Unprecedented In-Tunnel Diameter Conversion of the Largest Hard Rock TBM in the U.S.

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ABSTRACT: The largest hard rock TBM ever to bore in the USA, an 11.6 m diameter Robbins Main Beam TBM, recently underwent a planned in-tunnel diameter change to a more compact 9.9 meters. The first-of-its-kind conversion process for the Main Beam TBM was undertaken 2.8 km into the bore and was not done inside a shaft or pre-excavated portal. This paper will detail the unique dual-diameter machine designed for the Mill Creek Drainage Relief Tunnel in Dallas, Texas, USA, machine performance, and successful size conversion process that took place in early 2021—a process that utilized the four C's of construction to enormous benefit: Communication, Cooperation, Collaboration and Coordination.

IN SITU DIAMETER REDUCTION AT MILL CREEK

The Mill Creek/Peaks Branch/State-Thomas (MCPBST) Drainage Relief Tunnel is a five-mile underground tunnel that will provide flood protection for the east Dallas area. The project required a drainage tunnel starting at a diameter of 11.6 m and ending with a diameter of 9.9 m. The upstream 5.2 km are designed with a circular cross section for a peak flow of 425m3/sec. The downstream 2.8 km, running between the outfall shaft to the East Peaks Branch Intake (see Figure 1), was originally designed with a horseshoe cross section to allow a higher peak flow of 566 m3/sec. The horseshoe section was to have been excavated by the TBM initially and expanded by roadheader to create a flat invert. Two different sets of formwork would also have been required to cast the final lining for both the round and horseshoe profiles, making the process potentially time consuming and costly (Rowland, 2019). Because of the cost and time to excavate by roadheader, one TBM was instead selected.

Figure 1. The 5-mile route of the Mill Creek Drainage Relief Tunnel. Source: www.millcreektunnel.com

A Robbins re-built TBM along with a continuous conveyor (including a vertical conveyor) was chosen as the boring system. During early project discussions with the machine supplier, a decision was made to reduce the boring machine diameter in the tunnel, lowering project costs and reducing the construction period (see Figure 2).

Figure 2. The 11.6 m diameter Robbins Main Beam TBM at launch, the largest hard rock TBM ever used in the U.S.

Without a prepared chamber, in-situ diameter changes raised the number of challenges encountered. The changeover was designed and conducted in three distinct parts, with each presenting its own difficulties and corresponding opportunities to be collaboratively solved:

- The TBM proper
- The trailing gear
- The tunnel conveyor system

TBM Reduction

The TBM story begins with the design phase. Working with a rebuilt machine, the designers started with the concept to build a smaller machine and then install a wrap to make the larger diameter. In this way it was hoped to reduce the difficulty inherent in the diameter reduction. Several items that were taken into consideration were:

- Cutterhead segments and how to handle them
- Thinking ahead with skin weld placement with respect to interior accessibility
- Thinking ahead about gripper shoe wraps
- Adjustability of the drills
- The ground support platforms and the associated extensions

The original strategy was to excavate to the transition station, back the TBM system approximately 22 m, change the diameter, then commence boring at the smaller diameter while adding conveyor parts to adapt to the new diameter. During the initial design phase, the concentricity of the two diameters was discussed and it was decided the two tunnels should be concentric. A communication misunderstanding led to the conveyor system beginning component construction understanding the two tunnels to be eccentric—a fortuitous misunderstanding as we shall see.

As per the contract requirements the ground support consisted of rock bolts spaced five feet apart longitudinally, along with woven wire fabric, and crown straps as needed. Additional bolts, straps, and mesh were to be installed as needed. Part of the transition plan was to back the TBM approximately 22 m leaving cutterhead sections behind; upon arrival to the transition the ground turned bad—the crown became loose rock and required additional rock support that could not be removed, thus obviating the required back-up as the entirety of the work had to be done from supported ground. The straps and bolts protruded into the TBM envelope even with the roof support fully retracted, so another solution was needed. The contractor, Southland Holdings, and The Robbins Company personnel put their heads together and found a solution that required only backing the head a mere 76 cm. The process would be achieved by removing cutterhead sections and other pieces through Lateral Tunnel A, a 6 m diameter, 90 m long, horseshoe tunnel built using excavators and hydraulic hammers. The lateral tunnel connects with Drop Shaft A, at 52 m deep and 6 m in diameter. The arrangement allowed personnel and equipment to access and begin the conversion process through the lateral tunnel, and remove pieces on rails through the shaft and up to the surface (see figure 3).

