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Challenging mixed face tunneling at India's Sleemanabad Carrier Canal

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ABSTRACT: India's Sleemanabad Carrier Canal is a prime example of just how challenging mixed face conditions can be, although other examples exist. The water transfer tunnel is being bored using a 10 m diameter hybrid-type rock/EPB TBM. However, in 6.5 years of tunneling the machine had only advanced 1,600 m. Commercial issues for the original contractor stalled the project frequently, while ground conditions turned out to be even more difficult than predicted. Low overburden of between 10 and 14 m, combined with mixed face conditions, transition zones and a high water table restricted advance rates. The TBM manufacturer mobilized a team to refurbish the TBM and within a period of 6 weeks a team of 180 people had been deployed to take over all aspects of tunneling and support activities. Production rates improved dramatically as the TBM advanced more than 400 m in four months. This paper will discuss the problems faced and the methodology that enabled good advance rates in highly variable mixed face conditions.

1 INTRODUCTION

The Bargi Diversion Project in Madhya Pradesh, India, is a trans-valley irrigation project consisting of 197 kilometres of canal. It will transfer water from the Narmada river to provide irrigation to 245,000 hectares of land in drought prone areas in Satna, Jabalpur, Katni and Rewa Districts. It will also supply 284 million liters of domestic & industrial water per day to the city of Jabalpur and town of Katni. A section of the scheme comprises a 12 km long tunnel driven by a 10.0 m diameter Robbins hybrid rock/EPB TBM.

2 GEOTECHNICAL CONDITIONS

The geology along the tunnel alignment changes frequently. It consists of compact residual soils, silts, alluvium, highly weathered limestone and dolomite, with stretches of slate, massive crystalline limestone and fresh marble. The strength of the rock varies considerably with UCS values reaching as high as180 MPa. There is a highly permeable boulder horizon, which acts as a conduit for ground water located 2-3 m above the tunnel for the initial 2.7 km of the alignment. The ground water table is above the tunnel for the entire length of the drive. In some instances, the TBM has traversed transition zones between different geological conditions within 1-2 meters of boring, and in other cases the transition zone has extended for over 100 meters. These lengthy transition zones result in difficult boring conditions due to the mixed faced conditions. Figure 1 shows the predicted geological conditions for the initial 3,400 m of the tunnel alignment.

3 TBM SELECTION

The geological reports indicated that approximately 68% (8,160 m) of the tunnel would be driven through residual soils, silts and highly weathered/decomposed rock, with the remaining

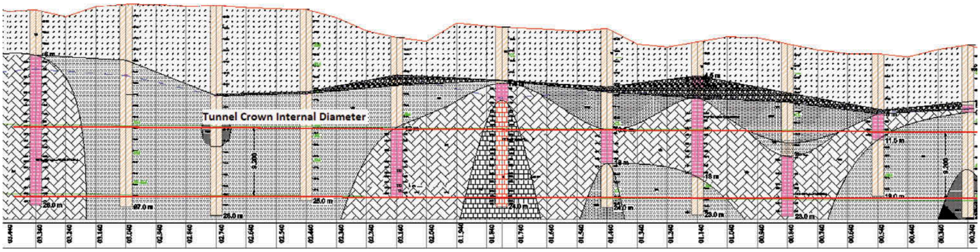

Figure 1. Geological alignment.

Table 1. TBM Technical Specifications.

CUTTERHEAD	
NOMINAL DIAMETER	10.0 m WITH NEW CUTTERS
TYPE	MIXED FACE DESIGN
NUMBER OF DISC CUTTERS/KNIFE BITS	53
CUTTERHEAD DRIVE	
TYPE	VFD ELECTRIC MOTORS (12 X 330KW)
CUTTERHEAD SPEED	0 - 5.4 RPM
CHD TORQUE AT 2.1 RPM	17,615 kNm
CHD TORQUE AT 5.4 RPM	6,966 kNm
MAIN THRUST	
CHD THRUST, EPB	23,731 KN
CHD THRUST, HARD ROCK	14,151 KN
MAX PROPELLING EXTENSION SPEED	100 mm/minute
BELT CONVEYOR	
DRIVE SYSTEM	HYDRAULIC MOTORS
CAPACITY	1,604 CUBIC METER/HR
SCREW CONVEYOR	
SCREW DIAMETER	1,200 mm
DRIVE SYSTEM	HYDRAULIC MOTORS
MAX TORQUE	300 kNm
MAX SPEED	18 RPM

32% (3,840 m) being driven through competent rock. Bearing this in mind, a hybrid rock/EPB machine was considered for the project. The hybrid machine would be configured with the option of switching out the screw conveyor with a TBM belt, and for interchangeability between disc cutters and soft ground tools (see Figure 2).

