11

TBM Advances

Chairman
L. Ozdemir
Colorado School of Mines
Golden, CO

Chapter 49

An Update on the Performance of Large Diameter (483mm) Cutters and High Performance TBMs

Gerald Dollinger, PhD., Manager Rock Mechanics Lab
Sigurdur Finnsson, Application Engineer
David Krauter, Design Engineer, Cutters
The Robbins Company, Kent, WA

Abstract

The paper is a follow up to a 1991 RETC paper on the development of large diameter cutters. At the outset, a short summary of all of the projects completed to date by Robbins high performance (HP) TBMs is presented. Secondly, the experiences and associated design improvements, with special attention being given to cutterhead profiles, is discussed. The paper concludes with a summary of the results with HP TBMs to date and ends with a discussion of the present state of the art with respect to large diameter disk cutters.

Introduction

In a paper presented at the 1991 RETC, the development of large diameter (483mm) cutters for high performance TBMs was discussed. These cutters have a bearing capacity of 311kN and are designed for improved performance under hard rock conditions. In the presentation, the detrimental effects of the expected increase in cutter tip width, cutter diameter, and spacing between cutter paths was weighed against the beneficial effects of increased cutter loading. It was concluded that an overall improvement in performance could be expected. It was also noted that the larger size of the 483mm cutter should help to increase the wear life of the rings.

The paper also pointed out some of the problems that had occurred with the use of the larger diameter cutters in the field on the 1410-251 TBM and discussed some of the remedies to these problems that were being proposed and implemented at that time. Among these problems was a marked increase in the number of blocked cutters on the head, particularly in the transition area between the face and gage cutters. This was attributed to cutter change policies that resulted in overloaded cutters and to problems with the cutterhead profile.

In the present paper, the recent field experiences with the new generation of high performance TBMs will be summarized and discussed. Of particular interest will be the effect of cutterhead profiles on cutter usage on the head.

Summary of High Performance TBM projects.

The following table lists some of the particulars of the six tunnel projects completed with Robbins High Performance TBMs to date. All the projects with the exception of TBM 152-261, which bored in Hong Kong, are located in Norway.

Table 1. Summary of Projects.

TBM MODEL	PROJECT	DIAMETER [m]	LENGTH [m]	BORING PERIOD
1410-251	Svartisen	4.3	6,021	09.89 - 10.90
1410-251-1	Svartisen	5.0	7,816	01.91 - 07.92
1410-252	Svartisen	4.3	11,861	09.89 - 04.91
1215-257	Svartisen	3.5	8,219	07.90 - 04.92
152-261	Cable Tunnel	4.8	5,253	03.91 - 02.92
1215-265	Meråker	3.5	10,120	09.91 - 08.92

It should be noted that the 1410-251 and 1410-252 TBMs are identical and the tunnel design called for an increase in diameter along 1410-251 TBM drive. Once the TBM had finished the first portion of its drive, the diameter of the machine was changed to 5.0m. Hence the 1410-251-1 notation.

The second table lists some of the specifications of the TBMs.

Table 2. General TBM specifications.

TBM MODEL	CUTTERHEAD POWER [kW]	NUMBER OF CUTTERS	CUTTERHEAD RPM	CUTTERHEAD THRUST [kN]
1410-251	2,345	29	11.94	9,031
1410-251-1	2,345	33	11.94	10,277
1410-252	2,345	29	11.94	9,031
1215-257	1,340	25	12.5	7,786
152-261	2,345	32	11.5	9,966
1215-265	1,340	25	13.4	7,786

All of the above machines were specified to accommodate a certain cutterhead diameter range. TBMs 251, 252 and 261, which were based on similar design principles, can range from 4.3m to 5.0m in diameter. The 257 and 265 machines which were of a comparable design, can range from 3.5 to 4.2m. Since the TBMs are designed according to the upper limit of those ranges, a direct comparison in terms of installed cutterhead power, based on the above table is somewhat difficult.

TBM Performance

Both the 251 and 252 machines were capable of boring at 32 tonnes per cutter when ground conditions were perfect. In poor ground conditions, however, the operating crews were reluctant to bore at the

maximum cutter loads and, instead, operated at 22 to 28 tonnes per cutter. Even under these conditions both machines averaged between 3.6 and 3.8 m/hr in 55 to 205 MPa mica and quartz-mica schist and gneiss. The 1410-252 machine holds four world performance records for TBMs in the 4.0 to 5.0m range. These include best shift, best day, best week and most excavated material in 24 hrs.

