Hydro-Cutter Rotation Effect

The characteristics of the robots used for hydro-demolition of the Reactor Building concrete are described in American Hydro Submittals (to SGT) 1 and 5, both dated 28 Aug 08.

The cutting head on each of the two robots consists of 2 nozzles mounted at opposite ends of a rotating supply pipe. The nozzles are 4.5 inches apart and rotate at a rate that is between 75 and 300 revolutions per minute. Nozzle pressure is 21,000 psi and water jet flow rate (each nozzle) is 75 gallons per minute. American Hydro (AHI) calculations show that jet thrust is 576 pounds force. Since the nozzles are located within just a few inches of the concrete surface, jet force acting on the concrete will be effectively the same as the thrust acting on the nozzles. Jet diameter reported by AHI is 0.157 inches. The thrust and jet diameter reported by AHI are close to the values independently derived for these parameters as shown below.

For a nozzle pressure and flow rate of p = 21,000 psi and f = 75 gpm, respectively:

Velocity, $v = \sqrt{(2\ g\ p\ /\ \gamma)}$

where g = acceleration of gravity = 32.2 ft / sec^2
p = pressure = 21,000 psi = 3.0×10^6 lb / ft^2
γ = unit weight of water ~ 62 lb / ft^3

and, $v = \sqrt{(2 \times 32.2 \times 3.0 \times 10^6 / 62)}$ = 1,765 ft / sec

Mass transfer rate, M = f x unit weight per gallon (8 lb / gal) / g

M = 75 x 8 / 32.2 = 18.6 slugs per minute = 0.31 slugs / second

Thrust, F = M x v = 1,765 x 0.31 = 547 lb ~ 576 lb per AHI calculation

(Thrust is rounded to nominal value of 600 lb in the subsequent computations and discussions)

For f = 75 gpm = 289 in^3 / sec and v= 1,765 ft / sec = 21,180 in / sec, area, A_j, of the jet at the vena contracta is:

$A_j = f / v$ = 289 / 21,180 = 0.0136 in^2

P/63

For a coefficient of discharge, $C_d = 0.6$, nozzle area, A_n, is:

$A_n = A_j / C_d = .0136 / 0.6 = 0.0227 \text{ in}^2$

Corresponding nozzle diameter, D_n, is:

$D_n = \sqrt{(4 A_n / \pi)} = \sqrt{(4 \times 0.0227 / \pi)} = 0.17$ inches

The above value computed for D_n is quite close to the 0.157 inch diameter value reported by AHI, who referred to this as the jet diameter but probably meant the diameter of the nozzle.

For a nozzle arm rotation rate of 75 to 300 RPM, every point under the nozzle arc will be subject to a nominal 600 pound load applied at a rate of 150 to 600 times per minute or at a rate of 2.5 to 10 Hz. This force would be sufficient to generate a large amplitude vibratory motion in any small concrete element having a natural frequency in the 2.5 to 10 Hz range. However, small elements of the concrete, such as pieces of coarse aggregate, have a fundamental natural frequency that is far above 10 Hz. A typical coarse aggregate stone, which has a modulus greater than the 4,000,000 psi specified for the concrete as a whole, has a longitudinal wave velocity, $v_w = \sqrt{(E / \rho)}$ where E is the elastic modulus and ρ is density.

For stone with a unit weight of 150 lb / ft^3, density is:

$\rho = 150 / 32.2 = 4.66 \text{ slugs} / ft^3$

For a modulus of 4,000,000 psi = 5.76×10^8 lb / ft^2:

$v_w = \sqrt{(5.76 \times 10^8 / 4.66)} \sim 11{,}000$ ft / sec

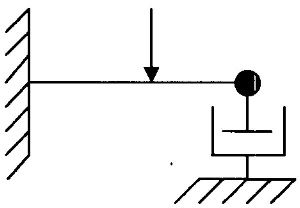
Travel time, t, for an impulse to pass from one face of a ¾ inch stone and reflect back to that face is:

$t = (\frac{3}{4} \times 2 / 12) / v_w = 1.14 \times 10^{-5}$ seconds

The corresponding fundamental natural frequency of the stone for longitudinal waves is $1 / t \sim 88{,}000$ Hz.

Since the fundamental natural frequencies of the individual concrete elements are so far above the greatest (10 Hz) excitation frequency, resonant response to the rotating water jets is not a concern.

Individual Reactor Building structural elements such wall panels between buttresses, have natural frequencies much closer to 10 Hz than to 88,000. While these frequencies could be computed, such a computation is not necessary since a wall panel has dimensions (about 86 ft x 60 ft x 3.5 ft) that are much greater than the 4.5 inch (0.4 ft) diameter of the water jet circle. Because of its size, the wall panel responds to the rotating water jet as it would to a constant point load of 1,200 pound (thrust of both jets on the rotating arm) applied at the center of the jet circle. This conclusion could be demonstrated by a complex finite element calculation. However, it can be qualitatively derived by an analogy that uses a quasi one dimensional (single degree of freedom) model as described below.



The above cantilever assembly consists of a zero mass beam element with a length, L, and a concentrated mass and a dashpot (providing positive, but less than critical, damping) at the free end. The arrow represents a constant downward force moving laterally back and forth from the mass to some point along the length of the beam.

If the force represented by the arrow moves from mass to the point of fixity and back in a time equal to the period of the cantilever assembly, it will excite large amplitude resonant vibrations at the mass end. If it moves from the mass to the mid-point (a distance of L / 2) and back in the same time, it will still excite significant amplitude vibrations. If it moves a distance of L / 4 and back, some level of vibratory motion would still be expected. However, as the distance moved continues to shorten (to L / 8, L / 16 and so on), it will reach a fraction of L at which the motion of the arrow will be imperceptible. At this point, the force can be treated as a fixed load that acts at the end of the beam. As such, it will not generate resonant vibrations in the assembly.

This analogy can be extended to a Reactor Building wall panel. If a 1,200 pound force traversed from the edge to the center of the panel and back in a time equal to the fundamental period of the panel, some level of vibratory response would be expected to result. However, as the distance of travel decreases, the level of response will, as in the example above, be expected to decrease. As the travel distance continues to decrease, it will reach a point at which the resulting vibratory response will be imperceptible.

Using the above discussion a guide, it is possible to intuitively conclude that a travel distance of 4.5 inches (0.4 ft) from the center of a 60 ft wide panel will generate no significant level of oscillatory response in the panel.

The above conclusion is also valid for the Reactor Building as a whole since overall building dimensions are significantly greater than those of a wall panel.

Therefore, in view of the above calculations and analogy, it appears reasonably clear that the rotating hydro-demolition jets will not result in meaningful oscillatory movement of the Reactor Building or its constituent structural elements.

Also, for major structural elements or the building as a whole, resonant responses of interest are generally due to bending. A single application of a force at point on a wall panel induces a bending deformation that results from the product of force and moment arm. If the force is applied and released, the wall panel will cycle in various modes (at various resonant frequencies) with amplitudes decaying due to internal damping. If the force is re-applied at a repetition rate equal to a resonant frequency of the panel, the amplitude of the cyclic motion will increase. The following sequence addresses this amplitude multiplication for a repetitive force applied at the free end of the cantilever beam shown above. A Reactor Building wall panel behaves in a similar, but more complex, manner.

- When the force is applied, the end of the beam deflects by an amount δ determined by the product of the force and the moment arm (L).
- When the force is suddenly released, the beam will oscillate at its natural frequency and, in one cycle, the end will return to a deflection of $k\,\delta$ where k is a factor less than one determined by the damping of the dashpot. At this point in the cycle there are neither external nor inertial forces acting on the beam.
- If the force is reapplied after one cycle, the bending moment generated by the force will increase the deflection of the beam end by an additional amount δ for a total deflection of $(1 + k)\,\delta$.
- After one more cycle, deflection will be $k\,(1+ k)\,\delta$.
- A third application of the force and corresponding moment at this point in time increases the deflection by an additional amount δ for a total deflection of $k\,(1 + k)\,\delta + \delta = (k^2 + k + 1)\,\delta$.
- Following multiple (n) applications of the force at the same periodic interval, the total deflection will be:

$$\text{Deflection} = (k^{n-1} + k^{n-2} + \ldots + k^2 + k + 1)\,\delta$$

As shown above, total deflection continues to increase with each application of the force but deflection is, in fact, determined by moment rather than force; if the force is applied at the fixed end of the beam, there is no resulting deflection at the free end. If the force is only moved through a small distance rather than being applied and released, the following happens.

- On initial application of the force, the free end of the beam still deflects by an amount δ.

- When the force is moved (assume instantly for this example) a small distance to the left, the end of the beam will oscillate but only through an amplitude determined by the difference between the deflection, δ, with the force at the end of the beam and the deflection, δ_1, resulting from the bending produced by the force and the slightly reduced moment arm.

- Deflection at the end of one cycle is $\delta_1 + k\,(\delta - \delta_1)$.

- Moving the force (again instantly) back to the end of the beam at the end of one cycle increases deflection by an amount, $\delta - \delta_1$, that is determined by the increase in moment arm and moment. Total deflection is then:

  $$\delta_1 + k\,(\delta - \delta_1) + (\delta - \delta_1)$$

- As developed above, the total deflection at the end of multiple (n) cycles of moving the point of force application is:

  $$\text{Deflection} = \delta_1 + (k^{n-1} + k^{n-2} + \ldots + k^2 + k + 1)\,(\delta - \delta_1)$$

In the above expression, δ_1 is the fixed displacement resulting from the bending moment due to positioning the force to the left of the end and,

$$(k^{n-1} + k^{n-2} + \ldots + k^2 + k + 1)\,(\delta - \delta_1) \qquad (1)$$

is the amplitude of the cyclic movements after n cycles of moving the force back and forth along the beam. For values of $k < 1$ (positive damping) and for large values of n,

$$k^{n-1} + k^{n-2} + \ldots + k^2 + k + 1 \sim 1 / (1 - k)$$

As in any damped vibration with a continuous forcing function, the amplitude has an asymptotic limit determined by the degree of damping. But, more significantly in the current example, the amplitude is also limited by the change in moment, which is determined by the distance through which the force moves along the length of the beam. If the movement is small relative to L, the factor $(\delta - \delta_1)$ in

Expression (1) will be small and the oscillatory amplitude through which the end of the beam moves will be limited to a correspondingly small value.

In the case of the rotating jets on the Reactor Building wall panel, relatively large amplitude vibrations could result if the jet force started and stopped at a frequency close to a natural frequency of the panel. This would be equivalent to moving the jet quickly from the center of the panel to the edge and the quickly back to the center at the same frequency. Moving the jet over the full half width of the panel (about 30 ft) maximizes the change in moment arm and results in maximum oscillatory amplitude. If the jet is moved through a distance of only 4.5 inches (~0.4 ft or about 1% of the panel half width) the change in moment arm and corresponding change in bending moment, as well as resulting oscillatory amplitude, will be small.

The following numerical example provides a conservative order of magnitude estimate of Reactor Building wall panel oscillation amplitude under a jet that rotates at the fundamental natural frequency of the panel.

The curved panel above the equipment opening is approximated as a 3.5 ft (d) 12 ft (b) wide beam spanning 60 ft (L) between buttresses, which are treated as simple supports.

Deflection, δ, under a 1,200 lb line load at the center of the beam is, for a modulus of 4,000,000 psi:

$$\delta = F\,L^3 / (48\,E\,I)$$

$$I = bd^3 / 12 = 12 \times 12 \times (3.5 \times 12)^3 / 12 = 889{,}000 \text{ in}^4$$

$$\delta = 1{,}200 \times (60 \times 12)^3 / (48 \times 4 \times 10^6 \times 889{,}000) = 2.6 \times 10^{-3} \text{ inches}$$

For a small shift, dL, in the position of the load, the change in deflection, $\delta - \delta_1$, will be approximately:

$$\delta - \delta_1 = [dL / (L / 2)]\,\delta$$

For a 0.4 ft shift in the position of the 1,200 lb force:

$$\delta - \delta_1 = (0.4 / 30) \times 2.6 \times 10^{-3} = 0.035 \times 10^{-3} \text{ inches}$$

