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Influence of Water on Granite Tunnel Rockburst by AE

Abstract: Rock mass at site has usually been in water-rich environments for a long periods. In order to study the effects of water on Granite tunnel rockbursts, natural and water-saturated specimens have been took experiment here. Rockbursts on roadways were monitored using the acoustic emission (AE) system from PCI-2. Results showed that water invasion reduced the compressive strength and elasticity of the rock, at rates of 10.8% and 18.3%. When the rock surrounding the roadway came into contact with water, the fracture morphology and energy dissipation methods changed, and the splitting intensity of surrounding rock on both the left and right sides were relieved. The AE information of Granite saturated with water during its rockburst evolution process was more enriched than that of natural Granite. The quiet periods in AE were shorter than in natural rock and the large electrical events appeared earlier. These results all suggested that the injection of water into rocks near roadways changes the rate of rock fracture formation and reduces energy storage, thereby, preventing and controlling rockburst.

Key words: water, roadway rockburst, biaxial, AE.

Introduction

In recent years, many roadways (including drift, shafts, inclined shafts, and other roadways) deep underground engineering has started to develop, and the probability of rockburst increased greatly. Rockburst is a common dynamic disaster that happens in underground engineering under high ground stress conditions. How to monitor, prevent, and control the rockburst effectively has been recognized as a serious problem affecting underground engineering projects worldwide.

So far, many academics have made some important achievements in the monitoring and prediction of tunnel rockburst. Today, Acoustic emission (AE)/ microseismic and Infrared monitoring have been took a widely used in prevention the disaster of rockburt [1, 2]. Since the Mogi [3] collected AE signal from rock fracture in 1960s. AE monitor has made rapid development. Madsen [4] found that it exist some extent between the precursor of rockburst and the high frequency of AE. M.C. He [5] studied rockbusrt through AE monitor under true-triaxial unlading condition. Frequency-spectra analysis has been conducted from the full-wave AE data. William [6] briefly examined differences and similarities between the support design philosophies applied in circumstances and those prevailing in most civil engineering tunnels, the advocated in the paper would improve the underground environment and

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substantially benefit the safety of the workforce. Brown [7] said that it is difficult to reach an agreement on the definition of rockburst. The successful answer to rockburst problems is explored by many research centers all over the world. T.H. Ma and C.A. Tang [8] captured the micro-seismic precursory information by Full-time continuous monitoring of micro-seismic equipment in Jinping II Hydropower Station in China. The relationship between the spatial and temporal evolution of micro-seismic activities and rockbursts was revealed. Xiangxin Liu [9] determined rock type by their AE time- and frequency- domain characteristics. The wavelet transform was used to decompose the AE signals, and the artificial neural network (ANN) was established to recognize the rock types and noise (artificial knock noise and electrical noise). Philip [10] took a study on rock deformed and fracture from a laboratory experiment in which basalt from Mount Etna volcano (Italy). The low frequencies were associated with pore fluid decompression and were located in the damage zone in the fractured sample. Zhenzhao Liang [11–13] used numerical simulation and laboratory to take rock failure process research, heterogeneous and fracture of rock was researched by Microseismic, AE and numerical simulation. Zhengzhao Liang and Xiangxin Liu [14] used acoustic emission (AE) technique to monitor the progressive failure of a rock tunnel model subjected to biaxial stresses. Results showed that the vertical stress enhanced the stability of the tunnel, and the tunnels with higher confining pressure demonstrated a more abrupt and strong rockburst.

Rock masses in excavation sites are in water-rich environments for long periods and are often themselves saturated with water, granite masses with the poorest permeability tend to be the most likely to burst. The groundwater environments in which these rock masses are located are subject to three functions: seepage effects, effects of water, and chemical functions. In view of the seepage effect and chemical effect, many scholars have performed studies, and some important results have been reported. However, research into the functional mechanism of rockburst in rock surrounding roadways in view of the water content of hard, brittle rock is not currently satisfactory.