Approximately 600 m of the anticipated 3,840 m of competent rock was divided into numerous, relatively short stretches. These short stretches would not justify the downtime of one month required to remove the screw conveyor, install the belt conveyor and change from EPB into hard rock mode. However, over 3,200 m of the competent rock was made up of three stretches of 700 m, 1,000 m and 1,500 m. The length of these stretches warranted the downtime required to convert from EPB to hard rock mode; hence, a decision was taken to utilize a hybrid machine for the Sleemanabad project. The main technical specifications of the TBM are shown in Table 1.

4 MACHINE ASSEMBLY & LAUNCH

The machine was assembled at the remote jobsite using Onsite First Time Assembly (OFTA), a method that allows for the machine to be initially assembled on location with testing of critical sub-assemblies in a workshop. The TBM was launched in early March 2011 in EPB mode with a full dress of soft ground tools as the geological information indicated mainly soft ground for the initial 500 m of boring. During the first 200 m of boring the TBM encountered mixed

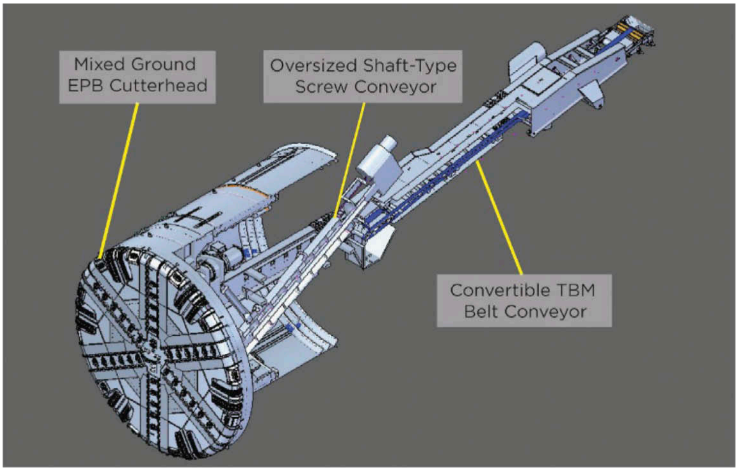

Figure 2. Sleemanabad TBM features.

geology containing residual soils and hard rock. This was the first of frequent changes in geological conditions that were encountered during the initial 1,600 m of boring. The strength of the rock dictated that the soft ground tools needed to be replaced with disc cutters. After changing out the cutter tools, the machine was boring in rock but still had to be operated in closed/EPB mode to prevent settlement of the soil above the crown of the tunnel (see Figures 3-4).

Figure 3. Onsite TBM assembly.

Figure 4. TBM launch.

5 POST-LAUNCH PROJECT HISTORY

During the following 6.5 years after the launch of the machine the project suffered a multitude of problems both commercial and technical. A comprehensive account of the commercial problems is not in the scope of this paper; nevertheless, it should be noted that they resulted in various minor delays of up to a few weeks due to shortages of spares, segments and consumables etc. They also resulted in the project being completely halted on two separate occasions for ten months and eight months respectively. The main technical problems that the project faced are detailed below.

5.1 *Failed Cutterhead Interventions*

On numerous occasions cutterhead interventions under hyperbaric conditions had to be either cancelled before they could commence or were aborted during execution due to excessive air losses. A critically long intervention time can lead to erosion blowouts. Small soil particles are blown out of the ground, increasing the pore size and reducing the flow resistance of the air (Babendererde et al. 2014). On the Sleemanabad project the cause of the air losses was air percolating through the permeable material above the crown of the tunnel, especially through the boulder horizon. The problem was exacerbated by the low overburden of only 10-14 m. The standard practice of injection of bentonite into the face to form a cake to prevent, or at least minimize air losses proved to be unsuccessful as the bentonite was pushed up to the surface along with the escaping air.

