A REAL-TIME MONITORING SYSTEM FOR THE ASSESSMENT OF STABILITY AND PERFORMANCE OF IN ABANDONED ROOM & PILLAR LIGNITE MINES

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ABSTRACT: The authors have been involved with the stability of abandoned mines beneath urbanized residential areas in Tokai region. These abandoned lignite mines were in operation until 1960s. There is a great concern about the stability of these abandoned mines during large earthquakes. The 2003 Miyagi Hokubu earthquake caused great damage to abandoned mines and resulted in collapses. The authors describe an integrated real-time monitoring system and they report some measured data up to now. The responses of monitoring system during a large roof collapse under gravitational condition as well as during and after two earthquakes are presented and their implications are discussed.

KEYWORDS: Abandoned mine, Earthquake, Multi-parameter monitoring.

RESUME : Les auteurs ont été impliqués par la stabilité de mines de lignite abandonnées se trouvant à l'aplomb de secteurs résidentiels de la région de Tokai. Ces mines étaient en exploitation jusque dans les années 60. La stabilité de ces mines abandonnées pendant de grands tremblements de terre est une préoccupation majeur. Le tremblement de terre de Miyagi Hokubu en 2003 a induit de nombreux dommages dans d'anciennes mines qui se sont soldés par des effondrements. Les auteurs décrivent un système de surveillance en temps réel et ils présentent quelques-unes des données mesurées. L'article présente et analyse les réponses du système de surveillance pendant un effondrement majeur du toit des exploitations sous l'effet de la gravité, aussi bien que pendant et après deux tremblements de terre. Les implications de cette analyse sont également discutées.

MOTS-CLEFS : Mine abandonnée, Tremblement de terre, Surveillance multi-paramètre.

1. Introduction

Lignite was extensively extracted using room and pillar mining technique in Tokai region of Central Japan until 1960s. These mines are abandoned since then and many of these areas have become urbanized. There is a growing concern on the response and stability of areas situated above the abandoned-lignite mines in Japan due to urbanization in recent years during earthquakes as well as in long-term.

One of such areas is Mitake town in Gifu prefecture of Japan, which was well known for mining activities until 1960s. Since the abandonment of the mines, some caving and collapses occurred in the town and the town authorities are also concerned with the stability and performance of the abandoned mines during earthquakes. Expected Tokai earthquake or Tonankai earthquake may particularly cause extensive damage in the town.

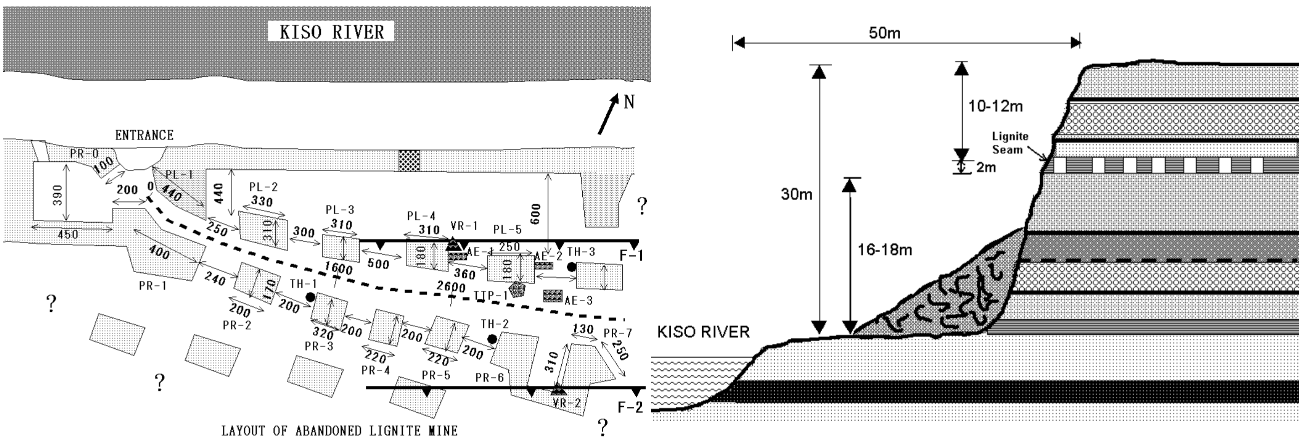
The authors have initiated a research program for investigating the stability and performance of an abandoned room and pillar lignite mine in Mitake town. A continuous measurement and monitoring program of acoustic emissions, electrical potential variations, temperature and humidity has been initiated since March 2004 besides intermittent measurements of deformation of the mine, pH values of underground water, seismic wave velocity and some index tests such as Schmidt hammer rebound value and needle penetration tests. Furthermore, certain areas within the mine are photographed in order to see the degradation process of the mine with time.

In this article, the authors describe the integrated real-time monitoring system and measured data up to now. The responses of monitoring system during a large roof collapse under gravitational condition as well as during and after two earthquakes are presented and their implications are discussed.

2. Mine Layout and Geology

The mine is situated nearby Kiso River, which was used for transporting the extracted lignite through boats. It seems that two lignite seams were exploited during mining operations, which were terminated about 40 years ago. Mining was mainly carried out using room-pillar method. Dimensions of a typical pillar were 2x2m and the seam height was about 1.8-2m. The extraction ratio varies from place to place. The section, which is monitored by the authors, can be sometimes 6-7m wide. However, a typical width of rooms is about 3-4m (Figure 1(a)).

