Tunnelling and Underground Space Technology 95 (2020) 103148

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Roadheader – A comprehensive review

Suraj Deshmukh[a], A.K. Raina[a,*], V.M.S.R. Murthy[b], R. Trivedi[a], R. Vajre[a]

[a] CSIR-Central Institute of Mining and Fuel Research, Unit – I, 17/C Telangkhedi Area, Civil Lines, Nagpur, Maharashtra 440001, India
[b] Department of Mining Engineering, IIT(ISM), Dhanbad, Jharkhand 826001, India

ARTICLE INFO

Keywords:
Roadheader
Mechanical excavation
Tunnelling
Review

ABSTRACT

Mechanical excavators are preferred to conventional drilling and blasting as blasting poses several regulatory and operational issues. The roadheader is a machine for excavating rock in mining and civil construction projects. It is a hybrid machine, with better manoeuvrability than that of tunnel boring machines. It can cut rocks even up to 160 MPa, if laminated or fractured, in different tunnel profiles and adapts easily to changing operational conditions. A comprehensive survey of literature pertaining to varied aspects of the roadheader is presented in this paper. This review classifies literature on roadheaders into multiple classes and sub-classes and identifies important parameters that define roadheader efficiency and the risk factors involved in its deployment. We also provide an account of recent technological additions that help collect data on roadheader performance during operations. Such data has the potential to rapidly improve roadheader design.

1. Introduction

Rapid urbanization has increased the need for tunnels in transportation and infrastructure. Conventionally, drilling and blasting have been used for constructing tunnels. However, transporting and using explosives in urban environments pose concerns. Blasting produces annoying ground vibrations and toxic fumes. Moreover, the rate of tunnelling using blasting is low and blasting significantly damages the parent rock mass even when controlled blast measures are deployed. To overcome these problems, mechanical excavators are used for mining and construction-related purposes.

The roadheader (RH) is the most widely used underground partial-face mechanical excavator. Roadheaders were first developed to mechanically excavate coal in the early 1950s. Later, their use was extended to civil constructions where RHs were extensively used for excavating railway tunnels, roadways, sewers, and diversion tunnels in soft and moderately hard ground conditions. Since 1970, they have been used in civil industries to form main haulage drifts, roadways, cross-cuts etc. and, in mining industries, to mine soft rock, coal, industrial minerals and evaporitic rocks.

The roadheader is a hybrid mechanical excavator and consists of a boom-mounted rotating cutting head with a conveyor for broken rocks Fig. 1. A crawler travelling track moves the entire machine forward into the rock face. High mobility, advance rates, reliability, low strata disturbance, safety and low labour deployment are some of the advantages of the RH. The main advantage of the roadheader is its high cutting power density provided by the small diameter of its cutting drum. This gives the RH the cutting edge over other mechanical excavators. Recent advances have made RHs more efficient in hard rock tunnelling. Increase in machine weight, size, automation and remote-control features, cutterhead and boom positioning, advances in hydraulic and electrical systems, muck pick and loading systems, efficient cutter head and metallurgical advances in cutterhead design are some of the changes that mark the development of the RH over time.

The development of the RH over time and with application to harder rocks are provided in Fig. 2.

It is evident from Fig. 2 that effort has been focussed on developing RHs for higher strength rocks. However, with the improvements, the weight of the RH has also increased which points to the fact that the compressive strength of the rock and the weight of machine are strongly related. This conclusion also highlights the drawback that, with higher weight of the machine, the handling problem increases.

2. Classification of roadheaders

Tucker (1985) classified roadheaders by their weight and the compressive strength of the rocks that they can cut. Thus, RHs with a weight of up to 30 tonnes and a cutting capability of up to 70 MPa were categorised as light duty. Those with weights of up to 34–45 tonnes with compressive strength 100 MPa were medium duty while those that were over 45 tonnes with compressive strength of 150 MPa could be classified as heavy-duty RH. Atlas Copco-Eickhoff suggested another

* Corresponding author.
E-mail address: rainaji@cimfr.nic.in (A.K. Raina).

https://doi.org/10.1016/j.tust.2019.103148
Received 4 April 2019; Received in revised form 20 September 2019; Accepted 13 October 2019
Available online 21 October 2019
0886-7798/

Nomenclature

Short terms

RH	roadheader
PID	proportional integral derivative controller
PCC	power control centre
ICR	instantaneous cutting rate
RMBI	rock mass brittleness index
SE	specific energy
VRCR	vertical rock cutting rig
UCS	uniaxial compressive strength
RPI	rock penetration index
VAP	vibration analysis programme
ANSYS	analysis system
LS-DYNA	advanced general-purpose multiphysics simulation software
RMCI	rock mass cuttability index
RQD	rock quality designation
SQP	series quadratic programming
NATM	new Austrian tunneling method
PFC2D	particle flow code 2-dimensional
MLP	multilayer perceptron system
ANN	artificial neural network
KSOFM	kohonen self-organising feature map
GP	genetic programming
GEP	gene expression programming
DAQ	data acquisition process
UPDS	ultra-wideband pose detection system

Abbreviations

σ_c	compressive strength
P	installed power in KW
k	energy transfer ratio
SE_{opt}	optimum specific energy
D	diameter
σ_t	tensile strength
BI	brittleness index

