Excavating Mexico City's Mega-Tunnel in Mixed Ground at 150 Meters Deep: Emisor Oriente Wastewater Tunnel Lot 5

Roberto Gonzalez1

1 The Robbins Company, Av. Patriotism No. 229, Col. San Pedro de los Pinos, CP 03800 , Mexico D.F., gonzalezr@robbinstbm.com

ABSTRACT

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 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.

Lot 5 of the TEO is no exception: An 8.93 m diameter EPB TBM is currently boring the 10 km long lot in abrasive basalt rock and sticky Taximay clay with water pressures as high as 6 bar. The machine started out from a 150 m deep shaft and—the deepest shaft built for a TBM launch in Mexico. The machine has undergone modifications for effective excavation including a high-capacity man lock, screw conveyor reinforcement, and abrasion-resistant cutterhead components including mixing bars.

This presentation will look at the challenges of the TEO Lot 5, examining machine assembly at the bottom of the deep shaft, and modifications and performance in the exceedingly difficult conditions that challenge the limits of EPB tunneling.

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

1. INTRODUCTION

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 raining 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 labeled 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 Tunnel Emisor Central, the main sewage system of the city.

2. The construction of the Tunnel 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. 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. The valley contained five original lakes called Lake Zumpango, Lake Xaltoca, Lake Xochimilco, Lake Chalco, and the largest, Texcoco, covered about 1,500 square kilometers of the valley floor, but as the Spaniards 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 the continued sinking of the city (by as much as seven meters), which weakens the system of water collectors and pumps (see Figure 2).

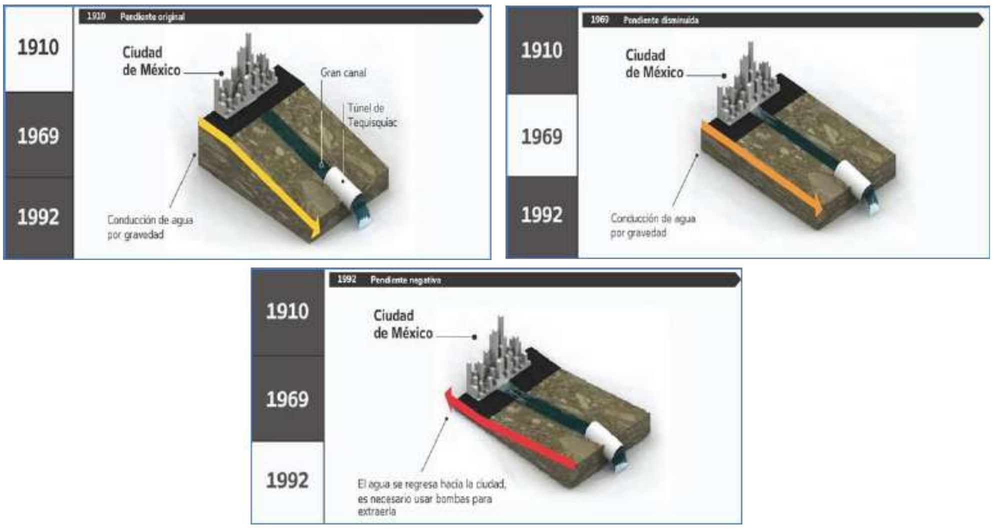

Figure 2. Change in slope of the Emisor Central between 1910 and 1992.

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 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:

3. Expand the capacity of drainage, which will reduce the risk of flooding.

4. Reduce the overexploitation of aquifers, which exacerbates the sinking of the metropolitan area.

5. 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 is currently being built 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).