The overburden ranges between 10-12m and it consists of relatively thick beds of sandstone, siltstone and mudstone. Although their strength is lower than lignite seam, they have few joints. The mined seam is about 16-18m above the river level and Figure 1(b) shows a typical vertical cross-section. The lignite extraction extends to a distance of about 40-50m from the entrance. Debris from mining operations or cliff collapses is found below the entrance level as shown in Figure 1(b). The slope of debris is about 35-40^{o} and it consists of relatively large pieces of rock blocks.



(a) Plan view of the instrumented area (b) Cross-section

Figure 1: Plane view of the instrumented area of the abandoned mine and a typical cross-section

3. Rock Mass Conditions

Rock layers generally dip towards SE with a gentle inclination and it has been folded. The folding axis is aligned in the direction of NE-SW. There are three lignite seams and their thickness ranges between 1-6m. The thickness of lignite seam at the mine is about 2m and it consists of intercalated mudstone and sandstone layers whose thickness ranges between 5 to 15cm. Joints are generally perpendicular or sub-perpendicular to layering and their spacing ranges between 10 to 60cm. The joint interval becomes smaller within lignite seam while it is widely spaced in mudstone and sandstone layers. Normal faults having a slight sinistral or dextral lateral sense are observed in the mine. The strike of major normal faults is aligned with the flow direction of Kiso River, which pass nearby the mine.

Rock mass classifications are done according to RMR and Q-system rock mass classification systems. RMR values correspond to BASIC RMR values, implying that no corrections are implemented. Rock masses are broadly classified as typical rock mass and fractured zone. Results are summarized in Table 1.

Table 1: Classification rates according to RMR and Q-systems

Rock mass	RMR	Q-value
Typical	37 - 53	2.08 - 2.50
Fractured	26 - 29	0.83 - 1.00

4. Instrumentations and Items of Measurements

It is also known that when rock starts to fail, the stored mechanical energy in rock tends to transform itself into different forms of energy. Experimental studies by the authors showed that rock indicates distinct variations of multi-parameters during deformation and fracturing processes. These may be used for the real-time assessment of the stability of rock structures (Aydan et al. 2001, 2003, 2005). The multi-parameter measurement system involve electric potential (EP) variations, acoustic emissions (AE), rock temperature (RT), temperature and humidity of the abandoned lignite mine. Measurements are initiated in March 2004 and the measurements of deformation of the mine, pH values of underground water, seismic wave velocity and some index tests such as Schmidt hammer rebound value and needle penetration tests are also carried intermittently. Furthermore, certain areas within the mine are photographed in order to see the degradation process of the mine.

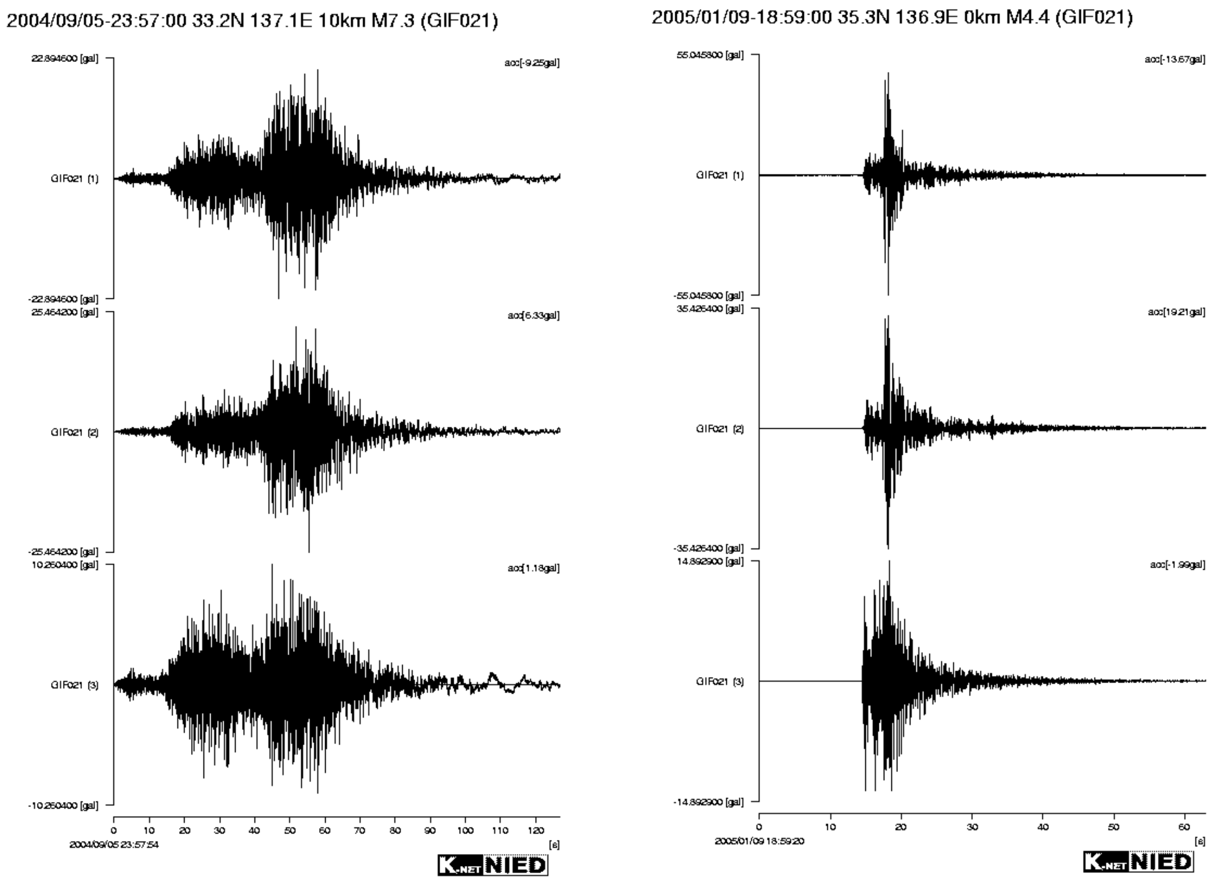
The temperature and humidity sensors are installed at certain spacing from the mine entrance as shown in Figure 1(a). Presently 4 temperature and humidity devices operate in the abandoned mine. Pillar denoted as LP5 has two temperature sensors, one of which was embedded at a depth of 10cm from the pillar surface while the other one is fixed on the pillar surface.

