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Influence of the roof lithological characteristics on rock burst: a case study in Tangshan colliery, China

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Abstract. Many factors influence occurrences of rock burst in coal mines, such as mining methods, control methods of the coal roof, lithological characteristics of the roof and floor, tectonic stress, groundwater and so on. Among those factors, lithological characteristics in the roof are the intrinsic controlling factors that affect rock burst during coal mining. Tangshan colliery is one of the coal mines that have suffered seriously from rock bursts in China. In this paper, based on the investigating the lithological characteristics of coal roofs and occurrence of rock bursts in Tangshan colliery, a numerical method is used to study the influence of roof lithological characteristics on rock burst potential. The results show that the lithological characteristics in the roof have an important impact on the distributions of stresses and elastic strain energy in coal seams and their surrounding rocks. Occurrences of rock bursts in this colliery have a close correlation with the thick-bedded, medium- to fine-grained sandstones in the roof. Such strata can easily cause severe stress concentration and accumulate enough energy to trigger rock bursts in the working face during mining operations.

Keywords: lithological characteristics; bursting potential; rock burst; numerical study; elastic strain energy.

1. Introduction

Rock burst is generally defined as a sudden rock failure characterized by the breakup and expulsion of rocks from its surroundings, accompanied by a violent release of energy, which is sufficient to

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cause injury and even death to miners (Blake 1972, Zhao 1995, Linkov 1996). Distribution of mine pressures, rock deformation and failure of the roof are not only the emphases to consider in mining, but also the inevitable problems to face in studying rock burst, coal bump and other mining induced seismic events. During mining, occurrences of rock burst and the bursting potential of rocks are influenced and controlled by many factors, such as mining methods, roof controlling techniques, lithological characteristics of the roof and floor, ground stresses etc. Among those factors, litholigic characteristics of the roof are not only the internal factor to determine the elasticity, brittleness and bursting potential of rocks, but also important conditions to induce a rock burst. Rocks are inhomogeneous and anisotropic geological materials. The macro-mechanical properties, such as uniaxial compressive strength, Young's modulus and deformation-failure behaviors of rocks, have a close relationship with the mineral composition and microstructures of the rocks (Olsson 1974, Hugman and Friedman 1979, Onodera and Asoka 1980, Fredrich *et al.* 1990, Robertson 1995, Wong *et al*. 1996, Hatzor and Palchik 1997, Prikryl 2001, Nasseri 2005). The coal roofs with different lithological characteristics differ in accumulating elastic strain energy and releasing instantly kinetic energy during rock failure induced by stresses (Pan *et al.* 2005, Pan *et al*. 2006, Meng and Pan 2007). Therefore, in order to comprehensively analyze the bursting potentials of rocks and evaluate the risk of rock burst, one needs to consider the influence of roof litholigic characteristics on variations of stress and energy fields during coal mining.

However, due to the dynamic nonlinear relationships of stress, strain and energy in coal seams and their surrounding rocks during mining, it is too complex to solve the whole mechanical and physical processes by using analytical methods. Moreover, the in situ observations have been limited to a few underground coal mining districts, and the practical three-dimensional data for roof pressures, displacements and energy are very difficult to obtain. Therefore, numerical modeling and simulation, as the mechanical analysis method, have been applied widely in many fields for theoretical analysis and engineering calculation (Hou 1993, Young and Boontun 1996, Kirzhner and Rosenhouse 2000, Hakami 2001, Brideau *et al*. 2006, Whittles *et al*. 2006, Heuze and Morri 2007, Wolf 2007, Cai 2008, Liu *et al*. 2008, Zhu *et al.* 2008). Based on the systematic investigation and study on roof lithological characteristics and occurrences of rock bursts in Tangshan colliery, China, the influence of roof lithological characteristics on the risk of rock burst was analyzed by using numerical modeling (FLAC^{3D}).

