Foundation Evaluation with Micro Intrusive Testing

By
Department of Civil and Environmental Engineering
The University of Alabama Tuscaloosa
Tuscaloosa, Alabama

For

UTCA
University Transportation Center for Alabama
The University of Alabama, The University of Alabama in Birmingham, and The University of Alabama at Huntsville

UTCA Report Number 01114
December 2002
Foundation Evaluation With Micro Intrusive Testing

Abstract
This research developed new abrasive-waterjet equipment and techniques for drilling small holes, approximately 3/8-inch in diameter, in reinforced concrete. The ultimate goal is to evaluate bridge foundations and abutments to determine the susceptibility of the structure to failure if scour occurs. The overall research effort consists of three phases: 1) equipment development and laboratory testing, 2) large-scale field tests, and 3) implementation on existing bridges to evaluate foundations and abutments. The current research and final report were for Phase I of this project – equipment development and laboratory testing.

Laboratory tests focused on abrasive-waterjet drilling of a variety of materials, including red brick, concrete masonry units, high-strength reinforced concrete, steel rebar, Pottsville sandstone, a telephone pole, a steel oil well casing and 3/4-inch thick glass plate. Drill rod and tip diameters used in these tests ranged between 1/8 and 9/16-inch. Operating at 5,000-psi with a water flow rate of approximately two gallons/minute, the garnet feed rate was between 1.3 and 6 pounds/minute. Within these operating ranges the abrasive-waterjet drill consistently produced holes between 3/8 and ½ inch to depths between two and 36 inches.

The laboratory results showed that this new abrasive-waterjet drill is capable of drilling a small diameter hole, approximately 3/8 of an inch, through typical civil engineering materials. The drill produced straight, in-gauge holes up to 16 inches deep. After a thorough literature review, the authors are confident that this is the smallest diameter waterjet application to date for geological or geotechnical drilling.
## Contents

Technical Report Documentation................................................................. ii
Contents ......................................................................................................... iii
List of Tables .............................................................................................. v
List of Figures ................................................................................................ v
Executive Summary ...................................................................................... vi

1.0 Introduction and Background........................................................................... 1
   Introduction .................................................................................................. 1
   Background ................................................................................................. 1
   Report Organization .................................................................................... 2

2.0 Literature Review............................................................................................ 3
   Introduction .................................................................................................. 3
   Assessment of Bridge Failure due to Scour . .................................................... 3
   General Waterjet Drilling Research ................................................................. 4
   Abrasive Waterjet Drilling ............................................................................. 5
   Waterjet Drilling Applications ....................................................................... 6
   Safety in High-Pressure Waterjetting ............................................................. 9

3.0 Design and Fabrication ................................................................................ 10
   Introduction .................................................................................................. 10
   Equipment Design ...................................................................................... 10
      Accumulator Cart ....................................................................................... 10
      Drill Stand ................................................................................................. 13
      Drill Rods and Tips .................................................................................... 14
   Parts and Prices ............................................................................................. 15
   Procedures .................................................................................................... 15
      Mixing Procedure ....................................................................................... 15
      Accumulator Charging Procedure ............................................................. 16
      Operating Procedure ................................................................................. 17
         Abrasive-Waterjet Drill Preparation ........................................................ 17
         Sample Preparation .................................................................................. 17
         Abrasive-Waterjet Operation .................................................................. 18
         Abrasive-Waterjet Shutdown ................................................................. 18
      Disassembly Procedure ............................................................................. 18
      Cleaning Procedure ................................................................................... 18
4.0 Testing.................................................................................................................. 19
   A Typical Test Run.................................................................................................. 19
   Drill Rods and Tips............................................................................................... 20
   Garnet Suspension............................................................................................... 21
   Problems............................................................................................................. 22
      Pump Surging................................................................................................. 22
      Water Rate..................................................................................................... 23
      Garnet Feed Rate Measurement and Control................................................. 23
   Drill Rod Bending............................................................................................... 24
   Deep Holes.......................................................................................................... 24

5.0 Results............................................................................................................... 25
   Introduction........................................................................................................ 25
   Sample Materials............................................................................................... 26
      Red Brick....................................................................................................... 26
      Concrete Masonry Unit.................................................................................. 26
      Reinforced Quickcrete.................................................................................... 27
      High-Strength Reinforced Concrete............................................................... 28
      Steel Rebar..................................................................................................... 28
      Pottsville Sandstone......................................................................................... 29
      Creosote Treated Wood Pole.......................................................................... 30
      3/4 –Inch Glass Plate....................................................................................... 30
   Water Rate.......................................................................................................... 31
   Abrasive Consumption......................................................................................... 32
   Hole Size............................................................................................................. 32
   Cutting Rate........................................................................................................ 33

6.0 Discussion and Conclusions.......................................................................... 34

7.0 References ...................................................................................................... 35

8.0 Companies Providing Waterjet Components .............................................. 35
### List of Tables

<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>Parts list for manufacturing equipment</td>
<td>15</td>
</tr>
<tr>
<td>4-1</td>
<td>Abrasive-waterjet mix design</td>
<td>21</td>
</tr>
<tr>
<td>5-1</td>
<td>Compendium of test results</td>
<td>25</td>
</tr>
</tbody>
</table>

### List of Figures

<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>Side view of accumulator cart</td>
<td>11</td>
</tr>
<tr>
<td>3-2(a)</td>
<td>Top view of accumulator stand</td>
<td>12</td>
</tr>
<tr>
<td>3-2(b)</td>
<td>Side view of accumulator cart</td>
<td>12</td>
</tr>
<tr>
<td>3-3</td>
<td>Top view of bottom plumbing</td>
<td>13</td>
</tr>
<tr>
<td>3-4</td>
<td>Drill stand</td>
<td>13</td>
</tr>
<tr>
<td>3-5</td>
<td>New tool plate to stabilize lathe</td>
<td>14</td>
</tr>
<tr>
<td>3-6</td>
<td>Safety shields on drill stand</td>
<td>14</td>
</tr>
<tr>
<td>3-7(a)</td>
<td>Top view of accumulator cart showing valve numbers</td>
<td>16</td>
</tr>
<tr>
<td>3-7(b)</td>
<td>Side view of accumulator cart showing valve numbers</td>
<td>16</td>
</tr>
<tr>
<td>4-1</td>
<td>No. 10 rebar sample being drill with 1/4 inch drill rod</td>
<td>19</td>
</tr>
<tr>
<td>4-2</td>
<td>Side view looking at the ends of each drill rod and tip</td>
<td>21</td>
</tr>
<tr>
<td>4-3</td>
<td>View of sample drilled with a 1/2 inch rod with an angled tip</td>
<td>22</td>
</tr>
<tr>
<td>4-4</td>
<td>Paint stirrer used to mix the abrasive suspension</td>
<td>22</td>
</tr>
<tr>
<td>4-5</td>
<td>Load cells used to measure weight of accumulator cart</td>
<td>25</td>
</tr>
<tr>
<td>5-1</td>
<td>First sample drilled using pure water</td>
<td>26</td>
</tr>
<tr>
<td>5-2</td>
<td>CMU block drilled with a 16 inch deep hole</td>
<td>27</td>
</tr>
<tr>
<td>5-3</td>
<td>Sample of reinforced quickcrete showing that the abrasive-waterjet smoothly drilled through rebar</td>
<td>27</td>
</tr>
<tr>
<td>5-4</td>
<td>High-strength reinforced concrete sample drilled with ½” rod</td>
<td>28</td>
</tr>
<tr>
<td>5-5</td>
<td>No. 10 rebar sample drilled in 40 seconds</td>
<td>29</td>
</tr>
<tr>
<td>5-6</td>
<td>Pottsville Sandstone sample</td>
<td>29</td>
</tr>
<tr>
<td>5-7</td>
<td>Creosote treated wood pole sample drilled with ½ inch drill rod</td>
<td>30</td>
</tr>
<tr>
<td>5-8</td>
<td>3/4 inch glass plate drilled with ¼ inch drill rod</td>
<td>31</td>
</tr>
</tbody>
</table>
Executive Summary

This research developed new abrasive-waterjet equipment and techniques for drilling small holes, approximately 3/8-inch in diameter, in reinforced concrete. The ultimate goal is to evaluate bridge foundations and abutments to determine the susceptibility of the structure to failure if scour occurs. The overall research effort consists of three phases: 1) equipment development and laboratory testing, 2) large-scale field tests, and 3) implementation on existing bridges to evaluate foundations and abutments. The current research and final report were for Phase I of this project – equipment development and laboratory testing.