Initially two geo-electric potential monitoring devices are set-up as shown in Figure 1(a). These two devices are just located on normal faults. An additional geo-electric potential monitoring device was installed in Pillar denoted LP5. The electrical resistance of ground is in the order of $K\Omega$ while the impedance of the devices is in the order of $M\Omega$. Therefore, the measured electric potential variations by the devices are directly related to those of surrounding rock mass.

The AE system was developed by the second author and it is limited only to counting AE events (Tano et al. 2005). Pulse signals, which correspond to AE waves exceeding a threshold are discriminated through a pulsar and recorded onto a pulse counter (logger) as AE rate counts. Such limited specification of the rate counting reduces the system cost so that it is capable of using two AE systems as one set. One of the AE systems is called an active unit while the other one is called a dummy unit. The active unit is directly attached onto the rockmass while the dummy AE sensor is not in contact with the rockmass. If signals are counted on both systems simultaneously, the count of active unit is neglected from the measured data. This active-dummy counting system can improve the reliability of the AE monitoring and check the noise condition in field.

5. Earthquakes During Monitoring Period

One of the purposes of this study is to monitor the behaviour of the abandoned during earthquakes. Two earthquakes relevant to the site took place during the monitoring period. The first earthquake, which is officially named as Tokaido-oki earthquake with a magnitude of 7.3, occurred on September 5, 2004. Although the epicentre of the earthquake was 236km away from the mine, the maximum ground acceleration caused by this earthquake was more than 20gal and the shaking period was greater than 20s (Figure 2(a)). In January 9, 2005, an earthquake, named as Komaki earthquake with a magnitude of 4.7, took place 25km away the mine and the maximum ground acceleration was more than 50gal at a nearby strong-motion station (Figure 2(b)) (K-Net, NIED) These two earthquakes also provided some unique data on the response of the abandoned mine during earthquakes.



(a) Tokaido-oki earthquake (b) Komaki earthquake

Figure 2: Acceleration records at Mino-kamo city induced by Tokaido-oki and Komaki earthquakes

6. Instability Problems During Monitoring

Besides instrumental monitoring, the visual inspection and photographing of the abandoned mine were carried out periodically. Since the data download is carried out at intervals of two-months period, the visual inspections and photographing of certain locations were done at each time of data download. The first remarkable collapse was observed when the authors visited the mine on May 14, 2004 after the visit on March 23, 2004. Since the collapse was not observed during the visit to the mine on March 23, 2004, it should have take place during the period between these two visits. The collapsed area (3m x 2m) was bounded by pillars denoted PL3, PL4, PR3 and PR4, and 25cm thick sandstone roof layer was fallen down as seen in Figure 3(a).

There was no remarkable collapse within the area of instrumentation until the earthquake on September 5, 2004. The authors visited the mine on September 17 and there were some notable roof collapses as seen in Figure 3(b). However, there was no remarkable collapse induced by the Komaki earthquake on January 9, 2005. Besides these major collapses in the mine, rock mass in the roof and pillars continues to degradate. The degradation of rock mass occurs in the form of flaking of rock pieces from the roof and pillars fall due to cyclic saturation and drying. Furthermore, some cracks in pillars continue to open up.

(a) Roof collapse between March 23 and May 17 (b) Roof Collapse due to Tokaido-oki earthquake

