Large-Diameter 20-Inch Disc Cutters: A Comparison of Tool Life and Performance on Hard Rock TBMs

Stephen Smading ▪ The Robbins Company

ABSTRACT

Optimization of disc cutter life and penetration rate in hard rock can be one of the biggest predictors of project success. With hard rock TBMs being used today in ever more difficult conditions and longer tunnels, the question of which type of disc cutter to be used becomes critical. At one such project in Northeastern China, varying disc cutter tool steels and sizes were put to the test on a total of nine different 8.5m diameter hard rock, Main Beam TBMs from various manufacturers. The TBMs excavated sections of a vast water tunnel in similar granitic geology.

This paper will look at the development of 20-inch disc cutters and the case for large diameter cutters, using the most recent example in China as a focus area of study. Varying advance rates, cutter life, tool steels, and challenges excavating the rock will be discussed. The paper will conclude with recommendations for optimal cutter life in TBMs destined to bore long tunnels in hard rock.

HISTORY

When the author began his career in 1980, TBMs featured 14 and 15.5 inch diameter cutters. The 15.5 inch cutter was an improvement over the 14 inch with a larger bearing set and its corresponding increase in thrust capacity. Shortly thereafter the 15.5 inch cutter was expanded to 17 inches by mounting a larger diameter disc on the same bearing set. While the thrust capacity of the cutter hadn't changed, the premise was that the 17 inch disc, with increased sacrificial material, would increase the mean time between cutter changes. This proved to be the case and the 17 inch cutter became the de facto standard even after the 19 inch cutter was developed in the late 1980s for the Svartisen Hydroelectric Project in Norway.

The TBMs employed at Svartisen were the first "high performance" TBMs. These HP TBMs were designed with both increased thrust and cutterhead power compared with earlier machines. While the 19 inch cutter featured increased thrust capacity, the material of the disc, the chrome/moly/nickel steel historically used, was not up to the task. It was not until the introduction of tool steel, and later modified tool steel, that the benefits of increased thrust capacity were able to be fully realized. While the benefits of 19 inch cutters were clear to the contractors actually using them, it would be at least fifteen years before they were generally accepted by the industry.

INCREASING CUTTER SIZE

There are two distinct benefits to be realized by employing larger cutters; higher thrust capacity and longer wear life.

Higher thrust capacity enables efficient boring in harder formations. To efficiently cut rock, the thrust force applied to an individual cutter must overcome the penetration resistance of the rock and initiate chip formation. Once the critical pressure has been achieved, penetration increases rapidly with a relatively small increase in cutter load. The critical pressure increases with rock strength and it is primarily for this reason that larger cutters have been developed to bore in harder rock. This principle is illustrated in Figure 1.

Longer wear life is the result of an increased volume of sacrificial material in the larger diameter disc ring. The migration from 19 inch to 20 inch on the same bearing core is based on the same principle as the improvement made to the 15.5 inch cutter by installing a larger diameter 17 inch disc back in the 1980s. The relative wear volumes of 17, 19, & 20 inch discs are compared in Figure 2.

The cross section of a 17 inch and a 19 inch cutter are effectively identical when considering just the sacrificial portion or "blade" of the disc. 30mm wear has been assumed for the 17 & 19 inch sizes in Figure 2, and the relative wear volumes are given. The 19 inch disc has 12% more wear volume than the 17 inch disc. The 20 inch disc however, has substantially more wear volume (60%) when compared to the 19 inch. The tip of the 20 inch disc has been extended by 13mm on the radius compared to a 19 inch disc while the rest of the disc profile remains unchanged.

The same principle of extended tip discs can be applied to the 17 inch cutter and when geology permits, numerous TBM operators have chosen an 18 inch disc or even

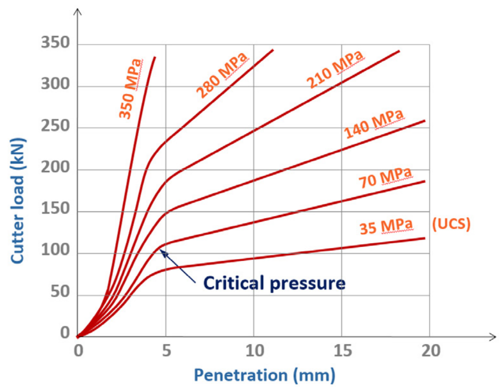

Figure 1. Cutter load vs. penetration rate in rock based on rock strength (MPa UCS)

