-RESEARCH PAPER-

International Journal of Mining and Geo-Engineering

IJMGE

IJMGE 56-3 (2022) 293-299

DOI: 10.22059/IJMGE.2022.318957.594892

Prediction of rockburst in water conveyance tunnel: a case study of Gelas tunnel

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Article History:

Received: 12 February 2021.
Revised: 14 October 2021.
Accepted: 05 March 2022.

ABSTRACT

In the presence of undesirable geological conditions, including rock masses with high overburden, crushed zones and faults, folds, dikes, and other abnormalities, rockburst has become a critical safety problem in the Gelas tunnel, a water conveyance tunnel, wherein some sections overlying the strata exceed 600 m. The main goal of this study is to determine the possibility of rockburst and its level along the second part of the Gelas tunnel. In order to study the mechanisms of rockburst occurrence in Gelas tunnel, measurements of in situ stress, geological investigation, uniaxial compression tests, and analytical approaches are carried out. So, in this study, some analytical approaches, including Linear elastic index, Tangential stresses criterion, Brittleness coefficient of rocks, and method of stresses are used to predict rockburst in 17 sections of the tunnel path. The average result shows that all the selected sections in the tunnel path have the potential of occurring rockburst at a range of low to moderate. About 65 percent of the sections are exposed to moderate risk of rockburst occurrence, and the remaining 35 percent are exposed to low risk of rockburst occurrence. The comparison between applied methods shows a lack of consensus conformity among them. The brittleness coefficient of rocks method turned out to be the most conservative approach for predicting rockburst occurrence since by this approach most of the sections in the tunnel path are susceptible to a high risk of rockburst occurrence. According to the average result, fault and Dolomitic zones with high overburden have the highest risk of rockburst occurrence.

Keywords: *Analytical approaches, Gelas tunnel, Rockburst.*

1. Introduction

Rockburst is one of the geological hazards which can occur mostly during deep mining. This phenomenon is known as an immediate unstable failure of rock mass associated with energy releasing [1]. Factors influencing rockburst are divided into internal and external factors: the internal factors include a high geostress, and geological structures; external factors embrace overburden, construction factors, and the shape of the underground cross-section [2].

According to Zhou et al., studies, a review from 1965-2018, there has not been any consensus among researchers on rockburst definition up till now [3]. The first definition of rockburst presented defines it as an out-of-control disruption of rock following a violent release of energy [4]. Recently regarding expression, during deep excavation rock masses undergo high in-situ stresses and maintain an elastic range, so since the stored elastic energy is high enough, it can cause to break the rock [5]. If the site is activated by a certain degree of disturbance like during excavation, the stored elastic energy can be released and be broken the rock mass. And the energy required to break the rock mass is higher than last, but not least rockburst described by Dietz et al. [6].

Rock mass status is an equilibrium level before excavation in the mining area. Hence, the equilibrium status will be destroyed via the digging process, and in situ stress will release during excavation. The released stress is commonly known as "equivalent released load". The release of concentered strain energy will occur suddenly when high stress or the presence of a weak plan cause to break of rock mass [7]. Several factors are useful in the rockburst phenomenon. Based on the results of Sinha and Li et al. geological conditions, and physical and mechanical properties of rock, are two of the factors which can easily affect rockburst occurrence [2,8].

Geological properties and physical characteristics of rocks are the main parameters in underground excavation, which can quickly get out of control. The location and orientation of geostructures such as dikes, folds, faults, and fractures mostly provide burst circumstances. Quantifying is problematic in interplays between bursts and anomalies, and research on this theory varies considerably [1,9,10].

Jiang et al. published a paper containing the fact that faults are the most commonplace stimulants of occurring rockburst, the impact of which is significant due to the discontinuity of the rock masses cut by the fault [11]. According to the study of Kouame et al., when the tunnel face is parallel to a fault or joint strike, it is easy to initiate a rockburst [10]. Wang et al. expressed that a fault varies the strata uniformity and produces stress singularities beside the fault, hence facilitating the process of prompting dynamic instability and rock bursts [12].

