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A Study of Rockbursts Within a Deep Mountain TBM Tunnel

산악 TBM 터널에서 발생한 암반파열 현상에 대한 연구

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요 지

암반파열 현상은 암반 내에 축적된 변형에너지의 급작스러운 방출로 인해 발생한다. 심부 광산에서는 이런 현상이 자주 발생하여 주요한 재해 중 하나로 다루어졌으나, 터널에서는 극히 드물게 나타나는 현상이었다. 따라서 터널 내 암반파열 현상에 대한 국내역사는 짧은 편이며, 정보도 제한적이어서 그와 관련된 연구는 거의 없는 실정이었다. 그러나 최근에는 터널의 심도가 깊어짐에 따라 터널내 암반파열 현상이 종종 보고되고 있어 터널의 안정성 문제뿐만 아니라 시공 중 재해 측면에서 볼 때 이에 대한 연구가 절실히 필요할 것으로 사료된다. 본 연구에서는 TBM 터널에서 취득한 암반파열현상 관련 자료의 분석을 통하여 그 현상을 포괄적으로 이해하는 방법을 제시하고자 하였다. 암반파열이 발생한 본 연구 터널의 현장자료 분석결과에 의하면, 대부분의 암반파열은 터널의 막장과 운전석 내에서 주로 발생하였으며, 일부 구간에서는 파열현상이 20일 이상 지속되기도 하였다. 또한 본 터널에서의 암반파열은 터널막장, 터널측벽 및 터널천장 등 터널의 모든 주변에서 발생하였고, 그 파열 깊이는 대부분 100cm 이하인 것으로 조사되었다. 본 연구에서는 이러한 암반파열 자료를 이용하여 암반파열 가능성을 취성도와 일축압축강도를 이용해 평가할 수 있도록 새로운 규준을 제시하였으며, RMR, 굴착공법, 굴착속도 및 터널심도 등이 서로 연관되어 암반파열 현상에 큰 영향을 준다고 판단된다.

Abstract

Rockbursts are mainly caused by a sudden release of the stored strain energy in the rock mass. They have been the major hazard in deep hard rock mines but rarely occur in tunnels. Due to the short history and limited information on rockbursts, the topic has rarely been studied in Korea. Some cases of rockbursts, however, have been reported during construction of a mountain tunnel for waterway. This study focuses on analyzing data on rockbursts obtained from a TBM (Tunnel Boring Machine) tunnel and suggests methods for a comprehensive understanding on rockbursts. From the analysis of the field data of rockbursts, it was found that most rockbursts mainly occurred at the section between the tunnel face and the TBM operating room, and the rock bursting phenomena lasted up to 20 days after excavation in certain areas. The data also show that the bursting spots are located all around the tunnel surface including the face, the wall, and the roof. The maximum size of bursting spots is usually less than 100cm. This study also suggests new scale systems of brittleness and uniaxial compressive strength to evaluate the possible tendency for a rockburst. These systems are scaled based on the scale system of strain energy density. In addition, with these scale systems, this research shows that there are potentially higher tendencies for rockbursts in this specific tunnel. Moreover this research suggests that properties of rock and rock mass, RMR (Rock Mass Rating) value, tunneling method, excavating speed, and depth of tunnel have a strong correlation with rockbursts.

Keywords : Brittleness, RMR, Rockbursts, Strain energy density, TBM, Tunnel

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1. Introduction

The rock masses at subsurface are initially in an equilibrium state of stress until they are disturbed by artificial excavations or natural disasters. Tunneling is a good example of the former and an earthquake the latter. Tunnel is excavated in the rock mass to make a long underground passage. Therefore, tunneling always breaks the initial equilibrium state of stress around tunnel even though stress is immediately redistributed to reach a new equilibrium state of stress. In tunneling, this cycling process of breaking and redistributing of stress is repeated with any advance of tunnel face and will end when tunneling is finished. However, in the process of stress redistribution, the rock left standing will endure more excessive stress due to the removing of the original support provided by the rock within the tunnel. This excessive stress displaces the surface of the rock left, that is, the boundary of tunnel. This change equals the work done on the rock, which becomes the potential energy of strain. The stronger the rock the higher the stored strain energy. Rockbursts occur due to the violent release of this energy stored in the host rock mass.

