Completing Mexico City's Mixed Ground Mega Tunnel: Emisor Oriente

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ABSTRACT

On May 23, 2019, the last of six 8.93 m diameter EPBs completed excavation at Mexico City's Túnel Emisor Oriente (TEO), a feat marking the completion of ten years and 62.1 km of tunneling. The TEO is a critically-designated plan to stem severe flooding while boosting wastewater capacity, and is the country's largest infrastructure project. The six EPB TBMs excavated some of the most complex geology on earth, ranging from abrasive volcanic rock to watery clays. This paper will cover the incredible challenges and solutions used to overcome what may be the toughest conditions ever bored by EPBs.

Key Words: Emisor Oriente, EPB, Wastewater, Mexico, Mixed Ground

INTRODUCTION

Mexico City, with its 19 million inhabitants, is one of the world's largest cities, but much of its infrastructure is struggling to keep up. Between 1970 and 2000 the population doubled and today it produces 40 m^3/sec of wastewater; however, capacity is only 10 m^3/sec. In addition, much of the city's wastewater is untreated and flows through a network of open sewers and underground lines.

The National Water Commission, CONAGUA, has developed a critically-designated plan to assuage health concerns and the potential for catastrophic flooding if a wastewater line should fail. The mainstay of their scheme is the country's largest infrastructure project, Túnel Emisor Oriente (TEO). The 62.1 km long tunnel will be connected to the first major wastewater treatment plant in Mexico City, and will alleviate flooding. A total of six TBMs are excavating the tunnel in some of the most complex geology on earth.

In the last 100 years, Mexico City has sunk by nearly 12 m. As a result, the city buildings, main streets, sewage systems, etc. have been extensively damaged. In addition, the city historically faces serious problems of flooding during the rainy season. In 2006 there was a high risk that major floods might occur in the city and suburbs, affecting a population of 4 million, six districts within the Federal District and three municipalities of the State of Mexico, flooding an area of 217 square km. The areas of greatest risk of flooding are the historic downtown and the Mexico City Airport and surrounding areas.

In 2007, the Mexican President Felipe Calderon labelled this situation a "National Emergency" and designated it as a top priority of the National Infrastructure Program (see Figure 1).

Figure 1. Seasonal flooding in Mexico City. *Image Credit: Wikimedia Commons.*

Two main actions were proposed:

1. Repair, maintenance and recovery of the slope of the Túnel Emisor Central, the main sewage system of the city.
2. The construction of the Túnel Emisor Oriente.

1.1. Background

The history of Mexico City is inextricably linked to the issue of its geographic location. The Metropolitan Area of the Valley of Mexico is built on a closed basin, which originally formed a lake system consisting of five large lakes: Texcoco, Xaltocan, Zumpango, Xochimilco and Chalco. The largest, Texcoco, covered about 1,500 square kilometers of the valley floor. Tenochtitlan, the ancient capital of the Mexica civilization, covered an estimated 8 to 13.5 km^2, situated on the western side of the shallow Lake Texcoco.

After the Conquest, the Spanish rebuilt and renamed the city. As they expanded Mexico City, they began to drain the lake waters to “control flooding”. In the rainy season, these lakes were converted into one lake of two thousand square kilometers. This condition explains the periodic floods that since the founding of Tenochtitlan inhabitants have faced and the resulting need to build major drainage works to control and evacuate wastewater and rainwater.

The idea of opening drainage canals first came about after a flood of the colonial city in 1555. The first canal, known as Nochistongo, was built in 1605 to drain the waters of Lake Zumpango north through Huehuetoca, which would also divert waters from the Cuautitlán River away from the lakes and toward the Tula River. Another canal, which would be dubbed the "Grand Canal" was built parallel to the Nochistongo, ending in Tequixquiac. The Grand Canal consists of one main canal, which measures 6.5 meters in diameter and 50 km long, and three secondary canals, built between 1856 and 1867. The canal was completed officially in 1894 although work continued thereafter. Despite the Grand Canal's drainage capacity, it did not solve the problem of flooding in the city. From the beginning of the 20th century, Mexico City began to sink rapidly and pumps needed to be installed in the Grand Canal, which before had drained the valley purely by gravity. Currently, and despite its age, the Grand Canal can still carry 42 m^3/s out of the valley, but this is significantly less than what it could carry in late 1975, which was 80 m^3/s. This decrease is due to the continued sinking of the city (by as much as seven meters), which weakens the system of water collectors and pumps (see Figure 2).

