A novel, non-circular Tunnel Boring Machine for Underground Mine Development

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The mining industry excavates many more kilometers of tunnel each year than the civil construction industry, but the use of tunnel boring machines (TBM) in mining has been limited in decades past. This has changed in recent years. With their circular bores, the machines have thus far been unable to tackle a larger issue for mines. Typically a flat floor is needed for mining vehicles to traverse. A novel non-circular boring machine is now answering that need. Its rectangular cross section allows for use of typical mine trucks and other rubber-tired mine vehicles. It provides more useable space, and minimizes the amount of excavated rock. The machine is currently cutting an access tunnel at a silver mine in Mexico. This paper reviews the design and operation of the novel TBM, and describes possible future adaptations to provide safe, sustainable mine development.

Tunnelling • Mining • TBM • Non-circular TBM • Mechanized tunnelling • Innovation • Mexico

1 Introduction

Tunnel boring machines (TBM) have been used in mining in decades past, but their use has been limited and sporadic. This has changed in recent years, with TBMs being used at Stillwater Mine, Grosvenor Coal Mine Slopes, and Sirius Minerals potash mine. These machines are all full face, circular TBMs. With their circular bores, these machines have thus far been unable to tackle a larger issue for mines – the need for a flat floor. While the mining industry excavates many more kilometers of tunnel each year than the civil construction industry, typically a flat floor is needed for mining vehicles to traverse.

An innovative type of non-circular boring machine is now answering that need with its ability to cut a rectangular profile in hard rock (**Fig. 1**). This cross section allows for use of typical mine trucks and other rubber-tired mine vehicles. It provides more useable space, compared to a circular profile, and minimizes the amount of excavated rock that must be hoisted out of the mine. This machine uses typical disc cutters to cut the rock (**Fig. 2**) and has a support structure similar to an open type TBM; however, the cutting geometry is entirely different. The machine is currently cutting an access tunnel at a silver mine in Mexico.

Fig. 1: The Robbins MDM5000
is capable of cutting hard rock up to 200 MPa UCS while creating a flat invert for access by rubber-tired vehicles.

2 Cooperative Development of a non-circular TBM for Fresnillo Silver Mine

The Mine Development Machine (MDM) 5000 was developed to drive mine development tunnels in rock at Fresnillo silver mine in Fresnillo, Mexico. Fresnillo is one of the world's oldest continuously operating mines and has been in operation for almost five centuries. The Fresnillo mine has a long history of embracing new technology. In 1838, an original Watts steam engine was brought from England to Mexico, skidded overland by teams of oxen and installed at the mine to provide dewatering. The engine is still displayed at the mine, proudly showcasing the mine's heritage.

More recently, Fresnillo has been eager to embrace mechanical excavation for mine development roadways. Fresnillo studied a 25 km long, circular TBM driven "Mega Tunnel" to connect four ore bodies in the Fresnillo region. The Mega Tunnel was to be bored with a 5 m hard rock TBM with continuous conveyor system for muck haulage. A precast concrete slab was considered to create a float roadbed within the circular tunnel bore. Fresnillo postponed the Mega Tunnel concept for economic reasons, but remained eager to find a mechanical excavation tool to expedite excavation of developmental roadways. These tunnels need a flat invert to allow use

Fig. 2: Disc cutters
mounted in the cutterhead are similar to those used and proven on circular TBM cutterheads around the world.

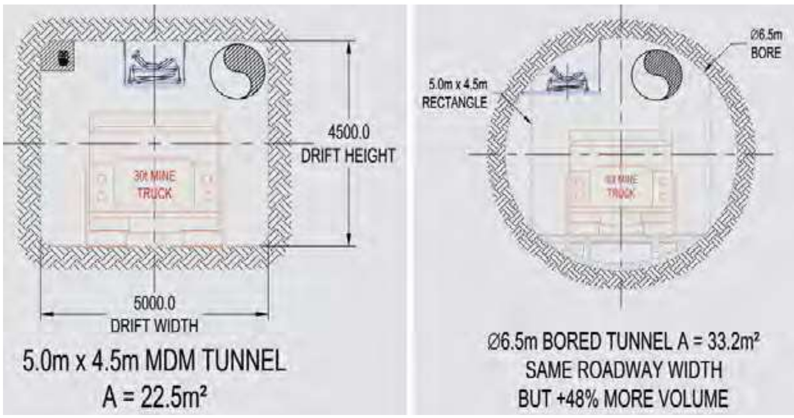

Fig. 3: A rectangular (above) vs. circular (below) tunnel cross section comparison

The circular tunnel has 30 % more excavated area per lineal meter as compared to the rectangular tunnel. This means more muck to remove from the tunnel.

of the fleet of mine trucks and other rubber-tired mine equipment. Robbins and their agent, Topo Machinery, worked with Fresnillo to develop a suitable Mine Development Machine proposal. Equally important to the machine design was the deployment and operation of the machine on a day-to-day basis, which Topo and Robbins formed a partnership to undertake.