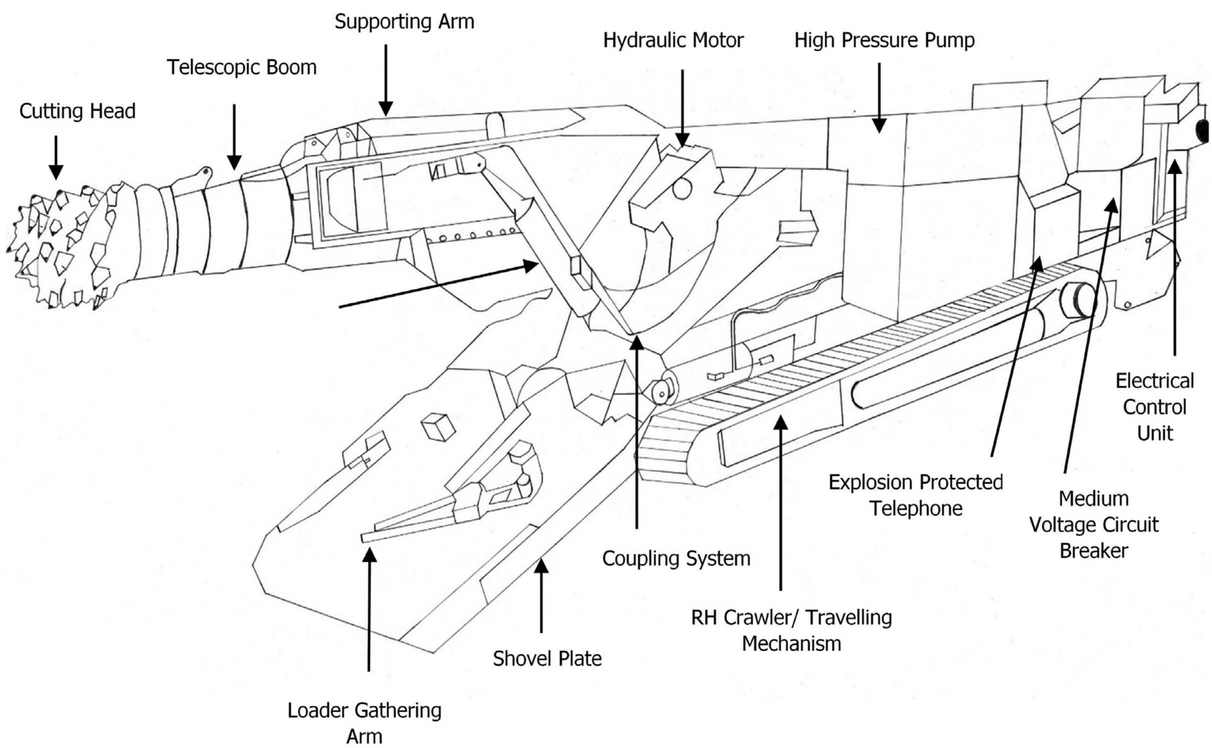

Fig. 1. Schematic diagram of a typical roadheader (drawn after https://www.rotarypower.com/product_applications/road-header/ (Accessed on 10.09.2019)).

classification according to weight for the RH (Schneider, 1988). RHs of 20 tonnes come under class 0, 20–30 tonnes in Class I etc. Neil et al. (1994) classified the RH on the basis of cutting action into longitudinal type milling/borer/axial head and transverse type ripping head.

Apart from this Jian and Hao (2008) proposed a summary of key technological issues in mechanized mining with a boom-type RH, and also proposed an alternative classification, based on the rational matching of working parameters. Boom-type roadheaders were classified as small size (up to 30 tonnes), mid-size (between 30 and 70 tonnes) and large size (between 70 and 120 tonnes). Roadheader classification as recorded by different authors is given in Table 1.

3. A classification of literature on roadheaders

Published literature on the RH can be classified into at least 11 groups as presented in Fig. 3. It is evident from Fig. 3 that literature has focussed on different aspects of the RH, ranging from cutter head design and pick configuration, to performance prediction, risk and failure analyses, dust suppression and positioning, using various analytical techniques such as regression and artificial intelligence. These classes of literature are discussed in further detail in this review. As far as possible, we have kept a historical perspective in the review to provide an understanding of the shifting trends in research on various aspects of roadheaders.

3.1. Design of roadheader cutters/cutting head

Mechanical rock and coal excavation machines, such as roadheaders, drum shearers and continuous miners, excavate rock material using a number of picks mounted on their cutting heads or drums. The shape of the cutting head and the configuration of the picks influence the performance of roadheaders. So, literature gives importance to the design of the cutting head.

Evans (1972) suggested that, by imposing force on picks, line spacing between the picks controls the cross-section area swept by the picks. Hurt and MacAndrew (1981) concluded that, by providing equal pick spacing, force variations can be maintained at a minimum level. Hurt et al. (1982), after analysing force balance, surmised that circumferential pick spacing must be kept equal around the cutting head periphery. Hurt and MacAndrew (1985) suggested that, in order to balance pick force, applying graded lacing at corner cutting is desirable.

Hekimoglu and Fowell (1991) introduced tramming of the tool holder to obtain equal circumferential pick spacing for 360° and over. Eyyuboglu (2000) suggested that the most reliable angles of wrap were 360° and 776°. The most important parameter in the cutting drum periphery is pick spacing. For effective cutting and for applying picks appropriate for the strata, the parameters used are indexed in Table 2.

It is evident, from Table 2, that line spacing and pick imposition have received greater attention in pick configuration. In engineering parameters, area and sweep volume have been used most.

Hekimoglu (1991) compared longitudinal and transverse cutting heads to show that consistency of product size is likely higher in the transverse type while arcing. In the case of the longitudinal type RH, the exertion of pick force is comparatively low while arcing and lowering. Eyyuboglu and Bolukbasi (2005) investigated the effect of circumferential pick spacing on the cutting head and conducted a force balance analysis by taking different engineering parameters into account. Their studies showed that no significant difference existed between the two cutting heads during the simulation. Shiyong (2005) established a programme based on the laneway and working parameters of the EBJ-132A roadheader to trace cutting head position and concluded that pick spacing plays an important role when designing a cutter head to attack effectively in different cutting conditions.

Fowell et al. (1987) concluded that the pick locking device influences tool performance and the economical way of achieving drag pick cutting efficiency is to recover worn and damaged tools. Alvarez et al. (2003) conducted an experimental study over two different types of roadheaders (45 KW and 15 t) to excavate a gallery, taking specific energy, cutting rate and tool wear into account. Their results showed that both types of cutting head work properly. Chupin and Bolobov (2019) suggested a high temperature thermomechanical treatment be applied to 35KhGSA steel which is mainly used for sandstone cutting.

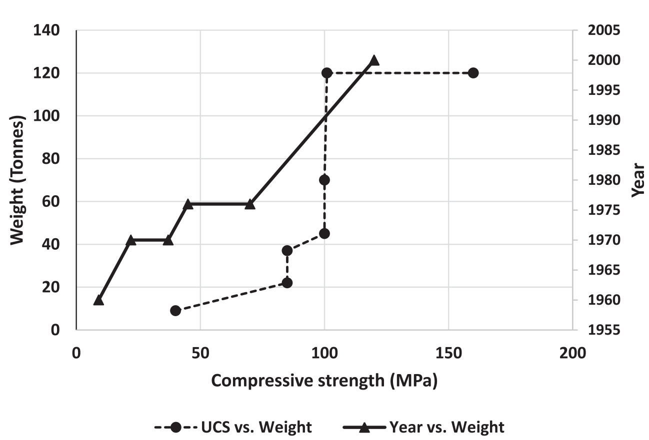

Fig. 2. Correlation between weight and compressive strength (drawn after Schneider, 1988; Tucker, 1985).

The result shows that there is a total increase of 23% in hardness and 38% of wear reduction as compared to the case in the conventional heat treatment process.

Kotwica et al. (2010) developed a cutter head trajectory for hard rock mining that underwent a field test on the KR150 roadheader and is an adaptable modernisation of the cutter head. Kotwica (2011) evaluated the problem encountered with the tangential rotary pick of the boom and presented a solution to counter the rapid wearing of the picks using appropriately placed water jets on the cutter head. Mezyk et al. (2019) developed a cutter drum powertrain system which includes a permanent magnet inside the cutting drum. The new system showed improved dynamic performance but experienced increased vibration during cutting. The focus is then on the angular velocity of the cutting drum which allows better control over cutting drum angular speed.