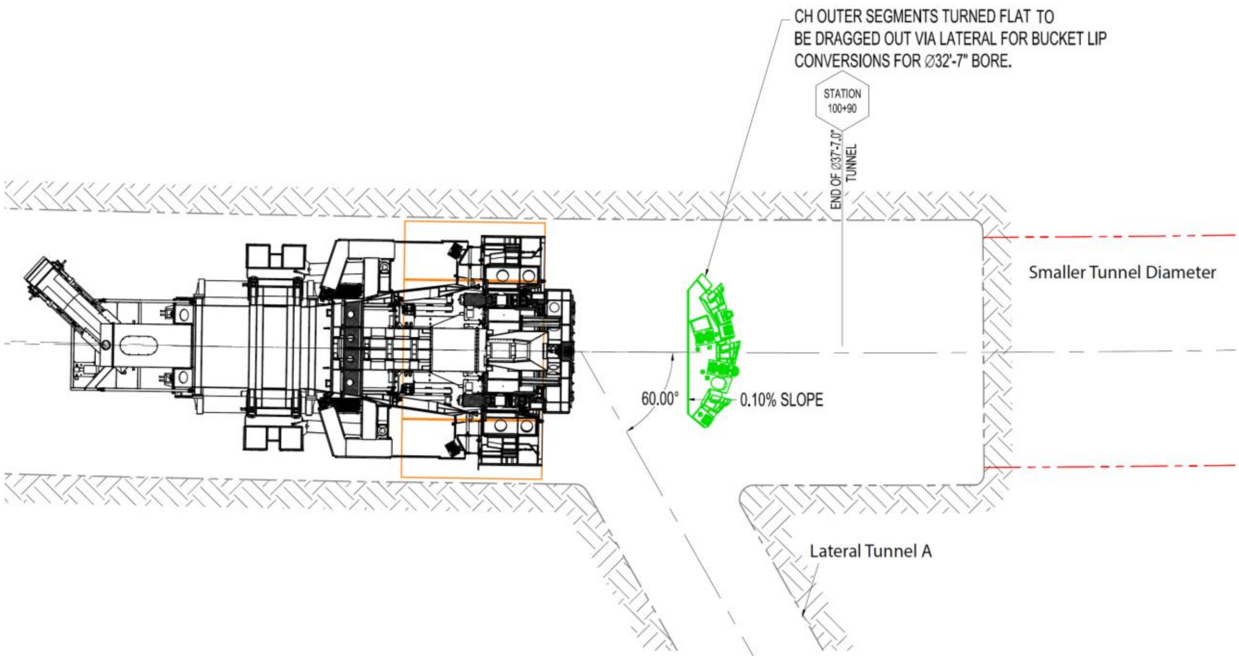

Figure 3. TBM Plan view in relation to Lateral Tunnel A at diameter change site.

The reduction took place from the front of the machine starting with the cutterhead and ending with the conveyor. The cutterhead was designed to have four spacer segments installed between the cutterhead center section and the outer sections, with four small, intermediate sections filling in the gaps at the so-called corners (see figures 4 and 5).

