Tunnel Boring Machine Advance Ground Investigation in Rockburst-Prone Ground Conditions on Neelum Jhelum Project

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Abstract. This paper details the methods by which various advance ground investigation methodologies were deployed on two Tunnel Boring Machines (TBMs) working on the Neelum Jhelum Hydro-power project. The project is located in the Azad Kashmir region of northeast Pakistan, in the foothills of the Himalayan range, with overburdens up to 1,870 m and high horizontal stresses, and with complex and challenging geology. The lack of previous project experience in similar conditions, required the use of a wide variety of geological prediction methods and systems. The geological phenomenon of greatest concern was rockbursts: although expected they nevertheless presented a significant danger to personnel and equipment. The ability to predict the likelihood, location, severity and number of rockburst directly impacts upon the tunnel safety and daily production rates. The advanced prediction methods used on this project include forward probing; Tunnel Seismic Tomography (TST), TBM boring parameter analysis, in-situ stress measurements, short term rockburst prediction and continuous microseismic monitoring. This paper describes the various methodologies and how the individual data was integrated on a day-to-day basis to support TBM operations.

1 Introduction

The Neelum Jhelum hydroelectric project is located in the Muzaffarabad district of Azad Jammu & Kashmir (AJK), in northeastern Pakistan. Geographically, the area consists of rugged terrain between 500 and 3200 m in elevation within the Himalayan foothill zone known as the Sub-Himalayan Range.

The project is a run-of-river type, employing 28.6 km long headrace and 3.6 km long tailrace tunnels to cut off a major loop in the river system, transferring the waters of the Neelum River into the Jhelum River, for a total head gain of 420 m (Fig. 1). The headrace tunnels comprise both twin (69%) and single (31%) tunnels, while the tailrace tunnel consists of a single tunnel. Design capacity of the waterway system is 283 cumecs.

The project will have an installed capacity of 969 MW generated by four Francis-type turbines located in an underground powerhouse.

When construction commenced in 2008, all tunnels were to be excavated using conventional drill & blast techniques. However, it soon became apparent that with the
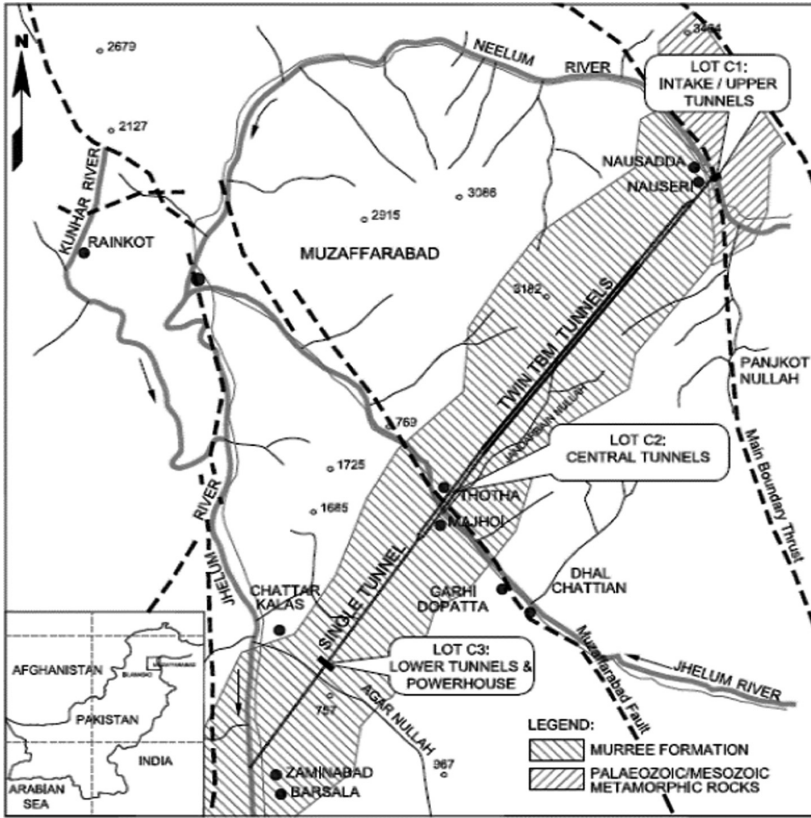
Fig. 1. Neelum Jhelum project layout showing TBM twin tunnels (in bold), major faults (dashed) and alignment geology

equipment being employed, a 13.5 km long section of the headrace twin tunnels underlain by high terrain that precludes construction of additional access adits, would take too long to excavate.

The construction contract was amended to allow the operation of two 8.5 m diameter open (gripper) hard rock TBMs to excavate some 10 km of the twin headrace tunnels (Fig. 1).

2 Geological Setting

The entire project is being excavated in the molasse-type sedimentary rocks of the Murree Formation, which is of Miocene age, and the lateral equivalent of the Siwalik Group in India. At the project site, the Murree Formation consists of intercalated beds of sandstone, siltstone and mudstone that have been tightly folded and tectonized, with generally steep bedding dips and bedding strikes rarely far from perpendicular to the

tunnel azimuth. The majority of the rock types, including the mudstones, have a significant calcareous content, typically between 20–30%.

Weakness zones and local faults are commonly observed and are invariably oriented parallel to the regional bedding strike. Sheared zones are generally developed in areas with significant amounts of weak mudstones. These "sheared mudstones", which often have a well-developed cleavage giving them a shale-like appearance, form a subset of the mudstones encountered throughout the project area and represent the poorest rock types found on the project. While shales are recognized in the literature as a major lithology within the Murree Formation, very few true shales have been identified on the Neelum Jhelum project.

The TBM tunnels are being driven in the central portion of a zone bounded by two major Himalayan faults that trend sub-perpendicular to the tunnels: the Main Boundary Thrust, a bounding fault that extends for the full length of the mountain range that approximately follows the course of the Neelum River at the upstream start of the headrace tunnels at Nauseri (Fig. 1), and a subsidiary reverse/thrust fault named the Muzaffarabad Fault that runs close to the course of the Jhelum River at Thotha. Rupture along this fault in 2005 resulted in the Muzaffarabad earthquake that caused over 75,000 fatalities.

3 Lithologies

3.1 Siltstones and Silty Sandstones

A suite of dark reddish-brown siltstones that grade to silty sandstones constitutes the most commonly occurring rock type on the project, with about 70% of the TBM tunnels excavated in this unit (as of the start of 2016). These rocks typically have uniaxial compressive strength (UCS) values in the 50–70 MPa range.

