TESTING AND PERFORMANCE EVALUATION OF A 32 INCH CUTTERHEAD USING MINI DISC CUTTERS

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ABSTRACT

This paper presents the results of a laboratory test program to investigate the performance of a 32 inch diameter mini-disc cutterhead designed for hard-rock microtunneling applications. The cutterhead was fitted with twelve, 5-inch diameter mini-disc cutters. Laboratory testing and performance evaluation of the cutterhead was carried out at the rock boring laboratories of the Colorado School of Mines Earth Mechanics Institute (EMI). Tests were performed on samples of a limestone and a welded tuff formation. The mini-disc cutterhead was found to perform well beyond expectations, achieving very high rates of penetration in both rock types tested.

INTRODUCTION

Microtunneling is experiencing rapid growth worldwide. Because of its significant inherent advantages, microtunneling is becoming a more widely accepted technique in comparison to trenching techniques for the construction of utility, sewer and other types of tunnels, particularly in urban areas. Unlike surface trenching, microtunneling causes practically no surface disturbance, a very attractive feature for urban tunneling. It is estimated that the microtunneling market in the US is expanding at an annual rate of about 30 percent as the technology continues to improve and as potential buyers become aware of the significant advantages offered by microtunneling techniques.

Despite its tremendous market growth, microtunneling is still primarily restricted to application in soils and softer materials. The current technology of equipment in the field is not capable of effectively attacking hard rock. Furthermore, microtunneling machines usually encounter severe difficulties in mixed ground conditions where large hard boulders may be present. In such cases, the boulders have to be removed by sinking shafts or the tunnel alignment has to be altered, both options requiring additional time and cost. Hence, the microtunneling industry has been searching for a means of economically tunneling through hard ground or large rock boulders intermixed with soils.

In response to the needs of the microtunneling industry, EEA has designed and fabricated a prototype 32-inch diameter cutterhead fitted with the recently developed 5-inch diameter mini-disc cutters. Testing and performance evaluation of the mini-disc cutterhead was performed at EMI laboratories at the Colorado School of Mines. Testing was carried out in samples of two hard rock formations, the Indiana Limestone and the Tiva Canyon Springs Welded Tuff.

OBJECTIVES

The primary objective of the test program with the mini-disc cutterhead was fourfold:

1. To observe the physical operation of the cutterhead, cutters and muck collection buckets.

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2. To develop cutterhead performance data in terms of thrust, torque and power as a function of penetration rate.
3. To monitor and observe any wear to mini-disc cutters during the boring process.
4. To validate the computer models used in the design, performance evaluation and balancing of the mini-disc cutterhead.

In addition to these main objectives, the test program was also intended to produce cuttings for size analysis, as well as to check the operational stability of the cutterhead in terms of smoothness of operation.

LABORATORY TESTING

Test Equipment

Laboratory testing of the 32 inch mini-disc cutterhead was performed on the Drill Test Fixture (DTF). The DTF features a high-torque hydraulic drive system with variable speed capability up to 60 rpm. Cutterhead thrust is provided with a hydraulic actuator capable of generating up to 200,000 lb. of force. A swivel mounted on the backside of the drive system can be used for vacuum muck pickup or for routing cooling and dust suppression water to the cutterhead. The DTF has the thrust and power capacity to allow testing of cutterheads or drill bits up to 3 ft. in diameter.

Data Acquisition

The DTF is instrumented to measure thrust, torque, rotation rate and the rate of penetration during testing. Signals from various transducers are fed to a computer-based data acquisition and analysis system. This system is designed to provide real-time data display, as well as instantaneous output of data summaries upon completion of a test. With an added capability of allowing full analysis of test data in terms of interrelationships of various test parameters and the statistical evaluation of data acquired.

Rock Samples

Testing of the 32 inch mini-disc cutterhead was carried out in two rock types, Indiana Limestone (IL) and Tiva Canyon Welded Tuff (TCw). The uniaxial compressive strength of these rocks was 9,000 and 24,000 psi respectively. The TCw rock was used extensively in previous rock cutting research performed at EMI. Due to its "spongy" characteristic, (i.e. lack of the brittleness that is typical of hard rocks), TCw rock was found to respond to mechanical cutting as a rock type of a higher compressive strength. From the analysis of previously obtained cutting data it was found that the TCw formation behaves more like a rock having a compressive strength of around 30,000 psi.