Because of high cutter bearing usage in the transition positions on the 251 machine, the cutterhead profile on 251-1 was modified by adding two cutters. The result of this modification was a reduction in the incidence of failed bearings. In spite of this modification, there was still a reluctance to operate the machine at the maximum cutter load. The average performance of this TBM in the mica and quartz-mica schists was 2.7-2.8 m/hr.

Based on the experiences with the 251 and 252 machines, the cutterhead profile for the 257 machine was modified to allow maximum cutter load in most rock conditions. The average performance of this machine was 3.6 to 3.7 m/hr. For a period of time this TBM held a number of Norwegian performance records. These, however, were later eclipsed by the 265 machine.

The 261 TBM was the first hard rock machine to bore in Hong Kong. The geology of the tunnel consisted mostly of massive granites, with unconfined compressive strengths up to 320 MPa. The knowledge gained from the previous high powered TBM projects was used in the design of this machine to further optimize the cutterhead profile. As a result, the cutter bearing usage was greatly reduced. Unfortunately, the number of cutter changes in the gage positions increased, resulting in increased downtime for changes in these positions. This TBM averaged between 2.8 and 3.0 m/hr and bored at cutter loads above 28 t/cutter much of the time.

The 265 machine benefitted from the experience of the previous four HP machines and had a much improved cutterhead design. This profile allowed the machine to bore at 32 tonnes in a wide range of rock conditions. The geology at the site consisted of a mix of metagabbro, greywacke and greenstone ranging in strength from 130 to 215 MPa. The TBM averaged between 6.3 and 6.5 m/hr and holds numerous world tunnelling records. The machine bored over a 1000m in its first month of operation.

Cutter Usage and Cutterhead Design of High Performance TBMs

In the 1991 RETC paper, it was noted that cutter change data for both 251 and 252 TBMs showed that both machines had higher than expected bearing usage in the transition positions on the cutterhead. This increased usage for the 251 machine is shown in Figure 1, which gives the percent of total bearing usage that occurred in each cutter position on the cutterhead. Analysis of bearing usage on the 252 machine, with the same cutterhead design, showed a similar pattern.

In addition to the high bearing usage in the transition positions, the cutter change data for both machines showed a lower average rolling distance life for cutters with normal wear in these positions. This reduction in rolling distance life for the 251 machine is shown in Figure 2. In this figure, the average rolling distance life for the cutters is given in terms of the percent of the average rolling distance for all of the worn cutters on the cutterhead. A similar rolling distance life pattern was observed for the 252 machine.

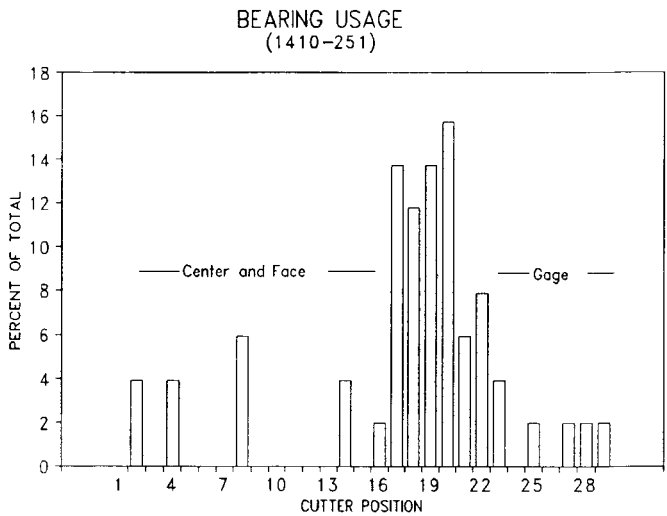

Figure 1. Percent Bearing Usage for 1410-251.

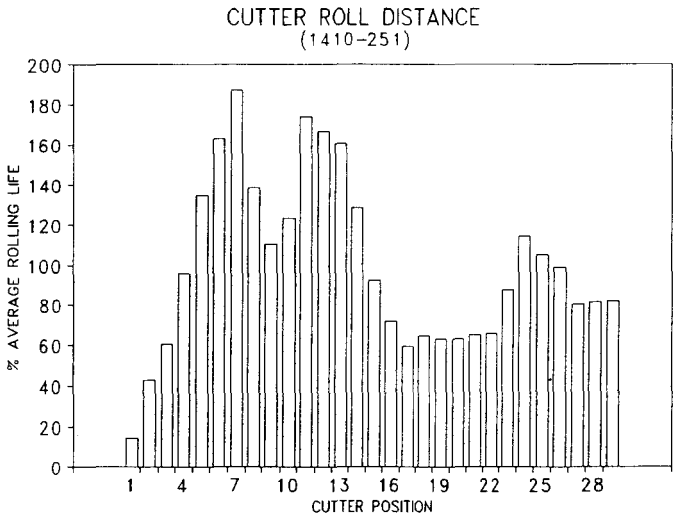

Figure 2. Percent Average Rolling Distance Life for Worn Cutters on 1410-251.

