A.K. RAINA
and
VMSR MURTHY

# Selection methodology for roadheader and tunnel boring machine in different geological conditions: national perspective plan project (CPRI) – a success story

*A national perspective plan project was completed recently which reports the development of a selection methodology for roadheader and tunnel boring machines, the two principal technologies in tunnelling. This involved comprehensive studies at five major tunnelling projects in India where roadheader or tunnel boring machines were deployed. The data on performance of the machines was collected along with the intact rock and rockmass properties. Samples were tested for various specialised laboratory properties. Secondary data was also used in one of the cases. Various models of field penetration index, static and dynamic rock boreability index, and penetration rate were developed for roadheader and tunnel boring machines involving laboratory and field data including dynamic properties. The models were used to define the selection methodology of the machines in various rock formations. In addition to the above, major national rock cutting testing facilities, namely, linear cutting, brittleness and tool wear properties of rock/cutting tools, was developed that can prove to be of great help in defining rock properties vis-a-vis the selection method for forthcoming projects. This paper summarizes the achievements of the research conducted and facilities developed.*

***Keywords:*** *Roadheader, tunnel boring machine, penetration rate, field penetration index, index of rock boreability.*

## Introduction

Roadheader (RH) and tunnel boring machine (TBM) are massive machines that have found their use in the excavations including mining and more so in tunnelling in the world. More recently, such machines have picked up the pace in hydropower projects and metro tunnelling in India also. However, the selection of such machines in a project is a cumbersome process and is mostly defined by the companies who supply these. There are several examples in India, where despite meticulous selection process, the machines have failed to meet the demand of the projects. Slight oversight in the selection process of such machines can thus pose peril to an excavation-oriented project with severe time and cost implications. It is thus imperative to have a thorough understanding of the subject of the selection process and the properties that lead to selection of a suitable machine in a particular project. In tune with above, a major research project under grant from CPRI was taken up by CSIR-CIMFR and IIT-ISM to develop selection methodologies for both RH and TBM. The project spanned for over a period of around 4 years where data from different tunnelling projects was collected.

The primary focus of the selection method is to have a proper understanding of the penetration rate in different formations. A detailed review of literature conducted (Table 1) revealed that significant research had been conducted on different aspects of machines. However, comprehensive studies in Indian conditions in literature were lacking.

A further analysis of the above data (Table 1) is provided in Fig.1.

Fig.1 reveals that the research has paced up after the year 2000 despite the fact that the RH have been vogue since 1950s in coal mines.

The RH pick and its characteristics, though very important, has received very little attention from researchers as shown in Fig.2. The pick design and investigations related to picks of RH is still a grey area for research.

In case of TBM, it is practically difficult to conduct search particularly in the year range 2000-2021 as the word TBM has been used by several other medical and physics journals for articles not pertaining to tunnel boring machine. The approximate estimate is provided in Fig.3. The number of papers obtained by using "tunnel boring machine" as search criterion yield better results as the same is unique.

The real boost to usage of TBMs started in 2001-10 and peaked by 2021 and is expected to grow with time as the use of TBM and related data generation continuously increases.

*Blind peer reviews carried out*

Dr. A. K. Raina, CSIR-Central Institute of Mining and Fuel Research, Nagpur Research Center, 17/C Telangkhedi area, Civil Lines, Nagpur 440 001. and Prof. VMSR Murthy, Department of Mining Engineering, Indian Institute of Technology(Indian School of Mines), Dhanbad 826004.

Table 1: Number of references, citations and patents as available online

| Search criterion | General | In title | General | In title | General | In title |
|---|---|---|---|---|---|---|
| keyword | Roadheader | Roadheader | “road header” | “road header” | +pick | +pick |
| Total hits | 8890 | 1020 | 1710 | 83 | 23 | 2 |

Source: Google Scholar as on 17.02.2021

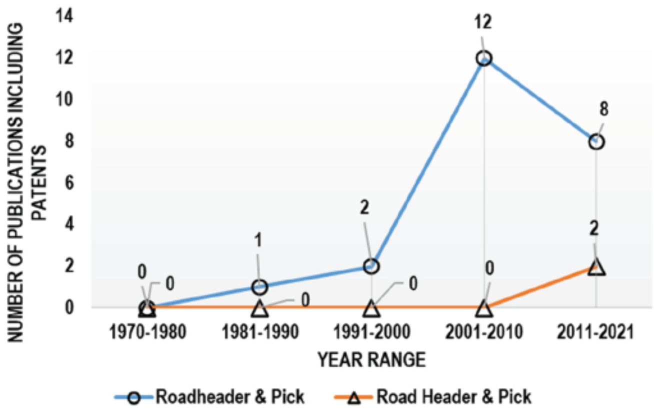

Fig.1: Citations of roadheader or road header in title of publication (Source: Google Scholar)