Figure 3: Some views of instability in the abandoned lignite mine

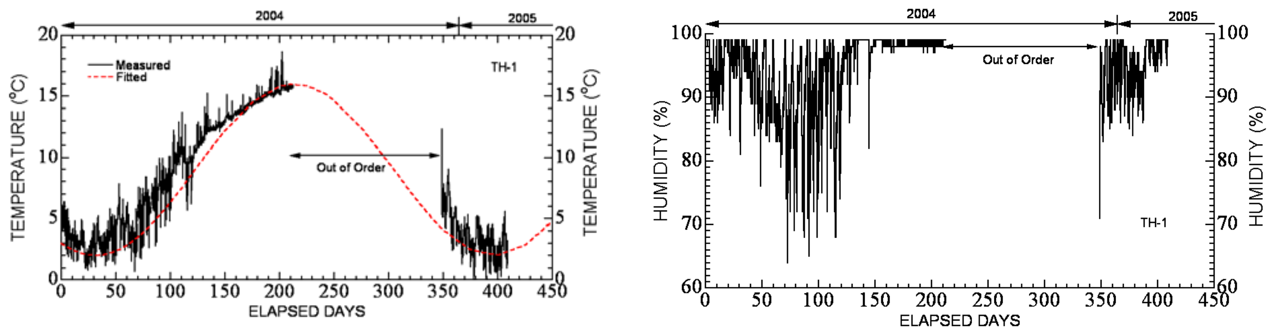
7. Results and Discussions

The measurements involve the environmental and stability conditions within the mine. First environmental conditions are described and then the measurements of acoustic emissions and geo-electrical potential measurements are presented in relation to some specific instability events during the period of measurements.

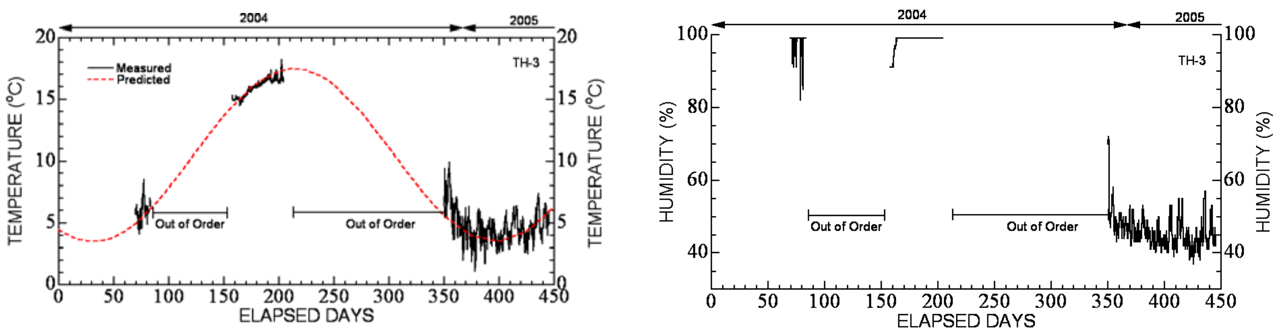
Figure 4: Some fracturing, crack opening in pillars and flaking of roof layers

7.1. Environmental Measurements

The environmental measurement items are the temperature and humidity of the mine, pH of ground water. Temperature and humidity variations in the abandoned mine during the period between March 10, 2004 and May 14, 2005 are shown in Figure 5. The overall temperature fluctuation for one year is about 12^{o} and the daily temperature variation ranges between 2-4^{o}. The humidity variation ranges between 60-100%. These results indicate that the soft sedimentary rocks would be subjected to cycles of wetting and drying. This observation clearly indicates that rocks would degradate, if they were prone to variations of water content.



(a) Temperature and humidity variations nearby the entrance of the mine



(b) Temperature and humidity variations inside the mine (40m away from the entrance)

Figure 5: Temperature and humidity variations in the mine

Figure 6 shows the temperature variations on the surface and inside of the pillar denoted LP5. The general trend of the temperatures at the pillar surface and 10cm inside the pillar surface are quite similar. However, the fluctuations of temperature at the surface are much larger than those inside the pillar. This simply implies that thermal loading in rock would be very high near the pillar surface. As a result the rock would be prone to degradation due to the daily and yearly cyclic thermal loading. Furthermore, the yearly variation of temperature is somewhat asymmetric.

The pH measurements were carried out at 4 different locations in the mine. The pH values are almost the same at measurement locations. They generally vary between 6.4 and 8.2. The pH values decreases during rainy summer season and increases during dry winter seasons.