The abrasive-waterjet drill developed during this research has three major components: 1) a 5000 pounds per square inch (psi) pump, 2) an accumulator cart, and 3) a drill stand. The 5000-psi pump is an off-the-shelf contractor-grade pressure washer. The pump supplies pressure to accelerate water and an abrasive past a critical velocity at the drill tip so that the abrasive water stream readily erodes the target material. The abrasive suspension is a mixture of water, garnet sand, and SUPER-WATER® (a polymer). The drill stand is a small metal lathe turned on end that holds, turns, and advances the drill rod. The diameter of the drill rod and tip were reduced in this research from typical commercial diameters of greater than one inch, to as small as 1/8 of an inch.

Laboratory tests focused on abrasive-waterjet drilling of a variety of materials, including red brick, concrete masonry units, high-strength reinforced concrete, steel rebar, Pottsville sandstone, a telephone pole, a steel oil well casing and 3/4-inch thick glass plate. Drill rod and tip diameters used in these tests ranged between 1/8 and 9/16-inch. Operating at 5,000-psi with a water flow rate of approximately two gallons/minute, the garnet feed rate was between 1.3 and 6 pounds/minute. Within these operating ranges the drill consistently produced holes between 3/8 and 1/2 inch to depths between two and 36 inches.

The laboratory results showed that this new abrasive-waterjet drill is capable of drilling a small diameter hole, approximately 3/8 of an inch, through typical civil engineering materials. The drill produces straight, in-gauge holes up to 36 inches deep. After a thorough literature review, the authors are confident that this is the smallest diameter waterjet application to date for geological or geotechnical drilling.
Section One
Introduction and Background

Introduction

This research focused on developing a method to evaluate concrete bridge foundations through direct inspection. To accomplish this, new equipment and techniques for drilling small diameter holes in concrete were developed. This method, entitled Micro-Intrusive Testing (MIT), drills holes (approximately 3/8-inch) with an abrasive-waterjet drill that was designed, built, and tested during this research project. The new drill was designed to drill through concrete, rock, and reinforcing steel. It is anticipated that with additional research, depths of 100 feet can be achieved, thereby making this drill an excellent choice for bridge foundation inspection.

The overall MIT research project is divided into three phases. Phase I - Design and Development of Abrasive-Waterjet Drill, Phase II – Large Scale Foundation Testing, and Phase III - Field Verification. Phase I, which was completed during the current research project, focused on forming an advisory committee, reviewing current literature, evaluating and selecting waterjet drilling equipment, reducing the waterjet drill diameter, and conducting laboratory tests on samples of concrete, rock, and reinforcing steel. Phase II of this project will focus on large scale testing of MIT. The first tests will be conducted on aboveground pre-cast concrete piles between ten and 25 feet long. Following the aboveground tests, in-situ tests will be conducted on existing piles with intentional defects to a depth of 90 feet. Phase III will focus on bridge foundation and abutment testing. During Phase III, actual bridges will be evaluated with the MIT approach.

Background

Foundation scour is the leading cause of failure of over-water bridges in the United States (FHWA HEC-18, Richardson et al., 1993). Unfortunately, scour often occurs during severe storm events when bridges are the most vital link in a transportation network. Bridge scour is caused by a river changing course or rising enough to remove soil from around or under bridge foundations or abutments. Removal of soil reduces the load carrying capacity of a foundation, which can cause failure. Failure caused by scour can be prevented if foundations are designed such that the entire bridge load is supported below the scour line.

The scour line describes the depth to which material can be removed from around a structure. Scour occurs when a flow field is disrupted by foundations or abutments, which causes sediment to be removed from the channel bottom. Scour depth is a flow phenomena affected by flow velocity, river channel material, the size, shape, and orientation of bridge piers, and the pile group configuration. Significant research is being performed to improve methods for calculating scour depth. Unfortunately, this is only half of the equation with respect to bridge failure.
Determining a bridge’s susceptibility to scour requires an accurate understanding of the existing foundation. Due to the advanced ages of many bridges, as-built drawings of bridge foundations often do not exist or are inaccurate. In this situation, an in-field testing method is needed to determine foundation length. Currently, non-destructive methods, such as impulse response, are being researched as a method to evaluate the length of bridge foundations. Unfortunately, these methods rely on knowing one of two variables: 1) the material properties of the pile, or 2) the length of the pile, neither of which are perfectly known for existing foundations. In addition, access to the pile head, which is often covered with a pile cap and bridge deck, is essential for non-destructive methods.

Suggestions made in FHWA’s HEC-18 (Richardson, et al., 1993) for improving the “state-of-the-practice” of evaluating scour potential include the need for more field data such as as-built bridge designs, the development of instrumentation and equipment to evaluate bridge scour potential, the need for instrumentation to determine unknown bridge foundations, and research on abutment scour, including as-built abutment dimensions. This project deals with one of these, determination of unknown foundations.

Report Organization

This final report is organized into seven sections. Section 1, Introduction and Background, introduces the overall abrasive-waterjet research topic and specifically the current research phase as it relates to foundation evaluation for bridge scour. Section 2, Literature Review, examines the body of literature pertinent to this research and justifies its contribution to the discipline. Relevant articles pertaining to bridge scour and waterjet technology are reviewed and summarized. Section 3, Design and Fabrication, discusses the selected waterjet equipment and design considerations. This section includes a detailed parts list and provides operating procedures for the abrasive-waterjet drill. Section 4, Testing, describes the laboratory tests and problems with the testing procedures. Section 5, Results, describes the materials tested and the performance of the abrasive-waterjet drill. Section 6, Discussion and Conclusions, discusses the findings of this research project. Finally, Section 7 introduces future work on the topic of abrasive-waterjet drilling, abrasive-waterjet cutting, and abrasive-waterjet parameter optimization.
Section 2
Literature Review

Introduction

This section focuses on the current literature concerning bridge scour and water jet drilling applications. More specifically, this literature review will address a few of the currently used methods of evaluating bridge failure due to scour and channel instability, as well as a background of water jet drilling technology and several currently used applications of this technology. The evaluated literature revealed that bridge scour analysis is possible with the correct parameters and that water jet drilling techniques have been used with much success in several areas of engineering technology.

Assessment of Bridge Failure due to Scour

Bridge scour can be defined as the erosion of stream channel bed material in the vicinity of abutments and piers. It can be categorized as the following:

- **Local scour** that occurs at the abutments or piers, and is typically caused by an obstruction of the natural channel flow.
- **Contraction scour** that occurs under and near the bridge that generally lowers the channel bed. This is caused by a constriction of the natural channel.
- **Channel degradation** that is a lowering of the entire channel bed, and that occurs regardless of whether the bridge is in place or not.

In the paper, “Fault Tree Analysis of Bridge Failure due to Scour and Channel Instability,” Johnson (1999) explains that scour at bridges is a complex process. There are several scour and channel instability processes that can occur simultaneously. Some of these processes include local scour at the piers and abutments, contraction scour, channel bed degradation, channel widening, and lateral migration. The interactions of these river processes are unknown, and their sum creates a very complex phenomenon that has, so far, eluded mathematical modeling. However, Johnson proposes using a fault-tree analysis as one way to examine the possible interactions of all these processes and their effect on bridge piers and abutments.

Fault-tree analysis is a systematic method of analyzing fault sequences that lead to an undesirable event, such as bridge failure (Johnson, 1999). A fault tree can assist in the identification of paths to failure and can be used to single out critical events. Fault trees can also be used to assess the probability of failure, to compare design alternatives, to identify critical events that will significantly contribute to the occurrence of failure, and to determine the sensitivity of the probability of failure to various combinations of events. Johnson used fault-tree analysis to examine the interactions and sequences of events that could lead to a bridge failure.
failure due to scour or channel instabilities at the piers or abutments. Based on the fault-tree analysis, the probability of failure of a bridge due to various combinations of scour and channel instabilities was calculated. This probability of failure was calculated for three bridges located across the country, all with different combinations of scour and channel instability:

- The Route 66 Bridge over Piney Creek in Clarion County, Pennsylvania failed in July of 1996 due to local and contraction scour around the abutments; fault-tree analysis yielded a probability of failure of 99.7%.
- Example bridge given in HEC-18 – events of concern included local and contraction scour; fault-tree analysis yielded a probability of failure between 0.0925% and 0.125%.
- The Route 51 Bridge over the South Fork Forked Deer River in Tennessee failed in 1973 due to local scour at the piers and rapid channel degradation and widening; fault-tree analysis gave a probability of failure of 5%, which is high for a bridge on a U.S. Route (Johnson, 1999).