The instantaneous release of energy and integrity of strata will be increased by the rising temperature, metamorphism, and recrystallization of rock near dikes [13]. Vieira and Durrheim by studying three dikes came up with the fact that the existence of dikes during tunneling will intensify excess shear strength and, consequently occur rockburst [14].

Naji et al. concluded that shear zones perform as impediments to the accumulation of geostress, which is immediately released as rockburst occurrence [9].

Naji et al. stated that Fold structures act as a barrier to the normal

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distribution of in situ stresses, which result in abnormal stress concentration nearby these structures. Additionally, synclinal, anticlinal, and other fold structures also make the condition worse in an already stressed environment [15].

The potential and severity of rockburst occurrence among varied rock masses are dependent to rock strength, fracturing and fragmentation properties, failure modes, and the loading situations as well. They can be estimated mainly based on the kinetic energy of expelled fragments [16].

In this study, the most common empirical approaches such as linear elastic index, Tangential stress criterion, Brittleness coefficient of rocks, and method of stresses were used to predict rockburst. Consequently, sections with high rockburst potential have been determined. Then, a comparison was made between the applied methods.

2. Evaluation and prediction of rockburst

The stress/strength, brittleness, and deep energy approaches are the most common empirical criterion methods for rockburst estimation [3]. In the literature, numerical simulation experiments were used to complete the great majority of publications linked to the understanding and prediction of rock bursts [17].

Numerical and empirical methodologies can aid in the prediction and evaluation of areas prone to rock bursts. They may, however, have some advantages and disadvantages that must be considered during evaluation and assessment [18]. The fundamental flaw of empirical methodologies is their lack of consistency, which might lead to doubts about their efficacy in some circumstances. Agents associated with these parameters might thus be identified as a possible indicator of the presence of rock bursts. However, numerical rockburst evaluations are reliant on model inputs, and some of the above-mentioned model inputs are irrelevant to the actual physical situation. Furthermore, absolute rockburst classification cannot be achieved from the rockburst of energy due to a lack of adequate energy criteria [19]. When it comes to rockburst, Zhou et al. say that there is no uniformly compromised strategy to expect [3]. Analytical and empirical models both have the property of producing fair findings. They are frequently derived by curve interpolation and have little physical meaning. The most significant benefit is its ease of use for engineering applications; however, a single assessment indicator/index cannot accurately describe the occurrence of rock bursts, and it is difficult to attain the requisite prediction accuracy. Many empirical methodologies have recently been introduced. Based on 220 rockburst occurrences, Farhadian developed a novel empirical approach to classify rockburst behavior in a study. The tunnel rockburst classification (TRC) chart was developed using three indicators: elastic energy index (W_{et}), tangential stress in a rock mass (σ_θ), and uniaxial compressive strength (σ_c) [20]. Wen et al., in a separate study, suggested that coal seam width is an important component in determining appropriate rockburst risk assessment. They devised a method for determining the danger of a rock burst based on the equivalent surrounding rock strength and coal seam bursting liability [21].

2.1. Linear elastic index (PES)

According to Kwasniewski et al., rockburst occurrence can be defined in terms of the elastic strain energy in a unit volume of rock masses which is [22]:

$$PES = \frac{\sigma_c^2}{2E_s} \tag{1}$$

Where PES is Elastic Strain Energy (kj/m^3), σ_c is Uniaxial Compressive Strength (Mpa), E_s is Elastic modulus (GPa).

According to Kwasniewski, the tendency of rockburst is determined based on Table 1 [23].

2.2. Tangential stress criterion (T_s)

In this criterion, both the state of in-situ stress in the rock mass and the mechanical rock property are considered. The prediction of the explosion is defined by this method by relation 2. This criterion takes into account the state of tension in both the mass and mechanical properties of the rock. In this criterion, the potential for rock bursts is predicted using Table 2 [24]:

$$T_s = \frac{\sigma_\theta}{\sigma_c} \tag{2}$$

Where σ_θ is the tangential stress in rock mass surrounding the openings (Mpa), σ_c is the uniaxial compressive strength of rock (Mpa).

According to Wang et al., Table 2 shows the classified index of rockburst tendency.