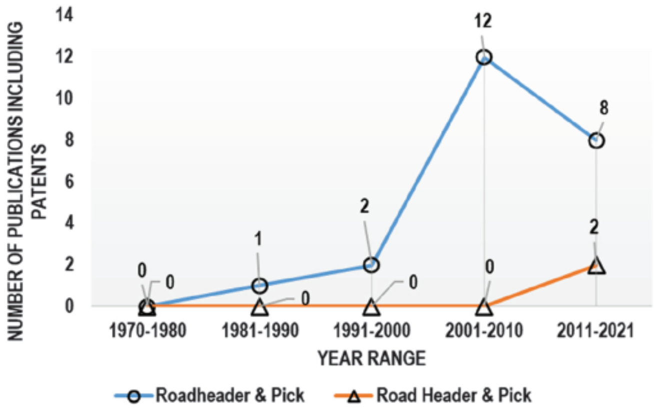

Fig.2: Citation of roadheader or road header and pick in title(s): Source Google Scholar

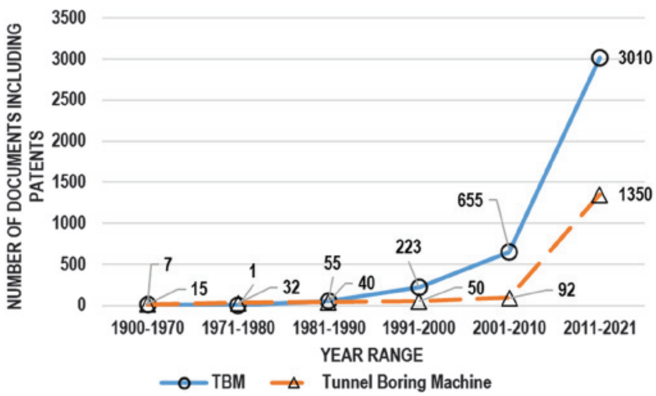

Fig.3: Publications with TBM or tunnel boring machine in title

## Classification of literature

The RH literature can be further classified into different categories which are defined below:

1. Design of the RH as a machine
2. Rock and rockmass related literature
3. Design of RH cutter head, picks and their spacing
4. Rock/rockmass and RH interactions
5. Performance characteristics and cutting rate modelling:
    a. General empirical models
    b. Numerical and mechanics-based models
    c. Intelligent system models

Similarly, the TBM literature can be classified into categories like:

1. Design of the TBM as a machine
2. Rock and rockmass related literature in relation with TBM
3. Design of TBM cutterhead, cutters, their spacing and their positioning on TBM cutterhead.
4. Alignment and positioning of the TBM
5. Rock/rockmass and TBM interactions
6. Performance characteristics and boring or penetration rate modelling involving:
    a. General prediction models
    b. Rock characterization for TBM selection
    c. Rock-TBM interactions
    d. Cutter wear
    e. Penetration rate models of empirical and artificial intelligence-based publications

The literature is so exhaustive that it is difficult to compile the same and present in proper context. There are however publications of RH (Deshmukh et al. 2020) and TBM (Grima et al. 2000; Mooney et al. 2012) that have tried to examine the literature of importance.

## Comparison between excavation methods

A comparison of driving tunnels with RH and TBM vis-a-vis blasting (Table 2) will not be out of place to bring out the advantages and disadvantages of the methods.

Drilling and blasting is still a preferred method of excavation for several reasons. Though there are constraints of explosive transportation, storage, use, hazardous by products and poor energy utilization, the method has great

TABLE 2: COMPARISON OF ROADHEADER, TUNNEL BORING MACHINE AND DRILL-BLAST METHODS ON VARIOUS COUNTS

| | Concerns | RH | TBM | Drilling and blasting |
|---|---|---|---|---|
| 1. | Ground vibration | Not so significant; concern to the machine | Low but continuous | High but transient |
| 2. | Noise | Localised | Low but continuous | High but transient |
| 3. | Accidents | Minimum | Minimum | High |
| 4. | Tunnel profile | Customised | Even | Uneven |
| 5. | Ventilation requirement | Not dependent but dust may be a problem | Low | High |
| 6. | Rock mass damage | Minimal | Minimal | Relatively high |
| 7. | Fragmentation | Good and uniform | Uniform | Uneven |
| 8. | Tunnelling rate | Moderate | Relatively high | Relatively low |
| 9. | Operations | Continuous | Continuous | Cyclic |
| 10. | Constraints | Machine selection, abrasion and odd geology | Major issues if stuck | Fumes, accidents |

TABLE 3: DIFFERENT EQUATIONS FOR PREDICTION OF INSTANTANEOUS CUTTING RATE (MODIFIED AFTER DESHMUKH, 2020)

| | Author/year | Model |
|---|---|---|
| 1. | Gehring (1989) | $ICR = \frac{719}{\sigma_c^{0.78'}}$ |
| 2. | Bilgin et al. (1990) | $ICR = 0.28P(0.974)^{RMCI}; RMCI = \sigma_c(\frac{RQD}{100})^{\frac{2}{3}}$ |
| 3. | Copur et al. (1998) | $ICR = 27.511 \times e^{0.0023 \times RPI}$ |
| 4. | Thuro and Plinninger (1999) | $ICR = 75.7 – 14.3 ln \sigma_c$ |
| 5. | Balci et al. (2004) | For $d$=5 mm, $ICR = 0.8\frac{P}{0.37\sigma_c^{0.86}}$; |
| | | For $d$=9 mm, $ICR = 0.8\frac{P}{0.41\sigma_c^{0.67}}$; |
| 6. | Keles (2005) | IRC=163.93 $\sigma_c^{-0.5737}$ |
| 7. | Ebrahimabadi et al. (2011) | $ICR = 5.56\ RMBI + 0.60a – 0.17$<br>$ICR = –0.18\ SE^3 + 28.57SE – 92.82$ |
| 8. | Ebrahimabadi et al. (2012) | $ICR = –35.22e^{–0.54\|logRMBI}$ |
| 9. | Comakli et al. (2014) | $ICR = k\frac{P}{SE}$ |
| 10. | Kahraman and Kahraman (2016) | $ICR = –0.88\sigma_t – 0.54n + 25.01$ |
| 11. | Choudhary et al. (2017) | $ICR = –0.18SE^3 + 28.57SE – 92.82$ |