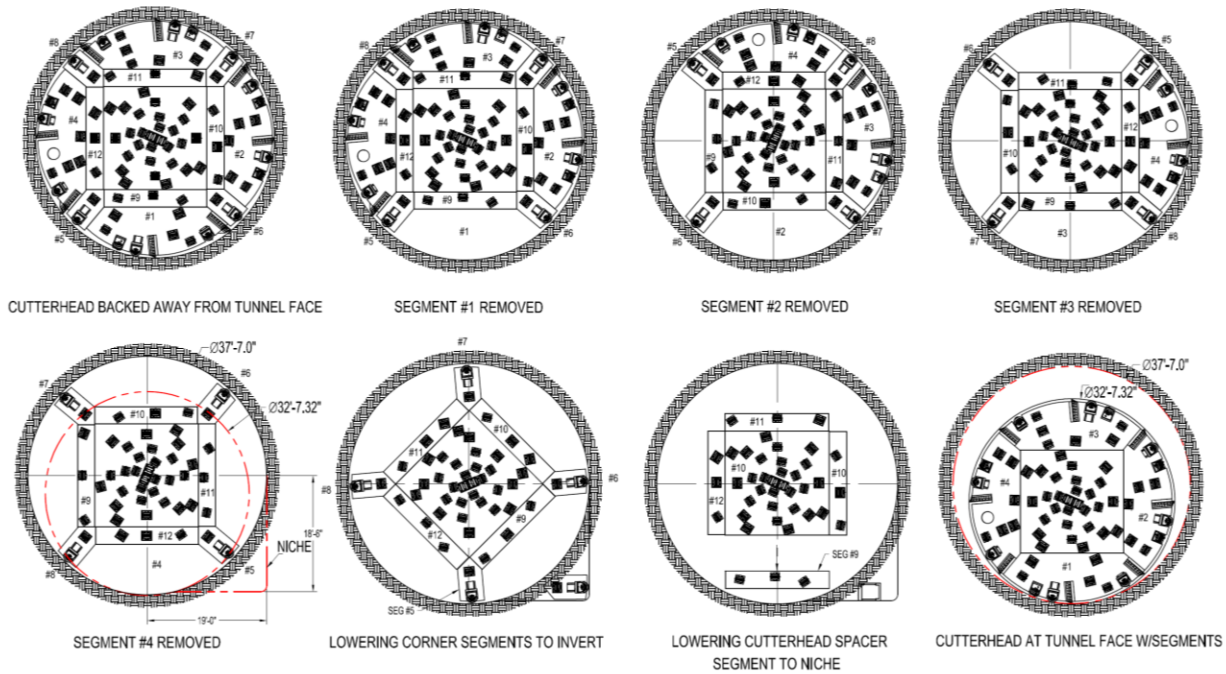

Figure 4. Cutterhead diameter change sequence

The team dismantled and removed the four cutterhead sections, the four intermediate sections, and the four spacers from a lateral tunnel, lateral A, which intersected the main tunnel precisely at the diameter change. The heaviest section weighed just over 15,000 kg and given the small access window, required a bit of planning to maneuver the pieces out of the lateral access to the surface for re-fitting for the small diameter, and returning to the installation position.

Figure 5. Cutterhead segments being removed in the lateral access

Working from the lateral tunnel, the welds securing the intermediate spacers were removed through the buckets. The team made the decision to remove the spacers in sections, cutting them from the lateral, leaving the mounting flanges in place. The spacers were then pulled from the cutterhead in sections.

The crews were then able to remove the cutterhead sections entirely from within the safety of the confines of the cutterhead and the lateral access. Working on the bottom section and from within the cutterhead, the crews then removed the fasteners and allowed the cutterhead section to rest on the invert. As the TBM was not retracted, the cutterhead sections settled in the invert nicely as they waited to be removed. To facilitate the cutterhead section removal, the cutterhead drive motors, controlled via variable frequency drives, were used to rotate the cutterhead and push the first cutterhead section out through the lateral where it could be collected and sent to the surface.

The cutterhead was then rotated 180º and the process was repeated, removing the next cutterhead section. After the first two sections were removed, the process was repeated until all the sections were removed. The next step was to remove the cutterhead spacers.

The spacer fasteners were removed from within the cutterhead. To control the lowering of the spacers, hydraulic jacks and spacers were used to lower each section in a controlled manner once the fasteners were removed.

The rest of the TBM, trailing gear, and conveyor work was accomplished while the cutterhead sections were being refurbished. When the cutterhead sections were returned, they were installed using the jacks and spacers that were used to remove the spacers. A dedicated transport sled was fabricated to facilitate the positioning and lifting of the spacers to the cutterhead center section.

Working from within the shield skin the crews removed the outermost skins from the roof supports and side supports. The crews then fashioned chain action rollers supported by hydraulic jacks to maintain roof support pressure against the crown, especially as the TBM advanced until the front of the roof support skin could be secured in the crown with some rock bolts and straps. The roof support skin and roof support extensions were secured in place using rock bolts and crown straps (See figures 6-7).

Figure 6. Transition area showing the roof shield skins and transition area from the top

Figure 7. TBM roof shield skin removal

As part of the planning phase it was thought that the smaller diameter roof shield extensions would be too unwieldly to maneuver within the confines of the tunnel. With minimal overhead clearance, just 76 cm, it was thought that hoisting a heavy shield extension from the invert up and around the main beam would be too great an obstacle. The solution was to cut the smaller diameter roof support extensions into three smaller pieces and weld them in place on the roof shield extensions. It was then just a matter of sliding the pre-cut pieces in position and completing the welds. During the excavation of the larger diameter there were a few inconveniences, but they were insignificant to the larger picture.

