Learned from construction of the 62km Tunnel Emisor Oriente in Mexico's challenging and varied ground

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ABSTRACT: In April 2009, tunnel boring started on the Tunnel Emisor Oriente (TEO) sewer project after decades of deliberation. The infrastructure will replace an open, untreated canal that conveys wastewater from Mexico City. The new tunnel will end at the capital's first wastewater treatment plant and reduce the risk of catastrophic flooding in downtown Mexico City. It was this risk that led President Felipe Calderon to label the project a "National Emergency". The TEO project was designed as a 62 km pipeline of 8.9 m diameter with a primary precast concrete segmental lining and a secondary in-situ concrete lining. 24 shafts up to 150 m deep support six TBM operations totaling about 10 km each. After five years of work, 34% of the bore is complete, and the owner of the project, CONAGUA, is rethinking their strategy based on incredibly difficult ground. This paper will discuss the new strategy from both the contractor and manufacturer perspective, including successful TBM modifications.

1 INTRODUCTION & HISTORY

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 downtown Mexico City.

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.

The city was connected to the mainland by causeways leading north, south, and west of the city. These causeways were interrupted by bridges that allowed canoes and other traffic to pass freely. The bridges could be pulled away if necessary to defend the city. The city was interlaced with a series of canals, so that all sections of the city could be visited either on foot or via canoe.

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 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 with gravity. Currently, and despite its age, the Grand Canal can still carry 150 m^3/s out of the valley, but this is significantly less than what it could carry as late as 1975 because continued sinking of the city (by as much as seven meters) weakens the system of water collectors and pumps (see Figures 2).

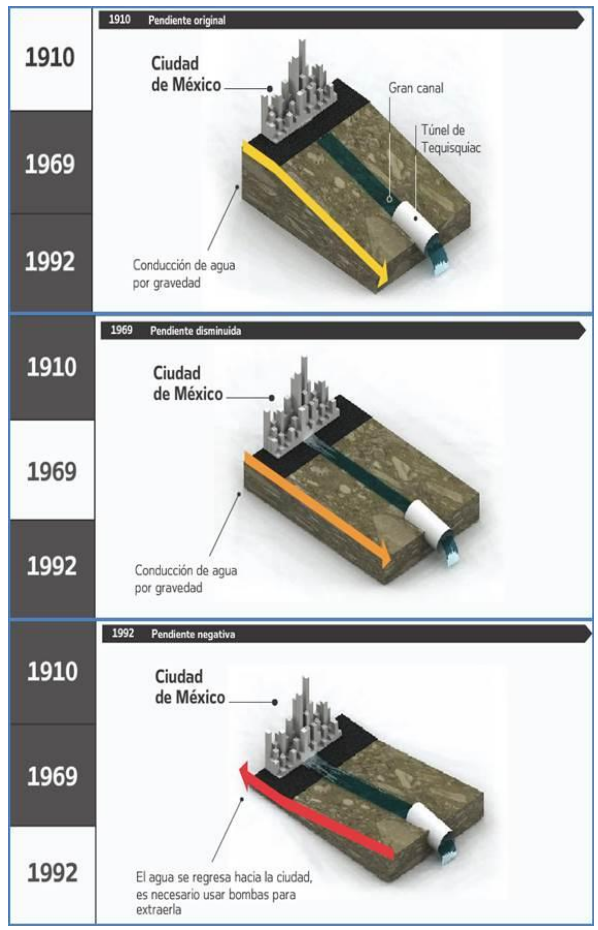

Figure 2. Change in slope of the Emisor Central between 1910 and 1992.

As a result of the decreased capacity, another tunnel, called the Emisor Central, was built to carry wastewater. Although it was 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 conclusion the construction of the City of Mexico on what were the lakes caused two permanent problems: the need for evacuation of rainwater to prevent flooding and sinking by the overexploitation of aquifers.

1.2 The System Today

Today the capacity of the drainage system of the metropolitan area is insufficient and has serious problems. Just compare the ability it had in 1975 with what it has now, which is 30% lower with nearly twice the population. This decrease is mainly due to steady sinking of the City of Mexico, caused by overexploitation of aquifers of the Mexican valley.

The Emisor Central, designed to lead rainwater in storm peaks, has operated for 15 years past its design capacity, in continuous use without maintenance. In addition the sewer is conducting untreated or "black" water, and this has caused accelerated wear. Although the Central is the tunnel upon which the security of the eviction of wastewater and storm water of the valley falls, it must close during the dry season months for repair and maintenance. This raises the urgent need for an alternative tunnel with the ability to maintain system operation throughout the year.