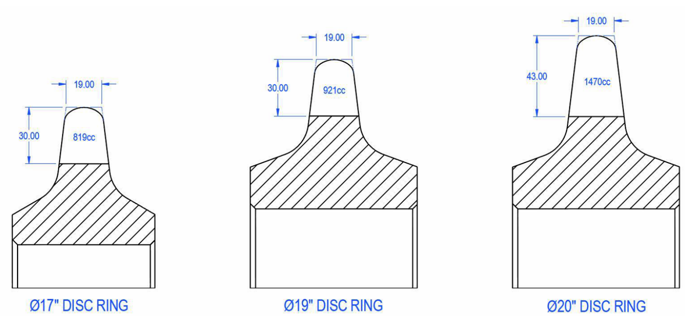

Figure 2. Relative wear volumes of 17-inch, 19-inch, and 20-inch disc rings

a 19 inch disc mounted on a 17 inch bearing core in order to take advantage of the added sacrificial material. This can be an effective solution in pressurized face tunneling to extend the time between cutterhead interventions.

LIAONING NOW PROJECT

One of the longest tunnels in recent history is Northeastern China's Liaoning NOW Water transfer project, measuring 120km in length. The government-commissioned tunnel, for irrigation and drinking water, has been divided into nine lots, designated T1 through T9 (for Tunnel No. 1 to 9, etc.). Each lot, except for T7, was excavated by TBM. Lot T7 is utilizing drill and blast. Lots T1 and T2 utilized new Main Beam machines from another manufacturer. Contractor China Sinohydro Bureaus 3 & 4, responsible for lots T3 and T4 respectively, elected new Robbins Main Beam TBMs, 8.53m in diameter. Similarly, T5 contractor Shanxi Hydraulic Engineer Construction Bureau ordered an 8.53m Robbins Main Beam. Chinese equipment supplier NHI contracted with Robbins to supply Main Beam machines of the same diameter for T6 and T8, and a rebuilt Robbins machine at 8.03m was provided for lot T9. All eight machines were ordered with Robbins continuous conveyors for muck removal (see Table 1 for summary).

Each of the eight TBMs excavating the Liaoning NOW project bored two consecutive tunnels ranging from 5 to 10 km long, totaling about 15 km each. The difficult and long tunnels pass through mainly granite, granite gneiss, and schist geology of varying abrasivity, and this geology was similar for all the drives. Mountainous terrain including valleys and rivers requires versatile ground support. Cover varies widely, from as little as 97 m to as high as 590 m at T6. Despite their nearly identical designs, some of the TBMs were fitted with 19-inch disc cutters and some with 20-inch cutters at the request of the various contractors. As such the project afforded a unique opportunity to test the relative efficiency of the two cutter sizes in similar geology (see Figure 3).

Figure 3. Cutterhead installed with US-manufactured 20-inch cutters

Three TBMs on the project utilized 19-inch cutters. Five TBMs utilized 20-inch cutters. The large number of machines on a single project presented a unique opportunity to compare not only 19 inch and 20 inch cutters but also to compare discs

Table 1. Liaoning NOW project summary

Lot No.	Cutter Size	TBM Type	Diameter	Length 1st Drive	Length 2nd Drive	Contractor
T1	19	Other Manufacturer	8.53m	7347	10016	China Sinohydro Bureau 14
T2	19	Other Manufacturer	8.53m	11453	8868	China Sinohydro Bureau 15
T3	20	Robbins	8.53m	8833	6507	China Sinohydro Bureau 3
T4	20	Robbins	8.53m	7275	8206	China Sinohydro Bureau 4
T5	20	Robbins	8.53m	7412	5270	Shanxi Hydraulic Engineer Construction Bureau
T6	20	Robbins/NHI	8.53m	6406	3650	Ministry of Rail Bureau 18 (MOR 18)
T8	20	Robbins/NHI	8.53m	5234	3354	CRTG
T9	19	Robbins (used)	8.03m	7495	2668	China Sinohydro Bureau 6

manufactured by different suppliers. Data on disc cutter consumption was not made available for the entirety of each tunnel but we were able to obtain sufficient data that some interesting trends were observed. Table 2 illustrates the distances over which disc cutter consumption data were obtained. Most data came from the first drives of each contract.