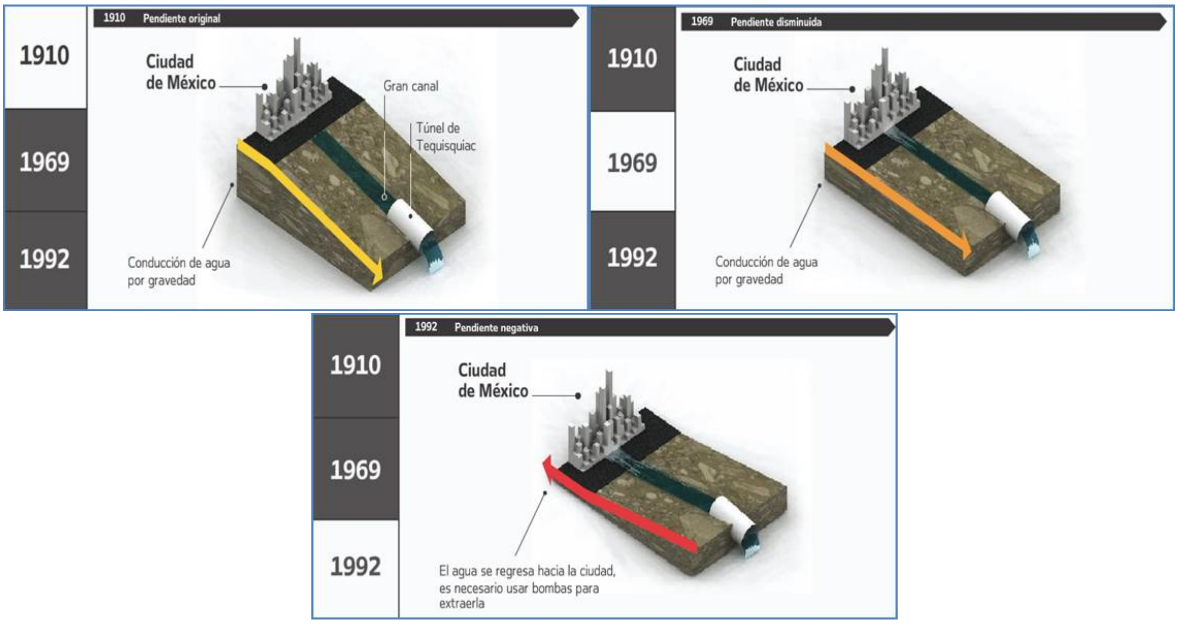

Figure 2. Change in slope of the Emisor Central between 1910 and 1992.

As a result of the decreased capacity, another tunnel, called the Emisor Central, was built to carry wastewater. Although it is considered the most important drainage tunnel in the country, it has been damaged by overwork and corrosion of its 6 m diameter walls. Because of the lack of maintenance, there has been a gradual decrease in this tunnel's ability to carry water. In fact when it was finished in the 1970s, the Emisor Central was able to carry 170 m^3/s; currently it is only capable of 120 m^3/s. Therefore, when the Emisor Oriente Project is in full operation it will work simultaneously with the Emisor Central, so that the Emisor Central can be taken offline for maintenance and repairs in the dry season.

In conclusion, the construction of Mexico City on islands in a system of lakes caused two permanent problems: the need for evacuation of rainwater as well as wastewater to prevent flooding, and the need to lessen/mitigate sinking by the overexploitation of aquifers.

2. TÚNEL EMISOR ORIENTE (TEO)

Mexico City's Emisor Oriente Wastewater Tunnel (TEO), a 62.1 km long mega project, is arguably one of the most challenging TBM tunnels in the world today. This monumental work of engineering will create a complementary and alternative conduit to Emisor Central, which will bring down the risk of flooding in Mexico City and its suburbs, and give security to 20 million people. In the rainy season, it will work simultaneously with the current deep drainage and, in the dry season, it will make for easy maintenance.

The TEO has three main purposes:

1. Expand the capacity of drainage, which will reduce the risk of flooding.
2. Reduce the overexploitation of aquifers, which exacerbates the sinking of the metropolitan area.
3. Treat the wastewater to promote its reuse in agriculture, instead of using sewage water for agriculture (a current practice in the Valley of Mexico).

The tunnel and water treatments plants are key components in these goals.

The TEO project is coming to an end and was funded mainly by the federal government, with a trust between the Government of the State of Mexico, Mexico and Hidalgo, with an initial investment for construction of 9,600 million pesos. The tunnel starts at port interceptor tunnel No. 2, the "River of the Remedies" and ends in the town of Atotonilco in Hidalgo (output Portal). It passes through the municipalities of Ecatepec de Morelos, Atenco, Tonatitla, Nextlalpan, Jaltenco Zumpango, Huehuetoca, Atotonilco, Tequixquiac and Hidalgo. It will have a wastewater capacity of 150 m^3/sec, and a profit of approximately MEX 19 million. Currently the drainage system of the valley of Mexico has a displacement capacity of 195 m^3/sec, but with the commissioning of the TEO, it will have a total of 345 m^3/sec.

The TEO includes 24 shafts, ranging from 23 meters to 150 meters in depth, plus an exit portal, which is the construction location of the Treatment Plant in the Municipality of Atotonilco, in the state of Hidalgo. The plant will be responsible for water reuse for agricultural irrigation. It will be the second largest plant of its kind in the world (see Figure 3).