The term 'rockburst' has been used to refer to a variety of sudden and violent dislocation of rock slabs around underground space. It occurs usually from the wall and roof of the space, and potentially may occur from the floor. A tunneling induced seismic event may occur as large amounts of energy are released. Obert and Duvall (1967) defined a rockburst as any sudden and violent explosion of rock from its surroundings, the phenomenon resulting from the stresses exceeding the strength of rock. Many researchers have studied the mechanism for rockbursts occurring at underground mines achieving useful results but there is a very limited amount of research that has been done on rockbursts in the field of tunneling.

It is known that there are two main causes of a typical rockburst. One of the primary causes is the static strain energy stored in rock and the other is the rock type involved. Rockbursts do not occur in weak rocks because the pressure which causes a rockburst is slowly released in the weaker rocks by semiplastic adjustments. The rocks affected are almost always hard, strong, and brittle. According to Obert and Duvall (1967), rocks affected usually have an unconfined uniaxial compressive strength of 100 ~ 400MPa and a modulus of elasticity of 40,000 ~ 90,000Mpa. In general igneous rocks and metamorphic rocks have higher potential of a rockburst than sedimentary rocks.

In this study, the analysis of rockbursts has been conducted by using of data obtained from the laboratory, field, and literature review. The tunnel being analyzed is a waterway tunnel passing through high mountains with depths of approximately 200m to 800m from the surface. The tunnel begins at Songsa-ri, Kilan-myun, Andong city and terminates at Chunghyo-ri, Jayang-myun, Youngchun city in Kyung-sang-buk-do, Korea as shown in Fig. 1. It is approximately 32.97km in length and is the longest waterway tunnel in Korea.

According to Kim and Kim(2001), the tunnel was constructed in three different rock types; intrusive rock, sedimentary rock, and volcanic rock. Each of these rocks had faults, dykes, and two to four sets of joints. The tunnel was excavated by blasting with NATM (New Austrian Tunnelling Method) concepts and TBM. The former has widths of 3.8m to 4.0m and the latter has a diameter of 3.5m. Tunnel lengths of NATM and TBM are 10.6km and 22.4km respectively. In addition, the main tunnel has three service tunnels to improve tunneling speed and efficiency. They are located at 8.8km, 15.6km,

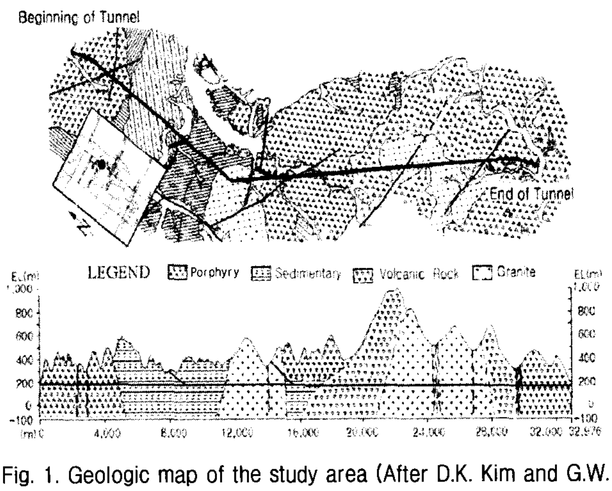

Fig. 1. Geologic map of the study area (After D.K. Kim and G.W. Kim, 2001)

and 29.5km respectively from the beginning of tunnel as shown in Fig. 1. Because the tunnel runs deep under the mountain, many dynamic rockbursts occurred causing notable problems. Especially there were many more bursts in the section of TBM excavation where the depths are higher than NATM section. With these results, this study focuses on what would be the main causes and factors of bursts in this TBM tunnel. Various values of scales for the tendency of rockbursts are calculated by using laboratory test data and the field data including RMR, tunneling method, excavating speed, and depth of tunnel.