3.2 Mudstones

Mudstones, which are also invariably dark reddish-brown, represent the weakest rocks in the Murree sequence, with UCS's in the 30 to 40 MPa range, but with the sheared mudstone sub-group exhibiting significantly weaker properties. Mudstones make up approximately 9% of the total TBM tunnel length, usually occurring as discrete beds of 2 m thickness or less. A review of the geological mapping shows that approximately 16% of the mudstones encountered in the TBM tunnels exhibit shearing, indicating that these poor quality rocks are encountered over only about 1.5% of the total tunnel length, and usually in discrete bands of a few metres' thickness. Furthermore, careful mapping of a 2.3 km section of TBM tunnel invert that had been left exposed for over a year at the commencement of the drives, showed that only 3.5% of the mudstones (or approximately 20% of all sheared mudstones) showed deleterious slaking tendencies.

3.3   Sandstones (SS-1)

In contrast to the reddish-brown colouration of most of the Murree lithologies, these strongest members of the Murree sequence are usually grey, with sharply defined contacts, both of which make SS-1 sandstones easily distinguishable in exposures and drill holes. Bedding thickness is highly variable, from a few metres to in excess of 50 m. SS-1 sandstone sequences can be continuous along strike over kilometres, and are easily distinguishable in high resolution satellite images as ribs of resistant rock crossing the terrain.

Laboratory test data at the start of the project had indicated mean UCS's of about 90 MPa in this unit, but subsequent tests on samples taken from beds that had produced rockbursts have given significantly higher results. Of the 30 samples tested recently, 77% gave results in the 130–170 MPa range, with the remaining 23% exhibiting higher strengths of up to 230 MPa.

3.4   Groundwater

The SS-1 sandstones form the principal aquifers in the Murree Formation. Nevertheless, despite the fact that approximately 20% of the TBM tunnels has been excavated in this unit, the TBM tunnels have remained mainly dry, indicating limited connection to zones of recharge.

4   In-situ Stresses

In-situ stress measurements for the project were initially directed at the two locations where overburden is most critical, namely at the crossing of the twin headrace tunnels under the Jhelum River and at the underground powerhouse (Fig. 1).

Most of the results were loosely clustered around a horizontal-to-vertical stress ratio (k) of unity, even though high horizontal stresses might have been expected parallel to the tunnel axis, given that the motion of the Indian tectonic plate approximately parallels the tunnel azimuth. Indeed, this is the major principal stress orientation indicated by the World Stress Map (reference 1).

A similar stress regime to that indicated by the ins-situ stress measurements had been anticipated for the TBM. However, subsequent in-situ stress measurements by overcoring in SS-1 sandstone beds in the TBM tunnels, which were initiated to investigate the rockburst phenomenon, have indicated a 'tectonic zone' of high stresses (k up to 2.2) where the major principal stress is oriented sub-horizontally, and nearly normal to the tunnel azimuth.

5   TBM Selection

20 km of the headrace tunnel system was excavated by TBMs in two parallel tunnels. Two open (gripper) TBMs, were used to excavate this tunnel system. The most relevant successful application of TBMs in similar ground conditions was at the Gotthard Base

tunnel in Switzerland. Here, very similar Open (Gripper) type TBMs excavated 85 km of the 157 km rail tunnel system.

At the planning stage, the most significant consideration for the TBM selection was the possibility of encountering squeezing ground, with diametrical deformations of up to 500 mm predicted. This excluded many types of TBM designs because of the risk of entrapment, or the crushing of precast linings. The Open (Gripper) TBM is best suited to deal with this potential condition, due to the short length of the front shield and its ability to collapse inwards various sections of the front shield, depending upon ground conditions, and still maintain the ability to excavate forward.

The second ground condition that required mitigation in the higher overburdens and more brittle rocks was rockbursting. Again, the open (gripper) TBM configuration best allowed for implementation of actions and measures to mitigate against rockbursts.

Furthermore, given the lack of detailed site investigation data because of the high overburden, this TBM design provided the best potential for varying rock support in response to unanticipated conditions.

The designed tunnel excavation diameter is 8.5 m diameter giving a total face area of 56.75 m^2. The tunnel gradient is ascending upstream at 0.8% from SW to NE (Fig. 1).

6 TBM Advance Ground Investigation Equipment

The high overburden over the TBM tunnel alignment precluded cost-effective ground investigations during the feasibility and early construction stages, other than geological mapping of surface outcrops. This mapping was performed for the feasibility study (completed in 1997), and again in more detail at the start of the construction programme. However, given that overburden for most of the route is in excess of a kilometre, prediction of the detailed geology along the tunnel route has simply not been possible, because the tightly folded nature of the bedding prevents reliable extrapolation of geological structures from the surface. This places a greater reliance than usual on advance ground investigations from within the TBM tunnels.

It is preferable that any information on potential adverse ground conditions is obtained as far in advance of the TBM encountering the feature as possible. This allows time to assess the situation and take predetermined counter or contingency measures, allowing the TBM to traverse the adverse condition in the most efficient manner possible, with minimal impact on tunnel progress. The open (gripper) TBMs are flexible to a degree in the range of hard rock conditions that may occur in that, progress is affected when ground conditions that are lower than anticipated competence limits e.g. softer and/fractured rock are encountered. These conditions lead to overbreak in the tunnel, requiring additional and non-standard support as well as cleaning of the debris caused by the overbreak, both of which impact progress. In addition, the rockburst phenomenon represents another ground condition limit that due to its violent and unpredictable nature also impacts TBM progress. These two conditions have come to dominate advance ground investigation systems on this project.

Initially, before the high horizontal stresses that contributed significantly to the severity of the rockbursts were known about, both TBMs were equipped with two separate and independent systems for carrying out advance ground investigation. These were:

- Probe drilling
- Tunnel Seismic Tomography (TST) System

Later in the project when the rockburst zones were encountered, additional ground investigation systems were installed in each TBM tunnel, these were:

- Overcoring for in-situ stress determination
- Microseismic monitoring
- Rockburst prediction based on point load strength determinations

