MINI-CUTTER TECHNOLOGY - THE ANSWER TO A TRULY MOBILE EXCAVATOR

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BACKGROUND

The single disc cutter was the key innovation influencing the successful development of the modern Tunnel Boring Machine (TBM). Early on, the cutter action was not well understood, but in 1956 the astounding tunnel advance record of 105 feet in one 24 hour period on a Toronto sewer job demonstrated the potential for the tunnel boring industry. That project set the stage for the next nearly 40 years of evolutionary development of both cutter and boring machine.

Development got off to a slow start. For the next 20 years, TBM manufacturers installed cutters in such a way that they cut concentric grooves about 3 inches apart. It was noted, however, that the harder a cutter was pushed, the further it sunk into the rock, and the faster the TBM went. The capacity of the disc cutters went from a humble 20,000 lbs for a 12 inch diameter cutter to 40,000 lbs for the new 15.5 inch cutter introduced in 1974 during the early phases of the Washington D. C. Metro Project, and on to today's 75,000 capacity 18 to 20 inch cutters. It wasn't until the mid to late 1970's that a research program at the Colorado School of Mines, was successful in developing a formulae which would describe the relationship between force on a cutter and its penetration (performance).

The recognized variables at the time included compressive and shear strength of the rock, diameter of the cutter, angle of the then triangular ring cross section, and the effect of spacing (distance between cuts). The original formulae developed and evolved along with the science, and naturally, it was computerized.

In the mid 80's, a rare opportunity for research in the field occurred as the Air Force missile program developed a deep base defense system. Millions of dollars in funding became available to study not only how to make a TBM go fast, but also to study how to make it go through fractured rock and rubble, and to give it the ability to turn from horizontal to vertical. These efforts contributed to the upgrading of the performance estimating program into a quite accurate science. Today, the most accurate of predictive programs take into account many more variables:

The Rock
Compressive strength
Tensile strength
Fracture spacing
Porosity
Grain size (and geometry in sandstone)
Hard mineral content

The Cutter
Cutter diameter
Blade width
Thrust capacity

The Machine
Thrust available
Torque available
Rpm

The Environment
Water inflow
Curves and slope
Rock support requirements
Human factors

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TBMs became bigger, more powerful and more versatile machines using 17, 18.25, 19 and 20 inch cutters, routinely running at loads above 65,000 lbs of thrust each. Thus, the TBM designs evolved which had the size and structure to utilize the over 400 lb. disc cutter and its large saddle mount. All well for the big equipment, but for small bore sizes, technology nearly stood still. For a cutterhead less than 6 or 7 ft diameter, it became physically impossible to install a large high capacity cutter of the current design.

SMALL BORE TOOLS

The principal tools for smaller cutterheads are multi-row carbide insert cutters, or button row cutters, cone shaped cutters, strawberry cutters, and even some with random spaced buttons. Many of the applications for small cutterheads, or bits as they are called in some industries, derive their power and thrust through a drill string. Torque and power are more limited therefore, than on the huge direct drive TBMs. When faced with limited torque and thrust, the cutters will obviously indent the rock less and spacing must be reduced to assure that chips will form. Some cutter types have reduced spacing to the extreme, where they virtually pound the rock to dust.

As shown in Figure 1, a large penalty is paid for making small chips or powder. The curve shows the relationship between energy consumed by the machine and the average particle size generated. A ton of rock can be excavated with less energy if cuttings are brought out in large particles. In an instrumented test, an off-the-shelf 9 inch tri-cone bit required 80 hp-hr/ton in concrete and 120 hp-hr/ton in basalt. Compare this with 3 to 7 hp-hr/ton that disc cutters achieve on large diameter cutterheads. Yet the single rolling disc cutter has not found common application on small diameter excavating tools. There are perhaps two principal reasons for this:

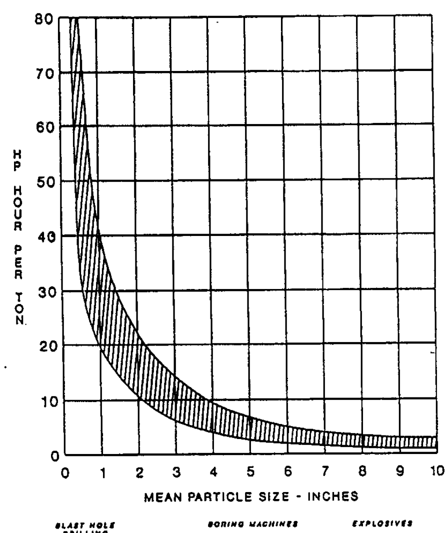

Figure 1. Excavation Energy Related to Particle Size

a) Those who have the technology of the disc cutter are primarily focused in the large bore industry. The importance of high thrust, maximum spacing (fewest cutters) and cutterhead balance is a closely held science. Large bore companies have not focused efforts on the small bore industry perhaps because they perceive greater profits in big bore jobs.

