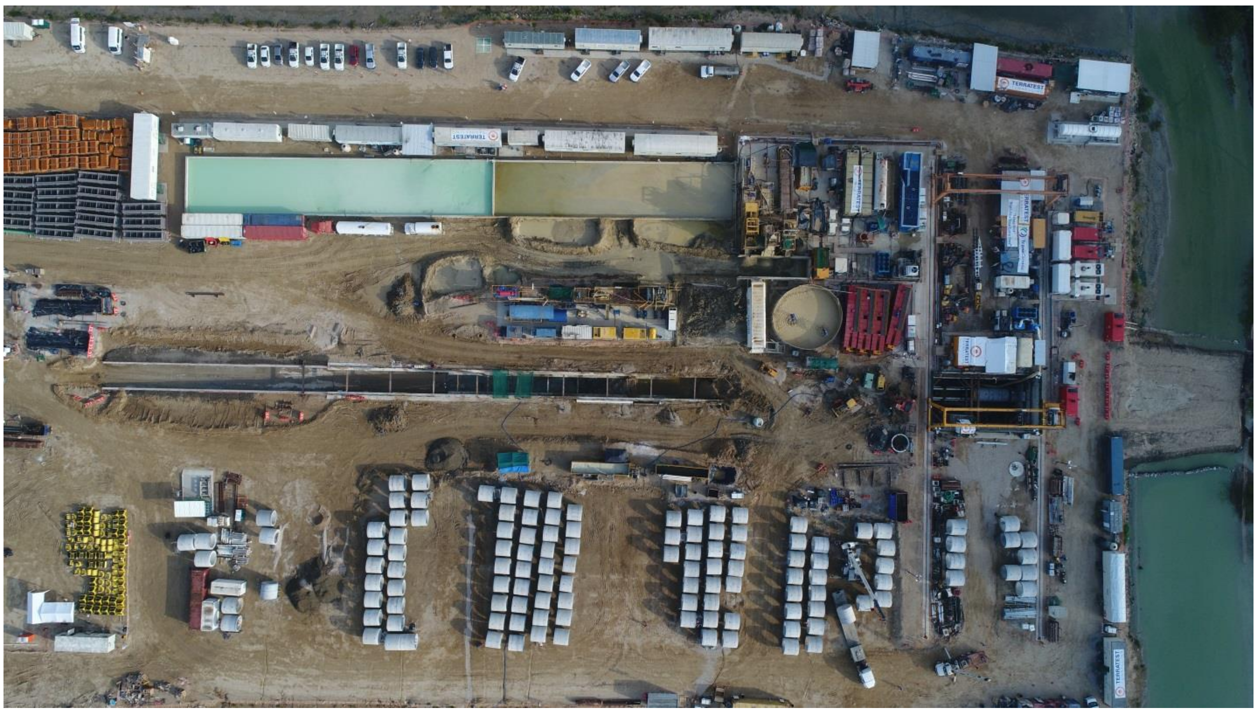
LAND FALL ALTAMIRA MICROTUNNEL PROJECT – A Lubrication Perspective (Longest Wet Retrieval Microtunnel in the World)



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Abstract

The Landfall Altamira Microtunnel Project is part of the Gasoducto Sur De Texas – Tuxpan 800 km (497 mile) pipeline. The bulk of the line will be laid offshore but there a 2246-meter (7369 ft.) onshore-offshore connector tunnel to the Altamira compressor station. This is a key component of the project completed by Eurohinca (Terratest Group).

Seven hundred sixty-six pipe sections were needed to complete the tunnel using a tunnel-boring machine (TBM) with a cutting diameter of 3280 millimeters (129 in.) One key to success was building a lubricating slurry with low filtrate loss (<10 ml/30 min.) for a forty millimeter (157 in.) annular space.

Using a slurry comprised of Baroid Industrial Drilling Products' QUIK-GEL™, QUIK-TROL® GOLD, and FUSE-IT® additives, the team effectively created an incompressible fluid cushion to minimize pipe-ground friction. The average skin friction in the tunnel was 0.4 kN/m^2 and average jacking force was 0.48 T/m. At the end of the drive, the interjacks were deactivated and the entire tunnel could be advanced using only the primary jacks, a demonstration of effective lubrication and a stable overcut. Penetration rates averaged 9.2m/d. Final pipe installation came on July 27, 2018 and the TBM reached the final goal of 2246 meters, becoming the largest single drive microtunnel with seafloor TBM rescue completed in the world.

Figure 1. Aerial View of Altamira Tunnel Project Site

Introduction

The Landfall Altamira Microtunnel Project (Figure 1) is part of the Gasoducto Sur De Texas – Tuxpan. The project involves construction of an 800 km (497 mile), forty-two inch pipeline from Brownsville, Texas to Tuxpan in the Mexican state of Veracruz. This pipeline will deliver 2600 million cubic feet of gas per day. Most of this pipeline will be laid offshore.

The 2246 meter (7369 ft.) onshore-offshore connector tunnel to the Altamira compressor station was a key component of the overall project completed by Eurohinca (Terratest Group). The tunnel-boring machine (TBM) had a cutting diameter of 3280 millimeters (129-in.) Baroid Industrial Drilling Products mud engineers design the Face Slurry to both stabilize the water sensitive Gulf Coast sedimentary deposits, and transport the cuttings to the solids control equipment.