Granite tunnel rockbursts have been simulated in testing machines that mimic the conditions of the excavation sites across a range of dryness and moisture. The PCI-2 AE system has been used before to monitor the process of rockburst. The AE waveform has been collected. The current work was performed to develop systems for the prevention of rockburst by evaluating the mechanism and effects of water flooding in the tunnels.

1. Simulation of Tunnel Rockburst

1.1. Sample preparation

Test samples were Granite blocks 150×150×150 mm^3 in size, each with a round hole 30 mm in diameter in the center, and the parallelism error of two head faces was within 0.02 mm. Specimens were prepared in accordance with the Standard for Test Method of Engineering Rock Mass (GB/T50266-99).

The moisture conditions were as follows: (1) State of natural dryness: the sample was placed at room temperature in the laboratory. (2) State of moisture: the sample was placed in a sink. The sink was filled with water up to 1/4 of the sample’s height, increasing to 1/2 and finally 3/4 after 2 hour. The samples were immersed completely after 6 hour and allowed to soak for an additional 48 hour.

The experiment was divided into 5 groups per state, and the natural dry samples were here named ZRHG-1, ZRHG-2, etc. The moist samples were named BHHG-1, BHHG-2, etc.

1.2. Laboratory equipment

Laboratory equipment: RLW-3000 microcomputer control servo test machine produced by Chaoyang Experimental Factory in Changchun China, PCI-2 AE system produced by the Physical Acoustic Company in the U.S., and an air conditioner produced by Gree Company in China (Fig. 1).

1.3. Experiment Scheme

This experiment mainly simulated the stress of rockburst on the walls of nearby roadways. After excavation of the roadway, the surrounding rock surface area approximated bidirectional loading condition. Biaxial loading was chose in this experiment. The horizontal fore was set to 30 kN, and the axial was loaded at a rate 0.3mm/min to occurrence of rockburst on the mode of displacement control loading.

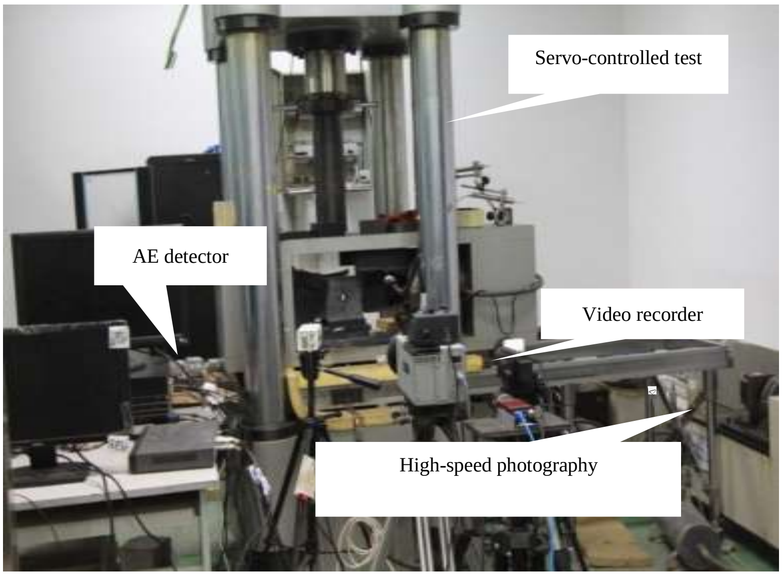


Fig. 1. Experimental equipment.

2. Experimental results

2.1. Results of rockburst tests

There were no obvious fracture phenomena around the holes at the beginning of loading. The rock around the holes was calm (quiet period, as shown in Fig. 2(a)). When the axial load increased to a certain point, burst dissipated the accumulated energy, making the holes from left and right sides of the wall begin to eject tiny particles (Fig. 2(b)). The experiment continued, and rock fragments were ejected from the holes and more rock flaked off the surface. The internal holes went into a state of “smoking” because of these violent ejections. Gradually, the rocks spilled, accompanied by ringing bursts. Finally, specimens around the holes in large area spalled. A large number of rocks jetted. The holes became deformed seriously. The rock specimens suddenly lost their stability, accompanied by loud noises. Because of the violent ejection state, smoke diffused around the specimens and on both sides of the holes visible cracks gradually appeared.