Due to the failure of bentonite injection it was decided to install safe haven grout blocks via drilling and injection from the surface. Initially this solution proved to be unreliable as there is a shortage of specialist contractors in the region and the sub-contractor employed to carry out the works lacked the necessary experience and equipment. The first attempt at pushing the TBM into a pre-installed grout block to carry out a cutterhead intervention under pressure failed completely due to excessive air loss. This caused a delay of approximately I week while waiting for a second grout block to be installed 10 meters ahead of the machine. Unfortunately, after boring forward into the second grout block, the second attempt at an intervention also failed due to excessive air losses. The quality and effectiveness of the safe haven grout blocks improved over time, but they were never close to being 100% effective and were the cause of many further delays.

5.2 *Cutterhead Damage*

Due to a lack of timely cutterhead interventions the cutterhead suffered wear damage to an extent that required repairs on three separate occasions. Because of the low overburden and mixed geological conditions, it was decided that excavation from the surface down to the TBM would be far easier than creating a subsurface chamber to carry out the repairs. Neither shaft segments nor piling equipment were available at site, but heavy earth moving equipment was being utilized on the canal works. The availability of this equipment made it possible to create an open pit type excavation (see Figure 5).

The residual soils and alluvial material were relatively easy to excavate but their low cohesion called for a multi-level pit with several benches and involved the excavation of around 30,000 m^3 of material. One of the problems faced during excavation of the open pits was liquefaction caused by the saturated nature of the soil and vibration of the excavation equipment (see Figure 6).

The three separate operations to repair the cutterhead, including excavation and backfilling of the pits, resulted in a total delay of over eight months.

5.3 *Muck spillage*

When boring in EPB mode, it is essential that a plug of material can be formed in the screw to maintain face pressure. In order to form the plug an adequate quantity of fines is required in the excavated material. The alignment of the tunnel up to Ch:1600 m contained over 300 m of

Figure 5. Excavation down to the TBM.

Figure 6. Liquefaction of the soils.

highly weathered or moderately weathered marble and slate, and 200 m of mixed face conditions where adequate quantities of fines were not present. The absence of fines along with the high water table and permeable geology caused problems in maintaining face pressure. This resulted in a relatively common issue for EPBs in this type of geology: high-pressure water and silt spilling from the transfer point between the screw conveyor and TBM belt conveyor.

A catchment box and pump were available at site (as part of the machine design and supply) but the amount of spillage greatly exceeded its capacity. Polymers and bentonite were injected into the tunnel face, plenum and screw conveyor, but they had minimal effect due to the excessive volume of water. The delays in manually clearing the spillage amounted to almost 80% of working time. Typically a 1.6 m boring stroke would be completed in less than two hours but the remainder of the 10-hour production shift would be taken up clearing away the spillage.

5.4 *Sinkholes*

A problem related to the failed cutterhead interventions was sinkholes appearing above the machine (see Figure 7). Several interventions were aborted up to 48 hours after they commenced due to progressive increase in air losses. It became standard practice to reduce hyperbaric pressure to a minimum (approx. 0.9 bar) to reduce the amount of air losses; hence, this also extended the

Figure 7. Sinkhole above the machine.

duration of the intervention. However, this sometimes resulted in water ingress steadily washing fines and silt into the cutterhead chamber and around the extrados of the TBM shields.

The bore diameter of the cutterhead with new cutters is 10.0 m, whereas the outer diameter of the TBM shields is 9.93 m (the differential is required for steering purposes and is standard design practice). The combined length of the TBM shields is 11.2 m which equates to 12.3 m^3 of annular space around the shields. When sufficient face pressure is maintained, the risk of convergence is minimized, but reducing the pressure allowed convergence to occur. The combination of inflow of fines into the chamber and convergence around the annular gap led to cavities forming over the cutterhead and shields and ultimately unravelling up to the surface. The sinkholes generally occurred once the machine had advanced 2-3 rings after the intervention had been completed. The section where the sinkholes occurred is part of the 95% of the tunnel alignment that runs beneath agricultural land, so there was no risk to surface structures. Access to the land over the first 1.5 km of tunnel was relatively straightforward, so earth moving equipment was deployed to backfill the sink holes. Usually after less than 24 hours boring was able to continue.

