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Paper

DRILLING AND SLOTTING OF HARD ROCK WITH ABRASIVE SUSPENSION WATER JET

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ABSTRACT

In densely populated area such as downtown Seoul, the removal of hard rocks for the building or structural foundation requires an extra effort due to complaint from the residents and the owners of neighboring buildings. The conventional methods, such as hydraulic breaker, drill & blast, diamond saw cutting instantly raise the complaint level and usually result in delayed construction schedule. The abrasive suspension water jet system has been developed for the hard-rock drilling, slotting, and notching operations in an attempt to replace the conventional methods. Various types of nozzle heads and manipulators had been designed and field tested in construction sites. Different types of manipulators are covered in this paper with some of the basic working parameters.

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1. INTRODUCTION

The impact based conventional rock fragmenting with hydraulic breaker, not to mention, drilling & blasting has become a major source of complaints on the construction sites in downtown area, often resulting in a delayed construction. Other techniques with less noise and vibration, therefore, are sought after by engineers in downtown rather urgently. Abrasive suspension water jet technique is regarded as a promising alternative for quiet drilling and cutting method in a very sensitive job sites in the heart of city of Seoul.

A building construction method called 'TOP-DOWN' is getting more popular in downtown area for larger size of building construction. This method starts with a ground floor slab and the structural beams are placed in the large diameter drilled holes, first to reach to foundation rock mass, followed by under-digging of the ground. The above ground structures are built on top of these underground beams, thus allowing the jobs to advance in both TOP direction and DOWN direction. As the ground level floor slab is placed first, the sound of excavation in underground is effectively blocked from the initial stage of the construction.

This, however, cannot block the impact-generated shock or vibration thru the rocks. The control of the excavation boundary facing the neighboring underground structure becomes more difficult as the operating space for a machine is limited by the upper-level slabs and related structures. When unexpected hard rock appears on the corner, the drilling machine and hydraulic breaker are left with minimal angle to attack the corner rock. As the drilling machine and hydraulic breaker requires thrusting force to be effective in drilling or breaking, the corner rock allows only one side to be dealt with. A method that may allow us different angles to deal with this corner is of many field engineers' interest.