19-INCH VS. 20-INCH CUTTERS

One would expect average cubic meter rates per disc cutter consumed to be roughly proportional to the additional volume of sacrificial material in a 20 inch cutter when compared to a 19 inch cutter. I-n addition one would expect that monthly advance rates might be somewhat higher as a result of less frequent cutter changes. These data lend support to both premises when comparing average cubic meter rates or when comparing the monthly advance rates from all eight tunnels.

Advance Rates

Figure 4 summarizes the advance rates of all eight TBMs. The first two columns show the monthly advance averages for the portions of each contract where disc cutter data were made available. The 19 inch cutters averaged 446m/month compared to 554 m/month for the 20 inch cutters. In this project, the machines with 20 inch discs had on average a 24% better monthly advance rate than those with 19 inch cutters.

Table 2. Data available for disc usage

Lot No.	1st Drive, m	2nd Drive, m
T1	7324	0
T2	4807	0
T3	8833	6507
T4	7275	8206
T5	4007	0
T6	3722	0
T8	1955	0
T9	6435	0

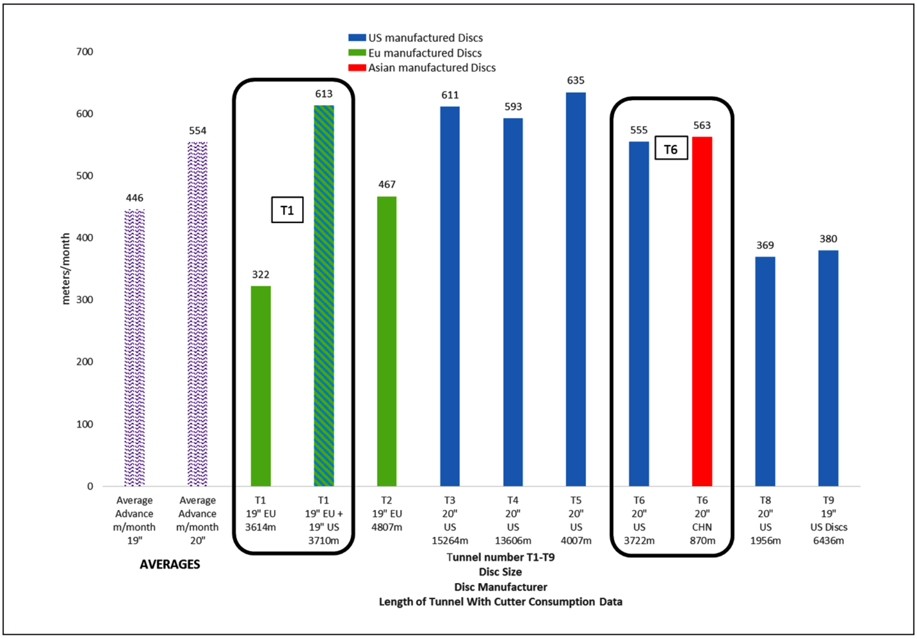

Figure 4. Average monthly advance based on disc cutter size

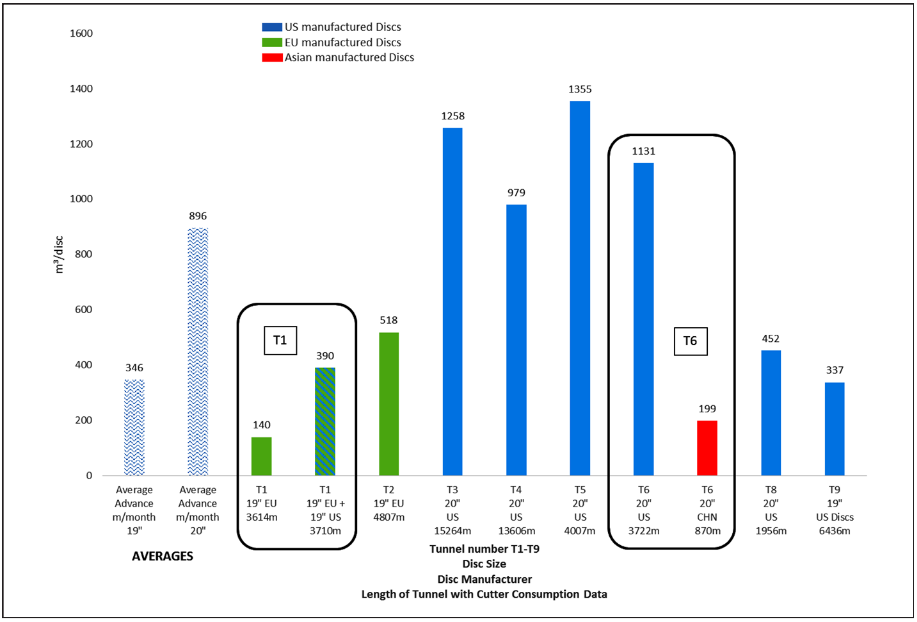

Figure 5. Cubic meters consumed per cutter disc

Cubic Meter Rates

Figure 5 is a summary of cubic meters per cutter disc consumed for all eight TBMs. Cubic meters per cutter disc, the best measure of cutter life and also a good indicator of total cutter cost, are also telling. The averages for all eight machines are shown in the first two columns of Figure 5. The average for 19 inch cutters is 346 cubic meters bored per cutter and for 20 inch cutters, the number is more than twice as high at 896 cubic meters bored per cutter.

DISCS MATTER