Figure 2, shows the relative overburden along the tunnel alignment (upper portion), and the extent, in plan, of employment of various investigative techniques (lower portion).
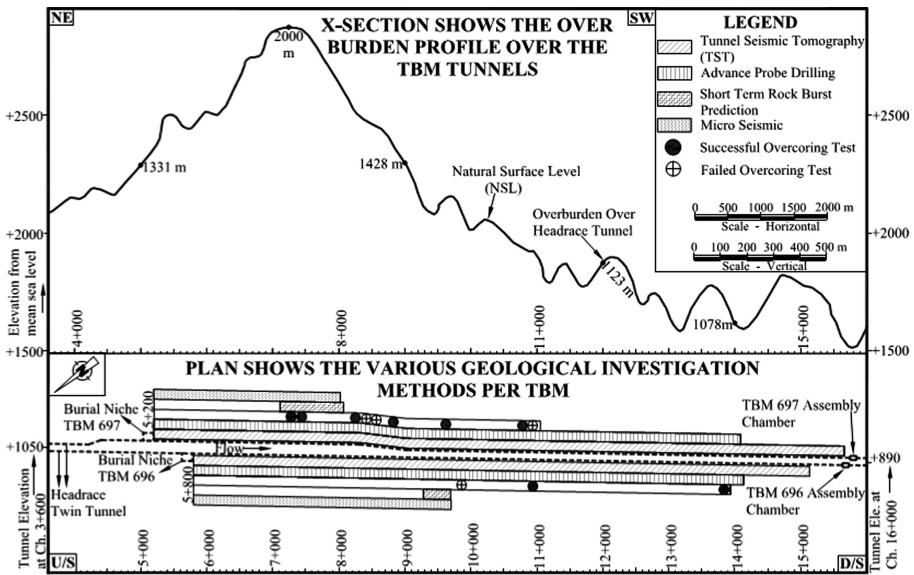

Fig. 2. TBM tunnel alignment and over burden with locations of ground investigations method

6.1 Probing

The design of any probe drilling equipment on a TBM needs to take into considerations the following criteria.

- Flexible and easy to use.
- Effective collaring or starting of probe holes, which is complicated by the shallow entry angles.

- Collaring as close as possible to the tunnel face, avoiding wasteful drilling above already excavated tunnel.
- Ability to move 360º if possible around the tunnel circumference.
- Spare capacity i.e. more than one probe drill to allow simultaneous probing or redundancy in case of breakdown.
- Adequately sized drills with capacity to drill at least 60 m long holes.

Each TBM was equipped with two different types of probe drills, both of which are located at the front of the TBM. One is in a fixed position at the tunnel crown 18 m from the face, and is capable of drilling holes above the shield up 7º from the centerline while the second probe drill is located on a rotary track that enables it to move the full 360º around the tunnel circumference. The probe drilling holes can also be used for any ground improvements such as pre-excavation grouting that may be required.

The principle of probe drilling is that there is always an overlap with the previous hole, so that in no circumstance does the TBM excavate into ground that has not been probed.

The advance information that can be obtained from a probe drilling is:

- Rate of penetration – high indicates weak rock and low indicates hard rock.
- Water inflow.
- Colour of rock chippings – at Neelum Jhelum, grey indicates harder sandstone and red indicates weaker mud rocks.
- Voids and fractured/faulted ground indicated by rapid fluctuations in penetration rate, grabbing of drill rods, and possible loss of flush return.

The information required most critically in the first 2.3 km of TBM tunnels was the presence of softer and or fractured rock that would result in overbreak in the tunnel. During this stage the probe results correlated 80% with the observed geology. After 2.3 km of tunnel excavation, the rockbursts commenced and the prime object became to locate and record the thickness of the SS-1 sandstone beds that are the source of the majority of rockbursts. During this stage the probe results correlated 95% with the observed geology.

7 Tunnel Seismic Tomography (TST) System

The TST system has been developed by Beijing Tongdu Engineering Geophysics Ltd. Corp.

This observation system relies on a series of receivers inserted into predrilled holes on both sides of the TBM tunnel (Fig. 3). A shot is then initiated (Explosive or Electrical) which initiates seismic waves. The reflection of these seismic waves from changes in geological strata are the collected by the receivers. Data processing integrates seismic migration image, velocity scanning and structural grain analysis with travel time inversion imaging, specially designed for tunnel prediction in areas of complex geological structures.

TST is designed to act as a long-range or middle-range forecasting tool, to predict the geological conditions 100–150 m ahead of the TBM. The geological features include, fault structures, interfaces of different type of lithology and rock engineering factors; TST will also highlight the possible areas that may lead to rockbursts.
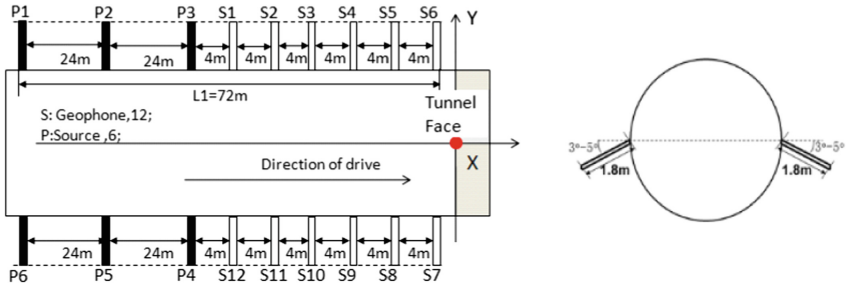
Fig. 3. TST general arrangements for drilling holes (Courtesy Beijing Tongdu Engineering Geophysics Ltd. Corp)

7.1 TST Hardware

TST includes Seismograph, Geophones, Signal Separator, Sparker and data cables (Fig. 4).
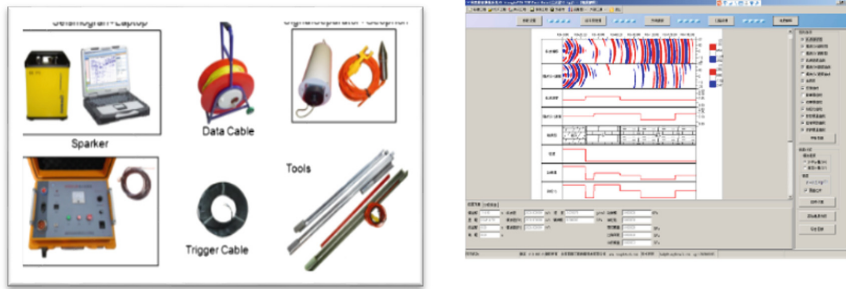
TST Hardware.   TST Software Output

Fig. 4. TST hardware and software (Courtesy Beijing Tongdu Engineering Geophysics Ltd. Corp)

7.2 TST Software

TST Data Process Software was developed by the manufacturer (Fig. 4). The system includes: System Setup, Signal Preprocess, Wave Separation, Velocity Analysis, Geological Structure Immigration.

7.3 TST Typical Report

An individual numbered report is produced for each TST operation and should ideally be available within 12 h of the completion of the site operations. The report along with the written interpretation consists of 3 main sections (1) the seismic mitigation image. Here the data is interpreted by adjusting the filtering parameters and an image of

significant changes in rock integrity produced. Typically the colours of red and blue are used to denote change boundaries of rock integrity. (2) Velocity through the rock. The higher the velocity the more competent the rock and vice versa. (3) Summary of findings with a prediction of rock integrity with approximate chainages.

7.4   Probe and TST Integration

At the TBM the typical arrangement for implementing a TST survey is every 100–110 m whilst probing is every 45 m (time constraints for production). Both methods have a standard format and the final reports for both techniques are produced within half a day, resulting in both reports being readily available at the TBM for the shift staff to use for day-to-day excavation activities.