2. Hazards of rock bursts in Tangshan colliery

As one of the coal mines suffered seriously from rock bursts in China, Tangshan colliery has undergone more than ninety rock bursts. Among those incidents eleven rock bursts caused casualties to miners and destroyed several kilometers of tunnels since the first rock burst occurred on June 7, 1964 (Li 2007). Currently, as coal mining goes much deeper in this colliery, rock bursts become more serious, and these threaten the safety of the mine operation. For example, a severe rock burst occurred in a working face of Tangshan colliery. Unfortunately, this caused two workers to lose their lives and three others were injured. This accident also resulted in serious destructions of underground roadways:

- The height of the roadway was reduced from 2.6 m to 1.2 m because of a heaving floor in the ventilation opening and even dropped to 0.32 m in some positions (Fig. 1A);
- The arched supports deformed seriously and girders were compressed to fracture (Fig. 1B); some

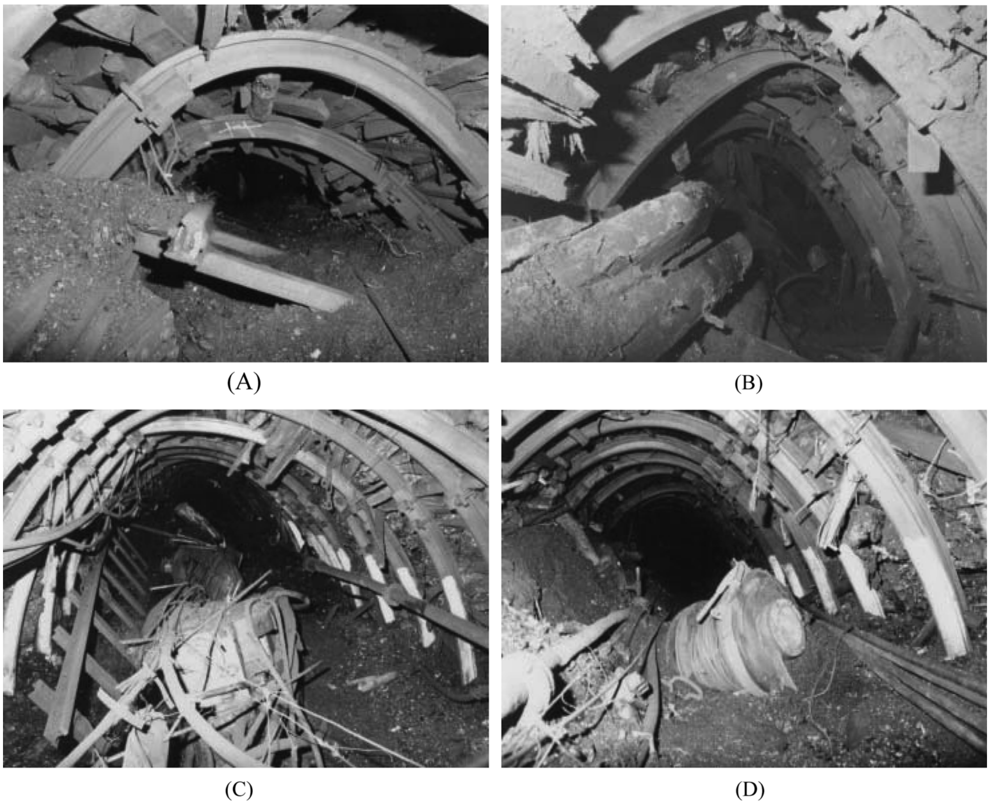


Fig. 1 The hazards of rock burst in Tangshan colliery

railways ruptured, some steel rails were buckled (Fig. 1C), and other rails were dislocated along the strike (Fig. 1A);

- A winch was thrown onto the tunnel floor (Fig. 1D); boxes of emulsion pumps and explosion-proof water bags were upset, and the door of the air duct was thrown three meters away (Figs. 1C and D).