One key advantage of using fault-tree analysis to evaluate such a complex process as bridge scour is the fact that no quantitative knowledge on the interactions of the multiple processes is needed.

Johnson and Ayyub (1992) also developed a method to assess the risk of bridge failure due to pier scour during the entire life of a bridge. The analysis involves simulating pier scour for a period time and determining the probability that the bridge will fail at various points of time during that period. Three factors were found to affect the probability of failure in various ways; these factors were sediment size, pier width, and pier depth. Larger sediment sizes were found to cause a significant decrease in the probability of failure. Conversely, as the pier width increases, the probability of failure associated to scour also increases. Finally, it was found that as the pier foundation depth increase, the probability of failure due to scour decreases (Johnson and Ayyub, 1992).

**General Waterjet Drilling Research**

Several papers have been written concerning the basics of water jet drilling technology. For example, Kolle (1998) performed a comparison of four different methods for rapidly drilling small-diameter (25 millimeter (mm) – 50 mm) and near surface holes in a variety of hard rock types. The four approaches that were evaluated include rotary diamond drilling, ultra-high pressure (UHP) water jet drilling, mechanically assisted UHP water jet drilling, and abrasive jet drilling. Results indicated that high-pressure water jet drilling provides a unique capability for drilling a constant-radius directional hole without the need for steering connections. Furthermore, UHP jet drilling offers high penetration rates because the power available at the bit is extremely high. In conclusion, it was reported that a UHP drill is capable of rapidly drilling small-diameter holes in a wide range of erosion-resistant rocks and that a UHP drilling system could be made lightweight because thrust and torque requirements are nominal (Kolle, 1998).

Other research by Wu, et al. (1987) found that the impact force generated by a water jet fluctuates, that is, it does not apply a steady cutting force. As a consequence, vibration will be induced in any target structure. Because the fluctuating impact of the jet can be the main
excitation source of a target structure, characterization of the water jet impact is essential to predict unstable cutting situations. The research concluded that the pulsation of the water jet induced by the components of the pumping system can be dampened if the connecting hose section is long enough and the orifice diameter of the nozzle is small. It was also concluded that different pumps, nozzles, and standoff distances create different characteristic jet structures. Furthermore, the pressure of the jet was not found to be an important factor affecting the jet pulsation frequency, but it does change the magnitude of the impact force. Finally, it was discovered that an optimum standoff distance with the maximum impact force exists for every pumping system (Wu, et al., 1987).

The presence of cavitation (i.e., the formation of vapor-filled cavities in water) is known to improve jet performance at least in certain applications such as rock cutting (Szymczak, et al., 1987). Although cavitation might occur within high-speed jets issuing into air, its effects have been mostly documented with the jet operating under submerged conditions. Canadian research investigated the structure of high-speed, submerged water jets produced by two different types of nozzles, namely, a plain conical nozzle and an obstructed conical nozzle. The research documented the inception of cavitation and subsequent collapse of cavities by using a laser as an illumination source and a 35-mm camera to photograph the jets. The obstructed conical nozzle was found to produce greater cavitation, thus implying greater jet performance (Szymczak, et al., 1987).

Dickinson, et al. (1987) developed a water jet nozzle for the continuous penetration of consolidated and unconsolidated earth formations. It produces a conically shaped cutting jet, which allows a hole to be cut much larger than the nozzle orifice. This characteristic is particularly desirable for continuous penetration, as it provides an adequate size hole for the nozzle feed line to advance with the nozzle. These “conical jet” nozzles have been tested at pressures up to 68 mega Pascals (MPa) and have successfully cut materials such as limestone, granite, and basalt (Dickinson, et al., 1987).

**Abrasive Waterjet Drilling**

Research has been performed to investigate abrasive particle behavior based on experimental determination of particle velocity (Swanson, et al., 1987). In these experiments, conventional garnet sand was mixed with magnetic particles of comparable size. This mixture was injected into a conventional water jet, and the resulting cutting stream was directed through a pair of current-carrying coils spaced a fixed distance apart. The magnetic particles induce a signal in each of the coils, which allowed a measure of the particle velocity (Swanson, et al., 1987).

Typical results showed that, with a water jet stream velocity of 1,800 feet/second (ft/sec), an abrasive particle achieves an average velocity of only about 400 ft/sec, indicating incomplete mixing. The relatively low overall efficiency of the water jet as an accelerating medium is explained by the failure of the particles to be effectively embedded into the jet stream. With the apparatus employed by Swanson, et al., abrasive particles enter the mixing chamber at essentially zero velocity and encounter the water jet which has a velocity ranging up to 2000 ft/sec or more.
The majority of particles have no chance of penetrating the jet and instead bounce off into the nozzle walls (Swanson, et al., 1987).

If the particles are injected directly into the center of the jet, they should acquire essentially the full jet velocity within an inch or less of travel. Since no particle velocities of this order were observed in the research efforts, it was assumed that the present mixing and acceleration of the abrasive by means of the water jet is a superficial and relatively inefficient process that should be improved (Swanson, et al., 1987).

Research by Galecki and Mazurkiewicz (1987) indicates that the effectiveness of hydro-abrasive jets depends on the energy that can be imparted to the abrasive particles. Theoretically, the relatively low velocity abrasive grains are accelerated to the resultant velocity of the slurry jet. As part of this acceleration process, a reduction in the abrasive particle size occurs which absorbs a portion of the water jet’s kinetic energy. Thus, the efficiency of the abrasive acceleration process is reduced, as is the maximum slurry jet velocity attainable. The research concluded that as the slurry nozzle diameter was increased, the disintegration of the abrasive particles within the head became less. Also, it was discovered that 70 percent to 80 percent of the initial abrasive was broken or disintegrated. Thus, for the given test conditions (water nozzle diameter of 0.35 mm and two pressure settings of 138 and 275 MPa), only 20 percent to 30 percent of the particles completed the acceleration and ejection process intact (Galecki and Mazurkiewicz, 1987).

A research team for the Bureau of Mines built and tested an abrasive water jet rock drill (Savanick and Krawza, 1987). The drill uses a 10,000 psi, 20 gallons per minute (gpm) water jet which entrains 22 pounds per minute (lbs/min) of sand. The drill has been used to drill rock as hard as quartzite with a compressive strength of 73,000 psi. The drill penetrated the quartzite at a maximum rate of 4 inches/minute (in/min). Other rocks drilled include charcoal granite (with a compressive strength of 20,000 psi), which was drilled at 6 in/min and Salem limestone (with a compressive strength of 8,000 psi), which was drilled at 30 in/min (Savanick and Krawza, 1987).

The abrasive jet drill has some unique and useful features as compared to mechanical drills. It can drill small holes, can collar a hole at any angle, can drill through fracture zones, can drill holes which overlap, can be translated perpendicular to the direction of drilling to produce a narrow kerf, and can chamber holes (Savanick and Krawza, 1987).

**Waterjet Drilling Applications**

There are several water jet drilling applications in use today. Some of the most intriguing applications make use of SUPER-WATER®, which is a concentrated industrial water blasting additive developed in 1974 (abbreviated S-W®). S-W® was first used to clean hard intractable deposits from hydroprocessing reactor exchangers in 24 hours instead of the three months taken by previous methods. This was accomplished at nominal pressures and flow rates of 10,000 psi and 10 gpm (Howells, 1999).
Later it was determined that S-W® was equally effective at lower pressures used in pressure washers (i.e., less than 6000 psi), and could be equally well applied to “soft” materials. S-W® can be used to clean concrete from totally plugged sewers and to remove sludge from nuclear power steam generators. The successful removal of epoxy-bound rubber from the space shuttle booster motors ultimately lead to ultra-high pressure jet cutting of shoe soles at 50,000 psi and then of use for an entire range of rubber and related products from semi-liquid Vistanex to 90 Durometer material (Howells, 1999).