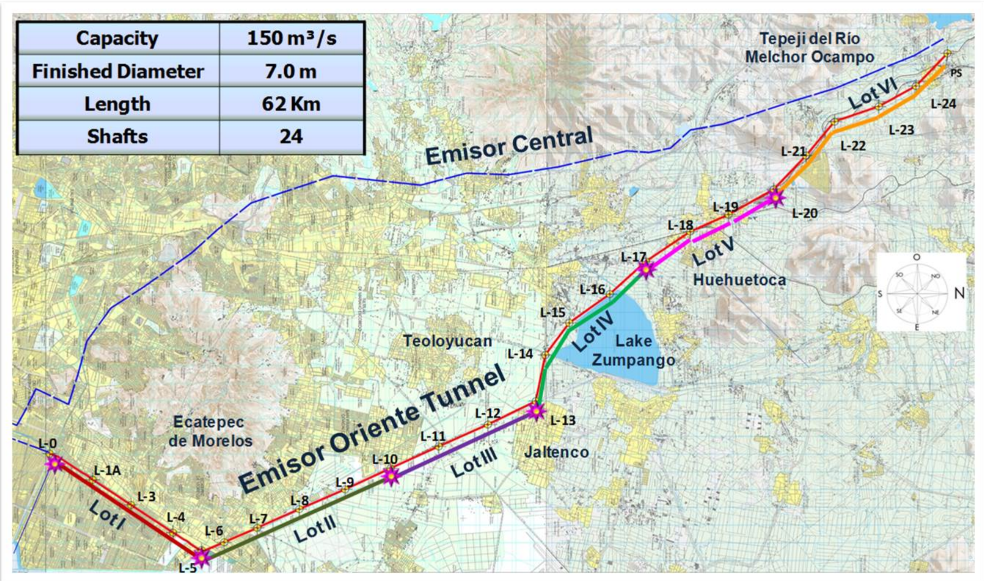

Figure 3. Overview of the TEO Layout.

2.1. Project Challenges

The ground conditions of the pipeline are some of the most difficult in the world. Located in the Valley of Mexico, geology consists of a drained lake bed with clays interspersed with volcanic rock and boulders from long dormant, buried volcanoes in the area. Water pressures on the alignment can be as high as 4 to 6 bars.

After ten years of work by EPB TBM tunnelling (six machines divided into separate lots), 100% of the excavation has been completed, and the owner of the project, CONAGUA, had to rethink their strategy several times based on the incredibly difficult and unforeseen ground conditions encountered—some of the highest pressures EPBs have ever operated under. The conditions range from very soft clays to highly abrasive materials, mixed ground, hard rock, and boulders under high water pressures, requiring frequent hyperbaric interventions in some of the lots and multiple modifications to the existing machines.

2.2. Contractual Setup

The project is property of CONAGUA, the national water and irrigation management authority of the Mexico Government. CONAGUA awarded the design, construction, and construction management of the project's delivery to Comissa, a consortium of Mexico's leading heavy civil contractors - ICA, CARSO, Lombardo, Estrella and Cotrisa (which has since been taken over by ICA). Group contractors Comissa were then awarded the six ~10 km long construction lots.

The external supervisors are Dirac and Lytsa, the companies that had the greatest experience supervising tunnels in Mexico.

The CONAGUA also contracted external advisors formed by a panel including well known experts in the tunnelling industry such as: Rick P. Lovat, Dr. Gabriel Fernandez, Dr. Pier Francesco Bertola, and Dr. Daniel Reséndiz Nuñez.

Other onsite advisors included Poyry from Switzerland.

3. TEO GEOLOGICAL CONDITIONS

Originally geology was based on 64 borehole tests conducted along the tunnel length, as well as six cross tunnel locations that were considered (see Figure 4).