The large samples of rock to be tested were cast in concrete with steel reinforcement to ensure proper support and confinement during testing. After curing, the cast samples were mounted on the DTF for the boring tests.

Mini-Disc Cutterhead

The cutterhead (Figure 1) is of the closed or shielded design, patterned after cutterheads designed for full-face tunneling in broken rock and mixed face conditions. The face shielding is intended to avoid the possibility of cutters being torn-off by broken rock and boulders. In operation, loose rock is held back and supported by the shield while the cutters break them into pieces small enough for passage through the muck buckets into the muck transport system. The cutterhead was fitted with radial muck pickup slots designed to capture a large portion of the muck generated before it falls to the invert. This is intended to minimize muck regrinding and thereby reduce gage cutter wear and cutterhead friction.

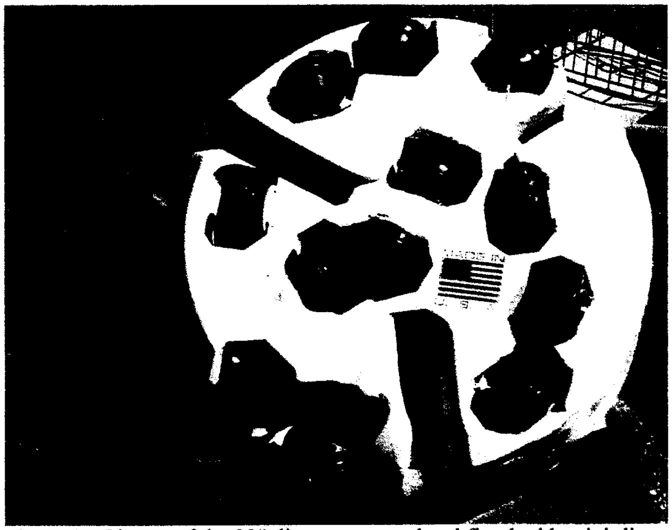

Figure 1. Picture of the 32" diameter cutter head fitted with mini-disc cutters.

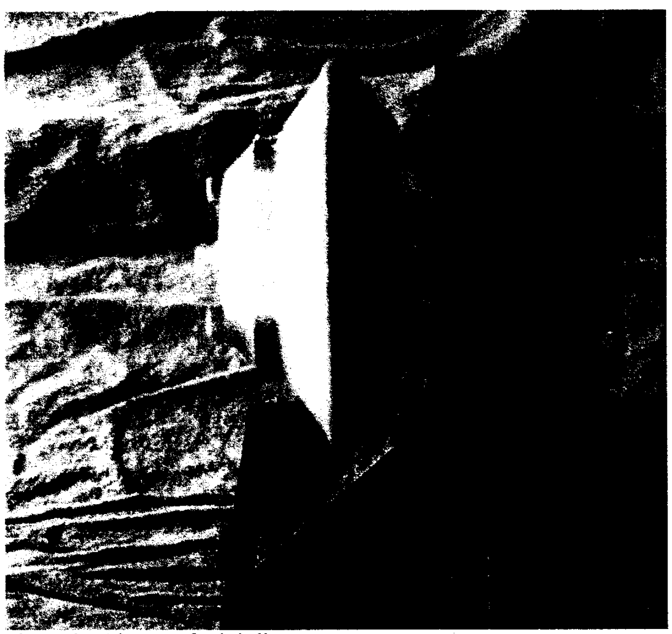

Figure 2. Picture of mini-disc cutter.

The mini-disc cutter was developed over a nearly two year period and was designed to provide a high performance and cost effective cutting tool (Figure 2). The primary challenge in this development was to find a bearing structure which would withstand the 30,000 lb. of load required to attack the hardest rock and to resist shock loading when a boulder is encountered. In addition, the cutter is designed for low cost and easy maintenance. When the ring wears out, it is simply removed and a new one mounted. This process automatically replaces the bearing and seal. All wear components are contained within the single cutter ring assembly.

