Successful Excavation of Mexico City's Emisor Poniente II Wastewater Tunnel—Use of a Dual-Mode, Crossover TBM in Challenging Geology

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ABSTRACT

In July 2015, the launch of a dual mode, Crossover type TBM marked the start of Mexico City's next challenging wastewater project: the Túnel Emisor Poniente (TEP II). The 5.5 km long tunnel travels below a mountain at depths of 170 m as well as a section just 8 m below residential buildings, and the geology is equally varied. Ground consists of andesite and dacite with bands of tuff and fault zones, as well as a section of soft ground at the tunnel terminus.

This paper will detail the unique 8.7 m diameter Crossover TBM designed for the challenging conditions, and the successful excavation of the machine through fault zones, soft ground, and more. Strategies for excavation and advance rates, and downtimes will be analyzed. As the machine can be converted from hard rock mode to EPB mode in the tunnel, the authors will also look at the conversion process and how both modes worked to excavate in widely varying geological conditions.

INTRODUCTION AND HISTORY

In the last 100 years, Mexico City has sunk by nearly 12 m. As a result, the city's 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—by flooding an area of 217 square km. The areas with greatest risk of flooding are the historic downtown area and the Mexico City Airport and surrounding areas.

In 2007, Mexican President Felipe Calderon labeled this situation a "National Emergency" and designated it as a top priority of the National Infrastructure Program.

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.
3. The construction of the Túnel Emisor Poniente II.

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 square km, 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. However, 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 just 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 open 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 large pumping facilities 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 and is altering the canal's slope.

As a result of the decreased capacity, another tunnel, called the Emisor Central, was built to carry wastewater in the 1970s. 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.

The System Today

Today the capacity of the drainage system in the metropolitan area is insufficient and has serious problems. Just comparing the capacity it had in 1975 with what it has now shows a significant decrease in efficiency: a 30% lower ability to convey wastewater 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 transfer rainwater in storm peaks, has operated for 15 years past its design capacity, and has been in continuous use without maintenance. In addition the sewer is transferring untreated or "black" water, and this has caused accelerated wear in the upper section of the tunnel. Although the Emisor 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 each year. 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 was deemed necessary to build a new deep tunnel system: the Túnel Emisor Oriente, 62 kilometers and seven meters finished diameter, and the Túnel Emisor Poniente II, a 5.5 km long tunnel with 7 m finished diameter (see Figure 1).

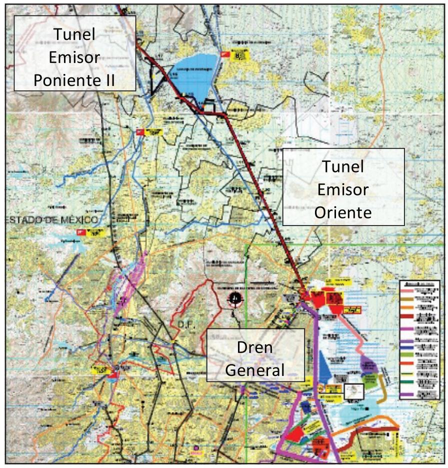

Figure 1. Map of the future wastewater tunnel network

TÚNEL EMISOR PONIENTE II (TEP II)

The Emisor Poniente II tunnel has three main purposes:

1. Expand the capacity of drainage, which will reduce the risk of flooding in the west side of the city.
2. Reduce the overexploitation of aquifers, which exacerbates the sinking of the northwest area.
3. Water treatment of the wastewater to promote its reuse in agriculture, instead of using sewage water for agriculture.

While the Emisor Oriente tunnel (TEO) has been written about in previous papers, we will mention it here with regards to its role in the overall system. 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), where the area's first wastewater treatment plant is under construction. 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 112 m^3/sec of wastewater. 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 and TEP II, it will have a total of 345 m^3/sec.