During the execution of this project there were two separate opportunities to compare the relative merits of different manufacturer's discs against each other; those manufactured in the US, vs. those manufactured in both Europe and Asia. This occurred on the T1 and T6 contracts.

Contract T1

The most striking difference compares the performance of the T1 TBM on its first drive using 19 inch cutters procured by the contractor from a European supplier with 19 inch cutters made in the US.

At T1, the contractor bored the first 3614m of the tunnel with cutters manufactured in the EU. For the final 3710m of the first drive, the contractor switched to a mixture of US sourced cutters and EU cutters. The US cutters were used in the transition area of the cutter profile. This is the area where the face transitions from being flat to turning out to cut the gage. It is well understood that the cutters in this area are the most highly loaded of all the cutters on the cutterhead.

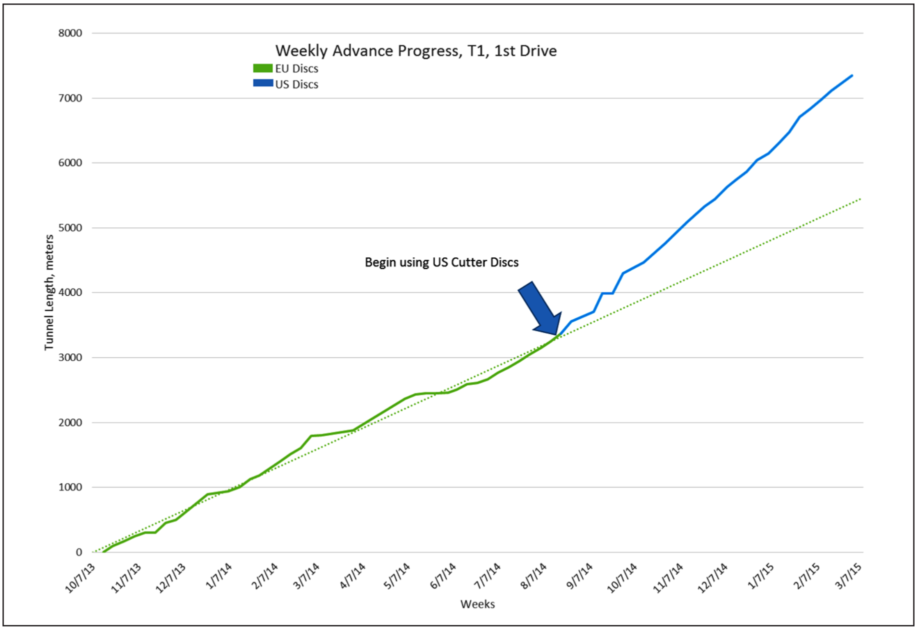

Figure 6. Relative advance rates over the length of the T1 drive

The performance was markedly better during the second half of the first drive with 543 discs consumed vs. 1479 discs consumed in the first half. Of the 543 discs, 225 were US discs and 318 were EU discs. This equates to a performance increase from $140m^3$/disc to $390m^3$/disc by deploying US discs in the transition area. Refer back to Figure 5 where the two bar graphs for T1 are enclosed with a black border and labeled T1. The EU discs are colored green and the mixed EU & US discs are shown in blue and green. In addition to an improved cubic meter/disc rate, the monthly advance rate improved significantly on T1 after the changeover. This is clearly illustrated in Figure 4 where the two bar graphs for T1 are enclosed with a black border and labeled T1 showing 322 meters/month for the first 3614m and 613m/month for the final 3710m of T1s first drive. Figure 6 shows the relative advance rates of both sections over the length of the first drive.