S-W® has been used for slotting and drilling granite and concrete and more recently in the abrasive suspension jet (ASJ) technique for precision cutting of “soft” metals like lead to hard ceramics. S-W® increases the effectiveness of the standard abrasive water jet by producing narrower kerf widths and reducing abrasive consumption by 50 percent. S-W® can even be used for the precise drilling of Baccarat crystal (Howells, 1999).

High-pressure water is used in many applications in the building and construction industry. One special application is the high-pressure water jet cutting. High-pressure water jet cutting is different from the usual construction applications of high-pressure water like cleaning, stripping paint, or demolition. (Peters, 1998)

Compared to the conventional cutting procedures of flat materials, the high-pressure water jet cutting has some characteristic advantages:

- No deformation of the material during the cutting process;
- No thermal influences on the material;
- No dust;
- Small kerf;
- Minimum loss of material during cutting;
- Easy to handle cutting tool;
- Integration of cutting tools into production machines;
- Three dimensional cutting;
- Capability of piercing the material; and
- Starting the cut almost anywhere at the surface of the material.

Furthermore, by adding abrasives to the water jet, the performance of the water jet cutting can be considerably improved. For high-pressure water jet cutting, the following equipment is required: a high-pressure system, a guiding system, a catcher system, and auxiliary systems (Peters, 1998).

The cutting performance is influenced by several parameters. The most important are the operating pressure and the water flow rate. These two parameters represent the performance of the system. For most materials, a linear increase in the cutting speed with increasing pressure can be expected. The same effect is observed when the water flow rate at constant discharge pressure is increased. This can be done easily by changing the diameter of the cutting nozzles. Further, an increase in the cutting speed at constant pressure and water flow rate decreases the depth of cut. However, it should be noted that the quality of the cut is an important feature. A smooth cut requires a much slower cutting speed than a rough cut. The difference in the cutting
speeds can range by a factor of three. Finally, an increase in the amount of abrasives will naturally increase the cutting speed (Peters, 1998).

Plain water jet drilling has found its most important application in the automotive industry with the cutting of bumpers, dash-boards, hat-rags, and the internal linings of cars to final shape. The electronic industry uses the high-pressure water jet for cutting insulation material, cleaning soldering pins, cutting circuit boards, and removing cable coatings. In addition, water jet cutting is used in the plastics industry for cutting foam. Especially in this application, the minimum deformation of the material during the cutting operation is an important advantage (Peters, 1998).

Another application of water jet technology is cutting asphalt concrete and cement pavements in conjunction with pothole repair. Water jet cutting has a distinct advantage over the conventional cutting methods such as jack hammering and diamond saw cutting, since it does not damage the pavement material beneath and adjacent to the deteriorated region. This is particularly important for bridge deck repair operations (Zeng and Kim, 1998).

A preliminary study on abrasive water jet cutting of asphalt and concrete yielded the following results:

- The material porosity is one of the most important material parameters. Porosity can negatively or positively affect the machinability.
- Abrasive water jet cutting technology can be effectively used for cutting asphalt concrete in pothole repair operations.
- The water jet unit can be integrated with other mechanical and electronic devices to construct a self-contained, mobile vehicle for completely automated asphalt pavement repair work (Zeng and Kim, 1998).

Another current application of water jet technology is the hydro-demolition of substandard bridges in the United States. Research by Nittinger (1987) illustrates that the use of water jet drilling for hydro-demolition is expedient and cost effective. Unlike the conventional jack hammer method, the use of hydro-demolition is quieter, eliminates pavement micro-cracks, does not debond rebars from sound concrete, does not damage rebars, and leaves a sound clean surface ready for overlay (Nittinger, 1987).

Because of the great number of substandard bridges in the country in need of repair and because of its ability to satisfy this need, hydro-demolition is becoming the acceptable answer to the repair problem. Hydro-demolition is useful in repair of bridges and parking garages, and stretches the taxpayer’s dollar through reduced repair costs while simultaneously yielding profits for the contractor (Nittinger, 1987).

**Safety in High-Pressure Waterjetting**

High-pressure water jetting is an environmentally friendly tool for cleaning and cutting, which is finding many new and extended applications. However, there are many hazards associated with
such a powerful tool, and a great deal of consideration must be given to carrying out risk assessments and following established codes of practice if it is to be used safely and effectively.

The prime danger of high-pressure water jetting is the water jet itself. This jet has an enormous amount of kinetic energy. If a jet can cut through concrete, then it will definitely have no problem cutting through human flesh and bone. Because there will always be a reaction force experienced by an operator holding any form of gun or lance, a firm footing is a key requirement. The work area must be clean and free from anything that could cause a trip or a fall. Arrangements must be made to remove the water so that it does not accumulate in puddles and cause a slipping condition for the operator. Another primary requirement for all high-pressure water jetting operations is the ability to shut off the water jet in a safe manner. The most common means of doing this is to use a valve in the high-pressure line (French, 1998).

The jet operator needs to concentrate on the job, and the work area must be behind a barrier so that the operator is not suddenly surprised by an approaching person. The barrier also prevents anybody from entering the area of activity and coming into contact with the jet or flying debris. Operation of the jet obviously produces a wet environment, and the operator needs to be wearing a full wet suit, safety boots, gloves, and a high-impact-resistant visor on a safety helmet (French, 1998). The operator of a waterjet should be familiar with the Water Jetting Association (WJA) “Code of Practice” which was developed with the support of the Health and Safety Executive (French, 1998).

In conclusion, high training standards with competent supervision, well-maintained equipment, and attention to detail in the risk assessment will give the high-pressure water jet industry the opportunity for continued expansion. The use of more remotely controlled jets is clearly the way to reduce the risk of contact with the water jet, slipping, tripping, and fatigue.
Section 3
Design and Fabrication

Introduction

This section describes the design and fabrication of the abrasive-waterjet drill. The abrasive-waterjet drill can be divided into three major components: 1) a 5,000-psi pump, 2) an accumulator cart, and 3) a drill stand. The 5,000-psi pump is an off-the-shelf contractor-grade pressure washer. The pump supplies the pressure needed to accelerate water, and an abrasive suspension past a critical velocity at the drill tip so that the abrasive water stream will readily erode the target material. The accumulator cart is made up of two accumulators that store the abrasive suspension. The abrasive suspension is a mixture of water, garnet, and S-W® (a polymer). The accumulator cart was modeled after a similar design by David Summers at the University of Missouri-Rolla. The drill stand is a small metal lathe turned on end that holds, turns, and advances the drill rod. The diameter of the drill rod and tip were reduced in this research from typical diameters of greater than one inch, to as small as 1/8 of an inch. Later in this section of the report, a table is presented to show the parts and prices of each part used in the fabrication later in this section, and the procedure is outlined for operating the abrasive-waterjet.

Equipment Design

The design process focused on the accumulator cart and the drill stand. In addition, drill rod and tip design was performed to reduce the rod diameter to as small as 1/8 inch.

Accumulator Cart

The accumulator cart is designed to hold the abrasive suspension at the operating pressure (5,000 psi) and continuously release a small amount of the suspension into the fresh water stream. The cart has two accumulators so one can be charged with the abrasive suspension while the other is being employed for drilling. This allows continuous drilling. The cart is two feet wide, five feet long, and five feet high as shown in Figure 3-1.
The cart holds two accumulators (A and B) and a paint pot. The frame of the cart is made out of standard angle iron, and is five feet tall, five feet long, and two feet deep. The two accumulators are positioned near the center of the cart and are inverted so they can be charged from the top. Bladders inside the accumulators push the garnet solution up into the water stream. The paint pot, positioned at the end of the cart, holds the abrasive suspension before it is pumped into the accumulators. Top and side views of the accumulator cart are shown in Figures 3-2(a) and (b).

The plumbing of the accumulator cart is designed to allow the majority of the water to flow up and across the top of the cart while at the same time pressurizing the accumulators. The pressurized accumulators slowly displace the abrasive suspension into the water stream. The high-pressure water first reaches the accumulator cart at a quick connect which is shown in the bottom view of the cart in Figure 3-3.

