International Journal of Minerals, Metallurgy and Materials
Volume 16, Number 1, February 2009, Page 12

Minerals

Comprehensive assessment on dynamic roof instability under fractured rock mass conditions in the excavation disturbed zone

Xing-ping Lai[1,2,3], *Fen-hua Ren*[2], *Yong-ping Wu*[1,3], *and Mei-feng Cai*[2]

1) Energy School, Xi'an University of Science & Technology, Xi'an 710054, China

2) School of Civil and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083, China

3) Key Laboratory of Western Mine & Hazard Prevention, China Ministry of Education, Xi'an 710054, China

(Received 2008-03-06)

Abstract: The damage process of fractured rock mass showed that the fracture in rocks induced roof collapse in Yangchangwan Coal Mine, China. The rock mass was particularly weak and fractured. There occurred 6 large-scale dynamical roof falls in the excavation disturbed zone (EDZ) with the collapsing volume of 216 m^3. First, the field detailed geological environment, regional seismic dynamics, and dynamic instability of roadways were generally investigated. Second, the field multiple-index monitoring measurements for detecting the deep delamination of the roof, convergence deformation, bolt-cable load, acoustic emission (AE) characteristic parameters, total AE events, AE energy-releasing rate, rock mass fracture, and damage were arranged. Finally, according to the time-space-strength relations, a quantitative assessment of the influence of rock-mass damage on the dynamic roof instability was accomplished.

Key words: fractured rock mass; excavation disturbed zone (EDZ); roof collapse; acoustic emission (AE); quantitative assessment

[*This study was financially supported by the National Natural Science Foundation of China (No.10402033 and No.10772144).*]

1. Introduction

Dynamic accidents caused by roof falls are common problems in underground coal mines. These accidents could have detrimental effects on workers in the form of injury, disability or fatality, as well as on mining companies due to downtimes, interruptions in mining operations, equipment breakdowns, and so on. Yangchangwan Coal Mine locates at Ningxia Municipality in northwestern China. The rock-mass became softened and fractured due to historic earthquakes, roof falls happened frequently to thereby have induced potential disasters [1]. A multiple-index monitoring method for the assessment and management of risks associated with mine roof falls was proposed based on an investigation of the monitory of large-scale roof dynamic collapse in this article. The results clearly demonstrated the influence on roof integrity, and particularly indicated the distribution of deformation, deep delamination, and strata failure into the roof and across the full span of the roadways.

2. Site description

Yangchangwan Coal Mine locates at one of the strong earthquake regions in northwestern China. Under the extruding stress in NEE-SWW direction, the surrounding rock mass is squeezed. Historically, there even occurred 6 intensive earthquakes (≥M7.0). The rock mass became softened and fractured, and dynamic collapse and roof falls occurred frequently to induce potential disasters. The excavation disturbed zone (EDZ) consists of mudstone and sandstone, and roof falls frequently happened. As shown in Fig. 1(a), the roof lithology is siltstone, with a thickness of 3.05 m, which contains various rock types, such as mudstone, sandstone, and coal seam. One result of the interactions of water with the porous structure of coal or coal-pillars is that ground water infiltrates through the coal seam to decrease the mechanical strength of the rock mass, which will lead to roof falls. Fig. 1(b) shows that coal pillars would significantly slab off and be unstable under the condition of disturbed mining.

Corresponding author: Xing-ping Lai, **E-mail:** lxptest@sina.com

The mechanical strength of the left (Fig. 1(c)) and right (Fig. 1(d)) walls was deteriorated which induced local falls with the maximum collapse volume of 216 m^3 on June 20, 2006.