2. Estimation of Various Scales of a Typical Rockbursts

2.1 Scales from the Cycling Uniaxial Compression

A typical strain stress curve for the cycling uniaxial compression on rock is shown in Fig. 2 where ε_p, ε_e, and ε_t represent plastic, elastic and total static strain respectively and EN_p and EN_e represent plastic and elastic strain energy respectively. Specifically, EN_p is irrecoverable energy and used for grain loosening, local crack propagation, and so on.

Excessive stresses on the rock due to the excavation

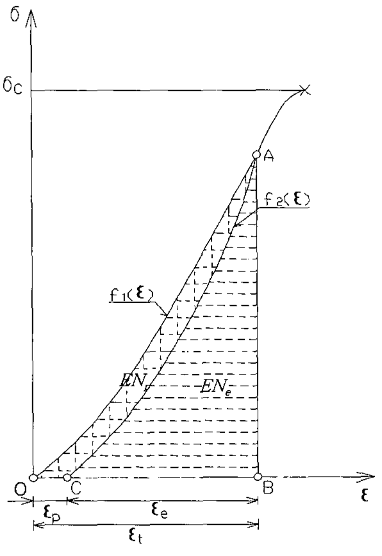

Fig. 2. A typical strain-stress curve

displace the boundary of the tunnel. This displacement equals the work done on the rock and is stored as potential strain energy if the rock is elastic. Since a rockburst is a sudden release of stored elastic strain energy, the occurrence of rockbursts depends on the rock's ability to accumulate elastic strain energy. In other words, rockbursts decrease when the permanent plastic strain, ε_p, increases. Therefore, this phenomenon can be seen in a rock specimen subject to uniaxial compression and used to calculate energy index, strain energy density, strength index, and stress index.

2.1.1 Energy Index

The potential for a rockburst can be expressed by the energy index (EN_i) which is the ratio of EN_e to EN_p as expressed in equation (1). According to Peng (1986), the larger the value of EN_i, the greater the susceptibility to bump which means sudden violent burst of coal. The potential for a coal bump can be classified as follows:

$$EN_i = \frac{EN_e}{EN_p} = \frac{\int_{\varepsilon p}^{\varepsilon t} f_2(\varepsilon)d\varepsilon}{\int_0^{\varepsilon t} f_1(\varepsilon)d\varepsilon - \int_{\varepsilon p}^{\varepsilon t} f_2(\varepsilon)d\varepsilon} \tag{1}$$

$EN_i < 2.0$, not susceptible,
$2.0 < EN_i < 5.0$, slightly susceptible, and
$EN_i > 5.0$, severely susceptible.

2.1.2 Strain Energy Density

However, unlike coal, intact rocks of volcanic rock and granite rarely have plastic strain from the cycling uniaxial compression test. It means that these types of competent rocks would have almost no plastic strain energy but have greater tendency to burst when broken. This tendency is estimated by a strain energy density (SED), the elastic strain energy per unit volume under the compression. The maximum elastic strain energy per unit volume would be as follows;

$$SED = \frac{\sigma_c^2}{2E} \tag{2}$$

Where, σ_c is uniaxial compressive strength, and E is the elastic modulus.

According to equation (2), the weakest rock would be the least likely to burst if other things are equal because weak rocks would reach their failure point far before they could store enough strain energy to burst. Wang (2001) illustrated Kwasniewski's work which scales the SED based on rockbursts as follows;

SED < 50 kJ/m^3, rockburst hazard is very low,
SED = 51 ~ 100 kJ/m^3, rockburst hazard is low,
SED = 101 ~ 150 kJ/m^3, rockburst hazard is moderate,
SED = 151 ~ 200 kJ/m^3, rockburst hazard is high, and
SED > 200 kJ/m^3, rockburst hazard is very high.