3. Roof lithological characteristics and rock burst

3.1 The primary coal seams and their surrounding rocks

Tangshan colliery has operated for more than 130 years, and the primary geologic periods of the strata from the top downward include Quaternary, Permian, Carboniferous and Ordovician. The newest bedrock formation is located in the Guye Group of the upper Permian. Similar to the other strata series in North China, the missing strata in the Tangshan area consists of the rocks in the upper Ordovician, Silurian, Devonian and lower Carboniferous systems. The missing strata has resulted in a direct overlapping of the formations in the Tangshan Group of the middle Carboniferous system on the limestone in the Majiagou Group of the middle Ordovician (Table 1).

There are eight minable coal seams in the Tangshan colliery, where the 5th, 8th and 9th are the

Table 1 Strata of Tangshan colliery

Stratigraphic units				Thickness/m
Erathem	System	Series	Formation	
Cenozoic	Quaternary		Alluvium	0~870
Paleozoic	Permian	P_2	Guye	
		P_1	Tangjiazhuang	± 200
			Damiaozhuang	70~90
	Carbonic	C_1	Zhaogezhuang	70~160
			Kaiping	60~70
		C_2	Tangshan	60~70
	Ordovician	O_2	Majiagou	

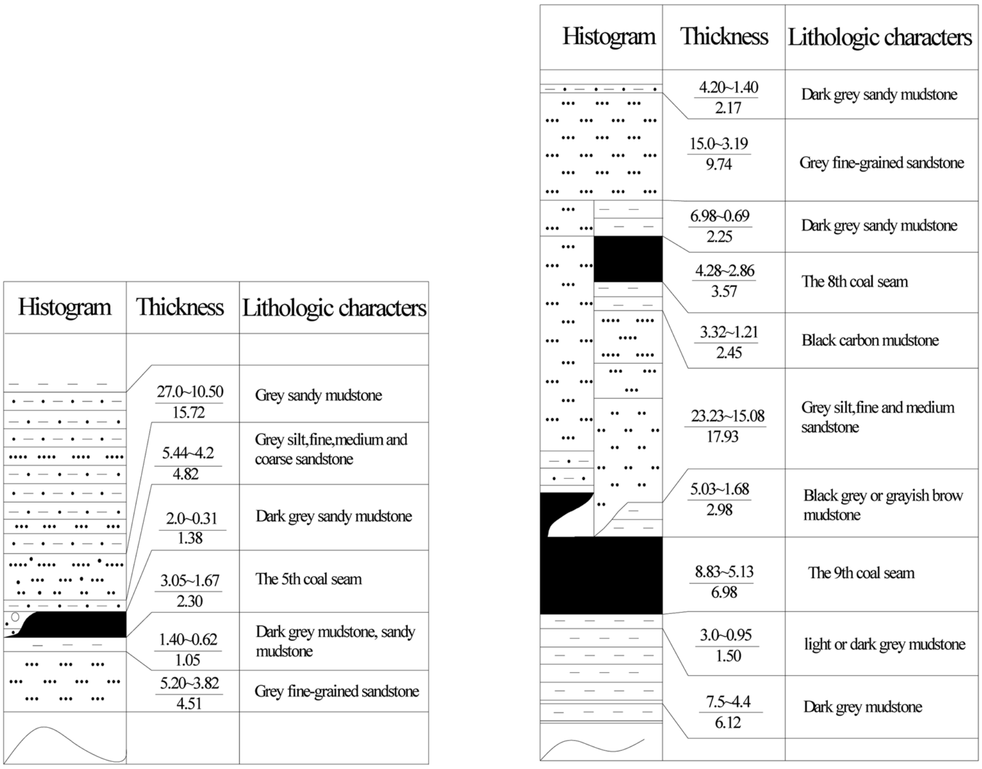


Fig. 2 The comprehensive histogram of principal coal seams and their surrounding rocks in Tangshan colliery

primary mining seams (see Fig. 2). Lithological characteristics of the primary minable coal seams and their surrounding rocks are described as follows.