b) The smallest high production single discs are 15.5 and 14 inches diameter, while the smallest special order discs are 12 inches. Even the 12 inch cutters, with their husky saddle mounts occupy too much cutterhead "real estate" to use effectively on small diameter cutterheads. And, it is commonly believed by traditional manufacturers and users of single disc cutters that a cutter of significantly smaller diameter cannot be made robust enough to survive the high forces imposed by excavating hard rock.

THE 5.0 INCH MINI-DISC DEVELOPMENT

The incentive for designing a small disc started by playing iterative games with the predictive computer program. This exercise quickly showed that the two most effective ways of improving performance, among the "man-made" variablesdiscussed earlier, were cutter diameter and blade width.

Then there was the energy curve. TBM's were excavating a ton of rock for 3-7 hp-hr, while raise drills with multi-row, close spaced cutters were 20-30 hp-hr/ton. And as mentioned earlier, tri-cone arrangements and strawberry cutters were as high as 80-120 hp-hr/ton. There appeared to be much room for improvement.

LINEAR CUTTING MACHINE TESTS

Excavation Engineering Associates, Inc. (EEA) decided to take on the small disc challenge. Prototype cutters were designed and built in both a tungsten carbide version (left unit on Figure 2) and hardened all steel model (right unit on Figure 2). They are shown mounted on a heavy test pedestal. The first tests were run on the Linear Cutting Machine (LCM) at the Colorado School of Mines (CSM), Earth Mechanics Institute Laboratory (EMI) to determine the performance potential. This machine controls spacing and depth of cut, while recording thrust, drag and side loads on the cutter. A very hard 43,000 psi (297 MPa) rock was chosen to shake out any weaknesses as quickly as possible. Figure 3 shows this test series underway.

Figure 2. 5 Inch Mini-Disc, Pedestal Mounted

Figure 3. Testing on the Linear Cutter Machine

Results were beyond expectation. Figure 4 shows the most significant summary plot, the thrust vs. penetration curve. At 2.0 inch spacing, a penetration of .125 inch was achieved with only 11,700 lbs of thrust. To put this achievement into perspective, a standard 17 inch TBM cutter requires over 60,000 lbs to achieve this penetration in the same rock.

Also, the specific energy was measured and at 2.0 inch spacing was only 6.9 to 8.5 hp-hr/ton. This is far superior to the best multi-row or button type cutters ever tested.

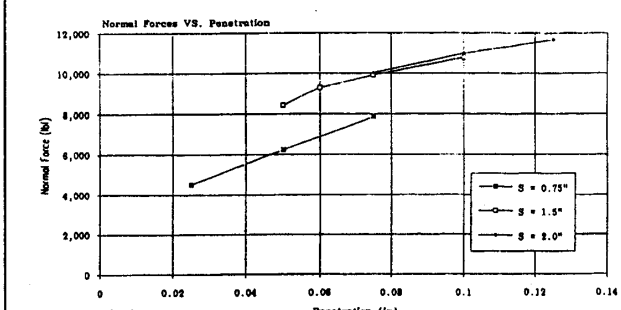

Figure 4. 5 Inch Mini-Disc Cutter Performance in 43,000 psi Rock

FULL SCALE TESTS

Figure 5 shows an array of cutters which illustrates a desired profile for an 18 inch boring head with a basic cutter spacing of 1.9 inches. In this case, the cutters are all pedestal mounted. This configuration is satisfactory for competent ground, but when operating in soils with boulders or in highly fractured rock, cutters and pedestal mounts may be subject to damage.

Since the Mini-disc is a cantilever design, the shaft can be built as an integral part of the cutterhead. A well is burned out in the forward plate of the cutterhead and the cutter shaft is welded into the cutterhead structure. In this way, the cutter is both recessed and protected. Rocks or boulders can not wedge between the cutters and damage the mounts. Figure 6 shows a typical inset cutterhead, in this example, 32 inches in diameter. In addition to the structural advantages, this style of mount allows changing of cutters from either side of the cutterhead.