3 Mechanical Rock Excavation, circular and non-circular

Circular, full face rock TBMs are well developed tools, but are not often used in mining, considering the many kilometers of mine tunnels that are driven each year. This is for a variety of reasons: difficult mobilization/demobilization in deep mines, inability to negotiate sharp curves and steep gradients that are part of the standard mining plans, and the fact that the mines usually desire a flat tunnel floor, not a circular profile. The TBM industry has made strong efforts to overcome the obstacles. A full face circular TBM remains the most efficient machine for mechanical excavation of tunnels in rock. However, if a flat floor is imperative, it must be created by secondary methods if a circular full face TBM is used to drive the tunnel.

Several secondary methods can be considered to create the flat invert roadway. These include follow on slashing of the bottom haunches by drill and blast, or by rock splitting. A precast floor can be set, or concrete can be poured in place to create the floor. Alternatively, crushed rock can be used to fill the circular invert to create the road. This invert space can sometimes be used for drainage pipes or drain channels beneath the slab to create the road. This setup can help offset the penalty of having to construct the flat bottom. However, the resulting cross section is often still not the most efficient for the intended use.

Many types of rock excavation machines have been introduced to cut a non-circular cross section with a flat bottom. Roadheaders in particular have become more capable in recent years. Robbins Mobile Miners were first used in the 1980s and 1990s, and more recently have been trialed and are under further development. Several other machines using partial face excavation with disc cutter technology have been tried. Unfortunately, most of these machines have been abandoned by the mines due to low productivity or high cutter wear.

If the main intention is to develop a roadway tunnel, and additional cross sectional area is not needed for ventilation flow or other purposes, then the most efficient cross section is rectangular. The comparison below shows a rectangular cross section compared to a circular tunnel that has the same floor width (**Fig. 3**. The circular tunnel has 30 % more excavated area per lineal meter. This means more muck to hoist and dispose. An efficient way of mechanically excavating a more or less rectangular profile remains much sought after in the mining industry. While the civil tunneling industry has been much more accepting of circular tunnels, an efficient rectangular machine could also be useful for many civil applications.

4 Evolution of the MDM Cutting Concept

Besides roadway tunnels, a mechanically excavated cross section is very useful to mine ore bodies that are in seams with parallel tops and bottoms. Such deposits are called “reefs” and are typical in platinum mines and other minerals. Mining the reef in deep platinum mines is very difficult and dangerous work. Many efforts have been made to mechanize reef mining as an alternative to drill and blast.

One such effort was the “Reef Mole”. This machine was conceived and developed by John Gibson and Andy Anderson, long time Robbins engineers who formed a new company after retirement. The machine was built and excavated in a platinum mine in South Africa. This machine cut out a 1 m x 5 m rectangle to excavate the ore.

The cutting action was performed by a swinging cutter head, rather than a rotating cutter head, as on circular TBMs. The head was swung horizontally by hydraulic cylinders, to create the rectangular cut. Strong grippers locked the machine within the excavated reef to resist the significant cutting forces. The geometry of the machine was arranged so that the cutters swept across the semi-circular shaped face with nearly constant penetration to provide the most effective cutting action. A vacuum system was used for muck removal.

The Reef Mole cut effectively in the very hard rock of the platinum reef, however, the machine was regarded as “experimental” by the mine. Thus, it did not get any priority for resources such as power, water, ventilation, haulage, personnel, etc. – all of which are precious commodities in a deep operating mine. Though promising, the Reef Mole was never fully utilized by the mine.

4.1 The MDM Design

As the need for mechanically excavated development tunnels at Fresnillo was discussed further, a machine concept evolved using a swinging cutterhead, similar to the Reef Mole. The goal was to produce a rectangular cross section, 5 m wide and 4.5 m high. In this case, the cutter head was swung vertically about a horizontal axis. A robust front gripper cylinder was located on this axis of rotation. This provided good stabilization and direct reaction of cutting forces. The gripper anchored within the vertical side walls of the cut. The machine was designated as MDM5000, for Mine Development Machine. A drawing of the machine is shown in **Fig. 4** and a closeup of the cutting action on the rock face in **Fig. 5**.