Once the water reaches the accumulator cart, water is directed to the top and bottom of the accumulator cart. The water pressure on the bottom of the accumulator cart allows the abrasive solution to be pushed up into the water stream on the top of the accumulator.
Figure 3-2(a): Top view of accumulator stand

Figure 3-2(b): Side view of accumulator cart
Drill Stand

The drill stand consists of a cart and a metal lathe that is vertically mounted, as shown in Figure 3-4. The metal lathe is used to hold, rotate, and advance the drill rod into the hole. A standard overhead projector cart was modified to serve as the base for the lathe. The lathe is positioned to drill vertically and is attached to the cart by a cable and counter weight and by replacing the original tool post of the lathe with a new plate which extends to the cart as shown in Figure 3-5. The counter weight and tool post guide allows the lathe to move up and down the vertical axis with ease. Safety shields were added to the front of the cart to prevent the abrasive-waterjet from spraying water on the lathe and operators, as seen in Figure 3-6.
Drill Rods and Tips

A drill rod is the steel tube that runs from the swivel to the drill tip. The drill tip is a tungsten carbide insert that has an orifice diameter of approximately 1/32-inch. Drill rods ranged in diameter from 1/8 to 1/2 inches and in length from four to eight feet. All the tips were approximately the same size, but were oriented either straight or at a small angle (approximately five degrees) to the axis of the drill rod.

In addition, tips were centered in some drill rods, and were offset in others. Multiple combinations of rods and tips were fabricated and tested in this research.
Parts and Prices

Although the equipment was completely assembled at the University of Alabama, many of the components were purchased. Table 3-1 lists the component manufacturer, part number, price per unit, and quantity used. The table also shows the total price of the abrasive-waterjet drill.

<table>
<thead>
<tr>
<th>Description</th>
<th>Manufacturer*</th>
<th>Part Number</th>
<th>Unit Price</th>
<th>Quantity</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal Lathe</td>
<td>Grizzly</td>
<td></td>
<td>$495.00</td>
<td>1</td>
<td>$495.00</td>
</tr>
<tr>
<td>10 Gal Paint Tank</td>
<td>Grainger</td>
<td>2C4682</td>
<td>$632.20</td>
<td>1</td>
<td>$632.20</td>
</tr>
<tr>
<td>6000 psi Pressure gages</td>
<td>Berkley Chemical</td>
<td></td>
<td>$173.12</td>
<td>1</td>
<td>$173.12</td>
</tr>
<tr>
<td>5 gal SUPERWATER®</td>
<td>Engineered Sales</td>
<td></td>
<td>$2,674.00</td>
<td>2</td>
<td>$5,348.00</td>
</tr>
<tr>
<td>Swivel</td>
<td>Stoneage</td>
<td></td>
<td>$496.75</td>
<td>1</td>
<td>$496.75</td>
</tr>
<tr>
<td>On/Off Valve</td>
<td>Swagelok</td>
<td>SS-83KS8</td>
<td>$116.90</td>
<td>8</td>
<td>$935.20</td>
</tr>
<tr>
<td>Regulatory Valve</td>
<td>Swagelok</td>
<td>SS-1RS8</td>
<td>$68.80</td>
<td>3</td>
<td>$206.40</td>
</tr>
<tr>
<td>3-Way Valve</td>
<td>Swagelok</td>
<td>SS-83XKS8</td>
<td>$174.60</td>
<td>1</td>
<td>$174.60</td>
</tr>
<tr>
<td>Union Tee</td>
<td>Swagelok</td>
<td>SS-810-3</td>
<td>$32.70</td>
<td>9</td>
<td>$294.30</td>
</tr>
<tr>
<td>Union Elbow</td>
<td>Swagelok</td>
<td>SS-810-9</td>
<td>$23.50</td>
<td>10</td>
<td>$235.00</td>
</tr>
<tr>
<td>Quick Connect Stems</td>
<td>Swagelok</td>
<td>SS-QF8-S-8PF</td>
<td>$15.80</td>
<td>5</td>
<td>$79.00</td>
</tr>
<tr>
<td>Quick Connect Body</td>
<td>Swagelok</td>
<td>SS-QF8-B-8PF</td>
<td>$34.90</td>
<td>5</td>
<td>$174.50</td>
</tr>
<tr>
<td>½ inch tubing</td>
<td>Swagelok</td>
<td></td>
<td>$6.64</td>
<td>40</td>
<td>$265.60</td>
</tr>
<tr>
<td>¼ inch tubing</td>
<td>Swagelok</td>
<td></td>
<td>$2.50</td>
<td>20</td>
<td>$50.00</td>
</tr>
<tr>
<td>1/8 inch tubing</td>
<td>Swagelok</td>
<td></td>
<td>$3.04</td>
<td>10</td>
<td>$30.40</td>
</tr>
<tr>
<td>Garnet</td>
<td>Barton Mines</td>
<td></td>
<td></td>
<td>1 ton</td>
<td>$1106.00</td>
</tr>
<tr>
<td>Grand Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$13,981.11</td>
</tr>
</tbody>
</table>

* Manufacturer contact information is listed in section 7 of this report.

Procedures

There are three different procedures that must be followed to successfully operate the abrasive-waterjet drill. These are mixing, accumulator charging, and drill operating.

Mixing Procedure

Using a digital scale, 100 grams of S-W® is measured and placed in a beaker. Five liters of hot water are poured into a five gallon utility bucket. Ten kilograms of garnet are weighed and placed in a large mixing bowl. The water in the five gallon bucket is placed under a drill press which has a large mixing blade attached to the press. The press is turned on at 200 rpm. The S-W® is slowly poured into the water allowing for complete mixing. This mixture is allowed to mix for five minutes. The ten kilograms of garnet is slowly poured into the mixture of hot tap water and S-W®. This mixture is allowed to mix for another five minutes. Best mixing results
are achieved when the drill press is turned off briefly and then back on as a final step. Once the mixture has thoroughly mixed and the garnet is suspended, the utility bucket is removed from the drill press and the solution is poured into the ten gallon paint pot.

**Accumulator Charging Procedure**

Once the garnet, water and S-W® mixture has been placed in the ten gallon paint pot, the top of the paint pot is put in place and securely fastened. The steps to charge the accumulators are listed below. Figures 3-7 (a) and (b) shows the accumulator cart with numbered valves.
• Connect air hose (110 psi max) to the paint pot.
• Connect 300 psi hose from paint pot to valve 10.
• Turn on valve 10.
• Turn valve 11 to fill the desired accumulator.
• Turn off valves 4 and 7.
• Turn on valve 6 to allow garnet to push air and water out of the bottom of the accumulator when charging accumulator A. Otherwise leave valve 6 off.
• Turn on valve 9 to allow garnet to push air and water out of the bottom of the accumulator when charging accumulator B. Otherwise leave valve 9 off.
• Turn on air pressure.
• The hose connecting the paint pot to valve 10 will vibrate while charging is in progress.
• When the hose stops vibrating, turn off valve 10.
• Turn off valve 11 (center position).
• Turn off the air supply to the paint pot.
• Release the pressure in the paint pot by pulling the safety release valve. Do not open the paint pot without first releasing the pressure.
• Once all of the pressure has been released, open the top of the paint pot to visually check the approximate amount of garnet solution transferred.
• Disconnect the air hose from the paint pot to eliminate a safety hazard of tripping on the line.

Operating Procedure

Position the power washer, accumulator cart, and drill stand in the desired location. The on/off valves on the accumulator cart are in the on position when the handle is in line with the tubing and off when the handle is perpendicular to the tubing.

Abrasive-Waterjet Drill Preparation
• Connect a water supply to the power washer.
• Connect the power washer to the accumulator cart with a 5,000 psi hose.
• Connect the accumulator stand to the drill stand with a 5,000 psi hose.
• Turn on valves 1, 2, and 3. (Valve 2 and 3 are regulating valves. They are in the on position when turned counterclockwise until they will not turn anymore).
• To use accumulator A, turn on valve 4. Otherwise leave it off.
• To use accumulator B, turn on valve 7. Otherwise leave it off.
• Valves 6 and 9 should always be off when running the abrasive-waterjet drill.