The 32 inch cutterhead design employs both a cutting plan and a muck (cuttings) removal plan. Removing the muck from the face is equally as important as cutting the rock. The thrust on a rolling cutter increases when the cutter is forced to operate through previous cuttings. There are several undesirable effects including:

a) Cuttings are reground wasting energy.

b) An overturning moment is imposed on the cutterhead support system or bearing.

c) The cutterhead may have a tendency to self-steer.

Figure 5. Cutter Profile for 18 Inch Cutterhead

The cutterhead shown in Figure 6 pulls the muck off the face as it is cut. Muck does not fall by gravity to the invert of the tunnel where it must either be picked up again or must work its way rearward by the pressure of built up muck. In EEA's cutterhead design, muck is pulled immediately inside of the hollow head where it can be removed by auger, vacuum, gravity, air lift, or slurry depending upon the type of boring unit being used. As a box hole drill or raise drill head, a similar concept is envisioned except that the cutterhead would have a stinger built into the center of the cutterhead. The instant pickup feature ducts the cuttings immediately away from the cutters and prevents packing.

Figure 6. 32 Inch Mini-Disc Cutterhead

The cutterhead was also tested at EMI Laboratory. Again results were more favorable than expected. Figure 7 shows the performance results in 25,000 psi rock on the 25 rpm test, 33 ft/hr penetration rate was obtained with 82 hp! The thrust vs. penetration curve is the most favorable ever recorded by CSM. A small increase in thrust resulted in large increases in performance.

Specific energy was also exceptionally low at 5-8 hp-hr/ton similar to TBMs. Again the lowest specific energy ever recorded by CSM for cutterheads or drill bits of this size.

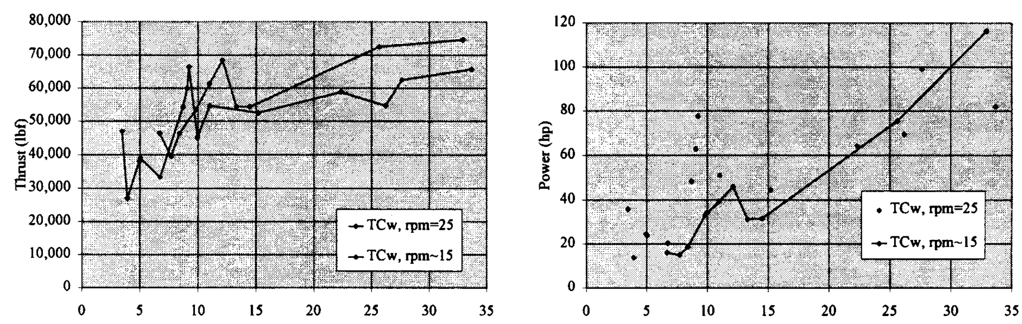

Figure 7. Performance of the 32 Inch Mini-Disc Cutterhead in 23,000 psi Rock

Figure 8 shows the cutterhead during test and Figure 9 shows the hole which was cut.

ADVANTAGES OVER CONVENTIONAL TOOLS

The tests described in this paper are only a few of an extensive test program. Both the carbide insert and the steel cutters have been extensively tested in various types of rocks with no failures. Only one cutter, a carbide insert type, was tested to destruction. It finally failed at 50,000 lbs thrust load. In actual practice, the penetration of the Mini-disc is so great that no more than an average of 15,000 lbs maximum should ever be required.

Figure 8. 32 Inch Cutterhead During Testing

Figure 9. Completed Test Hole in 23,000 psi Rock

Advantages over conventional tools for drilling, reaming and micro-tunneling are many, as follows:

Flexible Spacing - In a multi-disc rolling cutter, spacing is fixed by design. If the three rows are, for example, positioned at 3 inches apart; the customer can have his choice of 3 inch spacing, or 1.5 inch spacing. With the single disc, if rock conditions call for 1.65 or 3.3 inch spacing, the cutters can be thus positioned for optimum performance. Cutter mounts take up so little space, very close spacing are possible.

True Rolling - Multi-row cutters skid. Typically, the better quality multi-row cutters are tapered or conical in shape to minimize skidding. However, a cone can only be true rolling at a single radius. One company makes a whole series of cone angles to achieve as close as possible to true rolling throughout the cutterhead. However, the user's inventory must cover all cone angles.

Some manufacturers compromise having only one cone plus a "strawberry" cutter in the center. Others use a cone, a strawberry and a gage cutter. All cone shaped cutters skid, some worse than others depending upon how far off the ideal radius they are positioned. Even when true positioned, one disc may hit an imperfection in the rock and dominate the rolling velocity of the other two.

A small single disc cutter is always true rolling. Cutters are interchangeable from center to gage.

