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Role of Rock Excavation Tests for Predicting TBM Performance

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ABSTRACT

TBM tunneling for the metro, road, rail, hydel and irrigation sectors has grown phenomenally in the last decade with the hydel and irrigation sectors dominating the total demand for tunneling. The road sector also has a demand close to 300 km of tunneling by 2026. The majority of the tunnels are in hilly terrain through varied geology, posing several challenges. Inadequate information on the strength and abrasivity parameters of rocks subject to disc cutter loading along with other structural and stress related issues have mainly contributed to TBM stoppages. Projects also have got unduly delayed, putting the TBM business at risk. TBM tunneling technology has made significant strides with advanced diagnostics viz. Tunnel Seismic Profiler and collaborative manufacturing in India. It is expected that their application and "population" will grow at a rapid pace in the coming future. Predicting tunneling rates has been a major challenge and the need of the hour considering the huge investment and risks involved. Most of the developed performance prediction models utilize specialized rock excavation tests. These tests have proved useful for rational selection and operation of TBMs the world over. This paper presents the development of some indigenous and specialized rock excavation testing capabilities for Machine Tunnelling at IIT (ISM) Dhanbad and their use for TBM tunneling rate prediction. Using punch penetration tests coupled with Linear Cutting Tests on rock blocks can help estimate the TBM cutting rates with confidence. However, suitable correction factors at the field scale may be necessary for fine tuning the method.

Keywords: TBM Tunnelling; Rock excavation tests; Brittleness; Drillability; Penetration rate; Advance rate.

1. INTRODUCTION

Tunnel boring machines provide a fast and smooth excavation with least excavation induced damage when compared to drill and blast systems. Oflate application of these engineering marvels has taken deep roots in Indian tunnelling industry. This has also got into an accelerated mode due to collaborative manufacturing and assembling plants coming up in India. Today we have all major TBM manufacturers namely Herrenknecht, Robbins, Seli, Terratech etc, excavating tunnels using a variety of TBMs operating in hydro-electric, irrigation, road, rail and other strategic sectors. Considering the typical challenges faced in dealing with varied geology these machines could not gain wider acceptance and this calls for a complete understanding of the rock excavation feasibility tests both at lab and field scale. Lower TBM progress and higher cutter wear in quartzites was mainly due to its strength and abrasivity variations. Good experiences in projects like Kishenganga have pushed the tunnelling think tank to choose machines on a wider scale. However, successful application of these machines requires an in-depth understanding of various rock excavation response tests.

2. TBM TUNNELLING

Tunnelling using tunnel boring machines is in full swing in some of the hydel and irrigation projects, some got completed and a good number in progress. A few cases of TBM stoppages are also seen in the past and these are mainly due to geological variations and cover depth induced stresses. Seepage of water also has been one of the major issues throwing a larger challenge. Application of TBMs for HRT construction is quite common and some of the tunnels completed and in progress using TBM technology are presented in Table 1.

Table 1 – TBM applications in India with uncertainties encountered (Vishnoi, 2012)

Project	Uncertainties	Outcomes
Dulhasti Hydel Project, NHPC Ltd., Kishtwar, J&K	• Unfavorable geology through shear zones, high water seepage and incidences of roof collapse. • Tunnel failure during construction. • TBM got buried.	• Excess time for construction
Parbati Stage II Hydro Electric Project, NHPC Ltd., Kullu, H.P.	• Unfavourable geology with water inflows and rock bursts • high strength rocks with varied abrasiveness	• Inordinate delay in completion.
Veligonda Irrigation Tunnel,	• Varied geology, Fractured rock • High strength rocks • Fault gouge	• Low to high penetration • Varied cutter consumption
Tapovan- Vishnugad Hydro Electric Project, NTPC Ltd., Joshimath, Uttarakhand	• Water seepage and excess cutter wera	• Delayed construction

Considering the risks discussed above, high initial cost and delay in commissioning due to site constraints, it is necessary to evolve suitable test methods and prediction models for rational selection of TBM. Many prediction models for TBM performance have been proposed by many authors and the prominent ones, based on rock/rockmass parameters, are CSM (Rostami, 1997), NTNU (Bruland, 1998), and Q_{TBM} (Barton, 1999). Predicting TBM performance from rockmass properties was suggested by Yagiz (2008). The use of punch penetration index for fixing the optimum thrust for a given penetration helps in rational use of TBM capacity. Specific energy based estimation models are also popular as they consider the proto-type rock block tests that can simulate the cutting behaviour of disc cutters more closely to actual situations. Fixing the thrust and RPM of TBM in a given formation is the most vital exercise and as mentioned PPI and LCR based cutting tests can help in this significantly.

3. ROCK EXCAVATION TESTS FOR TBM APPLICATION

Considering the need, relevant test setup were designed, fabricated and used for generating relevant data for predicting the cutting performance using TBMs (Murthy and Raina, 2020), Key rock excavation tests for TBM performance prediction are described in the following sections:

3.1 Brittleness Index (BI)

The ability of rock to resist crushing by repeated impacts is determined in brittleness test. Density for each rock sample is determined and a standard sample size in proportion to a base density of 2.65 gm/cc is selected.