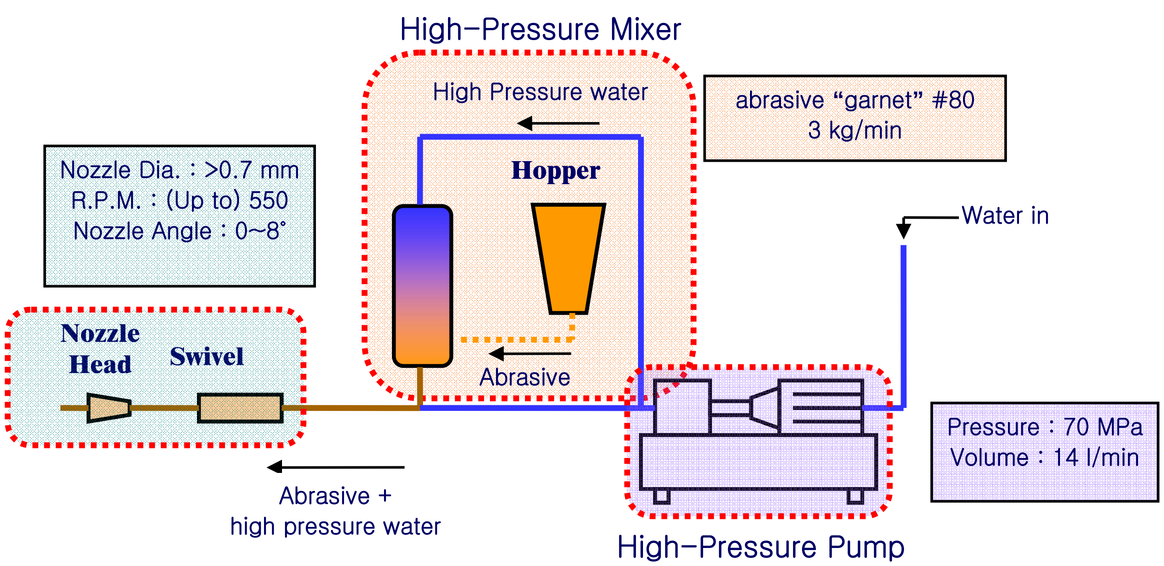


Figure 1. Abrasive suspension drilling/slotting system

2. ABRASIVE SUSPENSION WATER JET SYSTEM

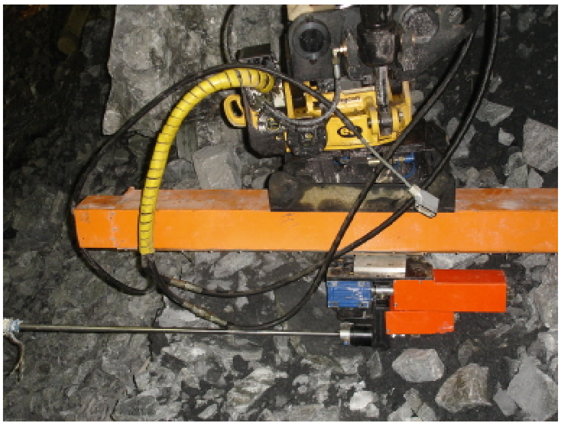
The abrasive suspension water jet cutting system has been known for many years and the name 'Diajet' is commonly used in many papers to describe the pre-mixed abrasive water jet system. This system requires both high-pressure pump and high-pressure mixer for the creation of abrasive-mixed high pressure water jet stream. A motion system with a rotary coupling is also required for this research of drilling and slotting. A series of nozzle heads were designed and tried to find out effective range of design parameter ranges. In most of the required operations, upto 4 degrees-of-freedom were required to move the nozzle head in adequate sequence.

2.1 Abrasive Suspension System

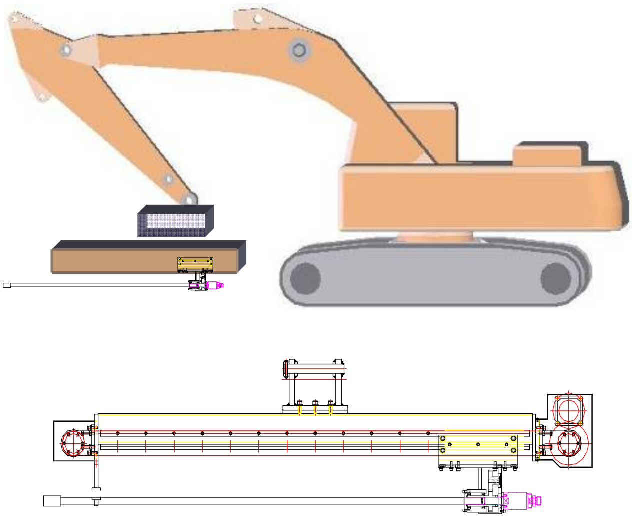
The abrasive suspension system used for this research comprises of triplex plunger pump and high pressure in-line mixer with a flow rate of 14 liter/min at 70 MPa and an abrasive consumption rate of 3kg/min of garnet #80. A single-batch mixer was built for the test purpose and lasted approximately 6 minutes before running out of garnet. (Figure 1)

2.2 Motion System

While only 1 DOF of traversing motion is required for the kerfing tests, 2 DOF of a rotation and a feeding are required for drilling. By combining these motions, linear slotting movement could be realized. A swing (pendulum) type motion brought in an extra DOF. The rotation of the nozzle head was mounted on top of the X-Y planar motion structures with an extra swing motion placed under the nozzle-head-rotating motor.



a) Connected with Tiltrotator® with 1 more DOF



b) Design with Rotation and Feed

Figure 2. Water Jet Drilling System with Rotation and Feeding equipped on Excavator

This 4-DOF system was mounted on different types of equipment. An excavator with Tiltrotator® was used to drill in hard rock. Forklift setting was very convenient for either linear slotting or swing slotting. The tilting and elevating of the forks allowed 2 more DOFs. Tripods were brought in where alignment with pre-drilled holes was required due to the difficulty of fine-tuning the heavy hydraulic system to maintain static position. The leak at the worn-out hydraulic valves resulted in poor position holding for its heavy arms and attachment for the required operating period, usually more than 5 minutes.