Where: $ICR$ is instantaneous cutting rate, $\sigma_c$ is compressive strength, $RQD$ is rock quality designation, $k$ is a constant, $P$ is power, $SE$ is specific energy, RPI is rock penetration Index, RMBI is rockmass boreability index, $a$ is a constant, $n$ is number of picks

degree of flexibility in operations, deployment and flexibility of use. Dust, explosive gases and human response to blasting along with the statutory requirements place lot of restrictions on the method and may become infeasible in case of urban excavations. The roadheader is a versatile machine with high degree of manoeuvrability but its size weight relationship creates issues that may render the machine unusable in highly abrasive rock or hostile geology. TBM is gaining ground particularly in tunnelling where tubes only are the requirement of the project and the movement of machine is practically on a linear dimension.

## Performance prediction models

### ROADHEADER

There are at least 11 performance prediction models that try to assess the instantaneous cutting rate of RH of different configurations in terms of compressive strength, specific energy or other rock cuttability classifications schemes developed for the purpose. Examples of such models are provided in Table 3.

Although equations provided in Table 3 are developed for different places these can be evaluated and used for purposes similar to those for which they were designed.

### TUNNEL BORING MACHINE

As provided for RH, similar equations have been developed in case of TBM (Table 4) which are of representative in nature and not comprehensive.

Some of the models with their disadvantages have been used by researchers for several studies. Few performance

Table 4: Penetration rate of TBM as correlated with rock properties or classifications by various authors (Raina and Murthy 2020)

| | Citations | Equation |
|---|---|---|
| 1 | Cassinelli et al. 1982 | $PR=-0.0059\times RSR+1.59$ |
| 2 | Nelson et al. 1983 | $PR=10.45-1.19\times H_A$ |
| 3 | Boyd 1986 | $PR=\frac{HP\times\eta}{SE\times A}$ |
| 4 | Innaurato et al. 1991 | $PR=\sigma_c(-0.437)-0.047RSR+3.15$ |
| 6 | Ramezanzadeh et al. 2008 | $PR=\frac{CSM\ ROP^{0.407}}{Exp(0.001\times JS-0.002\times\alpha-0.002\times PTI-0.632)};\ \alpha<45$ |
| 7 | Rostami et al. 1997 | $PR=R\times(1-\cos\phi)$ |
| 8 | Barton 1999 | $PR=5\times Q_{TBM}^{-0.2}$ |
| | | $Q_{TBM}=\frac{RQD_o}{J_n}\times\frac{J_r}{J_a}\times\frac{J_w}{SRF}\frac{20^9\times SIGMA}{F^{10}}\frac{20}{CLI}\frac{q}{20}\frac{\sigma_0}{5}$ |
| 9 | Bruland 1998 | $I_0=\left(\frac{M_{ekv}}{M_1}\right)^b$ |
| 10 | Ribacchi and Lembo-Fazio 2005 | $SP=250\times\sigma_{cm}^{-0.66}$ |
| | | $\sigma_{cm}=\sigma_c\times e\left(\frac{RMR-100}{18}\right)$ |
| 11 | Mahdevari et al. 2014 | $ARA=0.56\times(RME-26)$ for $RME>75$ |
| | | $ARA=0.213\times RME$ for $RMR<75$ |
| 11 | Bieniawski and Grandori 2007 | $ARA=-0.422\times RME_{07}-11061$ |
| 12 | Hassanpour et al. 2010 | $FPI=0.222\times RMR+2.755$ |
| | | $FPI=9.273e^{0.008\mathrm{GSI}}$ |
| | | $FPI=11.718Q^{0.098}$ |
| 13 | Salimi et al. 2016 | $P=\frac{ROP\times1000}{RPM\times60}$, $FPI=\frac{F_n}{P}$ |

Where $PR$ = penetration rate; $\sigma_c$ = uniaxial compressive strength of rock; $\sigma_{cm}$ = uniaxial compressive strength of rock mass; $ARA$ = average rate of advance; $FPI$ = field penetration index; $J_n$, $J_r$, $J_a$, $J_w$ and $SRF$ are original parameters of $Q$-system; $RQD_0$ is orientated-RQD in tunnelling direction; $SIGMA$ = rock mass strength; $F$ = average cutter load; $CLI$ = cutter life index; q = quartz content; $\sigma_0$ = average biaxial stress on tunnel face; Adj $ROP$ = adjusted rate of penetration; $CSMROP$ = calculated rate of penetration; JS = Joint spacing; $\alpha$ = angle between tunnel axis and plane of weakness; $ROP$ = rate of penetration; $L_b$ = boring length; $t_b$ = boring time; P = penetration per cutterhead revolution; $RPM$ = cutterhead rotational speed; $F_n$ = cutter load; $p$ = penetration rate; $H_A$ = Taber abrasion hardness; $\Phi$ = angle of shearing resistance; $HP$ = installed cutterhead power; $\eta$ = mechanical efficiency factor; $SE$ = specific energy; $A$ = tunnel; $RSR$ = rock structure rating; $R$ = cutter radius; $GSI$ = geological strength index; $RMR$ = rock mass rating; $I_o$ = penetration per cutterhead revolution; $M_{ekv}$= equivalent thrust; $M_1$= critical thrust; $RME$ = Rock mass excavability; $PTI$ = punch test index