2.2 Scale from Other Indexes

2.2.1 Strength Index

Hawkes (1966) suggested a rock strength index (RS_i) for the potential instability of underground openings. The RSi is the ratio of three times of maximum principal stress to the uniaxial compressive strength, $RS_i = 3\,\sigma_1/\sigma_c$. The scale system is as follows;

RS_i < 0.2, low,
RS_i = 0.2 ~ 0.4, significant,
RS_i = 0.4 ~ 0.6, high
RS_i = 0.6 ~ 0.8, very high,
RS_i = 0.8 ~ 1.0, dangerously high, and
RS_i > 1.0, unstable.

2.2.2 Stress Index

In the same way, Yoon (1994) introduced that stress index (S_i) is the ratio of the uniaxial compressive strength to overburden stress, $S_i = \sigma_c/\gamma h$. This index shows that if S_i is less than 2.5, then there would be pressure on the surface of tunnel. In general, the rating system is as follows;

S_i < 2.5, heavy rockbursts, and
S_i = 2.5 ~ 5, mild rockbursts.

3. Analysis of Rock Test Data to Predict Rockbursts

3.1 Prediction of Potential Rockbursts

3.1.1 Prediction from Strain Energy Density

According to Chapter 2, the potential occurrence of rockbursts can be estimated from the values of scale

Table 1. Rock test data and scales of rockbursts

Rock Type	E (GPa)	Uni. Comp. Strength (MPa)	Tensile Strength (MPa)	SED	Brittleness (B_i)	Strength Index (RS_i)	Comment
Porphyry	75.3	113		84.79		0.27	
Sedimentary I	91.5	231		291.59		0.14	
Sedimentary I	65	82	16	51.72	5.13	0.39	
Sedimentary I	65	159	9	194.47	17.67	0.20	
Sedimentary I	43	99	15	113.97	6.60	0.32	
Sedimentary I	43	147	15	251.27	9.80	0.22	
Granite I	63	93	15	68.64	6.20	0.33	
Granite I	63	64	9	32.51	7.11	0.49	
Volcanic I	80	132		108.90		0.24	
Volcanic I	38.3	112		163.76		0.56	rockburst
Volcanic I	77	242	16	380.29	15.13	0.26	rockburst
Volcanic I	77	192	14	239.38	13.71	0.33	rockburst
Granite I	61	153	13	191.88	11.77	0.25	rockburst
Granite I	61	96	13	75.54	7.38	0.40	rockburst
Granite I	72	225	10	351.56	22.50	0.17	rockburst
Granite I	72	127	13	112.01	9.77	0.30	rockburst
Volcanic II	56.2	236		495.52		0.17	
Volcanic II	118	267		302.07		0.15	

