameters that 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 worksheet represent a hypothetical situation developed for illustrative purposes. Resources and parameters contained on this worksheet that are also on the worksheets developed for pneumatic breakers (p. 45) and hydrodemolition (p. 86). These parameters have the same value where practical to facilitate a comparison between methods.

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		
Production Estimates:	Cutting Mandrel Width	6.50	feet	
	Operating Speed	5.00	ft/min	
	Theoretical 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	
DIRECT COSTS: *Mobilization:*	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 =	**$1,008**
Equipment Rental:	Equipment Purchase Price ($):	-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**
Equipment Operation:	Fuel	$20.00	per hour	
	Oil, Lube, Filters	$7.00	per hour	
	Teeth	$30.00	per hour	
	Cutting Mandrel	$8.00	per hour	
	Convetor	$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**
Labor:	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 per day x	2.05 days	**$2,392**
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 5.5 Milling cost estimating worksheet
(See appendix B for metric equivalents.)

5.4.1 Job-Specific Parameters

The job-specific parameters define critical aspects of the job that 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.

The area and depth of removal will be determined by the SHA based on the degree of the concrete deterioration and chloride contamination and the extent to which the bridge is being rehabilitated. The example illustrated in the worksheet is based on the assumption that the entire surface, comprising an area of 20,000 square feet (1850 m^2), is to be milled to a depth of 1 inch (25 mm).

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, 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. Knowing the number of mobilizations and the mobilization distance is necessary before a contractor can prepare an estimate. The worksheet presents the case in which there are two mobilizations totalling 200 miles (320 km).

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. This is assumed to be one ten-hour shift per day.

5.4.2 Equipment Production Parameters

The estimated equipment production is determined as presented in the previous section using 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 worksheet, the machine has a 6.5 foot (2 m) wide cutting mandrel and is expected to progress at 5 feet (1.5 m) per minute, thus realizing a theoretical production of 32.5 square feet (3 m^2) per minute. However this is reduced by a modification factor of 0.5, resulting in an actual estimated production of 16.25 square feet (1.5 m^2) per minute. At this rate it will take 20.51 hours or 2.05 working days to mill the specified area.

5.4.3 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 (400 km), the days in mobilization can be calculated as 0.8 days. When this is multiplied by the daily equipment and labor cost (see 5.4.4 and 5.4.6 below), the total mobilization cost can be calculated as just over $1000.

5.4.4 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 well known.

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.

5.4.5 Equipment Operating Cost

Operating costs 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. 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 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.

5.4.6 Labor Cost

The next major cost component of a contractor's 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 worksheet utilizes a three-person 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.

5.4.7 Total Direct Cost and Indirect Cost

Equipment owning cost, labor cost, mobilization cost can be directly attributed to a project. The total direct cost for the cost estimation worksheet is $6490.

A markup of 14% for indirect cost and profit is assumed as described in section 4.4.7 (p. 48).

The direct cost and the additional markups comprise the total estimated price to remove the concrete by milling, equal to $7398. 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 (1850 m^2) of concrete as calculated in the worksheet is $0.37 per square foot ($3.98/m^2).

5.4.8 Sensitivity Analysis

Figure 5.6 presents a sensitivity analysis based on the cost estimating worksheet. 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. Total mobilization cost ($1008), production estimate (16.25 sq. ft./min: 1.5 m^2/min) and unit resource costs were kept constant.

At low quantities of removal, an increase in quantity results in sharp reductions to the unit cost. Increases in quantity allow the fixed cost, which dominates the unit price at this point,

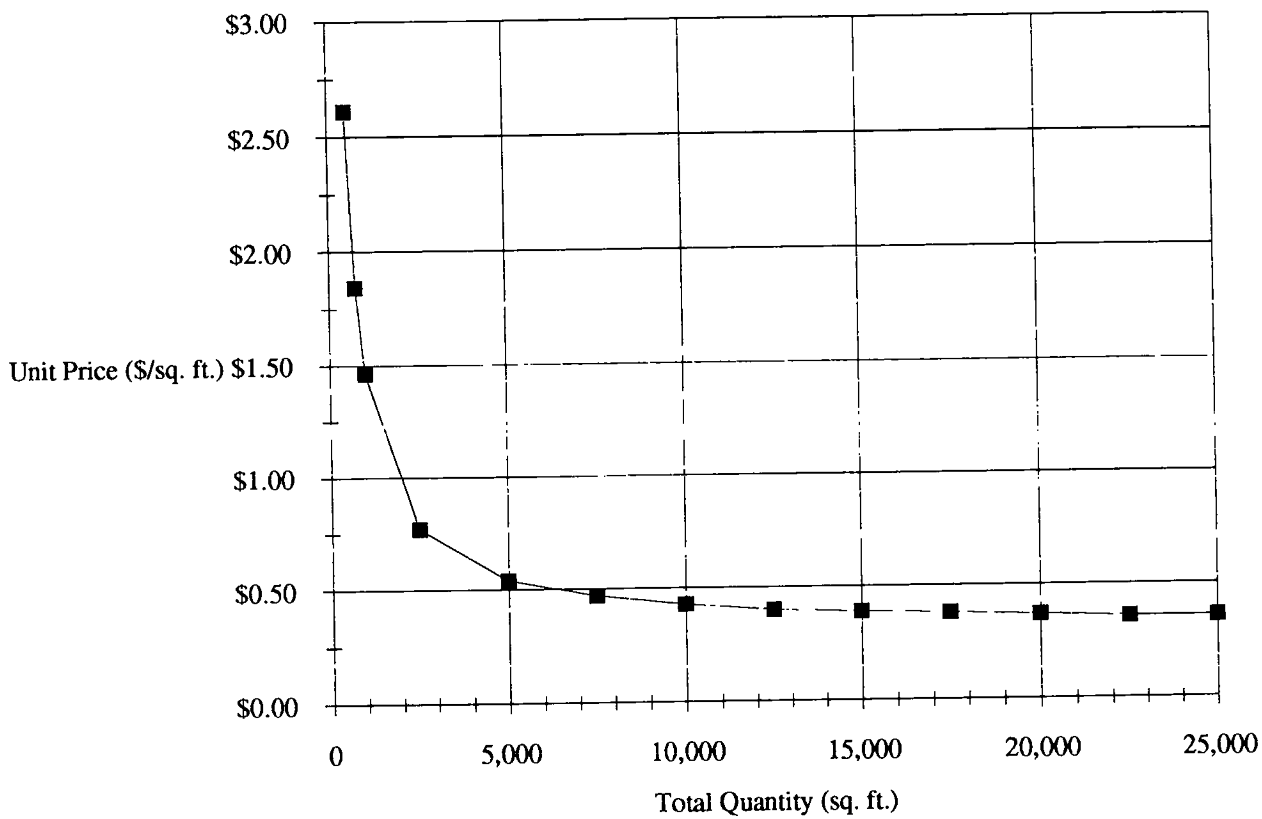


Figure 5.6 Sensitivity analysis of milling unit price to total quantity based on costs given in figure 5.5 (See appendix B for metric equivalent.)

to be more evenly distributed. Between 500 square feet of removal and 5,000 square feet of removal (46 and 460 m^2), the unit cost drops almost 80 percent from $2.61 per square foot to $0.54 per square foot ($28 to $5.80/$m^2$). 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.

5.5 Controlling Quality

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) 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 and it may also damage the residual concrete if the machine is pushed beyond its capabilities. Small machines are, however, inexpensive to mobilize, maneuverable and well suited to small, low-production or intermittent jobs.

   Large machines are well-suited to large continuous production projects. Many are designed and built for use on open pavement and may lack the control and 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.

2) Damage to residual concrete. Impact methods of concrete removal such as milling may produce a layer of damaged concrete with small cracks extending between one half and three quarters of an inch (12 to 18 mm) into the residual concrete. These microcracks 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.

   The cutting mandrel on milling machines rotates upward and away from the cut so as to break the concrete in tension. This reduces the potential for microcracking, which only becomes a serious problem if a heavy and powerful machine is forced to progress at too rapid a rate.

3) Damage to reinforcing steel. 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 critically controlled depths is a very costly, time-consuming and risky operation. It is frequently more cost-effective to use a milling machine to remove the concrete to a reasonable depth above the reinforcement, and to use other methods such as pneumatic breakers or hydrodemolition to remove any remaining damaged concrete.

4) Surface characteristics. 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.

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.

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

6

Hydrodemolition

This chapter examines hydrodemolition as a method for removing concrete as a part of the bridge rehabilitation process. It is capital-intensive technology that uses complex equipment to produce and direct a high pressure waterjet to erode the cement matrix between the concrete aggregate. It is capable of attaining a high rate of production while selectively removing deteriorated or contaminated concrete to the desired depth. It is effective in cleaning the reinforcing steel and preparing the surface for a subsequent overlay.

6.1 Technical Description

Hydrodemolition in its simplest terms involves the pressurization of water and the controlled delivery of a waterjet to demolish the cement matrix. 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.

6.1.1 Power Unit

Figure 6.1 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.