The TEP II will connect in an open channel to the Emisor Poniente I, and the combined flow will be transferred to the same treatment plant in the Municipality of Atotonilco, in the state of Hidalgo. The plant will be responsible for water reuse for agricultural irrigation, and will be the second largest plant of its kind in the world.

In order to excavate TEP II, a consortium of Aldesem, Proacon, and RECSA was chosen by the national water and irrigation management authority of the Mexican Government (CONAGUA). The consortium sought an alternative to a typical tunnel boring machine due to complex geological conditions, and chose an 8.7 m diameter dual mode, Crossover-type TBM manufactured by The Robbins Company. The machine is capable of excavating in both a pressurized EPB mode and a non-pressurized, hard rock mode.

Project Challenges

Geological Conditions

The ground conditions of the pipeline are mainly andesite rock with a compressive strength of 1500–2,500 km/cm^2; however, the tunnel also passes through two faulted areas with tuff and sand in contact zones, and the last 900 meters are in softer ground consisting of tuff and alluvial lake clays.

In order to deal with the abrasive, hard rock conditions, the TBM was designed to utilize 20-inch diameter disc cutters—the first time these large cutters have been used in Mexico. The machine was planned to be launched in non-pressurized hard rock mode and converted to EPB mode in the last 900 m—a section that also happens to be in a residential area with low cover just 1.5 times the machine diameter. The TBM bore also faced some local stigma and a lack of experienced personnel for the conditions—the last time that a TBM was able to bore through rock efficiently in Mexico was a 4.5 m diameter Robbins Double Shield that worked on a clean water tunnel back in 1998. This machine would need to be able to bore both hard rock and soft ground in an efficient manner (see Figure 2).

Limited Site Space

Due to existing infrastructure, housing, and a nearby water tank the launch site for TEP II was fairly small, which posed a huge challenge for logistics. The entire jobsite had to fit into a space of less than 10,000 m^2. The machine was assembled using Onsite First Time Assembly (OFTA), a method that involves initial assembly of TBM components on location, and can save both time and money that is then passed on to the contractor.

Major parts were refurbished and customized for majority hard rock conditions, as the machine had most recently bored a tunnel in softer rock in Laos. Many components were new including the shields, the cutterhead, main drive gearboxes, bull gear, and main bearing. Sub-Systems were factory-tested and shipped to the jobsite for initial assembly, where there was limited area for staging. Components had to be lowered into an 11 m wide pit. The machine was over 100 m long, but the starting chamber was only 50 m in length and required assembly of the back-up system in two stages.

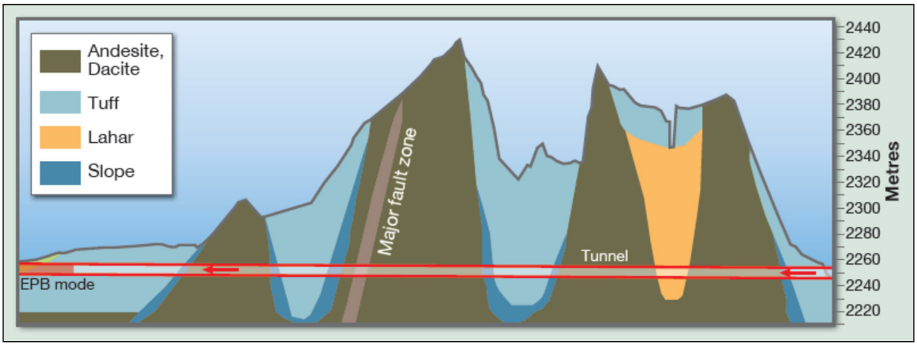

Figure 2. Project geology and corresponding machine mode

Figure 3. Cutterhead installation in a small launch shaft

Overall, OFTA took about 12 weeks—a process estimated to have saved at least 60 days as compared to a similarly-sized machine assembled in a shop (see Figure 3).