Hurt and Morris (1985) developed a computerized cutter head design for the roadheader that was also implemented on the Dosco-MK3 heavy-duty roadheader which worked successfully, worldwide. Rostami et al. (1994) developed a computer programme for optimizing the design of the cutterhead to improve machine performance and production. Average cutting force applied by the cutter head is simulated by $F_n = A{\cdot}P^b$ where F_n is the normal force, P is the penetration and A and b are the coefficients determined by the cutting test. Fowell et al. (1994) predicted the performance of drag tools by taking compressive strength as a major parameter. Tiryaki et al. (2001) developed a computer aided design programme to design the cutting head and improve its life span. Before designing, a laboratory test was conducted for triple tracking to access vibration analysis through a programme (*VAP*). Ergin and Acaroglu (2007) developed a computer programme to define roadheader stability with both cutting head types on the basis of four states: turning around the vertical axis, turning to the side, turning to the back and sliding. Li et al. (2012) derived a dynamic equilibrium equation for the performance of the boom-type cutter head using *ANSYS/LS-DYNA* software to simulate the cutting process and achieve main kinematic parameters and found that the cutting performance of the machine is also dependent on machine characteristics such as machine weight, machine power, cutter head type and types of cutter. It was found that the transverse type cutter head with mini-disc cutters could increase roadheader stability in hard rock conditions.

In spite of these developments, cutterhead selection and cutting tool configuration are still very difficult to assess. Cutter head selection is also based on the performance under different geological conditions.

3.2. Influence of geology on roadheader performance

Several rock properties affect the cutting force of a RH. Uniaxial Compressive Strength (UCS), Brazilian Tensile Strength (BTS), quartz content, Ratio of UCS to BTS, and Cone indenter hardness, tangent Young's modulus, density, porosity, static elasticity modulus, shore scleroscope hardness, specific energy, rock quality designation, Rock mass cuttability index, Cercher abrasivity index and point load strength, are some of the parameters of rock that are found to influence RH performance. The roadheader can cut fractured or closely jointed rocks of up to 160 MPa of UCS that has a bearing on the consistent development of roadheader machine power and weight (Pandey et al., 2017). Bilgin et al. (1997) investigated the geological factors, construction method and the physical and mechanical properties of rock formations on two different roadheaders viz. *ALPINE ATM 75* and *EICKHOFF ET 250*. Thuro and Plinninger (1999) developed a correlation between geological parameters, cutting performance and bit wear to predict tunnel stability for major tunneling projects. Thuro (2003) proposed a correlation between geological parameters, cutting performance and bit wear to determine tunnel stability.

Yilmaz (2005) determined that the ratio of uniaxial compressive strength to tensile strength and compared the same with the cutting efficiency of drag pick cutting. He observed an increase in cutting efficiency in rocks with higher brittleness. Ebrahimabadi et al. (2012)

Table 1
Classification of Roadheaders.

Tucker (1985)			Atlas Copco-Eickhoff (Schneider, 1988)		Neil et al. (1994)	
Year	Weight (tonnes)	Compressive strength of rock to be cut (MPa)	Class	Weight (T)	Longitudinal Type	Transverse Type
1960	9	40	0	< 20	Milling type	Ripping type
1970	22 to 37	85	I	20–30	Borer type	
1976	45 to 70	100	II	30–50	Axial head	
2000	120	100 to 160#1	III	50–70		
		#1 – if fractured or laminated	IV	> 75		

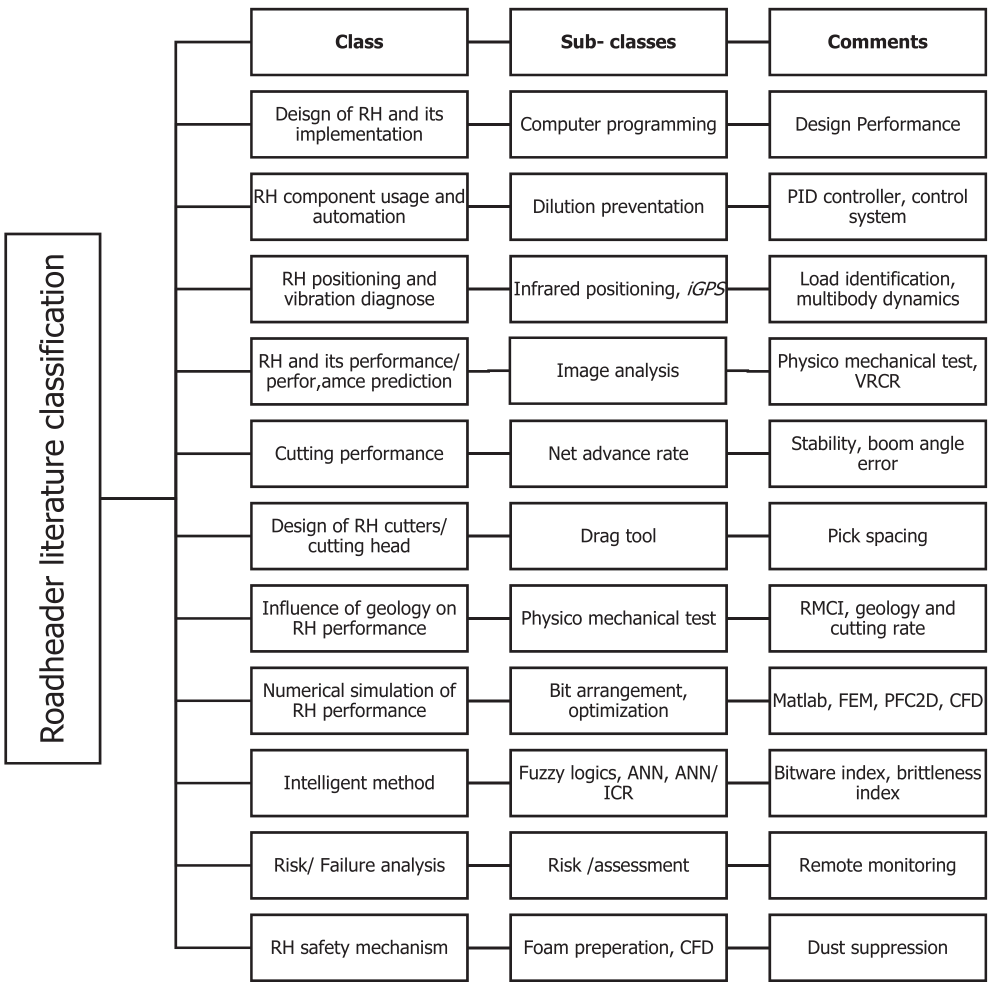

Fig. 3. Classification of Roadheader literature.

claimed a universal model to access roadheader performance for all kinds of rock strata with the help of the rock mass brittleness index (*RMBI*). They related intact and rock mass characteristics to machine performance. Pandey et al. (2017) concluded that the impact of the physico-mechanical properties of the rock mass are the most influencing parameters impacting the performance of the roadheader.

Bilgin et al. (2004) investigated geological impact on a 90KW shielded roadheader with respect to site conditions, first with horizontal phase and, next, with a 9° inclination, and concluded that the inclination helps to increase *ICR* from 10 to 25 m^3/h. The results show that *ICR* increases with respect to increase in water content from 3.5 to 11 l/min when plastic limit and the amount of Al_2O_3 content of the rock is low. Li (2000) developed a mathematical model based on the forces acting on the cutting head. According to him forces on structurally complicated and uncomplicated seams are distributed according to *Rayleigh* and *Chi-sup* functions. Wen-liang (2013) derived a kinematic model based on the elevation of the site and the turning mechanism of the roadheader.