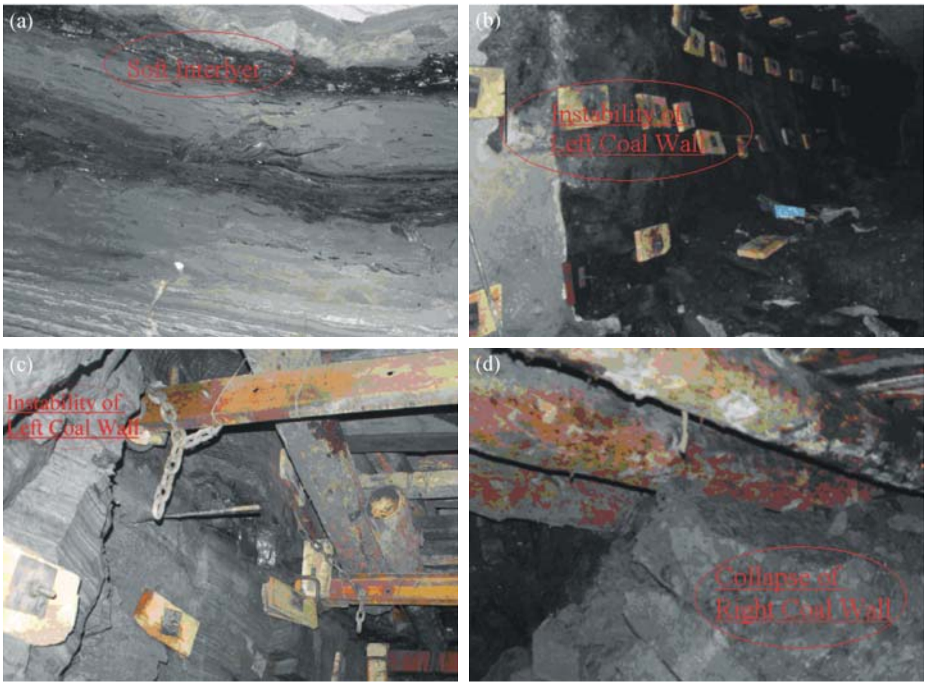

Fig. 1. Photographs of field investigation: (a) soft interlayer; (b) instability of the left coal wall; (c) instability of the upper corner at the left coal wall; (d) collapse of the right coal wall.

3. Methodology

The mechanical properties of the strata in Yangchangwan Coal Mine are very uneven. The *in-situ* stress field governs the deformation status in the rock stratum. The rock stiffness, the presence of faults and discontinuities, topographical variation, body force, and tectonic force contributed to the *in-situ* stress distribution necessarily [2]. This study proposed that the EDZ (broad-brush dashed zone in Fig. 2) includes the excavation zone, degradation zone, and collapse zone.

(1) Excavation zone.

In the excavation zone, the spans of roadways are large, and the ratios of height/span (*H*/*S*) are listed in Table 1.

Table 1. Dimensions (height, span) of collapsed roadways

Roadway	Height, *H* / m	Span, *S* / m	*H*/*S*
No.110204 maingate roadway	3.05	5.5	0.6
No.110202 ventilation roadway	3.55	3.7	0.9
No.110204 tailgate roadway	3.55	3.7	0.9

(2) Degradation zone.

Due to the first working mining and abutment loading conditions, the main mechanical strength of the left and right coal walls was deteriorated so as to pose unsymmetrical force and deformation. Ultimately, local falls were induced as shown in Figs. 1(c)-1(d).

(3) Collapse zone.

Roof characterization and properties significantly challenge No.110204 tailgate roadway. The surrounding rock mass was fractured. The roof integrity, fracture toughness and stiffness of rocks were deteriorated. Some of the most unpredictable and violent types of roof failure were due to dynamical collapse.

By considering the above-mentioned issues, the main reasons for instability are that the macro mechanical strength of different rock types became weaker and the distance (depth) to the stable rock was longer than the valid length of anchor bolts or cables. There was a very thin mudstone layer between 0.3 and 0.5 m. Ground water made the roof rock mass softened, which led to mudstone dilution and failure. In addition, frequent excavation made the stress redistributed and the roof relaxed. Field instrumentation and observations were carried out in No.110204 tailgate roadway (Fig. 2). In detail, the monitoring indicators included those for detecting the roof delamination, deep multi-point displacement of the roof, convergence deformation, strength of cables, acoustic emission (AE) in rock fracture, bolt force, *etc*.