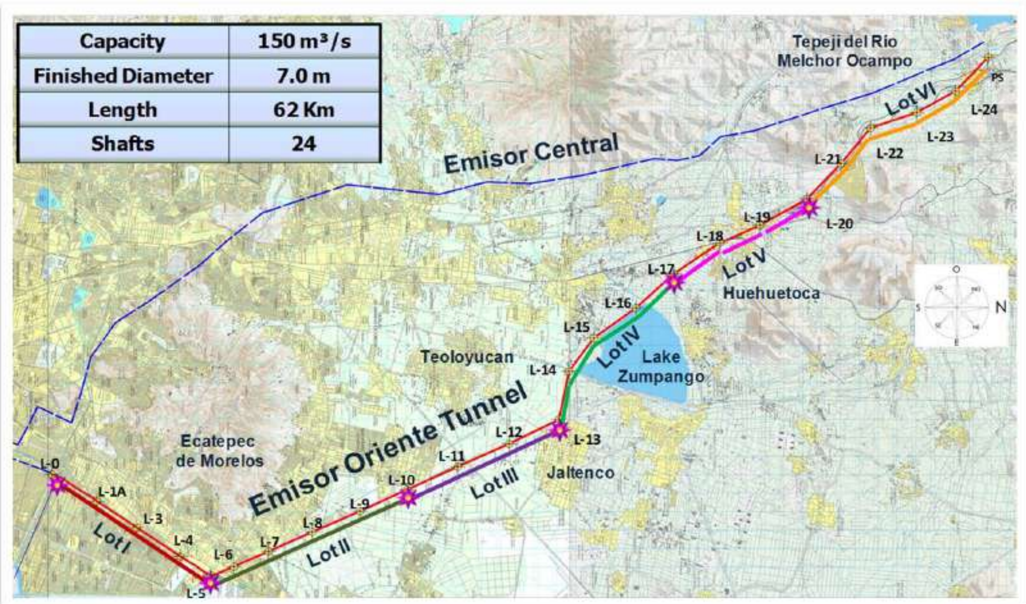

Figure 3. Overview of the TEO Layout.

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), 85% 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 either individually or in joint ventures.

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).

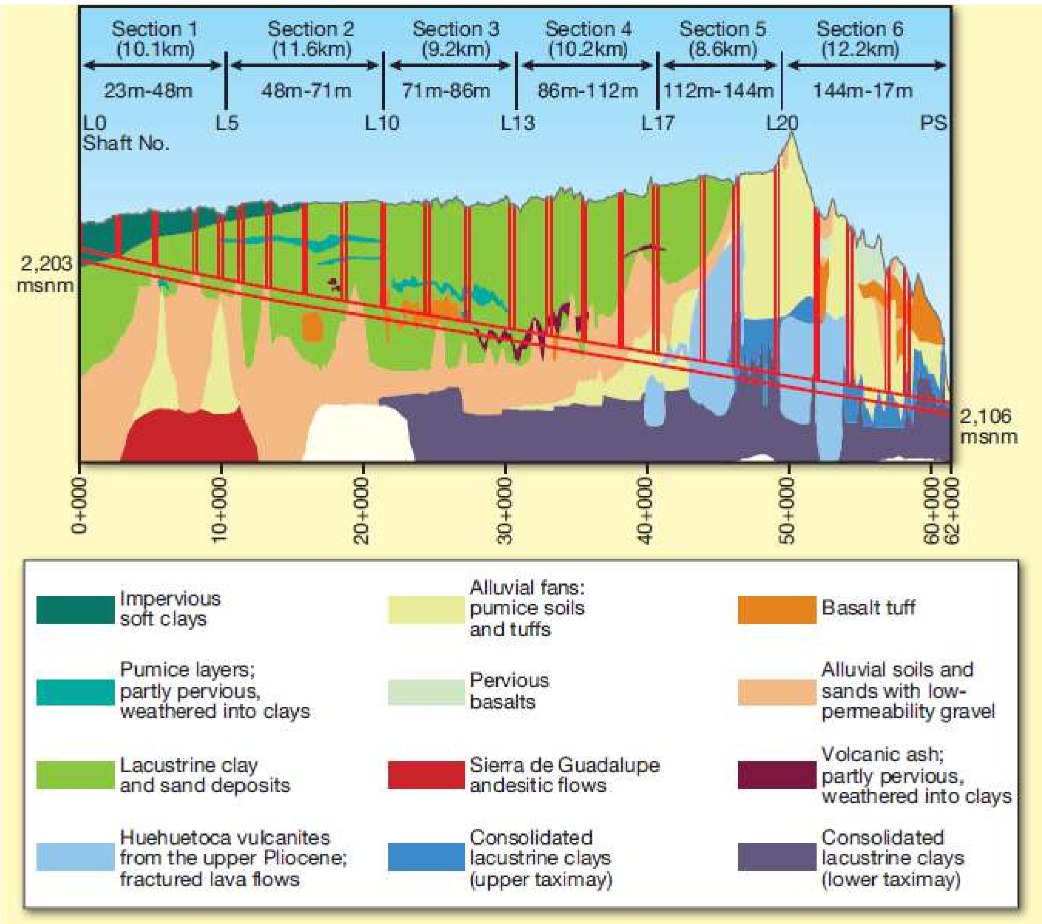

Figure 4. TEO geology. Image Credit: Tunneling Journal North America.