E=Elastic modulus, SED=Strain energy density

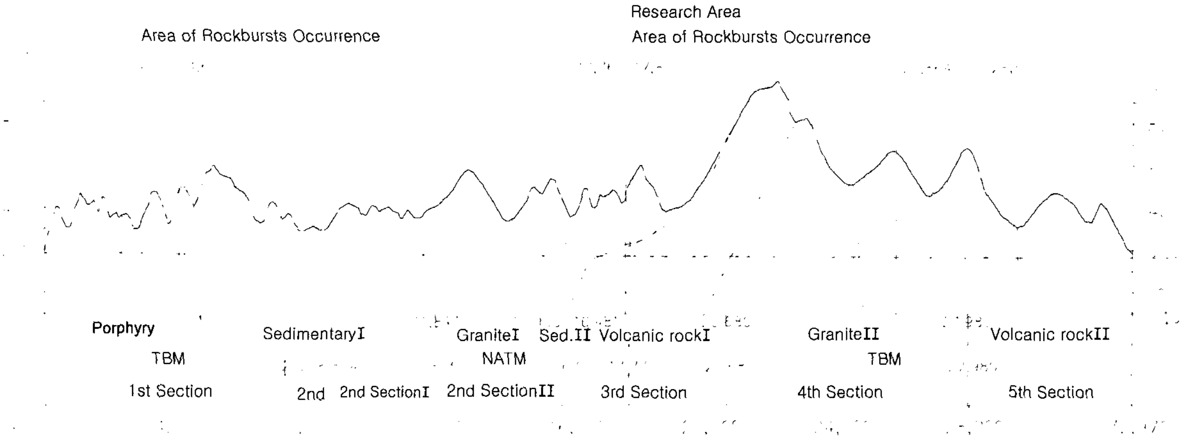

Fig. 3. The section view of geology and topography of the study area

indexes obtained from rock specimen under compression. The SED is most commonly used to estimate the potential occurrence of rockbursts as shown in Table 1. In this study, 18 NX size of intact rock test data were collected to calculate the SED at 12 different tunnel locations. Calculation results show that 10 out of 18 values of SED are greater than 150 kJ/m^3, meaning that there are high to very high potential of the rockburst hazard based on Kwasniewski's rating system. Actually 5 out of 7 are greater in actual burst area as indicated by the shadow area shown in Fig. 3. Actual rockbursts actively occurred at this area.

3.1.2 Prediction from Strength Index

The strength index (RS_i) is the ratio of three times of principal stress to uniaxial compressive strength as mentioned in Chap. 2.2.1. To calculate the strength index, in-situ stresses of the tunnel concerned are needed. However, because these stresses are not measured, vertical stresses are assumed as the major principal stresses. The results show the values range from 0.14 to 0.56, representing significant and high instability. Of course, the vertical stresses on tunnel wall are proportional to the height of overburden, that is, the height of overburden can also be a reason of rockbursts. The deeper the tunnel, the greater the pressure which could cause bursts. The overburden height and frequent bursting area are shown in Fig. 3. Most of burstings occur at the shadow area where the maximum height of overburden is approximately 800m. Rice (1935) reported that coal bumps often occur when the overburden is greater than 300m. Yoon (1994) said that rockbursts start at an overburden depth of 500m and become violent at the overburden depth of greater than 1000m. Hunt (1988) concurs that rockbursts are more common in deeper tunnels, especially with depths between 600 and 1000m.

3.2 Relationship Between Indexes and Rock Properties

3.2.1 Relationship Between SED and Brittleness

The brittleness is the ratio of uniaxial compressive strength to tensile strength of rock. To compare the values of SED with brittleness, the values of brittleness (B_i) are also calculated for 12 different rocks. The values are ranging from 5 to 22 as shown in Table 1, showing a fair correlation with a determination coefficient of 0.72 approximately as shown in Fig. 4. The correlation is as follows;

$$SED = 213.94 \, Ln(B_i) - 321.10 \qquad (3)$$

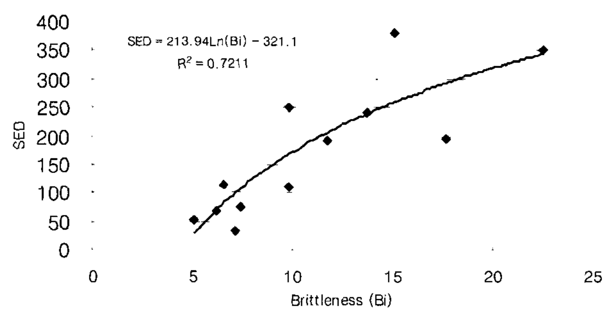

Fig. 4. Correlation between SED and brittleness (B_i)

3.2.2 Relationship Between SED and Uniaxial Compressive Strength (UCS)

Obert and Duvall(1967) reported that rocks with an unconfined uniaxial compressive strength of 100~400MPa have higher potential of a rockburst. In this research, it was also found out that uniaxial compressive strength of rock is one of the most important factors that indicate the potential of rockbursts. For this reason, the SED is compared with uniaxial compressive strength of rock (UCS) as shown in Fig. 5. The result shows a good correlation with a determination coefficient of 0.95 approximately. The correlation is as follows;