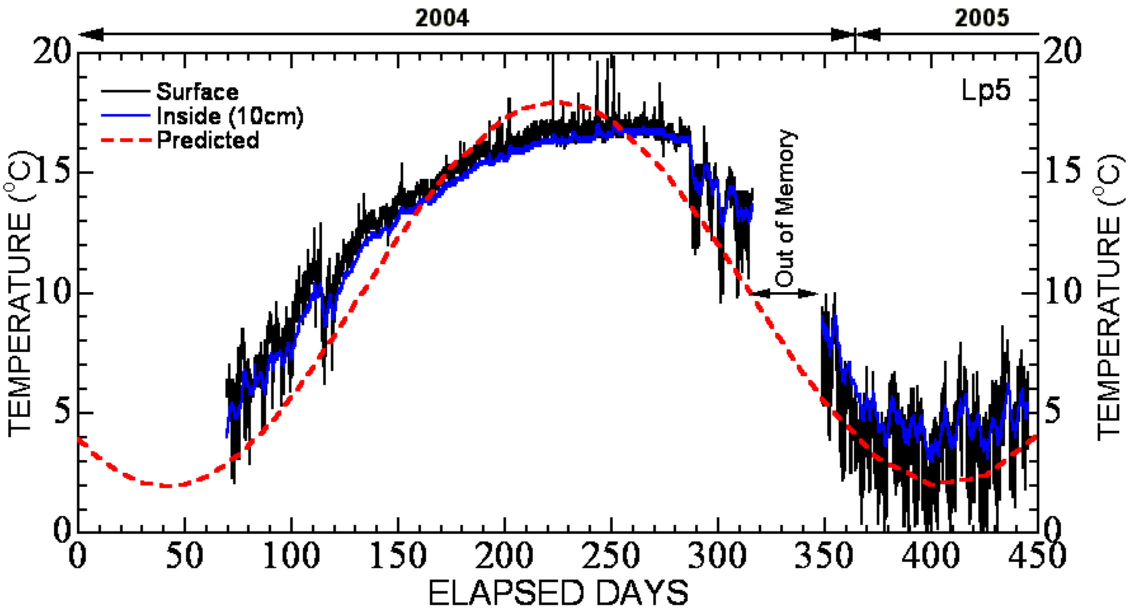


Figure 6: Variations of temperature on the surface and inside pillar denoted LP5

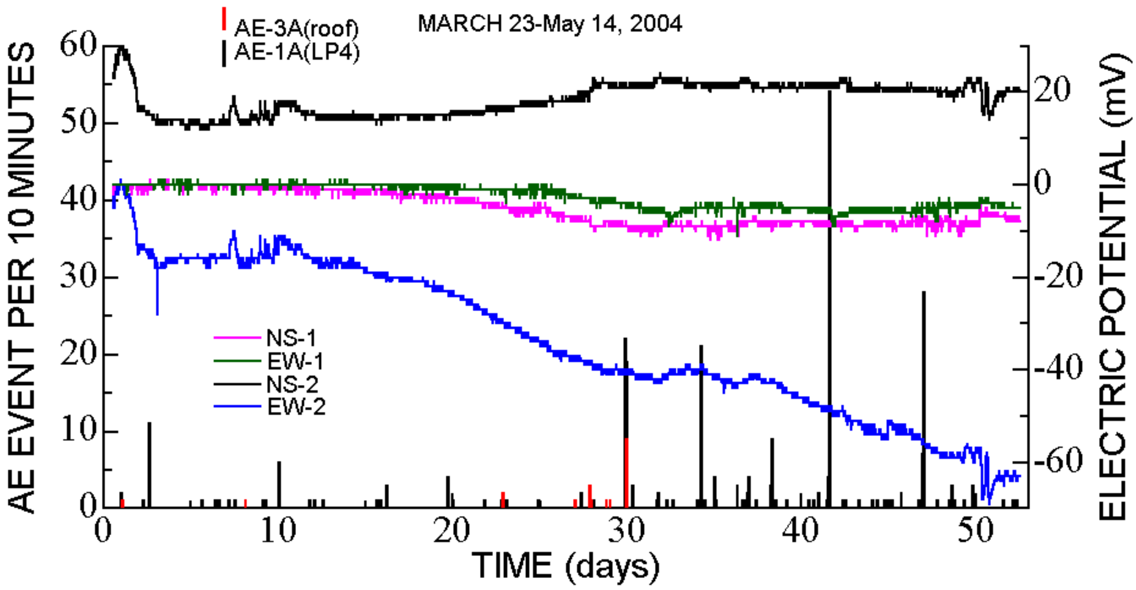


Figure 7: Variations of geo-electric potential and acoustic emission (AE) counts

7.2. Measurements Associated with Stability

Since three major events associated with mine stability took place during the period of monitoring, the monitoring results are discussed separately in the following subsections.

7.1 Period between March 23, 2004 and May 17, 2004

Geo-electric potential variations and acoustic emission (AE) counts per 10 minutes are shown in Figure 7 during March 23 and May 17. As seen from the figure there is almost one to one correspondences between geo-electric variations and acoustic emission counts. However, the fluctuations of the geo-electric potential starts much earlier than AE events as also observed in laboratory tests (Aydan et al. 2002, 2003, 2005) on samples from this mine and other sites. The collapse area is very close to the AE device set on pillar denoted PL4. More than 50 AE counts measured on May 2, 2004. However, high acoustic emission activity started to occur after April 20, 2004. Geo-electric potential variations started to occur about 10 days before the high acoustic emission activity. The geo-electric potential variation vectors indicated that the instability was located to the west of the devices. The actual event was observed about 5-10m west of the geo-electric devices.