The increased bearing usage and reduced wear life of the cutters in the transition positions is attributed to higher than average loads on the cutters. One reason for this was that the initial cutter change procedures allowed cutters with new rings to be placed in positions adjacent to cutters with highly worn rings. This produced high loads on the new cutters because of their greater penetration into the rock during boring. To rectify this problem new cutter change procedures were implemented which required the cutters in both the transition and gage positions to be changed when the difference in the height of adjacent rings reached a maximum value. This procedure was successful in reducing the bearing usage at both machine sites and has been used on all high performance TBMs. Since that time it has also been determined that some of the early high bearing usage on these two machines was due to the use of defective bearings with soft rollers.

The increased cutter wear rate wear in the transition positions, however, suggests that the cutterhead design may have also contributed to the higher loads on the transition cutters. This hypothesis was tested in the field by measuring the cutter loads on selected cutters using strain

gages mounted on the cutter shafts. It was also tested by calculating the theoretical cutter loads for the 251 and 252 cutterhead design using cutter load models developed within The Robbins Company. The results of both the field measurements and the model calculations is shown in Figure 3. It is clear from this figure that both the measurements and the model support the view that higher cutter loads existed in the transition positions than in the other positions on the head.

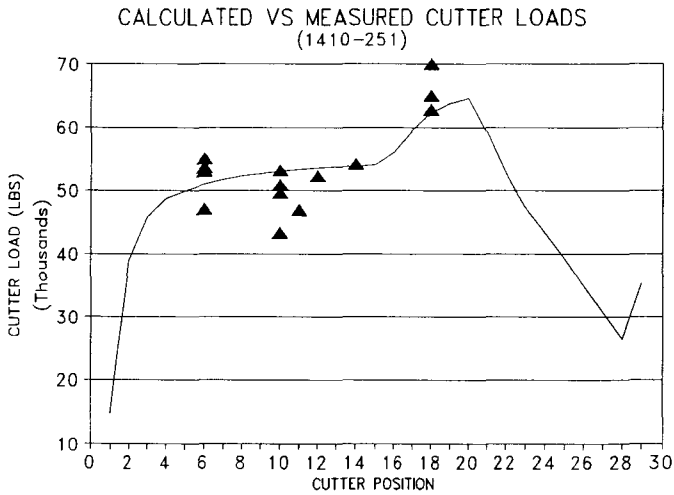

Figure 3. Calculated and Field Measured Cutter Loads for 1410-251.

Based on the cutter usage data for the 251 and 252 machines, changes were made in the cutterhead designs for the 257 and 261 TBMs to reduced the cutter loads in the transition positions. The effect of these changes on the calculated cutter loads for the 261 machine is shown in Figure 4. On this graph, the cutter loads are given as the percent of the average cutter load for the entire cutterhead.

In contrast to the cutter load profile for the 251/252 cutterhead (Figure 3), the 261 profile shows an even cutter load distribution for both the face and gage cutters. The effect of this profile design on the bearing usage for the 261 machine is shown in Figure 5. It is clear from this figure, that a nearly random distribution of bearing usage occurred on the cutterhead. In addition, the total bearing usage was greatly reduced.

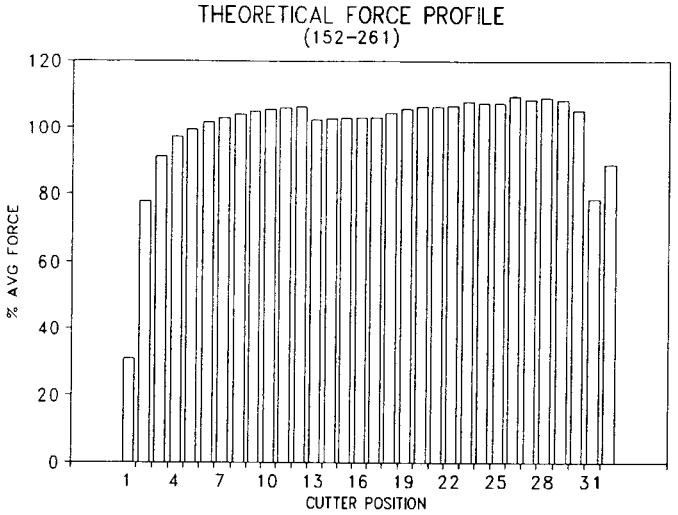

Figure 4. Calculated Cutter Loads as Percent Average Load for 152-261.