In this experiment, the inner holes of granite showed particle ejection, exfoliation, and finally collapse. This was consistent with findings reported by Professor HE Manchao who put forward that the process of rockburst must go through four stages, the quiet period, particle ejection, flaking and particle ejection.

(a) Quiet period **(b) Particle ejection** **(c) Spall with violent ejection** **(d) Ejection completely**

Fig. 2. Four stages of rockburst process.

As shown in Fig. 3, the peak strength of water-saturated granite and elastic modulus were significantly lower than that of natural dry granite. The elastic modulus decreased to 18.3% and the peak intensity to 10.8%. When the samples were full of water, their physical and mechanical properties degraded. Water reduces the crystal particle strength of the rocks and bonding capacity between mineral grains, which reduced the peak strength of the rock.

In addition, the presence of water in rock produced a softening effect, decreasing the elastic modulus and increasing the magnitude of the peak strength.

$$E_{\Delta}=(E_1+E_2+E_3+E_4+E_5)/5=(4.34+3.94+4.23+4.17+4.73)/5=4.282\ \text{MΠα}$$

$$E_{\Omega}=(E2_1+E2_2+E2_3+E2_4+E2_5)/5=(3.36+3.25+3.39+3.84+3.65)/5=3.498\ \text{MΠα}$$

$$⌠_{\Delta}=(⌠_1+⌠_2+⌠_3+⌠_4+⌠_5)/5=(1324+1481+1420+1421+1410)/5=1411.2\ \text{MΠα}$$

$$⌠_{\Omega}=(⌠2_1+⌠2_2+⌠2_3+⌠2_4+⌠2_5)/5=(1246+1247+1301+1224+1274)/5=1258.4\ \text{MΠα}$$

$$\otimes E=(E_{\Delta}-E_{\Omega})/E_{\Delta}=18.3\%$$

$$\otimes ⌠=(⌠_{\Delta}-⌠_{\Omega})/⌠_{\Delta}=10.8\%$$

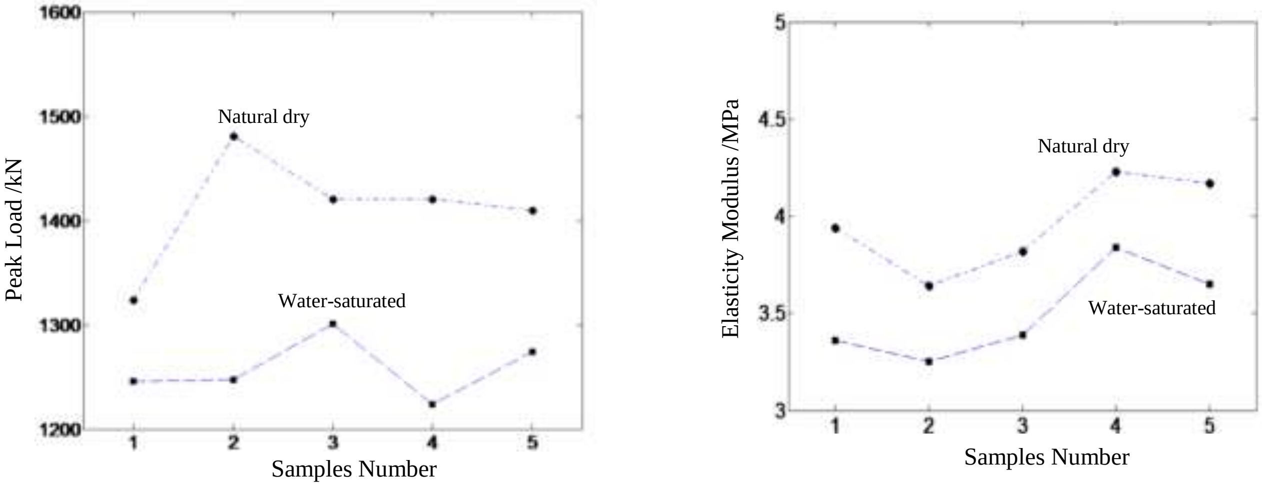


Fig. 3. Peak load and elasticity modulus of natural and water-saturated granites.