models like $Q_{tbm}$ have been claimed to be of universal nature and applied to various projects by the author.

## Research study details

A comprehensive plan for achieving the objectives of the study was initially drawn and followed (Fig 4). This involved a lot of sub-tasks covering site selection, investigation planning, rock sample and data collection pertaining to RH and TBM application and performance followed by in-depth analysis and model building.

The study was conducted at different sites in India. The main features of the projects are given in Table 5.

The data of the projects was obtained through extensive monitoring and at times logging the historical data. The data was compiled and analysed for advance analysis. A summary of the data obtained from the field(s) is summarized in Table 6.

Table 6 reveals that a wide range in rockmass and machine variables were analyzed in the projects which facilitated the development of the models for use in defining the selection methodology of RH and TBM along with other field definitions for use by engineers in future projects.

## Achievements

In tune with the objectives of the project, there are several achievements that can be classified as follows (Fig 5)

1. Laboratory based rock characterization set up for roadheader and tunnel boring machine selection.

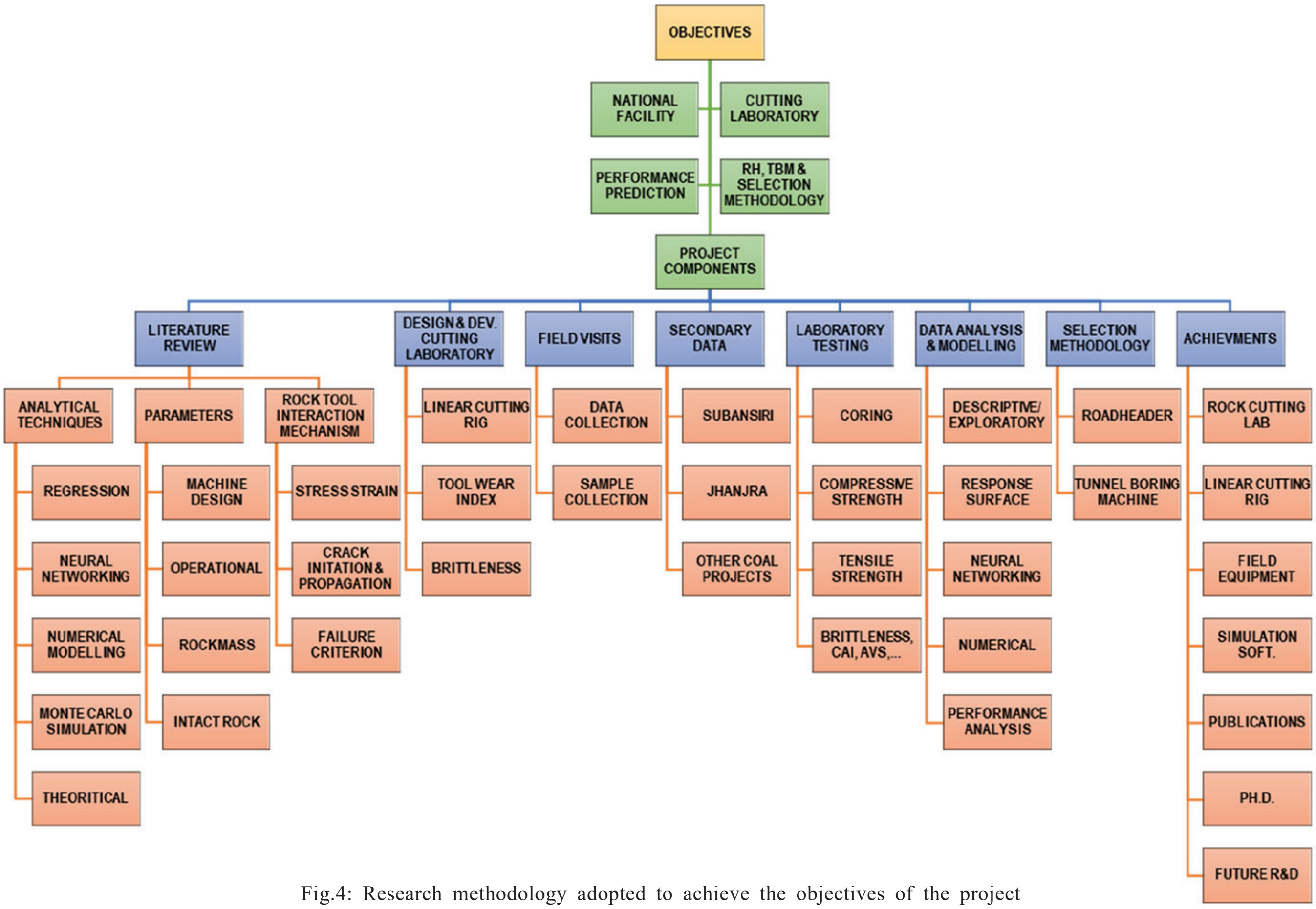


Fig.4: Research methodology adopted to achieve the objectives of the project

TABLE 5: DESCRIPTION OF THE SITES INVESTIGATED FOR DATA GENERATION (CHECK FROM THE FINAL REPORT)