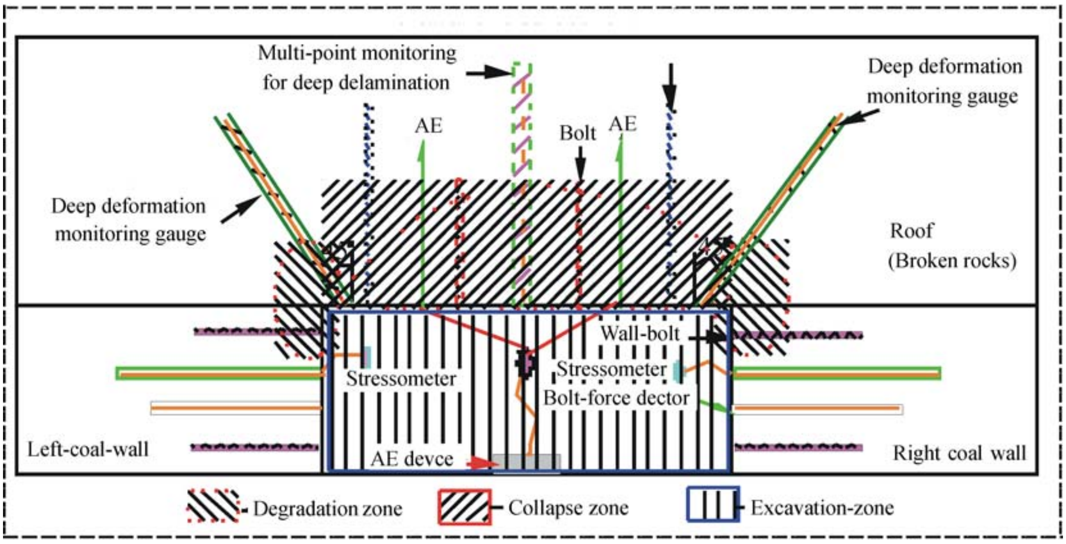

Fig. 2. Schematic design in situations monitoring reinforcing fractured roadways.

4. Statistics of the measurement and regularity

4.1. Roof delamination measurement at various depths

Measurement gauges for roof delamination were set in No.110204 tailgate roadway with different depths as shown in Fig. 3. The depth of the base-point was referenced to the roof characteristics and lithology. During the start-up period, the total deformations increase from 33 to 80 mm (Fig. 4). Especially, No.8 monitoring point was arranged adjacent to the stress abnormal zone in front of the large-scale roof collapse zone that occurred on Jun. 24, 2006.

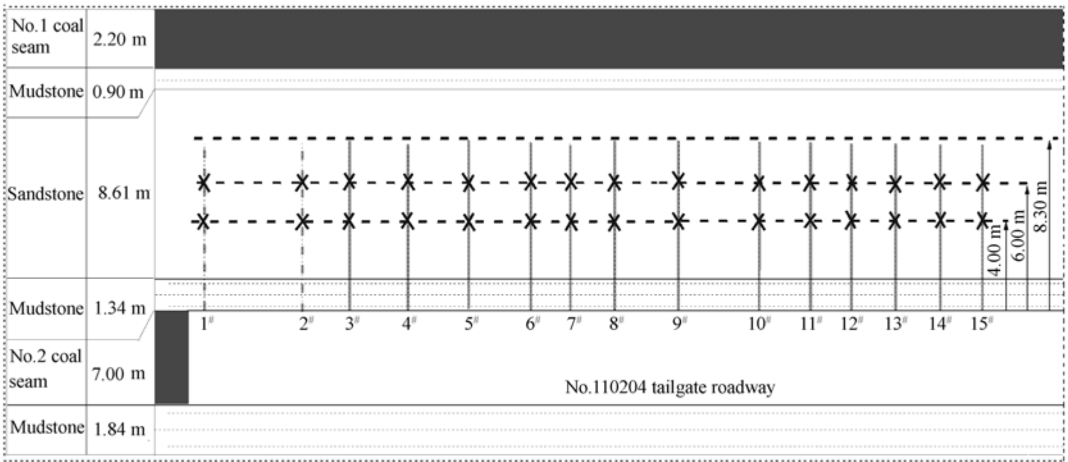

Fig. 3. Detailed measuring layout of roof delamination at different depths.

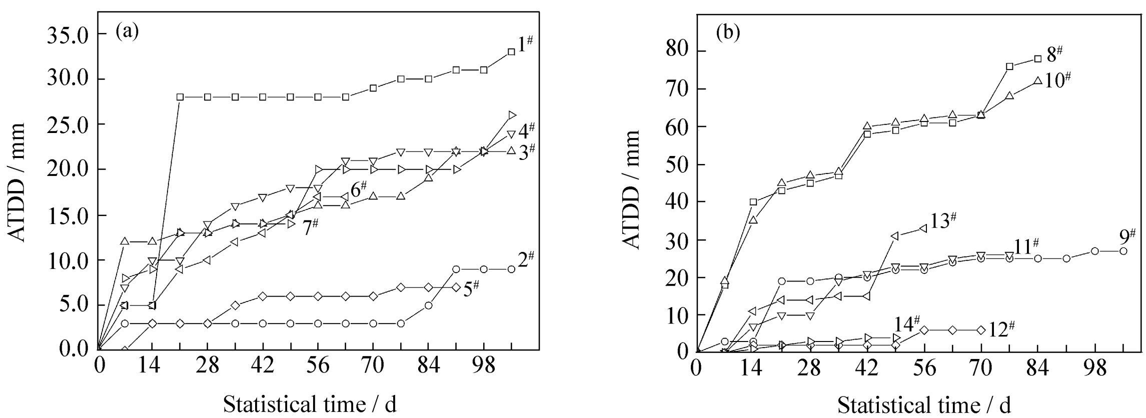

Fig. 4. Regularity of accumulative roof delamination at deep rock-mass (ATDD: accumulative total of deep delamination).