An AVN 2000 (Figure 2) with an outside diameter (OD) of 3200 mm and inside diameter (ID) of 2600 mm was used in conjunction a ring of hydraulic jacks in the launch pit to push the 3.2 meter by 3 meter (126 in by 9.85 ft.) concrete pipes. Seven hundred sixty-six pipes were needed to complete the 2246-meter tunnel. One key to success was building a lubricating slurry using QUIK-GEL™, QUIK-TROL® GOLD and FUSE-IT® additives with low filtrate loss (<10 ml/30min), creating an incompressible fluid cushion to minimize the friction as the pipes were advanced through the 40 mm (1.57-in) annular space. The average skin friction in the tunnel was 0.4 kN/m^2 (e.g. <1.0 kN/m^2 is considered excellent) and the average jacking for was 1460 tons (max 2800 Tons). Twenty-one interjack stations (IJS) were installed along length of the tunnel, but only four (two, three, four, and six) were activated during the drive. Penetration rates averaged 9.2meters per day with 25.5 m being the best daily advance. The first pipe was installed November 25, 2017 and the TBM reached the final goal of 2246 meters on July 27, 2018, completing the World's largest single drive microtunnel with seafloor TBM rescue.

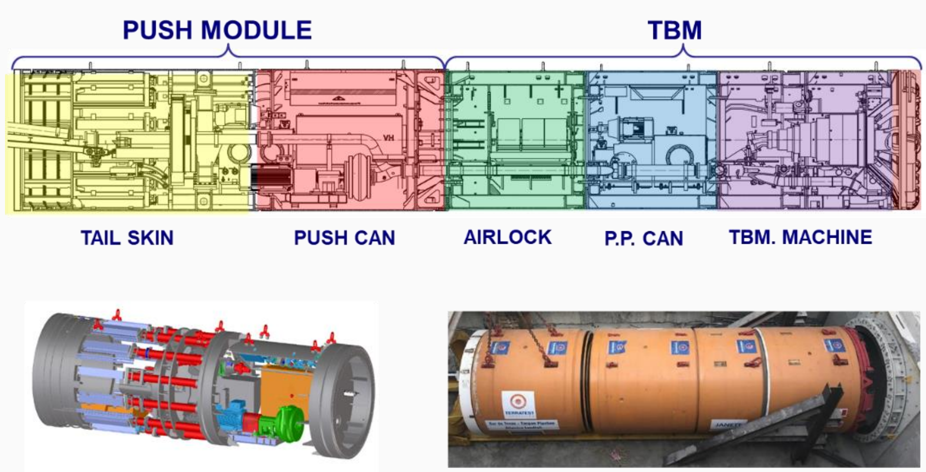

Figure 2. AVN2000 OD 3200mm ID 2600mm

Geological Considerations and Slurry Objectives

The tunnel drive encountered sedimentary geology comprised of typical coastal plain sediments, ranging from sandy clay to clayey sand with lenses of fine to coarse gravel usually in a matrix of clay or silt. Figure 3 shows the grain size distribution based on the available geotechnical samples and Figure 4 shows the drive alignment relative to the inferred geological model.

Since the clay and silt sized fraction as a stabilizing matrix for the sand and gravel, maintaining the integrity of this matrix was essential to achieving and maintaining stability at both the cutting face and overcut. Clays and silts are typically water sensitive, so a key slurry performance driver was building and maintaining a face and lubrication slurry that will minimize the water wetting of these formations. Sands and gravels are generally porous and permeable and where there was little clay/silt matrix, maintaining adequate filtration control maximizes formation stability.

In addition to the geology, the overall project had a number of challenges including:

- Length of drive (2246 meters)
- Complexity of drive (2 curves)
- Potential for saltwater contamination
- Environmentally sensitive area from TBM launch to completion and TBM rescue point

The intent of face and lubrication slurry formulations is to allow the operator to:

- Effectively advance the drive and maintain geologic stability while keeping the face slurry invasion into formation confined to, approximate diameter of cutting wheel and lateral distance along drive path
- Stabilize encountered formations at point of contact and facilitate transport of cuttings/spoils away from cutting face while allowing for efficient recycling and re-circulation of the face slurry
- Establish and maintain a stable and gauge working face allowing a stable overcut to transition to the lubrication phase, facilitating the lubrication slurry to effectively minimize jacking forces