In parallel, the site office produces a summary report based on the individual TST report, probe data and observed geology as it is acquired and then carries out a review for any correlation between predicted ground types and observed records recorded as the TBM advances (Fig. 5).
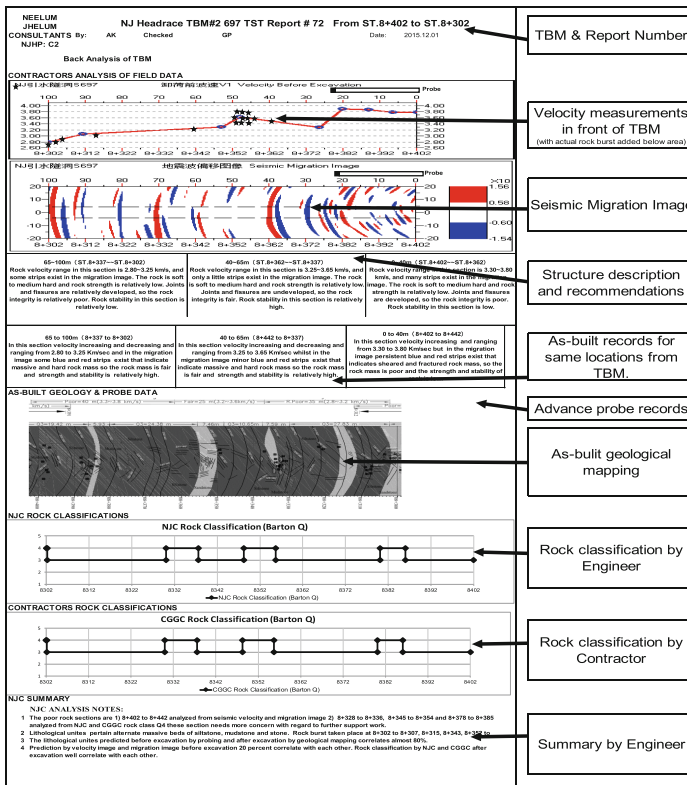

Fig. 5. Typical summary report of TST Table 1. Percentage correlation of TST reports with observed geology

Over the course of the project all TST, probe data and observed geology has been analyzed for the lead TBM for correlation. From the start of TBM tunneling and for the first 2.3 km the significant issue was that of softer and/or fractured ground conditions, from 2.3 km on rockbursts became the significant geological issue. Table 1, gives a summary of the comparison reports.

Table 1. TST correlation with different strata.

Correlation	Average correlation values	Range of correlation values
TST wave velocity and observed geology (soft/fractured ground)	66%	29–72%
TST wave velocity and observed geology (rockburst)	56%	20–80%

During the early sections of the lead TBM tunnel there was correlation between TST wave velocity observed geology, which had resulted in overbreak conditions. This portion of the tunnel did not experience rockbursts and was supported according to the rock class requirements. When rockbursts commenced, the tunnel support was increased and much heavier support was installed. The principle support element being the steel ring beams installed every 1.2–1.6 m with increased shotcrete thickness. In the rockburst section this correlation decreased, the heavier support may well have contributed to this reduction.
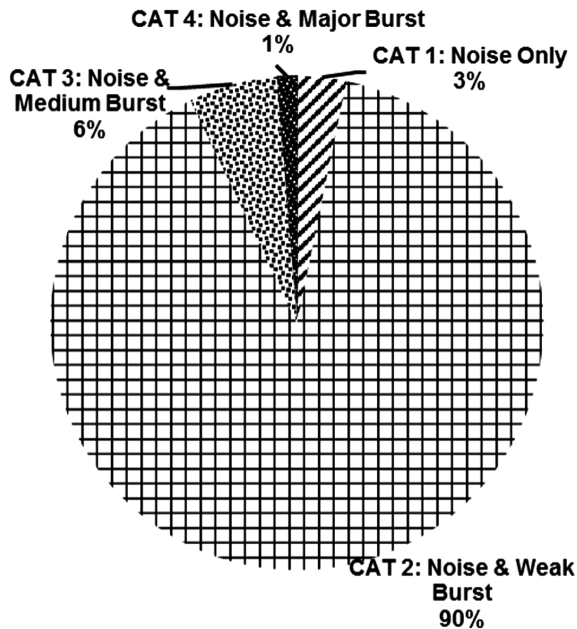
8   Rockbursts

No rockbursts were encountered in the initial 2.3 km of either TBM tunnel. After this point rockbursts in both tunnels commenced and gradually increased in number and magnitude.

The Canadian Rockburst Support Handbook defines rockbursts as "damage to an excavation that occurs in a sudden or violent manner and is associated with a seismic event." This definition is widely used in the mining industry, but was considered too specific for the Neelum Jhelum project. Consequently, a rockburst does not necessarily imply that damage has been caused to the tunnel excavation or the TBM: Instead, there may have just been a noise heard that would indicate release of seismic energy. This broader definition was adopted because even small rockbursts can affect the operation of the TBM. The rockbursts have been categorized as follows:

- CAT 1: Noise only: a slight popping sound is heard as energy is released but there no damage to the rock support or ejection of rock

- CAT 2: Noise and weak rockburst: a popping sound is heard as energy is released and there may be some light damage to the rock support and surrounding rock (e.g. cracking in the shotcrete and rock)
- CAT 3: Noise and medium rockburst: loud popping sounds are heard as energy is released and there may be spitting, spalling or shallow slabbing to the rock support and surrounding rock
- CAT 4: Noise and major rockburst: loud sound similar to an explosion, violent ejection of rock into the tunnel and severe damage to the installed support

The summary of the various categories of rockbursts are shown in Fig. 6.

Fig. 6. Chart of Rockbursts by category

Rockbursts, as a phenomenon, were first encountered in the mining industry and so much of the literature relates to rockbursts encountered in deep mining excavations. Traditional mining methods such as drill and blast do not require a high concentration of plant and equipment to be always present near the excavation face. This contrasts with TBM excavation in which complex equipment, with accompanying staff, is continually in close proximity to the excavation face. The TBMs on the Neelum Jhelum project are nearly 200 m long.

When rockbursts commenced, probing and TST results were analysed for location of SS-1 sandstone beds since these were the main source of rockbursts. Additional efforts were then made to analyse the TBM boring parameters as an advance ground investigation tool to identify potential rockburst conditions.

The most severe rockburst on the project occurred on 31st May 2015 on the trailing (by 180 m) TBM. This event, which equated to a 2.4 magnitude earthquake severely damaged the TBM, with the recovery operation taking 7.3 months to return it into operational condition. An unusual set of geological conditions, with the bedding strike locally running parallel to tunnel direction, and unrecognized SS-1 sandstone beds in the sidewalls masked by siltstone, significantly contributed to the severity of this rockburst.