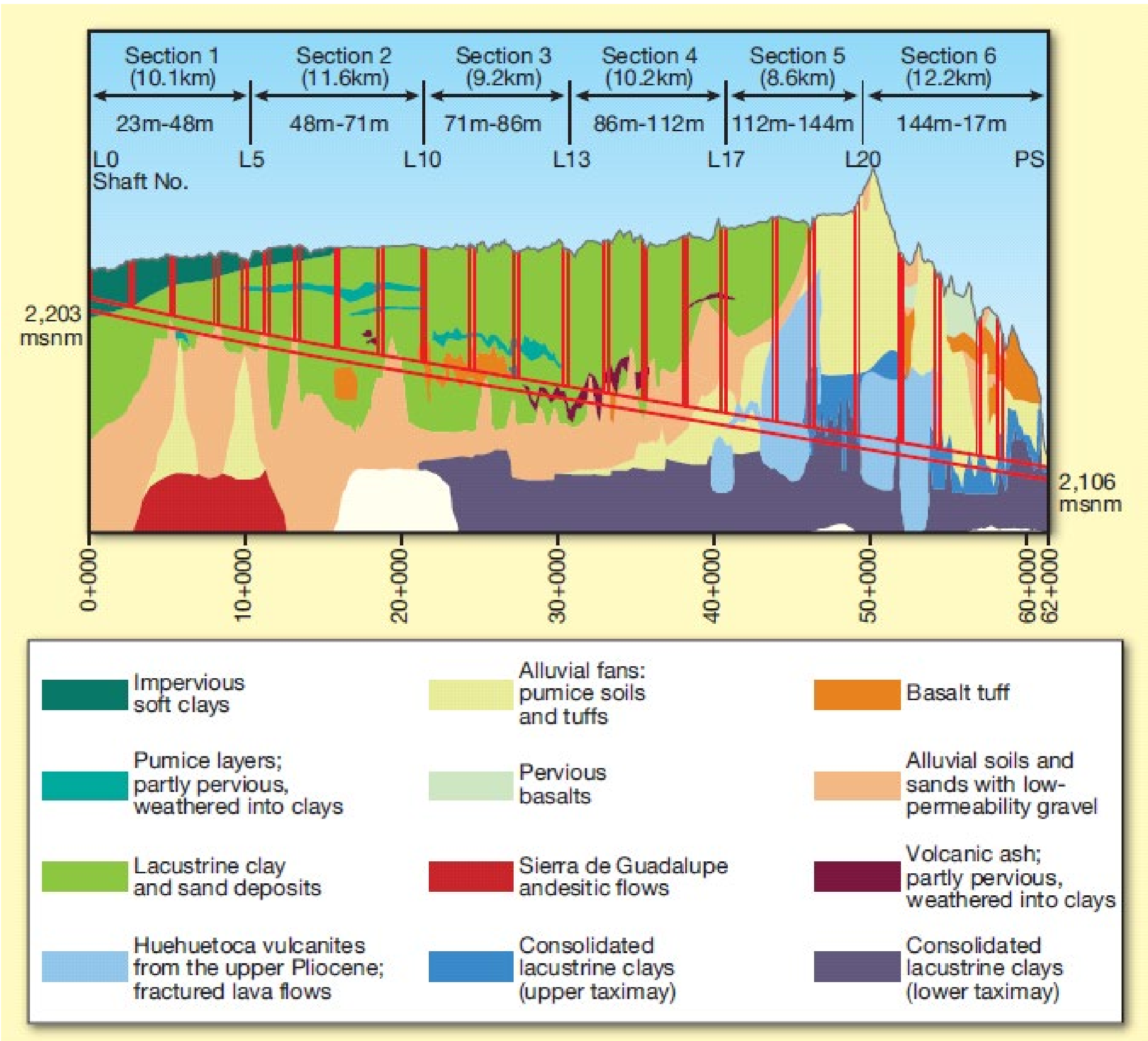

Figure 4. TEO geology. *Image Credit: Tunneling Journal North America.*

The results:

Lot 1: Quaternary lacustrine deposits of northern Mexico Basin.

Lot 2: Basaltic ashes and pumice, Quaternary strata, and northern flank lavas from Nochistongo.

Lot 3: Clay from the Pre-Quaternary lacustrine Basin of Mexico.

Lot 4: Fluvial Sands of the Plio-Quaternary Nochistongo Mountains.

Lot 5: Pliocene volcanic formations from the upper part of Huehuetoca.

Lot 6: Pliocene lacustrine deposits, Taximay medium and Taximay Superior.

The actual geology was revised several times, requiring a new strategy from both the contractors and equipment manufacturer and resulting in successful machine modifications. In this paper we will review the summary of the project based on the experience of how the contractor and equipment manufacturer had to overcome adversity on the six lots.

To date it is not only one of the most complex projects in Mexico, but also the first time EPB hyperbaric interventions have been done in Mexico. Based on the geological conditions in 2008 we will compare and analyse the expected conditions back in that year with the actual geological conditions and hyperbaric intervention experiences. We will also review the design of the machines and the challenges they faced.

4. STATE OF TEO IN 2019

The 62.1 km tunnel has been bored and the last meters of secondary lining have been also concluded. Only finalizing some civil works on the surface and concluding pending works and observation from the external supervisors remains.

The Atotonilco treatment plant was finished before the tunnel and is being tested and commissioned.

5. ORIGINAL TBM DESIGN CONSIDERATIONS

Before discussing Lot 5 in detail it is useful to review the type of machines and conveyor systems that were provided based on the 2008 geological information.

The three Robbins machines (provided for lots 3, 4, and 5) were built for abrasive basalt sections up to 80 MPa UCS mixed with sections of watery clay that have been compared to a soup, with water pressure estimated in the range of 4 to 6 bar (see Figure 5).