TBM DESIGN CONSIDERATIONS

Adaptable Cutterheads

The custom-designed Crossover TBM was engineered with a robust, back-loading cutterhead to tackle variable conditions. High pressure, tungsten carbide knife bits can be interchanged with 20-inch diameter carbide disc cutters depending on the ground conditions. Specialized wear detection bits lose pressure at specified wear points to notify crews of a needed cutting tool change.

The opening ratio in the cutterhead can be changed by removing bolted plates for the larger opening EPB configuration.

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 used to condition the muck for removal by belt conveyor.

Drilling Equipment

The TBM is equipped with two type of drills. A canopy drill is able to install pipes and form the umbrella, to be able support the ground above the machine in particular. This procedure is used on the contact areas or where the face is not self-supporting, mainly when boring through tuff and sand.

The second drill is a probe drill, for ground investigation in front of the TBM, and grouting ahead of the TBM in areas where the geology could be too fractured or non-self-supporting.

Continuous Conveyors for Limited Space

Muck from the TBM is deposited from the screw or machine conveyor 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 the launch shaft. The slope for the horizontal belt of 11.7% eliminated the need for a vertical conveyor. Once at the surface, a radial stacker deposits muck in a kidney-shaped pile for temporary storage.

Two-Stage Main Drive Reducers

The TBM torque is able to be increased when needed to excavate through soil and fault zones using two-stage gear reducers. In rock mode, torque can go up to 5,200 kNm and the cutterhead is able to go as fast as 6 rpm. In EPB mode the torque is able to go up to 9,917 kNm at 3.6 rpm, with a breakout torque of 14,875 kNm. The change is able to be made during tunneling with only the turn of a lever on each reducer.

Active Articulation

The articulation system was included in the design for EPB mode. Active articulation engages articulation cylinders between the front and rear shields to steer the machine independently of the thrust cylinders.

Bulkhead Closure Gates

The TBM has the capacity to close the gates in the cutting chamber, in order to avoid the entrance of running ground and water to the TBM for emergency, during the excavation in rock mode.

Special Antiroll System

The skew system will be used while boring in rock mode. This system allows the TBM to correct the roll by applying a perpendicular force to the thrust cylinders and thus correcting the roll of the TBM.

Two-Part Grout System

This is the second time that the two component grout system has been utilized in Mexico City, and the system has proven itself to work in Mexico's difficult geology. A two-part A + B grouting system (grout plus accelerant) hardens quickly and fills the annular gap while minimizing settlement.

Conversion Between Modes

The TBM started off tunneling in hard rock mode. Conversion to EPB mode requires several steps to take place. Removable plates must be installed in the cutterhead first, in order to create a larger opening ratio, from 6% to 25%. Disc cutters are then changed out for knife-edge bits and scrapers, two types of soft ground tooling. Next a rotary union is installed to inject additives and foam in front of the cutterhead in order to make a good mixture of the material. Once the opening ratio has been changed to be more like an EPB, the belt conveyor must also be removed and the screw conveyor installed to take material from the bottom of the mixing chamber. With this diameter of machine both the screw and belt cannot be installed at once. The process can be done in about eight weeks (see Figures 4–5).

LAUNCH AND EXCAVATION

The Crossover machine was launched in August 2015 in a hard rock configuration and mounted with 20-inch diameter disc cutters—a risky move given that the first sections of tunnel were in softer soils before the TBM hit more solid rock. There was some worry that this could clog the cutterhead as it might be sticky, but this thankfully did not happen. In fact, the machine's advance rates picked up quickly, with project records set in December, and again in January after the machine achieved a best day of 42.8 m and a best week of 185.1 m.