In order to solve the problem of the drainage system it is necessary to build a new deep drainage system: the Emisor Oriente Tunnel, 62 kilometers and seven meters in diameter.

2 TUNEL EMISOR ORIENTE (TEO)

Mexico City's Emisor Oriente Wastewater Tunnel, 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 exit 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 Emisor Oriente Tunnel has 3 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. Water treatment of the wastewater to promote its reuse in agriculture, instead of using sewage water for agriculture

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 capacity of 150 m^3/sec of wastewater, 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 145 meters 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).

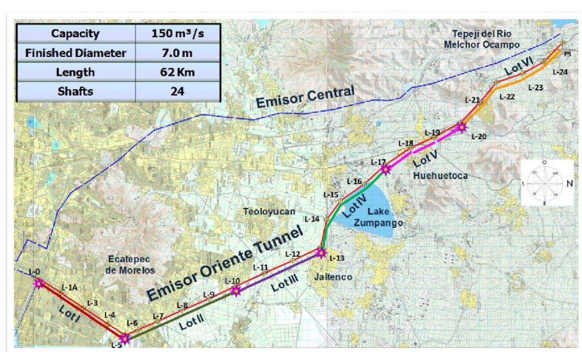

Figure 3. Overview of the TEO Layout.

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. The TBMs will utilize knife edge and drag bits that can be changed out for 17-inch diameter disc cutters depending on the geology. Two-stage screw conveyors will help to regulate varying water pressures of 4 to 6 bars—some of the highest pressures EPBs have ever operated under. An initial 900 mm diameter ribbon-type screw conveyor will accommodate expected boulders up to 600 mm in diameter.

After five years of work, only 34% of the excavation has been completed, and the owner of the project, CONAGUA, is rethinking their strategy based on the incredibly difficult and unforeseen ground conditions encountered. The conditions range from very soft clays to highly abrasive materials, hard rock, and boulders under high water pressures up to 6 bar, requiring frequent hyperbaric interventions and multiple modifications to the existing machines.

2.2 Contractual Setup

As mentioned before the project is property of CONAGUA, the national water and irrigation management authority of the Mexico Government, which 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).

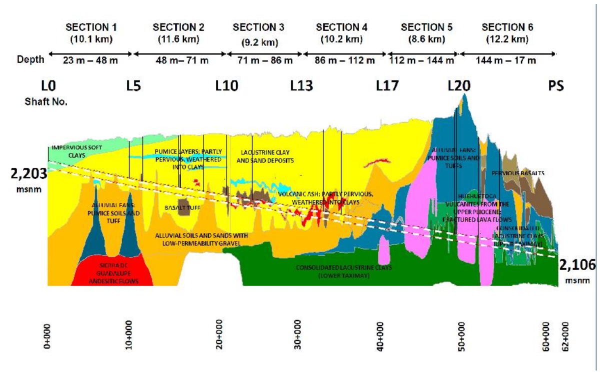

Figure 4. TEO Geology.

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.

This paper will discuss the new strategy from both the contractor and equipment manufacturer perspective, including successful machine modifications.

In this paper we will review the actual conditions of the project based on the experience at Lot 4--this Lot's first 1400 meters are very representative of how the contractor and equipment manufacturer had to overcome the 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 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 2013

These are the actual geological conditions of Lot 4 in the project and the overall advance:

Table 1. From Shaft 17 to 16 (2.5km)

	1st stretch	2nd stretch
Ground condition	Well consolidated sandy silt, soft to hard and sometimes very fractured, erratic rock fragments in the sediment well packaged that do not exceed 20 cm.	Pumice fragments of all sizes, well packaged in silty sand, apparently this is pyroclastic deposits (lahars) well compacted hard, supported by the matrix, fractures due to differential sedimentation may occur where water inlets in the front of the tunnel
Water pressure	maximum 4.5 bar	>4.5bar
Advance	1411 meters	

Table 2. From Shaft 16 to 15 (2.7 km)

	1st stretch	2nd stretch	3rd stretch
Ground condition	Pumice fragments of all sizes, well packaged in silty sand, apparently this is pyroclastic deposits (lahars) well compacted hard, supported by the matrix, fractures due to differential sedimentation may occur where water inlets in the front of the tunnel	Sandy loam soils compact drives with horizontal fractures due to differential sedimentation where there could be significant water inputs.	Lacustrine mudstones compact, horizons of fluvial sand and basaltic pumítica fine to coarse grained.
Water pressure	>4.5 bar	>4.5 bar	>4.5 bar
Advance	0		

