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Optimizing Soft Ground Excavation: Development and Design of EPB and Slurry Cutterheads

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1. Introduction

The history and development of soft ground tunnelling machines is a long one, and one in which the quest for optimal design to achieve safe and efficient excavation has always been a top priority. Modern soft ground tunnelling began with the introduction of Slurry TBM technology in 1967 and the development of Earth Pressure Balance (EPB) machines a bit later in 1974 in Japan. Many advances have since been made by Japanese manufacturers, as well as North American and European manufacturers. These advances were the result of lessons learned from the successes and failures of the technologies in a variety of geologies. In many cases the philosophies of Japanese and European manufacturers were quite different, resulting in unique machine features. In the case of both EPB and Slurry, many of these advances have involved the development of the cutterhead, which is the first part of the machine to come in contact with the soil. Cutterhead design is not only integral to operation of the TBM, but also to machine performance. Proper cutterhead design must incorporate a variety of project variables including expected geology and operation of the machine. To appropriately specify and evaluate soft ground cutterhead features, there must be an appreciation of how these features developed and how this applies to a job-specific geology.

This paper will review the fundamentals of cutterhead design and how particular attributes interact with the geology and other machine features to achieve efficient excavation. When possible, comparisons between EPB and Slurry technology will be addressed. Comparisons will also be made between the varying schools of thought in terms of soft ground machine design in both Europe and Japan. In addition, the features will be evaluated for potential outcomes with differing geologies and methods of operation. A thorough understanding of these items allows for an educated approach to maximization of machine advance and performance.

2. The Basics of Cutterhead Design: Opening Ratio

Besides rotational speed and torque values, the most specified cutterhead attribute is its opening ratio, which is specified as the amount of open area in the cutterhead structure divided by the total cutterhead area. This ratio has a big impact on how the machine is able to perform in a variety of geologies, though its impact on performance goes beyond a simple value. This value is also probably the most visible change that can be seen as the technology has progressed. It is also the area where EPB and Slurry heads have grown apart over time (see Figure 1).

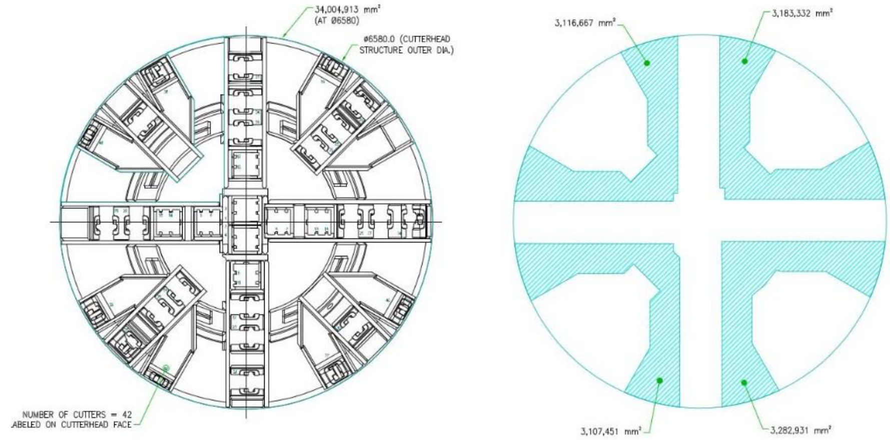

Fig 1.*Opening Ratio Example*

2.1 EPB Cutterheads

The biggest change in design has occurred in EPB cutterheads, which also have the greatest variation in opening ratio depending on the different geologies to be mined. Opening ratios in the first EPBs, like the first slurry machines, were relatively small compared to today's EPBs. This evolution was in large part due to the process of proving the technology. A high degree of mechanical face support was desired in case the technology did not prove successful, which in turn corresponded to a small opening ratio to allow for muck flow though the cutterhead. Contractors and owners did not initially trust the method to hold face pressure on its own. The EPB method quickly proved itself, and the perceived risk by project owners and contractors dropped correspondingly. As a result the high degree of mechanical face support was minimized, which is very beneficial to the EPB method. In fact, in ideal EPB conditions there would be no cutterhead required at all to break up the in situ soil: it is the machine bulkhead that is required to counterbalance the earth and water pressure as the machine is thrust forward. To efficiently balance this force requires that the earth pressure sensors in the bulkhead are able to accurately read the pressure at the cutting face, a measurement that requires appropriately fluidized soil and conductivity to the face. The position of the cutterhead is between the EPB sensors and the cutting face; therefore, by minimizing the cutterhead structure the pressure at the face is more accurately transmitted to the sensors and there is less restriction of material flow. This philosophy can be seen in many modern tunnelling machines designed for very soft ground.