3.1.1 Test procedure

The brittleness value, $S_{20,}$ indicates the magnitude of energy to crush the rock. A sample size of 500 grams of broken rock sample, within a size range of 16 and 11.2 mm, is hammered with a 14 kg weight for 20 times from a height of 25 cm. The Brittleness Index is computed from the material weight that passes the 11.2 mm size, with an average value of 3 to 4 such parallel tests. The test apparatus and different steps of testing are presented in Fig. 1 and Fig. 2. Test results are shown in Table 2. Sample size is determined as given below:

$$\text{Weight of sample (in g)} = (\text{Density of rock sample}/2.65)*500 \tag{1}$$

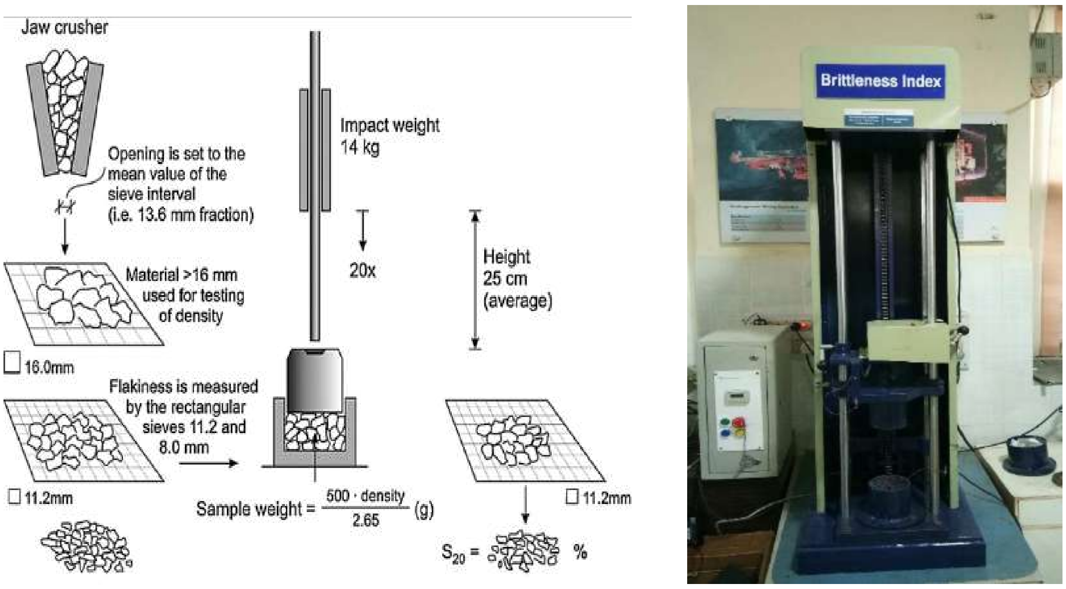
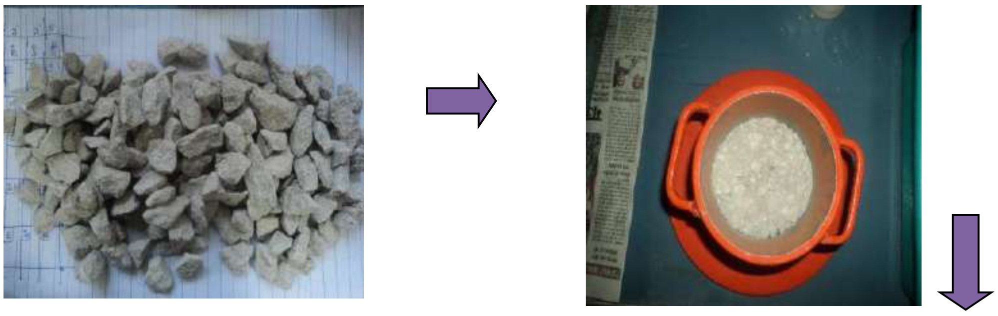
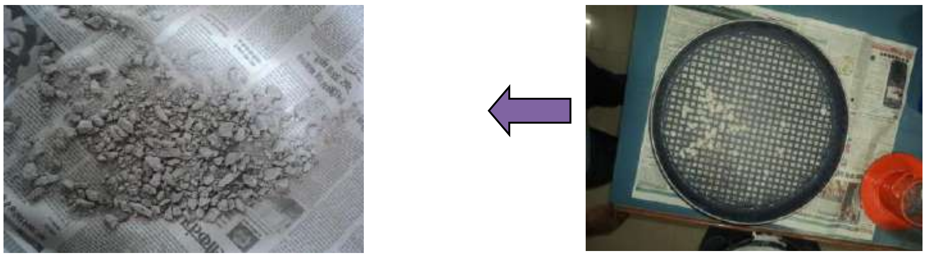


Figure 1 - Schematic of brittleness test (Dahl et al., 2012) and brittleness test apparatus



Initial sample of size between 11.2 - 16 mm

Crushed sample after 20 impacts of 14 kg wt.



Sample which passed through 11.2mm sieve

Sieving with 11.2 mm sieve size

Figure 2 - Different steps of brittleness test

3.1.2 Test results

Typical test results of Brittleness are presented in Table 2.