3. DRILLING PARAMETERS TEST

3.1 Known Parameters

The cutting tests were conducted on obsidian, granite and concrete. Concrete was found to be difficult material to drill due to its inhomogeneous nature of material constitution. The pressure of the flow, flow rate, abrasive mix rate, abrasive material, abrasive size and roundness are the parameters coming from the system. The RPM of the nozzle head, drill feed rate and the angle of the drilling (vertical to horizontal) come from the motion of drill head. Most of the times, the common sense approach worked well and the test result showed good coincidence as expected.

The parameters coming from the nozzle head, on the other hand, were quite possibly the most challenging ones to figure out when mingled with different material selection. The number of orifices, the positions, diameters and angles of orifices seemed dependent on the power of the system and the targeted drill hole diameter. As the drill-feed rate was increased to find out maximum drilling rate, the design of the drill head with consideration of draining resulted in better drilling rate compared to ordinary circular design. As the required hole diameter got bigger, the drilling with big nozzle head with 3 orifices showed poor result compared to double drilling with 2 different diameter nozzle heads.

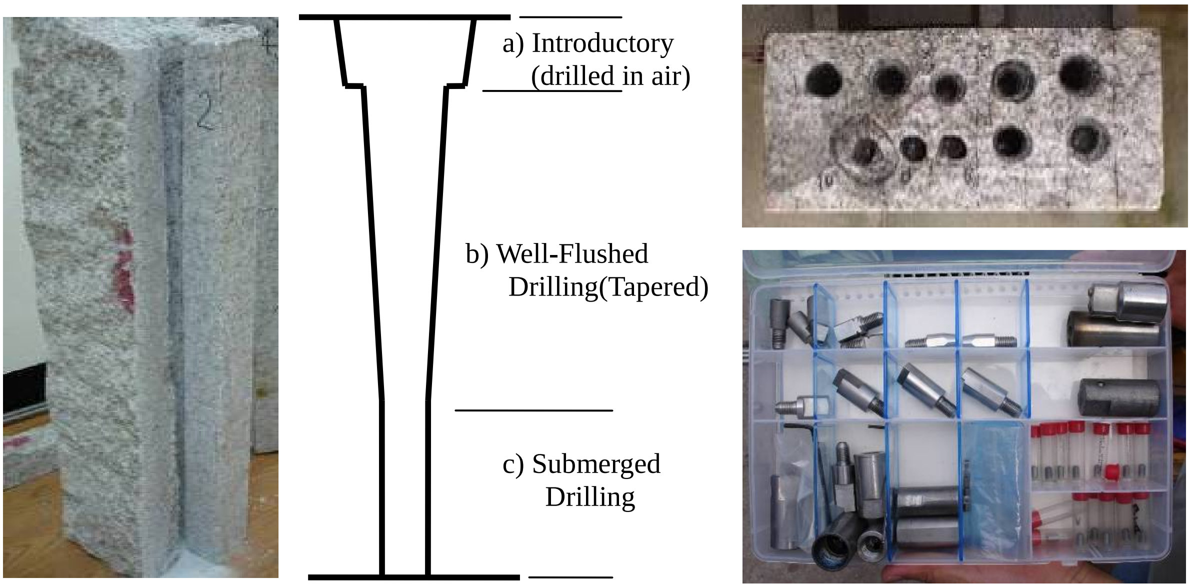
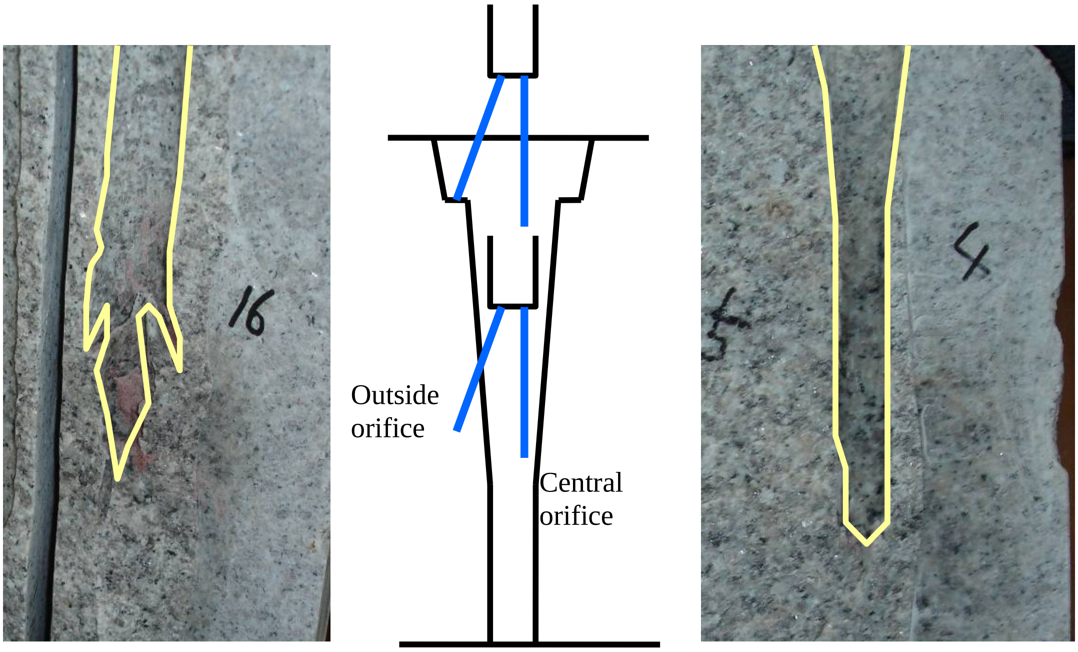