As shown in Table 1, water-saturated granite appeared to burst slightly later than granite in its natural, dryer state. When the loading time of natural granite was 82.4% of the peak time, the inner holes appeared cuttings ejection, which means rockburst occurred. When the loading time of natural granite was 89.7% of the peak time, the inner holes ejected particle, which indicates that rockburst had taken place.

Because of the invasion of water, rock strength, elastic modulus and stored elastic energy all decreased. The ability of the rock to absorb energy through plastic deformation increased. It was difficult for the moist samples to accumulate large amounts of energy in a short period of time. For this reason, particle ejection took place later.

Table 1

The time of rockburst of natural and saturated granites

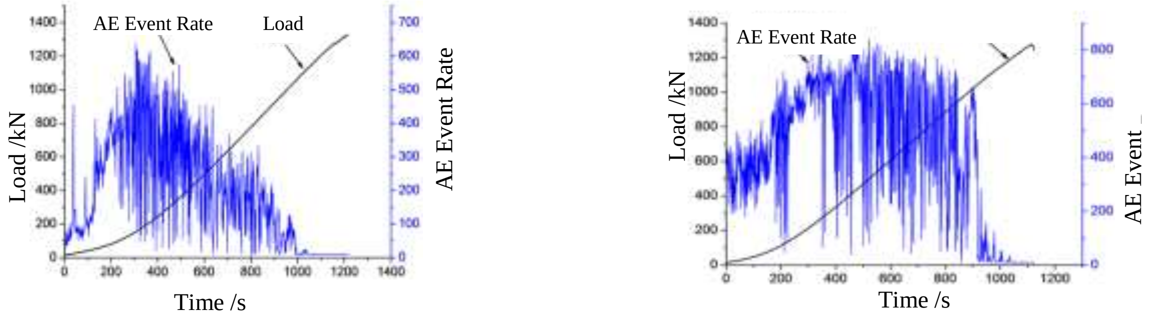
Natural sample	Time of rockburst (t/s)	Time of complete collapse t_c/s	t/t_c	Water-saturated sample	Time of rockburst (t/s)	Time of complete collapse (t_c/s)	t/t_c
ZRHG-2	887	1112	79%	BHHG-1	900	1030	87%
ZRHG-3	977	1161	84%	BHHG-2	939	999	94%
ZRHG-4	1018	1186	85%	BHHG-3	1047	1183	89%
ZRHG-5	906	1105	82%	BHHG-4	916	1007	91%
ZRHG-7	899	1124	80%	BHHG-6	903	1026	88%
Natural state	937.4	1137.6	82.4%	Water-saturated state	941	1049	89.7%

PS: t is the corresponding time of rockburst, $\mathbf{t}_c$ is the complete collapse of tunnel that caused by rockburst.

2.2. The AE Characteristics of rockburst

Characteristics of acoustic emission by damaged rocks are closely related to the extent of the cracks and other internal damage within Granite. The rate of rock acoustic emission of events and the amount of energy are important parameters in rock damage.

As shown in Fig. 4(a)–(f), the change rules of the rate of acoustic emission events were similar in naturally dry and water-saturated granite. Acoustic emissions were mainly concentrated when loading ranged from 10% to 80% of the peak, and the value varied constantly. The samples had earlier initial acoustic emission and higher frequency. These cluster characteristics showed a relationship with the material composition and internal structure of granite. The granite specimens were mainly composed of feldspar, quartz, and hornblende. The differences in the strength properties of various minerals, the inhomogeneity of crystallization connection, and the natural flaws in the internal structure made the granite sensitive to stress and crack propagation under loading activity. Acoustic emission activity was fairly common.