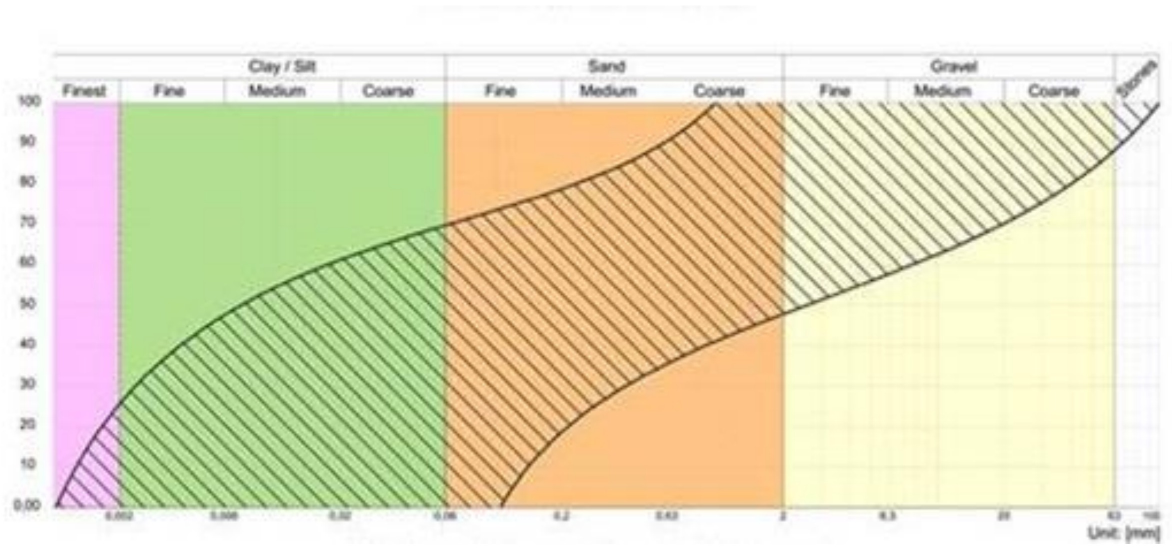

Figure 3. Grain Size Distribution

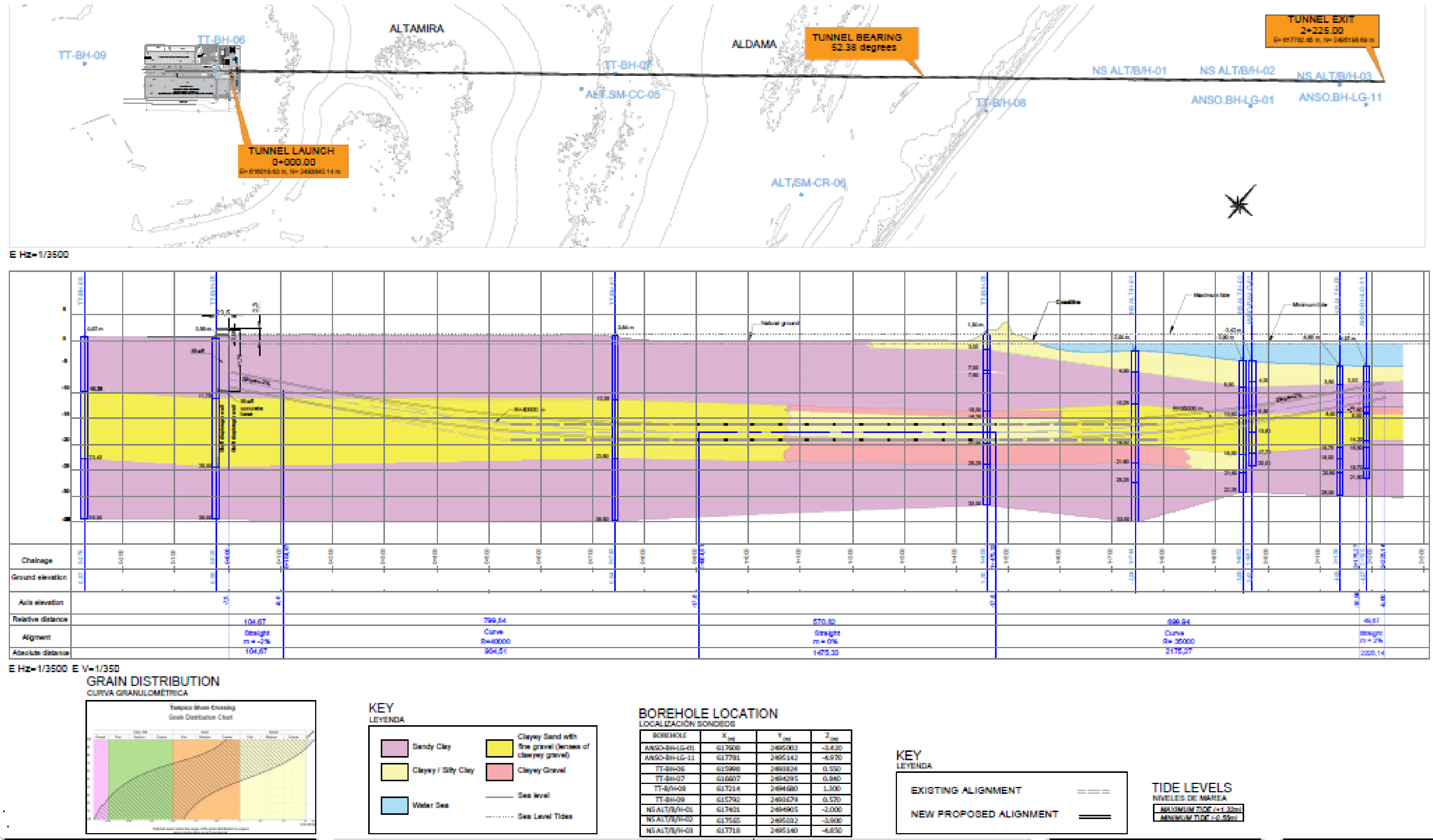

Figure 4 Tunnel Profile and Alignment Relative to Geological Model.

Face and Lubrication Slurry Design Considerations

Using the geologic models shown in Figures 3 and 4, desirable Face and Lubrication Slurry parameters were developed by pilot testing in the laboratory using the anticipated site make-up water with a range of Baroid IDP products. Tables 1 and 2 show the desirable Face and Lubrication Slurry properties. A contingency set of parameters were developed in case the drive encountered a coarser formation containing more sand/gravel.

Table 1. Desirable Face Slurry Properties based on Geologic Models

Face Slurry Property	Base Property	Lower/Upper Range
Mud Weight (SG)	1.02-1.03	1.02/1.10
Funnel Viscosity (sec/qt)	38 -45	36/48
Plastic Viscosity (cps)	8-12	6/15
Yield Point (lb/100 sq.ft)	10-14	8/20
Gel Strength 10s/10min (lb/100 sq.ft)	5+/22+	3/10 – 13/28
Fluid Loss (ml/30 min)	9-12	NA/18
Filter cake (mm)	1	1/4
pH	9	8/9.5
Total Hardness (mg/L)	<100	NA/125

Table 2. Desirable Lubrication Slurry Properties based on Geologic Models

Lubrication Slurry Property	Base Property	Lower/Upper Range
Mud Weight (SG)	1.02-1.03	1.02/1.10
Funnel Viscosity (sec/qt)	110	85/120
Plastic Viscosity (cps)	23	18/27
Yield Point (lb/100 sq.ft)	32	26/36
Gel Strength 10s/10min (lb/100 sq.ft)	21/54	17/24 – 45/62
Fluid Loss (ml/30 min)	6.5	NA/8
Filter cake (mm)	1	1/4
pH	9	8/10
Total Hardness (mg/L)	<100	NA/125

Since the project was located on the Gulf Coast, the available water for building the Slurries might contain some salinity (up to ~500 mg/L of TDS salts.) However, onsite testing of incoming water trucks measured the available make-up water TDS at ~1000 mg/L. Over the course of the project, incoming water samples ranged 1000 -1500 µS. This resulted in some modifications to original Slurry designs to cope with higher overall fluid salinity.