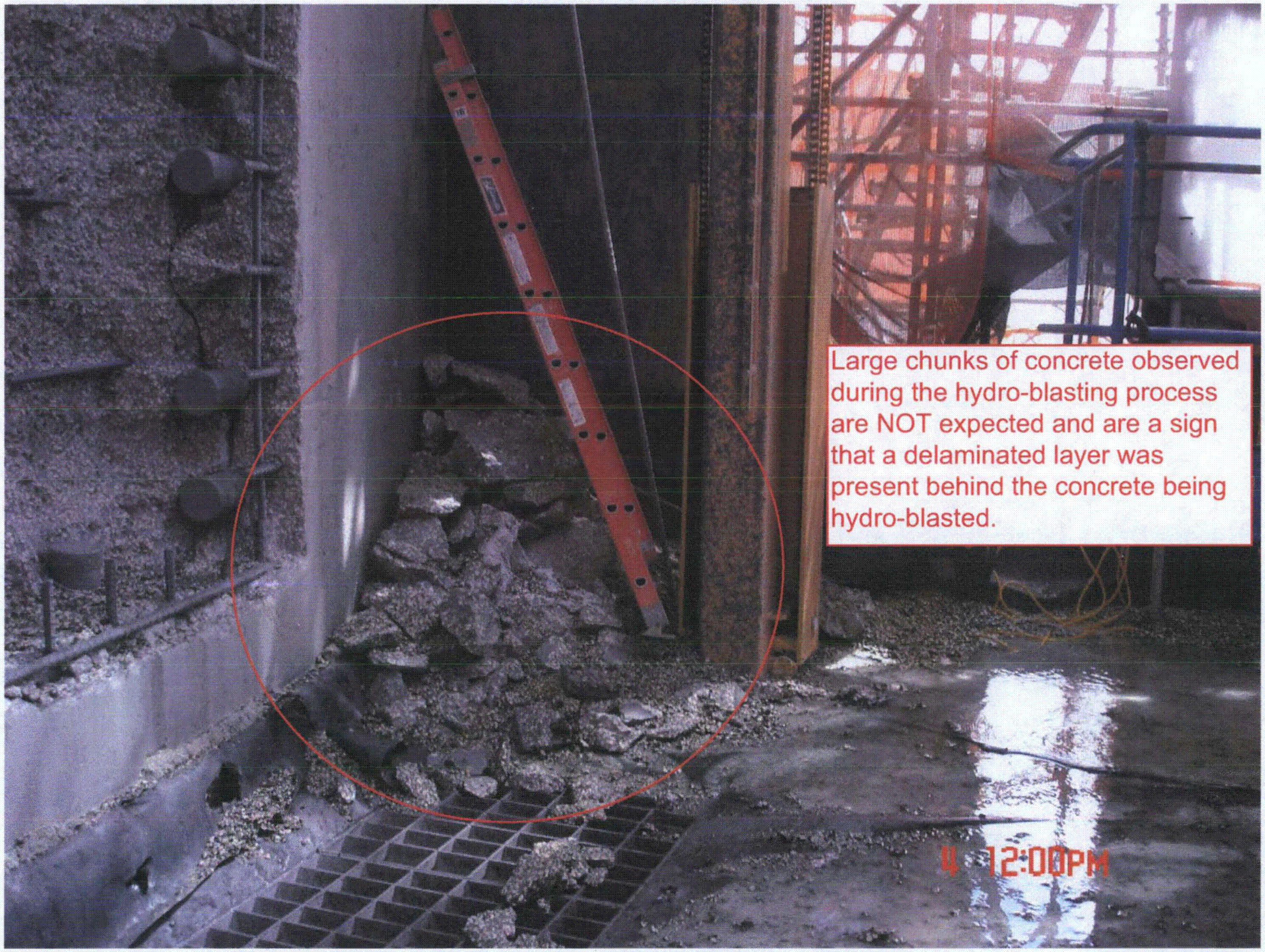
Assigning a value of 0.95 to k results in the following oscillatory amplitude, A, at the center of the beam.

$$A = 1 / (1 - k) \times (\delta - \delta_1) = [1 / (1 - 0.95)] \times 0.035 \times 10^{-3} = 0.7 \times 10^{-3} \text{ inches}$$

The oscillatory amplitude of the idealized beam is very small; i.e., only about ¼ of the static deflection under the 1,200 lb jet load. The amplitude of the actual reactor building wall panel oscillations will be even smaller than this for at least the following reasons.

- The curved wall is stiffer than the idealized flat beam.
- The idealized beam is 12 ft wide. The curved wall extends from the top of the equipment opening to the ring girder, a distance of about 86 ft, which increases the stiffness.
- The current modulus of the concrete is probably much greater than the 4,000 ksi design value, which also increases the stiffness.
- The natural frequency of the wall is unlikely to match the frequency of jet rotation.
- The rotating jets represent a much less severe oscillatory loading condition than a single 1,200 pound force that is quickly shifted laterally.
- The mass of the concrete is neglected in the above computation. In reality, this inertia of this mass would limit the deflection under the short duration load to less than the amount that was computed considering the stiffness alone.

Finally, it is concluded on the basis of the above computations and discussions that hydro-demolition jet induced vibrations of the Reactor Building wall as well as vibrations of the building as a whole will be negligible and need not be further evaluated.

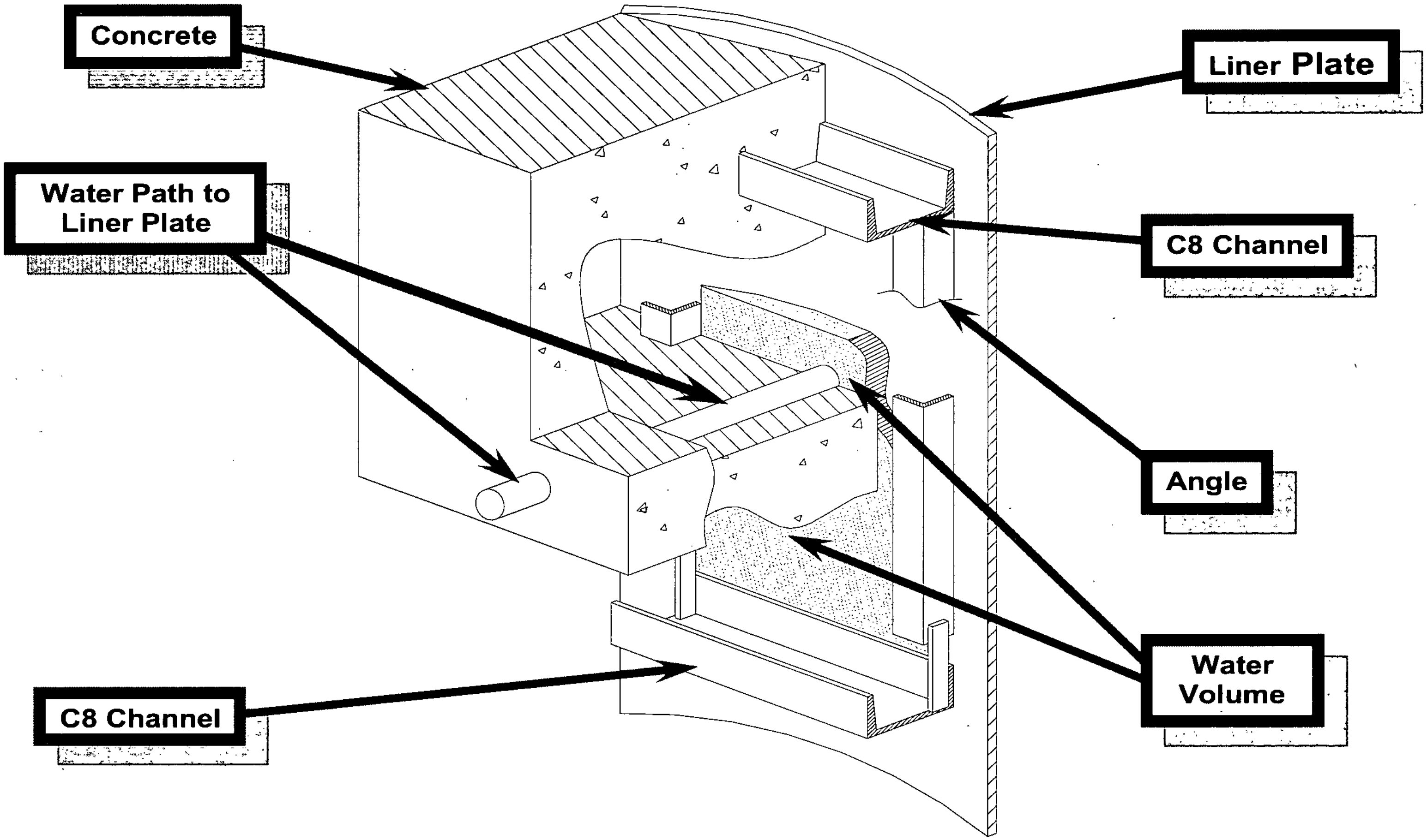


10/4: Cracks at bottom on right side and large chunks of concrete after hydro-blasting

Turkey Point 4 Liner Plate

Ronald Legrand

July 25,2005


Concrete
Liner Plate
Water Path to Liner Plate
C8 Channel
Angle
Water Volume
C8 Channel

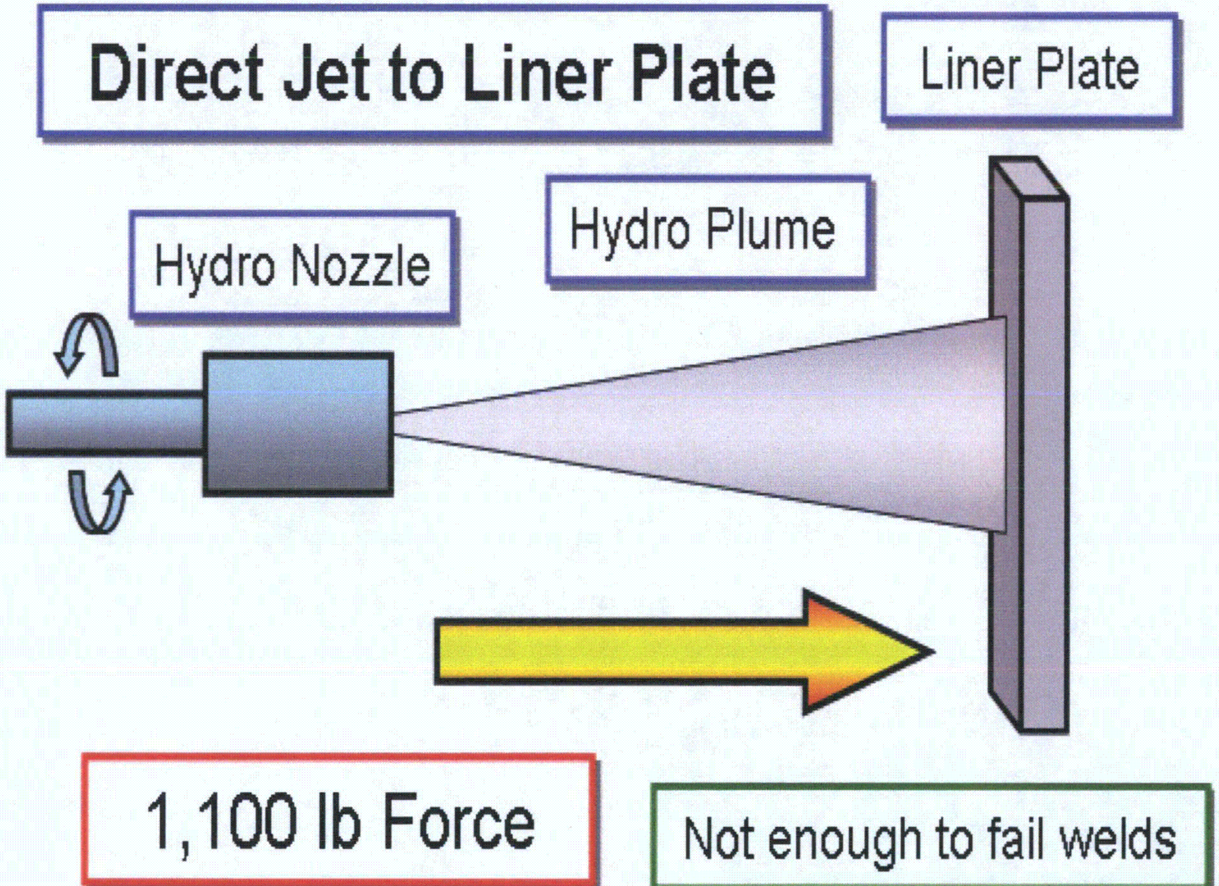
Turkey Point 4 Liner Plate

- Containment wall system description
  - 45 inch thick poured structure
  - ¼" thick carbon steel liner plate
  - Horizontal C8 steel channels 10 feet apart
  - Steel angles vertically 15" on center skip welded to liner plate and fillet welded to C8 or flat bar connected to C8 channel
  - Gaps at C8 and vertical angles

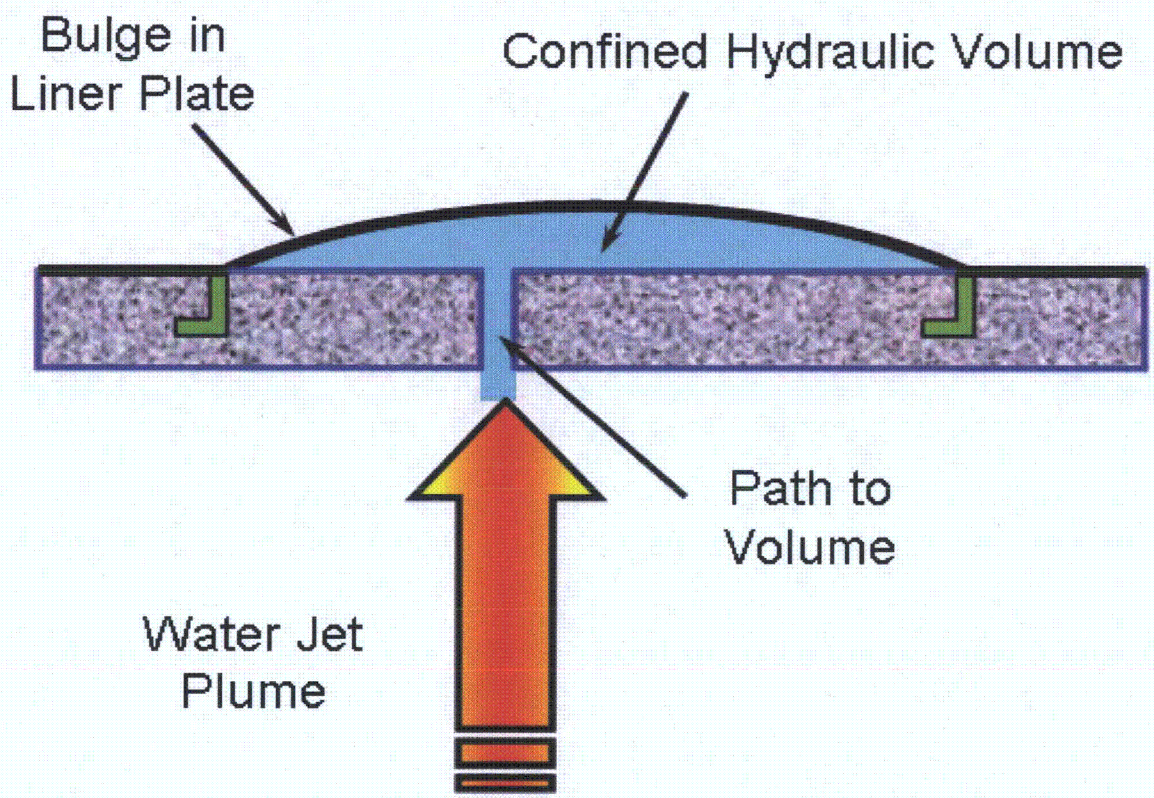
Hydrodemolition Process

- 2 independent operated robots concentrate high pressure water – 2 rotating nozzles
- 3-450 hp water pumps yield 150 gpm per robot-each nozzle has 2 orifices-75 gpm
- 20,000psi at pumps, 17,000 psi at platform
- Robot travels ~3"/second
- Distance to concrete controlled by nozzle extensions and 4 wheel configuration