Table 3. From Shaft 15 to 14 (2.4 km)

	1st stretch	2nd stretch	3rd stretch	4th stretch
Ground condition	Lacustrine mudstones compact, horizons of fluvial sand and basaltic pumice, fine to coarse grained.	Loam soils - well compacted sandy to hard, sandy horizons in fluvial silty matrix semiconsolidated, fractured in bedding planes where they could present major inlets.	Andesite - massive basalt, some open horizontal fractures, possible Water flow in contact fractures and prelacustrine soils.	Hard consolidated sandy silt with some vertical fractures.
Water pressure	>4.5 bar	>4.5 bar	maximum 4.5 bar	maximum 4.5 bar
Advance	0			

Table 4. From Shaft 14 to 13 (2.6 km)

	1st stretch	2nd stretch	3rd stretch	4th stretch	5th stretch
Ground condition	Hard consolidated sandy silt with some vertical fractures.	Plastic lacustrine clay (altered basaltic ash), some basaltic ash horizons and cemented gravels and loose, possible water flow in the tunnel face especially in different sediment contact.	Well consolidated sandy silt tough basaltic ash horizons, horizontal fractures mainly bedding planes where water flow may occur important	Plastic lacustrine clay (altered basaltic ash) some horizons, basaltic ash and cemented gravels and loose, possible water flow in the tunnel face especially in different sediment contact.	Lacustrine mudstones horizons and fluvial sand lenses of fine to coarse grained, well compacted sands are sometimes loose and sometimes interspersed with lacustrine clays packages at the bottom of the front, which can cause possible water flow.
Water pressure	max. 4.5 bar	max. 4.5 bar	max. 4 bar	>3.5 bar	max. 3 bar
Advance	0				

5 ORIGINAL TBM DESIGN CONSIDERATIONS

Before we go through Lot 4 we would like to review the type of machine and conveyors systems that were provided based on the 2008 geological information.

The three Robbins machines 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).

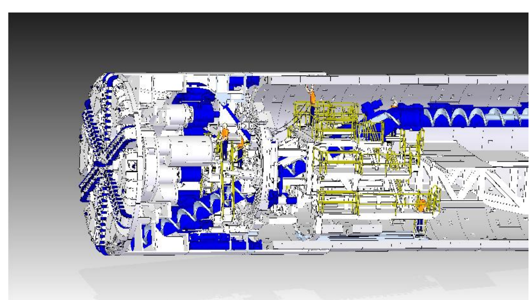

Figure 5. Original Machine Design.

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 tunnelling a number of small shafts, spaced every 3 km between the larger launch shafts, can be used to perform cutter inspection and changes. 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.

The design also allows for bearing and seal removal from either the front or back of the cutterhead. Twenty-five injection ports spaced around the periphery of the machine are used for injection of various additives depending on ground conditions, and for probe drilling. Additives such as Bentonite are currently being used to condition the muck for removal by belt conveyor (see Figures 6-7).

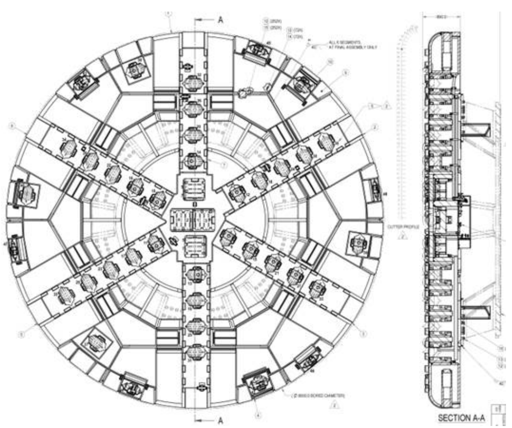

Figure 6. Hard Rock Cutterhead.

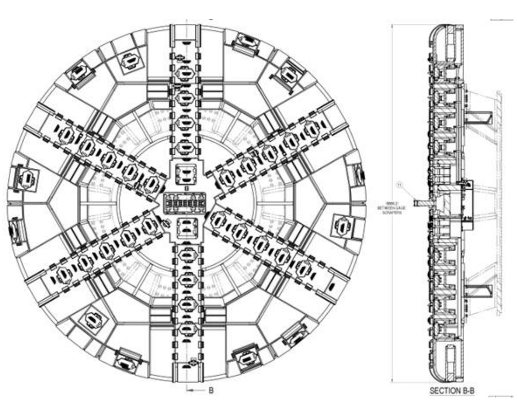

Figure 7. Soil Cutterhead.