To build face and lubrication slurries (Figure 5) within the range of desirable properties, the following products were used:

1) Soda Ash - to reduce excess calcium in fresh make-up water to a target <100 mg/l and maintain pH at a range of 8.5 to 9.5. Once soda ash has been added high shear mixing should continue for a minimum of one volume circulation to allow precipitation of excess calcium to occur. Objective is to enhance yield, hydration and performance of bentonite and polymeric additives.

2) **QUIK-GEL™ viscosifier** – High yield Wyoming sodium bentonite to build baseline viscosity, rheological properties and filtration control through development of low permeable filter cake for improved geologic stability.

3) **QUIK-TROL® GOLD filtration control additive –** Readily dispersible, high viscosity filtration control polymer to provide enhanced filtration control and improved borehole stability in both fresh and saline environments

4) **FUSE-IT® LCM** – Liquid lost circulation material and rheologic modifier. Used in low concentrations improves Slurry lubiricity and filtration control.

5) Supplemental Products – **QUIK-MUD® GOLD clay stabilizer** and **BARAZAN® D polymer additive** (salt water tolerant suspension ehancing polymer)

Figure 5. – Building lubrication fluid (left) – Addition of FUSE-IT in low concentration to reduce jacking force and skin friction (right)

The original laboratory pilot testing showed that a clay/shale stabilising polymer (QUIK-MUD GOLD) was very effective at stabilising the clay content of the formation, however, once it was determined that the make-up water and circulating Face Slurries were subject to significant salinity contamination, the use of QUIK-MUD GOLD was discontinued and replaced with

BARAZAN D polymer. BARAZAN D hydrates and has better performance in saline or brackish waters. The concentration range for each product used in the Face and Lubrication Slurry are shown in Table 3.

Table 3. Product Concentration Ranges for Building Face and Lubrication Slurries

Product		Face Slurry	Lubrication Slurry
Soda Ash	Kg/m^3	0.5 – 1.0[1]	0.5 – 1.0[1]
QUIK-GEL	Kg/m^3	22 - 35	40-45
QUIK-TROL GOLD	Kg/m^3	1.0 – 1.5	1.5 – 2.5
FUSE-IT	L/m^3	NA	0.1 – 0.3
BARAZAN D	Kg/m^3	NA	0.2 – 0.5

[1]Soda Ash concentration increased to 1.0 kg once salt water contamination reported