2.2 Slurry Cutterheads

In the case of slurry machines the face pressure is not controlled using feedback from the EPB sensors. Depending on the machine design either pressure transducers connected to the bulkhead or air pressure supplied to an air bubble ahead of the machine bulkhead are used to maintain a consistent pressure at the face. This means that a high opening ratio on the cutterhead is not as beneficial for machine operation as in an EPB. Another key feature of slurry operations is the formation of a mud or filter cake on the excavation face. Once formed it acts like a membrane between the in situ soil and the relatively viscous slurry, allowing the slurry to apply a counter pressure to the in situ soil forces while controlling the majority of the slurry materials. There are several ways in which the mud cake can be compromised, and knowing the status of the face during excavation with these machines is difficult. Once the filter cake is compromised the face pressure is not as effectively balanced and the face is prone to collapse. If the cutterhead has a low opening ratio, meaning that it offers a high degree of additional mechanical support, danger due to this failure mode is minimized. The Japanese manufacturers that developed slurry technology have not moved away from a low opening ratio on their cutterhead as the design has evolved over the years. As the technology moved into Europe some manufacturers tried to utilize designs with a more open layout similar to EPBs, though over time the design has shifted back to a more closed face setup (see Figures 2-5).

Fig 2*.* 1970 7.29m Slurry Courtesy of MHI

Fig 3*.* 1974 4.5m Hydroshield
Courtesy of Wayss & Freytag

Figs. 4 and 5 *Modern slurry TBMs with small cutterhead opening ratios*

2.3 Structure of the Cutterhead Openings

With the importance of the opening ratio understood, especially in EPB machines, it should be noted that not all openings are created equally: the shape and distribution of the openings is also important when evaluating the value of th opening ratio. Like other aspects of cutterhead design, this should be looked at with respect to the excavation tools required for the expected geology and the structure required to support them (knowing that the primary function of the cutterhead is to support the cutting tools).

In both slurry and EPB TBMs, the openings serve as the path that allows the material to flow from the face into the mixing chamber behind the cutterhead and ultimately out of the machine. As machines are most often circular the excavated volume compared to the diameter is a squared term, meaning that a higher opening ratio is required as we move away from the centre of the cutterhead towards the outer perimeter of the cutterhead. This ends up working well in relationship to the cutterhead structure required to support the excavation tools. The tools are positioned with an even radial spacing, meaning that less structure is required to support the tools by area as we move away from the centre. The centre, which is where in theory the lowest opening ratio should be required, ends up being the spot where special care needs to be taken.

With the radial tools spacing on the cutterhead, some tools are required at the centre, which necessitates a structure to support those tools. The higher the tool loading the more support structure is required. This support structure takes up a high percentage of the area at the centre of the head; in fact, in most cases the very centre of the head is completely consumed by structure. With little to no opening in the centre portion of the head, an area of localized high pressure is created that can decrease the fluidity of the ground and encourage packing of the cutterhead openings that are in close proximity. Behind the cutterhead an area of low flow is created, which has a tendency to solidify. This tendency has been verified in the field, as the centre of cutterheads usually become clogged first. The ultimate result of this tendency is that while theoretically there is a low requirement for muck openings in the centre, this is where design effort must be concentrated in order to allow for some openings while maintaining sufficient strength.

As the geology becomes harder, either as a whole or with certain hard elements like boulders, more aggressive tools are needed to loosen or fracture the ground in front of the machine. Besides the increased structural requirements of the tooling, harder geology creates issues with the muck transportation systems, both by slurry line and screw conveyor. There are two main methods for dealing with rock that may be encountered: The first is to allow the material to enter the cutterhead and deal with the rock using secondary methods on the machine. The second is to manage the size of the rocks that are able to enter the cutterhead by further closing off the cutterhead to only allow elements that are small enough to be managed by the muck conveyance system.