Table 2 - Test results of brittleness index (BI)

Rock Type	Initial Weight (gm)	Pass weight (-11.2 mm) (gm)	Brittleness index (%)	Range	Average
Quartzite	486	332.0	68.31	65.43 to 76.64	68.97
	486	318.0	65.43		
	486	318.5	65.53		
	486	372.5	76.64		
Gneissic Quartzite	516	356.0	68.99	61.57 to 71.02	67.49
	516	317.5	61.57		
	516	353.0	68.41		
	516	366.5	71.02		
Quartzitic Phyllite	509	359.0	70.53	58.64 to 70.53	62.94
	509	306.0	60.11		
	509	318.0	62.47		
	509	298.5	58.64		

3.1.3 Inferences

The brittleness values represent relatively a close range (consistent) within the rock type with one typical value in each case exceeding the value by 10%. Quartzite rocks exhibit higher brittleness over quartzitic phyllite while Gneissic quartzite displaying a close value with that of quartzite. This could be due to mineralogical similarity. Higher brittleness, in general, is an indicator of easier cuttability/boreability. However, this needs to be read along with Siever's J Value.

3.2 Siever's J Value

3.2.1 Test procedure

A miniature drill under a thrust of 20 kg (200N) presses a TC bit at 200 rpm and the depth penetrated in mm multiplied by 10 is termed as Sj value. 3 to 4 parallel tests are done for computing the average value. The drill bit has 8.5 mm dia and 110^g bevel angle (99^0), where, g is in grad, an angular measurement unit with 100 grads equivalent to 90^0. The Seiver's J value expresses indirectly the surface hardness of the rock. The test setup is shown in Fig. 3. A combination of the Brittleness Index value and the Seiver's J value gives the best possible relation between drilling rate index (DRI) and penetration.

Figure 3 - Test setup for Siever's J value determination

3.2.2 Test results

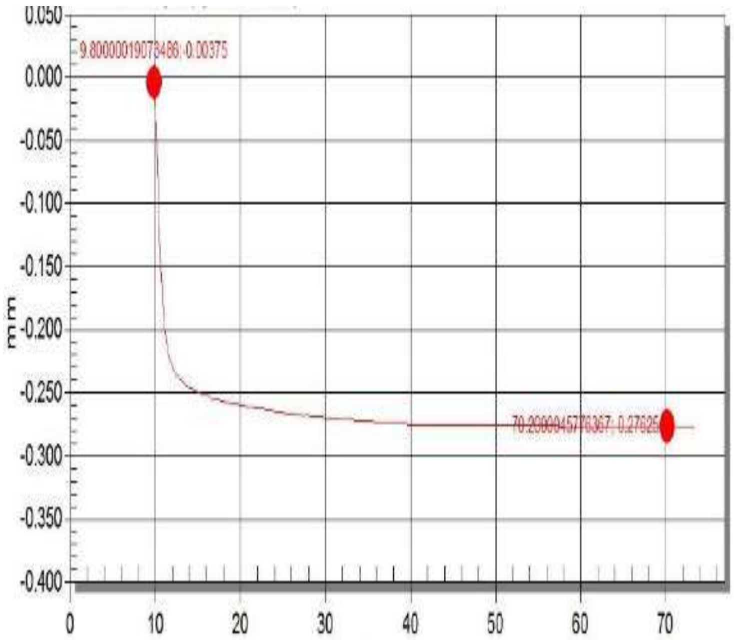
A few test results of Sj value are presented in Table 3.

Table 3 - Test results of Siever's J Value (Sj)

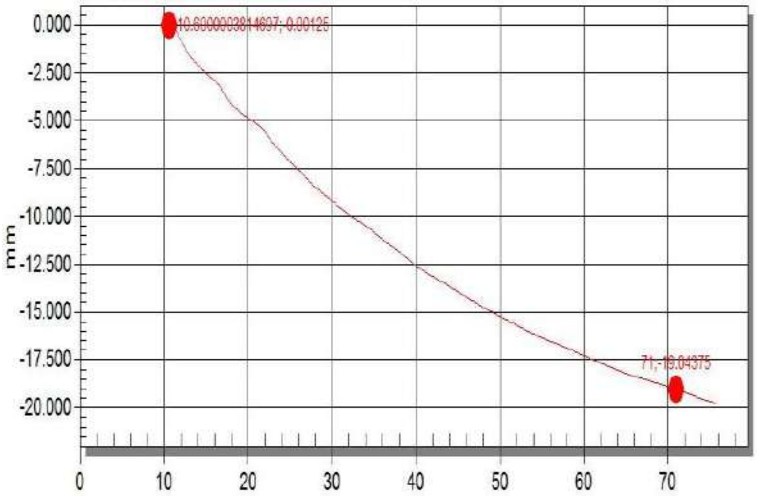
Rock Type	Penetration(mm)	Sj Value	Mean Sj Range	Mean Sj Value
Quartzite	2.8	28	25 to 28	26.3
	2.5	25		
	2.6	26		
Gneissic Quartzite	7.6	76	75 to 101	85.0
	10.1	101		
	8.8	88		
	7.5	75		
Quartzitic Phyllite	20.0	200	114 to 200	168.0
	11.4	114		
	19.0	190		

3.2.3 Inferences

The Sj values show consistent results within the rock type and follow a general trend of similar rock suits. Higher quartz content would have contributed to lower Sj values for quartzite in comparison to gneissic quartzite that exhibits a typical planar feature attributing to higher drilling rates while the quartzitic phyllite has shown a very high value due to lower hardness and abrasivity of minerals present over others. The penetration–time history of a typical hard-abrasive rock and soft-nonabrasive rock are presented in Fig. 4.