| Project Name | Lower Subansiri | Parbati-II | Kishenganga | Veligonda | MMRC#1 |
|---|---|---|---|---|---|
| Project type | Hydroelectric | Hydroelectric | Hydroelectric | Irrigation | Metro |
| Project details location capacity features | Arunachal Pradesh 2000 MWCGD, Tunnels, PS, HRT, TRC, PH | Himachal Pradesh800 MWHRT, PH | Jammu & Kashmir330 MWHRT, PH, SS, TRC | Andhra Pradesh18.8 km tunnels (9.2, 7 m finished dia.) | Maharashtra |
| Machine type | *RH* in HRT | TBM | TBM | TBM | TBM |
| Machine specs | L = 20.8 mWt. = 95 TP = 396 kW | Refurbished, Open, Dia. = 6.8 mP =3150 kWT = 5213kNmTh =13780 kNRPM = 7.5 maxCn = 52; Cd = 432 mm; Gripper | Double Shield Universal, Dia. = 6.18 mP = 2520 kWT = 86372Th = 25850 kNRPM = 9 maxCn = 52; Cd = 482.6 mm | Double ShieldDia. = 9 mP =3780 kW P = T = Th = RPM = Cn = 67; Cd = | Single ShieldDia. = 6.68 mP =2000 kWT = 8536 kNmTh = 40000 kNRPM = 7.28Cn = 46; Cd = 431.8 |
| Geological features | Mostly sandstone with high quartz content and iron minerals | biotite schist, carbonaceous phyllite, Manikaran quartzite and schistose granite gneiss | Panjal Volcanics, Hastoji Formation Shale, Razdan Formation meta-sandstone, meta-Siltstone | Kollam Vagu shales and quartzites and Cumbum slates and quartzites, phyllites | Deccan Traps (basalts), tuff, breccia and intertrappean shales |

#1 – Mumbai Metro Rail Corporation, CGD – Concrete Gravity Dam, PS – Pressure Shaft(s), HRT – Head Race Tunnel, TRC – Tail Race Channel, PH – Power House, SS – Surge Shaft, T – Torque, Th – Thrust, RPM – Revolutions per minute, Cn = Number of cutters, Cd – Cutter dia.Note: Several other data from Murthy (..) were also used for roadheader analysis

Table 6: Summary of field properties of various projects

| Project description | | Parbati-II | Kishanganga | Veligonda | MMRC P5 | MMRC P6 |
|---|---|---|---|---|---|---|
| Rock Types | | Schist, Quartzite | Andesite, metasiltstone | Phyllitic quartzite, quartzite | Breccia/Basalt | Breccia/Basalt |
| RMR Range | | 10-70 | 13-81 | 50-80 | 28-61 | 48-72 |
| RQD% | | 22-75 | - | 40-90 | 46-100 | 77-90 |
| Total length analysed (km) | | 1.88 | 14.81 | 2.78 | 0.88 | 2.99 |
| Machine variables | Thrust (kN) | 2931-13846 | 336-8881 | 1754-23054 | 4515-21511 | 3133-12607 |
| | Torque (kNm) | 733-2049 | 150-1161 | 678-3635 | 699-2835 | 656-2610 |
| | RPM | 2-7 | 1-7 | 1.45-7.7 | 0.97-2.5 | 1.1-3.08 |