In the first case where secondary sizing methods are used such as a crushing box, there is typically less impact on the slurry cutterhead design. On slurry machines the opening ratio is already relativity small, which controls the size of the elements able to enter the cutterhead in the first place. The elements that enter are able to be handled by a secondary piece of equipment like a crusher to further reduce the particle size. By making the openings relatively narrow and long on a slurry cutterhead, the openings are better able to size the material while still maintaining a sufficient opening for muck to flow.

On EPB machines this option for secondary crushing does not work as well. EPB machines are designed with larger opening ratios to allow muck to flow smoothly into the mixing chamber. This means that pieces of rock or boulders also enter the mixing chamber. Usually screw conveyors are able to handle larger rock pieces than a slurry machine with the largest boulders being approximately 1/3 that of the screw diameter. With little limitation on what can pass thought the head, the screw conveyor's limits can be easily exceeded, however. In these cases the screw conveyor can be oversized to ingest larger boulders, if the machine design allows for it. If this is not possible, then a ribbon screw can be used, which does not have a centre shaft and can handle boulders up to approximately 2/3 the screw diameter. A ribbon screw can operate by itself in low pressure, or in conjunction with a shafted screw to ensure higher pressure holding capabilities, which means that any boulders must be removed from the screw by way of an access opening, such as a boulder collecting gate.

The second case of managing the material size limits in EPBs requires that the openings in the cutterhead limit the size of the particle that enters the head. These physical limitations mean that the muck continues to be broken or reground by the main cutting tools until it can pass through the cutterhead and can be handled by the conveying system. As noted above this is not as notable on a slurry cutterhead, but on an EPB with a high opening ratio the effect is quite noticeable. There are advantages over the first option as it does not run the risk of encountering a larger than expected boulder that can't be handled by the conveyor. It also doesn't require the difficult removal of large rocks from the screw conveyor. However there are also significant disadvantages: with the reduced openings there is increased regrind, which increases wear to the cutting tools and the cutterhead. Impact loading due to the rock sections or boulders that are kept in front of the head also contribute to an increase in wear. The decreased openings additionally increase the resistance to flow so that higher concentrations of ground conditioning are required.

3. Cutterhead Shapes/effect on depth: Flat, semi-dome, dome

Flow through the cutterhead is not only effected by the size of the cutterhead opening parallel to the face, but also by the depth of the cutterhead which is perpendicular to the face, and through which the conditioned muck needs to flow. In ideal soft ground conditions this distance is something that is important, but is not something that is especially critical. As the ground conditions change to mixed ground this becomes an increasingly important factor. Mixed ground conditions will most often increase tool loading conditions, which necessitates a deeper cutterhead structure. How the tunnel wall is formed by the cutterhead is also a big part of determining what cutterhead depth is required.

There are three basic shapes when looking at the gage region of the cutterhead: flat, semi-domed and domed. The shapes are dictated by geology. As the geology become harder the method for breaking up and loosening the geology begins to change. If in soft geology, only scrapers are required to remove material from the face and pull muck into the cutterhead. As the geology become harder it become advantageous to put grooves in the face with rippers or knife edge bits to make it easier for the scrapers to pull material from the face. As the material changes to rock another mechanism is required to mine, kerf cutting, which is done using disc cutters that are pressed into the hard face with high forces. This action causes fractures in the rock so that chips fall out between the cutters. The setup requires larger distances between the cutters as they transition from perpendicular to the face to parallel to the face. The harder the rock the more gradual this transition should be as to not overload any individual cutter. This change can be seen in figures 6-8 below as we start with a flat cutterhead and transition to a semi-domed head where disc cutters are able to be installed in the gage position and finally to a domed cutterhead which can handle hard rock.