3.3. Cutting performance

Cutting performance is a term used in underground excavation to illustrate the influence of cutting rate and cutter wear parameters in different geological conditions. Several studies such as coordinate transfer, laboratory trials to access cutting rate, stability while cutting, comparison between performance of different types of roadheader etc. can be traced in literature.

Fowell and McFeat-Smith (1976) conducted a lab test on in situ samples to monitor the performance of DOSCO RH for the construction of roadway drivage of Blackhall colliery, County Durham. The mechanical parameters of RH were also correlated with rock mass properties and discussed the factors influencing the cutting performance

Table 2
Pick spacing parameters.

Sl. No.	Authors	Pick configuration										T	Engg. parameters					T
		1	2	3	4	5	6	7	8	9	10		1	2	3	4	5	
1	Evans (1972)					√	√					2	√	√				2
2	Roxborough (1973)					√	√					2	√	√				2
3	Hurt and MacAndrew (1981)	√				√	√					3	√	√				2
4	Hurt et al. (1982)	√		√	√	√	√					5	√	√				2
5	Hekimoglu (1991)								√		√	2				√	√	2
6	Hurt and Morris (1985)	√	√			√	√		√	√		6	√	√				2
7	Hurt and MacAndrew (1985)	√	√			√	√			√		5	√	√				2
8	Hekimoglu (1995)			√	√			√			√	4			√	√	√	3
9	Fowell and Johnson (1981)			√				√				2			√			1
10	Eyyuboglu (2000)											0			√			1
	Total Cites	4	2	3	2	6	6	2	3	2	2	31	6	6	3	2	2	19

Pick configuration: 1. Pick spacing, 2. Lacing type - Graded lacing, 3. Circumferential pick spacing, 4. Equal spacing, 5. Line spacing (picks), 6. Pick imposition, 7. Lacing, 8. Pick grouping, 9. Pick force, 10. Boom force; T is total.
Engineering (Engg.) parameters: 1. Area, 2. Sweep volume, 3. Angle of wrap, 4. Torque, 5. Specific energy.

respectively. They defined the specific energy as a ratio of the cutterhead power and ICR. However, the classification in terms of RQD proposed by them showed lot of scatter. McFeat-Smith and Fowell (1977) developed a curvilinear regression equation of sedimentary rocks to describe the cutting rate, tool wear and chip size of the debris based on laboratory test with actual cutting performance of RH. Fowell and Johnson (1981) presented performance prediction of boom type tunneling machine by taking cutting rate and tool consumption from intact rock properties into account. Their work briefly touches the utilization factors and parameters influencing the cutting performance for the assessment of a particular project. However, Bilgin et al. (2004) observed that performance criterion of the Mcfeat, Smith and Fowell is biased towards the joint density. Additionally, the models presented by Rostamiet al. (1994) and Rostamiet al. (1994) have received more attention due to the fact that the sand model incorporates full scale cutting test and identifies energy transfer coefficient that has a bearing on the roadheader utilization.

Guo et al. (2002) developed an equation using coordinate transfer by employing pick locus, velocity and acceleration of longitudinal cutting head. Using simulation, he showed that pick velocity and acceleration increase rapidly with rotation velocity. Hekimoglu and Ozdemir (2004) carried out laboratory trials to simulate the actual cutting position and angle of wrap in tool lacing and investigated that higher *RPM* might give poor performance due to higher tool force in the presence of greater angle of wrap. Bilgin et al. (2005) proposed statistical analysis to assess the net advance cutting rate on the basis of a laboratory tests on big blocks of rocks with a linear cutting machine.

Keles (2005) conducted a study on the medium weight milling type roadheader (*MK-2B*) by carrying out a physico mechanical test which, in turn, shows that the *ICR* instantaneous cutting rate has a strong correlation with specific energy. Acaroglu and Ergin (2005) determined the stability of the roadheader using a computer programme and investigated the effect of different cutting shapes. They concluded that the increase in tilt angle may negatively affect the sliding momentum of all cutting states. Acaroglu and Ergin (2006) developed a model to determine the stability state of the roadheader by examining the turning moment of the vertical axis, turning to the side, turning to the back and sliding to observe the Stability Index for different modes of cutting. Their results showed that turning about the vertical axis is one of the most critical states while arcing.

Fu et al. (2019) developed a pose detection method on the basis of an ultra-wide band pose detection system (*UPDS*). The *UPDS* system is used to access data related to heading, rolling and pitch angles. The UPDS involves three positioning algorithms: Indirect positioning algorithm (IPA-D), Taylor series expansion algorithm (Taylor-D), and Chan positioning algorithm (Chan-D). The comparison shows that IPA-D gives more precise results in both narrow and long roadways.

Though the cutting performance of roadheaders is a critical factor, the literature available is not adequate to address all types of roadheaders and under different conditions. Future research may need to focus on a coherent understanding of the cutting efficiency of various types of roadheaders under different geological conditions to enable informed decision making on the choice of roadheader to be deployed in specific situations.

3.4. Roadheader positioning and vibration diagnosis

The positioning of the boom is critical to achieve high production rate. To monitor and control the cutting section, attention has to be given to the positioning of the boom-type roadheader. Any mismatch in the cutting action may result in vibrations that ultimately affect the performance of the RH. The positioning of the roadheader thus plays an important role in the reliability of the roadheader.

Li and Han (2008) proposed a parallel link, work coordinate system through a coordinate transformation matrix that is relative to the tunnel coordinate for regulating forward and inverse problems to achieve better automatic control, monitoring the cutting section and instruct tunnel operations. Du et al. (2012) proposed an error encounter strategy of the pose of the boom type *RH* to work more efficiently by including adjustment of boom, shovel and support to reduce error and correction of cutting position contour.

Tao et al. (2017) developed an *iGPS* multipoint measuring system to assess even slight deflections and displacements of the roadheader on the basis of a random error transfer equation. Tao et al. (2018) devised an *iGPS*-based single station, multipoint, time-shared position and attitude measurement system through coordinate measurement. Further, they used the error transfer equation, deduced from mathematical modelling and random error modelling theory, to have better control on the positioning of the RH.

Vibration monitoring is very important for RH structure and design optimization as well as for researching fault diagnosis. The machine vibration correlates well with RH performance and thus determines its reliability. In the era of full mechanization, data from various sensors along with mathematical models are employed for vibration diagnosis. Li and Wu (2008) obtained a sinusoidal harmonic motion based on *ADAMS* vibration analysis module. They observed that 20 Hz, 29 Hz, 120 Hz and 134 Hz are the sensitive frequencies that determine the displacement response and mechanism of cutting of a RH. Jianguang (2012) established a mathematical model to analyse amplitude and frequency of components vibration of RH. Li et al. (2013) determined the vibration characteristics of RH by Lagrangian-Laplace transformation, natural frequency and three orders vibration mechanism is used to calculate the displacement response of longitudinal type RH with the help of pseudo-excitation method.

Ma and Liu (2013) developed a model to determine the motor excitation force on the star wheel loader. They determined RH failure position by analysing vibration, stress and strain of the rotation plate. Liet al. (2013) developed a load identification method based on vibration and stress signals by taking rock sample cut by *EBZ260 RH*. They obtained the results by determining a relation between average energy of vibration, acceleration and average stress that provided indirect measurement of dynamic load.