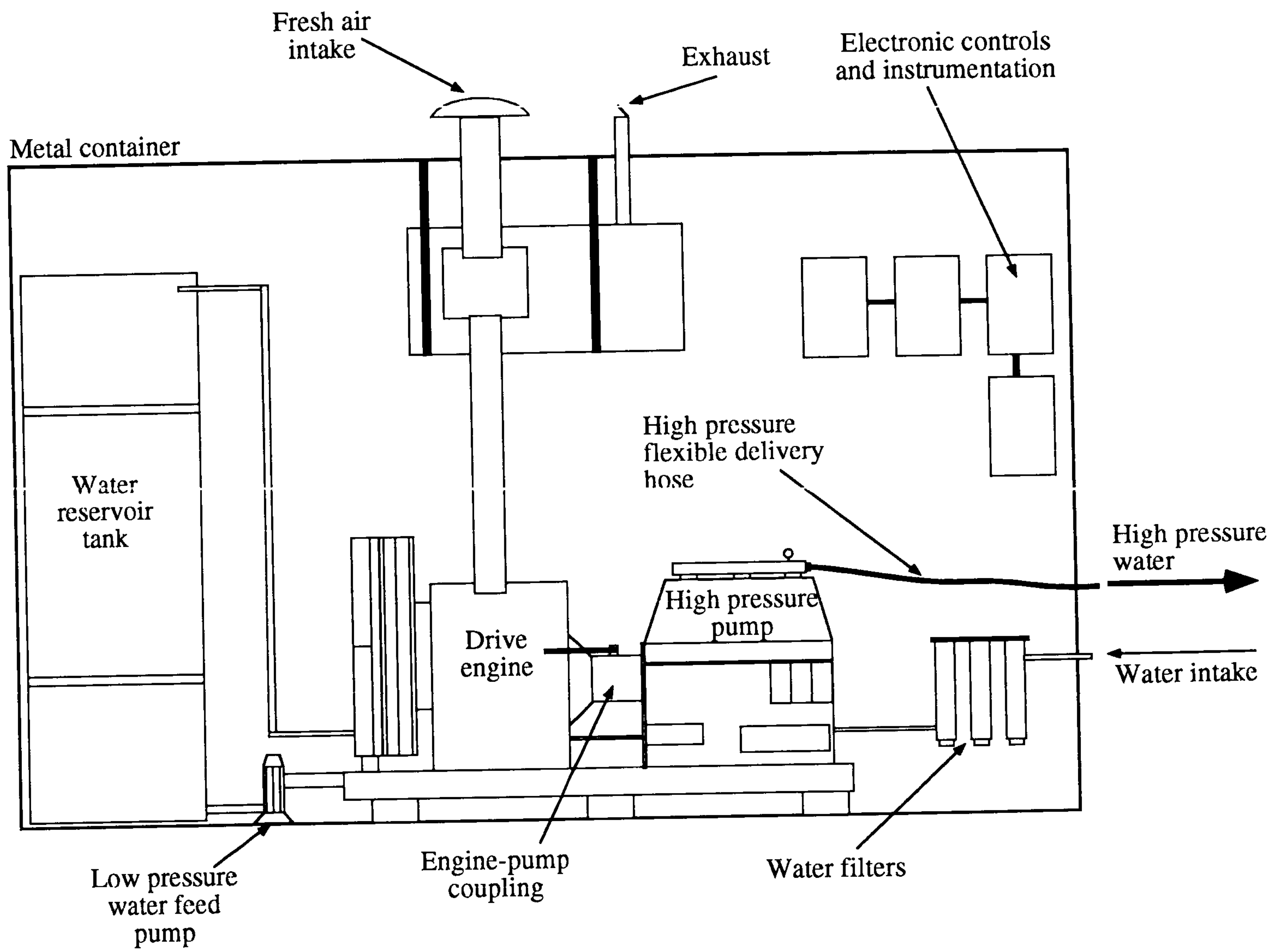


Figure 6.1 Hydrodemolition power unit

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.

The high pressure pump is driven by a 300 to 500 horsepower (225 to 370 kw) 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 (83 to 138 MPa) at a flow rate of 20 to 70 gpm (75 to 265 L/min). 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 (240 MPa) and 13 gpm (50 L/min).

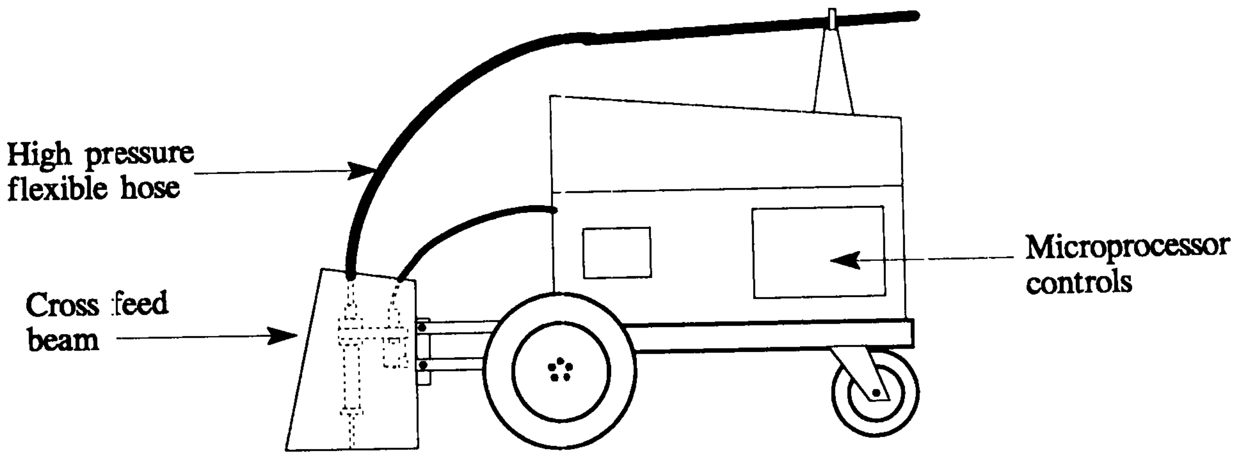
Hydrodemolition systems may utilize one or two power units. Using two power units running in tandem doubles the flow rate, roughly doubling the productive capacity of the hydrodemolition system.

6.1.2 Demolishing Unit for Bridge Decks

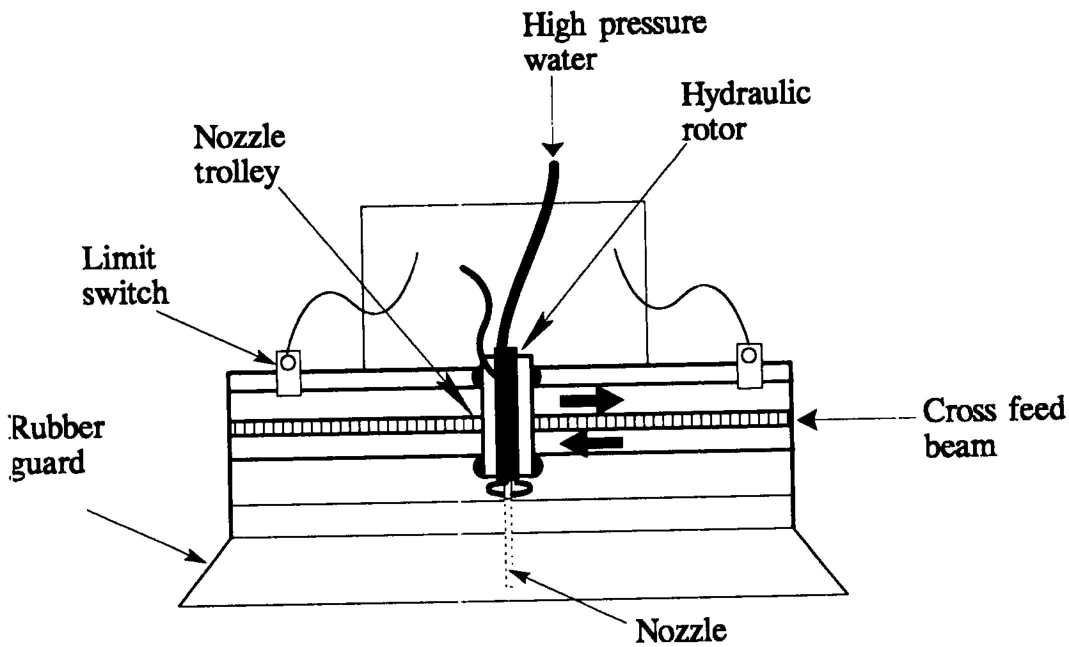
The demolishing unit used for bridge decks is a microprocessor-controlled, wheeled vehicle as illustrated in figure 6.2. A water delivery nozzle is attached to a trolley which traverses back and forth along a cross-feed beam at a programmed rate. The nozzle is rotated or oscillated at a constant programmed 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 trolley and the demolishing unit to ensure precise control over the fluid dynamic properties of the waterjet 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.



Side View



Front View

Figure 6.2 Hydrodemolition demolishing unit

6.1.3 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 that 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 that are difficult to access.

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

Some experimental equipment exists for special application concrete removal work such as columns and tunnels.

6.1.4 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 clean-up. If a water source is not available, a water supply truck will also be required.

The operating parameters for the hydrodemolition system are established through a process of estimation and testing. The summary of the process is outlined in figure 6.3, 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 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.