3.1.1 The 5th coal seam and its surrounding rocks

The average thickness of the 5th coal seam is about 1.67-3.05 m. The seam gradually thickens from the east to west and from the north to the south. The false roofs are dark grey mudstones with 1.5-2 m in thickness in old mining zones and 0.14-0.31 m in others. The immediate roofs are comprised of hard and well-cemented grey siltstone to medium-grained sandstone. There is a very thin coal seam located in between the false roofs and immediate roofs, making the false roofs easy to fall down during mining. However, the lithological characteristics of the main roof and the immediate roof vary gradually, and there is no obvious boundary surface between the two roofs. The main roof even contacts directly with the coal seam in some washed zones. The immediate floor of the 5th seam is comprised of hard sandy mudstone or siltstone of less than 1 m in thickness, and the main floor consists of hard and brittle medium- and fine-grained sandstones.

3.1.2 The 8th coal seam, 9th coal seam and their surrounding rocks

The thicknesses of the 8th coal seam and the 9th coal seam are about 2.86-4.58 m and 5.36-8.83 m, respectively. However, the combined seam of the 8th and 9th coal seam is generally more than 10 m in thickness. In Tangshan colliery, this combined seam in the southern panels is conventionally named the 8th coal seam with a thickness of 11.3 m; while in the western panel it is called the 9th coal seam with a thickness of about 10.9 m. The lithological characteristics of the roof, mainly grey sandy mudstone, vary widely in different areas. From the roof seam upward, the grain sizes of the rocks increase, and rocks vary from siltstones to coarse sandstones. Some rocks bonded with siliceous cementation are very hard, and others are weak because of their argillaceous cementation structures. Sandstone roofs in some cases directly overlap on the coal seam. The immediate floors are mainly made of dark mudstone with a thickness of 1-1.5 m.

3.2 Relation between occurrences of rock burst and roof lithological characteristics

A great amount of elastic strain energy accumulated in coal seams and their surrounding rocks is not only the dynamic force and energy source, but also the necessary condition to induce rock bursts. Different rock types present different mechanical behaviors and have different capacities to store strain energy under loading. For example, clastic rocks with different composition and micro-structures vary widely in uniaxial compressive strength, Young’s modulus and bursting potential. Dense and hard medium- to fine-grained sandstone has a higher strength and bursting potential than those of sandy-mudstone and mudstone (Pan *et al.* 2005, Pan *et al*. 2006, Meng and Pan 2007). In other words, the strong roof of sandstone is capable of accumulating more elastic strain energy under higher stresses and releases a great amount of elastic strain energy. Therefore, the strong roof aggravates the failure of coal (or rock) and easily triggers a rock burst while destabilizing.

In Tangshan colliery, rock bursts generally occurred during mining of the 5th coal seam, and the combined seam of the 8th and the 9th coal seams. The roof of the 5th coal bed is mainly comprised of grey siltstone, fine-grained sandstone and medium-grained sandstone, while the combined seam roof of the 8th and the 9th coal seams varies widely and generally consists of sandy mudstone and medium- to fine-grained sandstone. Table 2 lists the mechanical properties of coal seams and their surrounding rocks. The uniaxial compressive strength and Young’s modulus in the immediate (Lowest layer or layers of rock immediately above an underground opening) roof of the 5th coal seam are 103.2 MPa and 40.7 GPa, respectively; while in the main roof are 143 MPa and 36 GPa, respectively. Likewise, in the 8th and 9th combined coal seam, the uniaxial compressive strength and Young’s modulus of the immediate roof are 127 MPa and 39.9 GPa, respectively; while the uniaxial compressive strength of the main roof is 144 MPa. It can be seen that the roofs in the 5th coal seam and in the combined seam of the 8th and 9th coal seams all belong to strong roofs.