Quartzite



Quartzitic phyllite

Figure 4 – Penetration vs time history of miniature drilling tests (Sj)

3.3 Drilling Rate Index (DRI)

3.3.1 Test procedure

DRI tests on the cored samples are performed in the laboratory as per the standard procedures suggested in NTH method (NTNU, Norway). The Brittleness Index (BI) and Siever's J Values (Sj) are taken and are used to read DRI. A nomogram suggested is used to determine DRI from the measured brittleness index values. Figure 5 and Fig. 6 present the nomogram and some reported values of rocks respectively.

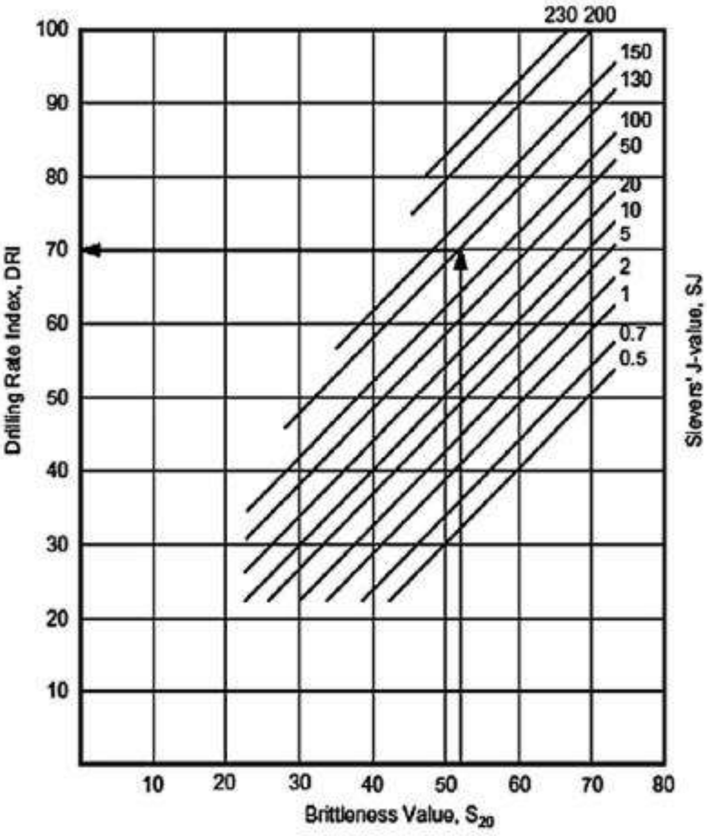


Figure 5 - Nomogram for estimation of DRI

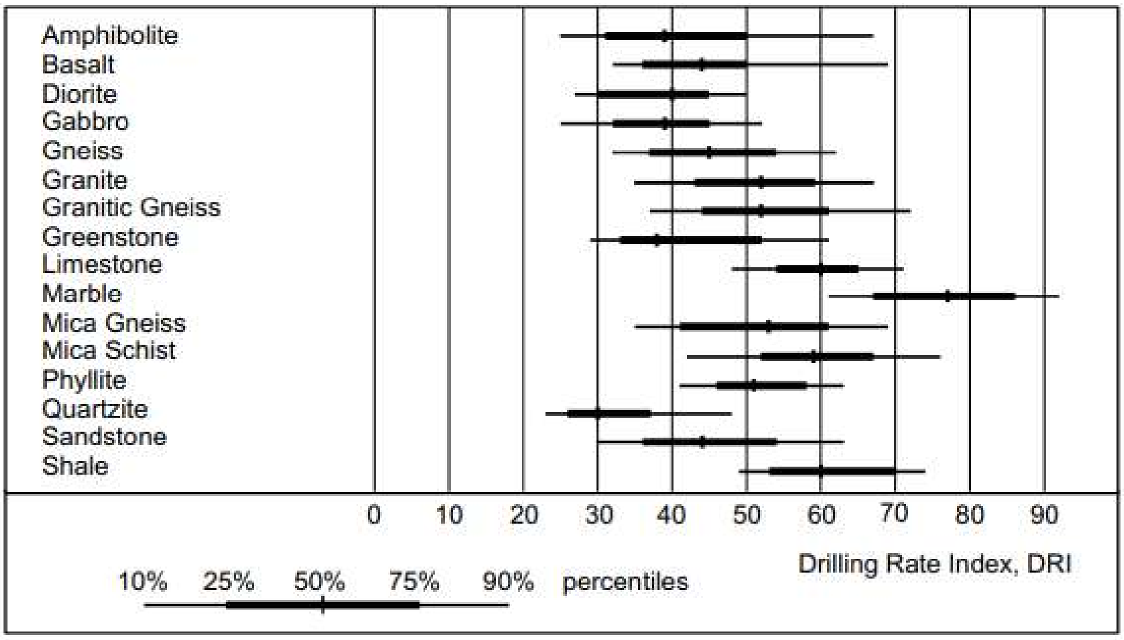


Figure 6 - DRI values reported (Bruland, 1998)

3.3.2 Test results

DRI values are determined from the nomogram from the determined Brittleness Index and Sj values. Values of DRI for some typical rocks tested are presented in Table 4.

The classes into which the rock suits fall from drillability viewpoint are shown in Table 5.