Swinging the cutterhead about the horizontal axis gave the opportunity for the head to push the cut muck rearwards, onto a muck apron, much like the muck apron on a roadheader. The apron covered the full 5 m width. Twin loading wheel "propellers" to each side of center pushed the muck towards the hopper in the center of the apron. A chain conveyor pulled the muck from this hopper and conveyed it to the rear of the MDM. Belt type conveyors are usually preferred for TBM type equipment, however, the conveyor is located low in the MDM, near the tunnel floor. It was thought that a belt type conveyor would constantly be running through the inevitable muck accumulated beneath and would suffer too much wear. Also, The MDM was intended to be used on steeper gradients. In such gradients, the net inclination angle of the conveyor in the MDM would be too steep to allow effective conveyance by a belt (**Fig. 6**).

The MDM is significantly front heavy due to the configuration of the machine, and the overhung cutterhead. This would cause the MDM to tip forward about the front fulcrum shoe in the muck apron. Significant rear structure and machine length was needed to counter the overhung weights and cutting forces. The rear of the MDM had a "Main Beam" which mimics the main beam of a typical hard rock TBM. It also had a rear gripper and thrust cylinders to advance the machine by skidding on the front fulcrum. The rear gripper and torque cylinders provided steering effect, much like on a hard rock TBM.

5 Mining Machine or Rectangular TBM?

The mining industry wants excavation equipment that is powerful and highly productive, yet lightweight and easily mobile. The MDM was developed as much as possible with these goals in mind. From the photo (**Fig. 7**), you may get the impression these goals were superbly met. You see a strong rock cutterhead on a very mobile, tracked carrier. However, this is only one module of the MDM. It is being transported down the mine ramp road on a special tracked carrier. The MDM was transported down the ramp as three main modules. You can see from **Fig. 4** of the entire MDM that significant structural and mechanical elements are needed to deliver the high cutting forces that provide efficient hard rock excavation – a setup typical of hard rock TBMs.

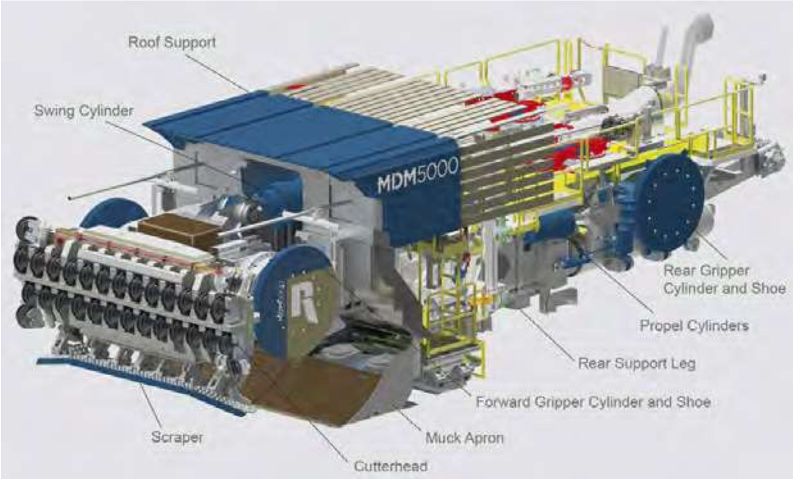

Fig. 4: The Mine Development Machine (MDM) 5000 excavates with a reciprocating cutterhead and swinging cutterhead motion to create a rectangular cross section tunnel.

Fig. 5: A closeup of cut rock face in MDM tunnel

Fig. 6: Front view of the MDM showing the muck apron

Fig. 7: The MDM cutterhead was transported underground on a mobile, tracked carrier to an assembly cavern.

Fig. 8: High tensile wire mesh and rock bolts are installed for ground support just aft of the MDM roof shield.

The MDM has significant size and weight, both of which are necessary to provide effective excavation in hard rock. It is not a lightweight, highly mobile mining machine like a roadheader or a continuous miner. Thus, the MDM is more like a “rectangular TBM” than a mobile mining machine. Even though efforts were made to make the MDM reasonably easy to transport and assemble, it still is a large machine with significant set-up and relocation times. Therefore, it is only practical for longer tunnels. The mining industry would like an excavation machine that can cut a few hundred, or even a few dozen meters, flit to a new location, cut a bit there, then move on. The MDM does not fit that application, but is effective for driving longer rectangular tunnels with high productivity, such as mine access tunnels and ventilation tunnels as well as ore haulage tunnels for deep ore bodies.