2.3. Brittleness coefficient of rocks (β)

Brittleness coefficient of rock is known as the ratio of unconfined compressive strength (σ_c) to tensile strength (σ_t) [25], which is defined as:

$$\beta = \frac{\sigma_c}{\sigma_t} \tag{3}$$

In general, β shows the highest severity of the rockburst. The first classified index, β, is shown in Table 3.

2.4. Method of stresses:

Method of stresses uses the lithological character of a rock mass (including tensile and compressive strength) to decide the rockburst possibility [26]:

$$\alpha = \frac{\sigma_c}{\sigma_1} \tag{4}$$

Where σ_c is uniaxial compressive strength (Mpa), σ_1 is the major principle of geo-stress. Table 4 shows rockburst tendency classification based on the approach of stresses.

Table 1. Classification of rockburst tendency according to the Linear Elastic Index [23].

Rockburst potential	$(\frac{kj}{m^3})PES$
Very Low (VL)	<50
Low (L)	50-100
Moderate (M)	100-150
High (H)	150-200
Very High (VH)	>200

Table 2. Classification of rockburst behavior according to the Tangential Stress Criterion [24].

Rockburst potential	Ts
No	<0.3
Low (L)	0.3-0.5
Moderate (M)	0.5-0.7
High (H)	0.7-0.9
Very High (VH)	>0.9

Table 3. The first classified index was based on the brittleness coefficient of rock [25].

Rockburst potential	β
No	40<
Low (L)	40-26.7
Moderate (M)	26.7-14.5
High (H)	<14.5

Table 4. Classification of rockburst tendency based on the method of stresses [26].

Rockburst potential	α
No	>10
Low (L)	10-5
Moderate (M)	2.5-5
High (H)	<2.5

3. Geological and Geostructural characteristics of the site

3.1. General Study of the site

The second part of the Gelas tunnel, which has a length of approximately 20660 meters and about 6.3 meters in diameter, is located in southern Azarbaijan-e Gharbi province, NW Iran (Figure 1). The tunnel transfers water from Lavin River to Urmia Lake and Naghadeh Plain at the north hillside of Bigom-Ghaleh Mountain [27]. In this research, the study of rockburst occurrence was carried out in the second part of the tunnel, which, due to geological structures and deep excavation, has the potential of occurring rockburst.

3.2. Engineering geological features of the site

Based on the geological studies of the site and some of the macroscopic and microscopic characteristics of the rock masses (color, texture, grading, mineralogy of the phenocrysts, and their sizes), the tunnel rock units turned out to be composed of igneous rocks (granite, granodiorite, and silicic vein), metamorphic rocks (hornfels, gneiss, marble and metacarbonates, schist, slate, and phyllite) and cretaceous sedimentary rocks (shale, limestone, and dolomite).

Some characteristics of the tunnel route, such as lithology of the layers, different geological structures (different thickness of the layers, discontinuity frequency, and weathering circumstances), and geotechnical characteristics were utilized to divide the case study into 11 engineering geological units. Figure 2 vividly shows that there are several faults, crush zones, and dykes in the tunnel route, also the main faulting feature, which from the end of the tunnel cuts it in 11+883 to 11+983 m. Table 5 indicates the characteristics of faults and crushed zones in the study area.

Several boreholes with suitable cores and block samples were chosen for laboratory studies to determine the geotechnical characteristics of the intact rocks and properties of the rock masses. Table 6 presents some of the geotechnical characteristics of intact rocks, and Table 7 describes field descriptions of geological engineering units to evaluate rockburst occurrence.

Figure 1. Location of the study area in Iran.