Table 4 - Determination of Drilling Rate Index (DRI)

Rock Type	Mean Brittleness Index (BI)	Mean Siever's J Value	DRI
Quartzite	68.97	26.3	75
Gneissic Quartzite	67.49	85.0	79
Quarzitic Phyllite	62.93	168.0	88

Table 5 - Category intervals for drillability (Bruland, 1998)

Category	DRI
Extremely low	<25
Very low	25-32
Low	33-42
Medium	43-57
High	58-69
Very High	70-82
Extremely High	>82

The DRI values for all the three rock types tested ranged from 75 to 88 representing very high to extremely high drillability. Low DRI values correspond to difficult drilling and vice versa.

3.4 Punch Penetration Index (PPI) Test

3.4.1 Test procedure

The punch penetration test helps assess the rock deformation under normal load using an indenter closely resembling the disc cutter edge profile (Dollinger et al., 1998). Yagiz (2008) also stated that the punch penetration test has a great potential to predict the penetration rate of tunneling machines. The test setup and samples prepared are shown in Fig. 7 and Fig. 8 respectively. The slope of the best fit line (kN/mm or lb/in) termed as penetration index (PI) can be employed for predicting the expected cutter force and corresponding penetration for mechanical excavation.

Figure 7 - Punch penetration cell

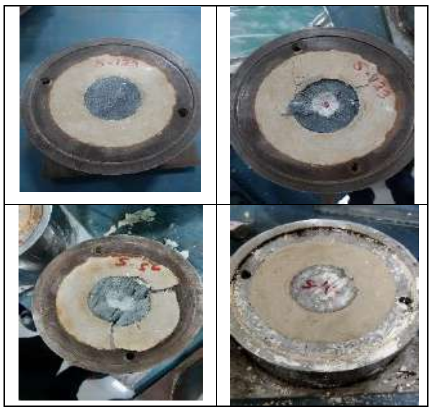


Figure 8 - Test specimen for PPI test

The force-penetration graph that determines the PPI is shown in Figs. 9a and 9b.

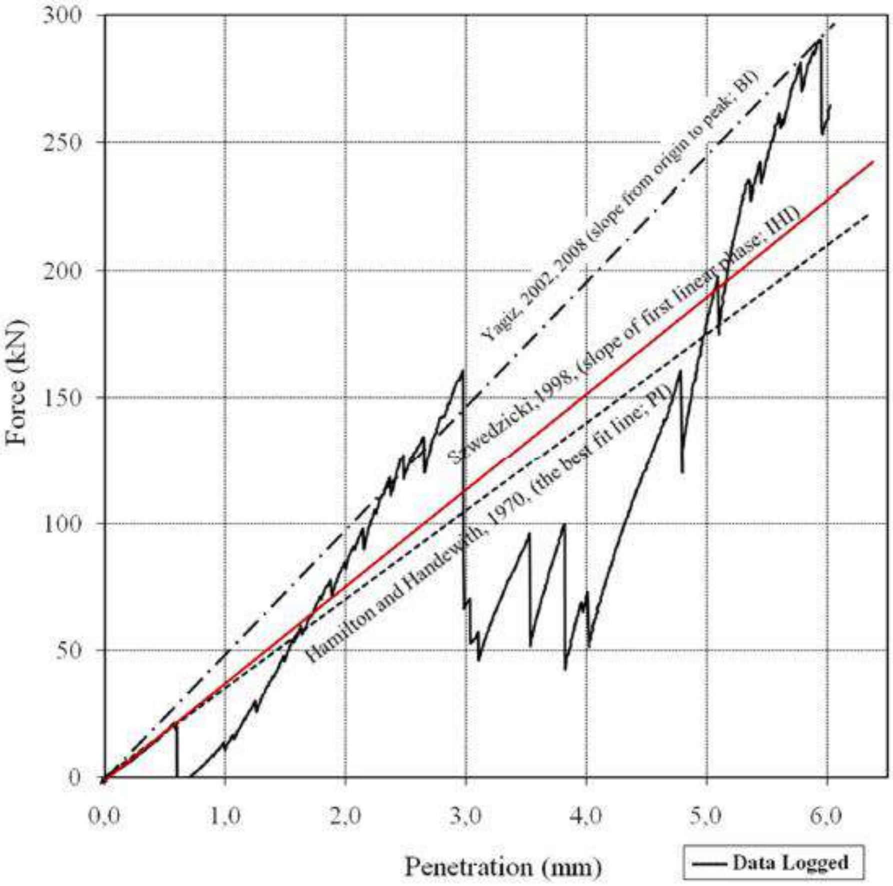


Figure 9a - Force-Penetration Graph of PPI Test (Yagiz, 2008)

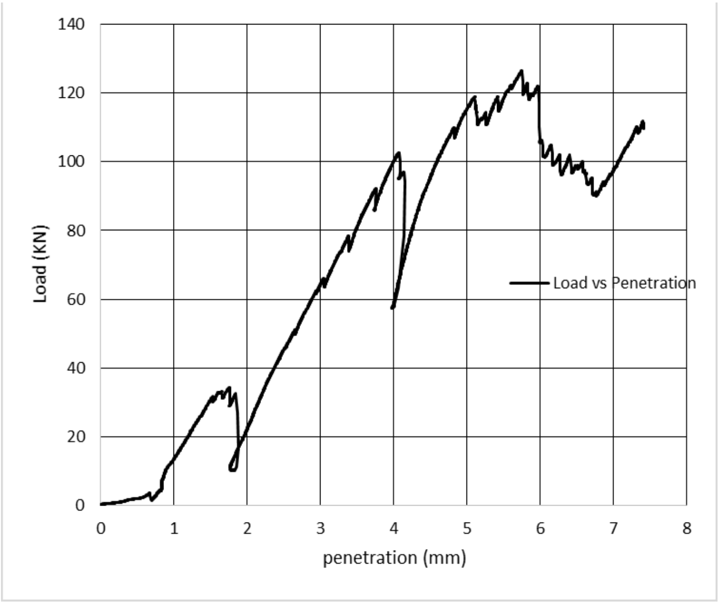


Figure 9b - Force-Penetration Graph of PPI Test (e.g.Quartzite)