Hydrodemolition Process



Gap Hydrodemolition Hydraulics



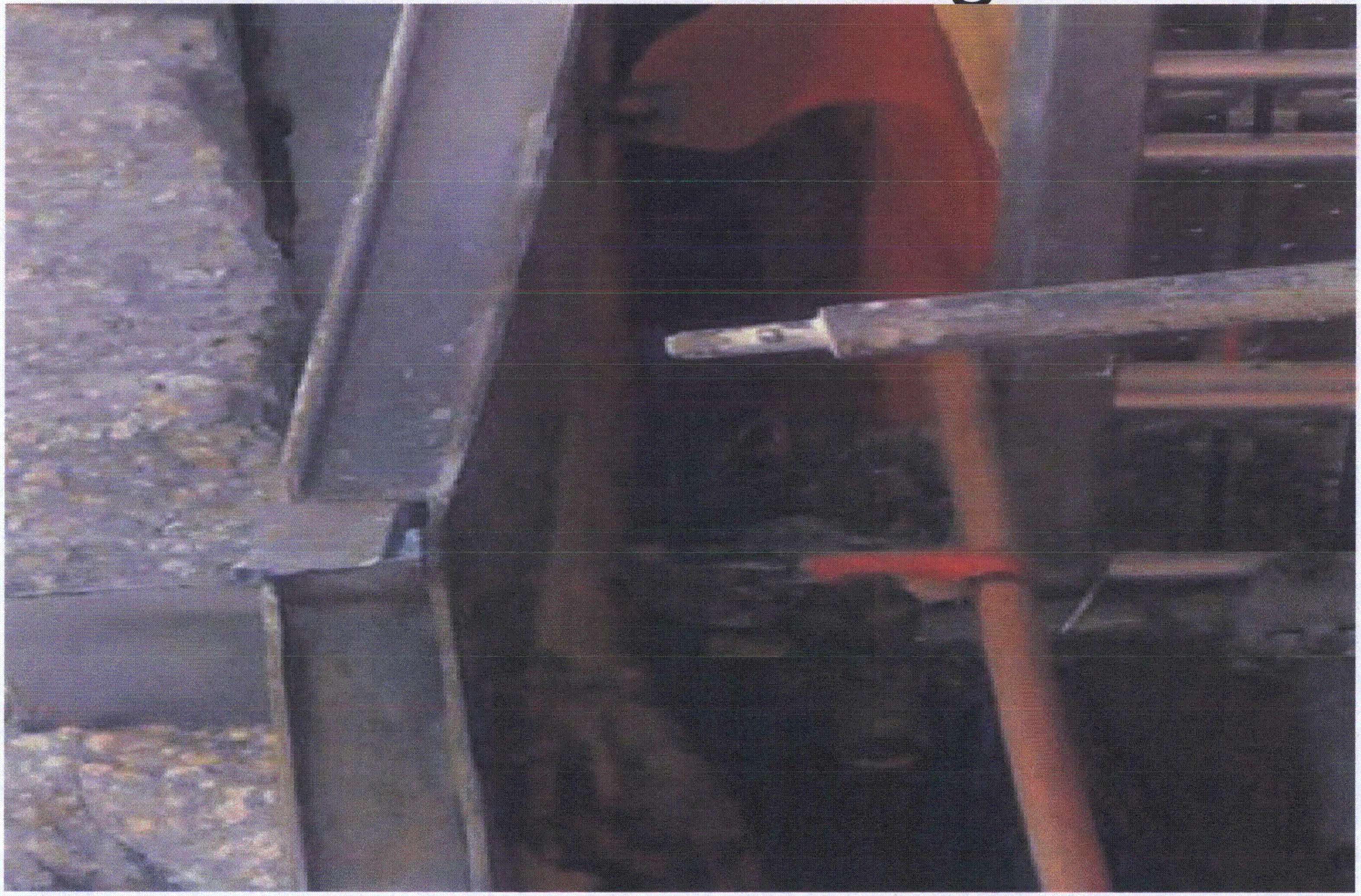
Separation of Liner Plate from Containment Wall

Concrete Void

Concrete Void

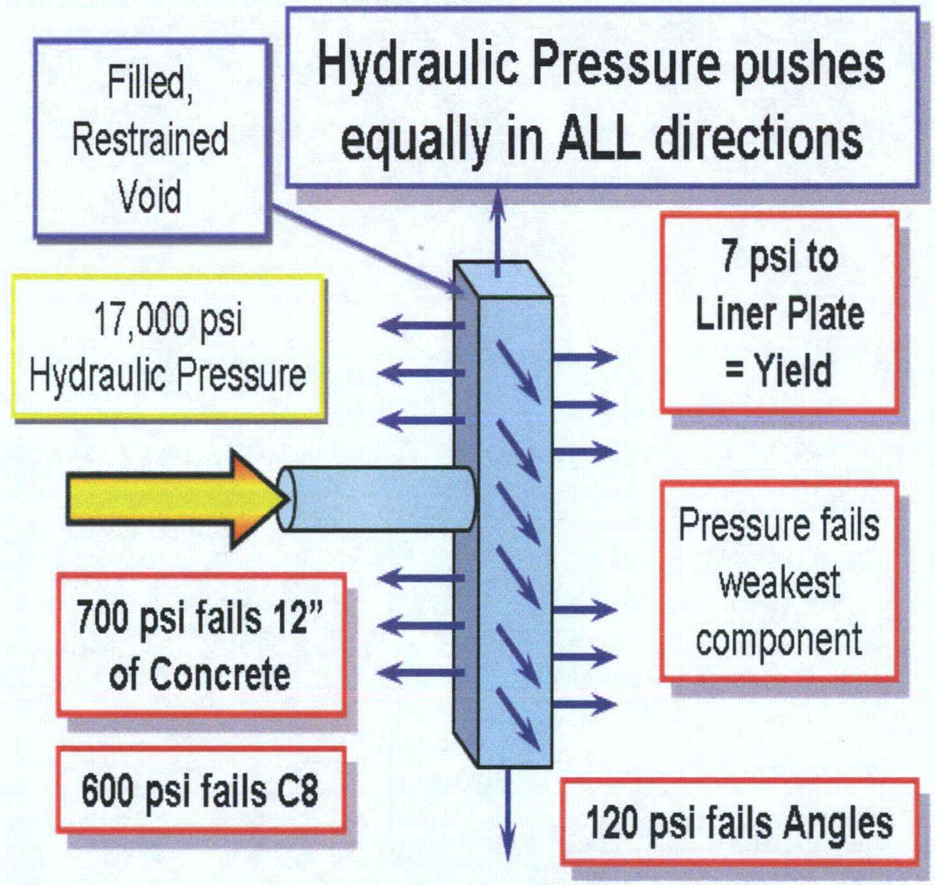
Upper East Side Liner Plate

Broken Stiffener Angle

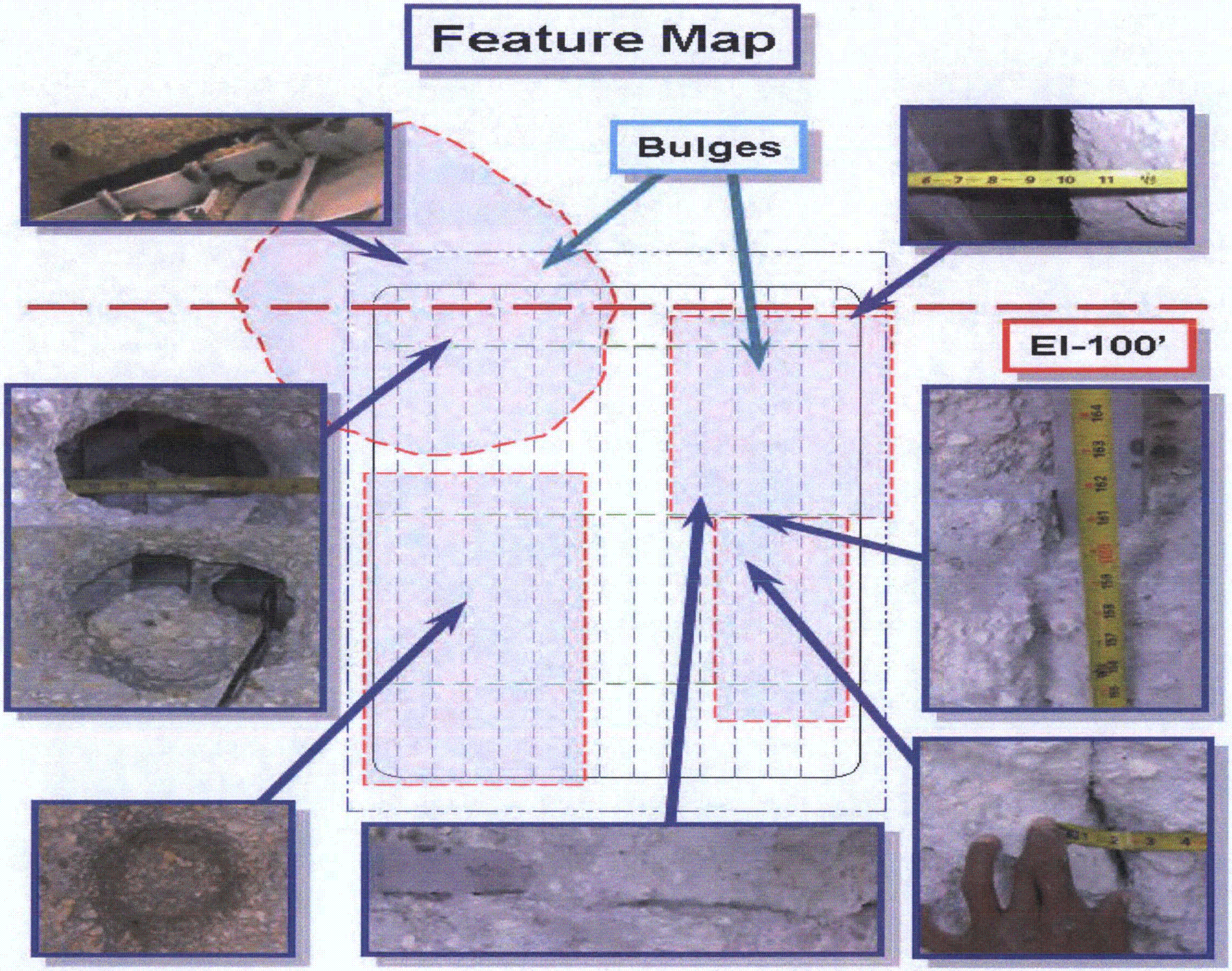


Gap Hydrodemolition Hydraulics

- Liner plate bulges- hydraulic reservoir
- 2.5 gps fill and pressurize gap in < 1 sec
- Pressure to fail vertical angles = 1%
- Pressure to fail C8 = 3.5%



Turkey Point 4 Liner Plate



Liner Plate Calculations

- 7 psi of hydraulic pressure yields ¼" liner
- 120 psi pulls vertical steel angles from concrete
- 600 psi will fail C8 horizontal channels
- 600 psi will crack 12" concrete
- 12" of concrete remained when damage
- Any of the steel members fail before 12" thick concrete

Turkey Point 4 Conclusion

- Bulges in liner plate with cracks and gaps in concrete provide an avenue for an hydraulic reservoir to fail critical components
- Nozzle passes over the defect long enough and close enough to fill the volume and pressurize the system to a level sufficient to fail components of the confining system

5. WATERJETS IN CIVIL ENGINEERING APPLICATIONS

5.1 INTRODUCTION

It is difficult to divide the use of waterjets in mining applications from those applications where the technique has, instead had a civil engineering purpose. This is because the two disciplines have many features in common, particularly in the excavation and removal of geotechnical material. Because of this dilemma it was decided to group the cutting of soil and concrete, and the procedures more commonly considered to be of a civil engineering use into one chapter, and those more clearly related to mining into a second. To make the mining distinction, the materials to be mined are considered to be rock, with the weakest category as a rule being considered to be coal.

Making this distinction has raised one unanticipated problem, since the earliest use of **hydraulic mining,** as the practice of using waterjets in excavation in known, was to remove soil. For this reason, and since the results correlate better with the studies of soil and weak rock removal, of more practical use now to civil engineers, this somewhat historical section has been included in the civil engineering, rather than the mining engineering section.

5.2 EARTH MOVING APPLICATIONS

The destruction of earth following any heavy rain, or during any severe storm at high tide continues to demonstrate the great power water has in moving earth. It is a power often applied with water under little pressure, yet results have a tremendous effect. This capability is not always recognized in modern applications, where use of higher pressures is argued for, without recognition of the capabilities waterjets have demonstrated at lower pressures in earlier and even current times.

The power that water has to break and remove material has been applied for many centuries; the Ancient Egyptians were familiar with the practice that is now known as "booming [5.1]." In this technology water is first impounded in a form of reservoir and then, when a sufficient head has this indicated that an increase of 50% in soil saturation increased the depth of penetration by up to 150% (from 25 to 62.5 cm). However, this, again, was found to be a function of soil type (Fig. 5.7) with finer sands and clays being more sensitive to the effects of density and permeability than the medium to coarser sand samples which were tested.