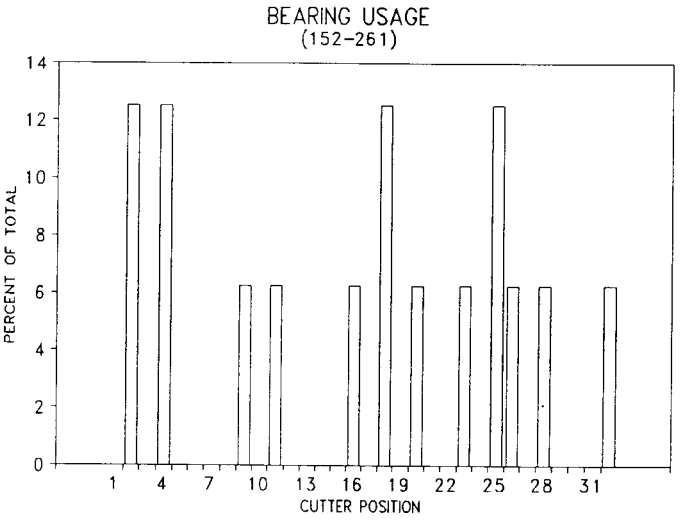

Figure 5. Percent Bearing Usage for 152-261.

Analysis of the rolling distance life for worn cutters on the 261 machine, however, showed that the rolling distance life of the gage cutters was lower than that of the both face and transition cutters. This can be partially explained by the fact that these cutters skid more than other cutters because they cut a helical path and it may be related to the fact that they pass through broken rock in the invert. In addition, there is a lower wear allowance in these positions. Along with these contributing factors, it was believed that the increased wear rate of these cutters was related to the high loads on the cutters as predicted by the theoretical load calculations.

In the design of the cutterhead for the 265 TBM, modifications were made in the location of the gage cutters so that the calculated loads in these positions would gradually decrease outward. The distribution of the theoretical cutter loads for this cutterhead design is shown in Figure 6.

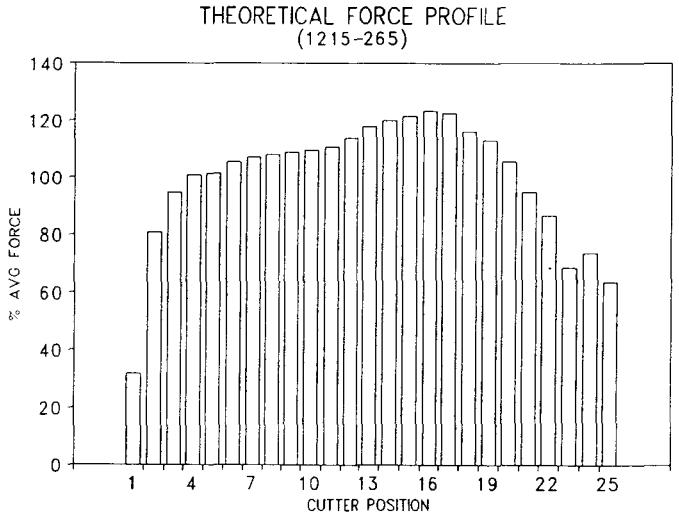

Figure 6. Calculated Cutter Loads as Percent Average C utter Load for 1215-265.

The result of this new cutterhead design on the bearing usage for the 265 machine is shown in Figure 7, and on the average cutter rolling distance life in Figure 8. Although two cutters in the transition positions show higher than normal bearing usage, the overall pattern of bearing usage on the 265 machine is much more evenly distributed than on the 251 and 252 machines. The number of costly interruptions to change blocked cutters was greatly reduced.

As expected, the average rolling distance life of the cutters increased across the cutterhead and reached its maximum value in the outside gage positions. This resulted in fewer cutter changes in these positions, where removing the cutters is more difficult and time consuming than changing face cutters. It also indicates that the normal loads on the cutters may be the most important factor in determining the rate of cutter ring wear in the gage positions.