6 INVOLVEMENT OF THE TBM SUPPLIER

The Robbins Company's initial involvement in the Sleemanabad project was to supply and commission the TBM and tunnel conveyor systems, then to supply key personnel for training the contractor's crews and to troubleshoot any technical problems with the equipment.

In September 2017 after seeing only 1,600 m of tunnel completed in 6.5 years the project owner and senior JV partner held discussions with The Robbins Company, with a view to them taking over the project. Although Robbins had not had a continuous presence at site during the previous 6.5 years they had been involved with the project in various capacities on and off since the launch of the machine. Because of this involvement they were familiar with the difficulties the project had faced and they accepted the challenge. Robbins' new scope of work covered all aspects of production operations including both tunnel and surface works, supply of rails, pipes, cables, consumables, grout, electricity and haulage of excavated material from site. Supply of segments remained in the scope of the senior JV partner. A team was mobilized to begin refurbishment and testing of the TBM in September 2018. By the end of October 2018, the size of the team was increased to 180 people to enable commencement of production operations.

7 PROJECT RE-START

In order to achieve improved production rates a thorough analysis of the cause of delays faced up until that point was carried out. The measures taken to mitigate these problems are listed below.

7.1 *Reduction of air losses during interventions*

The overall effectiveness and efficiency of cutterhead interventions played a key role in improving overall production on the Sleemanabad project. Historically, creating safe haven grout blocks from the surface had proved to be less than effective in preventing air losses during interventions.

During discussions it was decided that pumping a weak-mix grout solution from inside the TBM offered a better chance of success as the grout pressure would build up from the face of the tunnel, assisting migration of the grout solution into the discontinuities and permeable material above the TBM. Another issue that had to be considered was the fact that the tunnel alignment was moving away from relatively easy access points on the surface. This meant that transportation of drilling and pumping equipment to locations above the tunnel would become much more difficult. Over the course of the following three interventions weak-mix grout was pumped through the mixing chamber of the TBM and into the surrounding geology. On each occasion air losses were minimized, and the interventions were completed without major problems. The grout mix design was modified on each of these three interventions. The final design mix can be seen in Table 2.

Rather than setting a limit for the actual volume of grout to be pumped into the ground, buildup of grout pressure was used to determine when sufficient grout had been pumped. The benchmark used was 0.3 bar above EPB pressure used during boring. Once this pressure was achieved, pumping was stopped for 15-20 minutes to determine if the recorded pressure was a product of back-pressure during pumping. If the pressure dropped by more than 0.2 bar over 20 minutes, grouting recommenced until a steady state pressure was achieved.

7.2 *Time consumed with weak-mix grouting methodology*

The setting time for the weak mix is between 12-18 hours depending on variables such as the amount of grout pumped, amount of groundwater present, temperature, etc. The time taken to pump the weak mix must also be considered in the overall time calculation. Additional time must also be factored in for cleaning the cutterhead and changing cutters. This is of course a result of having to remove grout rather than merely cleaning soils from the cutterhead spokes, buckets and cutters. Generally, around 20 hours was factored into the overall cutterhead intervention schedule when using weak-mix grout for ground consolidation. It should be noted that 20 hours should only be used in the overall schedule when a decision to pump weak-mix grout is taken prior to an intervention commencing. At this point the mixing chamber is packed with excavated material and the temperature of this material is higher than the ambient temperature on the TBM. The chamber being packed full of muck minimizes the amount of weak mix required and the higher temperature reduces its setting time.

After carrying out several successful interventions using the weak-mix method, the TBM encountered a full face of residual soil. An intervention was attempted without pumping weak-mix grout and it proved to be successful. Unfortunately, the following intervention in very similar ground conditions had to be aborted due to excessive air losses. In order to reduce the air losses and complete this intervention, pumping weak mix grout solution from the TBM was again utilized; however, the addition of weak-mix grout at this point added an extra 18 hours to the standard 20 hours associated with using the weak-mix methodology.