Figure 3 Cross-Sectional View of Drilled Holes and Various Nozzle Heads



a) Outside stream branching out
-Nozzle head bounces at ridge

b) Outside stream forced inward
- Hole diameter decreases

Figure 4 Cross-Sectional Views of Failed Drill Holes drilled with 2-orifice nozzle head

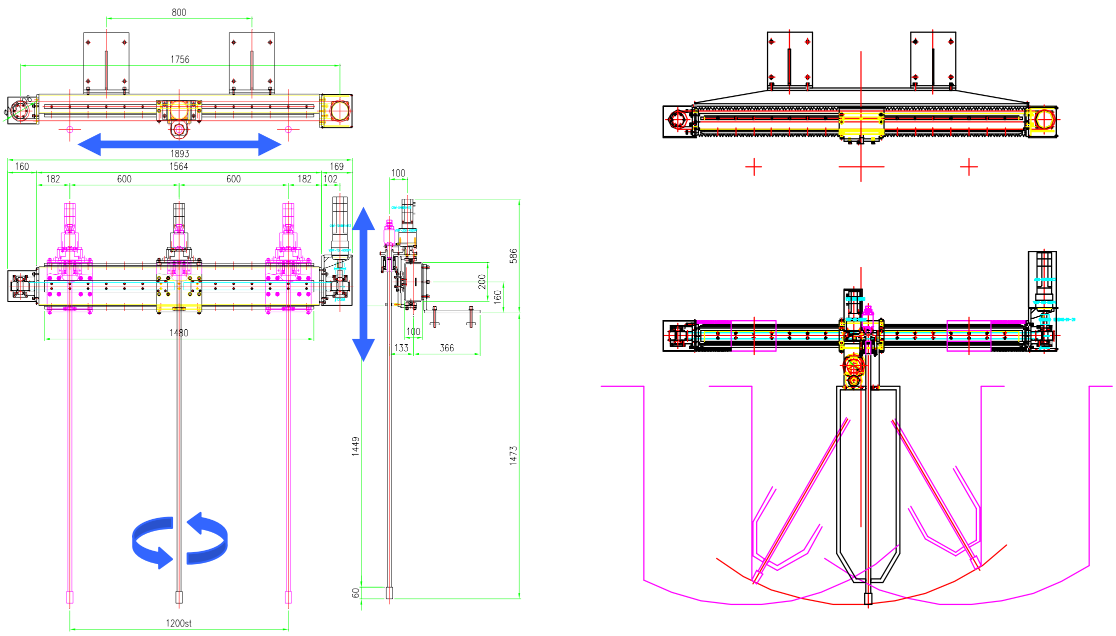
3.2 Drilling in Air and Submerged

Considering the individual jet power on each orifice and the hole diameter of less than 30mm, the 2-orifice type nozzle head seemed better choice over 1 or 3-orifice type heads. Figure 3 shows a typical hole cross-sectional view while drilled vertically. On the top of the rock block, a larger hole was drilled as the drilling nozzle heads starts spinning with a minimum standoff distance of 8~10cm from the top of the test rock and the water splashes in all direction. As the drill head advances, the water stream bounces only upward direction as the pre-drilled hole works as a guide tube for the water stream. The diameter of the hole decreases as the line of transportation of the water stream to escape from the bottom of the drilled hole to outside with debris and abrasives. The diameter soon reaches equilibrium as no stream of water shoots back upward and the drilling is carried under submerged condition.

3.3 Failure Modes in Drilling

As for the 2-orifice type nozzle head drilling, the orifice on the inner side removes the bottom rock of the hole and the orifice on the outer side shapes the hole wall to a certain diameter. It seemed that the position of the inner orifice, too wide angle of the outer orifice, slow feeding and irregularity of the rock could result in a ridge developed along the annulus in between inner and outer orifices, thus resulting in nozzle head bumping into the bottom of the hole not advancing.

A narrow angle on outer orifice and fast feeding rate, on the other hand, resulted in decreasing hole diameter, eventually ending up with stuck nozzle head.



a) Linear Slotting Design

b) Swing Slotting Design

Figure 5. Two Designs of Slotting Heads

4. SLOTTING SYSTEMS

4.1 Linear Slotting System

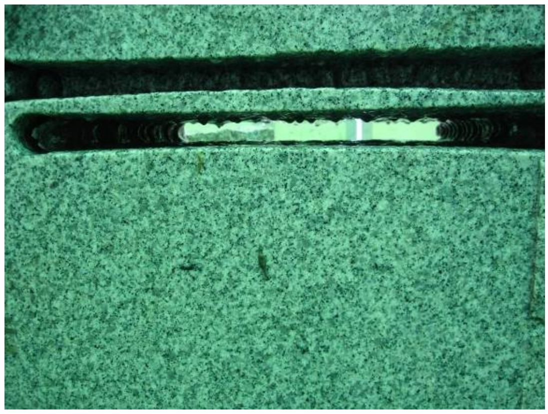