After this event, it was clear that additional ground investigation systems would need to be implemented (and others already ordered would have to be accelerated) to significantly improve the quality of identification of rockburst-prone locations ahead of each TBM. These systems would then allow the TBM crews to implement rockburst countermeasures aimed at lessening the potential rockburst effects, with the added benefit of increasing the crews' confidence by the identification and consequent mitigation of potentially hazardous conditions.

9 Correlation of Rockbursts with TBM Operating Parameters

When rockburst activity became a regular occurrence, an effort was made to identify correlations between boring data and the rock mass conditions encountered, in particular those associated with rockbursts. The findings of the analysis were adopted for guidance in determining the operating parameters of the TBM which would identify strata where the likelihood of rockburst activity was high.

There are five main TBM boring parameters to consider:

- Thrust force (F)
- Torque (T)
- Penetration rate (P)
- Advance speed (V)
- Cutter head Rotation

The TBM data acquisition system measures Thrust Force, Torque, Cutterhead rotation and Advance speed directly from sensors. Whist the Penetration rate is a calculated value obtained by dividing the advance speed by the Cutter head rotation.

Every rockburst time was recorded and then plotted against four of the above TBM boring parameters. The parameters have also been subdivided into bands associated with ground conditions. The results of this analysis are shown in Fig. 7.
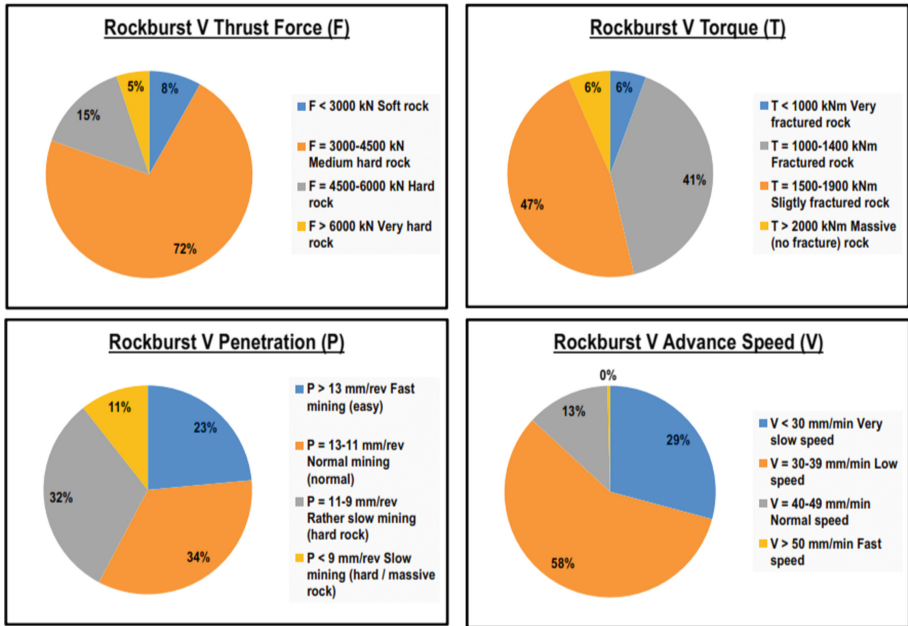
Fig. 7. Rockbursts recorded against TBM parameters.

9.1 Thrust Force

Thrust force is the force applied by the thrust cylinders to the cutterhead to cut the rock when excavation starts. The value of the thrust force depends on the strength (hardness) of rock mass i.e. the harder the rock mass, the greater the thrust force needed to be applied by the TBM operator to excavate it. The average ranges of the thrust force in mudstone, siltstone and sandstone are shown in Table 2.

Table 2. TBM thrust force for different rock types on Neelum Jhelum project

Rock type	Thrust force (kN)
Mudstone	F < 3000
Siltstone	2750 < F < 3750
Sandstone	F > 3500

9.2 Torque

Cutterhead torque is the power from the cutterhead motors that rotate the cutterhead in order to crush and cut the rock mass at the cutterhead. The torque value depends on the structure and roughness of rock mass. If the rock mass is soft, fractured and/or the surface smooth the torque value will be low. However, if rock mass is hard, massive, and/or surface rough, the torque will be high, because of the resistance of the rock mass

to the cutter discs arranged around the cutterhead. Furthermore, if the rock in front of the TBM cutterhead collapses, torque value also will increase. The average ranges of torque in mudstone, siltstone and sandstone are shown in Table 3.

Table 3. TBM torque for different rock types on Neelum Jhelum project

Rock type	Torque (kNm)
Fractured	T < 1000
Medium	1000 < T < 1500
Massive & rough	T > 1500

9.3 Penetration

Penetration rate is a reflection of the condition of rock mass, the hardness & structure, the harder the rock the lower the penetration if other operating parameters are kept constant and vice versa.

9.4 Advance Speed

If the advance speed is too high in weaker ground then the spoil conveyance system e.g. Conveyor belt can become over loaded or even blocked. The support installation can also impact advance speed since it is not good practice to advance fast and then stop abruptly whilst support is installed. Each project develops its operational boundaries. This parameter is directly controlled by the TBM operator in accordance to the condition of rock mass, machinery, and transporter of spoil material.

9.5 Cutterhead Rotational Speed

Rotational speed (or speed of rotation) is defined as the number of revolutions the TBM cutterhead completes per minute. The rotational speed directly influences the size of the excavated tunnel material. The rotational speed should be controlled in accordance to the rock mass criteria, i.e. rock hardness and rock structure. Rotational speed should be increased if the rock mass is getting harder, and should be decreased in more fractured rock mass. This is important to avoid any damage to the cutter discs and/or damaging the tunnel perimeter by plucking. If the rock mass becomes harder, the TBM also needs to increase the thrust force to achieve required penetration, as explained above. This also leads unavoidably to more pressure on the TBM cutter discs. To try and balance thrust force and torque, rotational speed should be increased. If this is not done, then the TBM cutter discs could possibly block up and stop turning, resulting in damage to the cutter disc by becoming flat. In a softer rock mass or fractured ground, rotational speed should be decreased since too high a speed will probably result in spalling or overbreak.

The relationship between rotational speed, thrust force and torque are shown in Tables 4 and 5.

The time of the rockburst was recorded and compared against the particular TBM operating parameter. All the above data was then plotted against the observed geology and analysed for correlation with the two significant geological issues of (a) soft/fractured rock and (b) rockbursts.