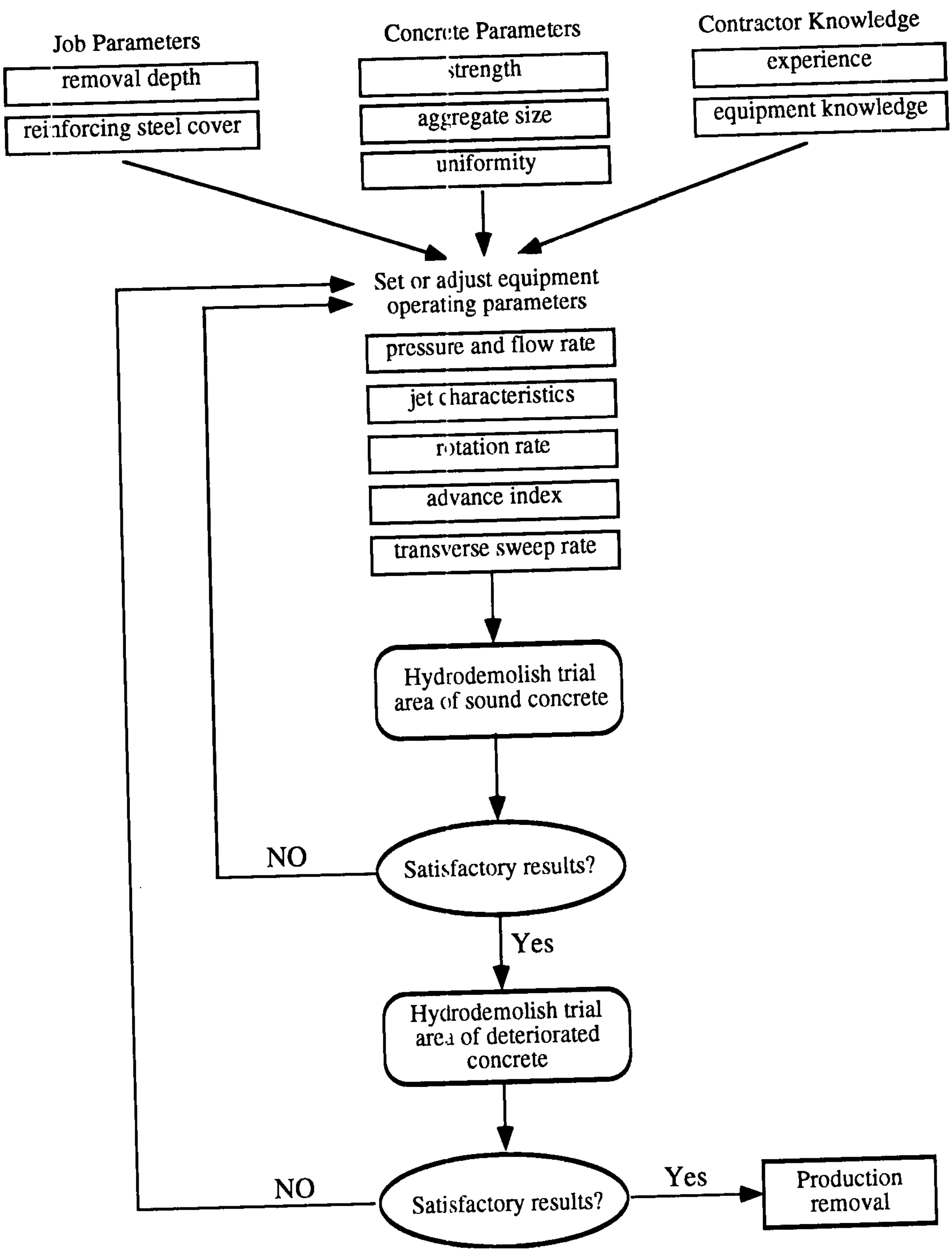


Figure 6.3 Summary of hydrodemolition calibration process

6.2 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 that require the extensive removal of deteriorated or contaminated concrete to a desired depth or level of soundness over a large continuous area.

6.2.1 Project Type and Location

Hydrodemolition using equipment of the nature described in section 6.1 (p. 71) can only remove concrete from flat level surfaces and from areas of a constant width as dictated by the limit switch settings discussed in section 6.1.2 (p. 73). Bridge decks that contain large quantities of contaminated or deteriorated concrete are ideally suited to hydrodemolition's ability to remove concrete from around and below the reinforcement while operating within the restraints imposed by the equipment geometry.

The high capital costs and the high degree of mechanization involved make hydrodemolition most favorable if operated on projects that 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 setups 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 patching or overlaying 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.

6.2.2 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.

6.2.3 Preparatory Work

Any of the identification methods described in section 2.1.1 (p. 13) or in publications arising from SHRP projects C-101, C-103 and C-104 may be used to delineate the area to be removed. The best results are obtained if the work is done immediately prior to hydrodemolition as contamination or deterioration may spread in the interval between initial design surveys and construction.

The work area needs to 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 that might 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.

6.2.4 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.

- Strength of material. Hydrodemolition removes concrete by applying a waterjet of greater energy than can be absorbed by the material being removed. The strength of the concrete will therefore determine how much energy it is capable of absorbing and the associated waterjet energy required to remove it.

- 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.

- 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 is not smooth and has a texture as determined by the maximum aggregate size as illustrated in figure 6.4.

6.2.5 The Area of Removal

Economic recovery of the high owning and operating costs of hydrodemolition equipment cannot be realized unless the equipment can operate over a large and continuous area.

The area which may be removed by hydrodemolition is physically limited by the machine geometry and method of operation. As discussed in section 6.1.2 (p. 73), the cross-beam width and limit switch settings will determine the width of the cut, and therefore the number of passes required.

6.2.6 Depth of Removal

Hydrodemolition is capable of removing concrete above, around and below reinforcing steel. The mean depth of removal is determined by concrete parameters and adjustable equipment operating parameters detailed in figure 6.3 (p. 76).

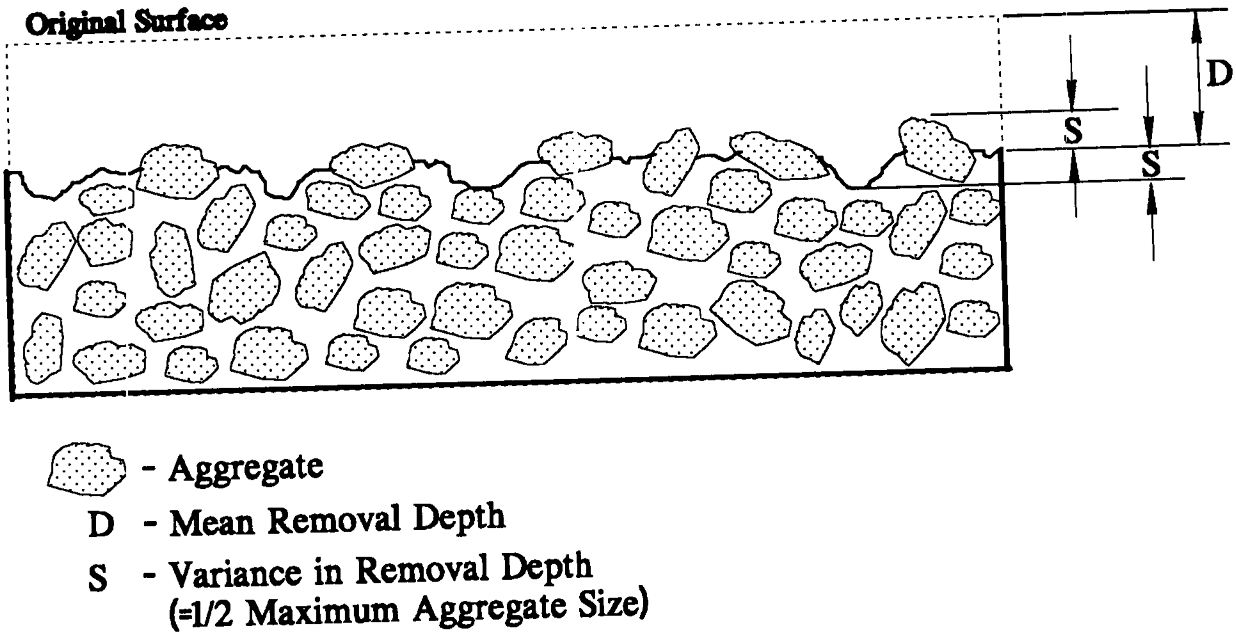


Figure 6.4 Mean depth of removal as a function of aggregate size

6.2.7 Debris Removal and Clean-up

The demolished concrete and other waste products arising from hydrodemolition form a combination of rubble, slurry and runoff water. Clean-up is accomplished by vacuuming or manually 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 sandblasted to provide a clean, bondable surface. The requirement to provide a good bonding surface for patches or overlays means that water or sandblasting 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 behind the advance of the demolishing unit using a hand held vacuum nozzle. The vacuumed area is frequently flushed with fresh water and re-vacuumed before the required level of cleanliness is reached.

Using an industrial vacuum truck generally requires a two-lane-wide work space. Figure 6.5 shows a typical hydrodemolition system setup 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 clean-up 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 cannot be used. Figure 6.6 shows a typical hydrodemolition system setup utilizing a manual clean-up operation.

In addition to the runoff control and debris filter methods discussed in section 6.2.3 (p. 78), 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. Sandbags 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.

6.3 Production Estimating

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

6.3.1 Theoretical Production Rate

The theoretical production rate is the quantity of concrete removed for each unit of time the waterjet spends actually hitting the concrete. This is a function of equipment parameters, concrete properties and job parameters.

- Equipment parameters. The primary equipment parameter affecting the instantaneous production of a hydrodemolition system is the power of the waterjet measured in terms of both the pressure and the flow rate of the water.