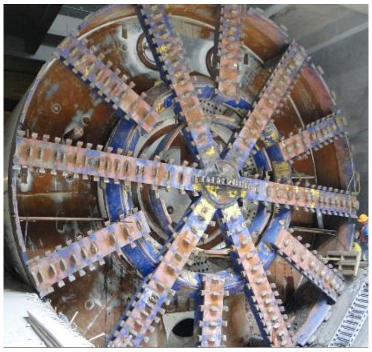

Fig 6*. Flat cutterhead style*

Fig 7*. Semi-Domed Cutterheead*

Fig 8*. Domed cutterhead style*

The shape of the structure that the muck encounters as it flows through the cutterhead also needs to change as the geology changes from soft ground to mixed ground that contains rock or boulders. In pure EPB cutterheads with a high opening ratio, optimization of muck flow can be realized with any structure that is encountered by efficiently splitting the flow around its shape. The concern with this approach as the cutterhead structure becomes more closed and the likelihood of large elements or boulders increases is that this shape will encourage boulders or rocks to become lodged in the structure. This will have the effect of further reducing the opening ratio of the cutterhead and may also create a high pressure zone in that area of the head--a particular concern if disc cutters are in use since they have a limited pressure operating range due to their seals. This range can be expanded if planned for by using pressure-compensated disc cutters, though these do not come standard so such conditions would need to be anticipated.

4. Cutting Tools

4.1 Scrapers

Scrapers are seen in both Slurry and EPB cutterheads and are used to pull geology into the cutterhead. In soft ground it is possible that they will be the only tool used for excavation. Scapers use a shearing action similar to the cutting action seen in chip formation in metal machining where the formed chip is the excavated material. The tip of the scraper is most often made up of a form of tungsten carbide, which provides a high degree of wear resistance in theis difficult application. As the geology gets harder the energy requirements to shear the soils also get higher, which limits the penetration rate of the machine or increases torque requirements. To lessen these torque requirements at a given penetration rate, a groove is put into the face using knife-edge bits by decreasing the shear area. As the geology moves to a soft rock or cobble the knife-edge bit takes on a more important role to loosen the geology. This loosening creates higher tool loads, so a tool with a larger cross section is required.

4.2 Scraper placement

Besides the design of the scrapers themselves, their placement on the head also affects their wear characteristics and even the desired parameters for machine operation. Regardless of the arrangement it is important that each part of the cutting face is covered at some point in its radius by a scraping tool. As most heads turn in both directions to counter machine roll this would need to be done for each direction or rotation. This placement is because the soil itself is very abrasive--the carbide tipped tools are designed to deal with this harsh environment but the cutterhead structure or wear plating is not able to last long and will be quickly worn away.

As there are a number of different cutterhead designs, especially with EPBs, we will look at two basic scraper configurations and the effects due to the change in the arrangement using the same basic cutterhead structure. In the first arrangement the scrapers are located on either side of the primary cutting tool (knife edge bits/cutters). The biggest advantage to this arrangement is that contact with the in-situ soil by the tool on the opposite side of the spoke is minimized since it was just cleared away. This is an important consideration as wear on the back side of the tool can be high, especially if it is not protected by tungsten carbide (typically a more costly type of tool). In the second arrangement, tools that are opposite each other are farther apart. If the cutterhead speed is kept constant the machine will advance farther by the time the backside of the second spoke comes in contact with the native soil, creating higher wear. So, from a wear prospective, a close back-to-back placement of the scrapers is advantageous (see Figures 9-10).