4.2. Roof caving and the convergence deformation of cross-section

With excavation advancing, the roof deformations were measured from August 2006 to the last reading on Dec. 20, 2006. A comparison of the measured roof subsidence with the convergence deformation of the cross-section using extensometers is shown in Fig. 5.

The total roof caving and convergence obviously increased during the measuring period. Following the excavation disturbance, the caving displacement and convergence of line 1# were more than those of others, with the total maximum deformation of 130 and 104 mm. With increasing excavation, the trend of deformation usually increased linearly with stress at lower stress levels. Also, it provided a good check if the rock was unstable or not.

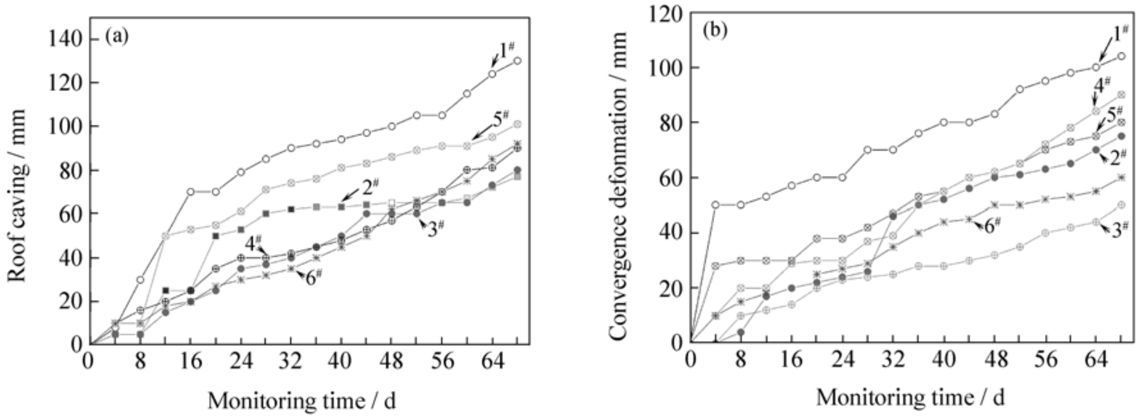

Fig. 5. Comparison of the measured roof caving (a) and the convergence deformation (b) of the monitored across-section.

4.3. *In-situ* investigation of bolts and cables

(1) Monitoring the anchoring strength of bolts and cables.

Rock bolts and cables are widely used in the field to maintain ground stabilization [3-4]. The anchorage quality, the loading status, and the bolt integrity are of most concern in the field. The rock bolt and cable work conditions or behaviors were evaluated through anchoring force test [5-10]. Using the MJ-40 bolt and MCJ-60 cable stress meters in the engineering field (Fig. 6), the anchoring strength of the roof-bolt cable and wall-bolt was increased during the monitoring period. The anchoring force of the roof-bolt cable and wall-bolt increased in 2006 (Figs. 7(a)-7(c)). The variable trends of the anchoring force of 1# cable were increased, with the force of 18.3 and 14.4 kN at 1# roof-bolt and 2# roof-bolt. The results clearly demonstrated that the temporal and spatial variation influenced the roof integrity, and particularly demonstrated the distribution of deformation, bed separation, and strata failure into the roof and across the full span of the roadway.

(2) Monitoring the axial tensile force of bolts and cables.

In the engineering field, the performance of the working bolt and cable was detected by the ML-20 pull tension gauge linking the bolt or cable with jacking apparatus (100 to 200 kN), the final outcome was the bolt or cable resistance. The trial results clearly demonstrated that the bolt and cable anchoring force exceeds 13 and 30 kN (Fig. 8), respectively. The cable (6 m, maximum 8.5 m) is deeper than the bolt (2.3 m, maximum 2.5 m). Also it could reflect the effects of the roof cable reinforcement system. All the results were consistent with the limitations. It indicated that the critical strength parameters were reasonable.