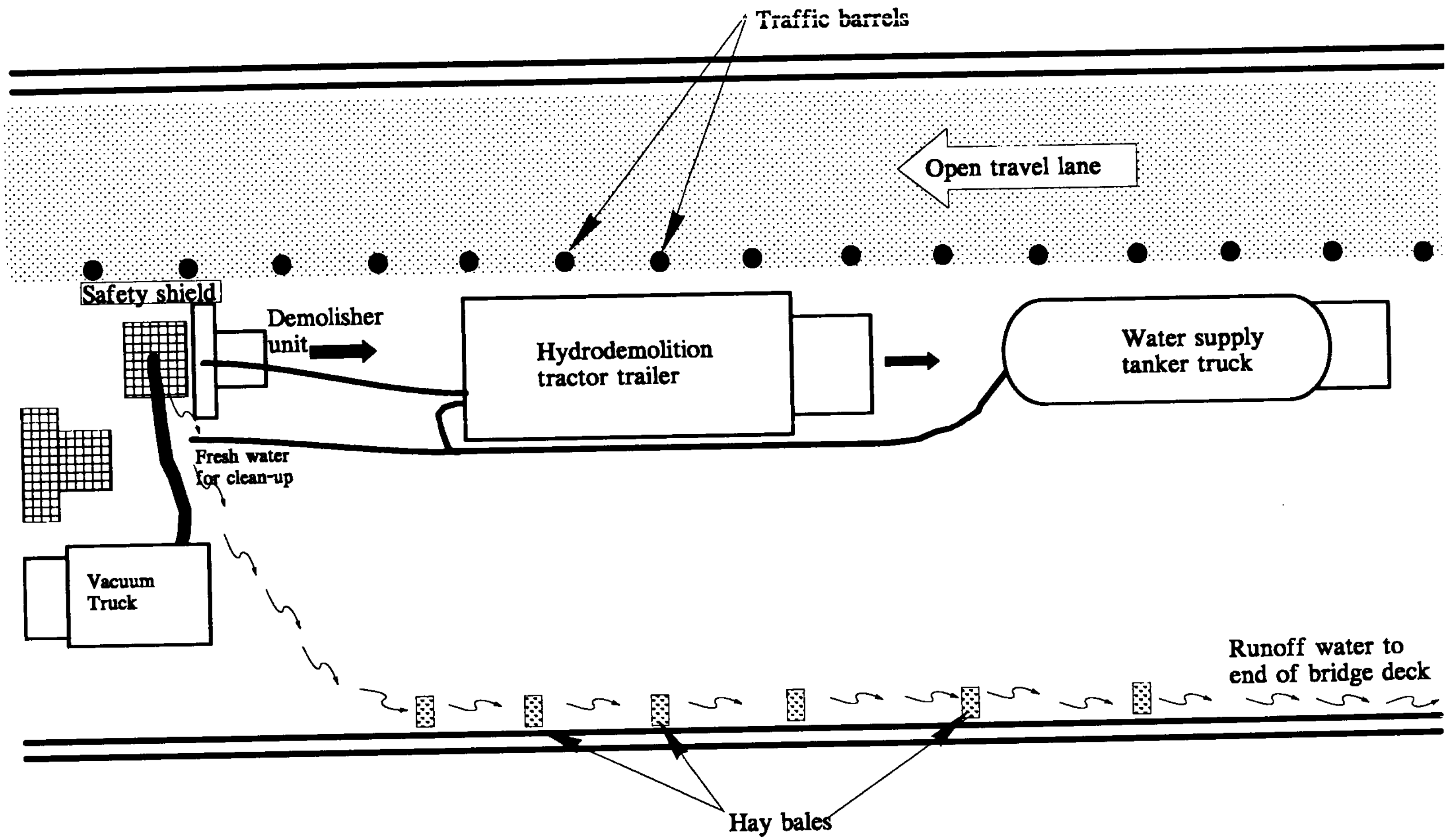


Figure 6.5 Hydrodemolition setup utilizing a vacuum truck

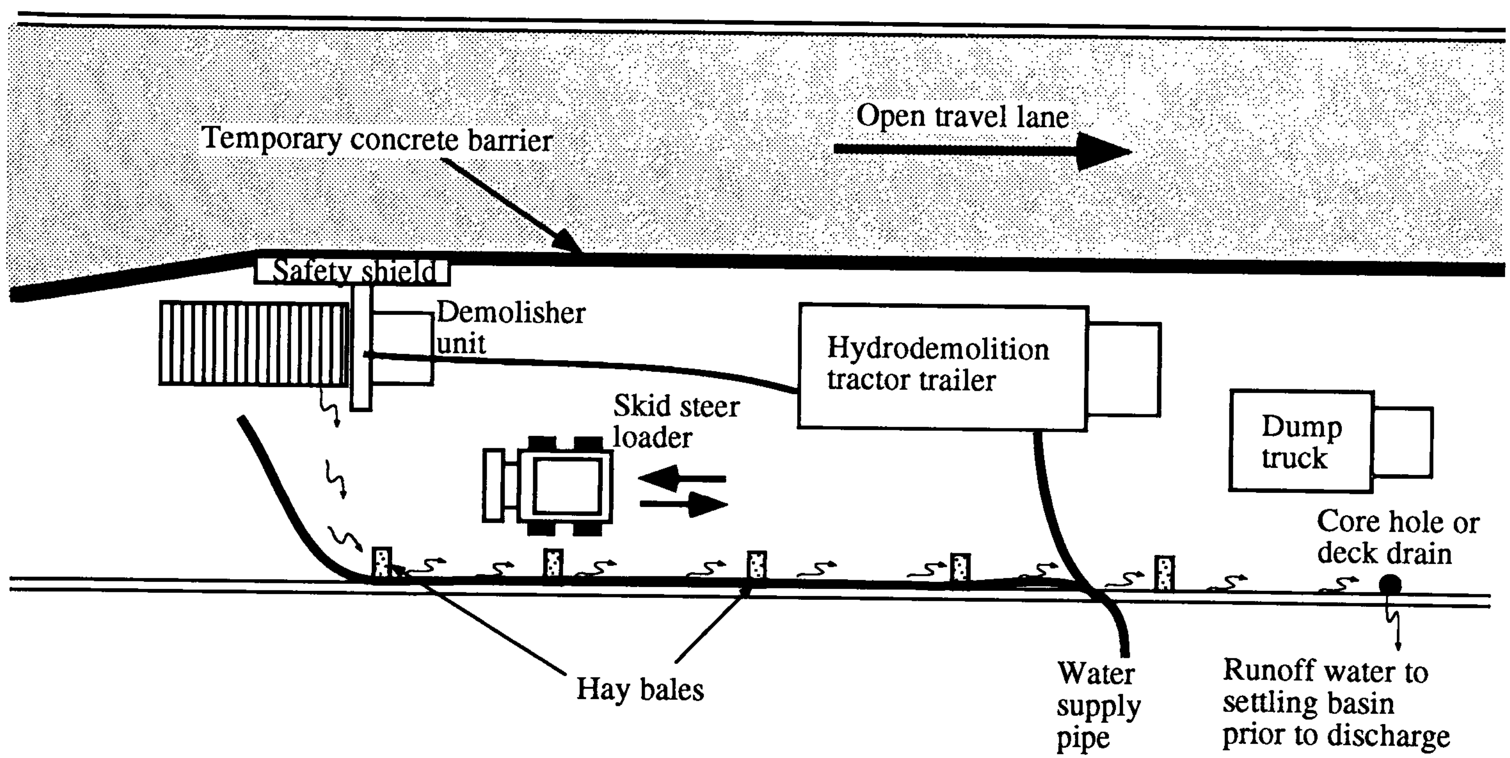


Figure 6.6 Hydrodemolition setup utilizing manual cleanup

- 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.

- Job parameters. The required removal depth is the main job parameter that influences instantaneous production. The depth related factors which contribute to hydrodemolition production were discussed in section 6.2.6 (p.79). If the concrete above the top mat of reinforcing is first removed by milling as discussed in chapter 5, then the loss in production due to the depth of removal can be reduced.

Figure 6.7 shows the range of theoretical productivity for hydrodemolition systems. These productivity rates are based on the hydrodemolition equipment manufacturer's productivity estimating guidelines for "typical" 4,000 psi (28 MPa) concrete and a removal depth of up to 3 inches (75 mm).

6.3.2 Modified Production Rate

Modification factors are used to scale down the theoretical production to reflect specific job characteristics. The primary parameters that 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 used typically 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 theoretical production rate depending on the reliability of the particular system.

6.4 Economics

This section examines the economics of hydrodemolition for concrete removal in bridge deck rehabilitation work by use of a hydrodemolition cost estimating worksheet as presented in

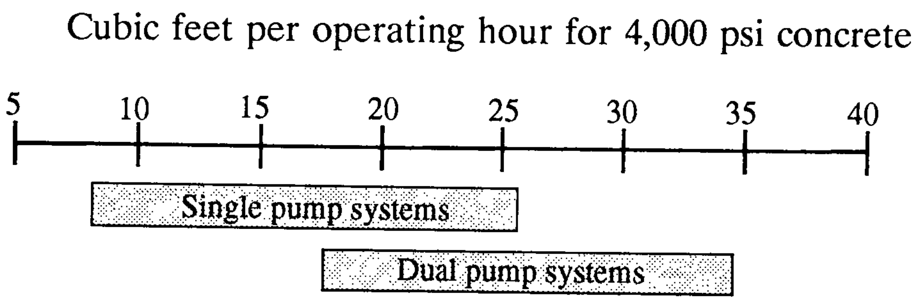


Figure 6.7 Range of theoretical productivity for hydrodemolition equipment (See appendix B for metric equivalents.)

figure 6.8. The worksheet presented in this section is similar to the work sheet presented in chapter 4 for pneumatic breakers and chapter 5 for milling machines. Although the work performed by the three methods of concrete removal varies in scope and complexity, worksheet 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.

6.4.1 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 because it is dependent upon the location of equipment and personnel.

Job Specific Parameters:	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					
Production Estimates:	Theoretical Production (cubic foot)	14.00	cubic ft/hr					
	Instanteous 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					
DIRECT COSTS: *Mobilization:*	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:							**$1,968**
Equipment Rental:	Equipment Purchase Price ($):	-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 Owning 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**
Equipment Operating:	Fuel:	$15.00	per nozzle hour					
	Oil, Lube & Filters:	$1.50	per nozzle hour					
	Water Filters:	$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 hrs	=	**$26,488**
Labor:	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**
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 6.8 Hydrodemolition cost estimating worksheet
(See appendix B for metric equivalents.)

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 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 200 miles (320 km).

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 6.2.6 (p. 79). The worksheet specifies that the concrete is to be removed to a depth of 2.5 inches (64 mm).

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 on how to rehabilitate the deck. It is difficult to accurately estimate the total quantity of removal if the rehabilitation is to be a patching operation. The capital-intensive nature of hydrodemolition makes it highly sensitive to quantity fluctuations. It is 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 (1860 m^2).

The fifth item describes the type of concrete removal work that 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 that require the entire surface to be removed as is the case in the example presented in the worksheet.

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 worksheet.

6.4.2 Equipment Production Parameters

The estimated theoretical production and the modification factor as determined in section 6.3 (p. 81) can be used to determine the estimated hourly production and the time to complete the work. The area of removal, 20,000 square feet (1860 m^2), can be divided by the theoretical production, 67.20 square feet (6.25 m^2) per nozzle hour, to determine the nozzle hours to complete the work, 297.6 nozzle hours. By reducing the instantaneous production (67.20) by the modification factor of 0.6, the estimated hourly production can be calculated as 40.32 square feet (3.75 m^2) 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 (10) and the shifts per day (1) restraint on the hours to complete the work, the days to complete the work can be determined as 49.60.