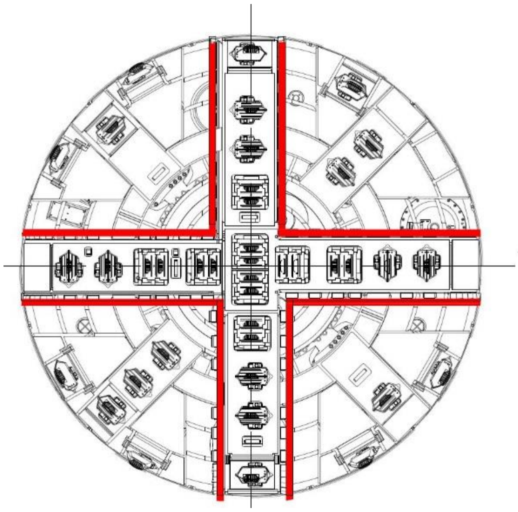

***Fig 9**. Close placement of scrapers*

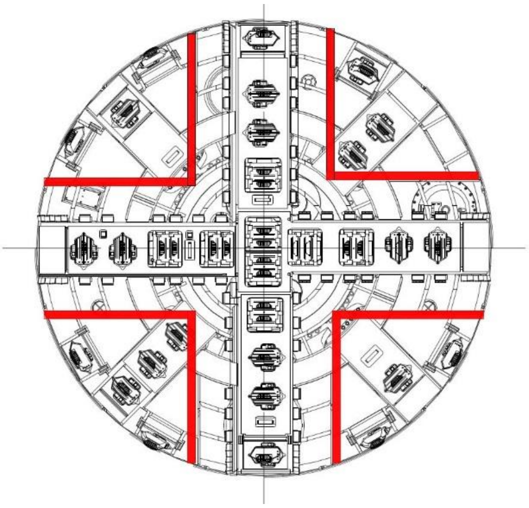

***Fig 10.** Wide placement of scrapers*

If the machine is going to be operated without using the EPB method, or in open mode, then other considerations need to be made. During open mode the face is stable and to decrease wear and torque requirements the mixing chamber behind the cutterhead is not completely filled. If disc cutters are in use then the advance rate is much more closely related to cutterhead speed. As the material is pulled into the head, there will be a tendency for it to flow back out into the low pressure zone on the back side of the spoke. This tendency increases as the cutterhead speed increases. The cutterhead with the wider tool placement is better able to hold material inside the mixing chamber, therefore increasing mucking efficiency and minimizing wear (see Figures 11-12).

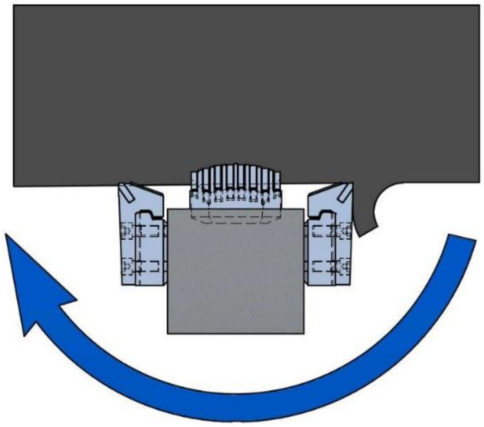

Fig 11. *Close tool placement*

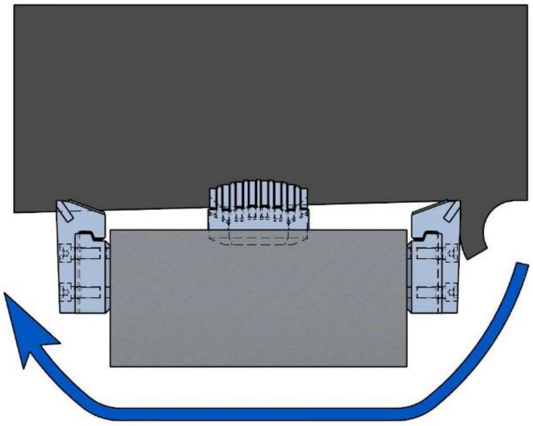

Fig 12*. Wide tool placement*

4.3 Disc Cutters

Disc cutters have shown over many years of use to be the best choice of cutting tool for breaking rock into smaller pieces for easy removal. However, just using the term 'disc cutter' does not describe all the types of disc cutters available. There are many types of discs available and many options for the configurations of those discs on a body rotating about a stationary shaft.

Disc cutters were first invented for breaking rock and have the longest life of any cutting tool in rock. When disc cutters are used in soft ground, though, their full life may not be achieved. Disc cutters rely on the force of the machine in contact with a hard surface to roll. During normal operation, the ring will wear equally around the circumference. However, when the disc cutter doesn't roll, only one side of the ring slides along the face and flat spots on the forward side of the ring are generated. Additionally, the ability of a disc cutter to rotate after a flat spot has developed is further hindered because of the sharp edge generated between the flat area and the remainder of the round edge of the ring (see Figure 13). Another consideration when using disc cutters is that since they rotate, they need bearings and use seals to protect those bearings from the harsh environment. These seals have pressure limits- knife edge bits do not have any seals and therefore do not have this limitation. Another consideration for the seals is that the disc cutters rotate due to the interaction between the cutting surface and the cutter tip. In soft geology the amount of force that can be generated for effective excavation can be quite small. However with disc cutters the rolling force required is much larger. To prevent a pressure differential between the inner seal and the outer cutting area at pressures above 4 bar, a special design has been developed. A pressure compensator device can be fitted to the cutter to equalize the pressure between the inside and outside of the cutter. Figure 14 shows a cross-section of such a cutter, which uses carbide inserts in the cutter body with hard-facing and also includes a pressure compensating retainer.