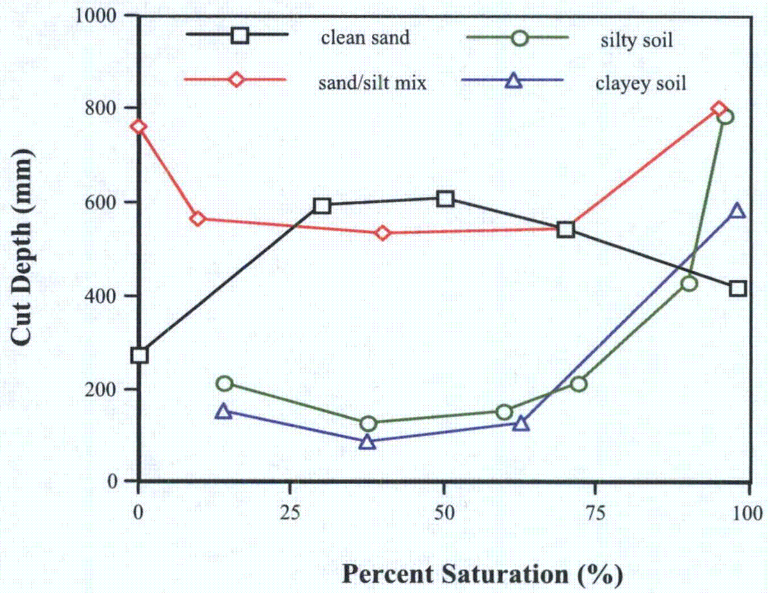


Figure 5.7 Effect of soil saturation on cutting depth (after [5.19]).

5.3 THE MECHANISM OF SOIL REMOVAL

The lessons that can be learned from the above case histories and experiments is not always clear to those who are studying the subject today. Where the jet encounters large grained, highly porous material, the jet can penetrate through the cracks and gaps in the material into a significant volume surrounding the impact point. This penetration of the water will either increase the pressure and complete the saturation of any water that is already present, as in saturated soils, or it will flow to saturate the soil. In so doing it surrounds individual grains. Once the soil is saturated, then the continued impact of water on the surface will pressurize that already in the soil. This will cause it to try to expand and to move. In doing this it causes "lift-off" of individual grains, and once separated can be carried away by the water flow. This is **erosion.** The water can also concentrate stresses around the hole, causing the growth of large cracks in the material.

5.5 CONCRETE CUTTING AND HYDRODEMOLITION

It is an interesting comment on the dangers of prediction to review, with over 20 years of hind-sight a paper presented on the use of waterjets for concrete removal at the first BHRA symposium in Coventry [5.70]. At that time the authors, who worked for a major British construction company, had evaluated the likely performance of waterjets as a potential new tool for the removal of concrete. Relatively poor results were obtained in terms of the energy required to meet a proposed performance criterion. In evaluating the likely performance which a machine would have to meet to be useful, it was concluded that the machine would need to operate at a pressure of at least 3,800 bar, and have a pump power of 370 kW. Since such a unit would cost, in 1972, around $250,000 - a cost too high for most construction companies,- the technology was therefore considered to be an impractical one for use in the construction industry.

In May of 1987 an article in the magazine Civil Engineering [5.71] commented that, within two years of its introduction, the State of Indiana Highway Department had included waterjetting in its standard specifications as a means of concrete repair. Such a turn around surely deserves comment. Not only perhaps specifically for this application, but because it illustrates just one of a number of situations where waterjet use was initially written off, on the basis of experimental results, but where it has since found a practical use. (Incidentally tunneling is another one such - but one where the applications are only now becoming apparent). It is appropriate, before discussing the topic in more detail, that the original prediction on cost was closer than some of the other estimates:

5.5.1 THE INITIAL STUDY

Concrete is a material of widely varying properties and composition. Simplistically it is obtained by mixing quantities of a cement, a sand and small rock pieces known as aggregate, with a specified amount of water. The mixture is poured into place and the water reacts with the cement to transform it into a solid material. This solid acts as a matrix to hold the sand and aggregate together in the solid form which is referred to as concrete. The mixture can be made up of varying quantities of each of the ingredients. The ingredients themselves will change from location to location, and this includes the chemistry of the water used in the process. It is especially important to note that the size and rock type which makes up the aggregate will change. This last change is, for many tools, the most critical one.

Consider how a diamond wheel cuts a slot through a concrete slab. The blade must cut through all the material in front of the blade, so that it can move forward. The advance is thus controlled by the ability of the blade to cut, to the required depth, through the hardest aggregate which is present, along the line of passage of the blade. Given that there are places where quartzite is the aggregate and that this material can have a strength of up to 4,200 bar, and the size of the problem becomes apparent.

Initially McCurrich and Browne [5.70] tested waterjet cutting at a pressure of 700 bar using a variety of nozzles to find if this tool could be used for slotting or drilling concrete. They also compared specific energies of cutting for the waterjet and comparative existing techniques (Table 5.8).

Table 5.8 Early comparative specific energies for removing concrete [5.70]

Technology	*Specific energy (GJ/cu m)*
pneumatic hammer	0.26 - 1.6
rotary percussive drill	0.21 - 0.84
drop hammer	0.001 - 0.003
thermic lance	33 - 134
plasma arc	0.87 - 4.3
diamond saw	1.10 - 4.50
waterjets	180 - 4,000

In evaluating the use of high pressure waterjets it was concluded that a minimum pressure of 2,200 bar would be required to cut the aggregate, which at that time was considered necessary in order to create a practical tool. The report also concluded that a jet pressure of 3,800 bar would be likely to be more effective. By the same token it was considered that a minimum nozzle diameter should be on the order of 1 mm. Traverse rates should be on the order of 1 m/sec which was considered optimum, with depths of penetration designed to be 0.3 mm or more.

5.5.2 ESTABLISHING THE PARAMETERS

This discouraging report slowed, but did not stop the development of the technology. By the second international conference, just two years later, there were three papers specifically directed at concrete cutting. Olsen [5.72] was concerned with the cutting of thin slots in concrete, to replace the diamond blade discussed above. In many applications where these thin cuts are required, such as for skid reduction surfaces and expansion joints, slot depths of 25 - 75 mm are considered adequate. Making use of a Flow Industries intensifier capable of generating 4,130 bar, studies were made of how changes in the jet pressure, flow rate and traverse speed affected the cutting ability of the waterjet stream. At lower pressures the earlier conclusions, that waterjets could effectively remove the sand and cement, but could not cut the aggregate, were substantiated.

Even at the full jet pressure it was, however, not possible to guarantee that the aggregate would all be cut. This was particularly true at higher traverse speeds (2.5 m/sec) where no aggregate was cut. Olsen therefore recommended that the optimum traverse speed be reduced to 250 mm/sec, since at this speed almost all the aggregate was cut, and the edge quality was acceptable. However, in the requirement for a greater cutting depth it was considered important, by both investigators, that the jet advance into the slot being cut. This requires a slot wider than the nozzle or holder. Since Olsen's nozzle was 0.305 mm in width, and the holder required a path 50 mm wide, the jet must traverse an oscillating path to cut wide enough clearance. This, in turn, reduced the forward advance speed, to around 30 mm/sec. Rather than use the high power suggested in the earlier paper, however, Olsen suggested mounting a small intensifier operating on a 20:1 ratio on a back hoe, which has a normal 18 kW hydraulic system which will produce 130 bar. This lower pressure would feed the low pressure side of the intensifier, which would thus be able to generate a jet pressure of 2,600 bar, albeit with only 1/20th the flow rate provided from the system hydraulics. This size of unit would be competitive with diamond saw applications. For larger field applications a 600 kW unit was alternately proposed, using a multiple array of 0.3 mm nozzles.

A similar series of experiments was carried out at this time in Canada [5.73]. Pressures were increased to 4,830 bar for these tests, using a 0.178 mm diameter nozzle. The study confirmed that a high feed rate was necessary to obtain better cutting efficiency, with multiple fast passes appearing more effective than one single slower pass. At this pressure and a feed rate of 5.1 cm/sec it was possible to cut approximately 5 mm deep into concrete. In order to obtain a wider cut it was possible to remove the intervening rib to a distance of some 7 nozzle diameters. Because this still produced some spalling of the edge of the cut, an undesirable feature where the jets are used to cut anti-skid grooves, a procedure to eliminate this was developed. This, in essence comprised a method of compressing the material along the edge of the cut (Fig. 5.34). This proved effective in leaving a clean edge to the jet cut.

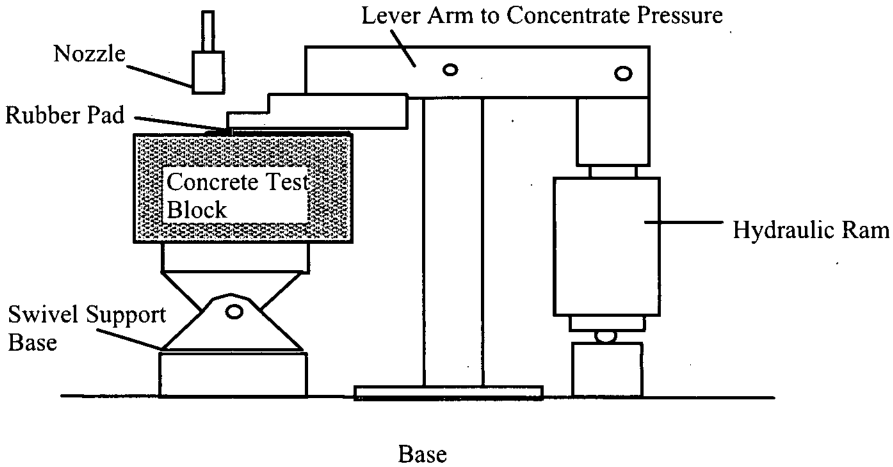


Figure 5.34 Method of compressing the cut surface to eliminate cut edge spalling [5.73].

It is worthy of comment that none of the above studies had commented upon work carried out by the Bureau of Mines on the same topic. Most likely this was because the work was only briefly referred to at the first conference [5.74] and because it dealt with large volume removal, rather than precision cutting. The study, described in more detail in a report [5.75] used the lower pressure, higher volume monitors which the Bureau had been using for conventional hydraulic mining trials, in order to cut concrete blocks. Jet pressures ranged from 234 - 345 bar and significant slots were cut into the blocks. While the average specific energy of removal was 1,630 joules/cc (1.63 GJ/cu m), values measured lay between 0.33 and 405 GJ/cu m. More significantly, even at these lower pressures the slots were open, with both aggregate and cement removed.

This point was noted by Japanese investigators [5.76] who noted that the Bureau study had been with jets of larger diameter. Thus in evaluating lower jet pressures, up to 500 bar, the effects of nozzle diameter and spacing between adjacent cuts were pursued in more detail. Although the specific energies of cutting still remained quite high in the results of this Japanese work, they did find (Fig. 5.35) that specific energy of cutting decreased with increase in nozzle diameter, and also with an increase in spacing between adjacent cuts, as long as the intervening rib of material could be removed. The most efficient removal of this rib of material appeared to occur when the two adjacent jets were spaced at a distance of between 9 and 18 nozzle diameters apart (Fig. 5.36).

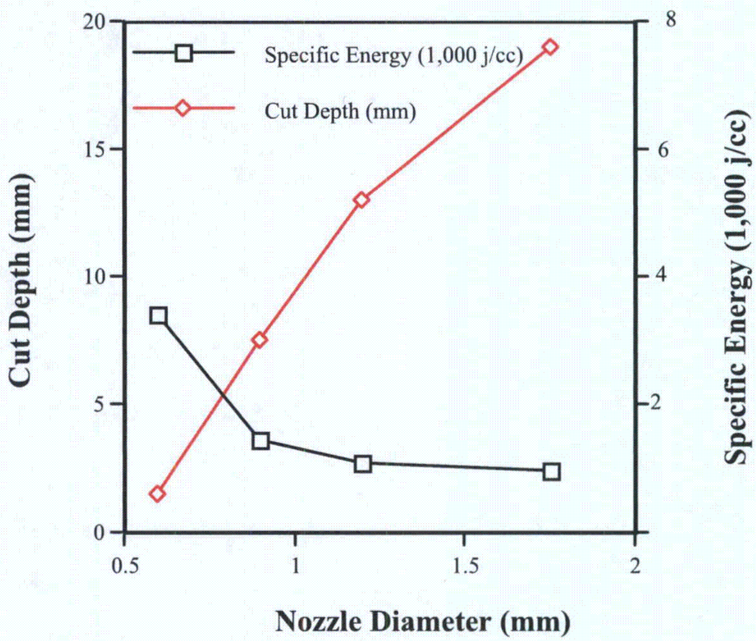


Figure 5.35 Effect of nozzle diameter on the depth of cut and specific energy of concrete removal (after [5.76]).

The machine that this investigation suggests is most practical is thus a 140 kW machine, operating at a pressure of 1,000 bar with a 2 mm nozzle diameter.

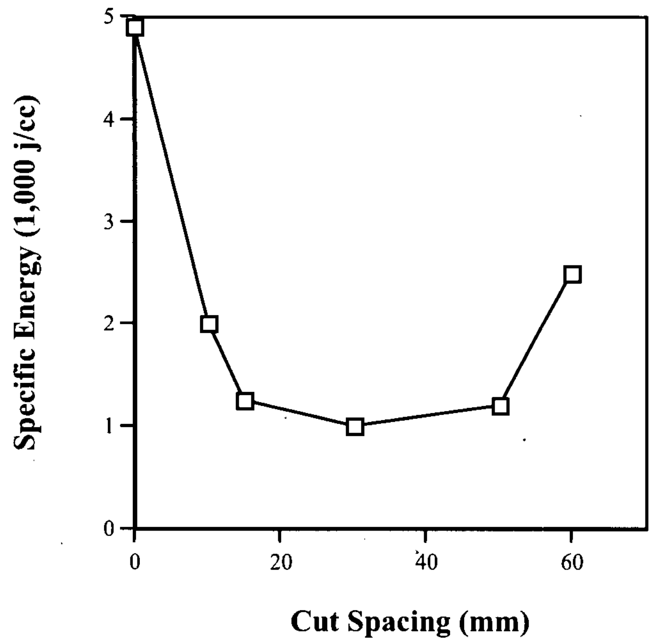


Figure 5.36 Effect of slot spacing on specific energy of concrete removal [5.76].