Cutters were arranged in a double-spiral pattern with an average face spacing of about 2 inches. All cutters were fitted with the steel cutting rings, except for those at positions #3 and #12 which had carbide-insert rings. The purpose of using a mixture of steel and carbide-insert rings was to evaluate their relative wear performance during boring of the hard rock formations utilized in this test program.

After mounting the cutterhead on the DTF, the data acquisition and control system was checked for proper operation. Collaring of the sample was then commenced, it was continued until all of the cutters had established contact with the rock. Collaring was performed at a reduced machine thrust and rpm to ensure proper hole alignment and to avoid any cutter overloading which might result in premature damage.

Test Procedures

After collaring, testing of the mini-disc cutterhead was initiated (Figure 3). As stated previously, the primary objective of the test program was to develop sufficient data to evaluate the boring performance of the mini-disc cutterhead as well as to observe its operation with regards to cutterhead functioning, rock cutting and muck removal. These latter issues are as important to the success of the cutterhead in the field as is the performance data. Several aspects of the cutterhead design were considered critical to achieving its desired cutting efficiency.

Figure 3. The rock sample after several tests with mini-disc cutterhead.

1. Operational smoothness of the cutterhead by direct observation during testing.
2. Clearance between the face shield and the rock face.
3. Design of the cutterhead to keep the face clean during cutting.
4. Clearance between the face muck buckets and the rock face.
5. Proper cleaning of the face by the face muck buckets.
6. Proper cleaning of the invert by the side buckets.
7. Relationship between cutterhead rotational speed and efficiency of mucking.
8. The face tracking and cutterhead profile, as well as cut spacing and proper chipping between the adjacent cuts.

During and after testing the cutters were checked for any cutter wear or failure. Each test consisted of running the cutterhead at a preselected thrust and rotational speed. The test program included a total of 44 tests with 14 in the Indiana Limestone and 30 in the Tiva Canyon Welded Tuff.

TEST RESULTS AND DISCUSSION

The most interesting test results are presented in Figure 4 - 6. Figures 4 and 5 shows the tests results in Indiana Limestone and Figures 6 and 7 those in Tiva Canyon Welded Tuff. The graphs show the variation of penetration rate with thrust and power for two rotation rates in each rock type. Once a threshold thrust is exceeded a small increase in thrust will result in a substantial increase in the rate of penetration (Figures 4 and 6). That is, once chipping between adjacent cutting paths begins to occur and the rock cutting process enters its efficient operating regime a small thrust increase will result in a large increase in penetration rate. This is typical of rock excavation with disc cutters. For mini-disc cutters the threshold of efficient cutting force occurs at a significantly lower thrust value than for large disc cutters. In contrast, for a 17 inch cutter testing in welded tuff, efficient interaction between adjacent cutter paths was not seen to occur until a cutter load of approximately 20,000 lb. was reached.

Indiana Limestone

The mini-disc head was able to achieve very high rates of penetration with relatively low thrust requirements (Figure 4). For example, at 25 rpm, a penetration rate of 30 ft/hr was achieved at a cutterhead thrust of only 40,000 lb (Figure 4). Assuming even loading of cutters, this means the average cutter loading was 3,300 lb per cutter which is a fraction of what would be required with the standard size disc cutters. An important result is that similar to thrust, a cutterhead fitted with the mini-disc cutters would also need a very low torque compared to cutting with the standard, large size disc cutters presently employed on mechanical excavation equipment. Low torque means low power which accounts for nearly all the energy consumed in rock excavation. As shown in Figure 5, the mini-disc cutterhead was able to attain high boring rates with very low power requirements. Only 80 hp was required to maintain a penetration rate of 30 ft/hr in Indiana Limestone (Figure 5). Low thrust and power requirements as experienced with the test cutterhead have significant implications in the design of machinery utilizing this technology. Machine structure, size and weight requirements are dictated by the thrust, torque and resultant power requirements of the cutterhead. Thus significant cost benefits can be gained by the low torque and thrust needs of this cutterhead. Specific energy is the amount of energy required to excavate a unit volume of rock. In mechanical excavation systems, the specific energy is commonly used as an accurate indicator of the systems efficiency. Naturally, the lower the specific energy requirements, the more efficient the rock excavation system becomes. For the mini-disc head in Indiana Limestone, the average specific energy was 12 hp-hr/cyd of rock excavated. This low value further verifies the high cutting efficiency of the mini-disc cutters.