Sample Preparation
• Place the sample underneath drill stem, and adjust height for the proper offset distance.
**Abrasive-Waterjet Operation**
- Turn on lathe to desired rpm.
- Turn on water at supply.
- Allow water to run through system and out of the drill stem.
- Put on safety goggles and ear protection before starting the pressure washer.
- Start pressure washer.
- Allow 5,000 psi water to run through system.
- If using accumulator A, slowly turn on valve 5, otherwise leave valve 5 off.
- If using accumulator B, slowly turn on valve 8, otherwise leave valve 8 off.
- The sound of the water coming out of the drill tip will change. This and the color the water jet spray will indicate the presence of the garnet solution.
- Once the garnet solution is present, engage the lathe to automatically move along the track bed.

**Abrasive-Waterjet Shutdown**
- When the lathe reaches the bottom of the track bed, turn off valve 5 if using accumulator A, or valve 8 if using accumulator B.
- Turn off the power washer to decrease the pressure from 5,000 psi to the pressure of the water supply.
- Turn off the water supply to allow the water to drain out of the system.
- Turn off valve 1.
- Remove sample to see results once water pressure is standard hose pressure.

**Disassembly Procedure**
- Disconnect the hose from the swivel on top of the drill stem to the accumulator stand.
- Disconnect the hose from the accumulator stand to the power washer.
- Disconnect the hose from the power washer to the water supply.
- Disconnect the 300 psi hose from the paint pot to valve 10.

**Cleaning Procedure**

The abrasive suspension has the potential to clog or corrode the hoses and tubing of the abrasive-waterjet drill. All of the hoses need to be cleaned and drained to prevent build up of any of the abrasive suspension residue left in the hoses. Fresh water should be run through the hoses to clean any of the remaining abrasive suspension. In addition, the paint pot should be cleaned with a brush and water.
Section 4
Testing

A Typical Test Run

Initial proof testing of the abrasive-waterjet drilling equipment and drilling tests (on different target materials) were conducted simultaneously. A typical test run is described as follows. The accumulator cart is placed on three load cells and the accumulators are charged with a garnet suspension, and an initial weight of the accumulator cart is recorded. Next, a sample is clamped to one or more cinder blocks. The sample is aligned with the cutting head, which is lowered to within one or two inches of the sample. The abrasive-waterjet drill seems to drill better with an inch or two of clearance rather than being set directly on the sample. With the drill rod rotating, the water is turned on, the pump is started, and the garnet feed and displacement valves are opened. When the garnet reaches the sample and rapid cutting starts, there is a clear change in sound and the abrasive can be seen in the water splashing on to the shields. Timing of a drilling run begins when the abrasive reaches a sample. Sometimes the drill rod is allowed to auto feed at a rate of about one inch per minute, and other times it is hand-cranked into the sample. Figure 4-1 shows a typical test, drilling a number 10 rebar sample with a 1/4-inch drill rod.

Figure 4-1: No. 10 rebar sample being drilled with ¼” drill rod
After sufficient cutting depth is achieved, the garnet flow is turned off, the time is recorded, and the pump and the water supply are turned off. The final cart weight is recorded and used to calculate the feed rate of garnet during the test. Finally the sample is inspected for hole depth (recorded as data), diameter variation, weight of material removed, materials penetrated (rebar, cement, aggregate, etc.), and any unusual features.

**Drill Rods and Tips**

A variety of different drill rods and tips were developed and tested during this research. They are divided into three diameters (1/2, 1/4, and 1/8-inch) and three tip orientations (centered, angled, and offset), as shown in Figure 4-2.

Two 1/2-inch stainless steel rods with 1/32-inch inside diameter (i.d.) tungsten carbide tips were tested. In one of the rods, the tip was set at a five degree angle while the other rod had a centered and straight tip. The 1/2-inch rod with the angled tip drilled quite effectively but made a large hole (ranging from 3/4-inches to 2-inches) with a very rough wall, as shown in Figure 4-3.

Two 1/4-inch stainless steel rods were also tested: 1) with a straight tungsten carbide tip, and 2) with a straight offset tip (0.030 inch Tungsten-Carbide Nozzle, Hunter Products Inc., P.O. Box 6795792, Partridge Dr., Bridgewater, NJ 08807-1802 USA, 800-524-0692 ). All of the 1/4 -inch rods drilled straight in gauge holes. The offset tip drilled to a depth of 36 inches. A 1/8-inch rod with a straight tip (0.030 inch Tungsten-Carbide Nozzle, Hunter Products Inc., P.O. Box 6795792, Partridge Dr., Bridgewater, NJ 08807-1802 USA, 800-524-0692) was also fabricated but not tested due to its tendency to bend easily.
Garnet Suspension

The most efficient garnet suspension was developed by an iterative process. The goal was to develop a mix to hold the abrasive in suspension for weeks or even months while maintaining the ability to flow. The abrasive suspension mixture was a combination of tap water, SUPERWATER®, and garnet. Several different mixtures were tested in ranges of 50-200 grams (g) of S-W®, five-ten liters of water, and 10-30 pounds of garnet.

Table 4-1 shows the final mix design. It contained ten kilograms (kg) of garnet powder (Barton 80 hpx, www.barton.com, Barton Mines Company, 1557 State Route 9, Lake George, NY 12845, 800 792-5462), five kg of water, and 100g of S-W® (Berkeley Chemical Research, Inc., P.O. Box 9264, Berkeley, CA 94709-0264, 510 526-6272). By percent weight the suspension consisted of 0.66 percent S-W®, 66.22 percent garnet with a specific gravity of about 4.2 and 33.11 percent water. The net specific gravity of the suspension was 2.02, and the liquid fraction of S-W® was 2 percent. The mixture had good flow characteristics, and an undisturbed sample showed little or no tendency for the garnet to settle out even when held still for over a month. Mixing was done with a drill press running at 200 revolutions per minute (rpm). The mix was placed in a five gallon pail and stirred with a paint stirrer having blade dimensions of 4.5 by 8 inches. The mixing blade is shown in Figure 4-4.

Table 4-1: Abrasive-waterjet mix design

<table>
<thead>
<tr>
<th>Water (lb)</th>
<th>SUPERWATER® (g)</th>
<th>Garnet (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>100</td>
<td>10</td>
</tr>
</tbody>
</table>
In abrasive-waterjet drilling, the energy of the high-pressure water is converted to kinetic energy of the abrasive particles. The abrasive used in this research was a crushed garnet with sharp angular particles, a particle size range of 125-355 microns, and hardness between 6.5 and 7.5. The S-W® used allowed easy displacement of the garnet abrasive. In addition, it improved drilling. S-W® is marketed as an additive for waterjetting to reduce friction and reduce jet dispersion. It produces a much more focused jet and has been shown to increase cutting and cleaning by up to 30 times (Howells, 1999). The recommended dosage is 0.2 to 0.3 wt percent. The dosage used for this research was approximately 0.1 wt percent.

Problems

Several problems were encountered during the current research. Many of the problems were solved during this project with adjustments to the equipment and testing procedures. It is anticipated that remaining problems (that did not interfere with the present research goal) will be solved in future projects.

Pump Surging

As with all experimental devices, some problems were experienced. If the lower chamber of the accumulator was not purged of air, the abrasive-waterjet drill would surge between 4,000 and 5,000 psi with inconsistent delivery of fluid. Replumbing the accumulator cart such that the accumulators were not allowed to drain during charging eliminated this problem. Surging between 3,000 and 4,000 psi was also experienced when a tip having a 0.030-inch i.d. was used. The orifice of the nozzle was slightly blocked, reducing the flow rate and causing the pump to drop into automatic recycle mode. Drilling out the tip to allow adequate flow solved this problem. The problem could also have been solved by reducing the setting on the pump bypass valve and running at a somewhat lower pressure.
**Water Rate**

Water rates were measured by placing a partially-filled and weighed trashcan under the jet. The trashcan was covered to prevent splashing. The pump was turned-on and the flow was accumulated in the trashcan for a timed period. After turning-off the jet the trashcan was reweighed to get the total flow during the timed period. This technique was crude and cumbersome, but reasonably accurate as verified by checking expected flows based on orifice size and pressure. This technique did not account for fluctuations in the flow rate during the tests, nor for changes that occurred when the garnet suspension was added to the water flow. To solve this problem, high-pressure flow meters are needed.