Dolipski et al. (2014) proposed a model on the basis of discrete structure for the analysis of vibration of masses acting on the centre part of the boom, the extendable part (telescope) and a reduction gear with transverse cutting heads and showed that the excitation of vibration is the effect of rock cutting. Liu et al. (2015) developed a multibody dynamic theory model for the bearing plate to assess vibration characteristics, which resulted in a frequency response diagram for RH system vibration and the load analysis of the bearings. Cheluszka and Mann (2019) developed a photogrammetric method to access cutterhead vibration using: an accelerometer mounted on the cutting head and high-speed camera connected with TEMA 3D software. The velocities and cutting moment recorded by the accelerometer and high-speed camera is used to determine acceleration. The method was then applied to two different cutterheads perpendicular to the floor.

3.5. Roadheader design and implementation

The unique design and construction of the RH provides various advantages such as reduced directional constraints and thus flexibility to deal with cutting conditions with lowering, undercutting, lifting and arcing, without hampering operational stability. The contributions to the design of present day roadheaders are summarised below.

Hurt and MacAndrew (1981) conducted investigations into the cutting tool and concluded that tools do not cut effectively in a cutting line. Tools that can withstand the rough conditions without breaking or cracking was the focus for Zhang and Zhang (2005). They introduced a casting technique design in the S200M RH to prevent forging blank, casting crack, shrinkage cavity and slag inclusion. Such a technique that defines the constructional quality of making a mould for a specific purpose is referred to as a constructing principle for roadheader design.

Rostami et al. (1994) developed a computer program for roadheader design optimization and performance prediction, and used it to check a heavy-duty roadheader of the 100-ton weight class (AM-105). They found that the excavation rate was 40 to 100 ton/hr in such heavy-duty roadheaders.

Performance in field situations, however, depends not only on the rate of excavation, but also on the removal of debris. Zhang et al. (2013) showed that roadheader shovel design determines lifting and dumping performance and delineated the design parameters to choose the perfect design for further computing. The performance of shipping sectors is also determined by the shovel board parameters of roadheader. Burkov et al. (2014) focused on the advantages of the roadheader feeder, and the importance of designing the crank and rod mechanism of the roadheader. Another issue that had to be resolved was dust generated during operations. Barham and Buchanan (1987) suggested a roadheader system with a water jet of up to 700 bar pressure to improve the cutting performance of a boom-type roadheader with low dust, increased pick life and reduced vibration. Seeing what is being excavated helps improve performance. Orteu and Devy (1991) suggested that colour image segmentation, automatic image classification, camera calibration and 3D scenes be used to select cutting performance, to separate rich ore from waste at the cutting stage.

4. Roadheader, its performance and prediction indices

The prediction of cutting performance for any type of excavating conditions, or rock formation in which the machine is deployed, is one of the main factors determining the economics of a mechanized mining operation. The instantaneous cutting rate or *ICR* has widely been applied and modified for specific places. Progress over a period of time or on hourly basis is also taken as a performance predictor but includes several other factors that may not represent cutting.

Gollick (1999) compared the differences in the performance of roadheaders of the past with those of more recent times to predict mining rate. Gehring (1989) proposed a performance prediction model based on the performance of a 250-KW transverse type Roadheader. Bilgin et al. (1990) proposed a performance prediction test based on the *in-situ* observation of many tunnelling and mining projects, and suggested a performance prediction model. Copur et al. (1998) developed a performance prediction model based on the variety of geological

Table 3
Roadheader performance prediction models.

Sl.	Author/year	Model	Comments
1	Gehring (1989)	$ICR = \frac{719}{{\sigma_c}^{0.78}}$ $ICR = \frac{1739}{{\sigma_c}^{1.13}}$	250 kW transverse type *RH,* 230 kW axial type *RH*
2	Bilgin et al. (1990)	$ICR = 0.28P(0.974)^{RMCI}$	*In-situ* observations $RMCI = \sigma_c(\frac{RQD}{100})^{\frac{2}{3}}$
3	Rostami et al. (1994)	$ICR = k\frac{P}{SE}$	*ICR* to specific energy relation
4	Copur et al. (1998)	$ICR = 27.511 \times e^{0.0023 \times RPI}$	Rock and *RH* cutting
5	Thuro and Plinninger (1999)	$ICR = 75.7 - 14.3 ln\sigma_c$	132 kW *RH*
6	Balci et al. (2004)	For d = 5 mm, $ICR = 0.8\frac{P}{0.37UCS^{0.86}}$ For d = 9 mm, $ICR = 0.8\frac{P}{0.41UCS^{0.67}}$	Energy transfer ratio
7	Keles (2005)	$ICR = 163.93{\sigma_c}^{-0.5737}$	*ICR* and rock properties (MK2B Milling type *RH*)
8	Ebrahimabadi et al. (2011b)	$ICR = 5.56RMBI + 0.60a - 8.17$; $ICR = -0.18SE^3 + 28.57SE - 92.82$	Axial type *RH* (DOSCO MD 1100) $RMBI = e^{BI}\left(\frac{RQD}{100}\right)^3$
9	Ebrahimabadi et al. (2012)	$ICR = 35.22e^{-0.54\lvert logRMBI \rvert}$	For axial type
10	Comakli et al. (2014)	$ICR = k\frac{P}{SE}$	Small scale linear cutting tests, Cerchar abrasivity test & physic mechanical tests
11	Kahraman and Kahraman (2016)	$ICR = -0.88\sigma_t - 0.54n + 25.01$	Correlation of physico-mechanical properties with *ICR* values (11 equations)
12	Choudhary et al. (2017)	$ICR = -0.18SE^3 + 28.57SE - 92.82$	75 Kw Dosco *RH*

formations and the equation derived to estimate *RH* cutting rate which shows that heavy duty *RH* can cut rock formations with *UCS* from 100 MPa to 160 MPa in closely jointed or fractured rocks. They determined that, for evaporitic rocks, $ICR = 27.511 \times e^{0.0023 \times RPI}$ where *ICR* is the instantaneous cutting rate, *RPI* is the rock penetration index and *e* is the base of natural logarithm. Thuro and Plinninger (1999) derived a prediction model based on the performance of a 132 KW RH.

Ning and Zhang (2004) established a mathematical model of correlation between working parameters and laneway section dimensions to analyse working mechanism and cutting unit. Balci et al. (2004) defined *k* as the energy transfer ratio, usually assumed as 0.8 for roadheaders. Keles (2005) determined the instantaneous cutting rate (*ICR*) of the boom type, medium weight milling type roadheader (*MK-2B*) by regression analysis to correlate *ICR* and rock properties and established that *ICR* is having highest correlation with lab cutting specific energy i.e. ($R^2 = 0.8411$). Rostami et al. (1994) concluded that the specific energy (*SE*) method is a simple procedure for quick performance prediction for the RH. Sutoh et al. (2010) developed a database from different sites for the performance prediction of the 300 KW heavy weight transverse type roadheader.