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 contractor and equipment manufacturer and resulting in successful machine modifications. In this paper we will review the actual conditions of the project based on the experience at Lot 5--this Lot’s first 4,400 meters are very representative of how the contractor and equipment manufacturer had to overcome adversity, since it was originally expected to be one of the less challenging 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 analyze the expected scenario back in that year and update the project scenario with actual geological conditions and hyperbaric intervention experiences. We will also review the design of the machines and the upcoming challenges.

4. STATE OF TEO IN 2017

These are the actual geological conditions of Lot 5 and the overall advance (Tables 1 and 2):

Table 1. From Shaft 20 to 19 (3.06 km)

	1st stretch	2nd stretch
Ground condition	High plasticity soft clay, silt and silty sand. (Taximay Formation) From the Quaternary.	High plasticity soft clay, silt and silty sand. (Taximay Formation) From the Quaternary.
Water pressure	maximum 3.5 bar	>4.0 bar
Advance	3,’065 meters	

Table 2. From Shaft 19 to 18 (2.7 km)

	1st stretch	2nd stretch	3rd stretch
Ground condition	High plasticity soft clay, silt and silty sand. (Taximay Formation) From the Quaternary.	Silty sand with isolated gravel.	Packed fragmented basalt.
Water pressure	>4.5 bar	>4.5 bar	>4.5 bar
Advance	1,205 meters		

5. ORIGINAL TBM DESIGN CONSIDERATIONS

Before discussing Lot 5 in detail it is useful to review the type of machine 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).

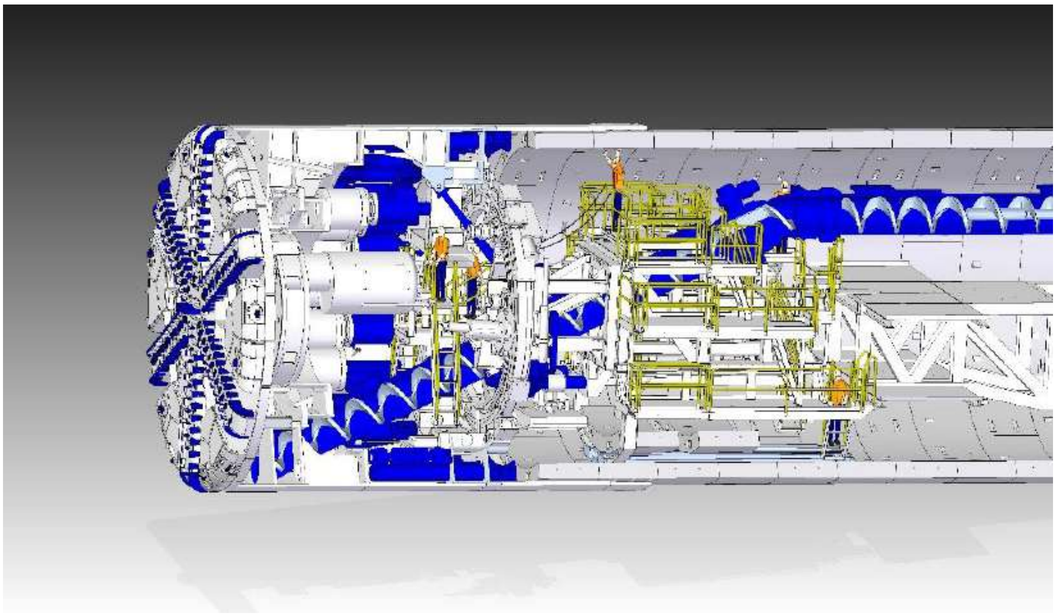

Figure 5. Original Machine Design.

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 can 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, are used to perform cutter inspection and changes, and to replace the tail seals. Specialized wear detection bits lose pressure at specified wear points to notify crews of a needed cutting tool change. The knife edge bits are 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 can 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 are currently being used to condition the muck for removal by belt conveyor (see Figures 6-7).