**Garnet Feed Rate Measurement and Control**

The current abrasive-waterjet drill runs and drills effectively, but lacks direct control over the garnet injection rate. This is a major drawback as the garnet rate is an extremely important parameter in determining the penetration rate. The Garnet suspension is fed by a small pressure difference between the top and bottom of the accumulators, approximately 20 psi. At present, the garnet consumption rate can only be calculated after a drilling run is completed by comparing the accumulator cart weight before and after a run. Unfortunately, the cart weighs about 700 lbs, and the changes in weight are usually only 20 lbs or less. The fractional weight change is small, and the weigh indicators do not display fractional pounds; therefore, all weights were recorded to only the nearest 1/2 pound using the load cells shown in Figure 4-5.

![Figure 4-5: Load cells used to measure weight of accumulator cart](image-url)
Drill Rod Bending

The small (1/4-inch and 1/8-inch) drill rods used in this research can be accidentally bent by a modest impact. As expected, a bent-rotating rod cuts a circle rather than drilling a round hole. This effect is ameliorated by holding the rod in a bushing while drilling and by the aligning effect of the borehole itself. It is anticipated that this problem will be eliminated by: 1) acquiring stiffer drill rods, and 2) developing a set of rollers for straightening the rods to assure straight drilling.

Deep Holes

At the time of this report the deepest hole drilled was 36 inches. Drill rods up to ten feet long have been fabricated and the abrasive waterjet drill is designed to effectively use these rods. However, for runs longer that ten feet, pipe joints or a coiled tubing system must be developed. Pipe joints may not be practical in such small pipe, but ¼-inch coiled tubing is used in deep applications (20,000 feet) in the petroleum industry. In order to use coils and unroll the coil into a hole as it is drilled, special fixtures are needed to handle a reel of tubing and roller-straightening equipment while rotating the pipe.
Section 5

Results

Introduction

This research focused on developing new abrasive-waterjet drilling equipment capable of drilling a small diameter hole (less than 1/2-inch) to a depth of 36 inches. Testing investigated both equipment and the drillability of typical civil engineering materials. These investigations were run in parallel with equipment modifications, specifically testing different drilling rods, tips, and tip orientations, while at the same time drilling different target materials. A synopsis of all the tests is presented in Table 5-1.

Table 5-1: Compendium of test results

<table>
<thead>
<tr>
<th>Date</th>
<th>Sample 1</th>
<th>Rod:tip (in)</th>
<th>Water (gpm)</th>
<th>Garnet (lb/min)</th>
<th>Duration (min)</th>
<th>rpm</th>
<th>Depth (in)</th>
<th>Hole Dia. (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/09/02</td>
<td>Brick</td>
<td>1/2:1/32</td>
<td>Small hole, water only, testing equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08/12/02</td>
<td>CMU</td>
<td>1/2:1/32</td>
<td>Small hole, water only, testing equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08/12/02</td>
<td>HSRC</td>
<td>1/2:1/32</td>
<td>Oversize hole, angled tip, testing equipment with garnet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08/12/02</td>
<td>Wood</td>
<td>1/2:1/32</td>
<td>Oversize hole, angled tip, testing equipment with garnet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08/20/02</td>
<td>CMU²</td>
<td>1/4:1/32</td>
<td>1.8</td>
<td>3.1</td>
<td>5.9</td>
<td>60</td>
<td>4.4</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>08/30/02</td>
<td>CMU³</td>
<td>1/4:1/32</td>
<td>2.7</td>
<td>1.1</td>
<td>7.7</td>
<td>60</td>
<td>16.0</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>08/30/02</td>
<td>HSRC</td>
<td>1/4:1/32</td>
<td>2.7</td>
<td>1.6</td>
<td>3.8</td>
<td>120</td>
<td>5.6</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>08/30/02</td>
<td>HSRC</td>
<td>1/4:1/32</td>
<td>2.7</td>
<td>1.0</td>
<td>4.1</td>
<td>60</td>
<td>4.4</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>08/30/02</td>
<td>RQ⁵</td>
<td>1/4:1/32</td>
<td>2.7</td>
<td>1.7</td>
<td>3.9</td>
<td>60</td>
<td>&lt; 0.25</td>
<td></td>
</tr>
<tr>
<td>09/05/02</td>
<td>PS</td>
<td>1/4:1/32</td>
<td>Demonstration only, no data</td>
<td>6 0.375</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>09/20/02</td>
<td>#10 rebar</td>
<td>1/4:1/32</td>
<td>2.7</td>
<td>7.9</td>
<td>0.7</td>
<td>1.3</td>
<td>&lt; 0.5</td>
<td></td>
</tr>
<tr>
<td>09/20/02</td>
<td>#10 rebar</td>
<td>1/4:1/32</td>
<td>2.7</td>
<td>4.2</td>
<td>8.5</td>
<td>&lt; 0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>09/20/02</td>
<td>3/4 Glass</td>
<td>1/4:1/32</td>
<td>2.7</td>
<td>0.1</td>
<td>0.8</td>
<td>&lt; 0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10/01/02</td>
<td>RQ</td>
<td>1/4:1/32</td>
<td>8</td>
<td>60</td>
<td>36</td>
<td>&lt; 0.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 CMU – Concrete Masonry Unit, HSRC High-Strength Reinforced concrete, RQ reinforced quickcrete, PS Pottsville Sandstone
2 A steel nozzle was used for this test, and the inside diameter of the nozzle washed-out from 1/32 to about 1/16-inch during the test. The water rate was measured from the original tip diameter.
3 The drill rod penetrated the block about 10 inches.
4 Drilled through a steel reinforcing cable at the surface, but the hole was too small to pass the drill rod.
5 Drilled through rebar, but the hole was too small to pass the drill rod.
Sample Materials

Eight different materials were drilled during this research project. The materials drilled and results are as follows:

**Red Brick**

A red brick was drilled while the equipment was being proof tested and operating procedures were being developed (Figure 5-1). A small hole was cut using pure water with a straight-centered nozzle on a 1/2-inch drill rod. The hole was cut in about one minute. The diameter of the hole was too small to allow the 1/2-inch rod to penetrate.

![Figure 5-1: First sample drilled, using pure water](image)

**Concrete Masonry Unit**

While becoming accustomed to the abrasive-waterjet drilling equipment, numerous runs were made on concrete masonry units (CMUs), commonly called cinderblocks (Figure 5-2). Cinder blocks are easy to manage and align and cut very rapidly with pure water or water-abrasive mixtures. The abrasive-waterjet drilled 16 inches through a CMU in seven minutes. It was found that cutting occurred up to seven inches in front of the tip. In Figure 5-3, a 14 inch welding rod is shown inserted into a hole drilled in a CMU.
Reinforced Quickcrete

(Figure 5-3) Several reinforced quickrete (RQ) samples were made to from a pile-like material. Samples were eight inches in diameter with lengths between 1 and 3 feet. Although these samples allowed long drilling runs, samples were improperly compacted and full of voids. The quickcrete samples did, firmly hold the reinforcing steel, which demonstrated that the abrasive waterjet drill would rapidly cut through rebar.
**High-Strength Reinforced Concrete**

The high strength reinforced concrete (HSRC) samples were sections of spun-formed light poles (Figure 5-4). The tested compressive strength was 11,000 psi. As can be seen from the photos, the samples had a dense aggregate packing and steel reinforcing cables. The abrasive-waterjet drill penetrated these samples rapidly and effectively.

![Figure 5-4: High-strength reinforced concrete sample drilled with ½” rod](image)

**Steel Rebar**

Numerous holes were drilled through steel rebar and cables (Figure 5-5). Penetration rates were quite rapid (1.27 inches in 40 sec in one case) and because the tip never touched the target material, there was no tendency for the drill to walk or skip off the steel rebar. While penetration of rebar is not a problem, creating a hole with a large enough diameter for the drill rod to pass through is a problem. Other researchers have solved this problem by using an angled tip, unfortunately there is not enough room in the 1/4-inch rod to angle the tip. Still others have used a tungsten carbide tip with two orifices – one straight and one slightly angled. Such an arrangement would probably work quite well, but such tips are not commercially available in a small size, and custom made tips are cost prohibitive. Another solution might be to use an “offset” tip where the nozzle is not in the center of the pipe. Such a tip was fabricated, and could be used to cut a full-sized hole through rebar if the standoff distance was about 1-2 inches.
Finally, an ultra-small 1/8-inch diameter rod was fabricated. It is expected that the 1/8-inch rod and tip will drill a large enough hole to have sufficient clearance for the small diameter rod to pass through, but it was not tested because it bent so easily.