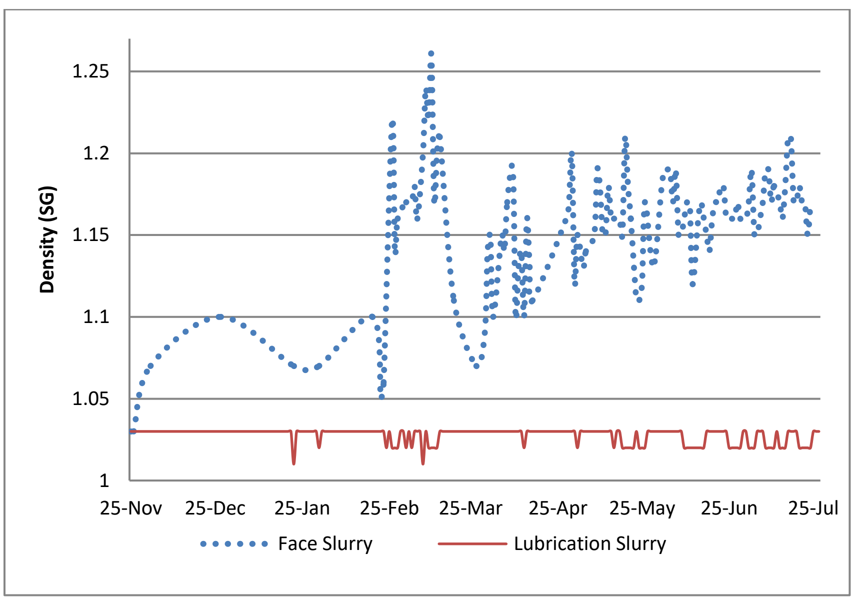

Figure 6. Face and Lubrication Slurry Density

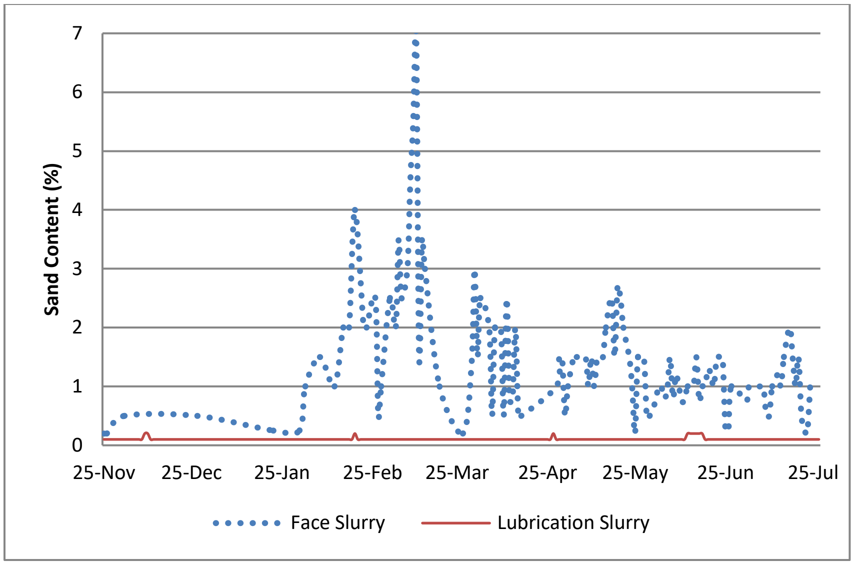

Figure 7. Face and Lubrication Slurry Sand Content

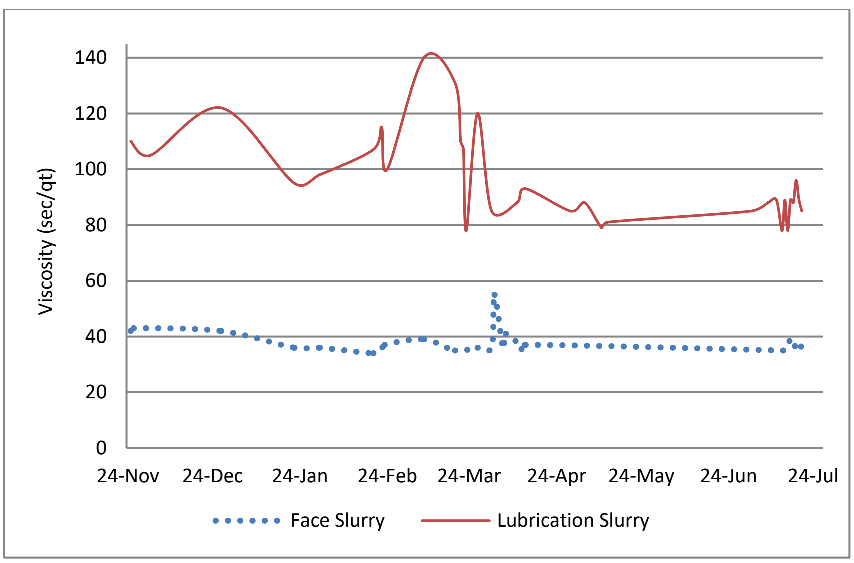

Figure 8. Face and Lubrication Slurry Viscosity

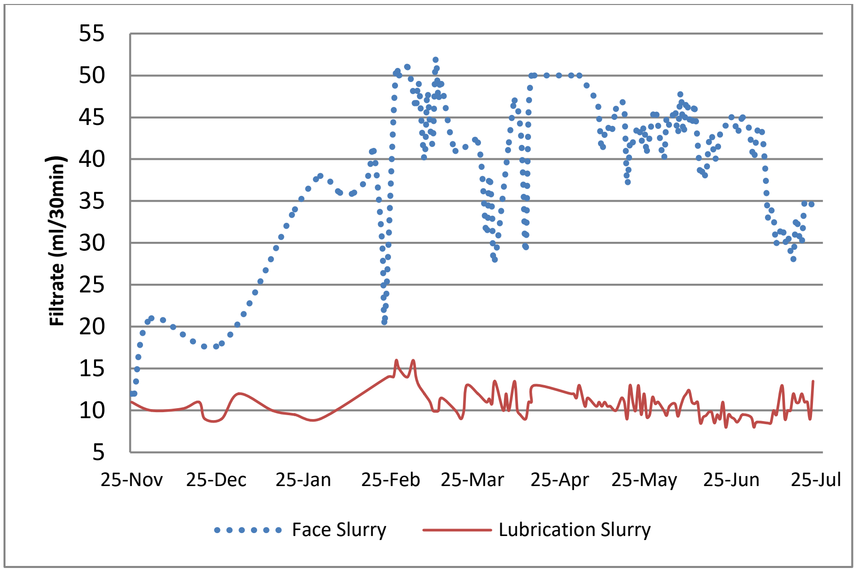

Figure 9. Face and Lubrication Slurry Filtrate

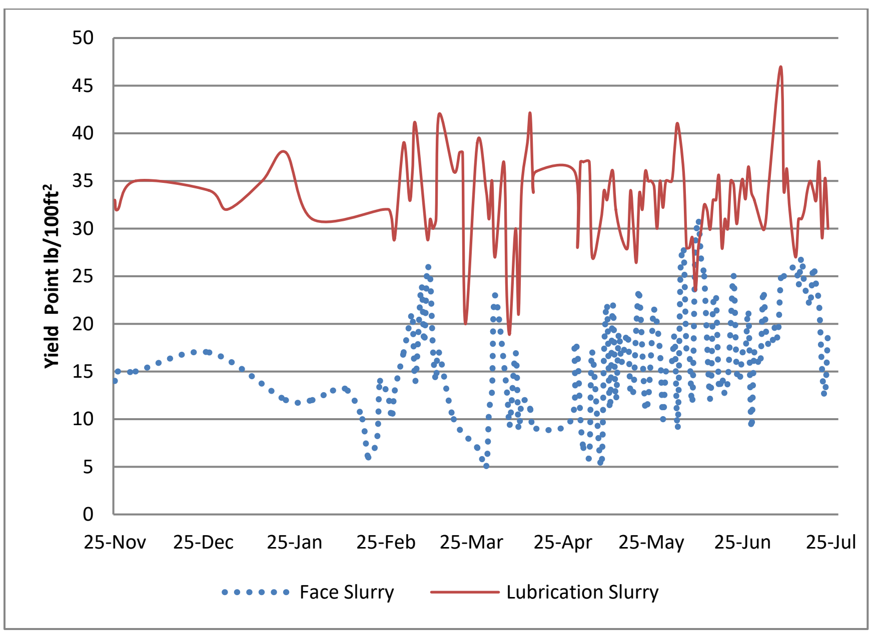

Figure 10. Face and Lubrication Slurry Yield Point

Results

Slurry Performance

For a long-term project, the ability to measure and document a large slurry property data set is beneficial. Figures 6 - 10 show the key slurry properties used to build and maintain both the face and lubrication slurries. Terratest employed a field laboratory (Figure 11) with a full range of FANN® water based fluid testing equipment. This facilitated the regular measurement and recording of Slurry property data. In addition, a third party to collected, measured and recorded slurry samples on a daily basis.