A clear difference in the approaches to concrete removal was becoming apparent in much the same manner as was occurring in the approach to cutting of rock, as will be discussed in Chapter 7. There was the attempt to use increasingly large pressure impulse jets for massive concrete fracture, then. there was the use of very high pressure, but small volume continuous jets for cutting thin slots in concrete, and finally there was the lower pressure higher-volume continuous jet approach directed more toward slot cutting and the volume removal of material. Ultimately a fourth option, that of adding abrasive to the water became available and that too has found a place in the technology. Because of the differences in approach and the resulting applications each of these options will now be discussed separately, even though for most of the decade of the 1980's all four options were in development and use concurrently.

5.5.3 HIGH PRESSURE SINGLE PULSE UNITS

Development of high pressure single shot or high pressure pulsing units was aimed at replacing the drop hammer and pneumatic pavement breaker. To be effective such a unit must not only be able to break concrete effectively on a single pulse, giving instantaneous productivity, but should also be able to recycle quite quickly and maintain consistent operation during a day, giving high levels of overall production.

Early experiments with high pressure water cannon types of equipment had been able to generate extremely high impulse pressures (see Chapter 2). They were, however, restricted to a lengthy recharge operation, so that quasi-continuous operation became more difficult. Two developments began to change this operation. Exotech, in Maryland developed a pulsating unit which could be mounted on a backhoe (and which was used in early ice cutting tests q.v.) [5.77]. Concurrently Burns at the University of Waterloo began work with the Gas Research Institute to find a way of developing a pulsed jet machine. The first experiments concerned the development of a unit which would use the power from a gasoline-air combustion to drive the piston of the intensifier [5.78]. Because of the need to retain a high jet pressure throughout the stroke of the piston, in order for the jet to be most effective, this meant that the gas in the chamber must still be at high temperature and pressure at the end of the stroke, when it would be vented to atmosphere, ready for the next cycle. As a result a considerable percentage of the energy created by the combustion was lost after the cycle, making this first design quite inefficient.

A second machine was therefore constructed, using the sudden release of compressed nitrogen, as the driving power to the piston (Fig. 5.37, [5.79]. Two units were constructed, capable of generating jet pulses of 328 cc to a maximum pressure of 6,900 bar. This jet could be discharged through a nozzle with a diameter of between 1.0 and 2.5 mm. By using gas as the driving mechanism the unit could be recycled (Fig. 5.39) at a rate of 8 shots a minute, with a maximum frequency, for the early design, of 10 shots a minute. Historically it has been this problem, that of designing a unit to fire at a relatively rapid rate, with the resulting shock loading that this imposes on the supply pipelines, which has limited the commercial development of this product for the market.

A field unit was constructed to fit on a trailer and field experiments carried out. At a peak pressure of 4,140 bar the pulsed jet consistently fractured 20 by 20 by 12.5 cm blocks of concrete from a single central impact, using a 2 mm diameter nozzle [5.80]. This was not possible with a 1 mm diameter jet. When larger blocks (40 by 40 by 15 cm) were struck these could be fractured by pulses from a 2 mm nozzle at 3,800 bar, either by individual blows breaking to the sides of the block, or when secondary impacts broke to the initial crater and to fractures developed from the initial pulse. At 4,200 bar jet pressure the blocks were consistently fractured.

When tests were carried out on large slabs but near an edge it was confirmed that this increased the amount of material that could be removed, and a single shot to the center of an area delineated by saw cuts 15 cm apart would remove the central volume of concrete to the depths of the saw cut. This could not be consistently achieved at a greater cut spacing. The effectiveness of the concrete removal did not appear influenced by the presence of rebar in the concrete. Jet action did penetrate along the interface between the concrete and the steel, breaking the concrete from the reinforcing.

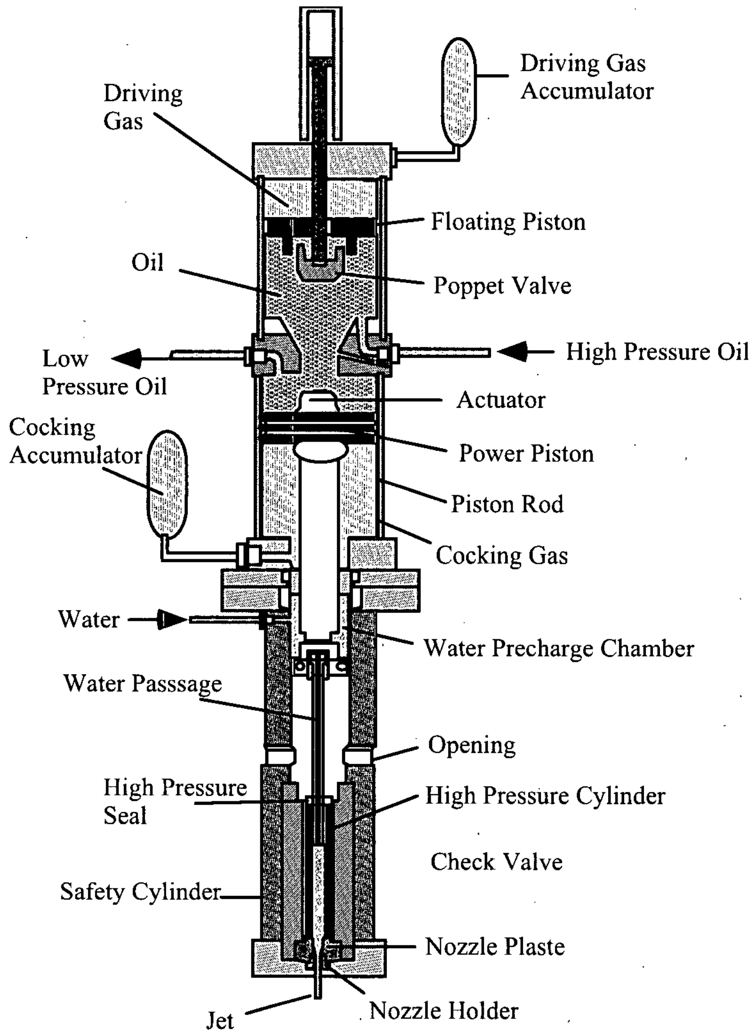


Figure 5.37 Design of a gas driven pulsation unit for concrete breaking [5.79].

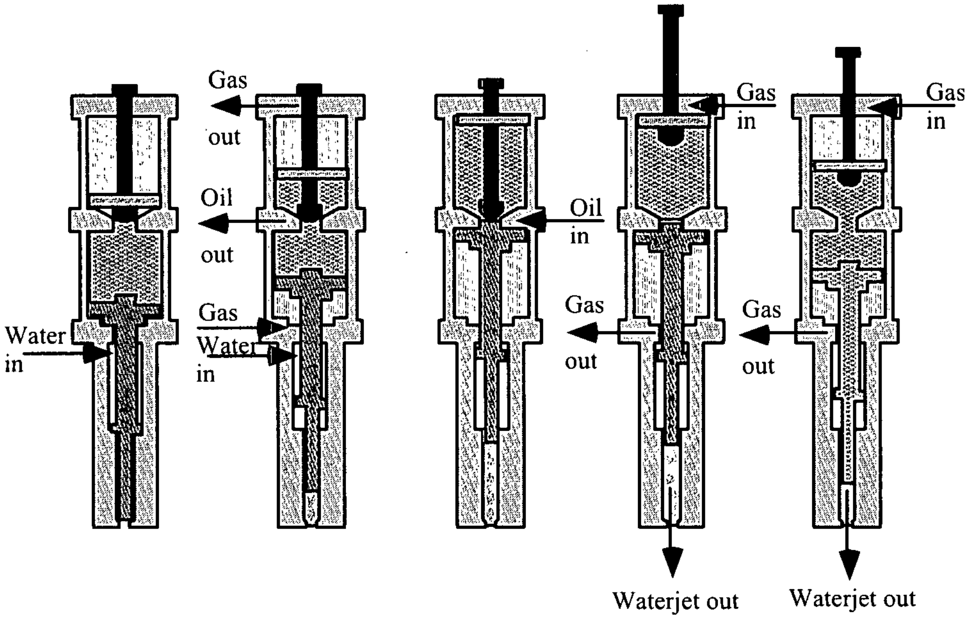


Figure 5.38 Schematic of operating cycle of the pulsation unit [5.79].

This ability of the jet to penetrate along interfaces and delaminate materials was also successfully demonstrated where an asphalt overlay had been applied to the concrete. For example 7.5 cm thick asphalt overlays could be removed from concrete by cutting two saw cuts 25 - 30 cm apart and firing the pulsed jet along the center line between them. The asphalt layer could then be lifted and removed by hand, even though it showed few fractures (ibid.).

The studies showed that for the jet to be effective in breaking concrete it had to penetrate over 50% of the concrete thickness. This required a relatively large diameter jet with a sustained pressure over the duration of the pulse. The system worked best when working within 8 cm of existing edges, but could be designed to work to earlier cavities created by the equipment. Subsequent experimentation confirmed these conclusions [5.81] and led to the recommendation for a change in the design of the equipment.

The concept of a pulsed jet device was further examined by Dravo [5.82]. A device was manufactured and attached to an impact breaker framework. Experiments showed that exponential nozzles had a much longer operational life, on the order of 85,000 cycles, in contrast to conventional conical nozzles. The noise generated by the device was a concern. Levels had earlier been measured at around 115 db in the working area of the Canadian device [5.80]. The technology from Dravo was transferred to Briggs Technology, and the driver for the water pressure changed to a Blow Down design (Fig. 5.39) which could achieve several shots a second ([5.83]. Seal problems became evident in the operation of the equipment, however, and the technology is not currently being aggressively pursued.

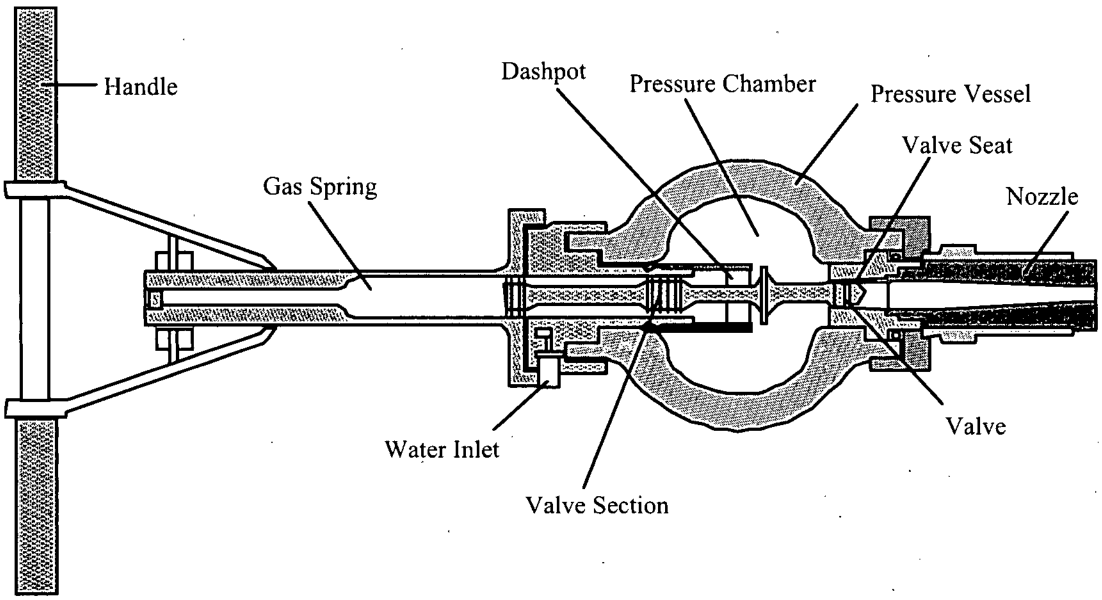


Figure 5.39 Blow down water cannon [5.83].

5.5.4 CONTINUOUS HIGH PRESSURE LOW FLOW SYSTEMS

The work which Olsen had begun at Flow Research had an interesting consequence. The islands around Seattle are connected by bridges with concrete decks. These must be occasionally repaired, a procedure which, historically is carried out by first using jackhammers to chip out the damaged concrete. This is manually intensive and can be quite slow. On one such bridge the contractor was falling significantly behind deadline using this method and approached Flow to determine if they could help. By using an intensifier system it proved possible to use the high pressure waterjets to remove the damaged concrete, and allow the concrete removal and repair to be completed on time. This early demonstration of the technology was probably the first such application for waterjets. It did not create an instant business because the cost benefit to waterjet use, while advantageous in rapidly clearing a bridge in an intensively traveled area, did not easily translate, in those days, into a normally competitive system.

Flow Research were not the only early investigators of this approach. Under funding from the National Science Foundation [5.84] tests were carried out by IIT Research Institute in Chicago in both the laboratory and field examining the use of jets operating in the pressure range between 4,000 and 7,000 bar. Because of the high pressures used, the flow volumes available only allowed the use of nozzles ranging between 0.4 and 0.6 mm in size. The study yielded a predictive equation for the depth of cut which might be achieved, in terms of nozzle diameter:

$$\frac{h}{d} = K_1 \left[\frac{d}{s} \cdot \frac{P}{\sigma_c} \sqrt{\frac{V_j}{V_t}} \right]^{\alpha}$$

The paper is also of interest, however, in that it compared both the costs of cutting concrete, and the rates of excavation achievable by waterjets and conventional methods (Fig. 5.40). Given that the data given was for the lowest waterjet pressure and smallest diameter tested, the authors suggest that increasing the jet operating parameters would have made the figure comparison even more impressive. A cost comparison was made of means for cutting an expansion joint in concrete. A wheel cutter would require 7.5 minutes to cut a slot to a depth of 22.8 cm, over a length of 3.66 m. Using a 4,140 bar jet, through a 0.4 mm orifice, it was projected that a waterjet system would take 4.64 minutes. The teeth on the wheel will normally cut between 2 and 16 joints, for an operational life of perhaps 2 hours. There are 108 teeth on the wheel, and in 1978 they cost $1.33 each. In contrast to the $23,000 capital cost for the cutter, a waterjet system was estimated to cost $66,000. However the jet nozzles, the main wear part, would last up to 800 hours. The authors suggest, based on these figures, that the benefit of using the waterjets would come after 299 hours of operation.