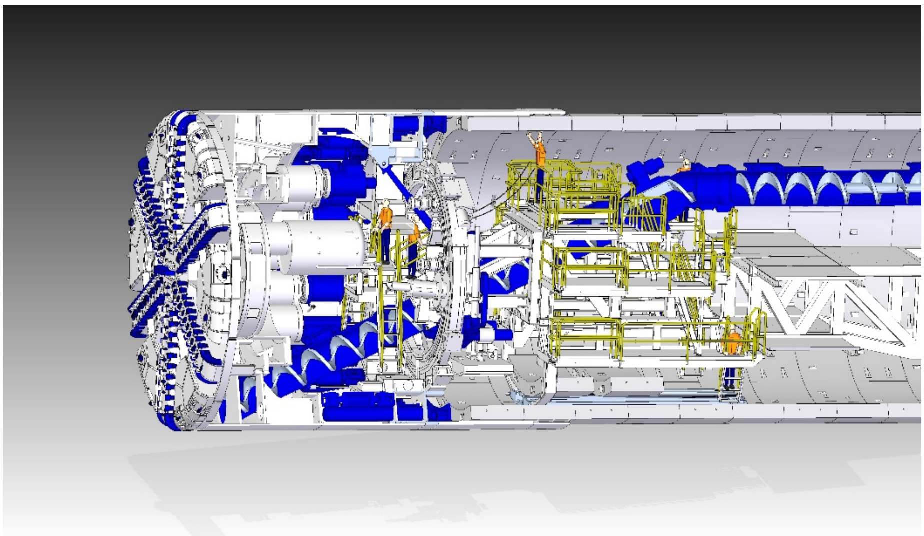

Figure 5. Original Machine Design.

5.1. Adaptable Cutterheads

The custom designed EPBs were engineered with mixed ground, back-loading cutterheads to tackle variable conditions. High pressure, tungsten carbide knife bits coould be interchanged with 17-inch diameter carbide disc cutters depending on the ground conditions. During tunneling a number of small shafts, spaced every 3 km between the larger launch shafts, were used to perform cutter inspection and changes, and to replace the tail seals. Specialized wear detection bits lost pressure at specified wear points to notify crews of a needed cutting tool change. The knife edge bits were arranged at several different heights to allow for effective excavation at various levels of wear.

Twenty-five injection ports spaced around the periphery of the machine could be used for injection of various additives depending on ground conditions and for probe drilling, with an additional six ports for the foam system. Additives such as Bentonite were used to condition the muck for removal by belt conveyor (see Figures 6-7).

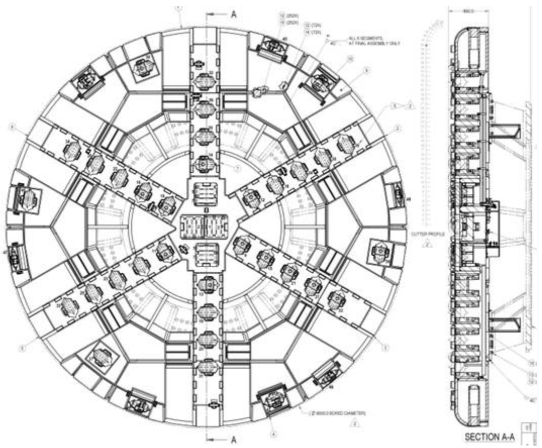

Figure 6. Hard Rock Cutterhead.

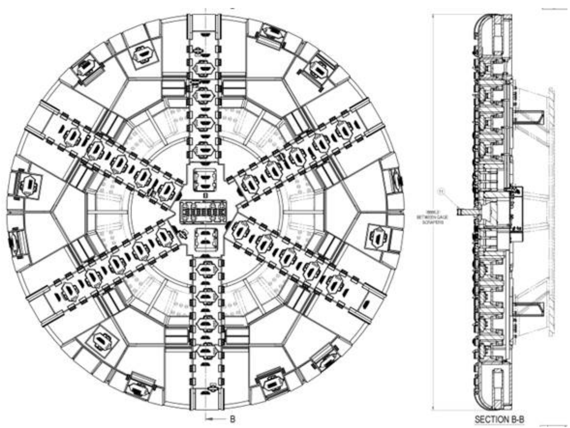

Figure 7. Soft Ground Cutterhead.

5.2. Two-Stage Screw Conveyor

High pressure conditions in concert with large boulders necessitated a two-stage screw conveyor design for the Emisor Oriente EPBs. An initial 900 mm diameter ribbon-type screw was capable of transporting boulders up to 600 mm in diameter up the center shaft for removal through a boulder collecting gate. Due to the expected high water pressures, a two-screw setup with a ribbon screw and shaft-type screw was deemed necessary in order to smoothly regulate pressure and maintain water-tightness.

5.3. Continuous Conveyors for Limited Space

Muck from all three machines was deposited from the screw to a fabric belt conveyor mounted on the trailing gear, which transfers to a Robbins side-mounted continuous conveyor. The continuous conveyor carried the muck to a vertical belt conveyor located at the launch shaft. Once at the surface, a radial stacker deposited muck in a kidney-shaped pile for temporary storage.

Due to the narrow shafts and small launch sites, the conveyor systems were optimized for space efficiency and safety. The belt was surrounded by a guard with recycle hopper to prevent hazardous falling muck while returning the material to the vertical conveyor.