6.4.3 Mobilization Cost

The third section of the hydrodemolition cost estimation worksheet 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 ($2.49/km) 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 unit of distance and the daily equipment and labor cost constitute the total mobilization cost for the job, $1968.

6.4.4 Equipment Rental Cost

The third section of the worksheet calculates the hydrodemolition equipment rental cost based on an annual equivalent cost distribution of the purchase price less an anticipated salvage value. The same standard methodology for calculating the annual owning cost for capital equipment that was used to calculate the annual cost of a milling machine in chapter 5 was used in the worksheet.

The first item in this section is the hydrodemolition equipment purchase price. Figure 6.9 shows the range of purchase prices for hydrodemolition systems. A purchase price of $440,000 was used.

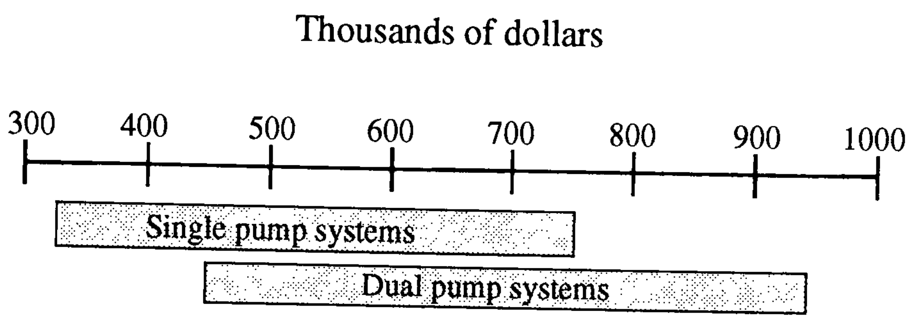


Figure 6.9 Range of hydrodemolition equipment purchase price

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 interest rate assumed for the capital investment in the equipment. The three major components are the capital lending rate, a profit on investment and the rate of inflation. These three rates were estimated as 12 percent, 7 percent and 5 percent in the worksheet.

The above figures yield an annual owning cost of $160,269. This cost is incurred by a contractor regardless of whether the equipment is idle or operating; therefore it is to the contractor's advantage to utilize the equipment as fully as possible.

The next 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 worksheet.

The last 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.

6.4.5 Equipment Operating Cost

The ten items in the operating cost section provide for the cost of wear items and spare parts used per operating hour by the 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 dual pump system.

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

6.4.6 Labor Cost

The sixth section of the hydrodemolition cost estimating worksheet calculates the labor costs incurred in operating and maintaining the hydrodemolition equipment. Hydrodemolition contractors typically use a two-person 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 worksheet 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 contractor's 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.

6.4.7 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 10 percent rate for overhead and administration is used for the worksheet example.

The percentage for profit typically ranges from 4 to 8 percent. A profit of 4 percent is used in the worksheet. If the hydrodemolition contractor feels that the job entails considerable risk (i.e., 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 the potential for quantity variations, the previous relationship with the general contractor and the previous relationship with the SHA.

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

6.4.8 Hydrodemolition Total Price and Unit Price

The total price for hydrodemolition 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, runoff 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 ($61.90/m^2).

6.4.9 Hydrodemolition Unit Price Sensitivity

The sensitivity of hydrodemolition's unit price to the total quantity of work is shown in figure 6.10. The curve was generated by varying the total area of removal in the hydrodemolition

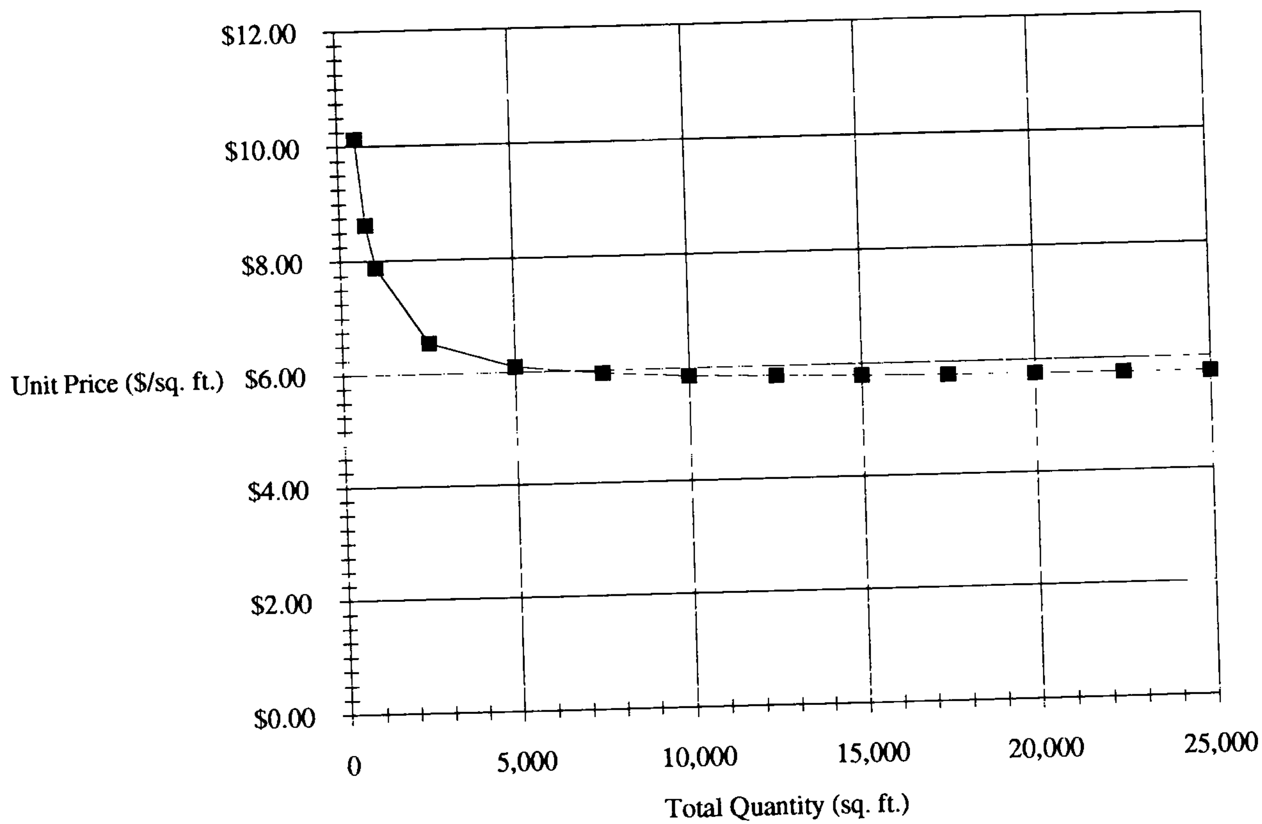


Figure 6.10 Sensitivity analysis for hydrodemolition unit price to total quantity based on costs given in figure 6.8 (See appendix B for metric equivalents.)

cost estimating worksheet. 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 worksheet components.

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

6.5 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 issues addressed in this section are quality requirements, residual cracking and specifications.

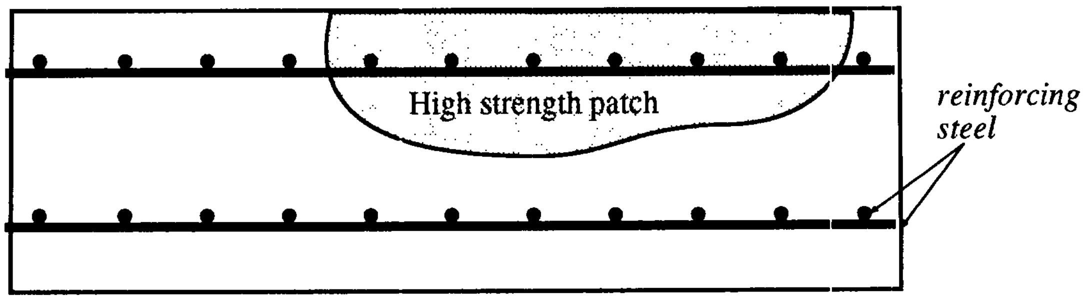
6.5.1 Quality Requirements

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 6.2.6 (p. 79), 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 6.11, typically is encountered when rehabilitating a bridge deck that has been previously patched.

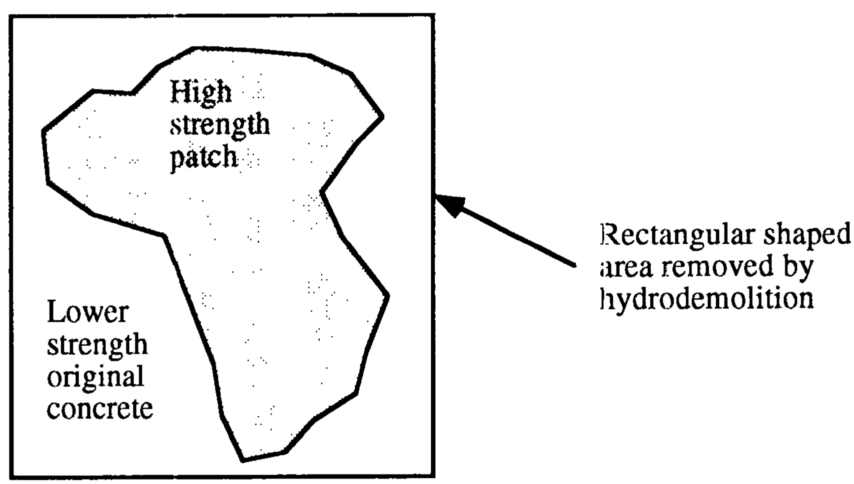
If the hydrodemolition system is calibrated to remove the high-strength concrete, then excessive amounts of original low strength material may be removed from around the perimeter or underneath the high-strength material. Absolute, precise depth control is not possible when the concrete's strength is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

Existing patches that 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 extensively deteriorated or low-strength concrete is encountered. The hydrodemolition system, calibrated for a higher



Sectional View



Plan View

Figure 6.11 High-strength patch in a bridge deck 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 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 waterjet. Figure 6.12 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 waterjet. If the mean removal depth is below the waterjet'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 waterjet 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 waterjet angle of impingement and the chosen mean removal depth. Larger steel bars move the waterjet 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 waterjet 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 which 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.