In beginning of loading, elastic deformation and very fine crushing of rock surface is seen. Later, there is crushing of rock fabric and finally chips of rock are formed. From linear behaviour in elastic loading to step behavior during crushing are observed as shown in Fig. 9a. As result, the brittleness may be computed as follows;

$$BI = \frac{F_{max}}{p} \tag{2}$$

Where, F_{max} is maximum applied force on a sample in kN, and P is corresponding penetration in mm.

Larger drops in highly brittle rocks to lower or no drops in soft rocks can be seen. Based on the results obtained from the punch penetration tests, the rock brittleness can be classified as given in Table 6.

Table 6 - Rock brittleness from punch penetration test (Yagiz, 2008)

Brittleness index (kN/mm)	Brittleness class
≥ 40	Very high brittle
35- 39	High brittle
30 -34	Medium brittle
25-29	Moderate brittle
20 - 24	Low brittle
≤19	No-brittle (ductile)

3.4.2 Test results

A typical value of PPI for quartzite rock tested is 20 (low brittle).

3.4.3 Inferences

Here fluctuation in the graph is very high which shows the brittleness behavior of quartzite which shows the chipping tendency of rock which is in the favor of TBM during excavation and also, we can pre-estimate the disc cutter thrust with respect to the required penetration for the given rock.

3.5 Linear Cutting Rig-Specific Energy Estimation

Disc cutters are used in TBM for cutting hard rock in tunneling and mining. They cut concentric groves on the tunnel face and the breakage is effected predominantly by tensile fracturing and chipping. The mechanism of disc cutting in the optimum condition is shown in Fig. 10.

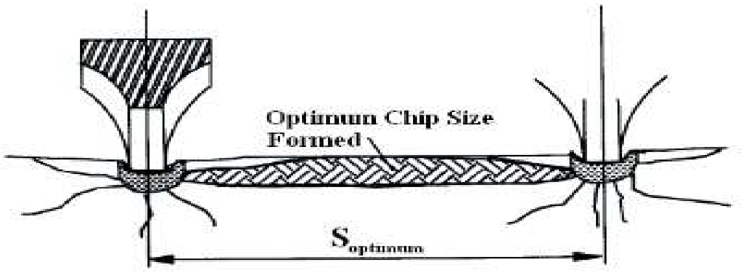


Figure 10 - Mechanism of disc cutting (Masoud and Reza, 2017)

Determination of cutting forces on disc cutter using liner cutting rig and arriving at specific energy for cutting a given rock is fundamental for cutting performance assessment of TBMs. The test equipment involves linear cutting rig, triaxial force transducers, thrust and linear hydraulic rams, instrumentation, data acquisition system etc. This is also useful to arrive at the optimum spacing to depth ratio (s/d) that yields lowest specific energy. Maximum load up to 400kN tons in vertical direction(Z-axis), 200kN in X direction can be applied. It is clamped below the hydraulic press by nut and bolt arrangement and below this the disc cutter is fitted with the help of a fixture. The specifications of triaxial transducer and disc cutter arrangement are shown in Fig. 11.


Tri-axial Force Transducer

Tri-axial Force Transducer	
Sensor	Strain-gage based
Vertical load range (Fz)	40 tons
Longitudinal load range (Fx)	20 tons
Transverse load range (Fy)	20 tons
Resolution	10 N
Accuracy	±0.1%

- Calculation of Specific Energy (SE)
- Measurement of forces
    - Rolling force
    - Side force
    - Reaction force

Figure 11 - LCR test setup with sensors and measurement parameters

3.5.1 Procedure

In TBM excavation disc cutter used is the primary tool for excavation. It is also known as roller cutters, which rolls on a specific radius on the cutter head and generates crack, which in turn generate chips. The tests can be conducted both with a miniature disc(6.5 inch) or a 17-inch disc cutter actually used in tunnelling, for eliminating any scaling factors. 6.5 inch dia disc is for standard test conditions at lab scale and is usually determined. The 17-inch disc cutter is having edge width of 19.5 mm is a constant cross section type disc cutter. The metal ring is of H13 tool steel. The metal sample tray is used to hold the rock sample in its position. The sample tray has a width of 520 mm and a length of 820 mm. After clamping the rock sample on the sample tray, lines with the help of chalk or marker are drawn on the rock surface with the desired spacing (Ex: 25mm, 50mm and 75 mm) against a reference cut.