(a) ZRHG-2 (b) BHHG-1

(c) ZRHG-4 (d) BHHG-3

(e) ZRHG-3 **(f) BHHG-5**

Fig. 4. Curves of load and AE event rate-time of granites.

The quiet period of acoustic emission is important and takes place before rockburst. The discussion of the quiet period of acoustic emission before rockburst was here discussed in two respects:

A. Duration of the quiet period

As shown in Table 2, because of the influence of water, the duration of the quiet period of granite acoustic emission was more apparent in moist samples. The quiet period lasted longer in the natural state than in the saturated state. The main reason for this is because of the presence of water, which inhibits the development of tensile failure from the surrounding roadway rock on the left and right sides, and causes the splitting cracks. Pressure shear cracks formed because water did not have the capacity of shearing. The pressure shear failure of rock required more energy than tension damage. As shown in Fig. 5, the saturated granite underwent crush failure and formed a typical single bevel shearing fracture surface. The naturally dry granite first underwent tension failure firstly, which was a typical splitting crack.

Table 2

Quiet period of AE events of natural and saturated granites

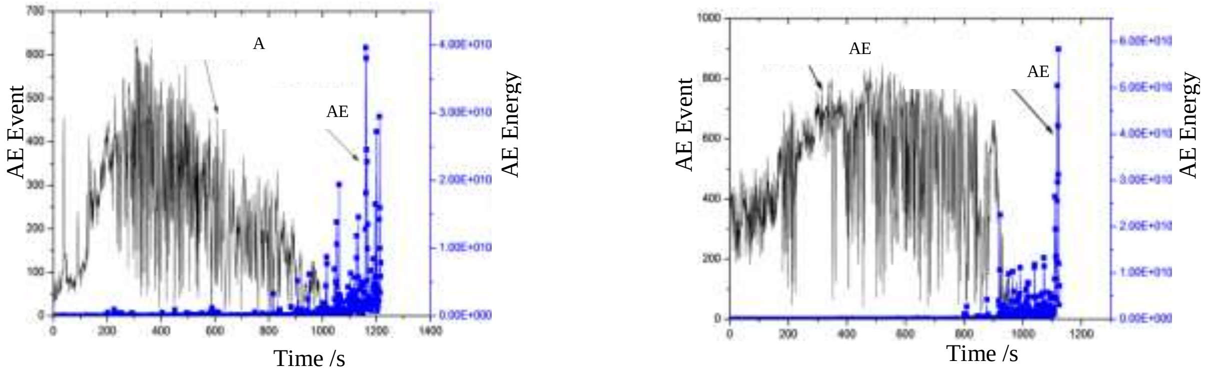
Natural sample	Duration of AE quiet period (t/s)	Water-saturated sample	Duration of AE quiet period (t/s)
ZRHG-2	220	BHHG-1	116
ZRHG-4	431	BHHG-3	58
ZRHG-3	210	BHHG-5	127
Average	287	Average	100.3

B. AE wave propagation.

When the axial loading reached 65–80% of the peak load, the acoustic emission events entered a quiet period (Fig. 4). Before rock failure, a large number of cracks formed inside each sample and gradually reached surface through sexual fracture and produced a significant area of resistance. The energy produced during the deformation of rock mainly dissipated on the shear sliding surface of the rock failure, attenuating the acoustic emission signal and leading to a pronounced AE quiet period.

The quiet period of acoustic emissions by water-saturated granite was shorter than that of natural granite. The reason for this was that the presence of water weakens the bonds between rock particles. Water was also associated with chemical corrosion which reduces the elastic modulus and strength of granite. Cracks were more likely to extend under these conditions. The acoustic emission signals are severely attenuated before rupture. The AE quiet period lasted longer than under natural drying conditions.