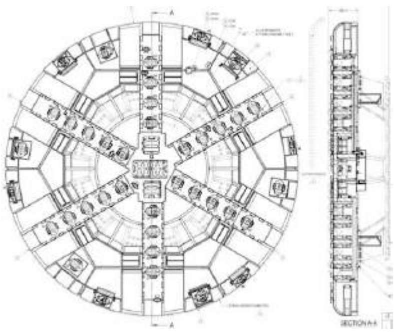

Figure 6. Hard Rock Cutterhead.

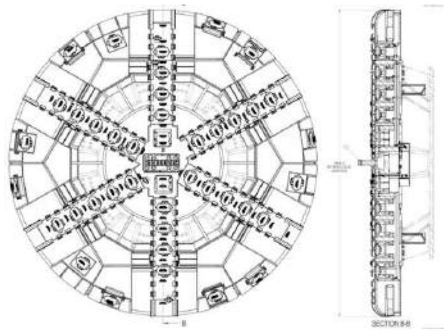

Figure 7. Soft Ground Cutterhead.

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 is 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 is 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 carries the muck to a vertical belt conveyor located at the launch shaft. Once at the surface, a radial stacker deposits muck in a kidney-shaped pile for temporary storage.

Due to the narrow shafts and small launch sites, the conveyor systems have been optimized for space efficiency and safety. The belt is 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 allows for splicing of belt with a footprint 170% smaller than a typical horizontal belt cassette. The 34 m tall belt cassette is used to splice in a 450 m length of belt, which takes roughly 12 hours and allows the machine to advance for roughly 200 to 225 m.

5.4. Lot 5 “Morelos” EPB Machine Design

The Lot 5 EPB, named “Morelos” in honor of an Independence leader in Mexico´s recent history, is one of three EPBs supplied by Robbins for this project. Morelos is an 8.93 meter diameter machine designed for mixed ground conditions. The cutterhead design, screw conveyor, and belt conveyor were designed as detailed earlier.

Morelos was additionally designed to handle curves, with a minimum of a 700 meter curve radius. To better handle curves, an active articulation system was included in the design of the EPB. Active articulation engages articulation cylinders between the front and rear shields to steer the machine independently of the thrust cylinders.

This EPB was fast-tracked in 2011 in order to help another machine bore TEO Lot 1. The machine, from another manufacturer, had been stopped for some time and this Lot was the most urgent to be constructed—the section would go into operation before the rest of the tunnel to prevent flooding in the specific area of a pumping station built near Shaft 5.

6. EPB MODIFICATIONS

After the machine finished excavating approximately 4.6 km of Lot 1, some modifications were made to the machine to accommodate the mixed ground conditions expected at Lot 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 8-11):

- 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 is 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.

- New design of the rotary union joint that improves the time to change the center disc cutters.

- New design of scrapers more capable of resisting load impact in mixed ground conditions in the presence of hard rock.

Figure 8. Man lock and Material lock.

Figure 9. Man Lock for 7 bar pressure.

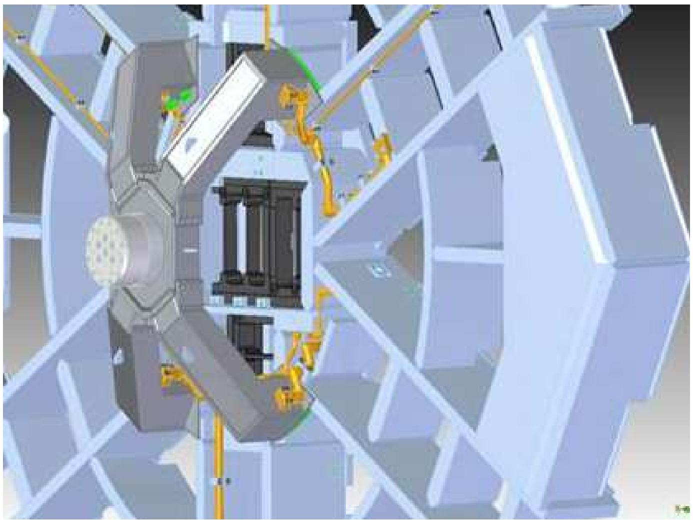

Figure 10. New Design of Rotary Union.