Fig. 6. Field monitoring anchoring strength: (a) 1# bolt; (b) 2# cable; (c) *in-situ* bolt pullout tests.

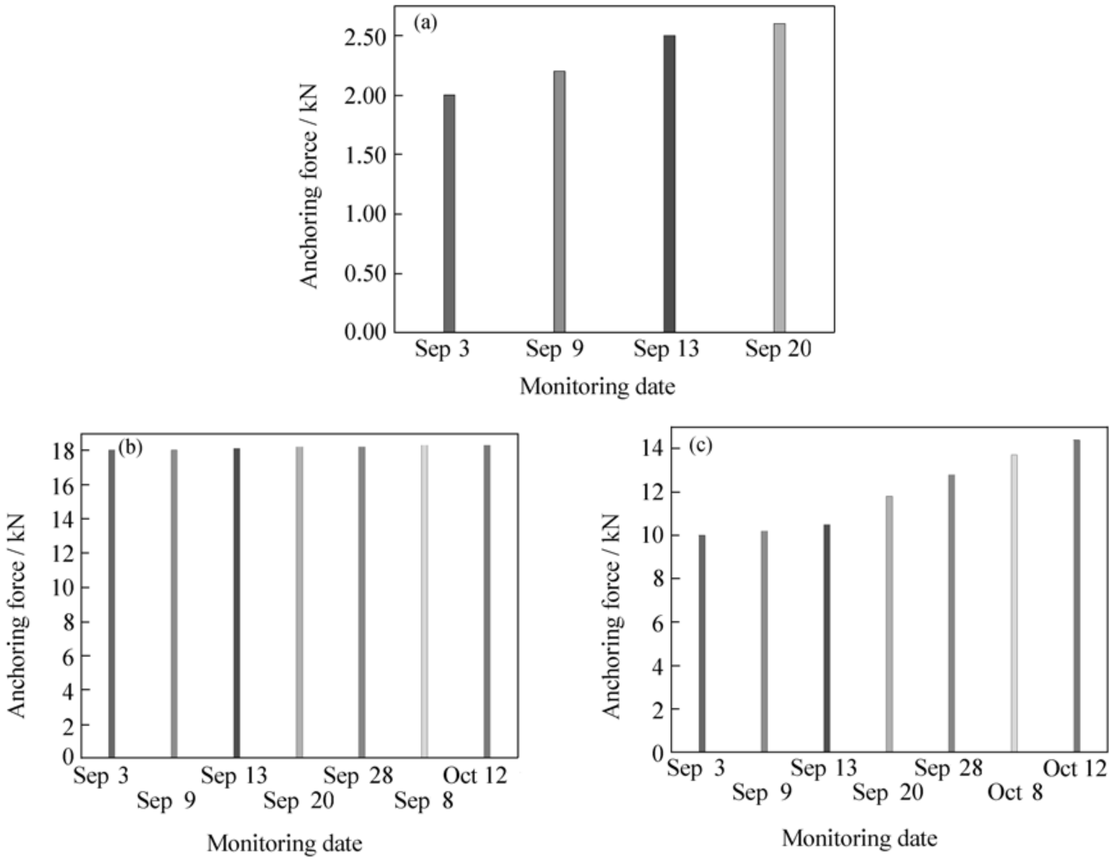

Fig. 7. Distribution of the anchoring bolt and cable force: (a) 2# wall-bolt; (b) 2# roof-cable; (c) 1# roof-bolt.