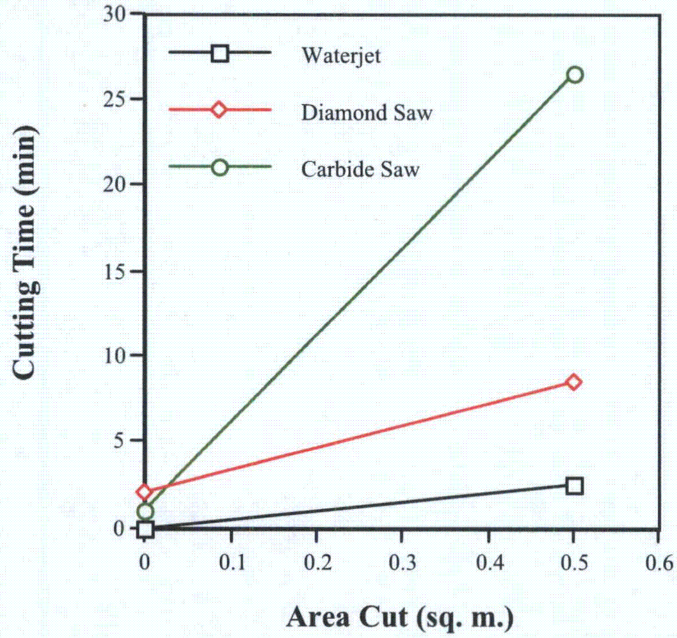


Figure 5.40 Comparative concrete cutting times for a 4,140 bar waterjet, a diamond saw and a carbide saw [5.84].

Although the work at IIT Research Institute continued with a field study after the initial laboratory data was obtained, that work was directed more at removing damaged concrete. It is thus, more relevant to first review the work continuing at Flow Research [5.85]. Working with the Electric Power Research Institute (EPRI) Flow had developed a machine to cut trenches in concrete. The system was designed based upon tests in cutting a concrete made up with a granite aggregate. The choice of the pressure was determined based on determination of **the threshold pressure** for this aggregate material. This is defined as the minimum pressure required to penetrate the material, and this was established as 1,000 bar. Because of some conflicting data which will be discussed later in the text, it should be pointed out that this result was obtained by cutting the concrete at different pressures (Fig. 5.41). A quite small nozzle was used for these tests, as well as a high traverse speed of 50 mm/ sec. In addition it should be noted that the data shown was the depth achieved after a total of ten passes. The data was extrapolated back to a zero depth of penetration, and it was reported that no penetration of the aggregate occurred at that pressure. Based upon a statement "From an energy stand-point, three times the threshold pressure is (the) most efficient pressure" it was then concluded that the machine should operate at a pressure of 3,000 bar.

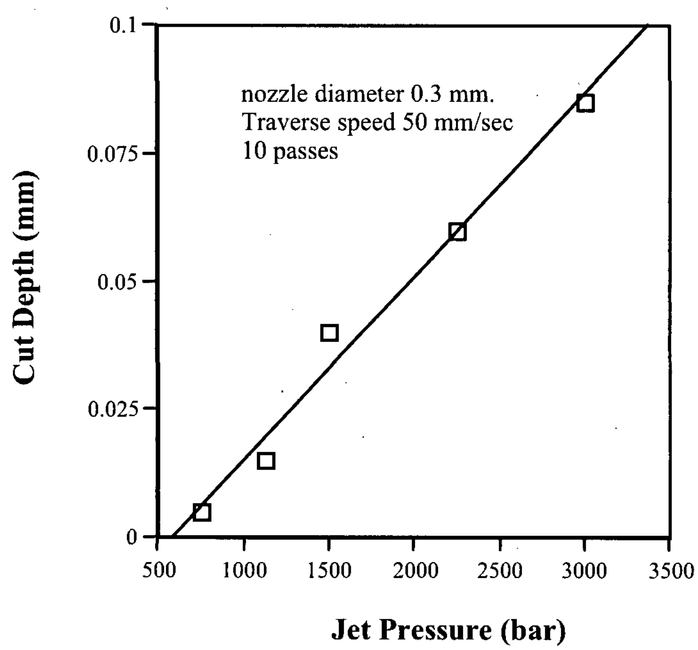


Figure 5.41 Depth of cut in concrete as a function of jet pressure [5.85].

Jet performance is considerably effected by the traverse speed of the nozzle over the surface. Under most test conditions the jet is not traversed fast enough to find an optimum value for the cutting rate in terms of the area of cut created in a second. For example, at IIT [5.84] the study had only carried out tests at speeds of up to 400 mm/sec at which point the curves of area created as a function of traverse rate were still increasing. The Flow study suggested that, for a 0.3 mm diameter jet this increase peaked at a traverse rate of 760 mm/sec (Fig. 5.42). The area of cut created is determined by multiplying the depth of cut by the traverse speed.

Although the jet is cutting efficiently at this speed the depth of cut achieved is quite small and thus, to cut through a 220 mm thick concrete slab some cutting strategy is required. The Flow approach was to cut through the concrete by using three nozzles to make a series of successive passes over the concrete surface, and then to insert a smaller nozzle into the trench thus created and cut through the remainder of the concrete (Fig. 5.43). The three jet assembly had the two outer nozzles inclined out by one degree, in order to cut a slot of constant width. The jets were 12.5 mm apart, and the material between the slots was thus thin enough to break off, and be removed by the jet action. The resulting slot was then wide enough to allow a single nozzle, and holder, to penetrate to the bottom of the cut for the final slotting.

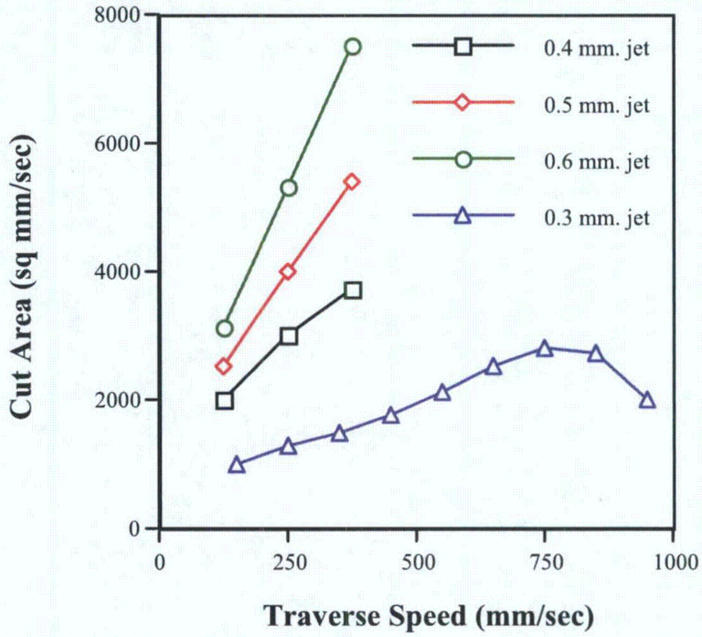


Figure 5.42 Area of cut created as a function of traverse speed [5.84 & 5.85]. The 0.3 mm data was obtained at 3,000 bar, the remainder at 5,510 bar. Standoff distance was 12.7 and 12.5 mm respectively.

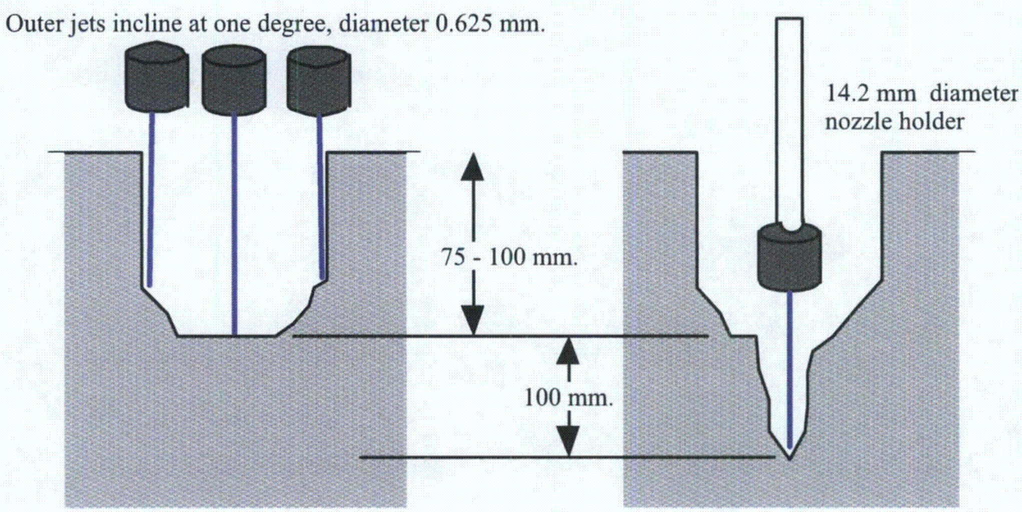


Figure 5.43 Nozzle arrangement to cut through concrete slabs [5.85].

This moving the nozzle into the slot was necessary since the efficiency of cutting dropped rapidly with standoff distance (Fig. 5.44), and thus as the number of passes is increased, and the distance to the cut surface increased, the relative gain which can be obtained from each cut became less.

Part of the reason for this is that the jet has only a given finite length. This effective length is reduced with higher jet pressures and smaller jet diameters and can also be diminished by entrant flow conditions into the nozzle, and very high lateral nozzle speeds.

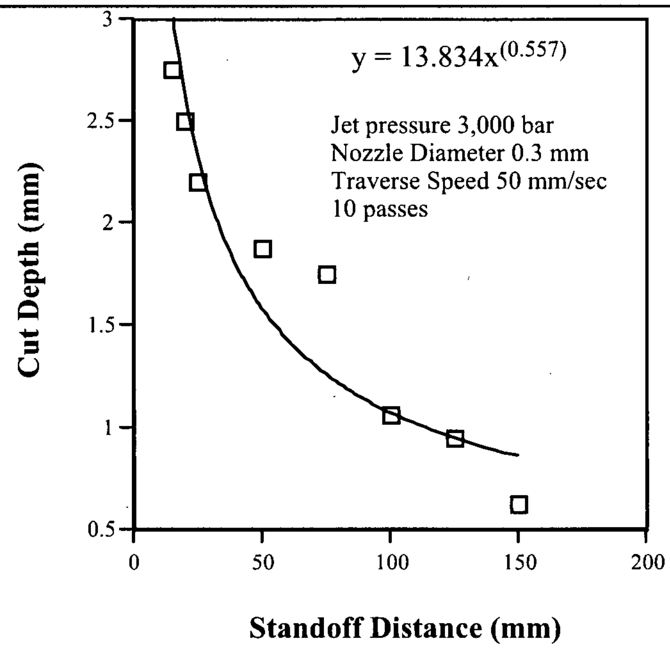


Figure 5.44 Effect of standoff distance on depth of cut [5.68].

Based upon this concept for concrete slotting a mobile equipment trailer was built containing a pump capable of producing a jet at a flow rate of 30.3 l/min at a pressure of 3,660 bar, with a power of 187.5 kW. In 1980, and based on the sale of 10 units a year, such a system was priced at $215,000. A single operator was priced at $20 an hour, and maintenance was estimated at $20 an hour. The price for cutting concrete then becomes a function of how much can cut each year, since this must absorb the depreciation of the machine. At 1,000 hours of use a year, and assuming that the machine can cut at 9 m/hour, a price of $10/m is reached, half that of a conventional trenching tool. Such an overall average rate, however, assumed that the highway consisted of both asphalt and concrete, and the jets could cut asphalt much more rapidly than they could cut concrete. The equipment was trailer mounted and tested in field operation by a number of utilities. Advantages anticipated for the unit included:

- lower, less offensive noise levels from both the equipment and the cutting.
- physically easier to operate.
- creates very little dust.
- does not stress the concrete around the excavation.
- one operator is required who can run the tool from a weatherproof cab.
- does not vibrate, and thus separate, the reinforcing rod from the concrete.

Concurrently work with the IIT Research Institute had switched to a slightly different application. While the utilities are interested in cutting through concrete for access, most highway construction involves the removal of damaged concrete and its replacement. The equipment which had been developed for cutting trenches in concrete was therefore tried in this application on a bridge deck in Cicero, Illinois [5.86]. The effectiveness of different operating pressures was evaluated by tests at four pressure levels from 700 to 2,800 bar, with the highest pressure being found most effective. A different approach was taken in order to achieve a significant penetration depth. Rather than traversing an array of fixed nozzles over the surface, the equipment used a dual orifice nozzle which was rotated as it traveled. This removed all the material in a trench ahead of the nozzle. The traverse speed was standardized at 50 mm/sec, using two nozzles each 0.5 mm in diameter, and rotating the nozzles at 600 rpm. The combined rotation and traversing of the nozzle assembly thus swept out a path over the area to be removed. It proved possible to remove a layer of concrete 63.5 mm deep over an area of 1.13 sq m in an hour using the unit. In comparison Klarcrete removes 0.57 sq m/hr, and a manually operated jack hammer 0.46 sq m/hr. The waterjet requires an 82 kW system, the Klarcrete a 193 kW system, and the jackhammer a 74.5 kW system.

It is already interesting to comment that the cost figures which McCurrich and Browne [5.70] had estimated were being reached, but that the development, being funded by the combined power utilities, and by the Federal Government was not precluded because of this. In fact such price levels have been sustained (but now in 1990's dollars rather than those of 1972) and equipment is quite widely being used.

The apparent success of waterjets as a method of removing concrete, and particularly damaged concrete led to an investigation of the technique by the US Army Corps of Engineers [5.87]. The study was particularly directed at the rapid repair of bomb damaged concrete for runways. This required that an acceptable device be capable of cutting through a slab of concrete, 30 cm thick, at a rate of at least 120 m/hr. Thus the areal cutting rate required should be at least 36 sq m/hour.

Because this is a repair need, the quality of the edge cut was important. Because of these requirements an evaluation of competitive methods in 1983 indicated that the diamond saw remained the most effective technology (Table 5.8), although further work on plain and abrasive laden waterjets was recommended.