Table 4. TBM thrust force and rotational speed on Neelum Jhelum project

Thrust force (kN)	Rotation speed (rpm)
F < 3000	rpm < 3.0
3000 < F < 4000	3.0 < rpm < 3.5
4000 < F < 5000	3.5 < rpm < 4.5
F > 5000	rpm > 4.5

Table 5. TBM torque and rotational speed on Neelum Jhelum project

Torque (kNm)	Rotation speed (rpm)
T < 1000	rpm < 3.0
1000 < T < 1500	3.0 < rpm < 3.5
T > 1500	rpm > 3.5

9.5.1 Summary

The conclusion of the analysis and examination of all boring parameters at the locations where rockbursts occurred indicate the way TBM is operated appears to have little to do with influencing rockbursts. A rockburst will happen when the rockburst conditions are met, i.e. (1) amount of energy accumulated around the perimeter is sufficient, (2) direction of energy, towards weak zone, and (3) line or zone of weakness to release energy and tangential stresses exceed the compressive strength of the rock mass. If all three of these factors reach a certain threshold, then a rockburst will happen, whatever the TBM operating parameters; it will make little difference if the TBM is advancing fast or slowly.

However, by analyzing the boring data there are some trends which can be used to indicate the likelihood of a rockburst occurring.

- Rockbursts occur in very hard and brittle rock masses that also have few fractures (i.e. massive). These parameters correspond to thrust forces from 3000 kN to 6000 kN, and torques from 1000 kNm to 1900 kNm. Recognition of these parameter ranges alerted TBM operators to the presence of rock masses likely to cause rockbursts. This is more important than may first appear, because while probe drilling identified the presence of an SS-1 sandstone bed, it rarely gave an indication of the degree of fracturing. In contrast, the TBM cutterhead by the very nature of its

design and operation, provided instant identification of the rock mass quality of the ground at the cutterhead that could be directly correlated with its rockburst potential.

- Rockbursts will not happen in soft rock masses or a highly fractured rock mass, i.e. those that result in thrust forces below 2750 kN, and torque below 750 kNm.
- Counter intuitively, rockbursts do not appear to occur in very hardest and most massive rock masses, where the applied thrust force and torque are above 7500 kN and 2500 kNm respectively. This may be because the rock mass is simply strong enough to withstand the imposed tangential stresses.

A note of caution needs to be added on the plotting of rockbursts against the TBM boring parameters data taken from the TBM data acquisition computer. The data shown is the average data throughout the TBM operation for a single stroke (one advance cycle that typically takes 45 min). In contrast, the rockburst is a sudden event lasting milliseconds.

10   In-situ Stress Measurements by Overcoring

The decision had already been made to implement stress measurements by overcoring to gain a better understanding of the rockburst phenomenon when the severe rockburst of 31st May 2015 occurred. This event resulted in the acceleration of the implementation of this technique. The Institute of Rock and Soil Mechanics (IRSM) from the Chinese Academy of Sciences was contracted to perform the overcoring tests in the TBM tunnels.

Ten locations were initially proposed for overcoring tests, concentrating on the SS-1 sandstone beds where a major rockburst had occurred. For this purpose eight locations were selected from the leading TBM and two from the trailing TBM. At eight of these locations, the rockbursts had resulted in damage of different categories to the TBM and tunnel installed support, and the remaining two locations were selected on the basis of overburden depth.

11   Number of Tests at Each Location

After discussion with IRSM, it was decided to perform three tests in a single borehole at each location, following IRSM's standard operating procedure. The minimum depth specified for the first test was 17 m, which is twice the TBM tunnel diameter. Each overcoring test required a 0.5 m long section of borehole.

12   Instrument Used for Stress Measurement

The Hollow Inclusion cell (HI cell) was used for the overcoring tests. This instrument measures micro strain using 12 strain gauges during and after the overcoring test. The data acquired is recorded on a laptop located at the test location. The elastic properties of the rock are measured using a biaxial test on the overcore specimen. During the

biaxial test, the applied stresses are increased from 0 MPa to 20 MPa at intervals of 5 MPa and then unloaded to 0 MPa gradually. From this data, the in-situ stresses can be calculated by applying Hooke's law.

12.1 Core Disking

Core disking was observed during the drilling of a number of bore holes in sandstone in both TBMs under different overburdens in Fig. 2 the overcore failed tests were due to core disking. It is a process in which drilled core breaks into disks with uniform spacing and shape (Fig. 8). Core disking is indicative of high stresses in the borehole that were released during drilling of core. The bore holes in which core disking was observed have higher stresses compared to the bore hole where core disking was not observed and the overcoring test was performed successfully.

Fig. 8. Core samples showing disking

Clearly, measuring the overcoring technique relies on the core staying completely intact. The presence of a single discontinuity, even if it is healed, can disqualify a test. Consequently, the breaking up of drill core into small disks totally precludes any overcoring tests. In the lead TBM, four overcoring tests were terminated due to core disking in bore holes. Whereas in the trailing TBM, one bore hole was terminated due to core disking. In all these bore holes, the core disking commences from 10 m to 14 m and continued to the end of the hole.

12.2 Summary

The overcoring results shows that the maximum principal stresses are sub-horizontal, and act from northwest direction, which is perpendicular to the tunnel alignment. These are the tectonic stresses. These stresses range from 73.9 MPa to 141.2 MPa. The intermediate principal stresses are parallel to the tunnel alignment.

13   Short Term Rockburst Prediction (Uniaxial Compressive Strength)

The aim of short term rockburst prediction was to attempt to link various geotechnical parameters identified in the already excavated tunnel immediately behind the TBM shield with other parameters. IRSM staff recorded various geotechnical parameters and after analysis issued rockburst prediction reports on a daily basis for both TBMs. The rockburst prediction reports covered 12 m of tunnel section, 6 m excavated section over the shield of TBM and 6 m unexcavated section in front of TBM cutterhead.

13.1   Parameters for Rockburst Prediction Analysis

The following geotechnical parameters of the excavated ground were used in the short term rockburst prediction analysis.

- Lithology.
- Uniaxial compressive strength (UCS).
- Geological Strength Index (GSI).
- TBM boring parameters (Cutterhead thrust, Penetration and Torque).
- Rock density.
- Uniaxial tensile strength of rock units (Laboratory test).

On the basis of numerical calculation and analysis of geotechnical parameters, the rockburst prediction was categorized into slight, medium and severe rockburst.

13.2   Effectiveness of the Short Term Prediction Technique

The short term rockburst prediction reports were produced and discussed at the daily meetings over the period January – April 2016. During this period many attempts were made to integrate the results with other forms of advance ground investigation and produce a concise rockburst prediction for both TBMs. The results when compared to other investigation methods such as the continuous microseismic monitoring, did not enhance the information already being supplied. Therefore this advance ground investigation method was stopped.