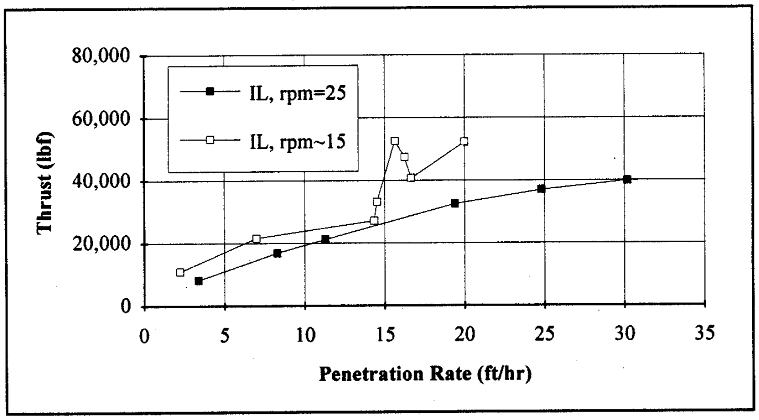

Figure 4. Plot of Thrust Vs. Penetration rate for Indiana Limestone

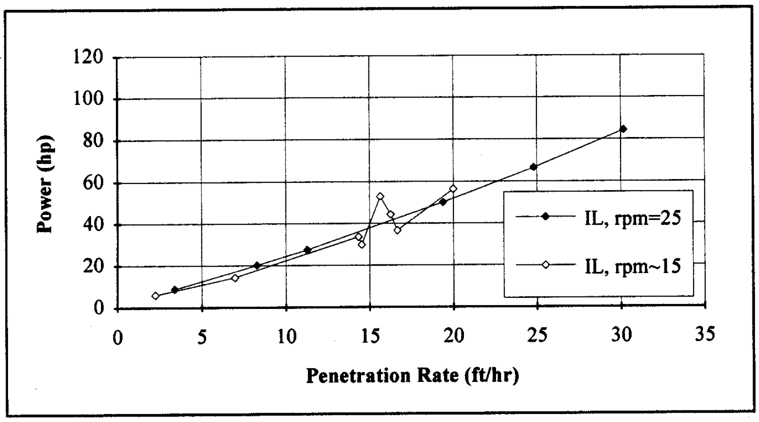

Figure 5. Plot of Power Vs. Penetration rate for Indiana Limestone.

Tiva Canyon Welded Tuff

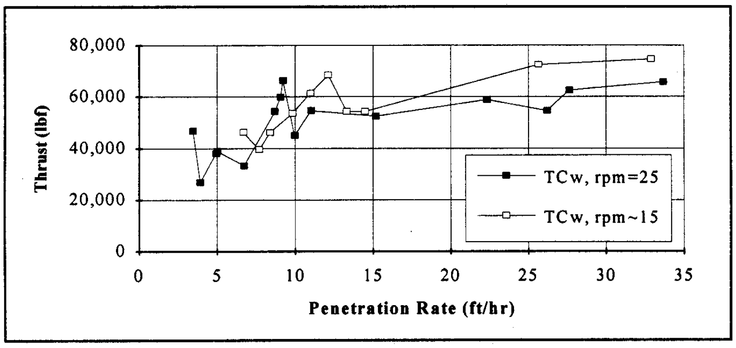

Figure 6. Plot of Thrust Vs. Penetration rate for Tiva Canyon Welded Tuff.