Table 5.9 Comparative performance of equipment for trenching concrete in 1983 [5.87].

Technology	*Type of action*	*Performance (sq m/hr)*	*Status in 1983*
carbide saw	cut	5 to 27	commercially available
diamond saw	cut	2 to 32	commercially available
waterjet cutting	cut	0.35 to 22	R&D/commercially available
waterjet and pick	cut	up to 18	R & D
abrasive waterjet	cut	34	R & D
concrete saw/impact	cut/break	4.75 to 30	R & D
powder torch	melt/cut	0.75	R & D
thermal lance	melt/cut	0.75	R & D
powder lance	melt/cut	0.75	R & D
fuel oil/comp air	melt/cut	10	R & D
laser	cut	0.1 to 35	mainly theoretical

The study also had an experimental component, and in July of 1981 a demonstration was held in Vicksburg [5.88]. At this time a different viewpoint was introduced into the discussion. The approach which had been the basis for equipment design until this time had been that the jets must cut through all the components of the concrete, including both aggregate and cement paste. However the cement paste is significantly weaker than the aggregate components, and can thus be much more easily removed. A design philosophy was therefore suggested in which the waterjets be used to erode the cement and not directly attack the aggregate [5.89]. While this would leave some aggregate in the cut supported by cement outside the cut, the removal of support for the rest of the aggregate would let it fall out, and be washed away by the water.

Such an approach has a more effective use in clearing larger areas of concrete, and is particularly suited for use in removing damaged concrete. Because of the technical requirements, it required greater fluid flows that the systems proposed to date, but did not require as great a pressure. In the demonstration it proved possible to cut a slot in blast fractured, but otherwise unweakened concrete at a jet pressure of 800 bar with two jets angled at 22.5 degrees from the vertical. The jets cut a slot some 5 cm wide at an advance rate of 0.7 m/min. to a depth of over 5 cm. Progress was slowed by the very large size of aggregate in the concrete at the demonstration site.

This approach was also successfully used in cutting through several reinforced concrete walls at the University of Missouri - Rolla using a jet pressure of 800 bar, and a flow rate of 80 lpm. The flow was directed through a single nozzle which was moved in an orbital path along the outlines of the vertical trench to be cut in the walls (Fig. 5.45). A slot some 5 cm wide was cut through the walls, to a depth of up to 0.6 m as the cuts were completed around the outlines of doors required in building refurbishment on the campus.

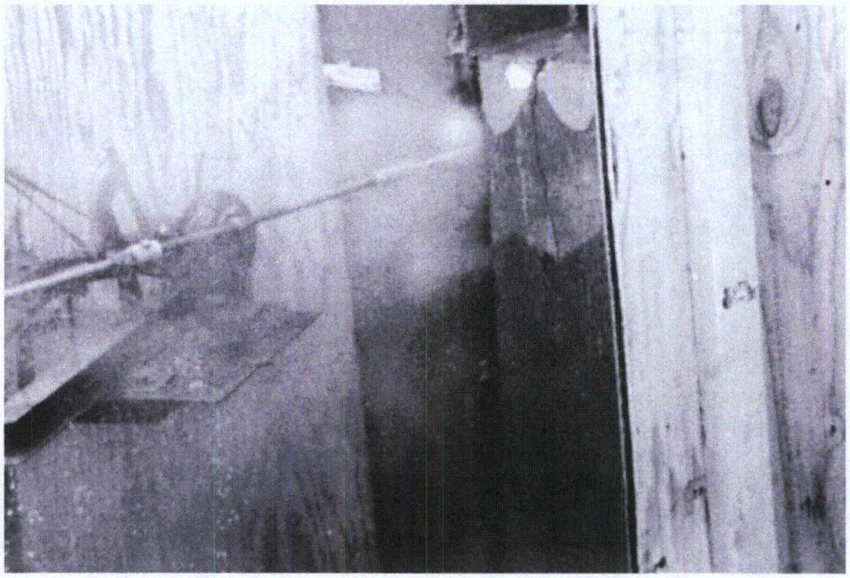
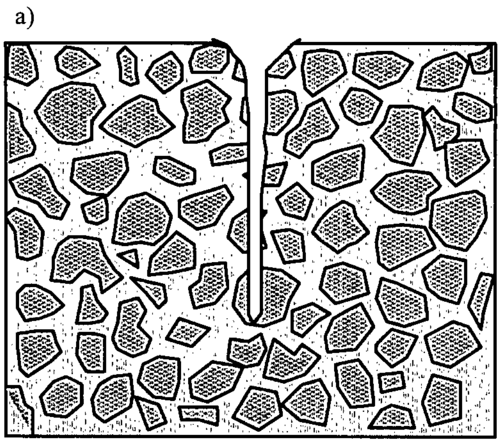
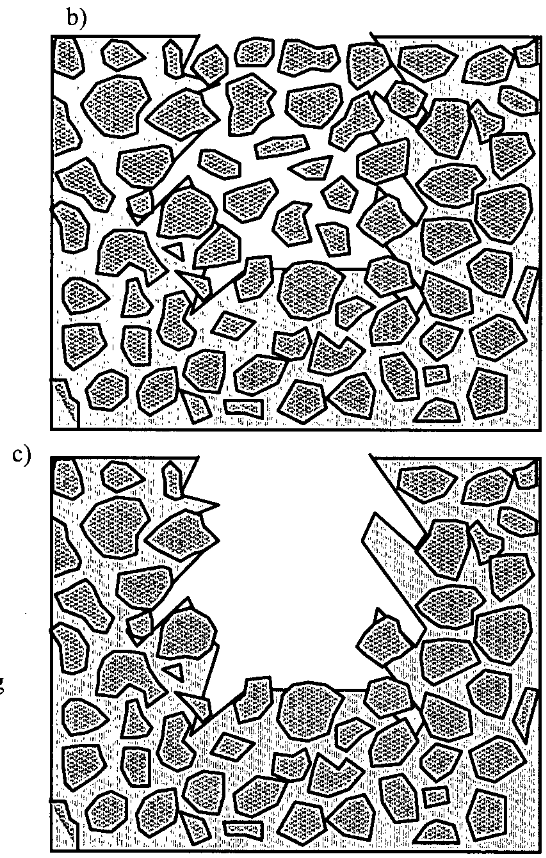


Figure 5.45 Slot cut to make a door at the UMR Rock Mechanics Facility.

5.5.5 CONTINUOUS, MEDIUM PRESSURE, MEDIUM FLOW SYSTEMS

The use of higher flow rates, and lower pressures to remove the cement paste, from around the large aggregate pebbles in the concrete, requires consideration of additional parameters in the design of equipment. Given the relative weakness of the cement paste, the pressures need can be much lower, but the power and range required to cut under and around the aggregate requires that the jet cut further, and that it be angled to range under the aggregate (Fig. 5.46). Thus the angle at which the jet is directed to the vertical becomes important in the system design (Fig. 5.47).





The ultra high pressure jet cut (a) cuts through all the aggregate and cement and leaves a narrow cut, it is constrained by its ability to cut the aggregate.

The medium pressure, higher flow rate jet (b) cuts only the cement paste but washes it out from around all the aggregate. This aggregate falls out (c) leaving a much wider cut. The cutting ability is constrained by the ability to access and remove the much lower strength cement paste.

Figure 5.46 Comparison of high pressure and moderate pressure cutting philosophies.

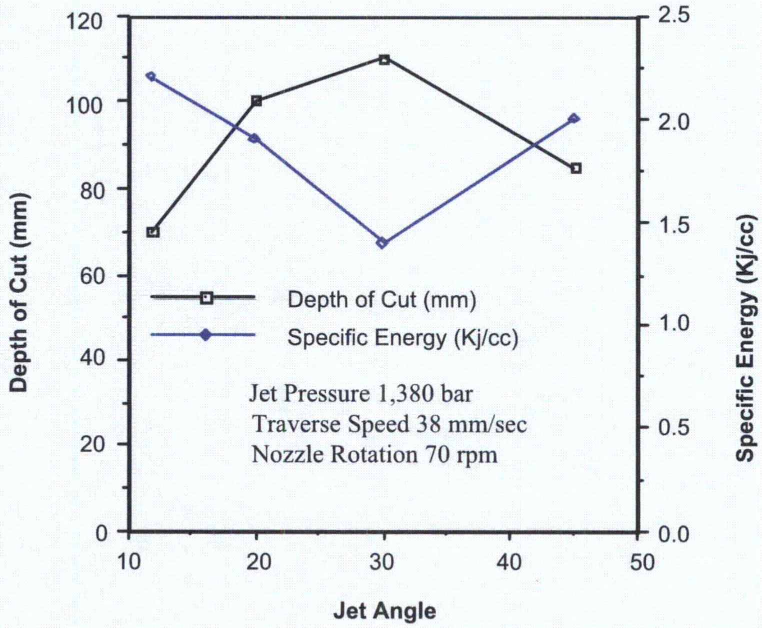


Figure 5.47 Effect of jet angle on concrete removal efficiency [5.90].

While this technique was being developed in America, a similar approach had become commercially successful in Europe. Developed with the technical name of **Hydrodemolition,** a research effort was initiated by the Italian company FIP in 1979 [5.91]. A prototype of the equipment was successfully demonstrated on the Viadotto del Lago in November of that year, and the first commercial equipment was available in 1980. The developed commercial version of the equipment was first tried in Sweden in 1984, and demonstrated in a Toronto parking garage in 1985. The equipment was given the name "The Shrimp". It operates at a pressure of between 850 and 1,000 bar. Concurrently with the later stages of the development of this equipment, competing firms were also introducing similar equipment.

This approach has proved to be very effective for removing deteriorated concrete. The reason for this, as will be discussed in Chapter 11, is that waterjets work by penetrating and extending cracks in the material. Deteriorated concrete is material with a greater number of cracks, and cracks which have grown in length. By using the power of the waterjet to fill and pressurize these cracks it is possible to get them to grow and spall off the damaged material. At the same time the pressure in the jet is set below that required for crack growth in the healthier underlying concrete. In this way the tool has some "inherent intelligence" in that, by the nature of the way it works, it can selectively remove damaged concrete while leaving the stronger healthy concrete in place.

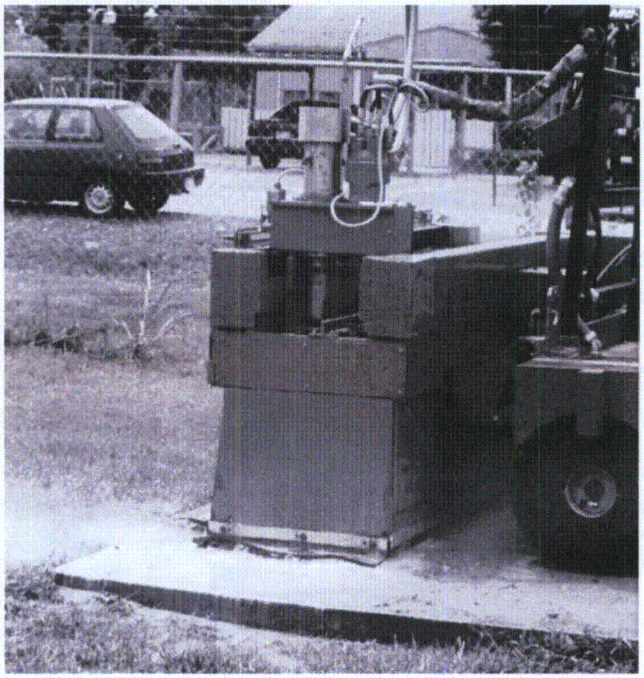


Figure 5.48 Equipment for removing concrete from surfaces.

A number of competing devices are now available, and illustrative examples of their performance, may be the best way of explaining how they work. In most cases the basic form of the equipment is the same. A trailer houses the high pressure cutting equipment drive and pumps, and this feeds water to a boom on which the cutting equipment is placed (Fig. 5.48). The high pressure nozzle moves along a guide rail within a shrouded channel, on the end of the boom. The shroud acts to contain the resulting spray and debris, which can be collected after the excavation has been completed. The jets will effectively remove concrete from above and below reinforcing rods and leaves the aggregate protruding from the concrete on the surface. This makes it easier to bond the patching concrete to the surface, and does not leave a thin flat plane as a joint, which might fail prematurely (Fig. 5.49)

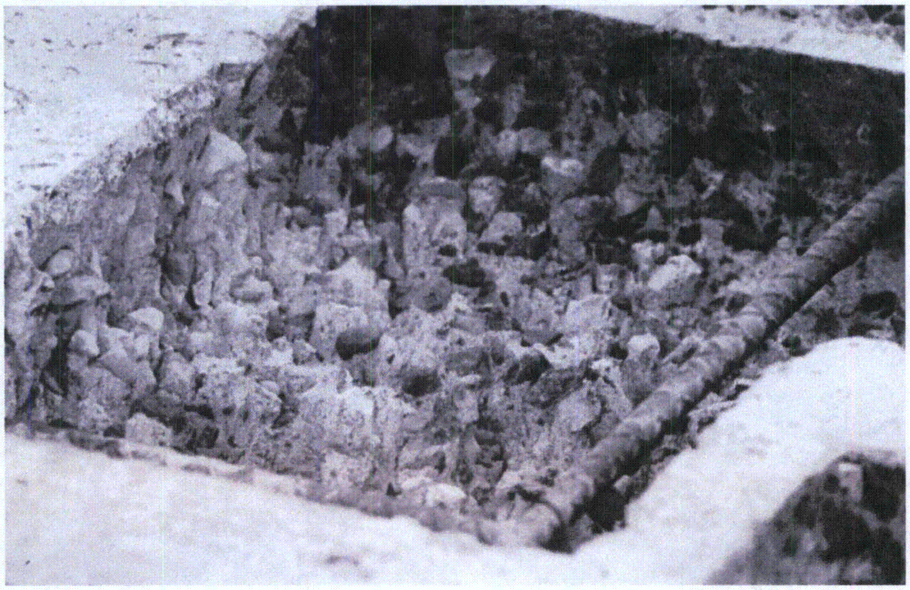


Figure 5.49 Concrete surface after waterjet removal of the top layer.