![Figure 5-5: Number 10 rebar sample drilled in 40 seconds](image)

**Pottsville Sandstone**

A Pottsville Sandstone (PS) core, taken from a local coal mining operation, was drilled as a demonstration for the annual meeting of the Alabama Mining Institute sponsored by the University of Alabama Civil Engineering Department (Figure 5-6). The sandstone sample was relatively homogenous when compared to other samples drilled. Because of that, the drilled hole was particularly small and consistent. The hole stayed within gage at about 3/8-inch for the full sample length of 7 inches.

![Figure 5-6: Pottsville Sandstone sample](image)
Creosote Treated Wood Pole

Since some bridge pilings are wood, the abrasive-waterjet drill was tested on a wood pole (Figure 5-7). The drill cut the wood pool rapidly, but produced long-stringy chips that were hard to clean from the hole.

Figure 5-7: Creosote treated wood pole sample drilled with ½” drill rod

3/4-Inch Glass Plate

A local manufacturer of architectural glass doors, walls, etc., provided samples so that the abrasive-waterjet drill could be tested on glass (Figure 5-8). With 5,000 psi pure water some penetration was achieved, but the glass cracked. Using abrasive, a hole was cut through the glass almost instantaneously (about 3 sec), but once again cracked the glass. Apparently cracking is a common problem when cutting glass. Additional attempts to drill glass will be made in the future at lower pressures.
For all tests the pump was running at the normal operating pressure of 5,000 psi. Under these conditions the flow rate is controlled largely by the nozzle diameter. Equation 5.1 shows a simple Bernoulli’s Law calculation modified for friction loss, which can be used to estimate the flow rate if the nozzle diameter is known. This method becomes unreliable as the nozzle diameter increases due to wear.

\[ Q = A \cdot C \left( \frac{2g \Delta P}{\gamma} \right)^{1/2} \]  

(5.1)

Where:

- \( Q \) = the fluid flow rate,
- \( A \) = the nozzle area,
- \( C \) = the friction coefficient,
- \( g \) = the acceleration of gravity, and
- \( \gamma \) = the specific weight of the fluid.
Flow range was also calculated by weighing total fluid pumped during a timed period of flow. This calculation matched well with the Bernoulli’s Law estimates. Flow rates varied between 1.7 and 2.8 gpm as measured by the foregoing methods, and the results are tabulated in Table 5-1. These reported rates are for pure water, and were not measured with garnet in the flow. It is likely that the total flow rate decreases when garnet is added since the net fluid density increases.

**Abrasive Consumption**

To calculate the abrasive suspension consumption, the accumulator cart was weighed before and after drilling. The suspension is injected by displacement with water, so the amount of garnet consumed is calculated as:

\[ W_g = \Delta W f_g S_s / (S_s-1) \]  

Where:
- \( W_g \) = the weight of garnet consumed,
- \( S_s \) = the specific gravity of the suspension = 2.02,
- \( f_g \) = the weight fraction of garnet in the suspension = 0.6622, and
- \( \Delta W \) = the change in weight of the accumulator cart during drilling.

In a like manner, the weight of S-W® can be calculated as:

\[ W_{sw} = \Delta W f_{sw} S_s / (S_s-1) \]  

Where:
- \( f_{sw} \) = the weight fraction of garnet in the suspension = 0.0066 and
- \( W_{sw} \) = the weight of SUPER-WATER® consumed.

The weight and weight change, \( \Delta W \), of the accumulator cart is the sum of three weights measured by three load cells. Because each load cell has an error of plus or minus 1/2 lb, the net error is less than plus or minus 1.5 lbs. An additional error in the accumulator cart weight might have occurred due to the poorly calibrated load cells.

The actual consumptions of garnet are tabulated in Table 5-1. A modification was made to the equipment to allow for additional control of the garnet flow. This modification created a restriction on the water leg of the plumbing, which resulted in a larger pressure drop through the accumulator and a substantial increase in garnet feed rate. The garnet flow rate before the modification ranged from 1.1 to 4.2 lbs/min. After the modification the flow rate was 7.9 lbs/min as shown in row 11 of Table 5.1.

**Hole Size**

The target hole size for this research project was a 36-inch long hole in concrete having a diameter of 1/2-inch. It is expected that such a small diameter will have a negligible effect on a pile’s strength. Drilling with 1/2-inch drill rods, holes were produced with substantially larger
than 1/2-inch diameters, but with 1/4-inch drilling rods, holes were consistently produced with diameters between 3/8 to 1/2-inch. The holes from the 1/4-inch rods also stayed relatively in-gage with variations in diameter of about 1/8-inch or less along the length of the hole.

**Cutting Rate**

At present, no reliable measurements of the rate of material removal have been made. Most samples were too large with respect to the hole size to measure a reliable weight change caused by drilling. Furthermore, most samples were too porous to allow measurement of the volume removed by measuring liquid displacement before and after drilling. Therefore, only the hole depth and average diameter were compiled and reported in Table 5-1.
Section 6
Discussion and Conclusions

Abrasive waterjet systems cut when the abrasive is accelerated above a critical velocity and the abrasive particles begin to chip out pieces of the target material upon collision. The higher the velocity, the more effective the cutting becomes. Most abrasive-waterjet systems use an external feed of abrasive. A separate feed of dry abrasive is incorporated into the liquid jet immediately downstream of the nozzle. The advantage of this system is that the mixing occurs at atmospheric pressure. The main drawbacks of this technology are 1) the requirement for separate liquid and particle streams results in an overly large cutting head, and 2) external mixing of water and abrasive is inefficient at accelerating the abrasive particles. Swanson et al. (1987) have shown that external feeds produce an abrasive velocity of only about 25 percent of the water velocity, so external feed systems require very high water pressures to achieve effective cutting.

The target hole diameter of 1/2-inch for this research was too small to allow an external abrasive feed in a deep hole. In addition, the system had to be low-pressure to be economical. The abrasive-waterjet drill designed in this research introduces a polymer-abrasive mix on the high-pressure side of the nozzle downstream of the pump. The system uses an off-the-shelf pressure washer to supply only 5,000 psi. This arrangement results in efficient momentum transfer between the water and the abrasive particles, which allows for drilling that would otherwise require 30,000 to 40,000 psi units.

In addition to the abrasive-waterjet equipment, special drilling rods and tips, between 1/2-inch and 1/8-inch in diameter, were developed. These rods are between four and ten feet long and are apparently the smallest diameter currently in use for geological and geotechnical applications. Holes as small as 3/8-inch in diameter, and as long as three feet, were drilled with these rods. An unexpected benefit of these small diameter long rods is that deep cuts can be made by moving the head back and forth while lowering the rod into the cut. This abrasive-waterjet drilling system rapidly drills long, small diameter holes through concrete, hard aggregate, and steel rebar, which meets the objectives proposed for this project.
Section 7

References


Section 8
Companies Providing Waterjet Components

Carbide Nozzle Tips, Hunter Products Inc, PO Box 6795792, Partridge Dr., Bridgewater, NJ 08807-1802 USA, 800-524-0692

Engineered Sales, 18 Progress Parkway, Maryland Heights, MO 63043, 314-878-4500

Garnet- Barton 80 hpx, www.barton.com, Barton Mines Company, 1557 State Route 9, Lake George, NY 12845, 800 792-5462

Grainger, www.grainger.com, 185 West Oximoor Road, Birmingham, AL 35209, 205-942-6741

Grizzly, P.O. Box 2069 Bellington, WA 98227, 570-546-9663

Stoneage, P.O. Box 2907, Durango, CO 81302-2907 USA

SUPER-WATER®, Berkeley Chemical Research, Inc., P.O. Box 9264, Berkeley, CA 94709-0264, 510 526-6272

Swagelok, Alabama Fluids System Technology, 237 Cahaba Valley Parkway, Pelham, AL 35124, 205-988-4812

Tool Specialties, P.O. Box 1628, Pelham, AL 35124, 205-933-9292