The vertical front support did not need to be removed from within; the crews needed only to remove the fore and aft welds to free the small diameter TBM and allow the TBM to push off the vertical front support when the time came. The crews carefully fashioned the side support skins and reinforcing ribs into supporting members for the gripper shoe skins. The gripper shoe skins were positioned carefully onto the side support skins and welded in place. A few rock bolts were installed into the side supports to ensure they did not shift as the TBM passed through, and crews worked closely in/on/around them. Once the cutterhead was re-assembled the TBM started mining forward (see Figure 8).

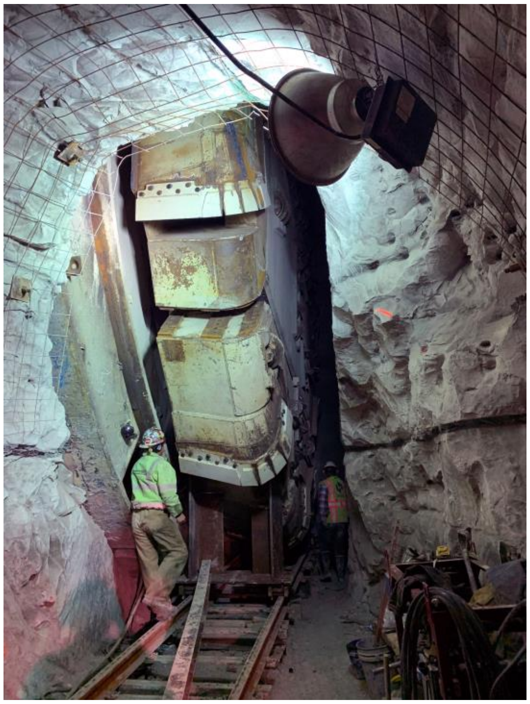

Figure 8. Installation of the smaller diameter cutterhead structure

This phase of the transition required many stops to remove the accumulated material from in front of the vertical front support. Mining with a concentric tunnel meant there was a 76 cm step between the two bores and the rock would accumulate and prevent the TBM from advancing until it was clear. Once the vertical front support was abutted to the transition step, the aft welds were removed and mining began again, with the TBM sliding from the vertical front support and into the new diameter, freshly bored tunnel. The gap between the vertical front support and the newly bored tunnel was about seven to ten centimeters and this gap was mostly filled with accumulated material from the mining operations and presented no difficulty.

Concurrent with the TBM advancement, permanent roof support anchors were installed to secure the shield skins to the tunnel wall. The temporary chain rollers and supports were then removed.

Once the TBM was excavating at the smaller diameter, the crews cut the shield wrap inner re-enforcements into manageable size parts and removed them on a flat car leaving the skin plate in place. The contractor was granted a variance to leave the roof support skins and skin extensions secured to the crown; to be cast in place during the lining of the tunnel.

With the TBM beginning to advance at the small diameter, the next part of the transition was the gripper shoe extensions. This again highlights where the planning phase is of utmost importance. During the side support extension removal phase, thought was given to the gripper shoes as they passed the transition area and carefully laid out cuts were made to the side support wraps and re-enforcing ribs such that the gripper shoe extensions would lay neatly in place supported by the cut outs. The gripper shoe extensions were then welded in place to the side support extensions with a couple of rock bolts securing the tops of the extensions.

After the gripper shoe extensions were laid into the side support cutouts, the remaining welds holding the extensions to the shoes were removed. The TBM then began a re-grip cycle with a noteworthy additional step. Just prior to the gripper shoes rear half being placed on the forward part of the gripper shoe extensions, the voids in the extensions were filled with sandbags to allow the gripper to apply full force to the tunnel walls. The sandbags prevented the supporting members of the wrap from racking under the propel and gripping forces.

The final item for the TBM reduction was the rear support shoe extensions. These were abutted against the rear of the vertical front support and then the extensions were removed; the next boring cycle brought the shoes to rest fully upon the vertical front support.

The trailing gear reduction was neatly taken care of during the design phase. Instead of reducing the diameter of the trailing gear, a smaller diameter trailing gear was utilized with extensions on the wheel bogies to bring the trailing gear to the correct elevation when the TBM was 11.6 m in diameter. All that remained at the diameter change was to remove the wheel bogie extensions and position the trailing gear in the small diameter. There were a few platforms that had extensions upon them that needed to be removed but they were minor and handled as needed.