After the experminetal lines are drawn on the rock block to be tested, the cutter is brought down and touched on the rock surface. The disc cutter is brought to starting position where edge effect is zero. Then the required thrust force is applied on the disc cutter (Ex: 20kN, 40kN, 60 kN, 80 kN). After applying thrust the penetration is recorded and visualized using CATMAN software through HBM data acquisition system which is installed on the computer connected to LCR. The applied thrust is recorded and visualized using the display connected to tri-axial sensor/pressure transducers. After applying required thrust the disc cutter starts its movement from one point to another point on the pre-drawn line with the applied thrust. The tray moves from one end of the machine to the other end generating a cut on the rock. Sensors are fitted on both the ends of the machine to limit the movement of the trolley within the safe operating distance. The experiments need to be carried out with varied spacing to depth ratio and the specific energy are computed.
The specific energy is calculated by the following expression:

$$SE=F_R/Q \tag{3}$$

Where, SE is the specific energy in MJ/m^3, F_R is the force acting on the cutting disc in kN and Q is the volume per unit length of cut in m^3 /m. It is also possible to determine the instantaneous cutting rate as:

$$ICR=k\cdot P/SE_{opt} \tag{4}$$

Where, ICR is the instantaneous speed of the rock cutting in place in m^3 / h, P is the power in kW, SE_{opt} is the optimum specific energy obtained from Rock Cutting Test in kWh/m^3 and k is a constant depending on the efficiency of the system, expressed as a ratio of the energy transferred from the excavating head to the surface of the front and between 0.85 and 0.9.

A typical plot relating s/d ratio and specific energy is shown in Figs. 12a and 12b.

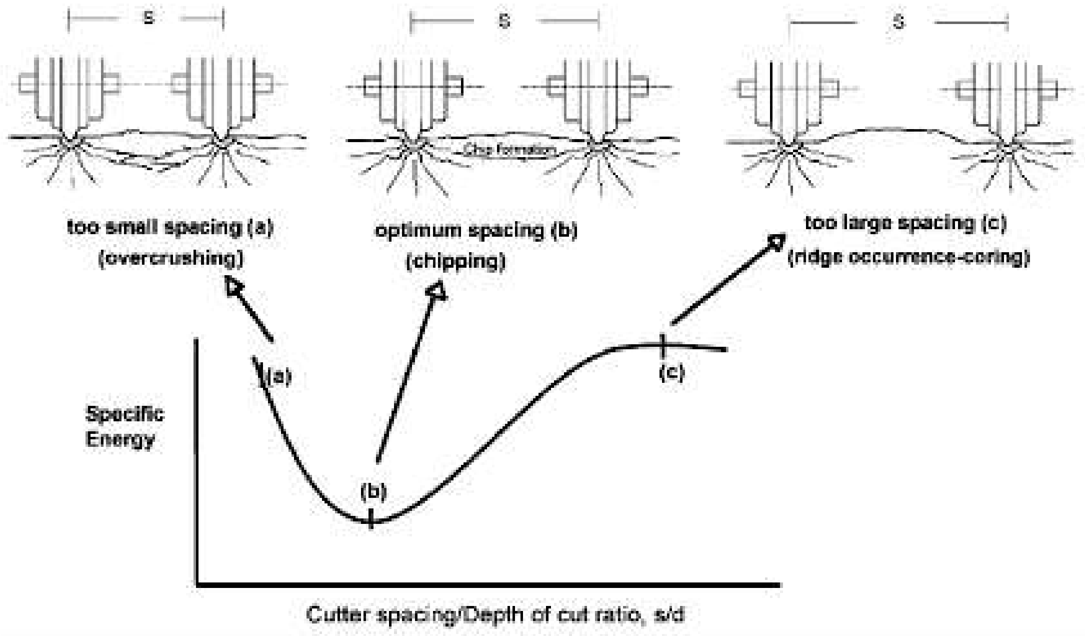


Figure 12a – Concept of optimum s/d ratio in disc cutting (Masoud and Reza, 2017)

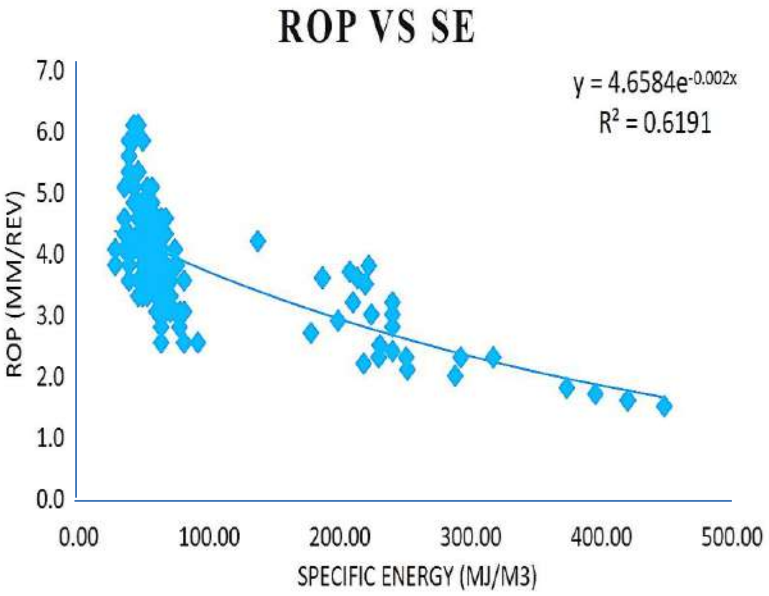


Figure12b - Effect of s/d ratio on specific energy(SE) and rate of penetration (ROP)

3.5.2 Predicting penetration rates

Specific energy values in disc cutting reported for some rocks at lab scale are presented in Fig. 13 (Marilena et al., 2017). The study was conducted with a 6.5 inch disc cutter with a penetration of 3 mm. The two rock types are limestone and marble. Prediction was done using CSM and NTNU methods.