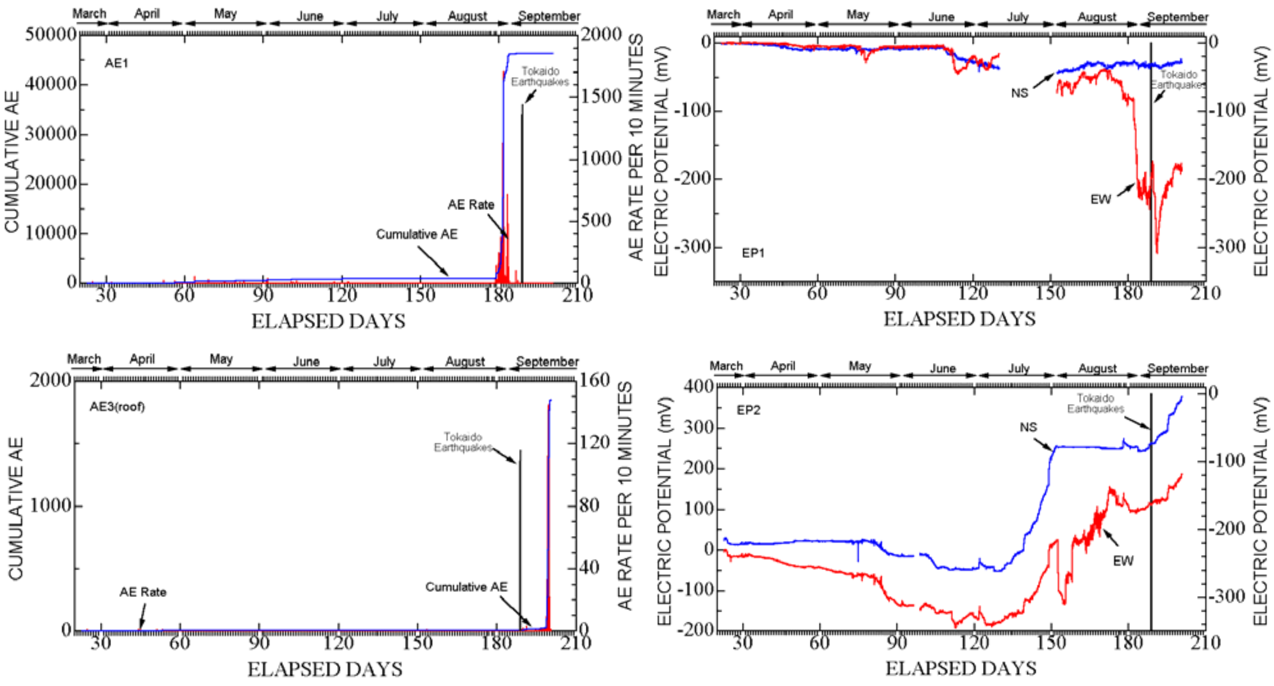


Figure 8: Variations of geo-electric potential and acoustic emission (AE) counts

7.2 Period Before and After Tokaido-oki Earthquake of September 5, 2004

Both geo-electric potential variations and AE counts per 10 minutes are shown in Figure 8. The acoustic emissions observed at the device numbered AE1 (PL4) before the earthquake. This pillar has a secondary normal fault to the principal one and a crack on the opposite side of the pillar continues to open-up, these acoustic emissions should be directly related to the fracturing of this pillar. EP1 device is also next to this pillar and very large geo-electrical variations occur during the acoustic emission activity. AE3 device is between pillars LP5 and PR5 indicated high acoustic emission activity just after the earthquake and the AE count was more than 400 on September 12. EP2 geo-electric device is about 5m to the south of AE3 and the geo-electric potential started to increase after the earthquake. The major collapses were observed near pillar LP5 and PL7, which are about 10m to the east of the AE device. The geo-electric potential vector of EP2 indicated that the instability locations were directed to NE. As for EP2 device the location was to the east. Particularly it is of great interest that the geo-electric potential vectors can be used to locate the spot of instability. Furthermore, it seems that geo-electric potential variations are also influenced by the crustal geo-electric potential variations associated with earthquakes. Since the Tokaido-oki earthquake was to SW of the site, the variations of geo-electric potentials point out the location of the source of geo-electric potential signals. It should be also noted that AE counts are generally associated with events whose sources are within the vicinity of 10m. Therefore, a dense network of the AE devices could be useful to locate the exact location of the instability spots. The combinations of these measurements together with geo-electric potential measurements can distinguish near-field and far-field events.

7.3 Period Before and After Komaki Earthquake of January 9, 2005

Geo-electric potential variations and AE counts per 10 minutes are shown in Figure 9 in association with the 2005 Komaki earthquake. Some acoustic emissions observed at the device numbered AE1 (PL4) before and after the earthquake. As said previously, this pillar has a secondary normal fault to the principal one and a crack on the opposite side of the pillar (its picture is shown in Figure 4) continues to open-up, these acoustic emissions should be directly related to the fracturing of this pillar. EP1 device is also next to this pillar and very large geo-electrical variations occur during the acoustic emission activity. Furthermore the geo-electrical potential vector indicates that the events have been occurring to the SW of the device. A new acoustic emission numbered AE5 was installed in December 2004 between pillars PL4 and LP5. The acoustic emission events measured by AE1 and AE5 occur almost simultaneously. During these events, the geo-electric potential measuring device EP1, which is close to AE1 and AE5 have fluctuations in the measured responses indicated. Both EP1 and EP2 geo-electric potential measuring devices indicate that some instability problems to the South or SW of the their location may be taking place. Since the observations are limited to a certain area due to concern of roof collapses and pillar failures, we could not confirm the implications of these geo-electric potential measurements by visual inspections. However, the effects of the 2005 Komaki earthquake could not be observed in view of the measurements shown in Figure 9.