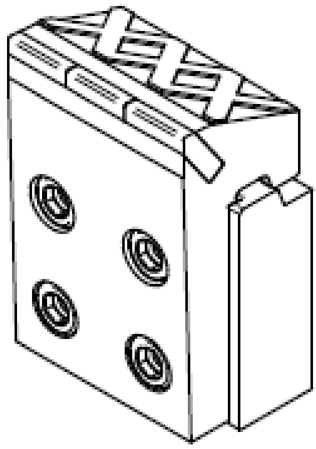

Figure 11. New design of the face scraper.

7. TUNNEL EXCAVATION AT SHAFT 20, LOT 5

At 150 meters deep, Shaft 20 is the deepest shaft of the project, demanding extra attention to Lot 5. The construction of the shaft was quite unique, as the contractor utilized a hydroroadheader 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.

Once the bottom of the shaft was reached, a starter tunnel of 28 meters was pre-excavated, in order to assemble the machine. The first back-up structure was lowered with the hydraulics and the main electrical components to enable start of the excavation without the need of umbilical cables or hoses. 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.

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 discharge muck 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).

7.1. Going through Mixed Ground Conditions

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 within this lot (see Figure 12).

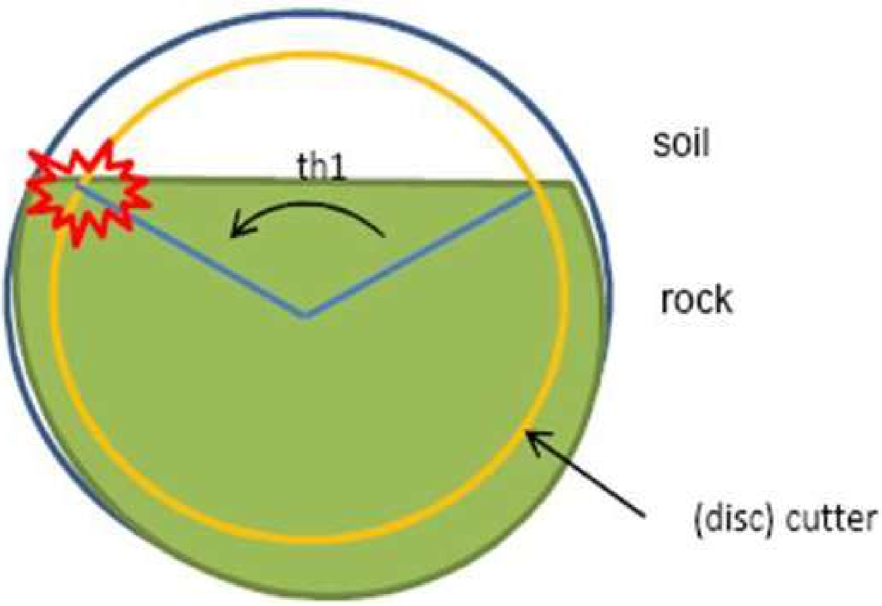

Figure 12. Diagram of impact loading.

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. Because of the mixed ground conditions, for the next 500 meters the expectation is that the conditions will not improve.

The production in this lot has been limited by mixed ground conditions. Abrasive material and high-water flow have been a constant in Lot 5. The machine has been 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, have helped the machine face the changing ground conditions.

The installation of cast-in-place secondary lining also was carried out with very good advance thanks to the telescopic form that ensures a continuous cast tunnel form for installation of the 350 mm thick concrete lining. The cast-in-place form has a length of 45 meters (see Figure 13). Crews have achieved advance rates over 180 meters per week.

Figure 13. Cast-in-place concrete form.

8. CONCLUSION

The Emisor Oriente Tunnel is a project that is not only logistically complex, but also geologically daunting. The conditions test the limits for EPB tunneling, and have necessarily limited advance rates. The project is not without its successes, however: The Robbins EPB at Lot 5 has the record of the best advance rate in a shift at the TEO project with 30 meters in 12 hours. The lessons learned from this project, once complete, will be invaluable in terms of proper EPB design for extremely abrasive and high pressure conditions.

9. REFERENCES

Hernandez. R and Jaime A. 2007 “Tunnel Emisor Oriente” Project Brochure by CONAGUA. México 2007

Willis Desiree. 2012. Mexico´s Mega Tunnel: EPB´s Excavate Mexico City´s Emergency Wastewater line. TBM: Tunnel Business Magazine pgs 39-43.