Higher Performance - If 6,000 lbs of force is placed on a three row cutter, each row or disc receives 2,000 lbs with which to indent the rock. With a single disc cutter, if thrust is 6,000 lbs, the disc receives 6,000 lbs to indent the rock. Performance, being about proportional to force per disc, is much greater with a single disc. The same size rig will drill larger holes with lower torque, power consumption and thrust.

Single Tracking - When multi-row cutters are used, they overlap. This is particularly true when smaller spacing are used. This results in more than one disc running in a single track or concentric kerf. Thus, while a single track disc may be penetrating say .1 inch, an overlapped, double tracking disc may penetrate at .05 inch. Forces and wear are thus not evenly balanced. Also, under these conditions there are more discs being used than are essential. Single tracking is the most efficient and cost effective cutting method.

Longer Wear - Because of the reasons above, minimal skidding, high performance (penetration) and single tracking, the single, true rolling cutter excavates more rock before it wears out. The Mini-disc carbide uses a complete ring, not buttons that turn or fall out. More carbide is used less discarded.

Ground Condition Tolerant - The same disc can be used in the hardest rock, in boulders and cobbles, in soft rock, coal, fire clay, and in free standing soil; all conditions but hydraulic soils. It is as close to the universal tool as science knows. A multi-row disc or button cutter tends to gum up in sticky ground. This will result in the cutter skidding and wearing a flat on one side. This will happen occasionally with a single disc too, but far less frequently. The tip of a disc cutter is sharp, like the prow of a ship and tends to push the dirt to the side. The multi-row cutter tends to pack the muck into the "valleys" between the discs and will gum up much quicker. Sometimes this packing causes a severe reduction of progress, sometimes skidding.

Low Cost Replacement - The strawberry cutter, commonly used in the center of a cutterhead must be burned off and a new assembly rewelded in place. Other multi-disc cutters which are saddle mounted are generally discarded whole. Some makes allow bearings or shaft parts to be reused. However rebuilding requires a shop with special tools. With the new Mini-disc, the cutter ring assembly is removed, discarded and replaced in the field with ordinary hand tools. One replacement cutter fits any position on the head. Figure 10 shows the assembly. Only five parts including a wear ring are involved.

Lower Initial Cost - The best news to a contractor is lower initial cost, as well as lower operating cost. All the advantages above, and yet a cutterhead with Mini-discs is less expensive than a cutterhead dressed with conventional cutters. If tungsten carbide inserts are required, the difference in cost is even more striking.

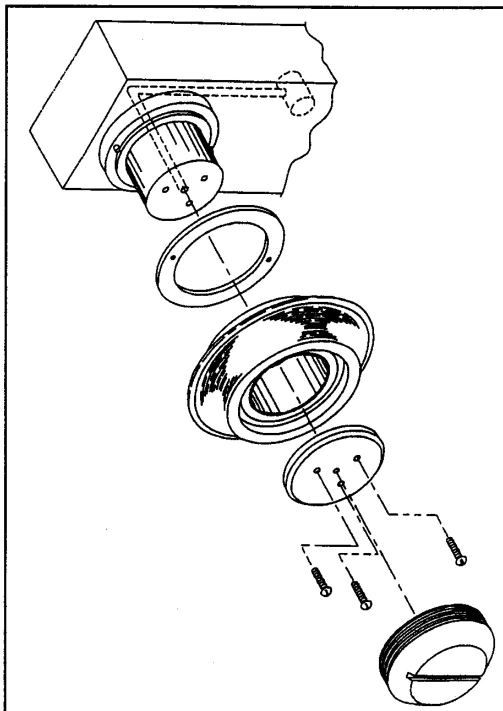

Figure 10. Mini-Disc Design Features

APPLICATION OF MINI-DISC CUTTER FOR MOBILE HARD ROCK EXCAVATOR

The mini-disc is highly suitable for application on mobile hard rock excavators. For the Exploratory Study Facility (ESF) at Yucca Mountain, Nevada, two feasibility and performance evaluation studies have been performed for mini-disc applications. From the main TBM tunnel alcoves will be excavated for scientific studies. The excavator for these alcoves must be compact and mobile with minimum disturbance to the activities in the main tunnel. For excavation of main test level openings at ESF, the potential application of mini-disc cutter roadheaders was examined. The main rock formation at ESF is welded tuff in which a large series of laboratory cutting tests have been performed with mini-discs. A standard roadheader with picks would not be able to cut this rock economically because of excessive bit wear, therefore a design and evaluation of a heavy-duty roadheader with mini-discs has been performed. Both of these feasibility studies gave very promising results, as discussed below.