Ebrahimabadi et al. (2011a) developed a performance prediction model based on discontinuity orientation and specific energy *SE* on the *DOSCO MD 1100* roadheader and showed that *ICR* may successfully be used for performance prediction. Ebrahimabadi et al. (2011b) developed a performance prediction model for medium duty RH based on Rock Mass Brittleness Index (*RMBI*) and showed that the *RMBI* is highly correlated with the instantaneous cutting rate (*ICR*). Abdolreza and Siamak (2013) developed an empirical relation based on rock mass properties and machine parameters to predict roadheader performance. Comakli et al. (2014) suggested a performance prediction model ($ICR = k\frac{P}{SE}$) on the basis of small scale linear cutting tests, the Cerchar abrasivity test and physico-mechanical tests, where the regression model is derived for the specific energy (*SE*) of a metallic ore. Kahraman and Kahraman (2016) developed performance prediction for the *Dosco Mk-2B* roadheader using multiple regression analysis by comparing physico-mechanical properties with *ICR* values. It was found that point load test and water absorption by weight have a high correlation coefficient i.e. $R = 0.89$.

Yasar and Yilmaz (2017) developed a performance prediction model based on vertical cutting rig (*VRCR*) to investigate optimum cutting condition, also performing several cutting tests were recorded on the core samples collected by two roadheader sites. Cheluszka et al. (2017) conducted studies on the dynamic loading cutting condition of the transverse cutting head and developed a correlation between load and energy, including angular speed of cutting to regulate speed by adding an inverter drive system with changing supply voltage frequency of an asynchronous motor. Table 3 summarises information about some important RH performance prediction models.

It was found that it is very difficult and expensive to determine specific energy (*SE*) from small-scale or full-scale cutting tests. This is why some researchers investigated the relation between *SE* and rock properties to suggest empirical equations for estimating *SE*. Correlating *SE* with *UCS* and *BTS*, for some rock and ore types, shows that the relation between *SE* and the product of *UCS* and *BTS* has a better correlation coefficient than that of the relation between *SE* and both *UCS* and *BTS* respectively.

4.1. Roadheader component usage and automation

As mentioned earlier the roadheader has various components or assemblies such as cantilever link, telescopic boom, drum, cutting picks and conveyor unit. The components have been evolving over time, especially for reducing manual operations by automation. This section will provide a brief overview of the literature that led to the evolution of the components for automation.

Raffoux and Janti (1986) developed a computerised sensing technique to perform on-line image processing and boom control in a potash mine in Spain to detect mineral distribution from the face. Jinhua (2004) deliberated on the status of mines in China wherein rapid drivages and bolt support technologies were taken into account to run highly mechanized coal mines. Wang et al. (2011) analysed key techniques such as cantilever excavator, cutting ability, section monitor, the design of the critical component, arrangement and stabilization of roadheader excavation.

Most experimental work for roadheader automation focused on underground coal excavation, remote control and real time monitoring. Gao et al. (2011) developed an automatic control of swing speed, motor current, hardness of coal based on *PID* and reported a 5% control precision according to coal industry standard MT/T971-2005. They claimed a novel electrical control system for the boom-type roadheader for automatic control of laneway section, autodetection of body section, traction and speed regulation.

Wu et al. (2011) developed a remote monitoring control system for the roadheader with the help of *PCC*, an industrial computer, the Linux operating system and mine loop network. They also developed an automatic protection system which responded within 20.6 ms in comparison to the required automation protection time of 0.1 s.

Wang and Song (2012) developed a mathematical model that included a relationship between the mechanical and electrical parameters of the *RH,* for control automation to drive a robot roadheader that, in turn, resulted in a consistent control system design. Suyu et al. (2013) devised a remote-control system for fully mechanized machines, with real time monitoring, with an option for remote fault diagnosis and alarm. Roman et al. (2015) developed a remote control-based roadheader system with inbuilt infrared sensor to reduce emergency situations encountered during an outburst of coal that improved the position reliability of the roadheader. In order to improve the visual control of the operator they deployed an infrared sensor in the system. Dolipski et al. (2015) proposed a *PID* controller-based rotational cutting speed control system to reduce energy consumption by transverse roadheaders. Tian et al. (2015) introduced a dynamic characteristics-based transfer function model for automation in cutting and profiling control systems for roadheaders. Heyduk and Joostberens (2017) designed an angular speed control system based on *cRIO* and *cDAQ* devices (National Instruments) and simulated the results in both normal and emergency conditions.

4.2. Risk analysis and failure analysis

Risk analysis is an integral method of investigation while deploying the RH in a project. Since, the cost of equipment is quite high and its failure during operations can lead to significant losses, risk analysis provides a basis for decision making. Moreover, since the operation of the RH is continuous, failure in components like link, crank, hydraulics and gear misalignment also pose a risk to operations.

Ma et al. (2012) conducted a survey using a risk matrix method to analyse the risk of the boom-type roadheader in a subway tunnel. Sabanov et al. (2018) proposed a risk assessment method of the roadheader for comparing the advantages and disadvantages of selective extraction of limestone in an Estonian mine and also discussed the sustainability of the roadheader in risky conditions. Ye et al. (2009) proposed a modern spectrum analysis method to diagnose the failure of the roadheader in adverse geological conditions while using real time information through the internet to detect failure in advance.

To supervise the machine automatically, Xu et al. (2010) developed a remote monitoring and control system to supervise roadheader application whose main purpose is to assess failure and generate alarm in such a situation. Wu et al. (2011) implemented an operational failure mechanism to diagnose the physical properties of the roadheader's hardware and software through real time monitoring. Yang et al. (2012) introduced black box hardware with a *SQLite* embedded database for fault diagnosis and determination of machine life cycle.

4.3. Roadheader dust suppression

Exposure to dust in mining continues to be a major risk to the health of workers. Dust particles such as coal dust, silica dust and other finely powdered materials, can damage lungs and airways. To overcome such problems, dust suppression technology has been introduced.

Wang et al. (2013) developed a new foam preparation system and application method in the Zhuxianzhuang coal mine, China to overcome dust generated by the RH. Their results showed that respirable dust exposures were reduced from 540.2 mg/m^3 to 84.3 mg/m^3 with the application of foam.

To study the mechanism more effectively, Han et al. (2014) used computational fluid dynamics (*CFD*) to simulate the air flowing field and distribution of particles ejected by the sprayer mounted on the cutter head. The results showed that the effect of ventilation on the droplets is faint in gentle breeze conditions. Lu et al. (2015) developed a foam preparation method with a jet device using a venturi foam generator to reduce threat to workers' health. They also report that the efficiency in suppressing total dust and respirable dust were 85.7% and 88.1% at driver position. Liu et al. (2017) investigated a water jet effect of the roadheader on rock breakage by reducing cutting torque and thrust force by maximizing cutting efficiency while achieving 70% dust suppression. Wang et al. (2019) developed a 3D CFD model and proposed a dust mitigation strategy to address respirable dust emission characteristics. Joy 12CM27 continuous miner is used for field investigation and it was found that the total exposure level of dust is greater than 500 mg/m^3. The main reason behind dust emission was blunt picks and missing nozzles. The model results in 90% control over dust characteristics.

