Onsite, First Time Assembly of TBMs: Merging 3D Digital Modeling, Quality Control, and Logistical Planning

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ABSTRACT: Traditionally, the delivery of Tunnel Boring Machines (TBMs) has been preceded by full assembly and testing of the TBM at the manufacturer's facility before dismantling and shipping to site. Recent years have seen a rapid development of 3D CAD tools, modular TBM and back-up designs, and more advanced Quality Assurance procedures. These advances can now prevent clashes of components and incompatibility of equipment without the need for full workshop assembly. To realize the benefits, a new method of TBM delivery has been developed called Onsite First Time Assembly (OFTA). This paper discusses the challenges and benefits of OFTA with specific examples given from several recent projects that employed this method of delivery.

WHY IS OUR INDUSTRY LAGGING?

Traditionally, hard rock and earth pressure balance (EPB) tunnel boring machines have been fully assembled in a factory, tested, disassembled, transported to the job site and reassembled onsite prior to starting operation. Conversely, other large scale industrial equipment is rarely fully preassembled and tested prior to being installed in the final intended location. For examples, think of small to midsized gas-fired power plants, bucket wheel excavators and specialized small manufacturing factories. Like tunnel boring machines, for all of these examples, time is of the essence. In the period from ordering equipment to having operational equipment, nothing is being produced and cash flow is negative. While elimination of the first three steps of the process (factory assembly, no-load testing and disassembly) does not result in a 100% equivalent savings in time and labor, it does result in a substantial savings of both. In addition, there is savings for reduced transport cost.

Given the similarities in complexity and delivery times for industrial equipment and tunneling equipment, it begs the question: Why have tunneling machine manufacturers, civil constructors and project owners resisted for so long the direct shipment of components to site for first time assembly? It is easy to understand why machine manufacturers with a large investment in fixed manufacturing facilities would be resistant to on site, first time assembly (OFTA), preferring the status quo which keeps prices higher and their facilities full of equipment. It is more difficult to understand the motivations of owners and consultants. Even today, in the face of mounting evidence of the benefits of OFTA, many consultants continue to stipulate in tender documents that the tunneling machine must be fully factory assembled and tested. This resistance to OFTA might be caused by the generally conservative nature of project owners and their consultants; however, it is more likely to be a simple habit from the past which it is time to break.

A CHANGING WORLD

The Evolution of Design and Manufacturing Tools

Thirty years ago tunneling machines were designed manually, on drawing boards with pencil and paper, with design calculations performed on what are, by today's standards, antique calculators. Project management software was only a dream. Twenty years ago, things improved somewhat with 2D CAD becoming the norm and the first wave of project management software becoming available. Over the past 10 years, the expansion of 3D CAD and improvements in project management software, including links to many enterprise/manufacturing resource planning programs (ERP/MRP), have given manufactures invaluable tools with which to insure the quality of design, the fit up of complex parts and the delivery of complex systems.

A Mature Industry

Thirty years ago, nearly every tunnel boring machine was unique in its design, custom built and manufactured specifically for the project. Today, that is very rarely the case. Thirty years ago perhaps scores of tunneling machines were made annually. Today hundreds of tunneling machines are made annually and, like automobiles, many of them are of the same make and model. Due in no small part to the sharing of knowledge through professional organizations such as those supporting this conference, today there is much common agreement regarding the "type" of tunneling machine best suited to certain geological conditions. Standard types are open hard rock, hard rock single shield or double shield, EPB or slurry shield. As a result, the design of each of these machine types have moved from their uniquely designed, custom origins to a vastly superior product today which is mature in design and subject to continuous improvement through incremental changes.

As a result of this maturation and evolution of the tunneling machine, when a civil contractor receives a machine today the probability is very high that at minimum the core of the machine has been produced many times previously. This provides both a more reliable product and the potential to eliminate the in-factory assembly phase with minimal risk for all involved.

A Total Program for OFTA

The use of 3D CAD software today makes it possible to accurately check the fit up of the component parts of complex machinery in the design phase. A thorough and time-tested quality assurance program insures that components are made per print, continuing the fit up guarantee through the next step of production. The availability of project management (PM) software with the capability to plan and monitor resources throughout the design and production process, and the linking of PM software to the ERP software for an entire company, provides a powerful tool for insuring that every component of these complex systems is delivered to the job site when it is needed during the assembly process.