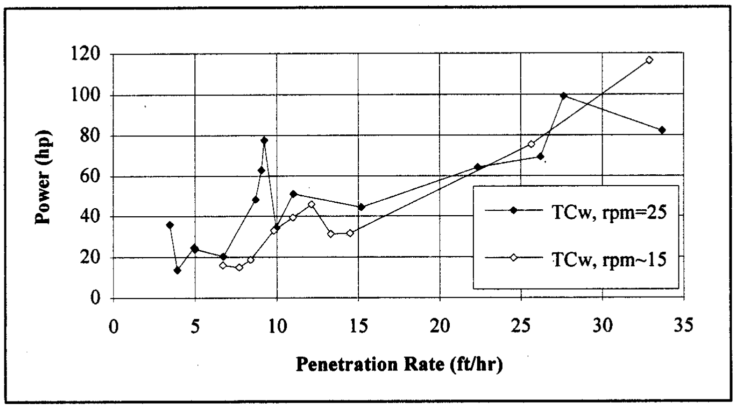

Figure 7. Plot of Power Vs. Penetration rate for Tiva Canyon Welded Tuff.

In the Tiva Canyon Welded Tuff sample the mini-disc cutterhead was able to achieve a penetration rate of approximately 33.5 ft/hr at a total cutterhead thrust of 65,000 lb at 25 rpm (Figure 6). This results in an average cutter loading of less than 5,500 lb per cutter. In contrast, when linear cutting tests were performed in this same rock with a 17 inch commercial size cutter the thrust to achieve the same depth of penetration was above 40,000 lb.

For the mini-disc cutterhead at 25 rpm, a 33.5 ft/hr rate of penetration only required a cutterhead torque of about 20,000 ft-lb., again confirming the very low torque requirements of the mini-disc cutters. Similarly, the cutterhead power requirements for the mini-disc head were found to be exceptionally low for excavation of welded tuff (Figure 7). At a cutterhead rotational speed of 25 rpm less than 90 hp was required to achieve a penetration rate of 33.5 ft/hr. The specific energy is again low, further confirming the very high cutting efficiency of mini-disc cutters as employed on the 32-inch cutterhead.

TEST OBSERVATIONS

As noted earlier in the test objectives and the procedures sections, in addition to acquiring performance data, a significant purpose of the test program was to observe the operation of the mini-disc cutterhead during testing. These observations were considered crucial to fully understanding and assessing the operational efficiency of the cutterhead. The most important observations made during testing included the following:

1. The cutterhead operation during the entire test program was extremely smooth, meaning it was well balanced and the cutter spacing and layout were properly selected. No unusual vibrations occurred during testing at different rotational speeds or cutterhead thrusts.
2. The clearance between the face plating and the rock surface was found to be adequate. No scouring was detected on the cutterhead plate. Very little paint was removed during the test series.
3. No packing of muck occurred on the cutterhead during boring.
4. The clearance between the face mounted muck buckets and the rock surface was correct as little wear was noticed on the bucket lips.
5. The position and size of the face muck buckets was correct. As was intended, the face mounted buckets were able to ingest a significant portion of the cuttings before they fell into the invert. This meant very little regrinding of muck in the invert and therefore, much lower torque consumption due to the reduced regrinding. It was estimated that only 20 percent of the muck fell to the invert.
6. The side buckets were also observed to operate satisfactorily, picking up any muck left in the invert by the face muck buckets. The invert received very little.
7. The preferred cutterhead speed of 25 rpm, as well as the optional cutterhead speed of 15 rpm, were found satisfactory for efficient mucking.
8. All cutters tracked properly and concentrically according to design profile (Figure 8).

No cutter failure or wear occurred during the entire test program. All cutters functioned properly. One cutter, No. 8, lost a hubcap during testing. Interestingly, the hubcap was picked up by a bucket immediately and was reinstalled. Its loss was not noted until after the test. The bearings and seals appeared to be unaffected by the test series. The carbide-insert cutters were in excellent condition. A small amount of scuffing was noted on cutters 1 through 6, but not on the carbide cutter installed in position 3.