The original design was to lead the trailing gear up a 2% slope requiring a substantial amount of civil works to build the ramp between the TBM and the first gantry of the trailing gear. There was not much space within which to work, so this design was not desirable. The bad ground encountered at the diameter change station eliminated the ability to back the TBM more than absolutely necessary. There were several discussions held in an effort to find a workable solution, and ultimately the contractor and Robbins decided a novel approach would work. The decision was to use rented hydraulic cylinders in conjunction with fabricated spacers and raise the entire trailing gear at the same time. This decision naturally created obstacles, but these were overcome (see Figure 9).

Figure 9. The gantry lift process

While the gripper shoe extensions were being removed the crews installed fabricated supports to the tunnel walls upon which were placed hydraulic jacks. Four jacks were used per gantry with each gantry having a dedicated pump and each jack having a dedicated isolation valve. During the lift crews took careful measurements to ensure the trailing gear raised at the same rate and at no point were any two jacks allowed to become more than 3mm different in extension, thereby ensuring the entire trailing gear lifted equally. (Each jack had a maximum capacity of 45 metric tons so with the maximum weight of the heaviest gantry at 61,700 kg the job was done with a generous safety factor.)

As the gantries were lifted, spacers were inserted as an extra measure of safety until all four gantries were lifted to the correct elevation. The wheel bogies were removed and spacers were installed to the gantries and the bogies installed to the spacers. The gantries were then lowered until the weight was borne by the bogies and mining resumed.

When the leading bogie for the first gantry reached the abandoned vertical front support mining was paused and the front of the first gantry was raised enough to install the same continuous chain rollers used for the roof support. They were installed onto spacers welded to the vertical front support, and then the gantry was lowered onto the chain rollers such that the weight of the front of the gantry was borne by the chain roller. The leading bogie and extension were removed from the front of the first gantry and mining resumed. When the TBM had pulled the trailing gear sufficiently far, mining was once again paused. The front of the first gantry was again lifted, the chain rollers removed and the bogie (without extension) was re-installed. The gantry was lowered and mining resumed.

This process was repeated until all the trailing gear was inside the newly mined tunnel (see Figure 10).

Figure 10. The completed diameter transition area

The tunnel belt also had to be transitioned to the smaller tunnel diameter.

- The transition occurred in a curve just after the first carry booster was scheduled to be installed
- Due to a collaborative misunderstanding the TBM division knew the tunnel was concentric while the conveyor division thought it was an eccentric tunnel
- Originally a carry booster was designed to be installed a few hundred feet into the smaller diameter tunnel, this required a substantial elevation correction to the tunnel belt in order to allow space between the carry belt and return belt to fit the booster rollers.
- The elevation difference was 76 cm on the radius, the installation of the first carrying booster was 91 cm—a fortuitous coincidence. The decision was taken to postpone the installation of the carrying booster until the transition while excavating the wall for installation until the belt elevation only required 15 cm of transition
- After the TBM and trailing gear passed through the transition diameter phase the team utilized a remnant of the large diameter shield as a mounting base upon which to install the first of five tunnel belt boosters, in this case a 375 kW dual motor carrying booster

The conveyor booster installation was relatively easy and was carried out in a timely manner.

Overall, the diameter change process took about four months to complete—the revised setup backing the machine up by only 76 cm saved about one month compared to the originally devised plans to excavate a transition station and back the machine up 22 m. The ground conditions, particularly poor rock quality in the crown, dictated the change in plans, and was ultimately highly successful.

Ground Conditions and TBM Performance

The TBM at Mill Creek is well equipped for rock bolting with dedicated rock drills mounted on a ring gear allowing for installation of rock bolts in the needed areas of the tunnel. Table 1 below gives a general overview of rock bolt types that may be considered in relation to the Rock Mass Classification. It should be noted that ultimately the decision on which type of rock bolt to be used should be decided on a case-by-case basis.