But, it takes humans, experienced humans, as well as software to make OFTA work. While this is true throughout the design and manufacturing process, it is especially true on the job site, where the complex tunneling machine must be assembled safely, quickly and correctly to achieve the targeted schedule and cost savings. Fortunately, the widespread global growth in the use of all types of tunneling machines over the past twenty plus years has resulted in a worldwide pool of highly experienced tunneling machine professionals. Wherever in the world a project might be, it is possible today to put onsite a team of professionals who can direct the assembly and operation of every type of machine.

Why OFTA?

Depending on the size and complexity of the tunneling machine being produced, and whether the machine is new or refurbished, the savings in both schedule and cost can be substantial. On a small, 3.0 meter simple machine the savings in schedule can be as little as a month or so and perhaps 5,000 man-hours and 100,000 US dollars in transport cost. On a complex 10 meter or larger machine the savings in schedule can be as much as several months and possibly 15,000 man-hours can be saved as well. Eliminating the transport to factory for preassembly of such large machines can reduce transport costs by more than a million US dollars. However, the reduced costs noted here are generally dwarfed by the large commercial gain inherent in delivering a major tunneling project on a shorter schedule.

The remainder of this paper discusses some recent projects on which OFTA delivery was employed, noting problems encountered and their resolution. In closing, the paper lists the requirements necessary for a manufacturer to provide a successful OFTA program while minimizing risks associated with the program.

RECENT PROJECTS EMPLOYING OFTA DELIVERY

Niagara Project—Canada

In 2005, Austrian civil contractor STRABAG was awarded a 600 million Canadian dollar design—construct contract for the Niagara tunnel project. The TBM bored tunnel is concrete lined at 12.7 m (41.7 ft) internal diameter and 10.4 km (6.5 mile) long. The project funnels water past the famous falls to the Sir Adam Beck Power Station, providing power to the province of Quebec. Figure 1 shows the tunnel route. STRABAG purchased a 14.4 m (47.4 ft) open, hard rock, high-performance TBM (HP-TBM) from The Robbins Company for the project, and specified OFTA delivery. The large, custom designed machine was contractually specified to be delivered, ready to bore at the job site, 12 months from the signing of the TBM supply contract.

The Niagara TBM—Design and Manufacture

The 14.4 m Robbins HP-TBM, nicknamed "Big Becky," is the largest hard rock TBM ever produced. The TBM is fitted with 254 mm (20 inch) diameter, back-loading cutters and the cutterhead is powered by 15 × 315 kW (4725 kW, 6330 HP) motors with variable frequency speed control. The TBM, without backup, weighs over 1100 t (1210 st).

The TBM was designed in Robbins USA offices with major components being manufactured in the