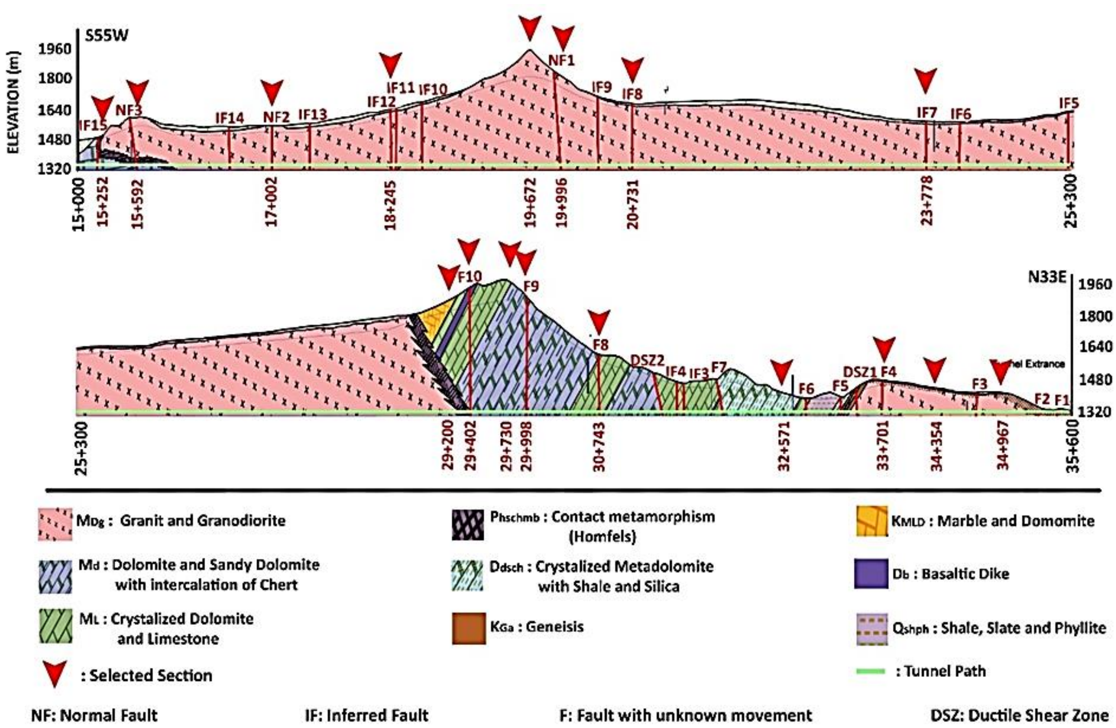

Figure 2 Geological sections of the Gelas tunnel [28].

Table 5. The characteristics of faults and crushed zones in the study area [28].

Fault name	Section (m)	Mechanism	Fault zone width (m)	Fault name	Section (m)	Mechanism	Fault zone width (m)
F1	35526	-	≈10	IF5	25250	-	≈10
F2	35414	-	≈20	IF6	24114	-	≈10
F3	34678	-	≈10	IF7 (Shavele Beyzabad)	23778	-	100
F4	33700	-	≈7	IF8	20730	-	≈10
DSZ1	33430	Sinistral strike-slip	≈30	IF9	20382	-	≈10
F5	33266	-	≈5	NF1	19994	Normal	≈5
F6	32903	-	≈5	IF10	18547	-	≈10
F7	32032	-	≈10	IF11	18281	-	≈10
IF3	31628	-	≈10	IF12	18245	-	≈10
IF4	31560	-	≈10	IF13	17393	-	≈10
DSZ2	31403	dextral strike-slip	≈30	NF2	17004	Normal	20
F8	30743	-	≈5	IF14	16560	-	≈10
F9	29998	-	≈5	NF3	15588	Normal	20
F10	29402	-	≈5	IF15	15190	-	≈10

Table 6. Geotechnical characteristics of the intact rocks [28].