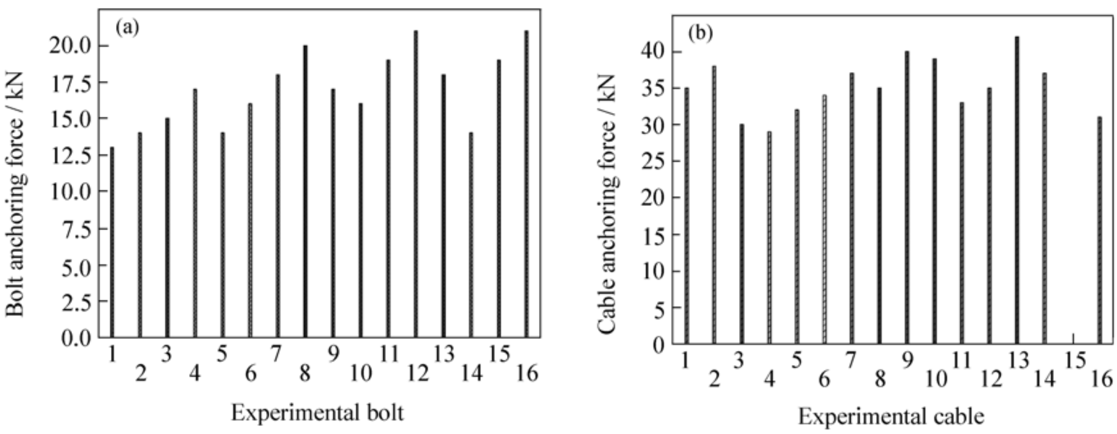

Fig. 8. Field test axial tensile force of bolts (a) and cables (b).

4.4. AE characteristics and analysis

Roof falls in underground coal mines, which have detrimental consequences, are closely related to the geology of the mining environment, the mining method, and the method of roof support or control. It is often difficult to predict them due to the uncertainty associated with the inherent variability of the roof fall phenomenon. There were certain emerging techniques for the inspection of rock engineering in applications [11-12]. AE was a useful nondestructive technique to determine whether damage in rock material has occurred. Furthermore, the AE technique was promising for such investigations. It could post the inherent mechanism of dynamic failure of micro-crack damage and evolvement (*i.e.*, the occurrence of unstable crack growth), macro-pre and post-failure behavior, reinforcement effect [13-17]. Recently, Cai *et al*. [18-19] proposed a model based on the tensile fracturing mechanism and energy conservation to estimate the source dimension of microseismic events near excavation walls. But these techniques were inadequate for bolt and cables in coal mines, particularly in extremely geological environments and fractured and weak rocks. By taking the local characteristics of coal seams (*i.e.*, seam inclination and continuity), surrounding rocks, and mechanical properties into account, the objective of the present study is to consider whether the measurement of AE characteristic parameters (total events and energy-releasing rate) provides valid indications of rock structure reinforced by bolts or cables. The proposed inspection technique utilized AE sensors arranged at a distance of 1800 m from the conjunctional entrance in No.110204 tailgate roadway (Fig. 9(a)). AE was used to assess the support design and verify the effect of bolt and cable reinforcement. The location of the microcrack events was associated with the development of damage in the field. In this way, AE characteristic parameters had potential to enhance the monitoring of rock engineering structure both during and after the construction.