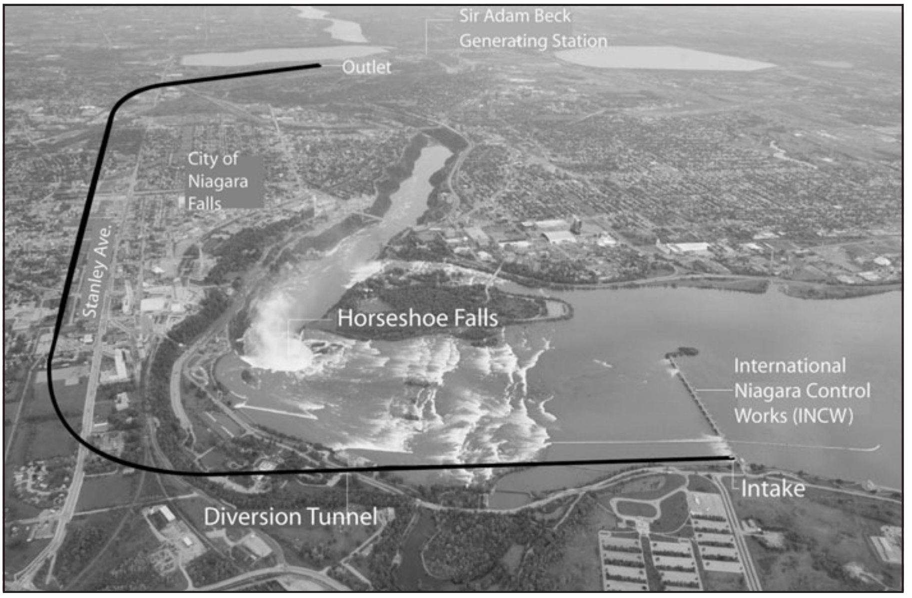

Figure 1. Niagara tunnel route

USA, Canada and Europe. The 400 t (1210 st) cutterhead was manufactured in the UK. Subcomponents were, where possible within the tight schedule, preassembled in workshops as they were manufactured. The timing of exworks delivery of the components was tightly controlled in order to assure arrival of components at the job site in the order required for assembly, without undue handling and storage in the limited space available at site.

The Niagara TBM—Onsite Assembly

For onsite assembly, the TBM manufacturer provided a team of experienced supervisors and specialist technicians. The contractor provided local labor and tools. Assembly was carried out in the open cut leading to the bored tunnel. Figure 2 shows the key components in place with the gripper cylinders and carrier being lowered into position for installation. Figure 3 shows a special tool used for installation of the main drive pinions.

The core design of the Niagara machine is similar to previous machines manufactured by Robbins. Many of the components had been fit up on previous jobs and it was only necessary to provide a high level of inspections following component manufacturing to ensure proper fit up at the Niagara job site. In spite of a very aggressive in-factory quality control program, a few problems were encountered during the assembly. Fortunately, the errors were rapidly corrected. Two of the issues involved interferences found on fit up of parts. In one case, during the manufacture of a large and complex weldment/machining, the cutterhead support, a single rough machining step had been overlooked. While hundreds of dimensions had been properly checked during the factory inspection, this single dimension had not been checked. In both cases of interference, a local specialist in onsite machining was employed to make the necessary small corrections. It must be stressed that had OFTA not been employed, these same errors would not have been discovered until in-factory assembly and the resultant repair time would have been the same as it was in the field. The extremely large size of the parts makes it easier to

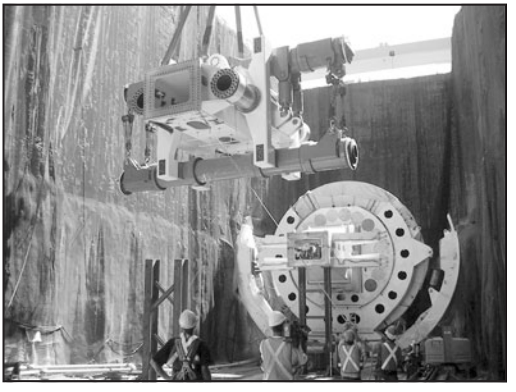

Figure 2. Installation of gripper cylinders and carrier onsite

Figure 3. Special tool for installation of final drive pinions

bring the machining tools and personal to the part than to take the part to a machine shop. In any case, in spite of the few problems encountered, the onsite assembly proceeded on schedule. Figure 4 shows the TBM cutterhead being installed onsite.

The Niagara Result

The TBM supply contract stipulated a 12 month, "ready to bore" OFTA delivery which was in fact achieved. This saved approximately 4 to 5 months when compared to a traditional 11 to 12 month factory assembly schedule, followed by disassembly, transport and reassembly onsite. In addition, it is estimated that 1.3 to 1.8 million dollars were saved in labor and transport costs by eliminating the factory pre-assembly for this very large machine. Figure 5 shows the machine fully assembled at site, ready to bore.

Alimineti Madhava Reddy (AMR) Project—India

The Indian civil contractor Jaiprakash Associates Ltd. was awarded the construction contract for the Srisailam Left Bank Canal (SLBC) Tunnel, which is part of the Alimineti Madhava Reddy (AMR) Project in Andhra Pradesh in southern India. During monsoon season, water will be transferred from the Srisailam Reservoir to 300,000 acres of farmland as well as providing drinking water to many villages. The tunnel is approximately 43.9 km (27.3 miles) long with no possibility for intermediate access. Above the tunnel route are a tiger reserve, wild life sanctuary and areas of protected forestry. In order to minimize disturbances to these sensitive environments, Jaiprakash elected to employ tunnel boring machines to excavate the tunnels. In 2005, Jaiprakash ordered two 10 m diameter, hard rock, double-shield TBMs from The Robbins Company. The tunnel is to be completely lined with concrete, and 60% of the tunnel is in very blocky, layered shale and quartzite. Because of these factors, double shield TBMs were selected in order to get the highest advance rates with simultaneous tunnel lining, ensuring the quickest delivery of the final operational tunnel. Figure 6 shows an elevation view of one of the tunnel boring machines.