14   Microseismic Monitoring

The project team was concerned about placing too much reliance on one system. Consequently, it was decided to investigate prediction techniques that have an established track record, and microseismic monitoring was such a technique. It was anticipated that using the short term rockburst technique and microseismic technique in parallel would obtain the best possible result in predicting rockbursts.

IRSM, the institution that provided the staff and equipment for the stress measurement overcoring, and for the trial of the short term rockburst prediction, also

specialized in providing microseismic monitoring services. IRSM employed the same technique for the Jinping II project which utilized similar TBMs and experienced extensive rockbursts. Several technical papers on microseismic monitoring (Feng et al. 2012, 2015) were researched and contact was made with IRSM to install similar monitoring systems on the two Neelum Jhelum TBMs (Fig. 9).
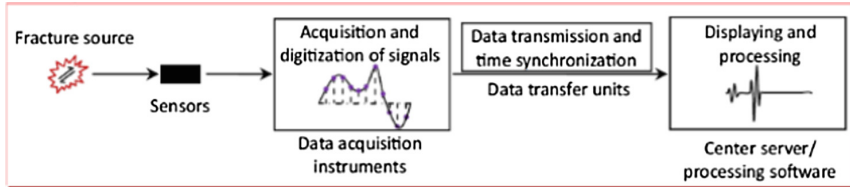

Fig. 9. Microseismic monitoring equipment installed on NJ Project (Courtesy of IRSM)

This paper does not go into detail concerning the development of microseismic monitoring, which is adequately covered by various technical papers by Professor Xia-Ting Feng. The principle of microseismic monitoring is the recoding of the fracturing process in rock masses caused by microseismicity in the surrounding rock. A series of sensors is positioned in the tunnel behind the TBM. A typical configuration is 3 sensors in an array and 3 arrays located between 8 and 60 m from the tunnel face. Theses arrays are moved forward as the tunnel advances. The sensors record the fracture data and transmit to an acquisition systems which digitizes the data. The digitized data is then transmitted to a central server and processed by IRSM software.

The outputs on a daily basis produced from IRSM's microseismic monitoring are shown in Figs. 10 and 11 along with a written statement on rockburst level and
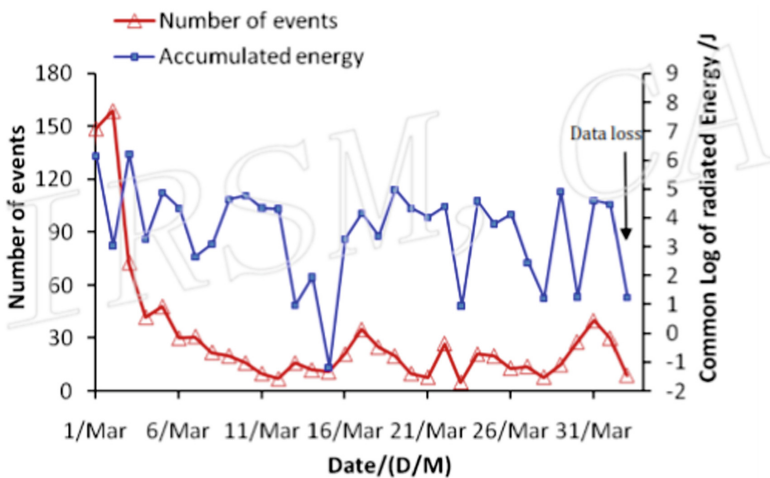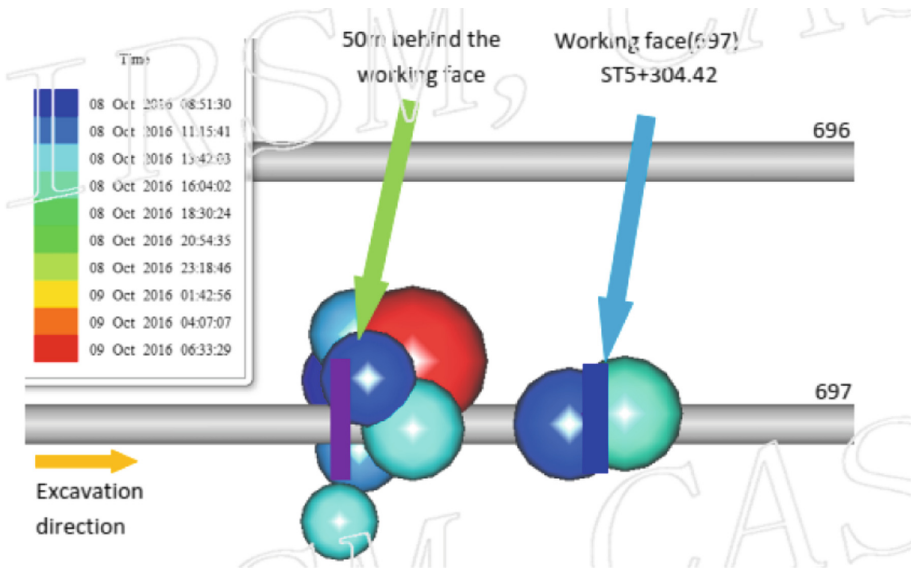

**Fig. 10.** Number and accumulated energy against time (Courtesy of IRSM)

Fig. 11. Temporal-spatial distribution of microseismic activity. Colour and size of sphere indicating time and magnitude of event *(Courtesy of IRSM)*

suggestions for support activities. Figure 10 provides the data on (1) number of seismic events recorded and (2) accumulated energy per event. These two sets of values are produced on a rolling daily basis. This data provided evidence of increasing likelihood of rockburst by increasing numbers of events. Whilst the trend of decreasing number of events recorded and increased average energy per event would indicate the possibility of a larger category rockburst. Figure 11 shows the temporal-spatial distribution of the recorded events. This information is recorded in relation to the TBM working face. Microseismic activity increasing on one the left or right side of the TBM tunnel would help decide priorities for tunnel support or location of counter measures With regard to microseismic monitoring, the authors of this paper aimed to integrate all advance ground investigation methods and expand on proven systems.