According to the field data observed in Tangshan colliery in the past few years (Table 3), the

Table 2 The physical and mechanical properties of the main coal seams and surrounding rocks in Tangshan colliery

Formations	Lithological characteristics	Compressive stength /MPa	Tensile strength /MPa	Young's modulus/ GPa	Poisson's ratio	Cohesive strength /MPa	Internal friction angle/°	Bulk density g/cm^3
Main roof	Medium sandstone	143	6.91	36	0.28	22	31	2.69
Immediate roof	Silt-fine sandstone or medium-fine sandstone	103.2	10.1	40.7	0.22			2.74
Coal seam	5th coal seam	18	2.31	4.5	0.32			1.34
Floor	Fine sandstone	101.3						2.74
Main roof	Fine sandstone	144	7.27					
Immediate roof	Sandy mudstone	127	7.05	39.9		37	33.5	2.68
Coal seam	The combined seam of 8th and 9th coal seam	19.7	1.58	5.9	0.22	7.5	25	1.37
Main roof	mudstone	80.4	5.25					

roofs with different lithological characteristics, even in the same coal seam, vary widely in mine pressures and have different bursting potential. The instability of the mudstone roof occurred and the roof collapsed while coal mining. For instance, the mudstone roof of the 12th coal seam and the partial roof of the 9th coal seam had short first weighting intervals and periodic weighting intervals. Table 3 shows that the first weighting intervals and the periodic weighting intervals in the mudstone roof of the 12th coal seam are 20-23.5 m and 5-12 m, respectively; and those of mudstone roof of the 9th coal seam are 20-28 m 10-15 m, respectively. The roadway only had slight deformation in those rocks which did not show busting potential, such as in No. 1227 and No. 2221 working faces. On the contrary, in the sandstone roof of the 5th and 9th coal seams, the first weighting intervals were much longer, 30-50 m and 15-35 m, respectively. Especially, when the roof is extremely thick and stiff, and the immediate and the main roofs have similar lithological characteristics and no clear border between the two roofs, rock bursts are most likely to occur, such as in No. 3652 and No. 5287N working faces. A further analysis of observed data in the representative working faces in the 12th, the 5th, and the 9th coal seams was conducted. The result indicated that the first weighting intervals and the periodic weighting intervals of mudstone roofs were obviously less than those of sandstone roofs. The reason for this phenomenon is that the thick and stiff sandstone roofs can accumulate more elastic strain energy and dissipate less deformation energy under stress concentration. Therefore, those rocks can release a great amount of elastic strain energy, which is most likely to induce a rock burst. On the contrary, the weak mudstone roofs break and collapse after mining and dissipate more deformation energy. Therefore, these roofs cannot accumulate enough elastic strain energy to cause a rock burst.

4. Numerical modeling of rock burst hazard in working faces with different roof lithological characteristics

4.1 Geological models

In order to study the effect of roof lithological characteristics on rock burst, three models were

Table 3 Statistical observation results of underground pressure on working face of roofs of different lithological characteristics in Tangshan colliery

Coal seam	Working face	Immediate roof	Main roof	Elevation /m	Mining height /m	First weighting interval/m	Periodic weighting interval /m	Approaching velocity of roof and floor /(mm·h^{-1})	Others
5th	2351	Grey mudstone	Grey mudstone	–610	2.0	19.0	9.6	Sudden change and with a wide range	
	2453	Grey siltstone	Grey fine sandstone	–650	2.6	31.0	12.4	Sudden change and with a wide range	
	7254	Grey fine sandstone	Grey medium-fine sandstone	–650	2.1	34.5	14.3	Sudden change and with a narrow range	
	3652	Grey medium-fine sandstone	Grey medium sandstone	–700	2.7	39.0	17.9	Sudden change and with a narrow rang	Rock burst
9th	2485	Dark grey mudstone	Grayish brown siltstone	–700	2.5	25.5	15.0	A maximum of 5.6	
	T2191	Grey mudstone	Light grey silt-fine sandstone	–600	9.0	31.0	14.0-16.0	A maximum of 6.0	
	5287N	Grayish brown siltstone	Grayish brown silt-fine sandstone	–600	2.7	50.5	34.0	A maximum of 8.0	Rock burst
12th	1227	Dark grey sapropelic mudstone	Dark grey mudstone	–500	2.7	20.0	6.3		Deformed weakly in roadway
	2221	Dark grey sapropelic mudstone	Dark grey mudstone	–610	1.8	22.0	5.0		No bursting potential
	2321	Dark grey mudstone	Grayish-white fine sandstone	–670	2.7	23.5	8.0-12.0		

established: Model I simulated the roof comprised of the medium-grained sandstone; Model II siltstone roof; Model III mudstone roof.