Table 2. Sleemanabad Project, Weak-Mix Grout: Design Mix 1 m^3.

Cement	130	kg
Bentonite	50	kg
Water	820	Ltrs
Retarder	2	Ltrs
Sodium Silicate	50	Ltrs

This is because the chamber is more than half empty during an intervention, so time is required to pump an additional 40 + m^3 of weak mix to replace the excavated material. Additional setting time is required for the extra grout and for cleaning the cutterhead and cutters as there is less soil in the cutterhead to prevent grout sticking to the cutterhead spokes, buckets and cutter tools.

There is no definitive rule applied at Sleemanabad regarding whether or not to pump weak-grout mix before an intervention because the geology changed too frequently for hard and fast rules. The decision was taken based on an observational approach; however, the overriding philosophy was: "if in doubt pump weak-mix grout". In the long term this philosophy vastly reduced the overall average time spent on each intervention by reducing the amount of interventions that needed to be aborted. It also completely negated the need for installing safe haven grout blocks from the surface.

8 CUTTER TOOL AND CUTTERHEAD DAMAGE

Reducing the amount of cutter changes automatically reduces the amount of downtime taken up for cutterhead interventions, and subsequently improves overall production rates. This was the case at Sleemanabad, where replacing six cutters under hyperbaric interventions could take over nine hours. This is in addition to the time spent cleaning and inspecting the cutterhead and cutter tools, which takes approximately six hours, in addition to the 20 hours associated with pumping weak-grout mix. The total intervention time for replacing six cutters was at least 35 hours, which equates to almost six hours per cutter.

Identifying individual damaged cutters as soon as possible is essential. When one cutter gets blocked and stops rotating, it leads to a higher load on adjacent cutters, with a possibility of a cascading failure (wipe out) of all the cutters in the worst cases (Shanahan 2010). Cascade wipe-outs can result in damage to the cutterhead, and the damage can occur over the course of boring only a couple of strokes. The problem with mixed face excavation in constantly changing geology is that it is extremely difficult to predict cutter wear patterns. Moreover, a couple of damaged cutters do not make a substantial difference to the observed operating parameters of a 10.0 m diameter machine being operated at 24,000 kN of thrust and 12,000 kNm of cutterhead torque. To improve the chances of identifying any change in parameters, Robbins deployed the most experienced operators that were available to this project. Also, a policy of carrying out an intervention if any anomaly in boring parameters was observed was implemented.

Another important factor in reducing cutter consumption was minimizing impact damage to the cutter discs in the mixed face geology. Impact damage occurs when the cutter discs are rotating through relatively soft material before coming into contact with harder material, which can result in radial cracks forming in the cutter discs and the discs breaking away from the hubs. The magnitude of the impact is dependent on speed of cutterhead rotation and depth of penetration per revolution. The higher the percentage of soft material in mixed geology, the higher the risk of damage to the cutter discs.

The closer the cutter is to the periphery of the cutterhead, the higher the risk of damage. Restricting cutter travel speed is the most important factor in avoiding impact damage and the rule of thumb used at Sleemanabad was a maximum cutter travel speed of 30 m/min. If we consider that the gage cutters on a 10.0 meter diameter cutterhead travel a distance of 131.42 m per revolution, then 0.95 rpm is identified as the maximum cutterhead rotation speed in order to remain beneath the maximum cutter travel speed of 30 m/min in mixed face conditions.

The second most important mechanism in reducing impact damage is restricting the depth of cutter penetration at the point of impact between soft and harder material (see Figure 8). Experience on the Sleemanabad project identified this depth to be approximately 8 mm.