14.1   IRSM Monthly Report

In the same manner as the correlation report for TST and probing, all the above microseismic data along with actual rockbursts recorded at the TBM and the observed geology was plotted on a one page summary report. This allowed back analysis and discovery of trends and patterns in microseismic recorded events and conditions observed in the TBM tunnel. A microseismic summary report was produced on a monthly basis (Fig. 12).
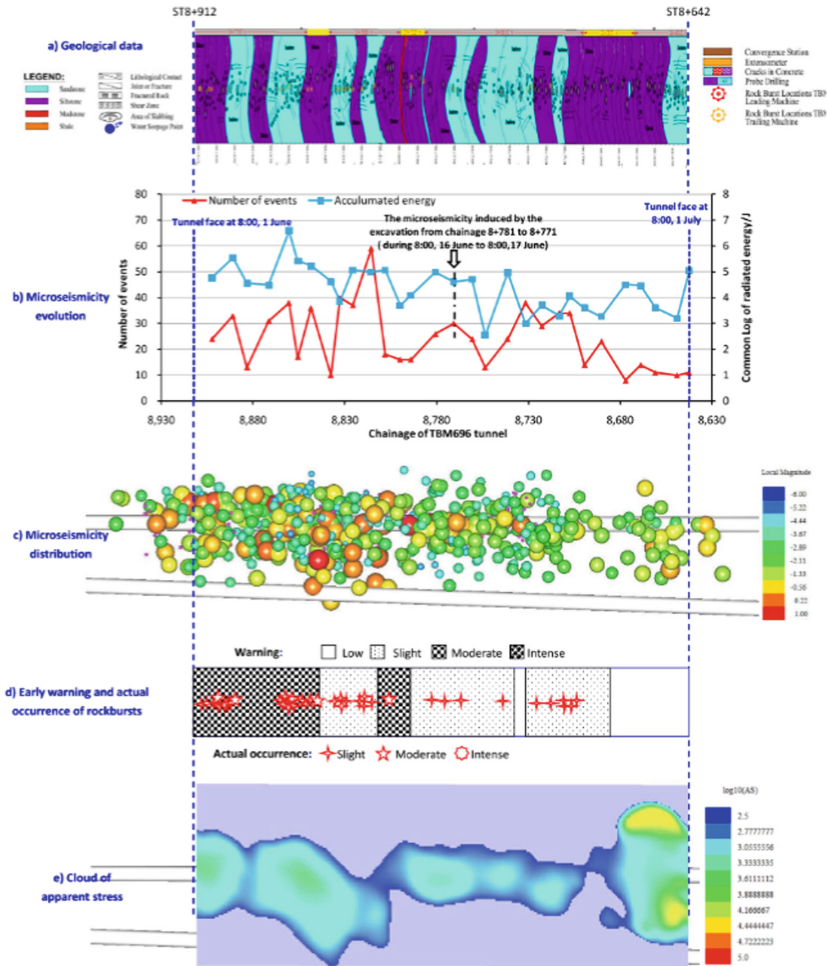
Fig. 12. Summary report for microseismic activity against observed geology for June 2016 (*Courtesy of IRSM*)

A scale mark of 50 m was added to the Temporal-spatial distribution of the microseismic activity chart. This allowed a detailed analysis of how many microseismic events took place in (1) in front of the TBM excavation face (2) from the TBM face back along the tunnel for 50 m and (3) beyond 50 m from the tunnel face.

14.2 Seismic Event Location

Further analysis was carried out to separate the location of the microseismic events into the following locations (1) Open side of TBM tunnel, (2) Above TBM Tunnel and (3) Pillar side of TBM tunnel.

14.3   Microseismic Events and Recorded Rockburst Events

Microseismic monitoring records the full range of seismic events; from those that cannot be heard by the human ear to the severe rock bursts.

14.4   Summary

Microseismic monitoring is an important mechanism for attempting rockburst prediction. However, this science is still in the development stage. The systems employed and the subsequent on-site adaptations have greatly increased the confidence in the prediction probability for a rockburst event. The day to day analysis uncovered more trends and patterns which have allowed both TBMs to advance safely and efficiently in rockburst prone ground conditions. During this stage the microseismic results correlated 88% with the observed geology in which rockbursts occurred.

15   Intergrating All the Data

This paper illustrates the variety of advance ground investigation methods that are available for use in a TBM tunnel to predict the geology in front of a TBM. They include established methods such as probe drilling and newer methods still undergoing development such as microseismic monitoring. The key issue is how to integrate these methods in such a way that they complement each other and contribute to a greater and more accurate understanding of ground conditions and specific geological entities in front of the TBMs that could impact progress e.g. Soft/fractured ground and rockbursts. The project team built on the basis of increasing the understanding by correlation of the observed geology with all the advance ground investigation methods implemented on the project.

The basic requirement is well planned shift/activity reports which provide in a clear and concise manner all the information required to carry out initial data interpretation and then upper level correlation.

Correlation with observed geology remained continuous throughout the project for Probe with TST and TBM boring parameters, the only modification was the change in focus on the correlation with overbreak and rockbursts.

The initial integration involved the probe drilling, TST data with the observed geology. The TST gave an indication of changes in rock integrity that could be checked when a probe was drilled in the same location. The observed geology in the tunnel would then confirm or not confirm any correlations between the two systems.

The TBM boring parameters were plotted against the observed geology. This resulted in the identification of operational bands within which balanced TBM equipment ware and tunnel excavation profile. This information was then available whilst the TBM was excavating.

When rockbursts commenced, it was beneficial that correlation of two investigative techniques had already been established and was in regular operation. This facilitated quick implementation of new geological investigation systems to the adopted formatto identify potential rockburst locations, and thus guide the application of counter or contingency measures.

The overcoring tests to determine the in-situ stresses primarily measured at locations of rockbursts, while not a routinely applied investigative tool, discovered higher than expected horizontal stresses. This information was significant and directly contributed to the application rockburst support.

Subsequent advance ground investigation methods attempted were short term rock burst prediction by point load strength testing, and continuous microseismic monitoring. Both methods commenced at similar times but the continuous microseismic monitoring proved to be the more reliable of the two methods. While the short term rockburst prediction system, which was unable to determine conditions ahead of the face, was dropped due to low than required correlation with rockbursts.

After adoption, the data generated by the microseismic method was correlated with the probe and TST data with the specific aim of identifying rockburst-prone locations ahead of the face. This correlation proved very successful. This led to further analysis to indicate any trends in location along the tunnel and across the tunnel which allowed safety recommendations to be issued concerning certain locations within the TBM.

All the above data was made available at the 08.30 am morning meeting, which allowed discussion and recommendations to be developed before the start of tunnel excavation at 12.30 pm. After the morning meeting the new data would be added into the particular correlation process for analysis, results being fed back into the following day's morning meeting.

16   Conclusions

There is no single advance ground investigation method that can completely predict the ground conditions in front of a TBM. There are however a number of systems that can give an insight into a particular aspect of the geological conditions that lie in front of the TBM. When the results of these methods are integrated, the prediction can be comprehensive.

The key issue was the cross correlation with other methods and observed geology in a standard format which allows the identification of patterns and trends. This may well be unique to this project. Some of the methods used were more successful than others, but various methods have been tried and implemented.

With particular regard to rockburst prediction it is still a developing science and on the project the use of every available advance ground investigation method yielded pertinent information which helps facilitate an increasing ability to predict the probability of a rockburst.

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