Figures 6 and 7 shows slurry density and Sand Content, respectively over the duration of the project. The lubrication slurry was continually prepared and pumped into the annular as the tunnel advanced. As such managing the density and sand content is relatively simple as long as the quality of the bentonite used has a low native grit content. Managing the Face Slurry density and sand content was much more challenging. The data indicate that for the first two months, the density was maintained in the 1.05 - 1.10 S.G. range. However, as the drive extended, so did the circulating volume until a point was reached where the solids control separation efficacy began to be compromised. The sedimentary deposits were not cemented or very cohesive, so cuttings easily broke down into their smallest unit size by the time they reached the separation equipment. At this stage (February – March), a second solids control plant was brought onsite and run in parallel to with the primary plant. Slurry density, while still higher than ideal, after the start-up of the second plant was maintained in the 1.13 – 1.19 S.G. range. By the time the drive was completed at 2246 m, the total circulating volume in the system was over 500 m^3 including ~ 150 m^3 of 200 mm flow and suction lines to and from the TBM cutting face.

Figure 11. Terratest Slurry Testing laboratory

Sand content (Figure 7) shows similar trends in performance to Slurry density. For the first two months of the project the sand content in the Face Slurry was maintained <1%, but began to climb into the 2-4% (peaking at 7%) when the primary solids control efficacy decreased. After the circulating volume was processed across two separation plants (end of March) the sand content was maintained in the 0.5 – 2.5% range for the duration of the drive.

Figure 8 shows the face and lubrication slurry viscosity as a function of time throughout the drive. As indicated in Tables 1 and 2, the desired lubrication slurry viscosity (110 sec/qt) was deliberately set significantly higher than that of the face slurry (38 - 45 sec/qt). The lubricating slurry was designed to form an incompressible cushioning fluid bridging the space between the overcut and the concrete pipe. The face slurry needs to have sufficient viscosity to aid in suspension of cuttings and stabilize the face, but not so high as to limit cuttings removal at separation plant. Both the face and lubrication slurries were successfully maintained within the desirable ranges. The data (Figure 8.) show that a deliberate change in lubrication viscosity was made as the drive reached the 900 - 1000 mark. The reason is illustrated in Figure 12, which shows the jacking force as a function of drive length. At close to 1000 m there is a spike in jacking force that was attributed to insufficient lubrication fluid being injected per unit length of pipe. Fluid flow is a function of viscosity and the smaller the diameter the pipe or hose the more the friction loss associated with viscosity. As a result, the lubrication slurry viscosity was modified from 100-110 sec/qt to 80-85 sec/qt in order to increase the pumping efficiency of the lubrication manifold and distribution lines. Both jacking force (Figure 14) and skin friction (Figure 15) were brought back under control following this action.

Slurry filtrate is shown in Figure 9. As is typically, in porous and permeable formations, the goal is to maintain as low a filtrate as practical. The lower the filtrate, the lower the fluid invasion into the formation and the better the likelihood of achieving stability. The lubricating fluid once injected into the annulus would serve as the fluid cushion for the duration of the drive, so design fluid loss goal was set very low (<10 ml/30min). The lubrication slurry filtrate was maintained throughout the project between 8 – 15 ml/30min. The face slurry filtrate was a more challenging proposition given the large circulating slurry volume and contamination from the saline groundwater. Given the formation porosity, it was estimated that ~2,000 L of saline ground water was added to the circulating slurry for every meter advanced. This effect is exhibited by the variability of the slurry filtrate that range from as low as 12 ml/30min near the beginning of the project but steadily rose to between 35-50 ml/30min after the first 6-8 weeks. By the last month of the project, when the circulating volume approached its maximum, the filtrate was brought back down into the 28-35 ml/30min range.

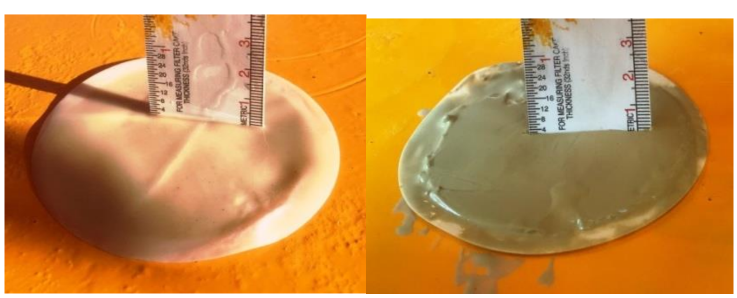

Figure 12. Typical Filter Cake Development, Lubrication (left) and Face (right) Slurry.

Filter cake development is function of the type and quality of solids in the slurry. Examples of typical lubrication and face slurry filter cakes are shown in Figure 12. A lubrication filter cake yielding 10 ml/30min filtrate is shown on the left and a typical face slurry filter cake yielding 32 ml/30min is shown on the right. The difference between the two filtrates and cake appearance is the quantity of solids in the slurry. The lubrication slurry at a density of 1.02-1.03 S.G. is comprised of <2% solids (100% Wyoming sodium bentonite), while the face slurry with a density of 1.15 S.G. is 9% total solids. The original fresh face slurry contained <2% solids but has been contaminated (7%) by fine solids (silts/clay/very fine sand).