The boundary conditions of these models were determined as follows:

(1) Horizontal restraints were set to the front, back, left and right boundaries of the model, *i.e.* horizontal displacement of model boundaries was zero, and boundary nodes were allowed to displace in the vertical direction.

(2) The bottom of the model was fixed: horizontal and vertical displacements on the bottom boundary nodes were zero.

(3) The top of the model was a loading boundary and its vertical stress was determined by:

$$\sigma_z = \mathrm{rH} = 0.027 \times 650 = 17.55\ \mathrm{MPa} \tag{1}$$

where σ_z is vertical stress, r is the average density of the overlying strata and H is the thickness of overlying strata.

4.2 Numerical models and parameters

The numerical modeling software FLAC^{3D} (Three Dimensional Fast Lagrangian Analysis of Continua) was used in this study. Since it can be used to model the mechanical behaviors of geological materials suffered by loading, especially in analyzing underground mining, destabilization and large deformation, this software has been applied widely in mining engineering. The Mohr-Coulomb-Mohr yield criterion was used in this modeling:

$$f_s = \sigma_1 - \sigma_3 N_\phi - 2c\sqrt{N_\phi} \tag{2}$$

$$f_t = \sigma_3 - \sigma_t \tag{3}$$

If $f_s = 0$, shear failure occurs, and if $f_t = 0$, tensile failure occurs.
Where σ_1 is the maximum principal stress, σ_3 is the minimum principal stress, c is the cohesion, ϕ is the internal friction angle and σ_t is the tensile strength, and N_ϕ is expressed as:

$$N_\phi = \frac{1+\sin\phi}{1-\sin\phi} \tag{4}$$

Mechanical parameters of rock strata adopted in numerical computation were determined by lab core tests. The rock bulk modulus (B) and shear modulus (S) are expressed as:

$$B = \frac{E}{3(1-2\upsilon)} \qquad S = \frac{E}{2(1+\upsilon)} \tag{5}$$

where B is the the bulk modulus of rock, E is the Young's modulus of rock, S is the shear modulus of rock and υ is the Poisson's ratio of rock.

Table 4 Mechanical parameters of Models I, II, and III

Numbers of formations		Lithological characteristics	Bulk density/ kg/cm^3	Compres-sion Strength/MPa	Tensile Strength/ MPa	Internal Friction Angle/°	Cohesive Strength/ MPa	Young's Modulus/ GPa	Poisson's ratio
1		Sandy mudstone	2.63	116.68	2.2	36	7.11	22.14	0.178
2		Grey medium-coarse grain quartz-sandstone	2.72	143	6.91	31	14	28	0.28
3	Model I	Medium-grain Quartz-sandstone	2.68	103.2	10.1	36.72	13	26.7	0.22
	Model II	siltstone	2.7	95	6.6	36	10	20	0.32
	Model III	mudstone	2.58	52.2	2.51	36.72	6.3	12.92	0.32
4		Coal	1.39	18	2.31	31.81	5.09	4.5	0.32
5		Deep grey mudstone	2.52	76.5	4.7	38.4	7	16	0.34
6		Silt-fine sandstone	2.76	101.3	6.66	36.49	18	22	0.2
7		Sandy mudstone	2.56	94.54	5.2	37	6.33	17	0.3