The drilling rod with slotting nozzle head was first built with traversing mechanism controlling the position of the rotating nozzle head. This system was mounted on a forklift and the test slotting was carried with concrete blocks. The forks of the forklift were raised to a required height over the rock specimen, and the system was lowered after each pass of cutting. As the slot depth increased and the more length of the nozzle head block had to be operated in between the cut wall of the slots, the following 2 parameters played major roles to increase the slot depth and maintain the slot width wider than the diameter of the nozzle head.

The first parameter was tilting fork lift as the whole setup weighed more that 150kg. As with the hydraulic valve of the excavator in drilling, the leak of the system pushed the setup to tilt to one side. Considering the longer operation period easily reaching up to an hour, maintaining the position became a major issue. A heavy nozzle head block also shook up the whole system as they went back and forth, stopping and starting abruptly.

The second problem came in from a small irregularity left on the sides of the slot walls. The streams from the nozzle head attack the wall side from the fixed angle only. Once the part of the wall was not removed, the lower side of that point could not be cut up to the desired slot width and frequently resulted in ever-increasing wave on a side wall.

a) Vertical Linear Slotting Setup b) Horizontal Swing Slotting Setup

Figure 6. Two designs of Slotting Head Setups



a) Linear Slotting Side and Top View
with different traverse speed

b) Swing Slotting Plane Cutting Front View
top - after 2 swings, bottom – 70cm deep

Figue 7. Slotting Tests with Linear and Swing Slotting on Granite

4.2 Swing Slotting System

By introducing the concept of swing or pendulum type motion on the slotting system, the maintaining of system position got easier as the swinging rod was the only moving part. Furthermore, as the system moved into the slot, the nozzle attack angle changed and overlapping cut with different angles resulted in greatly increased wall finish quality in swing slotting system.