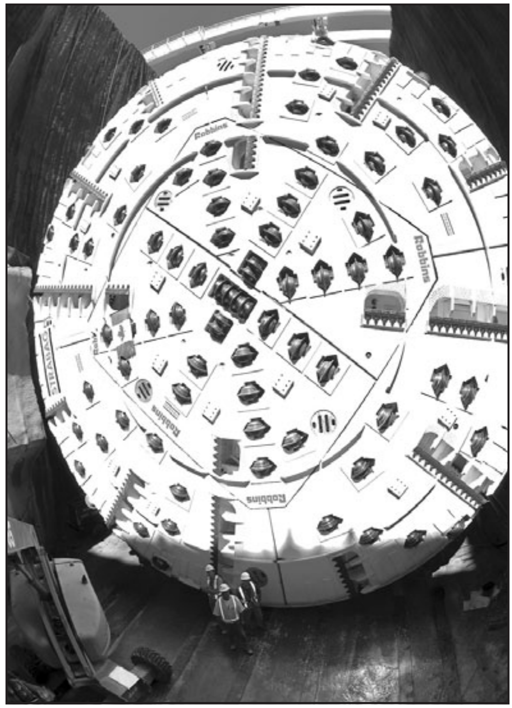

Figure 4. TBM cutterhead installed onsite

The AMR TBM—Design and Manufacture

The TBM supply contract required the first components to arrive onsite not later than eight months after order, with all components to be delivered not later than thirteen months after order. Contractor and machine supplier agreed to an OFTA delivery in order to have the machines ready to bore in the shortest possible time. Figure 7 is a photograph of the open cut assembly and startup area at the job site.

Unusual for modern TBMs, the 10 m double shield machines were in large part a completely new design for Robbins and so particular care was given in the design stage to ensure proper fit up of all parts at the job site. The major TBM structural components were manufactured in China, while the backup structure was manufactured in India. As is typical for modern TBMs, the other components

Figure 5. TBM and back-up assembled in launch chamber

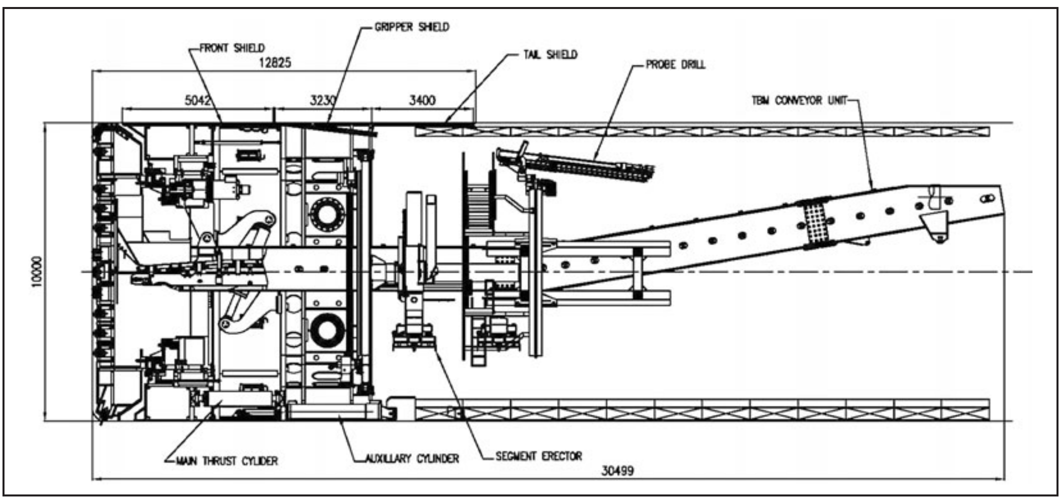

Figure 6. Drawing of double shield TBM, elevation view

(e.g., electric motors, gear reducers, main bearing, seals, hydraulic cylinders, etc.) were sourced from locations in the USA, Japan and Europe. Every component of the tunneling systems was tracked through design—from design drawing release through every step of manufacturing, transport and delivery to the job site. Figure 8 shows installation of the segment erector rotation ring at the job site, while Figure 9 shows cutterhead assembly.