Engineering Geological units	Lithology	m_i constant	Dry Density (g/cm³)	Saturated Density (g/cm³)	Deformation modulus (Gpa)	Uniaxial Compressive Strength (Mpa)
M_d	Cream dark Dolomite and Sandy Dolomite with intercalation of Chert	11	2.68-2.78	2.70-2.80	29.7	42-75
CZ	Crushed Dolomite	11	2.68-2.78	2.70-2.80	29.7	42-75
CZ	Crushed Granodiorite	32	2.66-2.77	2.62-2.78	44.850	62-113.9
CZ	Crushed Granodiorite	32	2.66-2.77	2.62-2.78	44.850	62-113.9
M_{Dg}	Granodiorite	32	2.66-2.77	2.62-2.78	44.850	62-113.9
CZ	Crushed Granodiorite	32	2.66-2.77	2.62-2.78	44.850	62-113.9
CZ	Crushed Granodiorite	32	2.66-2.77	2.62-2.78	44.850	62-113.9
CZ	Crushed Granodiorite	32	2.66-2.77	2.62-2.78	44.850	62-113.9
P_{hschmb}	Contact Metamorphism (Hornfels)	19	2.65-2.84	2.65-2.86	63	19.6-177.2
CZ	Crushed Dolomite	11	2.68-2.78	2.70-2.80	29.7	42-75
M_d	Cream-dark Dolomite and Sandy Dolomite with intercalation of chert	11	2.68-2.78	2.70-2.80	29.7	42-75
CZ	Crushed Dolomite	11	2.68-2.78	2.70-2.80	29.7	42-75
CZ	Crushed Limestone	10	2.68-2.78	2.70-2.80	29.7	38.4-86.2
D_{dsch}	Crystalized Metadolomite with Shale and Silica	12	2.71-2.88	2.73-2.89	26.3	37-68
CZ	Crushed Granite	32	2.64-2.72	2.64-2.74	30.650	35.7-65.7
M_g	Granite	32	2.64-2.72	2.64-2.74	30.650	35.7-65.7
M_g	Granite	32	2.64-2.72	2.64-2.74	30.650	35.7-65.7

Table 7. Field descriptions of geological engineering units in the Gelas tunnel route [28].

Rock category		
Engineering Geo. Unit	Geological Unit	Description
WMg	Gr	Slightly weak, blocky to irregular, weathered, broken, and unstable
Mg	Gr	Strong to moderately strong, blocky to massive and unweathered to slightly weathered, stable
Pgnschmb	K^{Ga}	Moderately strong, blocky to tabular and slightly weathered, stable
Ddsh	$K^{D, Sh}$	Moderately strong, blocky and slightly weathered, stable
Dshph	$K^{Sh, Fl, Sl}$	Moderately strong, blocky to tabular and slightly weathered, stable
Ml	K^{LD}	Moderately strong, blocky and slightly weathered, stable
PvbDgtu	Db	Moderately strong, blocky and irregular slightly weathered, stable
Md	$K^{D, Ds}$	Moderately strong, blocky and slightly weathered, stable
Phschmb	K^{Hf}	Moderately strong, blocky to columnar and slightly weathered, stable
MDg	Gr	Strong, massive to blocky and unweathered, stable
C.Z	-	Very weak, crashed, weathered, broken, and unstable

In this study, the probability of occurring rockburst in the Glass tunnel path will be discussed. In order to reach this purpose, 17 sections of the tunnel route were selected. The cross-section of the desired route is illustrated in Figure 2 in which the rock units and their surrounded area in the tunnel route are observed. The major part of the tunnel route is located in granite and granodiorite units.

In this area, undesirable geological conditions such as the presence of rock masses under stress and high overburden, crushed zones and faults, and the presence of folds, dikes, and other abnormalities, play an essential role in the probability of rockburst occurrence and consequently the engineers and engineering equipment safety as well as the performance and rate of the drilling device.

3.3. Prediction of rockburst occurrence in Gelas tunnel

Underground excavation in areas with tectonically active conditions requires a comprehensive geological investigation, which has improved with foreseeing problems related to the sustainability of tunnels. Gelas tunnel is located at the extreme northeastern part of the Sanandaj-Sirjan structural zone. The zone, which is a part of the orogenic belt of the Zagros Mountains, with a northwest-southeast trend, has 2000 kilometers long and 150-200 kilometers wide. Zagros orogeny is itself a part of the Alpine-Himalayan orogenic belt and, therefore, the study region is undergone some strong tectonic processes so that this high in situ stress itself can participate in an intensification of rockburst occurrence.