Figure 13. Low filtrate (8.5 ml/30min) lubrication fluid constructed from **QUIK-GEL™, QUIK-TROL® GOLD** and **FUSE-IT® additives**

The slurry yield point (YP) is shown in Figure 10. Similar to the aforementioned parameters, the face and lubrication slurry needed to perform slightly different functions, so the yield points goals were set for each accordingly. As previously stated the lubricating fluid once, pumped into place needed to stay in good condition in saline water for the duration of the drive. Since the drive took nearly 9 months to complete much of the injected lubricating slurry was in place for many months. As such, the YP was set at ~30 lb/100 ft^2, and varied over the project duration from 25 – 35 lb/100 ft^2. The face slurry was goal was ~14 lb/100 ft^2 and over the course of the project ranged 15-25 lb/100 ft^2. The increase in YP is attributed to the excess fine solids the slurry was carrying for much of the project. For example, a slurry density of 1.15 S.G. is equivalent of the water phase carrying 9% total solids.

Tunneling Performance

The tunnel location and record-breaking length of 2246 meters for single drive seabed recovery project, presented a myriad of challenges ranging from variable geology and salt water intrusion to pushing the limits of telemetry and geosteering technology. Throughout the drive, Eurohinca-Terratest collected a range of raw tunneling data, including jacking force, skin friction force, excavation face pressure, steering cylinder contact force, horizontal/vertical deviations (i.e., pitch and yaw) and penetration rates. Eurohinca-Terratest used this real time data collection throughout the tunnel construction to assess progress, compare actual versus design thresholds in order to make real time modifications to day-to-day tunnel operations.

This paper's focus relates to aspects of the slurry, so analysis of tunneling data is confined to data pertaining to how the lubrication and face slurry affected tunnel performance, specifically the jacking force and skin friction. A significant contributor to the overall tunnel performance begins with the entry or launch ring. Not only does the ability to limit groundwater seepage ensure a clean work area, but also it is conducive to creating slight positive pressure in the annulus, allowing the slurry to act as an incompressible fluid cushion. Figure 14 shows the steel and rubber gasket launch ring built by Eurohinca-Terratest. The image on the right shows the tunnel at 770m with dry work area in shaft with 10 m of water head.

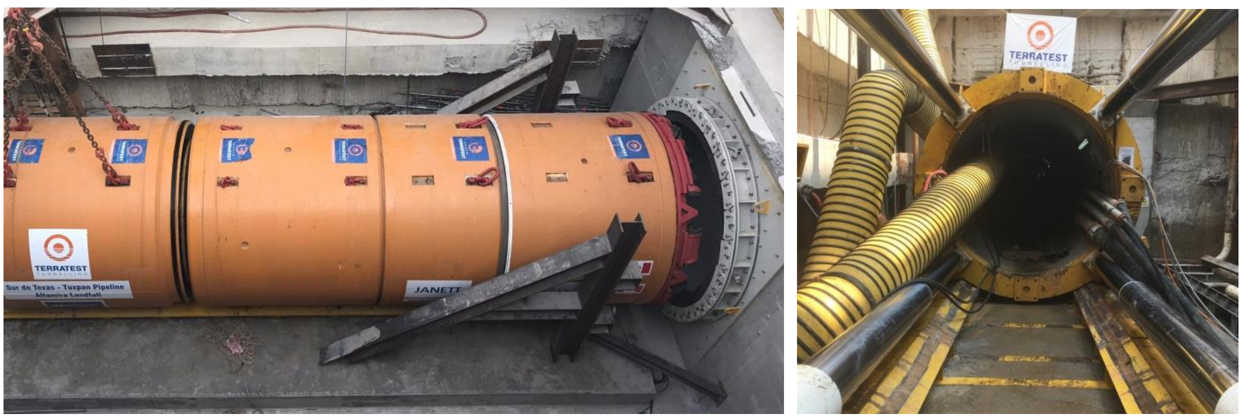

Figure 14. left) Eurhonica-Terratest TBM being installed in front of launch ring, right) Work area inside jacking shaft indicating launch ring successfully impeding ground water seepage.

Figure 14 and 15 show the jacking force and skin friction, respectively, as a function of distance. The average jacking force over the 2246 m was 1460 Tons (i.e., 0.65 T/m). Seven hundred sixty-six three meter pipes were installed to complete the drive using only four of the available 21 interjack stations. The maximum jacking force available to draw upon was 2800 Tons. Completion of the drive using only half the available jacking force was a testament to the Terratest-Eurohinca TBM operators and their support teams. Jacking forces (figure 14) indicate a linear increase in pressure from the launch ring to ~750 Tons at 300m into the drive. From this point the jacking forces fluctuate from 400 to 1300 Tons with a short spike between 900-1000 m of 1800 Tons. As previously discussed, this was attributed to reduced pump output of lubrication slurry as a function of line diameter, slurry viscosity and distance. The solution was to reduce the slurry viscosity by 20-30 sec/qt. At the conclusion of the drive, all the interjacks were deactivated and a successful test was conducted using only the primary jacks to determine if the entire tunnel could be advanced. From a fluid engineering perspective, it was encouraging to see that the primary jacking cylinders could move the entire 2246 m tunnel.