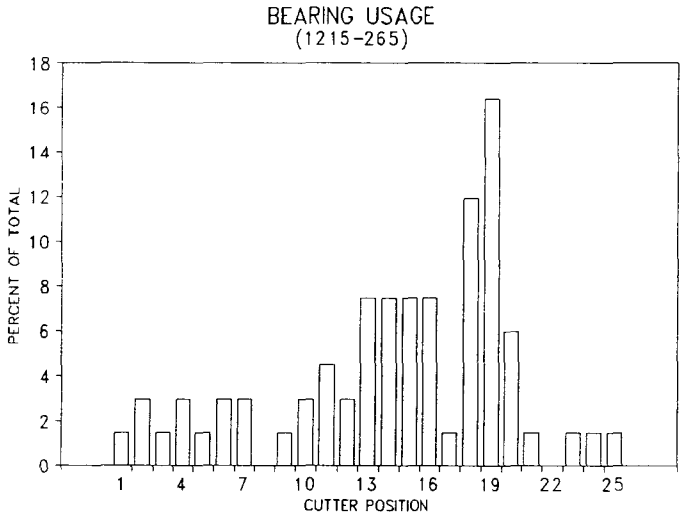

Figure 7. Percent Bearing Usage for 1215-265.

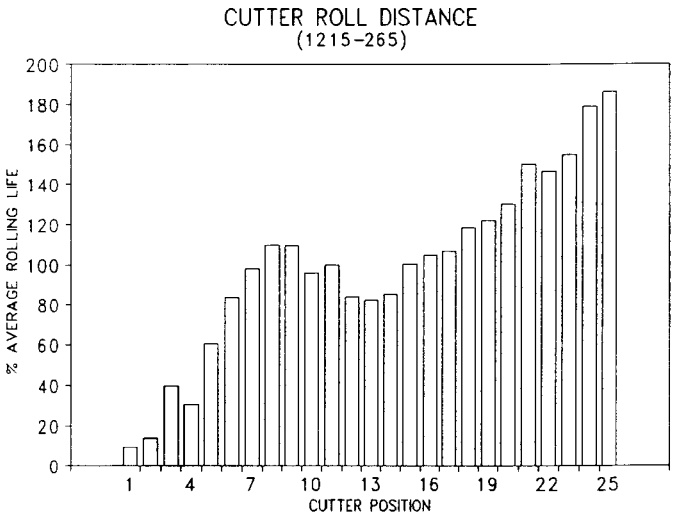

Figure 8. Percent Average Rolling Distance Life for Worn Cutters on 1215-265.

Cutter Housing Improvements.

The wedge lock cutter housing design has also proven far superior to the older V-Block style housings. The costs, for housing bolts and housings have dropped by about a factor of ten. The problem of broken and loose bolts has been virtually eliminated. It is noteworthy, that not a single housing has had to be replaced on all of the six projects. It should be pointed out that never before has so much tunnel been bored without having to replace housings. This has resulted in much time and money being saved by the contractors. The reason for this improvement is the isolation of the housing bolts from the severe cutter loads by means of a wedge clamping the shaft to the housing. This prevents the bolts from breaking and the housings from destruction. The wedge lock design can also be used on back loading housing designs and is currently offered for both the 432 and 483 mm cutters.

Cutter Changes

When the 483mm diameter cutter was first introduced, it was feared that cutter change time would be unacceptably high. This has proven not

to be the case, with the cutter change time ranging between 20 and 50 minutes depending on the cutter position and, more importantly, the skill and motivation of the changing crew. This short cutter change time for large diameter cutters was made possible by the ingenuity of the 251 and 252 crews who developed a simple, safe and rugged cutter changing system. Experience has shown that the most efficient cutter change systems come from the people who actually change the cutters and not from the drawing board. In underground excavation, it is most often the simple systems that work the best while more elaborate and complex systems get abandoned.

Summary and Conclusions.

This paper has illustrated that over the course of the design and operation of the five HP TBMs, continuous development has been taking place. Most of the development effort has been focused on the actual rock cutting aspects of the machines and on the design of the cutterhead.

There has also been, and continues to be, research focused on the cutters. The cutters essentially consist of the hub assembly and the disc ring. During the course of some 49 km bored, it is apparent that the hub assemblies, i.e. the bearings, seals, shafts and hubs, have performed much better than older generation cutters. Problems in these areas occur much less frequently and overall these assemblies are very reliable.

The cutter ring itself, is where the next gains are likely to be made. There is continued effort in researching materials and processes that fulfill the paradoxical requirements of hardness and toughness. Various ring geometries are also being investigated for the optimum ring profile. This development might be the topic of a separate paper and will not be covered any further in this discussion.

To summarize, the role of cutterhead profiles and how the resulting loads influence cutter and machine performance has been discussed and it is evident that gains have been made and our understanding of the most influential factors continues to grow. It is anticipated that this knowledge will benefit the next HP machines to be built. We can safely say that a new generation of TBMs has arrived and these machines have proven their capabilities in comparison to their older counterparts. However, further work remains to be done to optimize the performance of these machines in terms of advance rates and cutter costs. These tasks are continually being worked on.