Like other TBMs, the MDM tows a back-up system. The MDM back-up is composed of seven gantries, plus three storage gantries for supplies. The back-up gantries provide space to mount the power and control equipment, dust scrubber and ventilation system, muck removal, material, supply, and other systems. This is a real tunneling plant, that produces a finished, well supported roadway tunnel with life-of-mine piping installed.

If a lighter, more mobile machine is needed, these systems would have to be greatly abbreviated, and perhaps left behind on the tunnel floor and connected to the excavation machine with umbilical cables. Such a machine would have much less power and productivity.

6 MDM Roof Support Systems

Immediate, effective roof support was a strict requirement at Fresnillo. Like other TBMs, the MDM was equipped with a hydraulically operated roof shield that provided protection over the front gripper area, where there was no space available for roof support activities. Special high tensile wire mesh (“Minax”) for mine support and rock bolts were installed just aft of the roof shield (**Fig. 8**). The mesh was brought to the front of the MDM in rolls. Each roll was long enough to provide coverage across the width of the roof, and down each side to about springline. The mesh panels were 1.4 m wide to provide overlap at each row of roof bolts. Roof bolt spacing was 1.24 m. This spacing was chosen as it was adequate for effective support in the anticipated conditions. Also, the roof bolt spacing corresponded to the spacing of the hanger chains on the conveyor, which was used for muck removal.

The forward roof bolters and positioners were hydraulic percussive type drills supplied by Fletcher. These drills installed the bolts across the width of the roof. In addition, there were rear drills, supplied by TEI, that installed bolts into the side walls. The TEI drills could also be turned forward and articulated to drill a re-con hole into the face, or a series of holes into the face for spiling or pre-excavation grouting.

7 MDM Muck Removal

A Robbins extensible tunnel conveyor system was used to remove the muck produced by the MDM. The conveyor system was chosen for several reasons. The con-

Fig. 9: The rectangular cross section tunnel with crown-mounted tunnel conveyor

Fig. 10: Main frame of MDM on transport crawlers inside assembly chamber area

veyor had high capacity and did not introduce any exhaust pollution. Also, there was not enough room for high capacity mine trucks to pass within this tunnel. A further consideration was that the tunnel conveyor is able to safely remove muck at fairly high gradients. Future MDM tunnels are planned with up to 7 % gradient to develop deeper levels of the mine.

The tunnel conveyor was mounted in the center of the crown (**Fig. 9**). This left more room for vehicles and for installation of piping and other utilities within the tunnel. Also, this central position allowed the tunnel conveyor belt to be routed all of the way forward to the discharge of the MDM chain conveyor. A separate transfer conveyor, and additional transfer point were not necessary.

The tunnel conveyor structure was added continuously as the MDM mined forward, within the protection of the Installation Window. Personnel were thus not exposed to the moving belts. As mentioned before, the tunnel conveyor was suspended by chains attached to the roof bolts. No additional bolts in the roof were needed to suspend the conveyor.

The belt storage cassette paid out conveyor belt as the MDM mined forward, so the tunnel conveyor was continuously extensible. The cassette was fairly long so adequate space had to be prepared underground. The tunnel belt carried muck out of the tunnel, over the cassette, then to the main drive unit. The conveyor discharged at the main drive into a cross conveyor system, which could then selectively discharge muck into either of two 450 m^3 silos created by raise mining. The silos discharged into a loading area, where electric trains were loaded for transport to the shaft skip.

8 MDM Transport and Mobilization Underground

The MDM needed to be transported from the surface to the –695 m level of Fresnillo mine via the existing main ramp tunnel. This was an 8 km long trip down the ramp. This ramp had limited cross section, undulating bottom, steep gradients, and many sharp radius curves. The MDM was assembled as completely as possible on the surface, and transported down the ramp in three main modules: the cutterhead, the front main frame, and the rear gripper section. A special, tracked carrier was developed by Fletcher Mining Machinery, in collaboration with Robbins engineers. The carrier had multi-axis articulation so the modules could “duck and weave” to miss obstructions in the mine ramp, much like a person spelunking in a cavern passageway.