A unique vertical belt cassette allowed for splicing of belt with a footprint 170% smaller than a typical horizontal belt cassette. The 34 m tall belt cassette was used to splice in a 450 m length of belt, which took roughly 12 hours and allowed the machine to advance for roughly 200 to 225 m.

6. EPB MODIFICATIONS

The three Robbins EPBs had to endure some modifications to accommodate the mixed ground conditions on Lots 3, 4 and 5. Sections of hard abrasive rock coupled with high water pressures were discovered during shaft construction, and afterwards more boreholes studies were done that identified the challenging ground.

Modifications included (see Figures 8-12):

- A 7-bar man lock with an additional decompression chamber to allow two teams to work at the same time. Also, a material lock to be able to handle cutting tools more easily.
- A redesigned bulkhead to allow the new configuration of the man and material locks up to 7 bars and high pressure in the tunnel.
- Chromium carbide plates to reinforce the screw conveyor and removable wear plates added to each turn of the screw conveyor in order to withstand abrasive hard rock. The screw conveyor was also able to open up as a “coffin” to be able to check for wear and plates replacement.
- An air compression system in order to control the water inflows in the chamber during excavation.
- Grizzly bars in the cutterhead to be able to close the opening and rock sizes before entering the cutting chamber, for facing blocky fractured basalt.
- New design of the rotary union joint that improved the time to change the center disc cutters.
- New design of scrapers capable of resisting load impact in mixed ground conditions in the presence of hard rock.

Figure 8. Man and Material Lock.

Figure 9. Man Lock for 7 bar pressure.

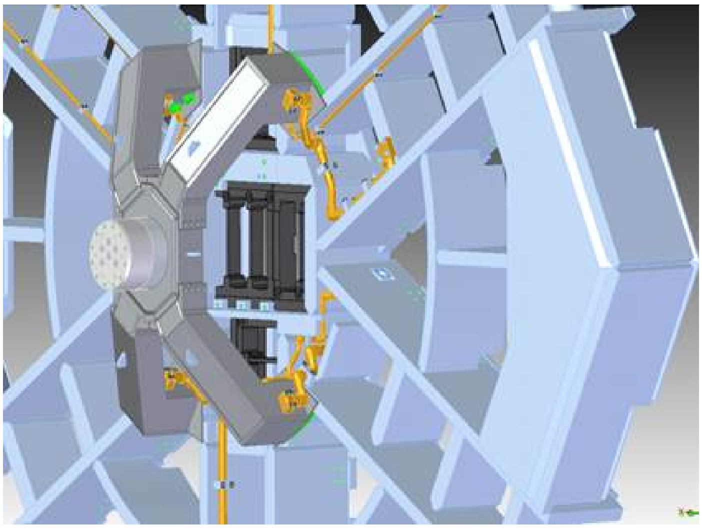

Figure 10. New Design of Rotary Union.

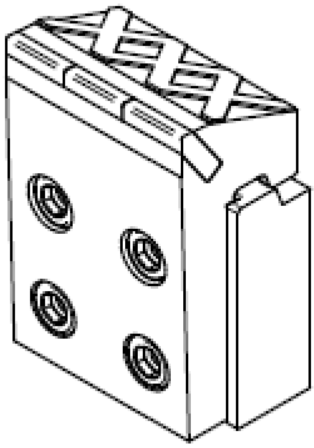

Figure 11. New design of the face scraper.

Figure 12. Screw Conveyor Helix Wear Protection plates.

PROJECT HIGHLIGHTS

Shaft Construction

Several methods were implemented to be able to build the starting and receiving shafts in very soft high content clay to very hard rock and mixed ground.

For the soft ground methods such as “milan” or slurry walls going up to 50 meters depth were used, and after that secondary lining with a slip form vertically provided rigidness to the structure.

Conventional cut and cover with steel ribs, mesh and anchors was also applied to be able to excavate after the first 50 meters. According to the design more or less one rib was installed after every meter.

One of the most important shafts constructed was shaft 20, as it is the deepest civil works shaft in Mexico, demanding extra attention to Lot 5. The construction of the shaft was quite unique, as the contractor utilized a hydroroadheader (see Figure 13) that was able to excavate panels or sections of the slurry wall or diaphragm walls up to 100 meters deep. After constructing the complete circumference of the shaft, the rest of the excavation was done by both the traditional shaft sinking method and the cut and cover method.

Figure 13. The hydroroadheader at shaft 20

Once the bottom of the shaft was reached, a starter tunnel of 28 meters was pre-excavated, in order to assemble the machine.

TBMs Assembled in Very Deep Shafts

At Lot 5, the machine was assembled in the launch shaft and commissioned in August 2014 with the bridge and all the rest of the back-up gantries at the surface. The first back-up structure was then lowered with the hydraulics and the main electrical components. Two months later in October 2014, after advancing 150 meters, the machine and its back-up gantries were completely assembled in the tunnel. One month later, the continuous conveyor system was installed and running.