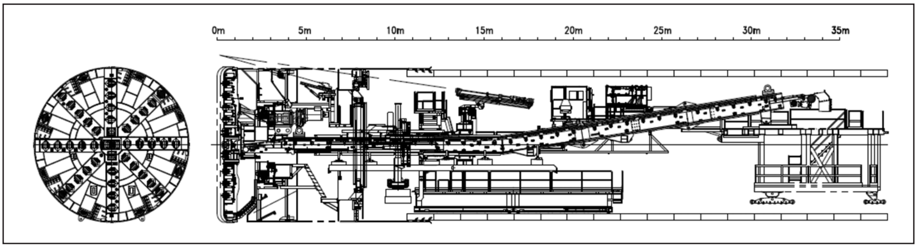

Figure 4. TBM in rock mode

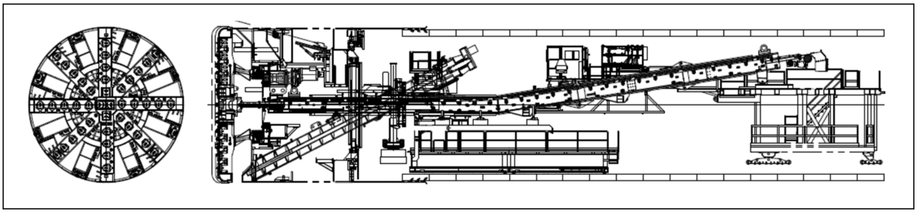

Figure 5. TBM in EPB mode

Early in 2016 the TBM hit the first of several contact zones, a 30 m wide fault of fractured and blocky rock. While the excavation through the contact zone was slow going, progress picked up again in the more competent andesite rock. After an intermediate breakthrough in March 2016 into an 80 m deep shaft followed by inspection and maintenance, the TBM continued on (see Figure 6).

By June 2016, the TBM was flying through fairly competent rock and had achieved two national records for TBM advance—57 m in one day and 702.2 m in one month. Continuous conveyors certainly contributed to the result, as the system at TEP II can remove 600 to 900 tons of material per hour, and has been able to match the speed of the TBM.

The next challenge for the machine was the major fault zone known as Falla Norte de Barrientos. More water was encountered than expected—about three liters per second--as well as soil that required cleaning out of the tunnel invert. The TBM was in rock mode so there was some spillage from the conveyor and a lot of cleanup. But, they were able to get through the zone in about 30 segments' length and advance rates went up again. Once out of the fault zone the ground was primarily fractured andesite.

CURRENT CHALLENGES

The core samples for the last 900 meter long section in soft ground weren't taken from the precise axis of the tunnel, due to houses and private property in the way. A large cavern of about 50 m^3 was encountered at only 14 meters' coverage in Autumn 2016, with high risk of ground settlement and damage to the houses above. The excavation was immediately stopped to analyze the situation; the cavern was filled with special Polyurethane Epoxies, then pea gravel and grout, to consolidate the empty space.

The conversion has also been a learning process. There was no special shafts constructed to be able to change the TBM from boring in Rock Mode to EPB. Several modifications had to be done to the cutterhead and bulkhead, and the ground at the face had to be stabilized for the workers to enter the cutting chamber and work on the

Figure 6. Intermediate breakthrough in March 2016

conversion. Due to space the screw conveyor and TBM belt conveyor weren't able to be installed at the same time. It was very challenging to be able to assemble a large component such as the screw conveyor inside the TBM.

Once the machine is through its last section of soft ground, disassembly will present a further challenge. The narrow exit site is flanked by equally narrow roads and nearby houses. The machine cannot be backed through the tunnel and must be disassembled and removed from the exit site using a 200 metric ton capacity gantry crane.

CONCLUSIONS

Crossover TBMs will start to be applied more and more in tunnels all over the world, as tunnels are trending deeper and more complex. TBMs must be able to adapt to bore in different and changing conditions, but an accurate geological study is needed to maximize effectiveness. Geological studies can detect features like fault zones and caverns ahead of time so that mitigation strategies can be planned from the start.

The machine at TEP II was, nevertheless, able to break country-wide records and was by far the most efficient way to excavate a tunnel. Good tunnel management and logistics reduce downtime, while a cooperative manner by all parties involved has enabled focusing on tunnel goals.

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