5.5.6 CASE HISTORIES

The technology is not restricted to removing concrete from the upper surfaces of flat roadbed and bridge decks. In 1984, for example, the road tunnel under the river Tyne in Northern England needed some 200 sq m of damaged concrete to be removed to a depth of 20 mm behind the reinforcing rebar [5.92]. The small cutting head required of a waterjet system, and its easy maneuverability led to the choice of this technique for removing the concrete. However problems encountered included poor visibility and the limited access space available, so that the total excavation period which SDL Pressure Jetting Ltd required for the project was some 7 weeks, including the time to twice dismantle and reassemble the special equipment built for the work.

In April 1985 [5.93] one of the interstate highway, I-190 bridges over the Niagara River near Grand Island, NY was closed for repair. Some 4,500 sq m of the bridge needed partial removal and replacement of the concrete, and 630 sq m needed total concrete replacement. The FIP equipment was operated at a pressure of 800 to 1,000 bar, at a flow rate of 240 lpm. The cutting nozzle swept out a path 1.9 m long with the nozzle oscillating to cut a channel from 2.5 - 7.5 cm wide, spaced some 10 - 15 cm apart due to the forward motion of the machine. The jet action thus removed the intervening material, and fully exposed and cleaned the upper course of the reinforcing steel. Each lane of the highway required two passes by the unit to completely cover the width. While normal performance of the unit is around 13.5 sq m/hr, the harder concrete at the site reduced the rate to 4 sq m/hr when cutting to an average depth of 7.5 cm The jet removed over 90% of the material, but some concrete remained to be removed by chipping hammers. This was largely concrete in the zone within 2.5 cm under the reinforcing, which the contract mandated be removed, even if undamaged and well bonded to the rebar. The unit could not also reach and remove the curbs and adjacent concrete. In 1985 this equipment also worked on the repair of the Lincoln Memorial Bridge in Washington, D.C.

Atlas Copco have studied the potential use of waterjets in construction and mining for a number of years, and have developed a "Con-Jet" machine for the removal of deteriorated concrete. This unit is built in three parts, a power unit, a remote control unit, and the boom mounted cutting arm, which contains the waterjet nozzle. Interestingly this unit was also tried on the repair of a Grand Island Bridge of I-190 in New York in 1985 [5.94]. The unit was operated at 1,200 bar and used 96 lpm of water. The unit took about 20 minutes to set up and the remote operation allowed the operator to stand up to 78 m from the action. Some 7 m from the unit the noise level was reported as only being 75 decibels. In order to speed operation on the bridge the contractor used two power units to supply a second nozzle on the cutting arm which was then above to remove between 90 and 180 sq m/day of concrete working 24 hours, and cutting to a depth of 7.5 to 15 cm. The concrete debris was then picked up by a vacuum truck. Using this process the bridge was repaired in some four months. This is the more remarkable since the contract was initially bid based on an estimated damaged area of 1260 sq m, but when examined it was found that some 6,750 sq m had to be treated.

The unit was reportedly able to scarify concrete at a rate of 8 sq m/hr in removing the top 6 mm of concrete, and at a speed of 7.2 sq m/hr when removing the top 12 mm of concrete. A 1985 price of $500,000 was given for the unit and support equipment, and operating costs were adjudged the same as for conventional methods, some $90 to $110 per sq m.

A comparison was made by the Indiana Department of Transportation (DOT) between this technique and conventional jackhammer operations in repairing two bridges in that state [5.95]. The jackhammer operation required some 7 persons 12 days to remove 317.2 sq m while the hydro-demolition unit took 6 days to remove 467 sq m. After two years of operation it was possible (ibid.) to obtain operating costs for the Atlas Copco system (Table 5.10) in 1987 dollars.

Table 5.10 Comparison of jackhammer and hydrodemolition [5.95]

Item	lane 1	lane 2	lane 3	lane 4	lane 5	lane 6
Method	hammer	waterjet	hammer	waterjet	hammer	waterjet
Days	12	6	17	12	20	3
Person/machine hours	756	39.5	1071	128	728	18
Repair size (sq m)	317.2	467.4	365	799	139	105.8
Ave depth (mm)	88.4	52.3	94.5	61.2	95.5	153.4
Repair rate	0.42	11.8	0.34	6.24	.19	5.87

Table 5.11 Operating costs for a hydrodemolition unit for a 10 hour day [5.95]

Item	*Cost ($)*
fuel - 0.013 l/sec	96.00
grease and lube	2.00
oil	0.50
filters	5.00
traction system (robot)	4.00
pump maintenance (8 year)	55.00
engine and radiator	8.00
pistons	20.00
cylinders	30.00
5 meter hoses	15
nozzles	50.00
miscellaneous	2.00
Total maintenance	**287.50**
machine operator	262.50
maintenance person	30.00
Total labor cost	**292.50**
Total operating cost	580.00

equipment cost amortization	945.32
average production	72 sq m/day
Cost/sq m	**$21.18**

The Equipment cost was derived based upon a delivered purchase price of $436,300 and a use of the equipment for 90 days a year.

This can be compared with the use of the Flow equipment which was demonstrated on the Dearborn Street interchange bridge in Seattle [5.96]. This equipment operated at 1,700 bar with a flow rate of between 57 and 167 lpm. Improved performance was achieved both by increasing the flow rate to increase jet power, and by keeping the horsepower constant and increasing the jet pressure (Fig. 5.50).

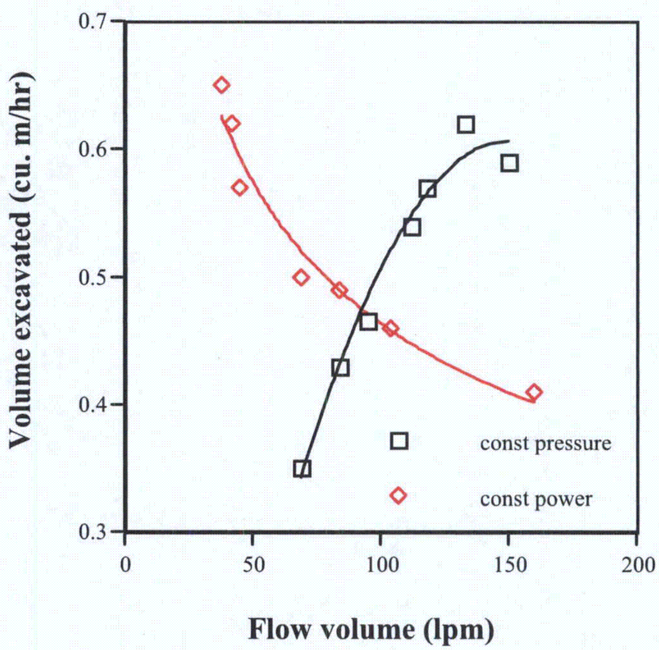


Figure 5.50 Change in volume removed with flow rate (after [5.78].

Schmid estimated that equipment maintenance and fuel would cost $5.00 an hour for a jackhammer, and that where labor costs were less than $12.00 an hour that the use of the waterjets would be economic using the Flow system. The paper also reported that the shear strength of a waterjet cut and repaired surface was some 2.3 times higher than a jackhammer repaired surface, and the pull-off strength was some 3.1 times higher.

The English problem is a little different to that in the United States since the major damage to bridges often occurs underneath the bridge, rather than on the more easily accessible deck. By changing to a 2,000 bar system, at a flow of 12 lpm it proved possible to use handheld equipment to access the work area, and to clean the damaged concrete from the rebar at a rate three to four times faster than that achievable at 1,000 bar [5.97]. In relation to the original cost estimate for equipment, a 1990 price ranged from $40,000 to $300,000 and this brought the equipment into the range affordable by a number of small companies.

5.5.7 INJECTION OF ABRASIVE FOR CONCRETE CUTTING

The continued need for a faster method of cutting slots in concrete led both EPRI and GRI to fund a study at Flow to examine the potential for abrasive injection into the waterjet stream as a more effective method of cutting concrete. This method had the advantage of also being able to cut through any rebar present in the concrete, and of achieving total penetration through the aggregate and cement to the bottom of the slab on a single pass, without the need to feed the nozzle into the slot.

Initial results [5.97] suggested that the use of garnet was more effective than either silica sand or silicon carbide. The optimum feed rate was at an abrasive flow of 68 gm/sec although a 38 gm/sec feed was only 11% less effective. The first trials showed that it was possible to completely cut a 380 mm thick slab of concrete at an advance rate of 0.4 mm/sec using a jet at a pressure of 2,415 bar, a waterjet diameter of 0.635 mm, and an abrasive feed rate of 72 gm/sec. In these experiments it was possible to simultaneously cut a reinforcing bar 10 mm in diameter, located 75 mm below the top surface of the concrete, but a second rod, some 127 mm lower was only partially cut at a feed rate of 1.3 mm/sec. The nozzle design used in the initial study was refined [5.98] and it then proved possible to cut through a 250 mm thick concrete slab and two 18 mm diameter courses of reinforcing (at 75 mm and 175 mm into the slab) at a feed rate of just over 25 mm/min using approximately half the amount of abrasive initially required.

It was then estimated (1983) that hourly costs for cutting such a slab would be approximately $12.00/hr for equipment, $9.00/hr for abrasive, and $4.00/hr for other expendables.

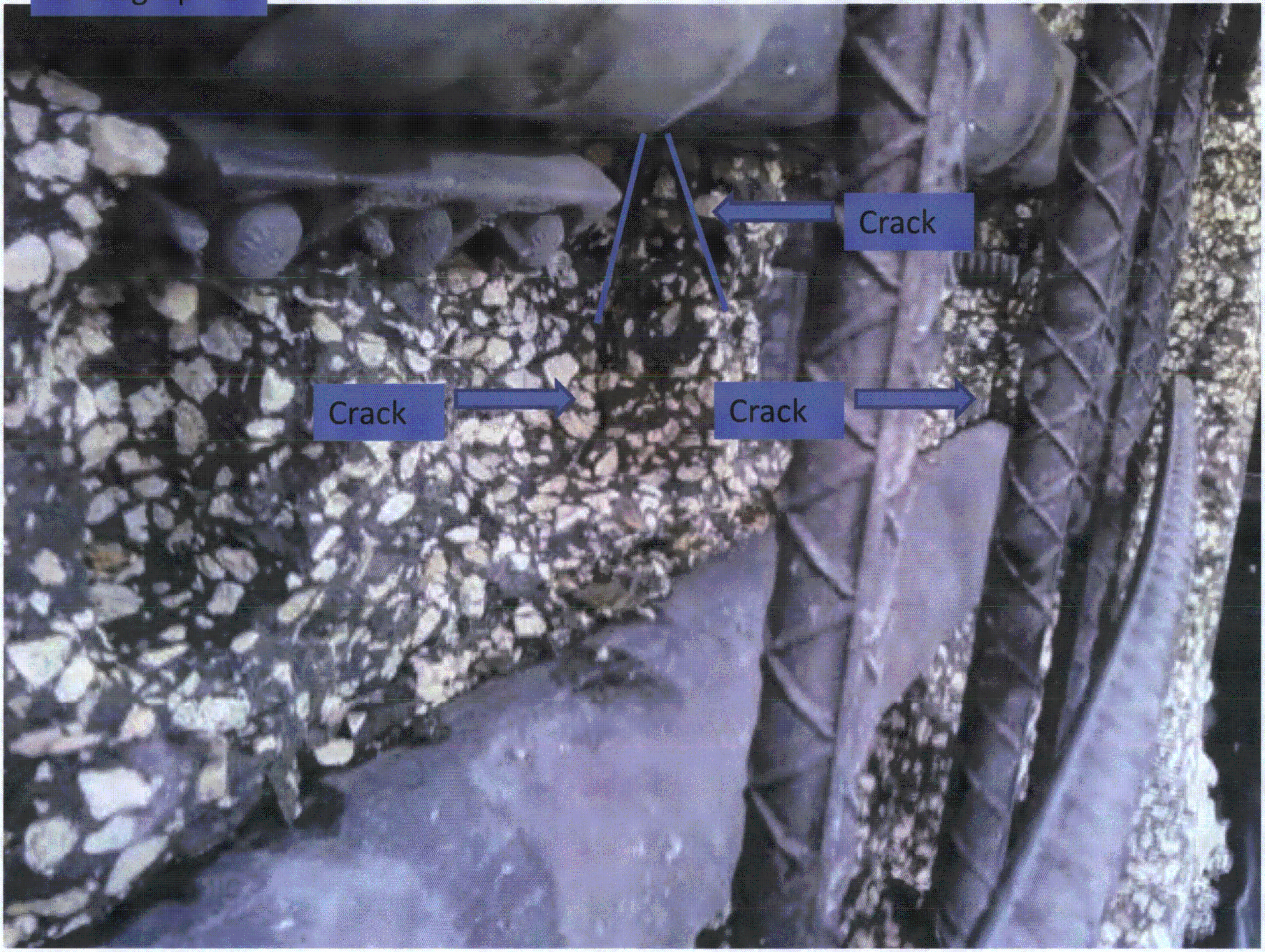
In order to improve on the initial performance data presented, Japanese investigators have also studied the problem of abrasive use in cutting through concrete [5.99]. Tests were carried out at flow rates of up to 15 l/min at a maximum of 2,940 bar. An initial comparison of the relative

Observation of photographs taken on 09/30.

- Cracks seen on 09/30 at 10:24am on photograph 1;
- Photograph 2 taken on 09/30 at 10:25am (from camera details). Also shows several cracks running from one hoop tendon to the adjacent one;
- Appears to be a V shape from the tendon sleeve;
- If a crack grows from the lower tendon up and another crack grows from the upper tendon down, and they do not grow in the same plane, they will not meet until reaching the adjacent tendon, and we have this V pattern;
- Photograph 3 (taken 9/30 at 12:25am from camera details) shows same cracks;


Photograph 1
Crack going through an aggregate
30 10:24AM

Photograph 2



Photograph 2