Specialized cutters are bound to be more expensive than standard cutters because they have additional parts or improved material properties. This cost is likely to be offset by the longer life of these types of cutters. Reducing the downtime required to change cutters and also the risk of cascading failures decreases the duration and cost of the project as well.

Fig 13. *Non-Rotating Cutter Damage*

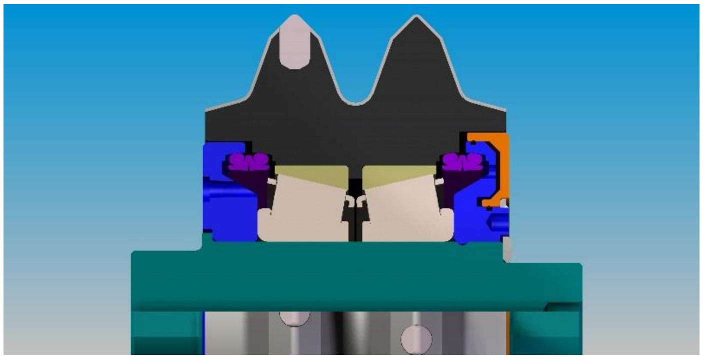

Fig 14.*Pressure Compensated Carbide Insert Cutter*

5. A comparison of Japanese and European design concepts

Every machine manufacturer has unique design features when it comes to cutterhead design and there is no one ultimate design for each manufacturer. That being, said there are two broad categories of design concepts that can be considered. For slurry machines this is a more notable difference, though as has been mentioned previously the design of the cutterheads is becoming more similar in both Europe and Japan. For EPB machines there remains more of a difference, with the Japanese philosophy tending to prescribe a machine that utilizes a lower cutterhead speed but has higher torque installed. As discussed in section 4 this leads to a close back-to-back scraper placement. This is in part due to the thought that a low cutterhead speed reduces wear, minimizes the need for additives and minimizes disturbance in front of the cutterhead. European machines will tend to have higher cutterhead speeds, which will minimize the required penetration and therefore the required toque. To efficiently operate with the higher cutterhead speed and in open mode a wider back-to-back scraper spacing is very often utilized.

6. Areas for Advancement

While there have been significant advancements in cutterhead design over the past 40 years, there are many areas that still remain for design optimization. The majority of opportunities for improvement will continue to be in the area of cutterhead maintenance and serviceability. In many cases these advancements will not be new concepts. For some it will be making existing concepts more robust or reliable to better survive in the difficult tunneling environment. For others it will be to improve machines and cutting tools in a way that they are not prohibitively expensive and may be more widely utilized.

The major reason for cutterhead maintenance is to inspect or change the cutting tools. A great way to reduce the maintenance is to increase the tool life. This is effected by many factors so there are many approaches that can be taken, including cutter placement on the cutterhead as previously discussed. The use of chemicals and additive like foam is one approach to extending tool life. Still another is the use of different tool materials. A good example of this would be the design of knife edge bits: the choice of carbide for use in this application is difficult, as the harder the material the better the wear resistance, though this also makes the cutter more susceptible to chipping due to impact loading. The material that holds the carbide in place can also wear way so that full chips of carbide can fall out, commonly called 'gingivitis'. The design of figure 15 takes advantage of the impact toughness of E5 carbide and wear capability of E2. With carbide forming the body of the tool the resistance to gingivitis is very high. While the individual tool cost is high, it can be a cost effective solution on the right job.