4.4. Simulation of roadheader performance

Simulation includes the merging of various new techniques that bridge the gap between conventional and new innovative techniques. Simulation includes computational fluid dynamics (*CFD*), series quadratic programming (*SQP*), multi objective optimization, *MATLAB* simulation such as Taylor series expansion and proportional integral derivative (*PID*), finite element simulation (*FEM*), particle flow code (*PFC*), multi-layer perceptron (*MLP*) and Caffery transform. Simulations by such methods have been used to address a multitude of issues pertaining to the RH. Several mathematical methods have been used by different authors and complex equations addressing RH issues have been solved with the help of MATLAB as summarised in Table 4.

Sullivan and Van Heerden (1993) reviewed the numerical modelling by computational fluid dynamics to tackle the dust generated by RH in underground coal mining. Zhang and Yang (2005) carried out a study on load fluctuation on the cutting head with the help of series quadratic programming (*SQP*), which optimized the bit arrangement and reduced fluctuation of load.

Zhang and Zeng (2005) proposed a multi objective optimization strategy to decrease energy consumption and load fluctuation on the cutting head by taking the average performance of picks and number of cutting picks. Li et al. (2013) proposed a finite element method (*FEM*) that simulates the dynamic properties of coal and rock affecting the cutting load. They claimed that their analysis provides a methodology to select cutting head in different geological conditions. Hongxiang et al. (2013) developed a *PFC2D* model to study rock fragmentation by RH pick and concluded that damage in hard rock is more remarkable than in soft rock. Chuanming (2013) proposed a multi body dynamic analysis method for the planetary reducer for the roadheader arm with the help of *Pro/E* and *ADAMS Software(s)*.

Han et al. (2014) proposed a particle tracking technology based on computational fluid dynamics (*CFD*). They showed that, under the normal forced ventilation, the droplets will drift to return towards the air side and the concentration of droplets in other parts around the cutting head decreases. Wang et al. (2014) suggested an environment friendly remote-control system to enhance labour safety and also developed a numerical simulation of cutting head swing type of transverse type RH.

Zhixin and Dawei (2015) established a multi-body dynamic model for the longitudinal RH to examine vertical vibration, by simulating hydraulic damping with vertical amplitude of cutting head on the basis of *ADAMS* software. Wu et al. (2015) established a mathematical model, based on boom position and the behaviour of boom positioning movement. Their simulations are based on measurements taken by laser profiler which show that the error from a 25 m distance of measurement is 0.0823 m on the X-Axis. In the case of roll angle, however, the measurement error is 2.0184° which satisfies measurement accuracy requirements. Seker and Ocak (2017) proposed a performance prediction of the roadheader on the basis of 6 different machine learning algorithms such as Zero R, random forest (*RF*), Gaussian process, linear regression, logistic regression and multi-layer perceptron (*MLP*).

4.5. Intelligent methods and their use

In order to bridge the gap between conventional and automatic handling, performance rating, laneway mapping or in the broad concept of predicting performance, artificial intelligence (*AI*) plays a vital role. Artificial intelligence includes gene algorithm, fuzzy logic, Takagi–Sugeno (TS) fuzzy method, Kohonen self-organizing feature (*KSOFM*) and genetic programming (*GP*).

Acaroglu (2006) implemented an analytical hierarchy process, a multiple attribute decision making method, to select the most suitable roadheader for the Cayirhan Coal Basin. Zhang et al. (2008) developed optimization of the cutting head based on a genetic algorithm and a multi-objective fuzzy method, which resulted in reliability enhancement and better energy utilization of the RH. Jasiulek et al. (2011) presented an artificial neural network machine control system for better

Table 4
MATLAB-based analysis and simulations for performance prediction of roadheaders.

Author(s)	Main focus	Comments
Li and Han (2008)	Wavelet packet analysis method	Disintegrated signal of cutting direction, reconstructed dominating components of vibrations from wavelet packets through a power spectrum
Li et al. (2009)	Profile cutting model of roadheader	Space kinematic and system simulation
Li et al. (2009)	Load model based on force analysis of cutting head	Load curve and resultant forces acting on the horizontal cutting head simulation
Wang et al. (2009)	Proportional integral derivative (*PID*)	Simulated for electric and hydraulic control system and resulted in good quality control
Mu et al. (2011)	Positioning of boom by controlling cutting arm	Simulation of automatic compensation for cutting section, analyzing lifting and swing actions of cutting arm
Xiaohua and Jiyang (2013)	Dynamic model based on mechanical-hydraulic coupling	Defined the relationship between lifting and turning moment of the boom. Their results show that the vibration of the lifting moment is greater than in turning
Cheluszka and Gawlik (2016)	Dynamic model based on the different subassemblies of RH	Solved 19 non-linear ordinary differential equations of the *2nd* order to assess the result of vibrating masses
Fu et al. (2017)	Ultra-wideband pose detection system (*UPDS*) to create *3D* coordinates system	Proposed a fusion positioning algorithm based on Caffery transform and Taylor series expansion to yield the approximate coordinates in X, Y and Z direction.

machine performance and quick response to sudden changes in machine operation. Jasiulek and Świder (2013) developed an artificial intelligence system to determine the angular speed of the cutter jib while cutting roadway drivages. Yazdani-Chamzini et al. (2013) developed a RH performance prediction model using the Takagi–Sugeno (TS) fuzzy system that is based on subtractive clustering and is capable of deriving the uncertainty and complexity between rock properties and roadheaders.

Wang and Zhang (2013) proposed a fuzzy control model for directional adjustment and forward control for improving the excavation procedure. Avunduk et al. (2014) devised a performance prediction model for roadheader study by *ANN* including a data set of *UCS*, *RQD* and measured *ICR*. They demonstrated that *ANN* provides a better solution than do empirical models.

Salsani et al. (2014) concluded that the predictive capability of artificial neural network is better than multiple variable regression analysis for the performance prediction of the *RH* while studying geological and geotechnical characteristics of site conditions. Ebrahimabadi et al. (2015) suggested a Neural network based cutting performance (*ICR*) of a medium duty roadheader in the Tabas coal mine which includes the multi-layer perceptron (*MLP*) and Kohonen self-organizing feature map (*KSOFM*). They stated that the *MLP* predicts more reliably while *KSOFM* is an efficient way to understand system behaviour. Faradonbeh et al. (2017) developed a genetic programming (*GP*) and gene expression programming (*GEP*) based model to predict roadheader performance by employing instantaneous cutting rate (*ICR*), uniaxial compressive strength, Brazilian tensile strength, rock quality designation, influence of discontinuity orientation and specific energy. Asadi et al. (2017) proposed an *ANN* model on the basis of a data set gathered by taking three major parameters that influence bit wear viz. brittleness index, *RQD* and instantaneous cutting rate.

Wang and Wu (2019) Developed a cutter trajectory planning section to experience the cutting of a tunneling machine. The Design includes multisensor parameters, the environment of roadway section which is modelled by grid method. The ant colony algorithm is used to plan the optimal cutting trajectory. The algorithm is iterated 50 times which gives comparatively better result than particle swarm optimization.

5. Case histories

Simmons (1993) conducted a comparative analysis of the performance of RHs versus tunnel blasting in which 2 RHs from different manufacturers were used in the excavation of top heading and recorded. Study estimated a pull of 3–3.6 m by tunnel blasting as compared to 36 m/day while avoiding any major disturbances in the rockmass in case of a Roadheader. Thuro and Plinninger (1998) determined bit consumption rate and low cutting performance of RHs in connection with the geological features available in 4 cases of Germany having different geologies and involved average performance based on the maximum values of UCS and bit consumption. They reported that soft rock formations were associated with problems of water intrusion and delay in removal of debris with RH haulage system and hence the cutting performance reduced.