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. Each of the three machines may encounter pressures of up to 6 bar, necessitating a two-screw setup with a ribbon screw and shaft-type screw 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 4 292-334 "Hidalgo" EPB Machine Design

The 292-332 EPB, named "Hidalgo" in honor of an Independence leader of Mexico´s recent history, is one of three EPBs supplied by Robbins for this project. Hidalgo 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.

Hidalgo was additionally designed to handle curves, with a minimum of 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.

6 EPB MODIFICATIONS

Some modifications were made to the machines to accommodate the new mix ground conditions. Sections of hard abrasive rock coupled with high water pressures were discovered during shaft construction and afterwards, more boreholes studies were done.

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 and high pressure in the tunnel.
- Hardox 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.
- An air compression system in order to control the water inflows in the chamber during excavation.
- Grizzly Bars in the cutterhead.
- New design of the rotary union joint that improves the time to change the disc cutters.
- New design of scrapers more capable to resist load impact in mixed ground conditions in the presence of hard rock.

Figure 8. Material Lock.

Figure 9. Man Lock for 7 bar pressure.

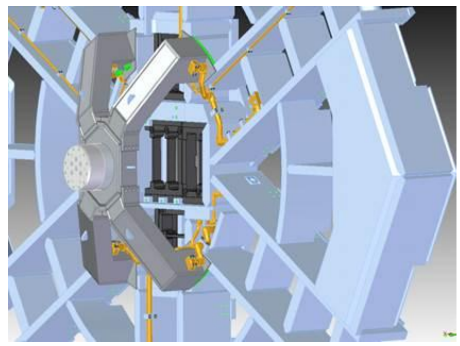

Figure 10. New Design of Rotary Union.

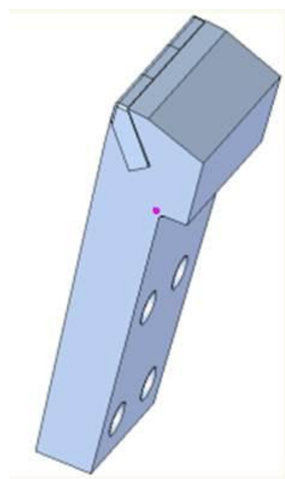

Figure11. New design of the face scraper.

7 TUNNEL EXCAVATION AT SHAFT 17

The machine was assembled in the launch shaft 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 were the main reasons to decide to inspect the cutterhead condition. The high pressure up to 3.5 bars determined the need to make a hyperbaric intervention. The erratic rock fragments and andesite deposits created wear problems in the cutting discs, which required a strict program of interventions in order to inspect, change and analyze the wear issues that the tunnel was presenting and that were not expected in terms of the geologic complexity within this lot (see Figure 12).

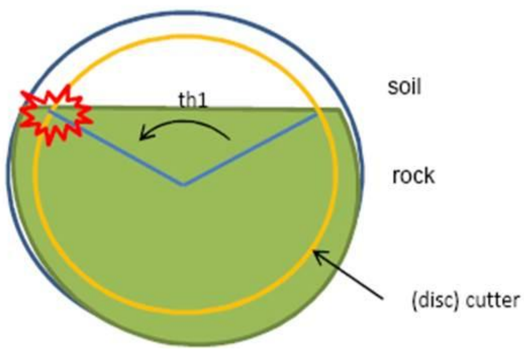

Figure 12. Diagram of impact loading.

7.1 *Hyperbaric Interventions*

As mentioned before watery lake clays combined with sections of abrasive basalt and large boulders create very challenging tunneling conditions. Crews of up to three people make hyperbaric inspections; the highest operating pressure thus far has been 3.05 bar, allowing the crew to work for 85 minutes before being depressurized for 130 minutes. Normally interventions are mostly done for inspection purposes, but in this case the wear issues and presence of cutting tools in the muck require 97 interventions in a period of more than 100 days for tools changing. It is important to mention that on June 2nd, 2013 the first hyperbaric intervention through an EPB in a tunnel was performed in Mexico.

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 pressure make this drive an excavation with a high degree of uncertainty. Because of the mixed ground conditions, for the next 900 meters the expectation is that the conditions will not improve until we arrive at Shaft 16.

In conclusion, production in this lot has been limited by mixed ground conditions and hyperbaric interventions because of the wear of the cutting tools. Abrasive material and high water pressure have been a constant in Lot 4. 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 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 4 has the record of the best advance rate in a shift in the TEO project with 22.5 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.

8 CONCLUSION

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9 REFERENCES

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