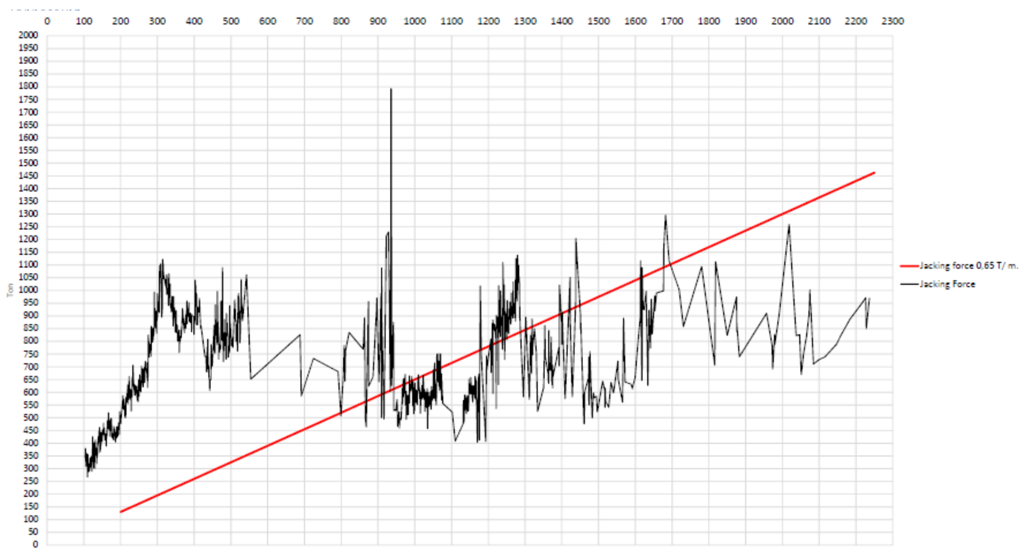

Figure 14. Jacking Force vs Distance for 2246m Altamira Gasducto Sur De Texas-Tuxpan. Data supplied courtesy of Eurohinca Terratest Group.

Skin friction data is shown in Figure 15. The average skin friction was <0.4 kN/m^2. By way of comparison, the Herrenknecht skin friction chart shows that <1.0 kN/m^2 is considered "Excellent". Similar to the jacking force data, up till ~300 m, the skin friction increased to ±3.0 kN/m^2. Once the tunneling operations were optimized for ROP (rate of penetration), and effective use of face and lubrication slurry, the skin friction between to decrease from the highpoint of ~3.25 kN/m^2 and after the aforementioned problem at 900-1000 m, continued for the remaining 1500 m of the drive at or below 0.5 kN/m^2.

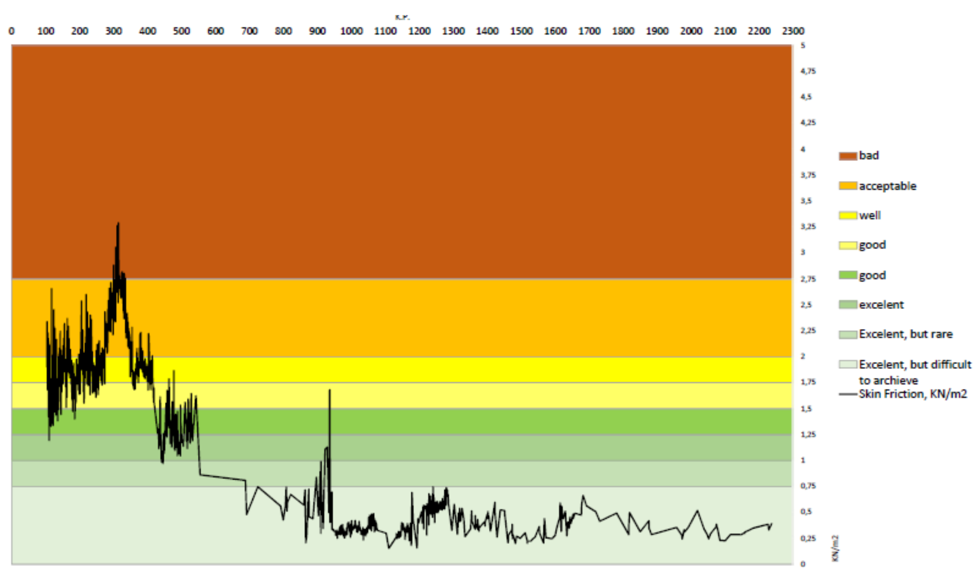

Figure 15. Skin Friction vs Distance for 2246m Altamira Gasducto Sur De Texas-Tuxpan. Data supplied courtesy of Eurohinca Terratest Group

Conclusions

The design and construction of the landfall Altamira single drive tunnel with seabed TBM rescue was a singular achievement under taken for the Gasoducto Sur De Texas – Tuxpan Project. The complex mix of geography, geotechnical conditions, environmental constraints, combined with stakeholder needs, presented the opportunity to showcase advancements in TBM, long distance, geosteering, communication and lubrication technologies.

From a lubrication slurry perspective, the primary challenges included:

1) Effect of saline groundwater on face and lubrication slurry effectiveness when in contact with the ground for extended period
2) Local geology with high percentage of fines and water sensitive clay
3) Fine solids accumulating in circulating face slurry resulting in difficulty in managing slurry density
4) Pumping low filtrate, high viscosity lubrication over long distances

Developing and following a lubrication and face slurry plan based on the anticipated geology was a significant driver in the success of the overall project. Developing the slurry around the base products, QUIK-GEL™, QUIK-TROL® GOLD, and FUSE-IT® additives enabled Baroid IDP engineers to build a low filtrate, lubricating slurry able to maintain its physico-chemical characteristics in the annulus for up to eight months.

The world record tunnel of 2246 m was completed by Terratest-Eurohinca in eight months with an average jacking force and skin friction of 0.65 T/m and 0.4 kN/m^2.