As shown in Fig. 5, granite rockburst during acoustic emission events and the energy absorption rate showed reciprocal characteristics.



(a)ZRHG-2

(b) BHHG-1

Fig 5. Curves of AE event rate and energy rate-time of granites.

When the rate of early-stage acoustic emission events was greater, the rate of AE energy absorption was low and stable. While the rate of the acoustic emission events before rockburst decreased into the quiet period, the AE energy rate increased sharply, peaking with damage. Granite was a brittle rock, and its elastic modulus was large. The ability of the rock to store energy elastically was greater. This brittleness was closely associated with a strong tendency toward burst. During the early stage of rockburst, the rock was mainly subject to the production and extension of micro cracks. There were many acoustic emission events.

More elastic strain energy was stored during the rockburst inoculation process. Although a lot of energy was released at the moment of destruction, the AE energy rate raised sharply. Results showed that rockburst produced a large number of small electrical acoustic emission events during inoculation but produced a few large electrical acoustic emission events before the rock was destroyed and energy was released suddenly. So when there is a small number of large electrical events, it can be concluded that the rockburst is about to happen.

3. Discussion

The fracture mechanism of rockburst is the same as the general rock damage fracture mechanism. Both of exhibited tensile, splitting, and shear failure modes. Rock fracture morphology was observed after burst, which indicated the mechanism underlying failure and rockburst processes.

As shown in Fig. 6, water-saturated granite bursted was corresponding to pressure shear failure. Samples in the dry state can undergo typical tensile rupture, which was a typical brittle failure. It required less energy, but released more energy and caused more damage than that carried by fragments during rockburst. The particles were small and they were ejected long distances. The compression-shear damage was caused by parts of the plastic deformation of rocks. In the process of failure, friction could affect the fracture surface and released some energy.

Water-saturated granite was damaged more seriously and fractured more profoundly than dry granite. These samples tended to undergo pressure shear that cannot cut shear cracks, called C1. A larger opening cleavage crack called C2, formed in the holes on the left side of the natural dry granite. A tension crack called C3 appeared in the holes in the upper left corner of the natural dry sample. A small X-type crack called C4 appeared near the left holes.

(a) water-saturated Granite

(b) dry Granite

Fig. 6. The fissure damage morphology of dry and saturated Granite sample.

Water can, to an extent, limit the splitting failure of granite surrounding roadways by disrupting the inoculation process of rockburst, reducing the number of bursts, and delaying rockbursts, but it cannot prevent the occurrence of rockbursts entirely.

When granite comes into contact with water, splitting failure on sidewalls of tunnel is restrained to an extent, which interferes with the development of rockbursts and both postpones the bursts and decreases their intensity.

Due to the limited understanding of the mechanical mechanisms that control rockbursts, experience leads judgement in construction. Because there are so few targeted measures, rockbursts are often handled poorly, and prediction is similarly difficult.

1. When granite is water-saturated, its AE perk intensity is reduced by 11.47%, and 8.16% for the elasticity modulus (Table 2). Water reduces the rock's ability to store energy, the rate of energy storage, and both postpones and reduces the intensity of the rockbursts.

2. Regarding infrared, before a rockburst, water affects the precursor features at both the highest and lowest temperatures, where the curves show obvious, sudden changes. As shown in Fig. 6, the rock-burst precursor feature of water-saturated granite is easy to depict.

Using water spray and water injection to prevent rockbursts would involve two major mechanisms: First, at a certain depth, water softens rocks, weakens its elasticity modulus and intensity, and decreases its tendency to burst; second, injecting water into drilled hole not only softens the rocks but also relieves tangential stress of sidewalls around the tunnel and reduces the density of stress, preventing rockbursts.

Conclusion

1. Water affected rockbursts in the form of rockburst, which is the way the energy was dissipated. Water suppresses the production tensile failure of rock surrounding roadways on the left and right sides and also suppresses the formation of splitting cracks. Water does not have the capacity to shear and can produce compression-shear cracks easily. Water-saturated granite can form typical single-cant shear fracture surfaces, but natural dry granite undergoes tension failure early, forming typical splitting cracks.