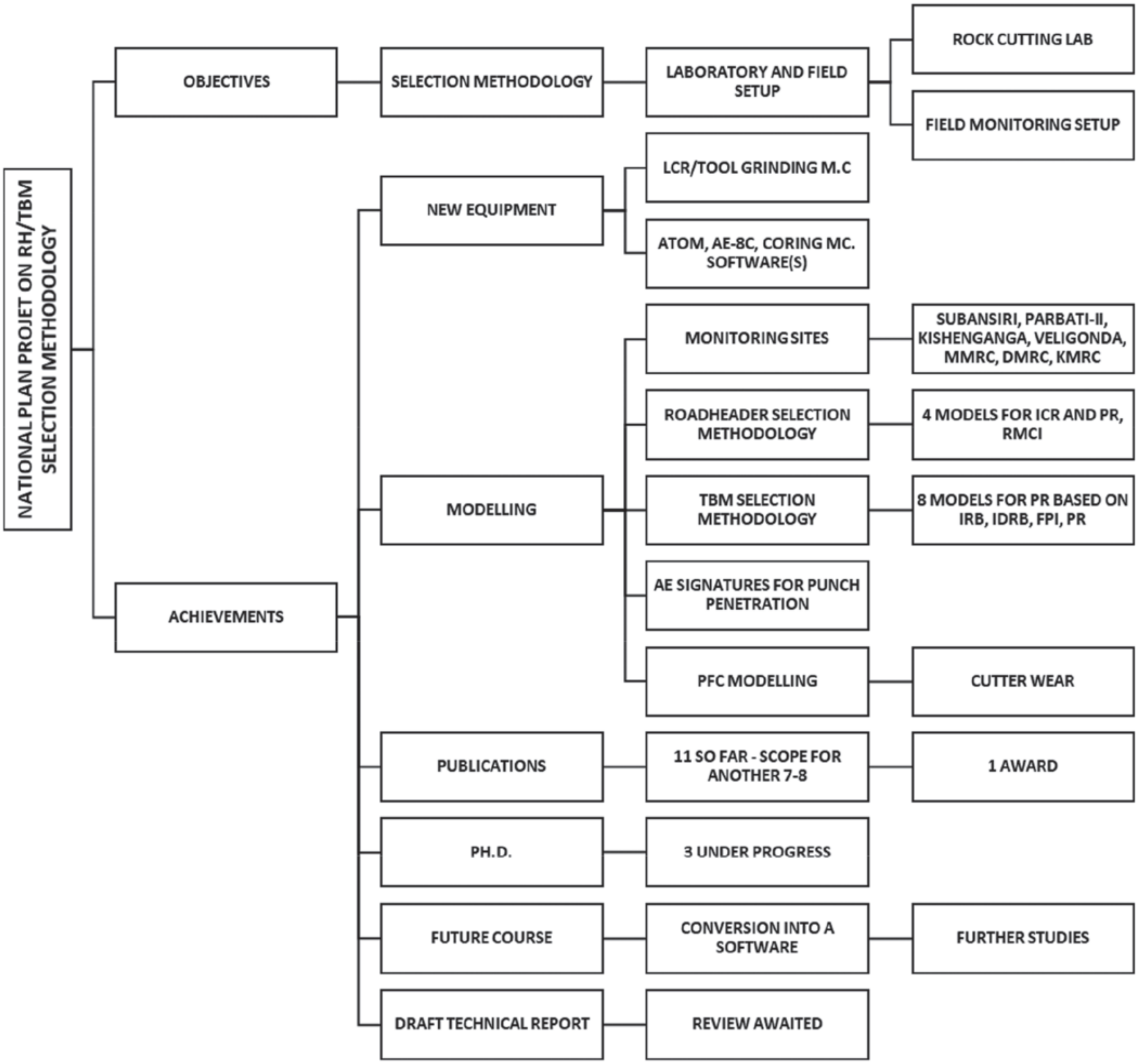


Fig.5 The achievements of the national perspective plan project completed.

a. Roadheader and TBM, being cost-centres in any tunnelling and mining project, require to be selected based on certain standard battery of tests, sound design principles and practical considerations.

b. Some of the rock testing facilities, namely, Cerchar Hardness Index, Cerchar Abrasivity Index, Siever'J Value and Fracture Toughness Index were available at IIT(ISM) Dhanbad. However, it was necessary to create remaining facilities for TBM related rock characterization studies. Discussions with top management of NHPC particularly to address higher cutter consumption in the Manikaran quartzite formation at Parbati-II hydro project.

c. Accordingly, facilities namely, Linear Cutting Rig, Tool Wear Index, Brittleness Index (modified) and Tool Shaping Machine for preparing specialised cutting tools, were designed and fabricated at IIT(ISM), Dhanbad under this project and were used for generating data for different rock suits from different project sites.

d. Tests on rock suits for projects, namely, Subansiri, Parbati Stage II, Kishenganga, Veligonda and Mumbai metro were conducted and the detailed database is provided. The test data provided the basis for classifying the rock/rockmass in conjunction with field data.

e. Cutter steel wear was also investigated using the tool wear index. Some advanced studies were carried out with TC coating on cutter steel using lasers. Existing IIT(ISM), Dhanbad facility was used for this. The analysis has clearly demonstrated the increase in tool hardness after the coating.

f. Facilities namely acoustic emission, seismic velocity along with relevant software were also obtained and used in the studies as far as possible.

g. Majority of the time under this was consumed in design, fabrication, trial runs, calibration, cross checking of values, rock and concrete block preparation and actual testing.

h. The test facilities, accessories and software obtained shall be of great use for continuing the R&D in the field of mechanical cutting of rocks. Doctoral and Masters Studies are on and the outcomes will be shared as they get completed in due course.

2. Methods to classify rock/rockmass for RH and TBM application for rapid tunnelling.

   a. *RH*

   i. Key parameters affecting the selection and performance of roadheaders were identified as UCS, BTS, Swedish Brittleness Index, Area under the Stress-Strain Curve (including post-failure deformation), CAI, CHI, CPRI, Equivalent quartz content, In situ Block Size, Orientation, RMR.

   ii. A comprehensive rockmass excavatability characterisation was thus performed while assigning ratings to different rock and rockmass variables identified as critical for cutting. The rock excavatability criterion established thus can be used for selecting roadheader in varied rock types.

   b. *TBM*

   i. Field penetration index in terms of thrust and penetration rate to define the machine variables.

   ii. Model for defining the rockmass compressive strength in terms of RMR.