An assembly and launch cavern was developed at the first MDM tunnel site on the –695 m level. The cavern was long enough to accommodate the full MDM and backup system, and the continuous conveyor cassette. This cavern required significant excavation to prepare, but allowed the MDM and the conveyor to be used immediately, from the first cut of the MDM (**Fig. 10**).

The cross section of the assembly and launch cavern was only slightly larger than the 5 m x 4.5 m dimen-

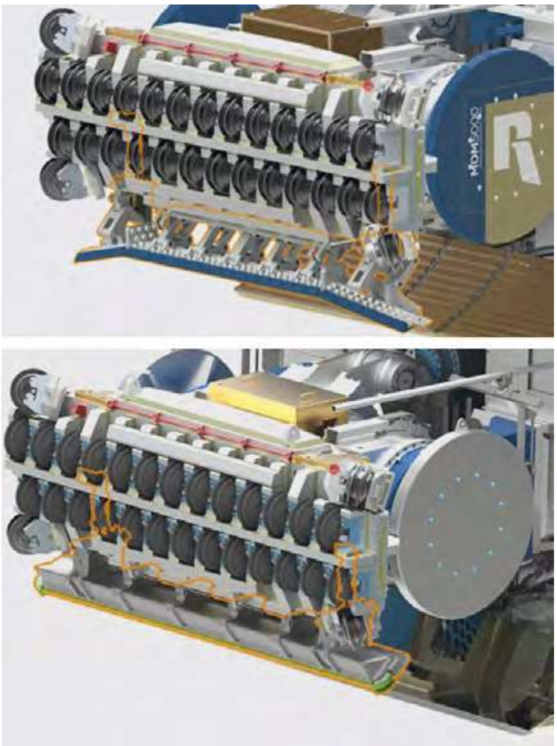

Fig. 11: Scraper design – original above and improved below

sions of the MDM cut. No grossly oversize excavation was needed. A local niche in the crown was prepared for a manual hoist. As the MDM sections were moved beneath this niche on the crawlers, the hoist was used to lift on the roof shield, drills, and other appurtenant pieces.

9 MDM Update

At Fresnillo, the MDM is excavating in andesites and shales with quartz intrusions. These intrusions have defeated earlier attempts to excavate these tunnels with heavy road headers. The MDM has also encountered water bearing ground and multiple fault zones that have slowed progress. Operational improvements in response to groundwater include regular probe drilling and grouting off of the water. Despite the challenges, the mine is committed to the tunneling method, which offers better safety, consistency, and a finished rectangular roadway product compared with drill & blast methods.

9.1 Component Improvements

The machine has undergone component enhancements during its bore to improve performance. These include:

- **Cutterhead improvements:** New gage cutters were designed to reduce side loading. Further designs are being developed to increase the number of gaged cutters.
- **Scraper improvements:** The original scraper was replaced with a more robust three-piece scraper that has a better 'angle of attack' to allow for more efficient mucking (**Fig. 11**). Observations are that the new design has resulted in quicker cycle times and aids in muck removal. Originally, each cycle would take 32 swings and 22 minutes; this has been reduced to 26 to 28 swings and 18 minutes.
- **Muck apron:** Cylinders have been added to the muck apron to enable it to be forced down and avoid raising up as muck accumulates in the invert. Other improvements are being investigated to improve the robustness of the chain conveyor.

10 Conclusions

The MDM is excavating rectangular profile development tunnels at Fresnillo. Most mines have regarded such new equipment as "experiments", and have not devoted adequate resources such as power, water, manpower, muck haulage, ventilation, etc. Fresnillo has devoted the necessary resources, and all parties are determined to make the MDM do the job it was intended to do.

The MDM is cutting the desired rectangular, flat invert profile. The MDM has passed zones of bad ground and high water inflows. Traditional mining methods have been used to augment the MDM ground support capabilities in particularly bad areas, so that the MDM could proceed through.

With its first use has also come some overall observations: due to the cyclic, swinging cutting action, the machine has lower productivity compared to a traditional, rotary TBM that cuts a circular profile. While there are still many benefits, most prominently a flat roadbed, the comparisons must be carefully evaluated for any significant mine excavation considering using this method.

The MDM is not the "lightweight, mobile rock excavation machine" that the industry covets. Such a lightweight machine may be possible, and development will surely be undertaken due to the demands of the mining industry. However, such a machine will surely have a penalty of decreased productivity.

11 References

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