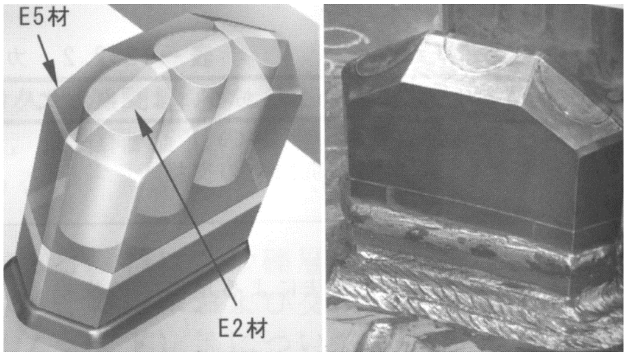

Fig. 15. *Unique carbide scraper concept*

Another needed area for advancement is in the often arduous process of tool inspection and replacement under pressure. To minimize the need for difficult cutter inspections, especially when face pressure needs to be maintained, several methods are currently available. One of the more common methods for doing this is by use of a wear detection bit plumbed hydraulically to a pressure sensor that will show an alarm if the hydraulic pressure is lost due to a hole in the tool. Ideally, this tool should be similar in construction to the tool that it is trying to measure, which usually means it will use carbide inserts and be hard-faced with the same material as the knife bits.

While not as complete as an inspection by a cutter change crew, in difficult situations it can be advantageous to complete a visual inspection of the cutting tools without the expense of having to go under pressure. This is can be done with a pressure-rated camera that is mounted thought the machine bulkhead. This by itself will give very limited information as the inside of the mixing chamber is usually covered so that visual inspection is not possible. By combining this with a high pressure water spray a better inspection can be done. At this point, access becomes an ever increasing benefit and cost. From a single point of inspection the systems capabilities can be increased so that a range of visual inspection with water spray can be reached as demonstrated in Figure 16.

Fig16. *Jet Snake Courtesy of OCRobotics*

At some point the tools must be changed, however. Like in the inspection process, tool changes are made more difficult in pressurized situations. The higher the pressure the more advantageous it is to have a design that can be serviced without the need for people to go under pressure. One approach would be to use an industrial robot to go under pressure instead of a human. This has been considered in the past, though never fully pursued due to cost considerations. It is, however, a compelling enough idea that it has secured some European-commissioned research funding.

The other basic approach of tool changes is to bring the tools to the people, who stay in atmospheric conditions. This can be done by creating passageways in the cutterhead itself that do not need to be pressurized and can be accessed from inside the machine. This atmospheric cutter change system allows for much easier access to the tools, though to allow people to move through the cutterhead structure it needs to be made deeper than it ordinarily would, which can be detrimental as discussed previously.   It is also possible to rotate the entire cutterhead so that it is inside the shield. This not only allows access to all the tools, but the full cutterhead structure. The rotation does require the cutterhead to retract in some manner, either by folding or retracting arms, both of which will limit the structural capabilities. The rotation and sealing mechanism is also challenging to manufacture at the scale of a TBM, further increasing the cost (see Figure 17, an experimental machine developed in Japan).

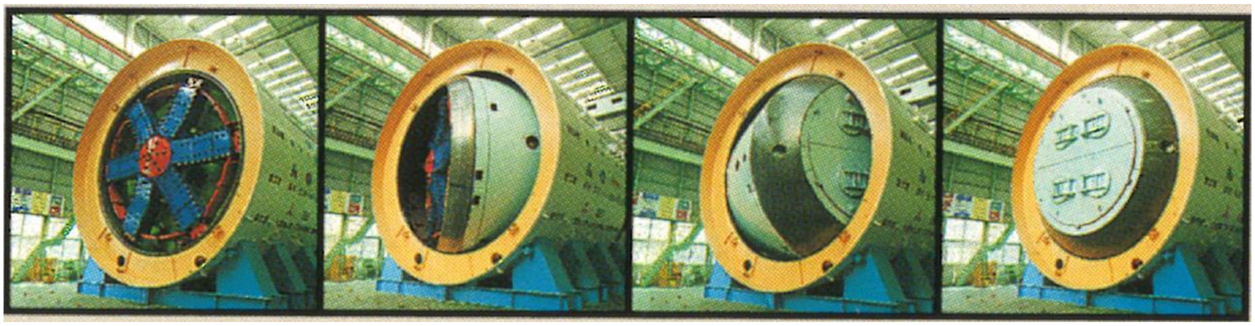

Fig 17. *Full Pressure Cutterhead Access design. Courtesy of MHI*

7. Conclusion

EPB and Slurry machines have developed significantly over the past 40 years. This is evident in many different aspects of the machine and certainly in the cutterhead designs. While these machines are becoming more mature and understood technology, they operate in a very challenging environment and there are still many areas open for improvement in the design and implementation of these products.