The AMR OFTA Result

The shipping dates required per contract were met. It has been estimated that a schedule savings of 4 to 5 months was achieved when compared to a traditional

Figure 7. Assembly proceeding in the granite open cut

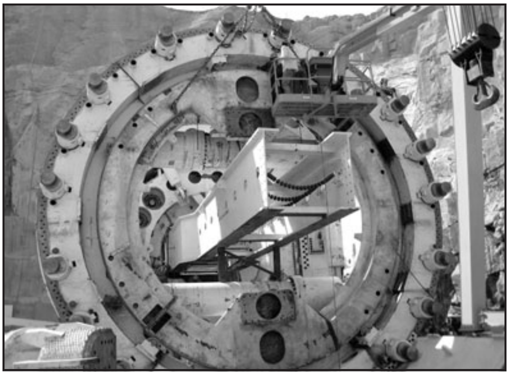

Figure 8. Installing the erector rotation ring—AMR, India

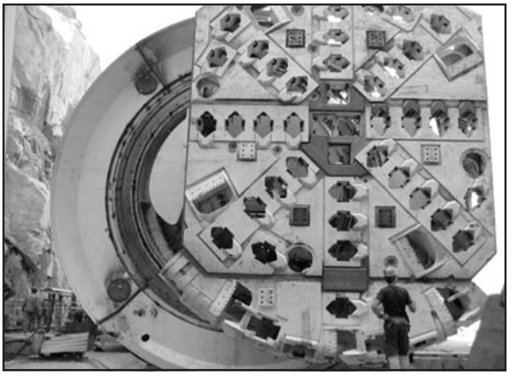

Figure 9. Installing the center cutterhead section—AMR, India

"factory assembled" delivery. Cost savings in reduced labor and transport costs were estimated to be greater than 3.5 million dollars for the two machines.

Again, the TBM manufacturer provided a large number of supervisors and technicians to direct and aid in the onsite assembly and testing of each machine. In spite of the machines being a new design, fit up problems at site were minimal and corrected rapidly without impacting the assembly schedule.

Jin Ping II Hydroelectric Project—China

At the Jin Ping II Hydroelectric project, four (4) parallel headrace tunnels are being driven with an average length of 16.6 km. Two of the tunnels are being excavated by 12.4 m open, hard rock TBMs and two by drill and blast. From intake structures near Jingfeng Bridge water will flow through the four Jinping headrace tunnels downgrade at 3.65% to the underground Dashuigou powerhouse. Eight 600 MW turbine generators will be installed in the power house for a total generating capacity of 4800 MW.

Figure 10. Pre-assembly of the cutterhead support and shields—Jin Ping II, China

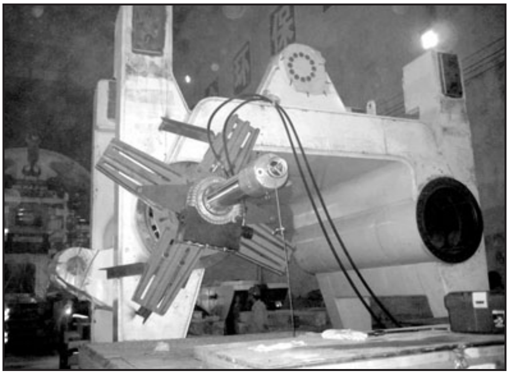

Figure 11. Onsite boring repair of gripper carrier way bushing

China Railway 18th Bureau (Group) Co Ltd. (CR18) won the construction contract for headrace tunnel Nos. 1 and 2, which includes one drill and blast and one TBM bored tunnel. CR18 awarded the TBM supply contract to The Robbins Company.