$$UCS = 10.25SED^{0.52} \tag{4}$$

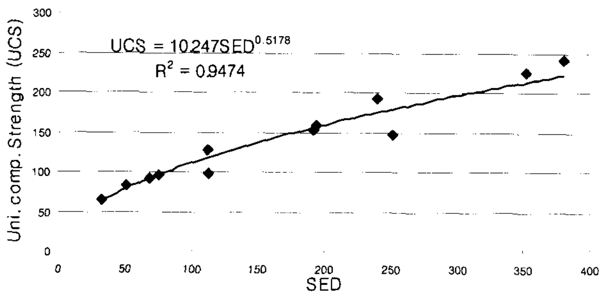

Fig. 5. Correlation between SED and UCS

In addition, the uniaxial compressive strength and the brittleness are compared in this research. This comparison shows a fair correlation with a determination coefficient of 0.79 approximately as shown in Fig. 6. This result indicates that the three values of SED, brittleness and uniaxial compressive strength are well interrelated one another. The correlation between uniaxial compressive strength and brittleness is as follows;

$$UCS = 110.54 \ Ln(B_i) - 114.84 \tag{5}$$

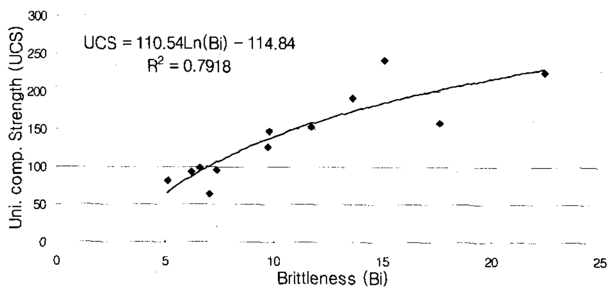

Fig. 6. Correlation between brittleness and UCS

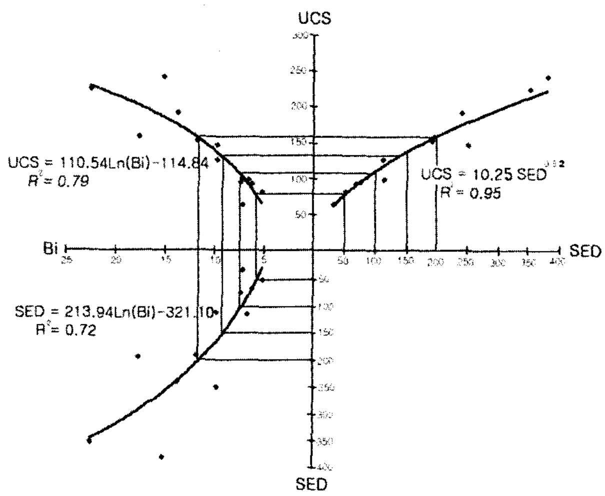

Fig. 7. Estimation of new scale systems of brittleness and UCS based on SED

3.2.3 Suggestion for New Scale Systems Based on Brittleness and Uniaxial Compressive Strength

It is true that brittleness and uniaxial compressive strength are strongly related to rockbursts. However, there are no good scale systems for them as yet. With the results of comparisons done in this research, new scale systems of both brittleness and uniaxial compressive strength for the potential of rockbursts can be suggested based on the SED scale system done by Kwasniewski as shown in Fig. 7 and listed in Table 2.

Table 2. The classification of rockburst hazard based on SED, Bi, and UCS

SED	B_i	UCS (MPa)	Rockburst hazard
< 50	< 5.75	< 78.40	very low
50~100	5.75~7.85	78.40~112.39	low
100~150	7.85~9.87	112.39~138.77	moderate
150~200	9.87~12.18	138.77~161.16	high
200 <	12.18 <	161.16 <	vry high

4. Analysis of Rockbursts Using Field Data

4.1 Analysis of Rockbursts Based on Rock Mass Qualities

For the entire tunnel length, rockbursts mainly occurred at the TBM sections. Specifically, more than 95% of them occurred at the 3rd and the 4th TBM tunnel sections. Therefore, the field data analyzed here are the data obtained from the areas where rockbursts actually occurred as shown in Fig. 3. The data was collected from 1) reports of field monitoring, 2) field geologic maps, 3) field RMR input data worksheets, and 4) reports of geologic investigation. According to the data, most of rockbursts occurred at the tunnel crown and wall. Photos 1 and 2 show the typical location and shape of rockbursts and the former shows the spot of a rockburst occurring at the crown and the latter shows the spot of a rockburst occurring at the wall but reinforced by shotcrete, respectively.