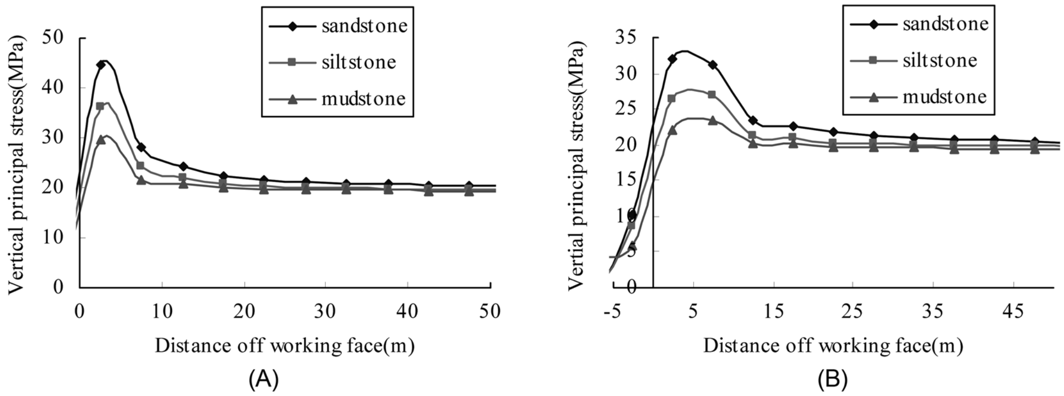


Fig. 3 The distributions of vertical stresses along the strike of a working face before roof failure in: (A) coal seams and (B) floors

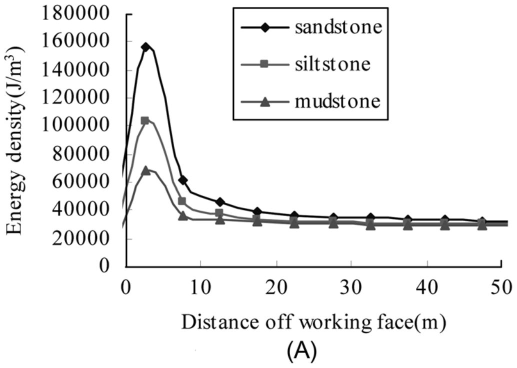
The models and their mechanical parameters used in this numerical analysis are presented in Table 4.

4.3 Effects of roof lithological characteristics on stress field

Roof lithologies play an important role in the distribution of the stress field in coal seam and its surrounding rocks during mining. The stress concentration levels of a coal seam and its surrounding rocks differ for different roof lithological characteristics during mining. Fig. 3 plots the vertical stress distributions in the coal seam and floors along the strike of the working face before the roof failed. The figure shows that roof lithological characteristics have an obvious influence on the coal seam and its surrounding rocks. Before the roof of the medium-grained sandstone begins to fail, the maximum vertical principal stresses in the stress concentration areas in coal seams and floors are 44.5 MPa and 32.1 MPa, respectively. For the roof of siltstone, the maximum vertical principal stresses in the coal seams and floors are 36.3 MPa and 26.8 MPa, respectively. However, for the roof of mudstone, the maximum vertical principal stresses in the coal seams and floors are 29.5 MPa and 23.5 MPa, respectively. In the stress concentration area in front of the coal wall with medium-grained sandstone, the maximum vertical principal stress is 1.23 and 1.51 times that of working faces with a siltstone roof and with a mudstone roof, respectively. In floors with medium-grained sandstone roof, the maximum vertical principal stress is 1.20 and 1.37 times that of working faces with a siltstone roof and with a mudstone roof.

4.4 Effects of roof lithological characteristics on energy field

During mining of the working face, redistribution of stress in coal seam and its surrounding rocks occurs because of the disturbing of mining. With mining advance, the coal seam and its surrounding rocks deform and even rupture because of the stress concentration. Deformation and failure of the seam and its surrounding rocks is a dynamic process of accumulation in elastic strain energy and dissipation in plastic energy. During the roof bending and coal seam compression, the roof and the seam can accumulate elastic strain energy; in the same time, some energy is dissipated to form plastic deformation of the seam and its surrounding rocks.