2. Granite can become saturated with water, which decreases peak strength and elastic modulus. The elastic modulus is decreased by 18.3% and the peak intensity by 10.8%. The decrease in amplitude of the elastic modulus is higher than peak intensity.

3. The activity of acoustic emission in the evolution of rockburst water-saturated granite is more colorful. The rate of acoustic emission events during the quiet period is low. The level of AE energy decreased.

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REFERENCES

1. Saltas V., Fitilts I., Vallianatos F. A combined complex electrical impedance and acoustic emission study in limestone samples under uniaxial loading. Tectonophysics. 2014;637:198-206.
2. Cress G.O., Brady B.T., Rowell G.A. Sources of electromagnetic radiation from fracture of rock samples in the laboratory. Geophys. Res. Lett. 1987;14:331-334.

3. Mogi K. Study of elastic shocks caused by the fracture of better o-generous material and its relation to earthquake phenomena. Bulletin of the Earthquake Research Institute. 1962:40. (Tokyo).
4. Calder P.N., Madsen D. High frequency precursor analysis prior to a rockburst. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 1989;26:3-4.
5. He M.C., Miao J.L., Feng J.L. Rockburst process of limestone and its acoustic emission characteristics under true-triaxial unloading conditions. International Journal of Rock Mechanics & Mining Sciences. 2010;47:286-298.
6. Ortlepp W.D. The behaviour of tunnels at great depth under large static and dynamic pressures. Tunnelling and Underground Space Technology. 2001;16:41-48.
7. Brown E.T. Rockburts: prediction and control. Tunnels Tunn. 1984:17-19.
8. Ma T.H., Tang C.A., Tang L.X., et al. Rockburst characteristics and microseismic monitoring of deep-buried tunnels for Jinping II Hydropower Station. Tunnelling and Underground Space Technology, 2015;49:345-368.
9. Xiangxin Liu, Zhengzhao Liang, Yanbo Zhang, et al. Acoustic Emission Signal Recognition of Different Rocks Using Wavelet Transform and Artificial Neural Network. Shock and Vibration. 2015. Article ID 846308, 14 p.
10. Benson Ph.M., Vinciguerra S., Meredith Ph.G., et al. Laboratory Simulation of Volcano Seismicity. Science. 2008;10(322):249-252.
11. Liang Z.Z., Tang C.A., Li H.X., Zhang Y.B. Numerical simulation of the 3D failure process in heterogeneous rocks. International Journal of Rock Mechanics and Mining Sciences. 2003;41(3): 419-419.
12. Liang Z.Z., Xing H., Wang S.Y., Tang C.A. et al. A three-dimensional numerical investigation of the fracture of rock specimens containing a pre-existing surface flaw. Computers and Geotechnics. 2012;45:19-33.
13. Liang Zhengzhao, Xu Nuwen, Ma Ke, Tang Shibin, Tang Chunan. Microseismic Monitoring and Numerical Simulation of Rock Slope Failure. International Journal of Distributed Sensor Networks. 2013. Article ID 845191.
14. Zhengzhao Liang, Xiangxin Liu, Yanbo Zhang, Chunan Tang. Analysis of Precursors Prior to Rockburst in Granite Tunnel Using Acoustic Emission and Far Infrared Monitoring, Mathematical Problems in Engineering. 2013. Article ID 214340.

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ЯНЬБО ЧЖАН, СЯНСИНЬ ЛЮ, СЮЙЛУН ЯО, ПЭН ЛЯН –
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Сейсмоакустическая оценка влияния воды на удароопасность гранитного массива при строительстве тоннеля

Аннотация: Проведены исследования сейсмоакустической активности относительно гранитного массива при строительстве тоннеля. Показано, что удароопасность массива при наличии воды снижается.

Ключевые слова: вода, удароопасность, двухкоординатный, сейсмоакустическая эмиссия.

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