The field data are classified in three groups based on the values of RMR, uniaxial compressive strength, and RQD. Table 3 shows the variance of RMR in the research area. It shows that most of the rockbursts (approximately 84%) occurred at the area with the RMR range of 41 to 80 and the greatest tendency of rockbursts (approximately 63%) was at the area with the RMR range of 41 to 60. It also shows the largest amounts (approximately

Photo 1. A typical shape of rockburst at the crown

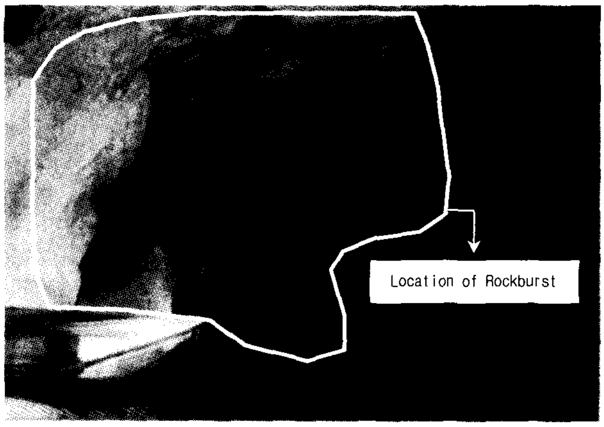

Photo 2. A typical shape of rockburst at the wall

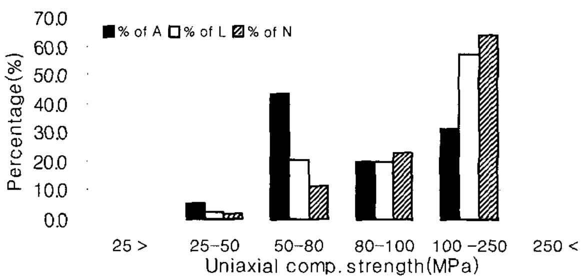

Fig. 8. Percentage comparison of amounts, length and spots of rockbursts based on UCS

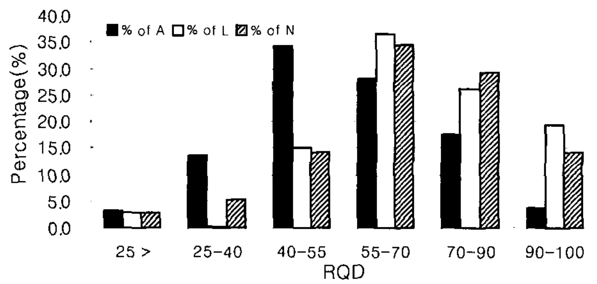

Fig. 9. Percentage comparison of amounts, length and spots of rockbursts based on RQD

Table 3. Classification and analysis of rockbursts based on RMR

RMR	TL	L	A	N	% of A	% of L	% of N
0~10	80.0	0.0	0.0	0.0	0.0	0.0	0.0
11~20	161.0	31.0	9.3	3.0	6.1	4.4	2.7
21~40	1505.0	125.0	48.8	14.0	32.0	17.7	12.4
41~60	5095.0	393.5	64.6	72.0	42.3	55.8	63.7
61~80	2928.0	155.8	30.0	24.0	19.6	22.1	21.2
81~100	971.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	10740.0	705.3	152.7	113.0	100.0	100.0	100.0

TL = tunnel length (m), L = length of rockburst (m), A = amount (m^3), N = numbers of bursting spot

42%) and the longest length (approximately 55%) of rockburts occurred at the area with the RMR range of 41 to 60 too. Fig. 8 and Fig. 9 show the variances of uniaxial compressive strength and RQD, respectively. Fig. 8 shows that approximately 63% of rockbursts occurred at the area with the uniaxial compressive strength range of 100～250 MPa. Fig. 9 shows that approximately 34% of rockbursts occurred at the area with the RQD range of 55～70% while the largest amounts occurred at the area with the RQD range of 40～55% and the longest length occurred within the range of 55～70 RQD%.