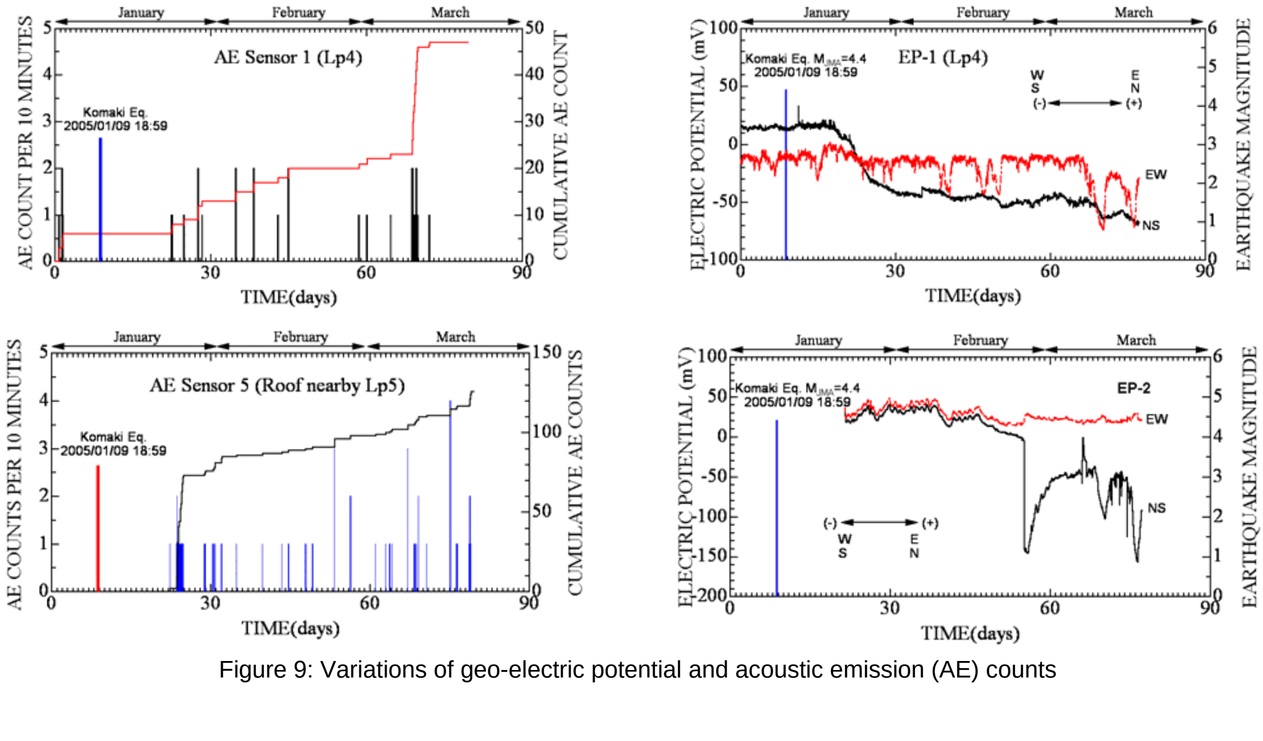


Figure 9: Variations of geo-electric potential and acoustic emission (AE) counts

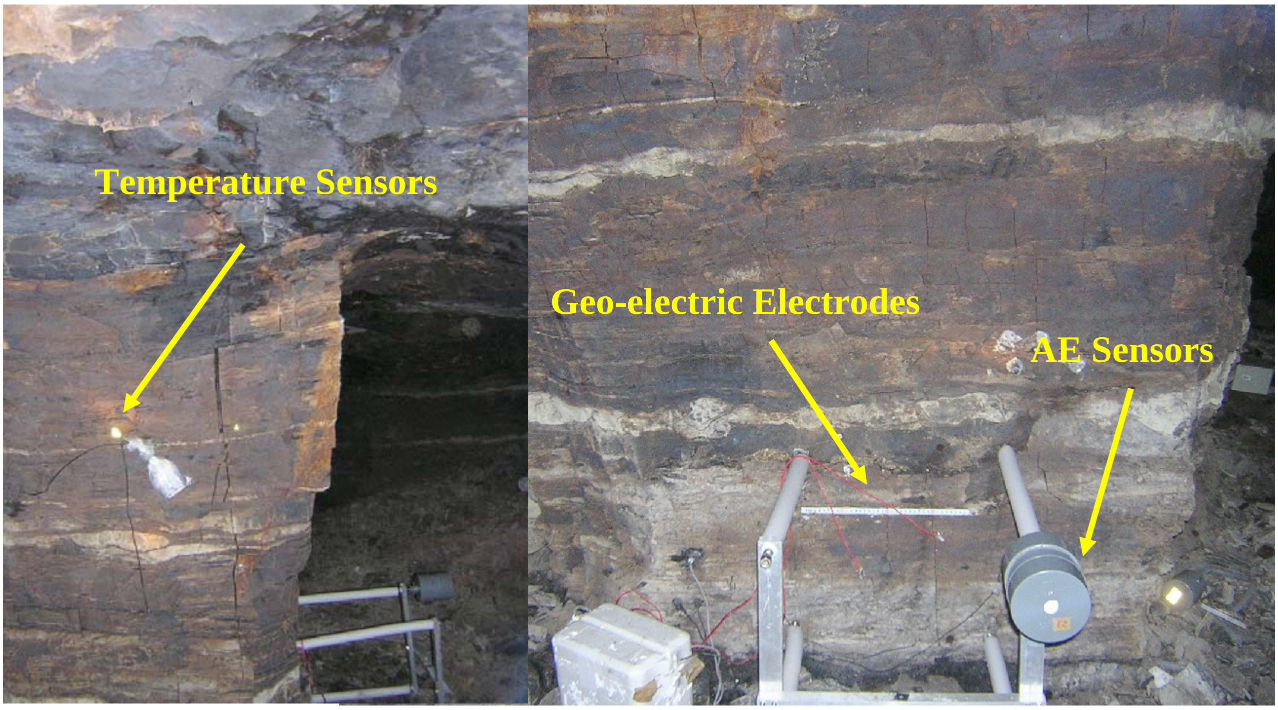


Figure 10: Instrumented pillar LP5.