3. Models to predict performance of RH/TBM considering the laboratory and in-situ rockmass properties

   a. *RH*

   i. Classification based on RMCI, RPI and SE suggested.

   ii. ICR definition

   b. *TBM*

   i. Detailed model for penetration rate in terms of RMR, CAI and machine variables.

   ii. PR in terms of FPI.

   iii. Rock boreability index (IRB)

   iv. PR in terms of IRB and machine variables.

   v. Dynamic rock boreability index (IDRB)

   vi. PR in terms of IDRB and machine variables.

   vii. FPI in terms of depth of tunnelling and abrasivity.

   viii. PR in terms of IDRB.

   ix. PR in terms of components of IDRB and machine variables.

4. Methods to evaluate the specifications of RH/TBM to be deployed.

5. Directions for future research.

Some of the initial findings have already been published and the models above will be published in future.

The project was completed in tune with the objectives of the study, developments, publications (), and complete findings were reported.

## Conclusions

A comprehensive investigation into RH and TBM performance in different geological formations and tunnelling project dimension were conducted in this study. The study is first of its kind in India where the shortcomings of existing research have been identified and addressed. Several models were developed in tune with the objectives along with development of rock cutting testing facilities of its kind in India. The prominent models and their key features are:

1. Main parameters affecting the selection and performance of RH identified, and model for instantaneous cutting rate,

2. A comprehensive rockmass excavatability characterisation of RH was thus performed while assigning ratings to different rock and rockmass variables identified as critical for cutting,
3. Definition of field penetration index for TBM,
4. Rockmass compressive strength for TBM,
5. Penetration rate of TBM vis-a-vis RMR and other machine variables,
6. Index of rock boreability and hence related model for penetration rate of TBM,
7. Penetration rate of TBM in terms of field dynamic rock properties and lab dynamic properties,
8. Penetration rate of TBM incorporating abrasivity and depth of working or possible stress domain.

The findings of the research and facilities are expected to benefit the tunnelling industry in the country for selection of machines before these are deployed. The penetration rate predictions in terms of different factors devised in this study are unique and can be further upgraded as more data becomes available. A need for standardization of terminology of roadheader and tunnel boring machine for better search and scientific writing is anticipated.

**Acknowledgements**

Thanks are due to Director, CSIR-CIMFR and Director, IIT(ISM) for facilitating the studies, CPRI for funding and project related management and staff for their help and cooperation. CPRI Project Code: NPP/2016/HY/1/13042016; CSIR-CIMFR Project Number GAP/MT/N/CPRI/105/2016-17; IIT-ISM Project Code CPRI/2016-17/492/ME

## References

1. Balci, C., Demircin, M.A., Copur, H. and Tuncdemir, H., (2004): Estimation of optimum specific energy based on rock properties for assessment of roadheader performance (567BK). *Journal of The Southern African Institute of Mining and Metallurgy*, 104(11), pp.633-641.
2. Barton N. (1999): TBM performance in rock using QTBM, *Tunnels Tunnelling Int.* 31, pp. 41–48.
3. Bieniawski, Z.T. and Grandori, R., (2007): Predicting TBM excavability-part II. *Tunnels & Tunnelling Int.*
4. Bilgin, N., Seyrek, T., Erding, E. and Shahriar, K., (1990): Roadheaders plean valuable tips for Istanbul metro. *Tunnels & tunnelling,* 22(10), pp.29-32.
5. Boyd, R.J., (1986): Hard rock continuous mining machine: Mobile Miner MM-120. In Rock excavation engineering seminar. Dept. Mining and Met. Eng, University of Queensland.
6. Bruland, A., (1998): Hard rock tunnel boring. Ph.D. Thesis, Norwegian University of Science and Technology, Trondheim.
7. Cassinelli, F., (1982): Power consumption and metal wear in tunnel-boring machines: analysis of tunnel-boring operation in hard rock.
8. Choudhary, B., Sharma, D., & Das, M. (2017). A Study to Investigate the Influence of Coal Properties on Bit Wear-ability of Roadheader. https://www.semanticscholar.org/paper/A-Study-to-Investigate-the-Influence-of-Coal-on-Bit-Choudhary-Sharma/df485bef93e4d2056ff8ed03c41656a9b83bedb2?p2df.
9. Comakli, R., Kahraman, S. and Balci, C., (2014): Performance prediction of roadheaders in metallic ore excavation. *Tunnelling and Underground Space Technology*, 40, pp.38-45.
10. Copur, H., Ozdemir, L. and Rostami, J., (1998): Roadheader applications in mining and tunneling industries. Preprints-society of mining engineers of AIME.
11. Ebrahimabadi, A., Goshtasbi, K., Shahriar, K. and Cheraghi Seifabad, M., (2011): A model to predict the performance of roadheaders based on the Rock Mass Brittleness Index. *Journal of the Southern African Institute of Mining and Metallurgy*, 111(5), pp.355-364.
12. Ebrahimabadi, A., Goshtasbi, K., Shahriar, K. and Seifabad, M.C., (2012): A universal model to predict roadheaders' cutting performance. Archives of Mining Sciences, 57.
13. Gehring, K.H., (1989): Cutting comparison. Tunnels Tunnell. 21 (11), 27–30.
14. Hassanpour, J., Rostami, J., Khamehchiyan, M., Bruland, A. and Tavakoli, H.R., 2010. TBM performance analysis in pyroclastic rocks: a case history of Karaj water conveyance tunnel. Rock Mechanics and Rock Engineering, 43(4), pp.427-445.
15. Innaurato, N., Mancini, R., Rondena, E., Zaninetti, A., (1991): Forecasting and effective TBM performances in a rapid excavation of a tunnel in Italy. In: Proceedings of the Seventh International Congress ISRM, Aachen, pp. 1009–1014.
16. Kahraman, E. and Kahraman, S., (2016): The performance prediction of roadheaders from easy testing methods. *Bulletin of Engineering Geology and the Environment*, 75(4), pp.1585-1596.
17. Keleº, S., (2005): Cutting performance assessment of a medium weight roadheader at Çayirhan coal mine (Doctoral dissertation, Middle East Technical University,).
18. Mahdevari, S., Shahriar, K., Yagiz, S. and Shirazi, M. A., (2014): A support vector regression model for