Moreover, located in the metamorphic–magmatic belt of SSZ, the major part of the tunnel rout paths through granite and granodiorite units and in some parts through dikes which itself can be a factor causing rockburst occurrence. Also, because of high in situ stress, there are some faults and folds that themselves have a critical effect on bringing rockburst in this area. So, the high overburden (deep tunneling), the presence of numerous fault zones, and the high thickness of crushed zones related to these faults apply extra pressure on the tunnel face and can cause an excavation disruption by a TBM and threaten human life. Also, existing of weak rock masses and crush zones alongside strong hard rocks with a high elastic module (Granit and Granodiorit) will intensify rockburst occurrences in this area.

Therefore, it is necessary to identify regions prone to rockburst occurrence and take measures needed to prevent it before starting excavation operations. In this research, the occurrence of rockburst along the tunnel route is predicted using analytical approaches and these approaches can determine which sections are located in a high-risk rockburst occurrence.

4. Discussion

Figure 3 shows the rockburst tendency in the Gelas tunnel path according to the linear elastic index, Tangential stress criterion, Brittleness coefficient of rocks, and method of stresses.

Based on the results of the Linear Elastic Index (PES), all 17 sections are predicted to have the potential of rockburst occurrence, but at the level of low and very low. Sections with a very low potential of rockburst occurrence have the maximum elastic strain energy, which is estimated to be about 86.5 kj/m^3, which is mostly related to crushed zones of Granodiorite.

According to the Tangential Stress Criterion (T_s), in the sections of the Gelas tunnel route, the maximum value of T_s is estimated to be about 0.70, where there are crushed or strong Dolomite and Sandy Dolomite with the chert interlayer (Md) at the depths 550-600 meter, which is predicted to be at the moderate rockburst occurrence. Regarding this criterion, there is no high level of risk for rockburst occurrence, and even in some sections, there is no risk of occurring rockburst.

According to the methods of stresses, the least amount of α is related to the lithology of dolomite and sandy dolomite with the intermediate layer of Chert (Md) (depths 534, 581, and 614 m). Based on this classification, it has the middle risk of rockburst, the other sections are in the category of either without rockburst or low tendency.

Section number	Location (Km)	Overburden (m)	Geological Engineering unit	Analytical Methods: PES Result	PES Behavior		T_s Result	T_s Behavior		β Result	β Behavior		α Result	α Behavior		Average result of analytical methods	
1	15252	157	M_d	57.61	L	1	0.38	L	1	22.83	M	2	13.88	N	0	L	1
2	15592	248	CZ	57.61	L	1	0.44	L	1	22.83	M	2	8.77	L	1	M	2
3	17002	206	CZ	86.23	L	1	0.27	N	0	11.44	H	3	16.12	N	0	L	1
4	18245	297	CZ	86.23	L	1	0.31	L	1	11.44	H	3	11.32	N	0	M	2
5	19672	615	M_{Dg}	86.23	L	1	0.45	L	1	11.44	H	3	5.39	L	1	M	2
6	19996	474	CZ	86.23	L	1	0.39	L	1	11.44	H	3	7.01	L	1	M	2
7	20731	328	CZ	86.23	L	1	0.32	L	1	11.44	H	3	10.24	N	0	M	2
8	23778	236	CZ	86.23	L	1	0.28	N	0	11.44	H	3	14.34	N	0	L	1
9	29200	565	P_{hschmb}	73.14	L	1	0.4	L	1	13.59	H	3	6.25	L	1	M	2
10	29403	581	CZ	57.61	L	1	0.66	M	2	22.83	M	2	3.74	M	2	M	2
11	29730	614	M_d	57.61	L	1	0.69	M	2	22.83	M	2	3.53	M	2	M	2
12	29998	534	CZ	57.61	L	1	0.63	M	2	22.83	M	2	4.07	M	2	M	2
13	30743	270	CZ	65.34	L	1	0.43	L	1	15.58	M	2	8.56	L	1	M	2
14	32571	107	D_{dsch}	52.4	L	1	0.38	L	1	12.73	H	3	18.64	N	0	M	2
15	33701	153	CZ	41.93	VL	0	0.43	L	1	8.11	H	3	12.58	N	0	L	1
16	34354	112	M_g	41.93	VL	0	0.39	L	1	8.11	H	3	17.49	N	0	L	1
17	34967	95	M_g	41.93	VL	0	0.38	L	1	8.11	H	3	20.32	N	0	L	1