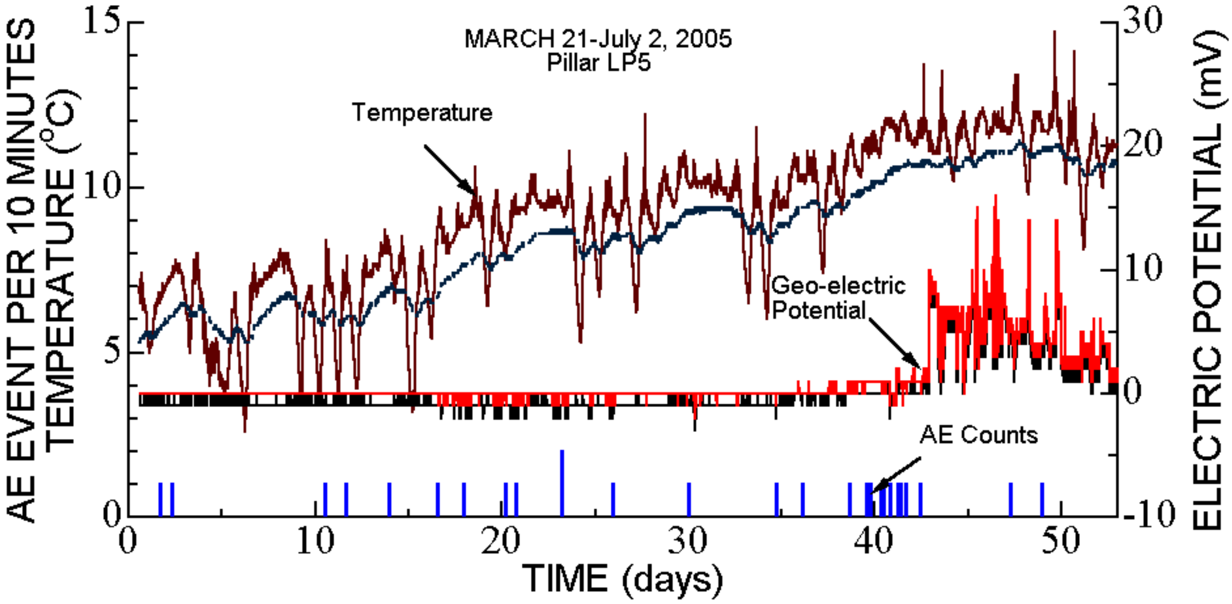


Figure 11: Multi-parameter response of Pillar LP5 during March 21 and July 02, 2005

7.4 Multi-parameter Observations on Pillar LP5 During March 21, July 02, 2005

Pillars resemble to the samples under uniaxial compression tests in laboratory. A geo-electric potential measuring device was recently installed in the pillar denoted LP5 in addition to temperature and acoustic emission measurements. Compared with the initial state of this pillar, vertical cracks in this pillar were open up further. The geo-electrical potentials were measured in vertical (UD) and horizontal (NS) directions. Figure 10 shows the instrumented pillar LP5. Figure

11 shows the variations of geo-electric potential, temperature and AE events during March 21 and July 02, 2005. As it is noted from the figure, some acoustic emission events have been taking place. This implies that the crack opening and propagation has been occurring. Particularly the AE events have been increasing since the beginning of June, which roughly corresponds to rainy Munson season in Japan. Simultaneously, geo-electric potential variations become larger. This may indicate that overall electric resistivity of the pillar decreasing so that the geo-electrical potentials associated with crack development become more amplified. The temperature variations seem not to be associated with the AE and geo-electric potential variations.

8. Conclusions

The authors described a real-time monitoring system and its application to the investigation of the stability and performance of an abandoned room and pillar lignite mine in Mitake town. During the monitoring period, two earthquakes relevant to the site occurred and their effects on the abandoned mine were observed both instrumentally and visually. Both geo-electrical potential and acoustic emission (AE) measurements are indicators of forecoming instability problems related to seismic loading as well as degradation and creep of surrounding rocks and variation of surcharge loadings. The main conclusions from this study may be summarized as follows:

- Temperature and humidity measurements indicate that surrounding rock is subjected to daily and yearly cycles of wetting and drying and thermal loading. These undoubtedly cause further degradation of surrounding rock and it can be counted as one of the causes of instability in long term.
- AE counts are generally associated with events whose sources are within the vicinity of 10m. Therefore, a dense network of the AE devices could be useful to locate the exact location of the instability spots.
- The geo-electric potential measurements indicate that it is possible to infer the for-coming instability problems and their locations and timing. However, it seems that geo-electric potential variations are also influenced by the crustal geo-electric potential variations associated with earthquakes. The combinations of geo-electric potential measurements together with Acoustic Emission (AE) measurements together can distinguish near-field and far-field events.

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