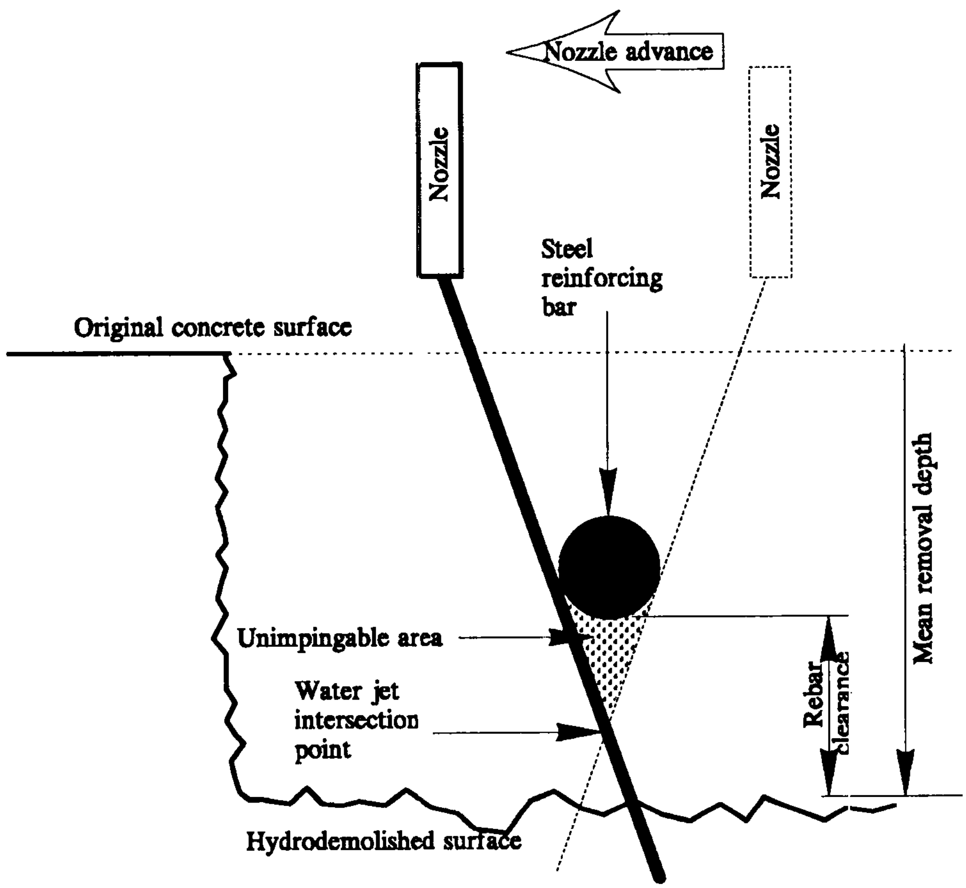


Figure 6.12 Nozzle advance and rebar shadow

6.5.2 Specifications

Pneumatic breakers and milling machines are relatively well-known technologies for concrete removal. Most SHAs have developed specifications for use with these methods, have tried them and found them adequate. This issue has, therefore, not been discussed in chapters 4 and 5. The same is not true for hydrodemolition and many SHAs are still actively developing suitable specifications.

Appendix A presents a guide specification based on input from equipment manufacturers and SHAs to assist in the process.

A prevalent problem with the hydrodemolition specification is the use of method specific clauses which limit 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 that address only the aspects of the work that 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 6.5.1 (p. 93), 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 alternate methods.

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.

7

Review of Technologies and Conclusion

Chapter 2 reviewed a number of concrete removal and bar cleaning tasks and identified three technologies, pneumatic breakers, milling machines and hydrodemolition, for further study. This was done in chapters 4, 5 and 6 with two objectives in mind:

1) to provide a good understanding of the strengths and weaknesses of each technology, and

2) to provide a basis for comparing the technologies relative to one another in terms of a given set of criteria.

This chapter seeks to achieve the second objective and also shows what can be done when technologies are combined to maximize strengths and minimize weaknesses.

7.1 Comparative Abilities

This section will take the information presented in chapters 4, 5 and 6 and arrange it so that the comparative abilities of each technology become very clear. This will be done by summarizing the information under each of the five headings used in the chapters and producing summary figures to highlight the main points.

7.1.1 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 wide variety of 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 them to specialized high production operations which entail the removal of surface and/or cover concrete.

Hydrodemolition is a highly sophisticated concrete removal technology which utilizes a computer calibrated high pressure waterjet 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 waterjet. Hydrodemolition equipment is still in the evolutionary stages and accordingly requires intensive maintenance and often 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 who operate milling and hydrodemolition equipment require substantial technical skills but have limited impact on the productivity of the work itself due to the highly mechanized nature of the equipment.

Figure 7.1 summarizes the technical description of each technology.

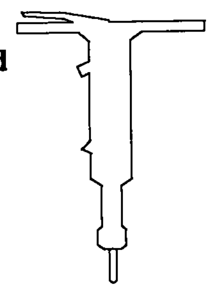
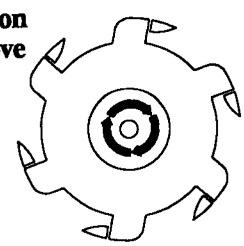
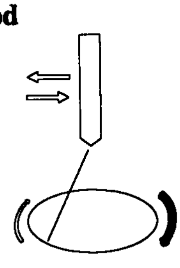
Technical Description		
Pneumatic Breakers	**Pneumatic breakers are small inexpensive, hand-held tools that utilize the percussive force generated by high frequency impacts of a cutting tool to fracture concrete. A compressor is required to supply the air to the power tool.**	
Milling Machines	**Milling 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.**	
Hydrodemolition	**Hydrodemolition is a complex, capital intensive method that uses the force of a computer calibrated high pressure water jet to destroy the cement matrix and remove the concrete. The equipment comprises a power unit and a demolition unit.**	

Figure 7.1 Technical description summary

7.1.2 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 used to remove the damaged concrete.

The small size and excellent maneuverability of pneumatic breakers ideally suit them to removing small areas of damaged concrete from 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 high production methods such as milling and hydrodemolition, to remove concrete from restricted, hidden or hard-to-reach 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 on flat, horizontal surfaces. Obstructions such as joint faces and utility boxes may interfere with a milling machine's cutting mechanism and pose a serious threat to operations. Inconsistently placed reinforcing bars 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.

Hydrodemolition can remove concrete from between, around, and below the reinforcement over a large area. However, the equipment is restricted to removing concrete from rectangular areas as dictated by the movement of the demolition unit. A standard unit is 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 setup space.

Continuity of operations is essential for both milling and hydrodemolition to achieve maximum utilization. The degree to which operations can proceed unimpeded is primarily determined by the area of removal, the available access and any obstructions which interfere with progress.

These characteristics are summarized in figure 7.2.

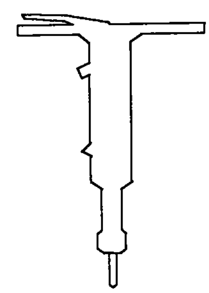
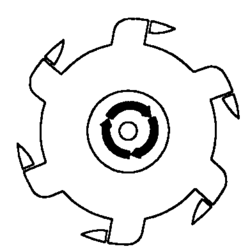
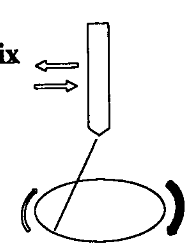
Work Characteristics		
Pneumatic Breakers	Pneumatic breakers are best used removing small, scattered patches of matrix and core concrete from horzontal, vertical and overhead surfaces on all bridge structural elements. A skilled operator is able to differentiate between concrete of varying degrees of deterioration.	
Milling Machines	Milling is confined to removing cover concrete from flat horizontal surfaces. It is best used if there is a large continuous area requiring removal to a uniform depth. Obstructions and inconsistent reinforcing steel cover will severely interfere with operations.	
Hydrodemolition	Hydrodemolition is most effective for removing matrix and core concrete from large continuous areas. It is able to selectively remove concrete of less strength than the energy imparted by the water jet.	

Figure 7.2 Work characteristics summary

7.1.3 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 can 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 which involves frequent repositioning of the tool.

Milling machine production is determined by the weight and power of the machine, the width of the cutting mandrel 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 and the large, continuous, obstruction-free areas on which they are typically used.

The production rate for hydrodemolition operations is determined by the rate at which the waterjet removes the concrete and the ability of the equipment to operate without interruptions. The rate at which the concrete can be removed is affected by the breaking energy of the waterjet, the strength of the material being removed and the standoff distance.

This information is summarized in figure 7.3.

7.1.4 Economics

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

Figure 7.4 combines figures 4.4 (p. 49), 5.6 (p. 68), and 6.10 (p. 92) to provide an insight into the relative unit costs of performing the work under the conditions assumed in the estimating worksheets.