Thuro et al. (2002) determined that weathered rocks assume key importance as excavation turn out to be labour-intensive along with associated problems. They suggested that investigations to find relationships between excavation parameters, rock strength properties and geological parameters rather than introducing a new classification system for excavability. They also showed the possibilities to measure geotechnical parameters for rockmass excavation by drill blast and cutting by Roadheader. During a case study in Zeulenroda Germany sewerage tunnel, a 130 kW RH performance was estimated by taking work kJ/m^3 (excavated) vs. cutting performance m^3/h into account. The best correlation coefficient was observed was $R^2 = 89\%$. In case of drilling and blasting ammonium-nitrate and gelatin were used and work (kJ/m^3) vs. explosive consumption (kg/m^3) were correlated. The correlation coefficient was calculated to be $R^2 = 67\%$.

Genis et al. (2007) studied the geotechnical conditions of Dorukhan Tunnel, Zonguldak, Turkey. During observations, they found that for the excavation of phyllite/heavily broken phyllite, tectonic breccia and moderately weathered granodiorite smooth blasting and Roadheader as excavation method was better. Tunnel geometry used by them included top heading of 1.5–2 m and a bench of up to 2 m, respectively. Rockmass quality was determined in terms of RMR, Q System, GSI, RMi and NATM methods. Authors concluded that the rock mass properties and numerical modelling are not exact methods to define the tunnel behavior. They further concluded that for the refinement of both the models back analysis is the only alternative while taking results of instruments installed into account.

Mauriya et al. (2010) described the Himalayan region tunneling project including mainly hydro-power, water supply and sewerage tunnels. They found that drilling and blasting remains dominant option over mechanical excavation. Paper reviews the challenges in tunneling, geological problems in case of thrust zone, shear zone, folded rock sequence in-situ stresses, rock cover and ingress of water, in detail. They also observed that tunneling rate with conventional drill and blast method varies from 7.5 m to 81 m on monthly average basis depends on lithology and geometry of the tunnel. Hong (2010) summarized the development of mechanised roadway technology, from the past 40 years, in China, taking existing problems such as dust control efficiency, component reliability and automatic control into account, to develop the appropriate technology.

Ocak and Bilgin (2010) studied the site condition of Istanbul Kadikoy–Kartal metro tunnels and compared mechanical excavation by roadheader to drilling and blasting. They showed that the production rate of the RH is 218.3 m^3/day whereas drill and blast were found to produce 187 m^3/day. Choudhary et al. (2017) reported a study of a 75 KW *Dosco RH* in two different coal mines, 2 m high and 4.5 m wide on the first location, and 2.8 m high and 4.2 m wide at the second, which showed that the roadheader was performing below predicted levels. The main reasons for underperformance identified by them were inefficient muck disposal, poor workmanship, lighting and insufficient ventilation.

Brino et al. (2013) from a study in Gypsum mines observed that the selection of excavation method is defined by the orebody morphology and characteristics. They reported that in that Gypsum mining RH costs were less than that of drilling and blasting and is the best suited method. They recommended optimisation of fuel consumption along with use of conveyor belts for sustainable operations with RH. Mohammadzadeh and Ebrahimabadi (2016) defined a risk matrix to compare drilling blasting and RH excavation and identified that RH application has a lower risk in comparison to blasting. They also suggested that transverse type cutterhead is better than the longitudinal one. They, in order to eliminate operational issues pertaining to RHs, even recommended realignment of tunnels so that hard rock forms the bottom of tunnel. Comakli (2019) monitored the performance of RH in terms of ICR, CAI and other mechanical tests of eight different cold storage cavern excavations in pyroclastic rocks. They developed a new relationship between the UCS and RH performance for rocks up to a UCS of 10 MPa.

6. Current and future trends of development

Despite the advantages, the RH has some disadvantages such as high pick consumption rate in very abrasive rocks, making excavation uneconomical due to frequent bit changes with increased machine vibrations and maintenance costs (Copur et al., 1998). Liu et al. (2019) developed a roadheader-assisted coal cutter (RACC) specifically used for extracting coal on the basis of tensile failure. A new method called cutting inside and spalling outside was also discovered on the basis of column model and beam model respectively. The results show that tensile stress causes more deflection in column model than compressive stress in beam model, comparatively 20% of improvisation in the excavation is experienced. Cheluszka et al. (2019) developed an automatic control system for the roadheader cutting head to access the actual cutting speed. This technique includes a software control system on the basis of the frequency convertor. The feedback system gives text results by varying with assumed control limits in case of cemented or sand blocks.

It is known that the cost of the RH is quite high. Machine selection is performed on the basis of tunnel dimensions and ground conditions that, in turn, determine production rate and bit consumption. Deployment of the RH is mainly dependent on how effectively the performance rating is investigated. Accordingly, if not selected as per geological conditions, the consequences can be economically detrimental to projects deploying the RH. Hence, machine performance must be predicted before starting tunnelling with a RH to make operations profitable, productive and competitive. Considering the versatile nature of the RH, it is expected that such machines will be customised to excavate hard to very hard rock formations also. This would mean balancing the power to weight ratios of the machines i.e. the weight of the machines should not increase exponentially. The focus should thus shift to improving the cutter head and the picks. The picks will need to be analysed for their performance in harder rocks. With the use of modern high strength materials in the picks, the possibilities using the RH to cut hard rocks can become a reality. The cutting mechanism in such types of rocks will need to be revisited with respect to the material used, as well as the spacing and orientation of the picks.

Technological advancement directly becomes an integral part of excavation in today's mining and underground space development. Advancement is not only in design and management systems but also the new properties and computer systems to perform intellectual and even creative functions.

7. Conclusions

The roadheader is a versatile machine that can be deployed in the partial face excavation of soft to moderate hard rocks. There are significant references in the published domain that address various issues pertaining to the roadheader. These references can be classified as: machine design, cutter head design, pick spacing and orientation, machine stability, dust suppression, automation, risk analysis and application of advanced mathematics and neural networks. A comprehensive account of such classes has been given and discussed in the paper. From the cited references it can be deduced than over a significant period of time RHs' have advanced from simple to complex system that can be deployed, even in moderately strong rocks. The performance prediction and monitoring methods have also evolved simultaneously. The advancement in RH has a bearing on economics feasibility as there is a weight-power conflict in such machines. Latest IoT based monitoring methods that provide continuous data on various machine and performance parameters can provide more insight into designing a RH that is in turn with the requirements of individual projects.

Declaration of Conflict of Interest

The authors declared that there is no conflict of interest in this publication.

Acknowledgement

Authors are thankful to the Director CSIR-CIMFR for his permission to publish the paper. Thanks are due to Ministry of Power, Government of India and Central Power Research Institute for research grant NPP/2016/HY/1/13042016. Thanks are due to Gita and KP Madhu for suggestions and editorial corrections.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tust.2019.103148.

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