After only 250 meters of excavation, new geology started to present itself, with sticky greenish clay with very little water, making it difficult to properly extract the material through the conveyor system. Much of the muck and material ended up in the bottom of the shaft, dropped from the vertical conveyor. The contractor made several stops for cleaning due to the material getting stuck on the muck discharge chutes. The TBM faced trouble due to the sticky clay material clogging the cutterhead, necessitating the higher usage of additives to reduce wear and improve the performance. After going through the sticky clay material from Shaft 20 to Shaft 19, the ground conditions changed radically, around 100 meters before Shaft 19. The TBM faced high water pressure with mixed ground; mostly hard clay, silty sand and isolated gravel. Once the TBM finished the drive through Shaft 19, the material excavated went from a mixture of clay with silty sand to a complete face of hard rock (basalt) with a high-water flow (200 l/s).

Going through Mixed Ground Conditions at Lot 5

The erratic rock fragments and andesite deposits created wear problems in the cutting discs, which required a strict program of several cutterhead inspections in order to inspect, change and analyze the wear issues that the tunnel was presenting. These wear issues were not expected in terms of the geologic complexity (see Figure 14).

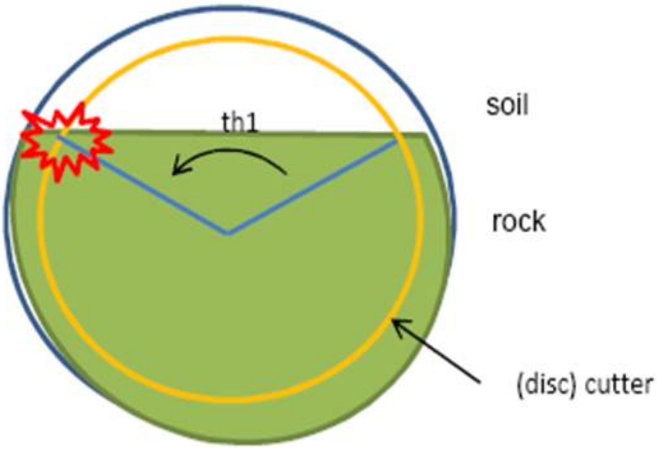

Figure 14. Diagram of impact loading.

As mentioned, watery lake clays combined with sections of abrasive basalt and large boulders created very challenging tunneling conditions. Normally interventions are mostly done for inspection purposes, but in this case the wear issues and presence of cutting tools in the muck required many interventions over a period of more than 20 days for tool changes when high water flow was at its peak.

In the next 1,000 meters, the ground conditions improved but the pumice fragments of all sizes, sand with gravel, vulcanite, lava deposits, alluvial fans with boulders, sand matrix and high-water flows made this drive an excavation with a high degree of uncertainty. Despite the challenges, the machine achieved breakthrough on February 28, 2019.

The production in other lots was also limited by mixed ground conditions. Abrasive material and high-water flow were constants. The machines were modified and the capability to change from disc cutters to cutting tools, as well as the capability to open or close the cutterhead using grizzly bars, helped the machines to face the changing ground conditions.

Lots 3 and 4: Abrasive Basalt Rock

The Lot 3 tunnel, for contractor CARSO, ran for 9.2 km from Shaft 10 to Shaft 13. The TBM was launched in February 2012. After excavating several kilometers, the machine encountered worsening geological conditions with partial rock and soil at the face, causing impact loading on the cutters and cutter mounting system and severe wear on the cutterhead and cutting tools beyond what was expected. The machine also encountered a large amount of fines in the excavation face, causing clogging and requiring significant quantities of foam to be used.

As such, the contractor and Robbins proposed a new set of modifications, which were carried out at shaft 11, the 3.2 km mark. A new screw conveyor was fitted with Trimay wear plating to better handle abrasive rock chips, and a newly designed cutterhead featured more wear plating and slightly different cutter spacing. The redesigns worked, and the machine ultimately achieved breakthrough in 2018.

Meanwhile, perhaps one of the biggest tests for the EPBs came at Lot 4. The 10.2 km long lot ran from Shaft 17 to Shaft 13 at depths of up to 85 m. The TBM was assembled in the launch shaft no. 17 and commissioned in August 2012, with the bridge and all the back-up gantries at the surface. Two months later in October 2012, after advancing 150 meters, the machine and its back-up were completely assembled in the tunnel. One month later, the continuous conveyor system was installed and running.

After 405 meters of excavation, the presence of rocks, scrapers, parts of the mixing bars and other wear materials in the excavated muck prompted a cutterhead inspection. With high pressure up to 3.5 bars, it was determined that a hyperbaric intervention was necessary, and on June 2nd, 2013 the first hyperbaric intervention through an EPB in a tunnel was performed in Mexico. More interventions followed, forcing the contractor to perform hyperbaric interventions in order to change the cutting tools in a very complicated and harsh environment.

After about 50 hyperbaric interventions the remainder of the project's interventions were done in open air. Despite the challenges of pumping water of up to 180 l/s and cleaning fines from the tunnel each time the operation was performed, atmospheric interventions were still lower in cost and quicker than those done at hyperbaric pressure. By the time of breakthrough on May 23, 2019, the machine had achieved a project record of 30 m in one day, and a high of 528 m in one month.