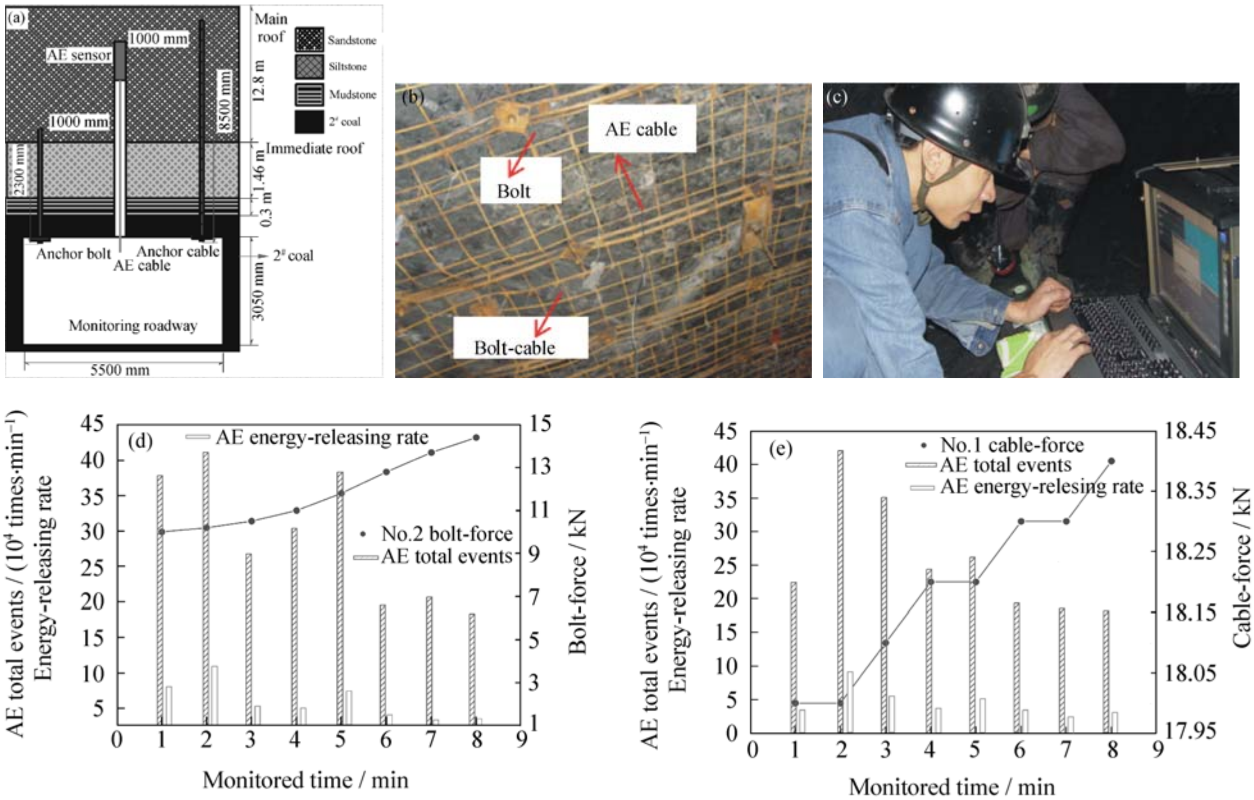

Fig. 9. Arrangement of the roof bolt, cable and AE sensor (a), field AE work conditions (b, c) and comparison of AE characteristics between bolt-force (d) and cable-force (e) in the roof reinforcement zone.

If the local stresses exceed the local strength, cracks would occur, grow, and interact. This progressive fracturing of rocks results in the formation and growth of the macro-fracture. According to AE characteristics, the increased stress leads to crack or damage. If the anchorage force can keep the fractured roof/dangerous rocks stable, it would decrease the horizontal squeezing deformation and confine the roof structure. The AE characteristic parameters would decrease. The quantitative correlation between acoustic emission and micro-fracturing and its evolution would obviously be recorded by the receiver (Figs. 9(b)-9(c)). During the monitoring period, the AE total events kept rising, ranging from 182053 to 421343 times/min, with the energy-releasing rate from 22456 to the maximum of 90398. This indicated that cracks were extended. After construction, the AE was relatively quiet and the rock mass remained stable (Figs. 9(d)-9(e)). It also indicated that no new cracks extended, implying a reloading process after rock unloading. Ultimately these would verify that the parameters of bolts and cables (anchorage length, location and strength) were reasonable.

According to the time-space-strength characteristic relations, during the monitoring period, the AE total events kept rising, ranging from 1.8×10^5 to 4.2×10^5 times/min, with the energy-releasing rate from 2.2×10^4 to the maximum of 9.0×10^4. This indicated that cracks had extended. After construction, the AE was relatively quiet and the rock mass remained stable (Figs. 8(b)-8(c)). At the same time, with durative increasing in the anchoring-force of bolts or cables, the total AE events and AE energy releasing rate kept descendible and then stable. It also indicated that there were no new cracks and space extending, which implied a reloading process after rock unloading. Ultimately these verified that the parameters of bolts and cables, anchorage length, location, and strength, were reasonable.

AE is useful for inferring stress redistribution. During the pre-failure regime, the AE events usually increased linearly with stress at lower stress levels, and were plateaus at higher stress levels. With increasing structural damage levels, the AE could drop to the value less than the observed at the initial state.

In conclusion, the AE activities from the locations of the roadway were found to be consistent with the field monitoring results. This approach takes account of stress redistribution and provides stress and displacement patterns in the rock mass which are consistent with AE observations for excavation design. Thus the AE events in the rock mass could evaluate the effectiveness of the rock support system and the overall stability of the excavation zone.

5. Conclusions

The large-scale mined-out areas will inevitably remain unstable due to highly efficient and rapid mining. The roof instability directly influences safe mining. Applied to site investigation and field instrumentation, tests on the strength of bolts and cables, deformation monitoring, and AE characteristics for rock mass pre-failure and destabilization can be performed. The AE activities from the locations of the roadway were found to be consistent with the field monitoring results. At the same time, the stress/force and displacement patterns in the rock mass were consistent with AE observations for excavation design. Thus the observed AE activities in the rock mass were utilized to assess the effectiveness of the rock support system and the overall stability of the excavation zone. These methods provide effective forewarning indicators for assessing the potential dynamical instability-prone area.

References

[1] F.H. Ren, X.P. Lai, M.F. Cai, *et al*., Quantitative prediction and evaluation on the regularity of asymmetric damage and distortion upon broken mass roadway. *J. Univ. Sci. Technol. Beijing* (in Chinese), 30(2008), No.3, p.221.