Figure 9 shows two mixed face conditions typical of the transition zones that were encountered along the alignment of the Sleemanabad project. In the mixed face conditions shown in A the gage cutters would travel through 90° of soft material before coming into contact with rock. If we look at a penetration rate of 15 mm/revolution (which is achievable in soils and softer rock), the penetration at the point of contact with the harder geology is as follows:

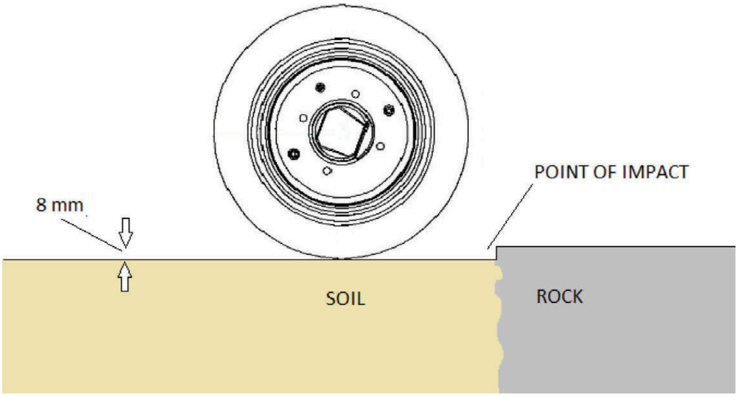

Figure 8. Restricting depth of cutter penetration at point of impact between hard and soft material.

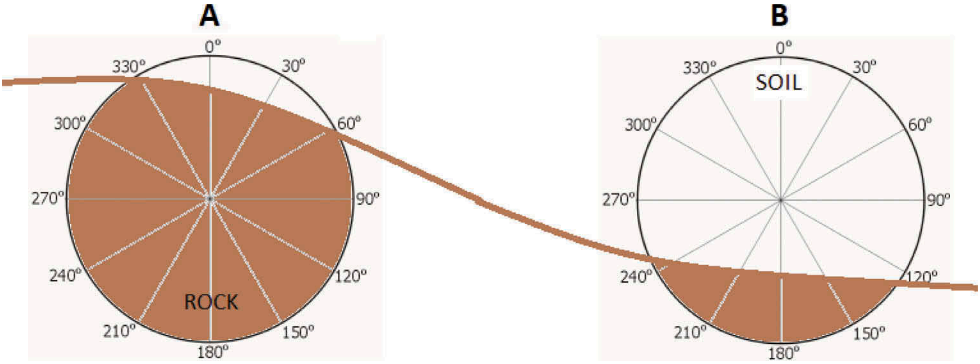

Figure 9. Two mixed face conditions typical of the transition zones at Sleemanabad.

15 mm/360°*90° = 3.8 mm penetration at the point of contact with the harder geology, which is within the acceptable parameters set at site.

In the mixed face conditions shown in B the gage cutters would travel through 240° of soft material before coming into contact with rock. With the same penetration rate of 15 mm/revolution the penetration at the point of contact with the harder geology is as follows:

15 mm/360°*240° = 10 mm penetration at point of contact with the harder geology, which is beyond the acceptable limits set at site. In this case the TBM main thrust pressure would be decreased to reduce the penetration per revolution to approximately 12 mm (12 mm/360°*240° = 8mm).

Face mapping was carried out during each intervention and muck samples taken during each stroke to provide the best possible information to ensure correct operating parameters could be identified. Information on the actual boring parameters of the machine was downloaded from the data logger on a daily basis to confirm that the designated operating parameters were being adhered to.

9 MUCK SPILLAGE

Muck spillage was the most significant cause of delays after failed cutterhead interventions and cutterhead damage. Major spillage often occurred immediately after failed interventions or extended interventions, as well as in areas containing insufficient fines to hold a plug in the

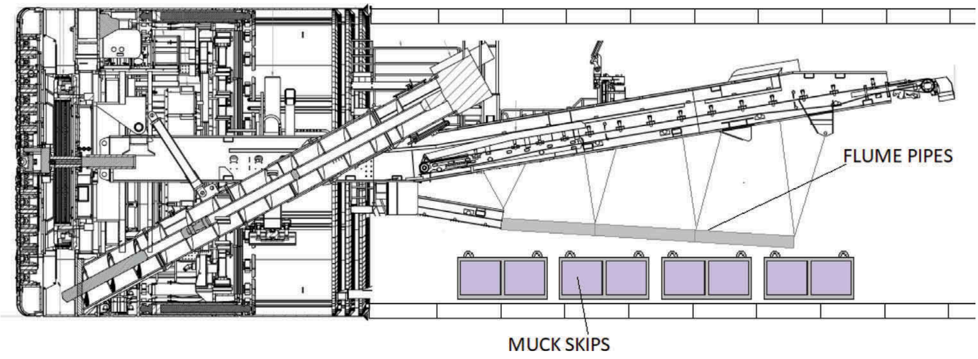

Figure 10. Overlapping flume pipes were used to funnel spillage into muck skips.