Quick Installation of Secondary Lining

The installation of cast in place secondary lining also was carried out with very good advance, thanks to the telescopic form that ensured a continuous cast tunnel slip form for installation of the 350 mm thickness concrete lining. The tunnel cast in place form had a length of 45 meters and achieved over 180 meters per week (see Figure 15).

Figure 15. Cast-in-place form

Lessons Learned

The lessons learned during tunneling were as varied as the geology. Regarding wear, the basalt bored on the project was very abrasive. Reinforcement of high wear components, such as screw conveyor flights and screw casings, was critical when the machines were boring in rock conditions. Contractors also found that while operating in soft ground, excavation rates were higher, but more additives were used, while in mixed ground the machine advance needed to be slowed down to avoid impact damage and excessive wear to the cutters.

Of all the lessons learned, the most consistently mentioned advantage was the use of continuous conveyors rather than muck pumps. The contractors noted that advance rates were achieved thanks to the conveyor design. The tunnel conveyor was composed with elements such as the booster, vertical belt, curve idlers, and advancing tail piece, as well as elements on the surface.

LOOKING BACK: EVENTS THAT LED TO THE EXTENDED PROJECT SCHEDULE AND HIGHER COSTS

The following points are based on my opinion, being involved in the project since the very beginning. Of course, it is easy to judge after the project has finished, but the purpose is merely to continue to review the many lessons learned, in order to avoid repeating the same mistakes.

1. **Not having enough precise geotechnical information, and project design before the project started.**
   For example, a baseline report wasn't finished until 2010, and the project started in 2008.
   Many factors led to this situation and are understandable as it was an emergency plan from President Calderon's administration.

2. **Contractual Responsibilities and Tunnel Regulations.**
   Due to the same urgencies of getting the tunnel up and running, it was decided that the owner would purchase the 6 TBMs and deliver them to the contractor COMISSA. This situation of shared risk created a lot of grey areas and conflicts between contractors and the owner. In my opinion a shared risk is okay when having the right geotechnical information and tunnel design from the beginning, but in this case it created a lot of delays to get to agreements regarding important economic decisions. Example grey areas included the price per meter and whether this included or did not include wear parts, what is wear part, what is a maintenance part, etc.

   Other grey areas resulted from not having enough experience of the norms and regulations in mechanized tunnelling, and not adopting other countries' regulations. For example, it took at least three months for a price to be authorized to make a hyperbaric intervention, as it wasn't performed before in the country.

3. **Tunnel alignment and lots based on distance instead of geological profile.**
   The machines could have been designed specifically for the lots in soil and or rock if the shafts were placed according to geological profile rather than trying to make them equal distances of approx. 10 km. In this, they could have avoided the changing geology as much as possible.

   The tunnel alignment should have gone deeper in order to avoid the mixed ground conditions. For example on Lot 3 almost 3 km of rock were excavated in mixed ground that was half face rock and half soil, making it very difficult to excavate. Improvements in the alignment could also have led to more specialized machines according to the geology and thus higher excavation rates.

4. **Spare parts not readily available at site**s. Not enough money was invested in spare parts, resulting in lost time. The lesson is clear: not having the correct and right number of spares at the jobsite is prohibitively expensive due to downtime.

5. **Lack of maintenance.** Another grey area in the contract left a big gap of responsibility for the maintenance cost of the equipment in general. A lack of maintenance and resulting long downtimes could have been avoided if the responsibility was, for example, with the contractor only.

6. **Unforeseen site events.** A number of unforeseen events resulted in delays:

   - In order to avoid a flood in 2011, water was deviated to Lot 1 where a non-Robbins machine was excavating. This machine required extensive repair, and this caused the Robbins machine initially intended to start in Lot 5 to be instead installed for use on Lot 1. The TBM bored in the opposite direction with an intermediate shaft constructed in the middle. This decision was made promptly and diligently by the authorities of CONAGUA, as Shaft 20 at Lot 5 wasn't ready at the time of the flood.

- Time was lost due to losing the cutterhead of the roadheader in Shaft 19.

- High wear was detected on screw conveyors, cutterheads, and excavation chambers in all the EPBs, requiring modifications.

- High pressure water was detected when excavating Shaft 10. This resulted in long delays to shaft construction and made it difficult to start boring there.

- There was a failure of one of the vertical conveyors due to misalignment. This was remedied but required some downtime.

- Hyperbaric interventions were carried out at Lot 4 beginning 150 meters from start of excavation.

7. CONCLUSION

The Emisor Oriente Tunnel is a project that is not only logistically complex, but also geologically daunting. The conditions tested the limits for EPB tunnelling and necessarily limited advance rates. The project is not without its successes. However, the lessons learned from this project, now that it is complete, will be invaluable in terms of mechanized tunnelling projects, contracting, regulations, machine design and mega project management in the future.

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