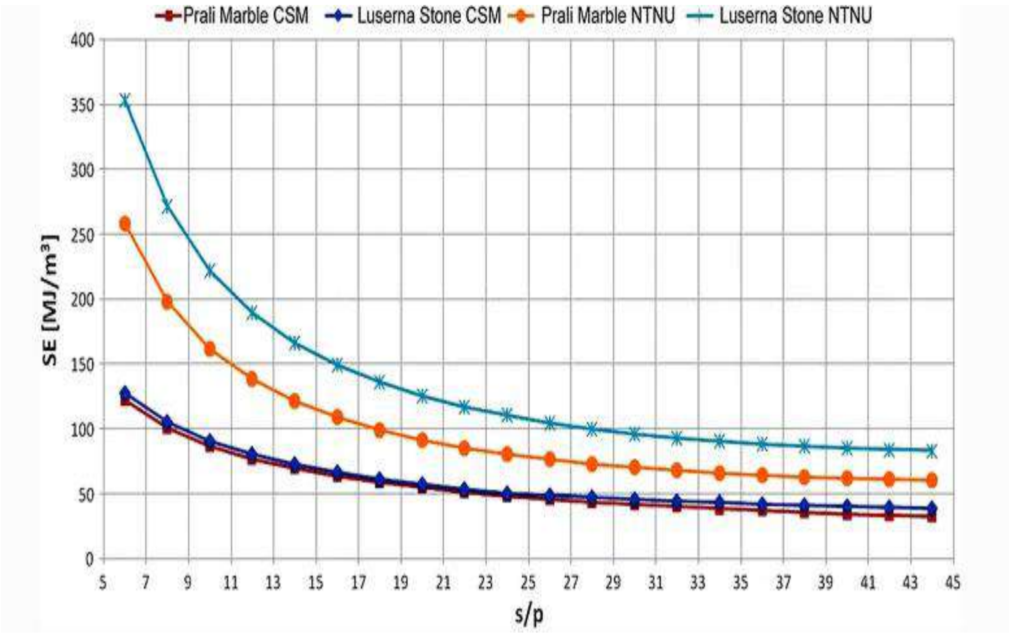


Figure 13 - Specific energy estimation in rocks at lab scale (Marilena et al., 2017)

From the similar studies conducted on the developed Linear Cutting Rig at IIT(ISM), for the specific energy values for a typical rock, the penetration rates have been estimated and presented in Table 7.

Table 7 - Estimated and actual penetration rates of TBM in quartzite rock

S.No.	Variable	From LCR studies	Actual Values	Reasons for variation
1	No. of Cutters(N)	52	52	-
2	RPM	6	6	-
3	Total Thrust	6237 kN	9000 kN	Large variations in UCS and fracturing intensity
4	Total Torque	3755 kN-m	6000 kN-m	Large variations in rockmass index and abrasivity, Rolling force variation due to varied depth of penetration under same thrust
5	Power (kW)	2356	3150	Due to 2 and 3.
6	Efficiency	2816 kN-m and 4677 kN	4500 kN-m and 6750 kN	Machine and cutter age and rock mass variations
7	SE (MJ/m3)	104.17	183.87	Chipping under normal thrust due to fractures present
8	Cutting Rate (m3/hour)	69.22	43.17	Due to chipping
9	PR (mm/rev)	5.3	4	-
10	Actual PR	3.7	2.8.	Lower PR due to higher UCS and higher wear along with higher FPI

Penetration rates of TBM in Quartzite rock have been evaluated on the basis of tests conducted on rock specimens which are free from major joints, fissures and other geological discontinuities. Thus, the estimated PR is higher than that of actual PR. These are rock blocks cut from the operation site and sent as per the desired dimensions. Thus, they represent the site features such as structure at block scale (0.7m long X 0.5m wide X 0.3 m thickness) and saturation pre-existing at that location. Since there is a time gap between the time of release of the block from the site and the actual test in the laboratory, it is a dry block test. Since the test is being done on a block-scale, the variations are represented relatively in a better manner than the core sample-based studies. Thus, the results can be reasonably extrapolated. However, as the degree of saturation and structural disposition are the key contributors, suitable corrections to the values estimated through LCR tests need to be applied, based on the rock response to these features.

3.5.3 Inferences

Specific energy at lab scale helped in estimating the cutting rates and advance achieved using TBMs in field with reasonable confidence. The suggested methodology needs further augmentation with more case studies for reliable predictions.

4. CONCLUSIONS

Rock excavation tests form a sound basis for developing a fundamental understanding on the disc cutter performance and tests particularly, Punch Penetration Index (PPI) and Specific Energy have been found to be very useful for cutting rate estimations with confidence inter-alia selection and operation of TBMs at their optimal capacity. Considering the lab test facilities available at IIT(ISM) Dhanbad, a scaled study, both at lab and field, can help arrive at realistic performance estimates. TBM tunnelling is going to be the lead technology for Indian infrastructure sector growth and considering the huge investment and planning required in commissioning such technology sound basis for selection is necessary. Thus, the suggested rock excavation tests can certainly be handy not only in selecting the TBMs but also in fixing their operational regime based on the rock variations.

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