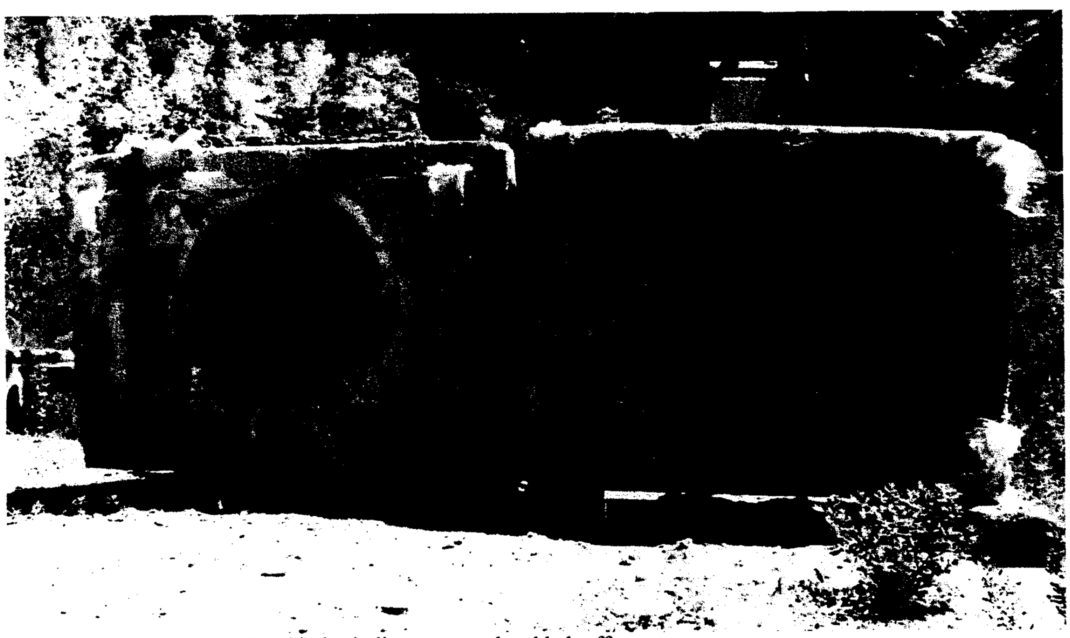

Figure 8. Picture of completed holes in limestone and welded tuff.

CONCLUSIONS

The mini-disc cutterhead performed well above expectations. The penetration rates attained in the two rock types tested were significantly higher than was estimated from computer models beforehand. The torque and power requirements to attain a given rate of penetration were also lower than expected. The high efficiency of mini-discs was further verified by the very low specific energy of excavation obtained from full-scale tests in the laboratory. In the 24,000 psi welded tuff, a penetration rate of 33 ft/hr. was achieved at 25 rpm with a total cutterhead thrust of only 65,000 lb. The power required to sustain this rate was less than 90 hp. As expected, the performance was even better in the 9,000 psi limestone where a penetration rate of 30 ft/hr was achieved at 25 rpm with a cutterhead thrust of around 40,000 lb. The cutterhead operation during the entire test program was extremely smooth due to proper balancing of the head and the correct selection of cutter spacing and layout. No unusual vibrations occurred during testing. The cutterhead face plate was free of scouring, indicating adequate clearance between the rock surface and the face plate. No packing of muck was found to occur on the cutterhead during testing. Test observations indicated that approximately 80 percent of the muck generated during boring was picked up by the face positioned muck buckets before falling to the invert. The side muck buckets were also found to operate satisfactorily, picking up any muck left in the invert by the face buckets.

All cutters tracked properly and concentrically according to design profile. No cutter failure or significant wear occurred during the entire test program. In particular, the two carbide-insert cutters mounted on the head were in excellent condition.

In summary, the test program was extremely successful in demonstrating the very high cutting efficiency of mini-disc cutters for microtunneling applications.

REFERENCES

Ozdemir, L. and Rostami, J. Testing and Performance Evaluation of 32-inch Diameter Mini-disc Cutterhead for Micro Tunneling Applications, Earth Mechanics Institute, Colorado School of Mines, Report to Excavation Engineering Associates Inc., September (1993).