predicting tunnel boring machine penetration rates. *International Journal of Rock Mechanics and Mining Sciences*, 72, pp.214-229.

19. Nelson, P.P., O'Rourke, T.D. and Kulhawy, F.H., (1984): Cutter wear and its influence on tunnel boring machine performance. In Design and Performance of Underground Excavations: ISRM Symposium—Cambridge, UK, 3-6 September 1984 (pp. 239-246). Thomas Telford Publishing.
20. Ramezanzadeh, A., Rostami, J. and Tadic, D., (2008): Impact of rock mass characteristics on hard rock tunnel boring machine performance. In 13th Australian Tunnelling Conference 2008 (p.213). Engineers Australia and Australasian Institute of Mining and Metallurgy.
21. Ribacchi, R. and Fazio, A.L., (2005): Influence of rock mass parameters on the performance of a TBM in a gneissic formation (Varzo Tunnel). *Rock mechanics and rock engineering,* 38(2), pp.105-127.
22. Rostami, J., (1997): Development of a force estimation model for rock fragmentation with disc cutters through theoretical modeling and physical measurement of crushed zone pressure (Doctoral dissertation, Colorado School of Mines).
23. Salimi, A., Rostami, J., Moormann, C. and Delisio, A., (2016): Application of non-linear regression analysis and artificial intelligence algorithms for performance prediction of hard rock TBMs. Tunnelling and Underground Space Technology, 58, pp.236-246.
24. Thuro K. & Plinninger R. J. (1999): Predicting Roadheader and shearer excavation performance-Geological and Geotechnical influences, Deptt. For General, Applied and Engineering Geology Technical University of Munich, Germany.

**Bibliography**

25. Pandey, P.K., Raina, A.K., Deshmukh, S., Trivedi, R., Vajre, R. and Murthy, V.M.S.R., (2020): Influence of geology on tunnel boring machine performance: A review. *Journal of Mining and Metallurgy A: Mining,* 56(1), pp.1-14.
26. Deshmukh, S., Raina, A.K., Vajre, R. Trivedi, R. and Murthy, VMSR, (2020): Mechanical Impact of a Roadheader, Recent Practices and Advancement in Mineral Industry, (Proc. RPAMI), 21-22 Feb. 2020, VNIT, Nagpur: 159-165.
27. Deshmukh, S. Raina, A.K., Murthy, V.M.S.R., Trivedi, R. Vajre, R. (2020): Roadheader – A comprehensive review, Tunnelling and Underground Space Technology, 95, https://doi.org/10.1016/j.tust.2019.103148
28. Deshmukh, S., Raina, A.K., Vajre, R., Trivedi, R., Murthy, VMSR and Dash, B. 2019. Disc cutter consumption and chip size distribution of a TBM in a difficult Himalayan Tunnel, Geomine 2019, Nagpur, Oct. 14-15. (e-proceedings)
29. Deshmukh, S., Raina, A.K., Pandey, P., Vajre, R., Trivedi, R. and Murthy, VMSR, 2019. Mechanical wear of cutters in tunnel boring machines – a comprehensive review, *Journal of Mines, Metals and Fuels,* 67(9): 391-402.
30. Deshmukh, S., Raina, A.K. and R. Vajre 2019. Application of tunnel boring machine for the construction of Kalkaji to Vasant Vihar DMRC tunnel-Delhi, India, Recent Advances in Mining Technology, Acharya Institute, 23-24 May, Bengaluru: p65.
31. Deshmukh, S., Vajre, R., Raina, A.K. and Trivedi, R., May (2019): Sensor Networking with IoT in Underground Excavation to monitor Productivity and Safety. *Mining Engineers Journal MEAI,* 20(10), pp.15-23.
32. Deshmukh, S, Pandey P, Trivedi, R., Raina, A.K. (2018): IoT: the new benchmark for driving innovation in mining industry, *Mining Engineer's Journal,* 19(6): 19-25.
34. Pandey P.K., Deshmukh, S., Raina, A.K., Trivedi, R. and Murthy, VMSR. 2017. Roadheader Performance – Impact of Geology, 7th Asian Mining Congress, 8-11 November 2017, The Mining Geological and Metallurgical Institute of India (MGMI), Kolkata, India: 257-262.