Production Estimating

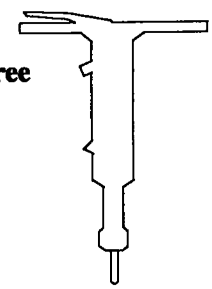
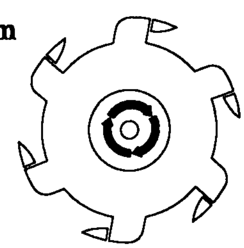
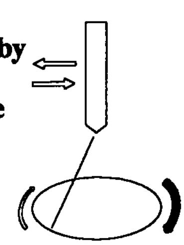
Pneumatic Breakers	**Breaker productivity is primarily determined by three components: the weight and associated power of the equipment, the skill and motivation of the operator and the degree of reinforcing steel interference.** 
Milling Machines	**The machine charateristics of power, weight, drum width, operating speed and the ability of the machine to be operated continuously are the primary determinants of a milling machine's productivity.** 
Hydrodemolition	**Hydrodemolition's production capacity is determined by the breaking energy of the water jet, the strength of the material being removed, the stand off distance and the ability to be operated continuously.** 

Figure 7.3 Production estimating summary

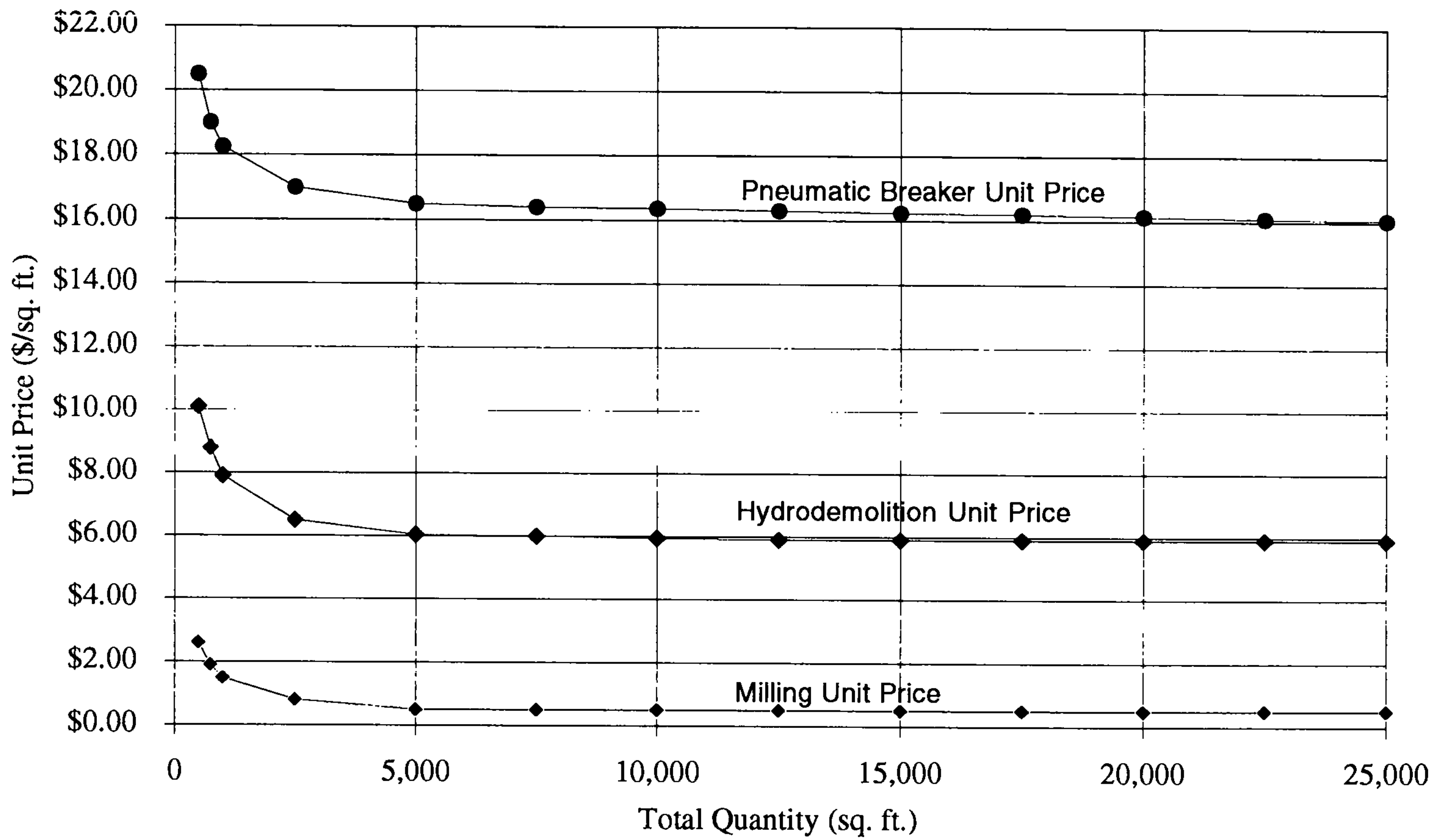


Figure 7.4 Relative unit costs under assumed conditions
(See appendix B for metric equivalents.)

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 and high labor cost associated with pneumatic breakers results in a high unit cost. Milling machines and hydrodemolition however, are designed for and generally operated in conditions that allow them to achieve very high production rates. This provides for a more economical operation and results 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 component of pneumatic breakers is labor which, being variable, changes in direct proportion to quantity. The cost-quantity ratio thus remains relatively constant to produce a relatively uniform unit cost over a wide range of quantities.

The high capital cost associated with milling and hydrodemolition is fixed and must be recovered regardless of the quantity of removal. These methods are, therefore, much more economical when used for removing large quantities of material as the fixed cost can be more widely distributed.

Figure 7.5 summarizes the economic aspects of the three technologies.

7.1.5 Managing and Controlling Quality

A problem common to concrete removal methods that use impact to fracture the material is the possibility of producing microcracks in the residual concrete.

This problem is minimized with pneumatic 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 and do not direct the impact into the material which is to remain and thus the possibility of microcracking is reduced. A well-maintained cutting head and the proper operating speed will reduce the possibility of damaging the residual concrete.

Milling machines may also damage the bridge and the machine by pulling up reinforcing bars. This risk can be reduced if the depth to the reinforcement is determined at several locations over the bridge deck prior to milling operations.

Economics of Operations

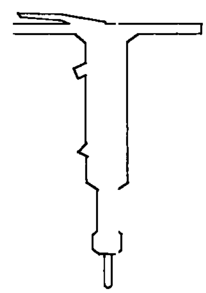
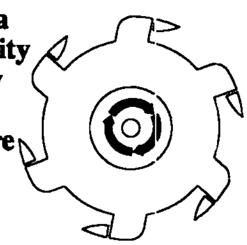
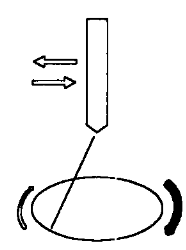
Pneumatic Breakers	**Labor is the primary cost component of pneumatic breaker operations. The unit cost will remain relatively constant in response to variations in quantity of removal because of the variable nature of the labor cost. The low production rate associated with pneumatic breakers results in a high unit cost.**	
Milling Machines	**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 the large fixed cost associated with equipment operations become more widely distributed.**	
Hydrodemolition	**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 quanitities of material due to the sensitivity of the unit cost to quantity.**	

Figure 7.5 Economics of operations summary

A hydrodemolition machine is only able to properly remove concrete that is of a strength similar to that for which the machine was calibrated. The waterjet will not have sufficient energy to remove material that is of a higher strength. Low-strength material may be removed to a greater depth than desired, possibly even all the way through the bridge deck.

The large volume of runoff water generated by hydrodemolition is an environmental and safety concern that must be addressed.

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

A summary of the quality management and control issues is presented in figure 7.6.

7.2 Combined Strengths

The study of comparative abilities performed in section 7.1 showed that each technology had very specific strengths and weaknesses with regard to work characteristics, production, economics and quality. The following is a brief summary.

1) Pneumatic breakers. They are the most expensive method but also the most flexible. They can be used for all sizes and shapes of area, to all depths and on all bridge structural elements.

2) Milling machines. These provide the least expensive method of concrete removal but they are also the most inflexible. They can only be used to remove large areas of surface and/or cover concrete on decks.

3) Hydrodemolition. This technology lies between pneumatic breakers and milling machines in terms of cost and flexibility. Surface, cover, matrix and core concrete can be removed, but economies are only realized if work is done on large horizontal areas such as decks.

Much can be done by combining the strengths and weaknesses of the methods as determined below.

Managing Quality

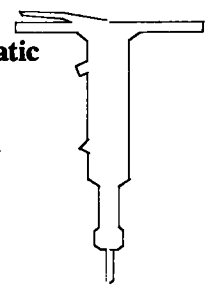
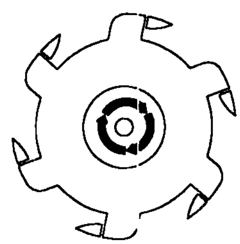
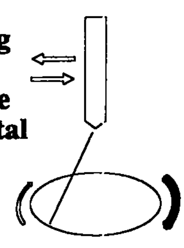
Pneumatic Breakers	**The primary quality concern associated with pneumatic breakers is the condition of the residual concrete and exposed steel. A concerted effort also must be made to accurately estimate the quantity of material which will require removal in an effort to reduce quantity variations.**	
Milling Machines	**Accurate determination of depth of material above the reinforcing must be made to avoid striking or pulling up a reinforcing bar. The condition of the residual concrete with regards to microcracking must also be monitored.**	
Hydrodemolition	**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. Environmental concerns associated with runoff control must also be addressed.**	

Figure 7.6 Quality management and control summary

7.2.1 Milling and Breakers

Combining these two technologies on bridges with relatively minor deterioration in cover and matrix concrete results in the following sequence of operations.

1) Contaminated and deteriorated concrete is milled from the deck to a level conservatively above the reinforcing steel.

2) Areas around joints and drains inaccessible to the milling machine are removed using pneumatic breakers.

3) Areas of deterioration remaining below the reinforcing steel are determined by sounding and removed to the required depth using pneumatic breakers.

4) Deteriorated concrete in the substructure is identified by visual inspection or sounding and removed to the required depth using pneumatic breakers.

5) All exposed steel is sandblasted to remove loose material and rust immediately prior to patching damaged areas and overlaying the deck.

7.2.2 Hydrodemolition and Breakers

Combining these two technologies on bridges with relatively large areas of deterioration in cover and matrix concrete results in the following sequence of operations.

1) The level of contamination and deterioration in the deck is determined using half-cell potential measurement, core sampling and/or sounding. Large areas that require removal are delineated, or a decision is taken to hydrodemolish the whole deck and rely on the selective removal capability of the technique to identify areas of above or below average deterioration.

2) Contaminated and deteriorated cover and matrix concrete is removed using hydrodemolition equipment calibrated to achieve the desired results.