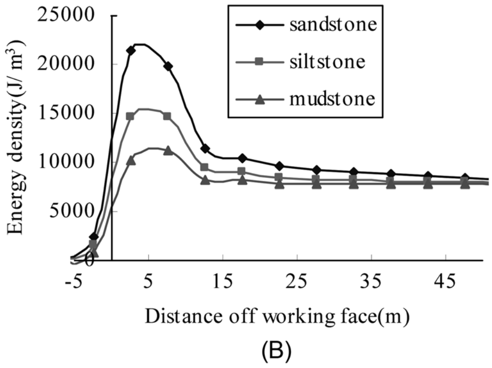


Fig. 4 Energy density distributions along the strike of the working face before roof failure in: (A) coal seams and (B) floors

To different working faces with different lithological characteristics, the accumulated elastic strain energy in the coal seam and its surrounding rocks differs remarkably while the roof breaks. Fig. 4 plots energy density distributions in the coal seams and in the floors along the strike of working face before the roof fails. In the energy concentration area in front of the coal wall, the maximum elastic strain energy density is 155590.3 J/m^3 in the working face with the roof of the medium-grained sandstone. This elastic strain energy density is 1.5 and 2.27 times that of working faces with siltstone roof and with mudstone roof, respectively. In other words, from the beginning of mining to the roof failure, the amount of accumulated elastic strain energy increases as the strength and stiffness of the roof increases.

The numerical modeling results show that the lithological characteristics of the roof significantly influence the distribution of stress fields and the variations of elastic strain energy density in the coal seams during mining. The stress concentration and the energy accumulation in the coal seams and their surrounding rocks increase as the Young's modulus in the roof increases, resulting in a higher potential to induce rock bursts. The reasons for this can be explained as follows:

The hard roofs consisting of the medium-grained sandstones, have high compressive strength and Young's modulus; therefore, they have stronger abilities to resist deformation and failure, and provide a strong holding force on the coal seams during mining. With the progress of mining, there are higher stress concentrations and elastic strain energy accumulation in the front of the coal walls, which makes the coal seams have a high bursting potential. If the loading on the coal seams increases, the coal seams begin to fail and a great amount of elastic strain energy stored in the coal seams releases and aggravates the failure of the coal mass. Once the released energy is enough to induce a rock burst, the compressed coal mass fails suddenly and is thrown into the worked-out section of the mining area. For example, the first roof failure interval was about 40-50 m in Model I. When the working face was mined 40 m along the strike, the medium sandstone roof still did not cave, which resulted in high stress concentration and high elastic strain energy accumulation in the abutment of the coal mass. Thus the bursting potential of the coal mass increased. On the contrary, in model II and model III, the roofs of silt sandstones and mudstones demonstrated less ability to resist to deformation and failure, and provided a lower holding force on the coal mass because of their low compressive strength and Young's modulus. During coal mining, the roofs of siltstones caved easily and the first roof failure interval was only 20-30 m. The roofs of mudstones began failure and caving, when the working face was extracted less than 10 m; therefore, it was difficult for the roofs to concentrate high stresses and accumulate enough elastic strain energy to induce a rock burst.

5. Conclusions

Comprehensive investigation of the roadway deformation, the distribution of mine pressures, occurrences of rock bursts, and the lithological characteristics of the surrounding rocks of the primary coal seams were conducted in Tangshan colliery. The associated numerical modeling was also performed. The following conclusions were drawn from this study. In Tangshan colliery, rock bursts generally occurred during mining of the 5th coal seam, and the combined seam of the 8th and the 9th coal seams. The roofs of the 5th coal seam were mainly comprised of grey siltstone, fine-grained sandstone and medium-grained sandstone, while the combined seam roofs of the 8th and the 9th coal seams generally are comprised of hard sandy mudstone and medium to fine grained sandstone. These roofs have high uniaxial compressive strength and high Young's modulus and demonstrate a strong holding force on coal seams. Around mining working faces, the high stress concentration was generated and a great amount of elastic strain energy was accumulated near the coal roadways, which made the coal seams demonstrate high bursting potential. The numeric modeling results also show that the lithological characteristics of roofs play an important role in influencing the distributions of stress fields and the variations of elastic strain energy density in coal seams and floors. The maximum vertical principal stress in the coal seam with a sandstone roof is higher than that of coal seams with a siltstone roof or with a mudstone roof.

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