Contract T6

At T6, the contractor bored the first 3722m of the tunnel with cutters manufactured in the US. Then the contractor switched completely from the US cutters to Asian manufactured cutters. Data were only available for 870m after the changeover to Asian discs, but it was long enough to observe two phenomena.

First, referring back to Figure 4, there is no significant difference in monthly advance rates seen in the two bar graphs enclosed in black and labeled T6. With US cutters, the average was 555m/month and slightly higher at 563m/month with the Asian discs installed. The advance rates comparing both types of discs are also illustrated in Figure 7 where no significant difference in the slopes of the data are apparent.

The important difference between the US discs and the Asian discs is readily apparent in Figure 5 where the cubic meters per cutter disc consumed are compared. Refer the two bar graphs enclosed with a black border and labeled T6. During the first 3722m

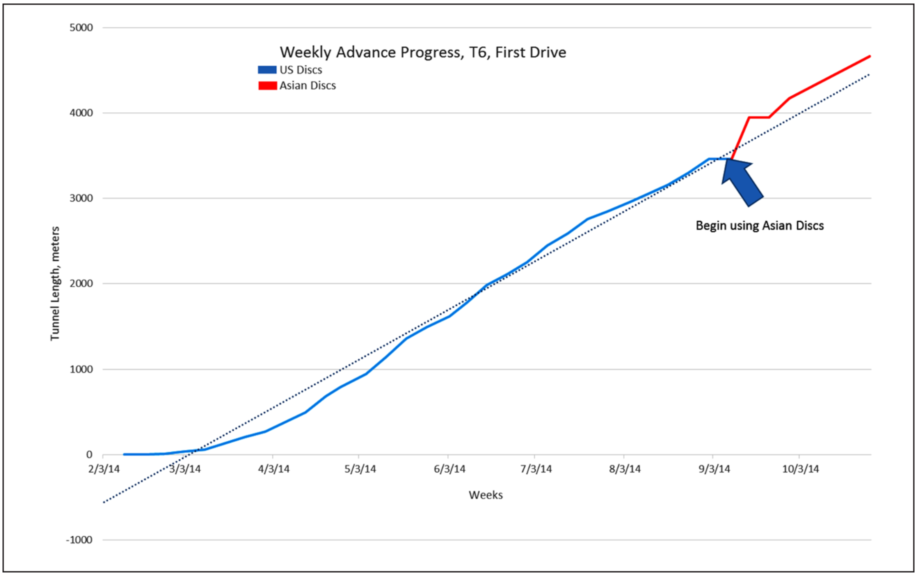

Figure 7. Advance rates on the T6 drive

of T6, US discs were used and the average rate of rock excavated per disc consumed was 1131m^3/disc. Compare that the performance of the Asian discs at 199m^3/disc. Excavation performance of the discs was reduced by a factor of 5.7. This represents a significant cost increase both in discs consumed (even when the discs are substantially cheaper) and in down time for cutter changes.

CONCLUSION

Contractors should carefully consider whether the use of larger discs will provide an economic benefit. The choice of 20 inch cutters over 19 inch cutters (coupled with an aggressive cutterhead management program) can provide longer time between cutter changes and longer overall life between rebuilds.

Contractors will also benefit from carefully considering the technology applied by each manufacturer to their disc cutters. Any competent manufacturer can make a disc cutter but the proof of the quality of the disc will not be apparent until the steel meets the rock. Nearly all disc cutter manufacturers now offer a tool steel disc ring and most have similar composition. It is, however, less the composition of the disc ring than it is the subsequent processing that makes the difference in performance. Less expensive disc cutters will not be economical in hard rock when considering the total cost over the duration of a project and this becomes more and more significant as the rock becomes ever more challenging.