MECHANICAL ALCOVE EXCAVATOR

It would be desirable to excavate the alcoves at ESF mechanically since blasting would not only damage the rock but would also require the dismounting of utilities and interfere with any activity further down the tunnel. Due to the special requirements, the excavator was designed to cut straight out from the main tunnel within a 12 ft by 12 ft transportation envelope. The power requirements on the alcove excavator has been kept to around 100 hp to minimize the size of the machine.

After several different cutting concepts had been studied for the excavation of the alcoves, a 6 ft drum appeared most promising. A concept drawing of the drum concept Mechanical Alcove Excavator is shown in figure 11. The performance and requirements of the excavator were investigated by developing a computer program based on data from prior mini-cutter tests. The drum plunges into the face a depth of 2.0 ft (0.61 m), it then slews across the top, moves downward, and slews across the bottom, covering the entire 11.5 by 21.3 ft (3.5 by 6.5 m) face. Upon completion of this action, an estimated 92 minutes, the plunge and slew procedure is repeated a second time. The machine is then "re-gripped". This is done using a hole drilled in the floor and set with hydraulic packers, rather than using bulky hydraulic grippers. After advancing the sliding platform 4.0 ft (1.2 m), two plunges can again be made. Total time for a complete cycle is estimated at 189 minutes (1.27 ft/hr, 0.39 m/hr).

Other interesting features of the machine include:

a) A hollow drum cutterhead which both cuts the rock and picks up the cuttings, transferring them by a short screw conveyor onto a 12 in. (0.30 m) transverse conveyor belt.

b) A 120 hp (90 kW) A.C. electric drive composed of two 60 hp (45 kW) motors.

c) Slewing by means of a 1.375 in. (35 mm) diameter cable powered by two winches.

d) A pantex lifting arrangement which maintains the axis of the cutterhead parallel to the axis of the tunnel.

e) A gripping technique consisting of a drill and two packer units.

f) Fluid spill mitigation incorporated in the design; electric drive, dry cutters, low oil volume, short hoses, catch trays, etc.

g) The roof, floor and ribs of the tunnel are smooth. Because of the slewing and pantex beam lifting device, no scallops are cut into the tunnel ribs (unlike a swinging action). Also the face is vertical, the most favored configuration for broken or highly fractured rock.

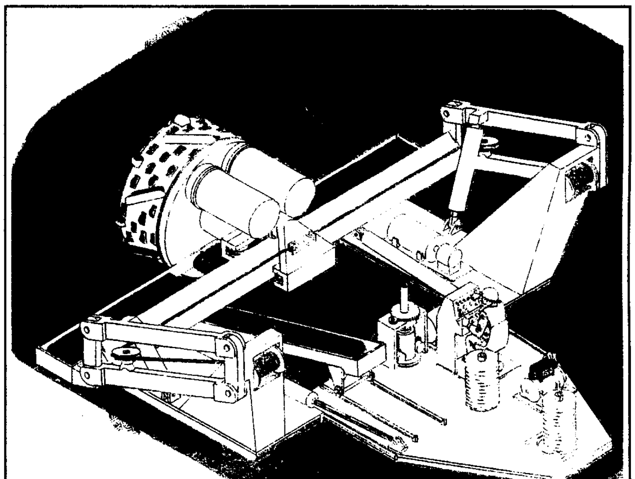

Figure 11. Mechanical Alcove Excavator

The configuration and performance of the Alcove Excavator make it suitable for excavating other side drifts and tunnels as may be required for the Exploratory Study Facility at Yucca Mountain. In the main test area a large number of tunnels will be excavated. By installing more power on this machine the test areas can be excavated quickly and a high production rate can be achieved. More power can be installed on the machine due to the fact that there will not be the same limitation on the size of the machine structure. One of the potential repository layouts suggests alcoves for storage of high-level radioactive waste and this excavator would be suitable for that purpose.

ROADHEADER APPLICATION

An extensive study was performed to investigate the technical and economic feasibility of using mini-disc cutters on heavy-duty roadheaders to excavate hard rock. A computer program was developed to evaluate various head shapes and cutter layouts using actual cutting data generated from laboratory testing of the mini-disc cutter. The results of the study have shown that heavy-duty roadheaders equipped with mini-discs can effectively attack and excavate hard-rock formations such as welded tuff in an economical manner. Laboratory tests will soon be performed with a roadheader cutting drum fitted with mini-discs. Following this will be a suite of field tests using a heavy-duty roadheader with mini-disc cutters. All studies and testing performed to date show great promise for this technology.

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