Rockburst phenomena in tunneling

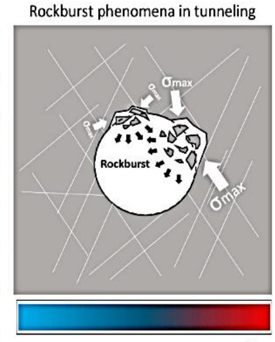

Figure 3. Assessment of rockburst tendency in the path of the Gelas tunnel.

5. Conclusion

According to the divisions of Iranian construction-sedimentary units, the Gelas tunnel is located within the belt of the metamorphic and ophiolitic zone of Sanandaj-Sirjan. In the tunnel path, there are deposits of sedimentary rocks, metamorphic, volcanic, and igneous sediments. The major part of the tunnel route is located in granite and granodiorite units. Based on Engineering Geological studies, and considering the presence of rock units in the tunnel excavation, 11 engineering geological units are recognizable.

In this area, undesirable geological conditions, such as the presence of rock masses under stress and high levels of overburden, crushed zones, and fault zones, the presence of dikes, folding, and other abnormalities, function as exacerbated agents of rockburst. So, it is involved in the safety of engineers and engineering equipment, as well as the performance of the TBM.

In this study, the probability of Rockburst occurrence in the Gelas tunnel path is discussed. Hence, 17 sections of the tunnel route were selected and rockburst potential was predicted. So, according to availability, and valid sources, linear elastic criteria, tensile stress criteria, coefficient of tension and tensile criterion have been used to predict rockburst occurrence. Consequently, sections with high rockburst potential have been determined. Then, a comparison was made between the applied methods.

The overall results in Figure 3 vividly indicate the fact that 3 methods including PES, TS, and β predict rockburst occurrence for all of the 17 selected sections in the tunnel path; however, based on the α method, approximately less than 50 percent of the sections have the potential of rockburst occurrence.

On the other side, to compare the 4 methods in a detailed sectional scale, two approaches of Ts and α have more conformity to each other in a rockburst level of occurrence. The highest probability of occurring rockburst is related to sections with high overburdens and low-strengthen rock masses (section No. 10, 11, 12). However, according to the β method, although the abovementioned sections show a moderate level of rockburst occurrence, other sections, which the other three methods evaluated as low or no level of rockburst occurrence, show a high level of occurring rockburst. So it can be deducted that the β method is not adapted to the other methods. For, β method is dependent on just lithology so that rock masses with a high amount of elastic modules like granite and granodiorite, in this study, show a high risk of Rockburst. However, in some of these sections overburden is not so high and some of them are near the surface. Even in this approach, sections with approximately the same condition but different overburden are evaluated as the same level of rockburst occurrence. Also, since the TES method detects rockburst occurrence just based on two factors of Uniaxial Compressive Strength and Elastic Module, but other factors which highly influence this behavior do not be taken into account, sections with Granodiorite show a top amount of TES regardless of being crushed, being at high deep or near faults.

So it can be deduced that the two methods of β and α cannot predict rockburst occurrence so well because they do not take into account other influential geological conditions including joints, deep, in situ stress, tectonic activities, and so forth.

Accordingly, based on the factors influencing rockburst occurrence, it can be identified that among the four applied approaches, the closest methods to the geologic judgment of rockburst occurrence are the method of stresses and the Tangential method. In these methods, the parameters of Uniaxial Compressive Strength, the major principle geostress, as well as tangential stress of rock masses, can present the effect of existing tectonic stress, overburden, and so on.

Lacking consensus conformity among the 4 applied methods, regarding the prediction of rockburst occurrence, set the stage for bringing about an average result between them. So, Figure 3 average result shows that all the selected sections in the tunnel path tend occurring rockburst in a range of low to moderate. However, approximately there is no chance of occurring a high level of rockburst in the tunnel path.

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