The Jin Ping TBM—Design and Manufacture

Limited road access to the job site meant that the largest TBM components needed to be delivered by river. However, seasonal low and high water flows on the river made for a short seasonal window within which the components had to be delivered to site. If the parts could not be delivered to site within this window, it would be several months before there would be another opportunity. As a result, OFTA delivery was specified in order to reduce delivery time and reduce the risk of missing the transport window.

In this case, many of the core TBM component designs were the same as those employed on Niagara and previous projects, which reduced the risk of fit up problems onsite. The backup system was, however, a completely new design. Robbins designed the machine at their facilities in the USA and China. The main TBM structural elements were manufactured in the city of Dalian in northeast China. Where the schedule allowed, some factory preassembly was done to check critical component fits and reduce onsite assembly time. For example, the main bearing, gear, and pinions were installed in the cutterhead support and the ring gear-pinion mesh was checked. Also, the muck chute, side supports, roof support, and front support were temporarily installed in factory to check fits. Figure 10 shows factory preassembly of components on the cutterhead support. All remaining components were assembled for the first time onsite.

The Jin Ping OFTA Result

The onsite assembly was not 100% error free but once again it was proved that correction can be made onsite nearly as quickly as in a factory, even on a job site as remote as the Jin Ping, China site. Early in the assembly it was discovered that the bushings in the gripper carrier ways had not been finished machined in the factory. Shipping the part to a Chengdu factory, the nearest large city, was not possible due to severe damage to local roads and machine tools, which occurred in the severe Sichuan province earthquake in 2008. A machining contractor in Shanghai was employed to bring a portable boring unit to the job site and make corrections to the part. The part was line bored onsite in only 3 days. Figure 11 shows the line boring machine in use at site.

At the peak of effort, Robbins provided 42 people to support the assembly: 16 supervisory personnel from the USA and Europe and 26 engineers, mechanics and electricians from China. Despite record breaking snowstorms and a magnitude 8 earthquake, the TBM and backup was fully assembled and ready to bore in only three months. People experienced with field assembly of large diameter hard rock TBMs opine that the three month assembly period could not be improved upon by pre-assembly of the machine in a factory prior to delivery to site. Again, the savings in time with OFTA is estimated to be in the 4 to 5 month range and cost savings are estimated to be approximately 2.3 million dollars in labor and transport costs. Figure 12 shows the TBM in the onsite assembly hall, ready to walk to the face to begin boring operations.

Mexico City Metro Line 12—Mexico

Mexico City's metro has the 5th highest ridership in the world, carrying 1.46 billion passengers in 2008. In 2008 a joint-venture of Alstom and Mexican partners