4.2 Analysis of a Rockburst Based on Other Field Factors

4.2.1 Excavation Method and Tunnel Depth

The studied tunnel was excavated by two tunneling methods, NATM and TBM. In the case of TBM, which is faster and less damaging to the tunnel, the radial stresses on the tunnel surface are suddenly reduced and move to the abutment places. This can cause very high stress on the surrounding rocks and create an increased probability of bursts. Following this idea, tunnel excavation speeds are analyzed and listed as shown in Table 4. This table shows that TBM tunnel advanced faster than NATM. There were approximately 3 times differences and TBM tunnel advanced more than 40m/day at certain areas. In fact, there were some burstings in the 1^{st} section of TBM even though overburden depths of this section are often less than those of NATM section. It means that fast tunnel advancing speed with less damage to the rock mass might play a role in rockbursts in lower depth of overburden. Also the rockbursts data show that the tunnel depth plays a great role in rockbursts in TBM tunnel since most of rockbursts occurred at the area of greater tunnel depth as shown in Fig. 3.

4.2.2 High Remnant Stress

There are many factors that cause rockbursts. High remnant stress is one of the important factors. High remnant stress can be accumulated by faulting, folding deformation, metamorphism, slow cooling of magma at great depths, and removal of overburden causing stress relief. It is often many times greater than the overburden stress. Usually, it ranges from 3 to 10 times greater. However, there were no measured remnant stresses near the faults or inside of folding in this research. In future study, it should be measured and used to estimate the relationship between remnant stress and rockbursts.

5. Conclusion

One of the main causes of rockbursts is the sudden release of the stored elastic strain energy so the values of SED were calculated in actual bursting area. The results show that the energy at 5 out of 7 locations is greater than 150 kJ/m^3, implying a very high rockburst hazard. This research also shows that SED, UCS, and brittleness are strongly interrelated to each other so that two new scale systems for the rockburst hazard based on brittleness and UCS are suggested in Table 2.

In addition, this research shows that most of the rockbursts (approximately 84%) occurred on the rock

Table 4. Excavation activities of TBM and NATM tunnel

Section	Method	Real-TL (m)	Total working time (day)	Real working time (day)	Tunnel Advancing (m/day)	Mean tunnel advancing (m/day)
1^{st}	TBM	7292.0	1066.0	645.0	46.5	11.3
2^{nd}	NATM	1484.0	696.0	429.0	6.0	3.5
	NATM-1	2959.0	1085.0	691.0	7.0	4.3
	NATM-2	3780.0	1123.0	863.0	9.0	4.4
3^{rd}	NATM	2099.0	721.0	552.0	9.0	3.8
	TBM	6177.0	737.0	511.0	39.0	12.1
4^{th}	TBM	5473.0	700.0	451.0	36.0	12.1
5^{th}	TBM	3358.0	337.0	232.0	43.0	14.5
Total		32622.0		4374.0		

TL=tunnel length(m)

mass having the RMR range of 41 to 80 and the greatest tendency of rockbursts (approximately 63%) was on the rock mass with the RMR values of 41 to 60. Approximately 63% of rockbursts occurred within the range of uniaxial compressive strength of 100～250 MPa and approximately 34% of rockbursts occurred at the RQD range of 55～70%.

This research also shows the following results;

(1) There is a high potential for rockbursts if tunnel depth is greater than 400m and excavated by TBM in the granite or volcanic rock.
(2) Fast tunnel advancing speed with little damage on rock mass plays a role in rockbursts at lower depths, less than 400m. It is important to note that there are rockbursts even though tunnel depth is less than 400m in TBM tunnel.
(3) However, there are no rockbursts in NATM tunnel if the tunnel depth is less than 400m no matter what host rock is.

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