[2] C.L. Li, Rock support design based on the concept of pressure arch, *Int. J. Rock Mech. Min. Sci.*, 43(2006), No.7, p.1083

[3] R.K. Goel, A. Swarup, and P.R. Sheorey, Bolt length requirement in underground openings, *Int. J. Rock Mech. Min. Sci.*, 44(2007), No.5, p.802.

[4] Z.C. Guan, Y.J. Jiang, Y. Tanabasi, *et al.*, Reinforcement mechanics of passive bolts in conventional tunneling, *Int. J. Rock Mech. Min. Sci.*, 44(2007), No.4, p.625.

[5] C.S. Zhang, D.H. Zou, and V. Madenga, Numerical simulation of wave propagation in grouted rock bolts and the effects of mesh density and wave frequency, *Int. J. Rock Mech. Min. Sci.*, 43(2006), No.4, p.634.

[6] M. Moosavi and R. Grayeli, A model for cable bolt-rock mass interaction: Integration with discontinuous deformation analysis (DDA) algorithm, *Int. J. Rock Mech. Min. Sci.*, 43(2006), No.4, p.661.

[7] B. Liu, Z.Q. Yue, and L.G. Tham, Analytical design method for a truss-bolt system for reinforcement of fractured coal mine roofs: Illustrated with a case study, *Int. J. Rock Mech. Mining Sci.*, 42(2005), No.2, p.195.

[8] B.K. Hebblewhite and T. Lu, Geomechanical behavior of laminated, weak coal mine roof strata and the implications for a ground reinforcement strategy, *Int. J. Rock Mech. Min. Sci.*, 41(2004), No.1, p.147.

[9] Z.G. He, S. Qiang, S.H. Chen, *et al.*, Composite element method for jointed rock masses reinforced by hollow friction bolts, *Int. J. Rock Mech. Min. Sci.*, 41(2004), Suppl. 1, p.551.

[10] E. Unal, I. Ozkan, and G. Cakmakci, Modeling the behavior of longwall coal mine gate roadways subjected to dynamic loading, *Int. J. Rock Mech. Min. Sci.*, 38(2001), No.2, p.181.

[11] X.P. Lai, M.F. Cai, F.H. Ren, *et al*., Assessment of rock-mass characteristics and the excavation disturbed zone in the Linxin Coal Mine beneath the Xitian river, China, *Int. J. Rock Mech. Min. Sci.*, 43(2006), No.4, p.572.

[12] X.P. Lai, M.F. Cai, and M.W. Xie, *In situ* monitoring and analysis of rock mass behavior prior to collapse of the main transport roadway in Linglong Gold Mine, China, *Int. J. Rock Mech. Min. Sci.*, 43(2006), No.4, p.640.

[13] S.D. Butt, C. Mukherjee, and G. Lebans, Evaluation of acoustic attenuation as an indicator of roof stability in advancing headings, *Int. J. Rock Mech. Min. Sci.*, 37(2000), No.7, p.1123.

[14] X.P. Lai, L.H. Wan, and M.F. Cai, Couple analyzing the acoustic emission signal from hard composite rock damage, *J. Univ. Sci. Technol. Beijing*, 11(2004), No.1, p.1.

[15] M.F. Cai and X.P. Lai, Monitoring and analysis of nonlinear dynamic damage of transport roadway supported by composite hard rock materials in Linglong gold mine, *J. Univ. Sci. Technol. Beijing*, 10(2003), No.2, p.83.

[16] M. Cai and P.K. Kaiser, Numerical simulation of the Brazilian test and the tensile strength of anisotropic rocks and rocks with pre-existing cracks, *Int. J. Rock Mech. Min. Sci.*, 41(2004), No.3, p.450.

[17] M.D. Beard and M.J.S. Lowe, Non-destructive testing of rock bolts using guided ultrasonic waves, *Int. J. Rock Mech. Min. Sci.*, 40(2003), No.4, p.527.

[18] M. Cai, P.K. Kaiser, and C.D. Martin, Quantification of rock mass damage in underground excavations from microseismic event monitoring, *Int. J. Rock Mech. Min. Sci.*, 38(2001), No.8, p.1135.

[19] M. Cai, P.K. Kaiser, Y. Tasaka, *et al.*, Generalized crack initiation and crack damage stress thresholds of brittle rock masses near underground excavations, *Int. J. Rock Mech. Min. Sci.*, 41(2004), No.5, p.833.