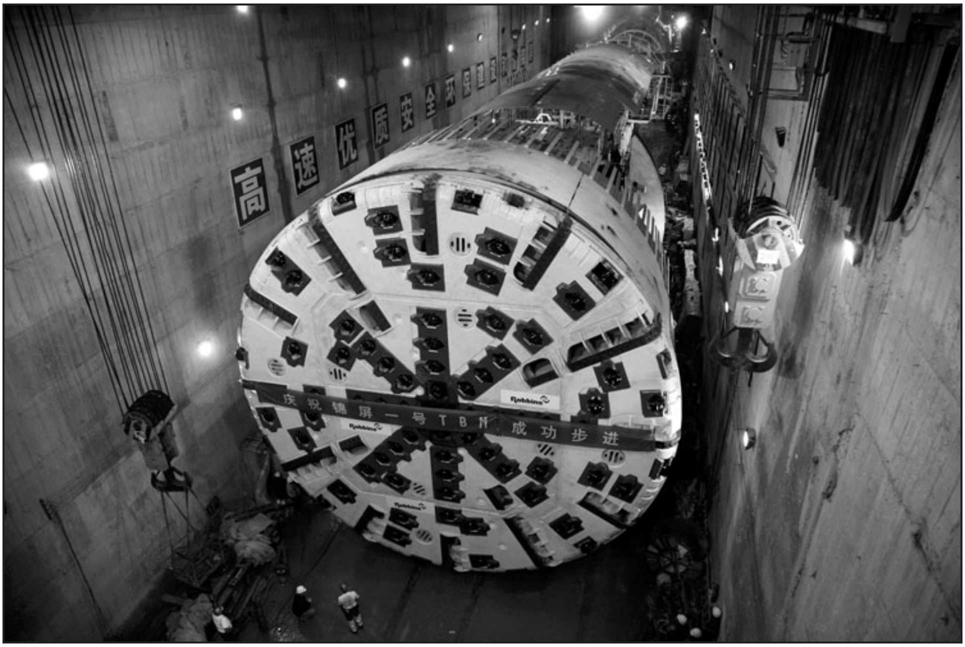

Figure 12. OFTA—ready to bore

ICA and CICSA was awarded a 1.74 billion US dollar contract to build metro Line 12 in the southeast sector of the city. The new line 12 will be 24 km long from Mixcoac to Mexicaltzingo, have 22 stations and connections to lines 2, 3, 7 and 8. The contractors will utilize a Robbins 10.2 m (33.5 ft) diameter EPB on a 6.2 km (3.9 mi) long section of tunnel for the new line. The tunnel passes under the water table through high water content clays as well as sands, silt and gravel with the potential for boulders up to 800 mm (30 inches). Figure 13 shows a 3D CAD drawing, section view through the EPB machine.

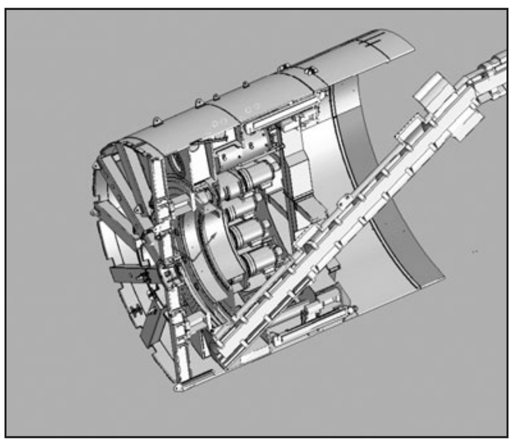

Figure 13. 3D CAD section view of MX 12 EPB—Mexico MX12

The Mexico Line 12 EPB—Design and Manufacture

The 10.2 m EPB was designed in Robbins' USA and China offices. Primary structural components were manufactured in Japan, China, Korea and Mexico. The main bearing, drive components and hydraulic and electrical components were sourced in the USA, Europe and Japan. This machine contained a combination of previously produced designs (cutterhead support/main bearing and seal assembly/main drives) and new designs. The main bearing and seal were installed in the cutterhead support at the factory in Korea prior to being transported to the job site. Again, an extensive quality control program was in place and rigorous dimensional checks were performed on major components prior to their delivery from the factories.

The Mexico Line 12 OFTA Result

At the time of writing, the MX 12 on site assembly had just started with the primary major components arriving at site. Figure 14 shows the lowering into place of the bottom half of the front shield –Ring A. Figure 15 shows the cutterhead sections being joined with the pedestal at the top of the assembly shaft on site. Figure 16 includes two views of the cutterhead support: the upper photo is of the forward pinion support bearing and a bit of the ring gear, while the lower photo shows the same view after installation of the drive pinion.

Assembly is proceeding on schedule and as of this writing no major fit up problems have occurred.

SUMMMARY

Specialist TBM tunneling contractors frequently own several TBMs that are refurbished and moved from job to job. Having been fully assembled once or more previously, it is extremely rare for these *used* TBMs to ever be fully assembled in a factory. They go straight from the contractor's storage and repair facility to the job site. Robbins has now successfully demonstrated the potential for Onsite, First Time Assembly of *new* TBMs. Several TBMs of different types (hard rock—open, double shield and EPB machines) have been delivered using the OFTA method. In every case there has been a substantial reduction in the time required to start boring—as much as 5 months. There has also been great savings in cost—more than two million dollars for a large diameter rock machine. There may be a further, though hard to quantify, advantage in the in-depth training the contractor's personnel receive during the onsite assembly, when working closely with the larger supervision staff provided by the machine manufacturer with OFTA delivery.