screw conveyor. This is because air losses and/or reduced face pressure allowed water in the surrounding geology to migrate into the chamber of the machine. When boring recommenced, this water mixed with excavated material and turned it into a slurry-like consistency, which resulted in significant amounts of spillage. As with the stretches containing insufficient fines, pumping polymer into the chamber and screw conveyor had no noticeable effect on the amount of spillage. Because the amount of spillage could not be reduced, the only remaining solution was to spend a set amount of time setting up a system to catch the spillage rather than spend substantially more time cleaning it up. As mentioned previously a catchment box and slurry pump were available at site but the amount of spillage greatly exceeded its capacity. At the start of boring a stroke the amount of spillage was as high as 200 L/minute consisting of approximately 90% ground water and 10% a mixture of silts, fines and small rock chips.

The solution applied was to fix a permanent chute below the transfer point of the screw conveyor/TBM belt conveyor. Before each boring stroke commenced four muck skips were placed on and behind the segment feeder. The segment crane and segment feeder were used to place the skips into the correct locations and remove them after the completion of the boring stroke. A series of overlapping flume pipes (half pipes) were used to funnel the spillage into the skips (see Figure 10). The excess water was allowed to flow over the upper edges of the skip and as each skip was filled with silt/fines/rock chips a flume pipe was removed to allow the next skip in line to be filled. The excess water was pumped into a settling tank before being pumped out of the tunnel.

Setting up the muck skips and flume pipes took approximately 30 minutes. Removing them at the end of the stroke and cleaning up the minor spillage took approximately 60 minutes. Another 30 minutes was lost loading a ring onto the segment feeder because the muck skips were located on the segment feeder while boring the stroke. A total delay of around two hours per stroke was a major improvement compared with up to eight hours that had previously been spent cleaning spillage after each stroke.

10 TAIL SKIN BRUSH LEAKAGE

Another problem that had to be overcome when Robbins took over the project was that the tail skin brushes had been damaged. Replacing damaged brushes in the geological and hydrological conditions present at the time of the takeover needed to be avoided if at all possible. It would have been an extremely difficult and time-consuming operation with a real risk of losing ground, resulting in an inundation of water and silts into the tunnel. To resolve this problem a back-to-basics approach was adopted. Rice chaff was sourced from a local farmer who had recently harvested and threshed his crop. Four bags (approximately 0.1 m^3) of chaff was added to each 8 m^3 batch of grout. Initially grout could be seen leaking through the tail skin brushes, before small quantities of chaff were also observed escaping through the brushes.

The amount of chaff escaping gradually reduced until both grout leakage and chaff leakage stopped completely. The use of chaff will continue until the machine enters geology that is suitable for replacement of the brushes. Preventing grout loss and silt ingress through the tail skin aided production rates significantly as cleaning of grout and silt from the ring build area and segment feeder had been a major issue.

11 CONCLUSIONS: IMPROVEMENT IN PRODUCTION

On the Sleemanabad project it had taken 6.5 years to complete just over 1.6 km of tunnel. Even after deducting almost two years of stoppages due to commercial issues the average production rates in the remaining 4.5 years equate to less than 30 m per month. The improvements described in this paper, along with mobilization of highly experienced personnel, improved maintenance regime, improved planning of production activities and improved utilization of downtime resulted in a huge improvement in production rates. During the first four months after the restart 400 m of boring was completed. Neither new technology nor additional equipment was deployed on the project. The principle reason for the improvement in production rates was the experience and skill set of the team that was mobilized. In an industry that is becoming increasingly driven by the introduction of the latest available technology it is important that we don't lose the skills that have been developed and passed down by generations of tunnellers. New technology often makes our task easier, but when operations don't go as planned, there really is no substitute for experience.

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