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Novel rockburst criterion based on the TBM tunnel construction of the Neelum–Jhelum (NJ) hydroelectric project in Pakistan

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ABSTRACT

The assessment of rockburst proneness has become a major technical bottleneck in brittle, and high-strength hard rock under high local stresses. Various approaches or criteria have been used over the years to predict rockburst, many of them were within an acceptable range, while some too conservative, simple and missing comprehensive consideration of rockmass quality and excavation characteristics, particularly during the tunnel construction phase. Aiming at the shortage, a novel rockburst criterion was put forward, which is defined as the ratio between the rockmass strength and the horizontal stress perpendicular to the tunnel axis as determined. First, the rockmass strength based on the Hoek–Brown strength criterion was estimated by accounting for important parameters such as rock strength, brittleness coefficient, the quantitative geological strength index (GSI), the TBM construction disturbance, and the in situ stress. Furthermore, in practical application at the NJ-TBM tunnel, the quantitative models of the geological strength index (GSI) and rock uniaxial compressive strength were proposed based on the boring/specific energy (SE) information and the field penetration index (FPI) recorded in the TBM performance database, respectively. The observations and classification of 26 rockbursts cases in different geological units indicate that the novel criterion greatly enhanced the accuracy and applicability of rockburst prediction during the construction phase, through comparative analysis with the traditional criteria.

1. Introduction

Rockburst is an instantaneous, severe as well as common geo-hazard occurring in brittle, massive and high-strength hard rock under high local stresses (Jenkins et al., 1990; Stillea and Palmströmb, 2003; Ma et al., 2015; Cai, 2016). When the mechanical state of rock was observed to be unbalanced, dynamic instability occurred in which potential energy was released in a sudden, sharp, and violent form, along with other phenomena such as slabbing, spalling, ejection, and throwing (Hedley and David, 1992; Kaiser et al., 1996, Kaiser and Cai, 2012). This catastrophic hazard has constrained the efficient and safe construction of tunnels and introduces greater threats to underground openings, equipment, and worker safety (He et al., 2015; Sousa, 2012). The assessment of rockburst proneness has become a major technical bottleneck in deep-buried tunnel construction (Ma et al., 2015) and contributions toward a better understanding of rockburst events will help develop and advance understanding of rock mechanics.

Thus far, various theories or approaches regarding rockburst prediction have been conducted, focusing on two aspects: field monitoring for real-time rockburst and theoretical analysis based on rockburst failure mechanisms.

The exact location and time of rockburst occurrences are determined using data from appropriate in-situ measurements and testing methods including the microgravity method, the photo-elastic method, the convergence measurements method, the drilling-yield method, and the acoustic emission and microseismic techniques, among others (Chen et al., 2015; Ma et al., 2015). However, monitoring approaches for rockbursts have often been of limited application, due to the expensive and immature nature of the technology caused by the complexity of rockmass and various environmental factors in deep-buried tunnels.

Theoretical analysis based on the rockburst failure mechanism consist of strength, stiffness, energy, instability and fractal theory et al. The corresponding single strength-stress ratio index or stress-strength

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Table 1
The corresponding rockburst criteria and classification items.

Multiple discriminant criteria	Reference	Formula	Rockburst grade			
			No	Light	Moderate	Intensive
The strength-stress ratio index or stress-strength ratio index	Barton et al. (1974)	σ_{ci}/σ_1	> 10.00	10.00–5.00	5.00–2.50	< 2.50
	Russenes (1974)	$\sigma_{\theta\max}/\sigma_{ci}$	≤ 0.20	0.20–0.30	0.30–0.55	≥ 0.55
	Hoek and Brown (1980)		0.34 Minor spalling	0.42 Severe spalling	0.56 Heavy support	0.70 Severe rockburst
	Turchaninov (1978)	$(\sigma_{\theta\max} + \sigma_L)/\sigma_{ci}$	≤ 0.30	0.30–0.50	0.50–0.80	≥ 0.80
	Code for geological survey of water resources and hydropower projects (2008)	$\sigma_{ci}/\sigma_{\max}$	> 7.00	4.00–7.00	2.00–4.00	< 2.00
	Zhang et al. (2012)	σ_1/σ_{ci}	≤ 0.15	0.15–0.20	0.20–0.40	≥ 0.40
The burst energy coefficient	Goodman (1980)	$R = W_E/W_P$	> 1 (Having the rockburst tendency)			
The strain energy storage coefficient	Kidybiski (1981)	$F = W_{st}/W_{sp}$	≤ 2.00	2.00–5.00		≥ 5.00
The brittleness coefficient of rocks	Zhang et al. (2012)	$B = \sigma_{ci}/\sigma_t$	< 15.0	15.0–18.0	18.0–22.0	> 22.0
The integrality modulus		K_v	< 0.55	0.55–0.60	0.60–0.80	> 0.80