It cannot be argued that there is no increase in risk with OFTA, but experience has shown that the risk is definable, largely controllable and most important recoverable. The primary risk is, of course,

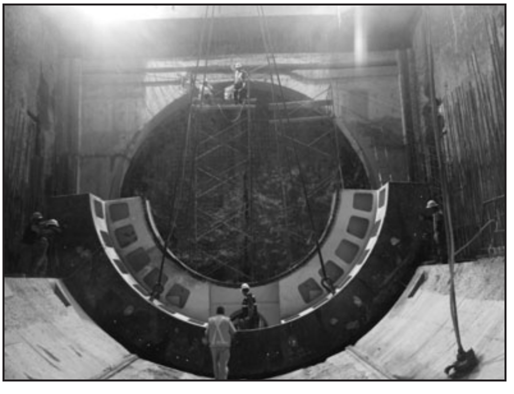

Figure 14. Installing lower section of A Ring—Mexico MX12

Figure 15. Assembling cutterhead sections with pedestal—Mexico MX12

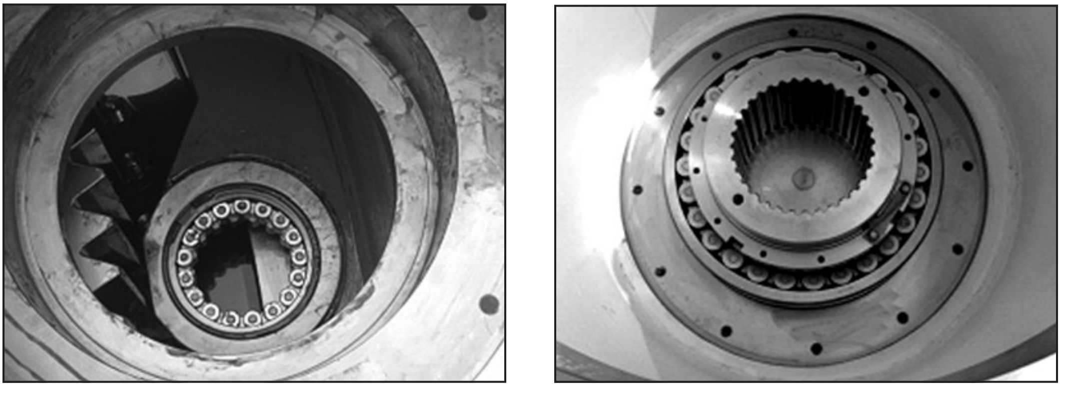

Figure 16. Installation of drive pinions—Mexico MX12

errors in design or manufacturing which result in a misfit of components during assembly at site. This risk is mitigated through the use of previous designs, 3D CAD, the implementation of proper design procedures and checks, and the implementation of an aggressive quality control program. Finally, as has been shown on the OFTA deliveries to date, when problems are encountered during onsite assembly, the schedule can generally be recovered through onsite correction carried out with the assistance of specialist fabrication and machining companies.

Key components of a successful OFTA program include:

- Use of prior, proven designs where possible
- 3D design and computer aided test fitting of critical components
- 100% dimensional inspection of critical components at the fabricators
- Pre-assembly of subcomponents/modules when schedule allows or is not impacted by pre-assembly
- Aggressive quality control of all components manufactured to ensure proper fit up at site
- Absolute control of the total tunneling machine system bill-of-materials, to ensure that every part, large and small, which is required for the system is sent to the job site
- Logistical planning and control, to ensure that every part arrives at the job site, when it is required, in the order that it is required for efficient assembly and use of storage space
- Resource planning, to ensure that all tools and personnel of every type, qualification and quantity required for assembly are onsite when needed
- Advance alternative recovery planning, in order to be ready to react quickly to possible failures in any of the above steps
- A larger than usual team of highly experienced personnel must be provided by the machine manufacturer to supervise and assist with the onsite assembly

Project owners have an obligation to the public to deliver underground infrastructure at competitive prices, on the quickest practical schedule and without undue risk. Contractors need every tool available to meet these demands. It is time for tunnel owners and contractors to move into the new millennium. OFTA offers an opportunity to save both time and cost. Experience to date prove that it can be done with little risk with the use of modern design, quality control and project management tools. It is time for all involved to eliminate from future tunneling construction contracts the requirement for TBMs to be fully shop assembled and tested prior to delivery to site. Onsite, first time assembly is a practical, cost and schedule saving alternative.

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