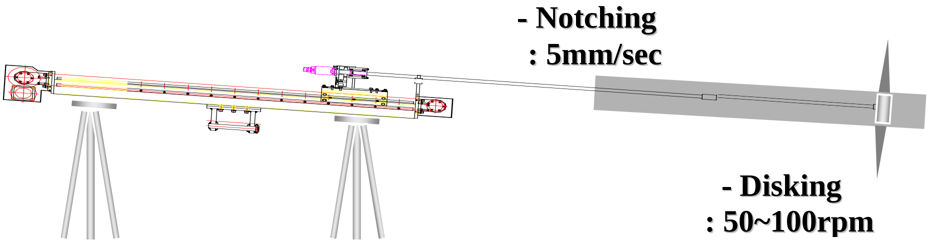


Figure 8. Notching and Disking in Pre-Drilled Hole

5. NOTCHING AND DISKING

5.1 Working with Hydraulic Rock Splitter

One of the silent methods to fragment the rock is by using hydraulic rock splitter. Drill holes with diameter of 70~200mm should be drilled with drilling machine or cored with diamond coring machine. The hydraulic rock splitters with different diameters are then placed inside the prepared holes. In favorable condition, the hydraulic power pushes the rock on top of the hole, resulting in the crater shaped rock removed from its place. Even more favorable cases with certain geological conditions end up splitting a big chunk of hard rock.

In unfavorable situations, however, the application of hydraulic power to the splitter brings no response from rock mass. This happens frequently when no visible geological structures could be observed. Making notches along the wall of pre-drilled holes could help initiate the crack-developing in hard rock due to the stress concentration at the tip of the notch.

5.2 Notching and Disking Head

Same nozzle could be used for notching and disking. For notching purpose, the nozzle head was pushed into the drilled holes with 2 orifices cutting notches on both sides of the head. Cut materials along with abrasives were drained backward naturally following the notch paths. The nozzle head was then fixed in depth and rotated to cut a dish-shaped void inside the rock.

Figure 9. a) Pulling out the nozzle head b) Tripod setup for feeding and rotation

The notch feeding rate worked in a similar way with traverse rate in linear kerfing, while notching depth matched with kerfing depth. The notching operation with the nozzle head starting from the bottom of the hole resulted in shaky operation due to the bouncing stream from the bottom hole. The proper draining was achieved with nozzle head advancing into the drilled hole.

The proper range of RPM and duration of disking are yet to be found to achieve maximum void radius in submerged condition. An improvement in design of nozzle head might help push out abrasives and cut rocks from the disking area and prevent secondary grinding of rocks.

As soon as the cracks were developed from the notches or disks, they helped the hydraulic splitter to push the rock blocks, until the developing cracks met the planes of discontinuity and started following the weak geological plane.

Figure 10. a) Notch made along the hole b) Measuring the notch depth

Figure 11. a) Disk made along the hole b) Measuring the disk depth

5. CONCLUSIONS

The abrasive suspension water jet system with water flow rate of 14 l/min at 70 MPa and an abrasive consumption rate of 3 kg/min were used for this research to replace the conventional drill & blast and hydraulic breaker. In both drilling and slotting operation, holding the position of the nozzle system assembly in the same spot could not be achieved in both forklift and excavator, regardless of system weight. Placing 2 tripods underneath proved to be an effective way of maintaining the position.

The analysis of failed drilling holes showed the parameters of the drilling head played important roles deciding the drilling patterns. The angle of the outer orifice should be chosen carefully to prevent branching and narrowing. The linear slotting setup resulted in magnifying the irregularities on slot walls and tilting of the system. A swing type slotting setup was designed and built and was shown with relatively fine surface finish.

The notching and disking were tested with the same nozzle head in pre-drilled holes. These cuttings were made to enhance the hydraulic rock splitter system operation. Although the geological conditions govern the crack-developing pattern, the notching and disking could help increase the productivity of non-impact excavation..

6. REFERENCE

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