Table 1. Ground Support Requirements based on Rock Mass Classification

Rock Mass Class	Description of ground conditions	Rock Mass Rating	TBM Production (m/hr)	Ground Support	Rock bolt Type	Installation Time (Approximate)
Type I	Very Good	81-100	1.5 – 3.2	Generally no support required only spot bolts	Mechanical Anchor / Split Set Friction Bolt	≤ 3 mins per bolt
Type II	Good	61-80	2 – 3.5	Local bolting with occasional mesh	Mechanical Anchor / Split Set Friction Bolt	≤ 3 mins per bolt
Type III	Fair	41-60	1.1 – 1.5	Systematic bolting with wire mesh in crown	CT Bolt Resin anchored Bolt	3-5 mins per bolt
Type IV	Poor	21-40	0.8 – 1.1	Systematic bolting with wire mesh crown on side walls. Light Steel ribs and local shotcreting	CT Bolt Resin anchored Bolt	Depends on length of hole to be drilled & exposed ground condition
Type V	Very Poor	<20	<1	Systematic bolting with wire mesh over crown and side walls. Heavy Steel ribs and shotcreting	CT Bolt Resin anchored Bolt	Depends on length of hole to be drilled & exposed ground condition

The Mill Creek machine is operating in Austin Chalk and Eagle Ford Shale with a compressive strength of between 17 MPa and 30 MPa. The requirement for systematic rock bolting is in part due to the rock being classified as mainly Type III and some areas of Type IV conditions. In Type IV conditions the contract called for eight additional rock bolts, resulting in 76cm linear spacing with wire mesh covering the crown and steel straps as needed. Once through the learning curve the crew began installing eight bolts in the Type III conditions in 20-25 minutes (see Figure 10).

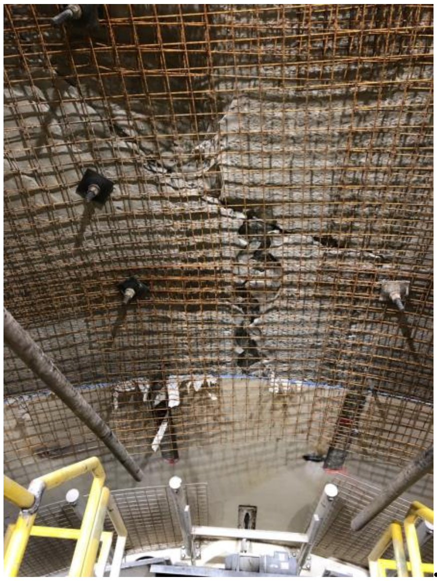

Figure 10. Rock bolts and wire mesh installed in the tunnel crown

Probing is also required to 60 m in front of the machine in every 46 m of mining, thereby providing a safe zone of 15 m ahead of the machine. To date there have been no significant water inflows into the tunnel.

Due to the required systematic approach to production the machine is currently averaging approx. 16 m advance per day. Limiting factors to production are the probing requirements and the capacity of the vertical conveyor. At the time of writing the machine has achieved some impressive performance results:

- Best Day: 41 m (at the 11.6 m diameter)
- Best Week: 118 m
- Best Month: 498 m

At the current rates of advance boring is scheduled to be completed in June 2022.

Due to the relatively favorable ground conditions in much of the tunnel, including low rock strength and low abrasivity, only eight (8) cutters were changed during the length of tunnel bored at the larger diameter. At the time of diameter change the full dress of cutters was changed. As in the larger diameter tunnel, cutter inspection times and the downtime associated with them are limiting and are generally only carried out when trouble is suspected.

CONCLUSIONS

Construction sites can be contentious working environments, and sometimes it is far too easy to put the blame on another party for whatever fails to transpire. If, however, we consider the four 'C's approach to this situation:

- Communication: Exchanging ideas and information
- Cooperation: Understanding the goals of all stakeholders to achieve the desired results while minimizing downtime
- Collaboration: Working together collectively on a plan that could not have been designed by one party
- Coordination: The ability of the management to lead the team in completing the works (Macfadden, 2018)

Then we can achieve the desired results. The success of the in-situ diameter change in the tunnel is a result of this "four C's" approach between all parties involved with the project. It is obvious that the ability of the TBM manufacturer's engineering & management team and the contractors project team to communicate and understand the requirements of what had to be done resulted in the successful diameter change.

Moreover, it was the ability of the personnel carrying out the work to communicate on a daily basis to adapt to the problems they faced and come up with solutions as situations arose that led to the smooth transition from one diameter to another.

This was a unique, time & cost-effective solution to a not-so-common situation. A diameter change in mid-tunnel is a rare event. The success of this in-tunnel diameter change shows that with careful planning and co-operation there is an opportunity to use this method albeit adapted to the particularities of any project that would require a similar mid-bore diameter change in future.

REFERENCES

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