Note: σ_{ci} is uniaxial compressive strength; σ_1 is maximum principal stress of in situ stress; $\sigma_{\theta\max}$ is maximum tangential stress of cross section in disturbed zone; σ_L is radial stress of cross section in disturbed zone; $\sigma_{\max}$ is the maximum horizontal stress perpendicular to the tunnel alignment; $\sigma_1, \sigma_{\max} < \sigma_{\theta\max}$. W_E is the elastic strain energy accumulated before rock failure; W_P is the elastic strain energy accumulated.W_{sp} represents the spent energy by plastic deformation during unloading process. W_{st} represents the stored energy in the rocks.σ_t is the tensile strength.

ratio index (Barton et al., 1974; Russenes, 1974; Turchaninov, 1978; Hoek and Brown, 1980;Code for geological survey of water resources and hydropower projects, 2008; Zhang et al., 2012), the rockmass integrality modulus K_v, the brittleness coefficient of rocks B (Zhang et al., 2012), the strain energy storage coefficient F (Kidybiski, 1981) and the burst energy coefficient R (Goodman, 1980) have been proposed and widely applied in practice as long-term preliminary or regional prediction of rockburst tendencies during the exploration phase. The corresponding rockburst criteria and classification items were listed in Table 1.

However, widely used, due to the complexity of rockmass and various excavation characteristics, single rockburst criteria have been found to have some limitations in accuracy and reliability. Take the most common strength-stress ratio index for example, uniaxial rock strength and in situ stress are considered simply, and rockmass quality and excavation characteristics are ignored, resulting in the predicted deviations when evaluating the character of rockbursts.

With the advancements in the understanding of rockburst mechanism, taking into consideration the limitations of the single index criteria, scholars have gradually begun to apply multi-index comprehensive criteria to predict rockburst(Gu, 2001; Zhang et al., 2012;Shang et al., 2013). The relationships depicted in the evaluation indexes are basically conjunctive “and-type” relationships, rarely classified as ”or-type“. Because a rockburst does not represent a clear-cut system due to many uncertainties, a wide range of prediction methods are required, classifying the factors affecting rockburst occurrences as random, fuzzy, matter–element analysis theory, or even both (Adoko et al., 2013; Wang et al., 2015). While the influence factors of rockburst are considered more comprehensively with parallel multi-index comprehensive criteria, it is noted that the validity of existing random or fuzzy models, to some extent, depends upon the subjective understanding of the researchers. Additionally, some parallel multi-index criteria are only applicable to long-term or regional predictions during the design phase. These criteria are limited in applicability and reliability, particularly during the construction phase.

The occurrence of rockburst is closely related to the characteristics of rockmass, in situ stress, geologic structure, and excavation disturbance. Various approaches or criteria have been used over the years to predict rockburst, while some too conservative, simple and missing comprehensive consideration of rockmass quality and excavation characteristics, particularly during the tunnel construction phase. This paper aims to address the above shortage mentioned by taking into consideration the multiple factors present during the tunnel construction phase, and establish a novel criterion to evaluate the rockburst tendency accurately.

In this paper, first, based on the details of geological settings, as well as the in situ and laboratory tests, the detailed statistical analysis of rockburst characteristics and the limitations of traditional criteria are summarized. Then, a novel rockburst criterion is presented using the strength-stress ratio, which is defined as the ratio between the rockmass strength σ'_{rm} and the maximum horizontal stress perpendicular to the tunnel axis $\sigma_{\max}$. The rockmass strength, based on the Hoek–Brown strength criterion, replaces the uniaxial compressive strength σ_{ci} by accounting for important parameters such as the rock strength σ_{ci}, the brittleness coefficient σ_{ci}/σ_t, the quantitative GSI, the excavation disturbance factor D, and the minor principal stress σ'_3. Furthermore, in practical application at the NJ-TBM tunnel, the quantitative models of the geological strength index (GSI) and rock uniaxial compressive strength (σ_{ci}) were proposed based on the boring/specific energy (SE) information and the field penetration index (FPI) recorded in the TBM performance database, respectively. Based on the rockburst database consisting of 26 observations and classification at the NJ-TBM tunnel, the applicability and reliability of the novel rockburst criterion is verified through comparative analysis with the traditional rockburst criteria in the end.

2. The TBM tunnel of the Neelum–Jhelum hydroelectric project (NJ-TBM tunnel)

2.1. Project description and geotechnical conditions

The Neelum–Jhelum Hydroelectric Project is located in the Muzaffarabad district of Azad Jammu Kashmir (AJK), Pakistan (shown in Fig. 1). Just over 11 km of the twin tunnel system will be excavated by TBM, while the remainder will be excavated by drill-and-blast. The maximum depth of the tunnels is nearly 2000 m. In the tunnel areas under deep cover, the rockmass is generally very tight and no large inflows or groundwater pressures have been encountered. Therefore, the rockmass will be considered dry.

The project is located in the Himalayas, a geologically young mountain range of spectacular height that developed as a result of the collision between various continental and micro continental plate fragments during the late Mesozoic to late Cenozoic periods. The main geological formation outcropped is the Murree Formation, except at the tunnel intake, which is partly in igneous or metamorphic rocks belonging to the Panjal Formation.