3) Areas inaccessible to the hydrodemolition equipment and areas of particularly hard concrete are removed using pneumatic breakers.

4) Deteriorated concrete in the substructure is identified by visual inspection or sounding and removed to the required depth using pneumatic breakers.

5) All exposed steel is sandblasted to remove loose material and rust immediately prior to patching damaged areas and overlaying the deck.

7.2.3 Milling, Hydrodemolition, and Breakers

The low cost of milling large areas of cover concrete can be used to advantage by using a milling machine to remove all the material above the reinforcing steel after the first step described in section 7.2.2 has been completed. This greatly increases the productivity of the hydrodemolition which follows. The reduction in volume of concrete to be removed by hydrodemolition produces a corresponding reduction in the quantity of wastewater produced and this greatly improves the environmental and safety impacts.

7.3 Conclusions

A great deal of skill and experience is required to effectively match the technologies available to the project at hand. Many issues have been discussed throughout this report concerning how various tasks (defined in terms of the method used to identify the work, the area of removal, the location of removal and the depth of removal) relate to the various techniques available. The five factors that dominate the selection process are:

1) Quality. Any chosen method must satisfy the quality constraints of selectivity, residual damage and bond quality. If this is not done, then the method is simply not feasible.

2) Availability. The equipment, materials and skills needed to implement the chosen method must be available and it must be possible to use these on the project site. Specialized subcontractors, manufacturers and the contractor's own forces all contribute to providing the required resources.

3) Flexibility. The chosen method must be sufficiently flexible to accommodate changes in the scheduling, quantity and pace of work brought about by the unforeseen changes which can occur during a project. Methods that appear to be more productive but which require precise planning and precise knowledge of existing conditions seldom fulfill their promise.

4) Total Cost. The unit cost of performing the work by a given method is seldom the only criterion. The cost of traffic control, of repeated mobilizations brought about by limited access times and the cost of user delays must be factored into the analysis. The relative importance of concrete removal cost to total project cost is another important factor in selecting the chosen method.

5) Contractual Risk. In most cases the contractor carries the risks associated with the selection of the method to be used. This risk is substantial when large sums must be invested in the equipment needed, when the funding and continuity of work is not clear, and when the contract and specifications appear to inhibit innovation. Many of these factors are under the control of SHA personnel.

Quality, availability, flexibility, total cost and contractual risk can easily override the technical aspects. These vary with time and location and thus it is extremely difficult to make any firm rules as to which method must be used under all circumstances. This difficulty is somewhat eased by the realization that the methods described are more complimentary than competitive. Each has its role to play under given circumstances.

Appendix A

Guide Specification for Hydrodemolition

Section xxx: Concrete Removal and Surface Preparation

xxx.1 Description

This section specifies the removal of bridge deck concrete, the steel reinforcement cleaning and the concrete surface preparation prior to the placement of new concrete.

The concrete removal shall be accomplished by hydrodemolition. Mechanical impact methods may only be used to remove concrete in areas not accessible to the hydrodemolition equipment or for any minor touch-up required. A milling machine may be used to remove concrete to a depth above the top of the first steel reinforcing mat.

The concrete to be removed shall be as indicated on the plans and/or as determined by the Engineer.

The following definitions of the quality of existing concrete are used.

Sound concrete is defined as concrete that is free from spalls, cracks and/or delaminations.

Deteriorated concrete is defined as concrete that has spalls, cracks and/or delaminations.

Contaminated concrete is defined as concrete that has a chloride content greater than 2.0 lbs/cy (1.18 kg/m^3). Contaminated concrete may be either sound or deteriorated.

xxx.2 Materials
The contractor shall furnish all materials, equipment, and other resources necessary to complete the work.

xxx.3 Construction Requirements
The Contractor shall take all steps necessary to prevent cutting or otherwise damaging the reinforcing steel bars. Any bars damaged by the Contractor shall be repaired or replaced at no additional cost to the state and with no additional allowance for contract time extension.

Following the concrete removal, the Engineer will inspect any exposed steel reinforcement. If, in the opinion of the Engineer, the bars are deteriorated at any point to less than 50% of their original cross section, the Contractor will be directed by the Engineer to remove and replace these bars or sections of bars. New bars of the same size shall be spliced by providing the laps shown on the plans.

xxx.3.1 Concrete Removal by Mechanical Impact

Insert existing state DOT specifications.

xxx.3.2 Concrete Removal by Milling

Insert existing state DOT specifications.

100.3.3 Concrete Removal by Hydrodemolition

(a) Equipment. The hydrodemolition equipment shall consist of a water supply system, a high pressure water pumping system and a demolishing unit. The demolishing unit shall be fully automated to provide precise control of the water-jet and guarantee consistent operation.

The hydrodemolition equipment shall be capable of removing concrete from around and below the steel reinforcement. The hydrodemolition equipment shall clean all exposed reinforcing steel of rust, concrete fragments, laitance, loose scale and other coatings which may destroy or inhibit the bond with the new concrete.

The hydrodemolition equipment shall be operated by qualified personnel certified by the equipment manufacturer. Operator certification shall be submitted to the Engineer for approval prior to beginning the hydrodemolition operation.

The Contractor shall maintain on site an adequate supply of wear items, repair parts and service personnel to guarantee that the hydrodemolition operation will not be interrupted for more than 24 hours when an equipment breakdown occurs.

The Contractor shall be responsible for supplying the water and all other materials necessary to do the work specified.

The Contractor shall be responsible for disposing of all removed concrete at an off-site location.

(b) Testing and Calibration of Hydrodemolition Equipment. A trial area shall be designated by the Engineer to demonstrate that the equipment, personnel and method of operation are capable of producing results satisfactory to the Engineer. The trial area shall consist of two patches, each of approximately 30 square feet (3 m^3). The first trial patch shall consist of sound concrete as determined by the Engineer. The second trial patch shall consist of deteriorated concrete as determined by the Engineer.

The hydrodemolition equipment shall first be calibrated on the sound trial patch to remove concrete to a depth of (____) +/- (1/2 of the maximum aggregate size in the existing concrete).

The hydrodemolition equipment shall then be used to remove concrete from the deteriorated trial patch using the operating parameters established from the sound trial patch. If all the deteriorated concrete is removed as determined by the Engineer then the hydrodemolition system shall be considered calibrated. These operating parameters shall used as the basis for the production removal.

The Contractor shall record the calibrated hydrodemolition equipment's operating parameters and provide the Engineer with a copy. The Contractor shall not change the hydrodemolition system's operating parameters unless directed or approved by the Engineer.

(c) Hydrodemolition Work Plan. Prior to beginning the work the Contractor shall submit for approval to the Engineer a hydrodemolition work plan. This work plan shall include complete details of the following items:

The Contractor shall provide a means for controlling runoff water. The contractor shall make every attempt to prevent the runoff water flowing into adjacent lanes open to traffic. Runoff control measures must be approved by the Engineer.

The Contractor shall be responsible for compliance with all environmental regulations regarding the discharge of runoff water into the environment. The Contractor shall provide specific details of the method of runoff water treatment and obtain any necessary permits required for its discharge into the environment.

The Contractor shall provide additional safety shielding from flying debris.

The Contractor shall clean up all debris before it dries and rebonds to the deck. Should the hydrodemolition debris dry or rebond to the deck the Contractor shall clean the deck to the Engineer's satisfaction at no additional cost to the state and with no additional allowance for contract time extension.

The Contractor shall provide a method for handling expected and unexpected blow-throughs of the deck. This method shall provide for the containment of runoff water and debris and the protection of the area under the bridge deck. In the event of an unexpected blow-through the Contractor shall immediately stop the hydrodemolition equipment and implement the containment and protection procedures.

xxx.3.4 Steel Cleaning and Surface Preparation

Additional cleaning of the exposed steel reinforcement will not be required for areas of the deck treated by hydrodemolition, provided that concrete is placed within 48 hours of the hydrodemolition treatment.

Additional cleaning of the exposed steel reinforcement by sandblast or high-pressure water blast shall be performed if the steel reinforcement is exposed for greater than 48 hours prior to the placing of concrete or if a particular area of the deck was not treated by hydrodemolition.

Additional cleaning of the concrete surface by sandblast or high-pressure water blast shall be performed if the hydrodemolished surface is exposed for greater then seven days.

The final prepared surface shall be free of oil, dirt, concrete fragments, sandblast residue, standing water or any other material which may adversely affect the bond of the concrete. If the Contractor uses compressed air to clean the deck it shall be oil-free compressed air.

Any areas of the prepared deck surface contaminated by oil, grease or other materials detrimental to good bonding of the concrete as a result of the Contractor's operations shall be removed to such depth as deemed necessary by the Engineer. Such cleaning and removal work shall be at no additional cost to the state and with no additional allowance for contract time extension.

xxx.4 Method of Measurement

(a) Concrete removal shall be measured and paid for at the contract unit price bid per unit area as follows:

Partial Depth Removal includes removal of concrete to any depth not exceeding the total depth of the deck.

Full Depth Removal includes total depth removal of concrete through the deck.

(b) Steel reinforcing bar replacement not due to Contractor damage during operations shall be measured and paid for at the contract unit price bid per unit of weight for steel.

xxx.5 Basis of Payment

Accepted quantities of these items shall be paid for as indicated below. Payment shall be compensation in full for all labor, equipment, tools, materials and incidentals required to complete the work as described in this section.

Pay Item	Unit
Partial Depth Concrete Removal	Square Foot (m^2)
Full Depth Concrete Removal	Square Foot (m^2)
Steel Reinforcing Bar: Size ___	Pound (kg)

Appendix B

Metric equivalents for figures appearing in text

Quantity	From Inch-Pound Units	To SI Units	Multiply by
Length	Mile Yard Foot Inch	km m m mm	1.609 0.914 0.305 25.4
Area	Square Yard Square Foot Square Inch	m^2 m^2 mm^2	0.836 0.092 645.16
Volume	Cubic Yard Cubic Foot Gallon	m^3 m^3 L	0.764 0.028 3.785
Mass	Pound	kg	0.453
Pressure	Psi	KPa	6.894

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