Proceedings of the International Symposium on Engineering Lessons Learned from
the 2011 Great East Japan Earthquake, March 1-4, 2012, Tokyo, Japan

THE DAMAGE TO ABANDONED MINES AND QUARRIES BY THE GREAT EAST JAPAN EARTHQUAKE ON MARCH 11, 2011

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ABSTRACT: The East Japan Mega Earthquake with a moment magnitude 9.0 occurred on March 11, 2011 and shook almost the entire Japan. There are many abandoned lignite mines in the close vicinity of the epicentral area such as Miyagi and Iwate Prefectures.and many sinkholes occurred following the earthquake. There are also reports on the delayed occurrence of numerous sinkholes in the same areas. In addition, some collapses and settlement occurred in abandoned underground quarries in Oya town of Utsunomiya City. The authors investigated damaged areas soon after the earthquake and they present their investigations results. They also discuss their implications in short and long-term performance of abandoned mines and quarries in this article.

Key Words: Great East Japan earthquake, abandoned mines, underground quarries, sinkholes, settlement,

INTRODUCTION

The East Japan Mega Earthquake with a moment magnitude 9.0 took place at 14:46 (JST) on March 11, 2011 (JMA, 2011). The earthquake was a subduction plate-boundary earthquake and the rupture area was 450 km long and 200 km wide. This earthquake caused gigantic tsunami waves, which destroyed many cities and towns along the shores of Tohoku and Kanto Regions of Japan. The casualties caused by this tsunami exceed 20,000 people. The tsunami destroyed and heavily damaged buildings of various type, transportation facilities and infrastructures. The authors visited Oya (Tochigi) in Kanto region and Iwaki (Fukushima), Wakayanagi, Ohira (Miyagi) and Ichinoseki (Iwate) in Tohoku region and made observations on the collapsed abandoned lignite and coal mines and underground stone quarries and associated damage to super structures (Figure 1).

The earthquake occurred along the subduction zone between North American plate (NAM) and Pacific plate (PAC) and the inclination of the rupture plane was estimated to be 14-16 degrees. The faulting was due to thrust faulting with an estimated offset of 25-30 m. The seabed was uplifted by 5 m while the land sank-down by about 0.8 m with a horizontal movement of 4.6 m. The rupture initiated in the area where an earthquake with a magnitude of 7.5 was anticipated and it propagated bi-laterally.

Figure 2 shows the maximum ground acceleration contours, which are obtained using the data of KNET(2011) and KiKNET(2011) (Iwatate and Aydan, 2011). The highest ground acceleration reaching to the level of 3g was recorded at the Tsukidate strong motion station of KNET. Although the ground conditions are very good at this station, it is still difficult to understand the cause of high ground motions recorded at the Tsukidate station.

In this article, the authors present the outcomes of their investigations in areas Oya (Tochigi) in Kanto region and Iwaki (Fukushima), Wakayanagi, Ohira (Miyagi) and Ichinoseki (Iwate). Furthermore, they discuss their implications of the observations in relation to the in short and long-term performance of abandoned mines and quarries, which are widely distributed all over Japan.

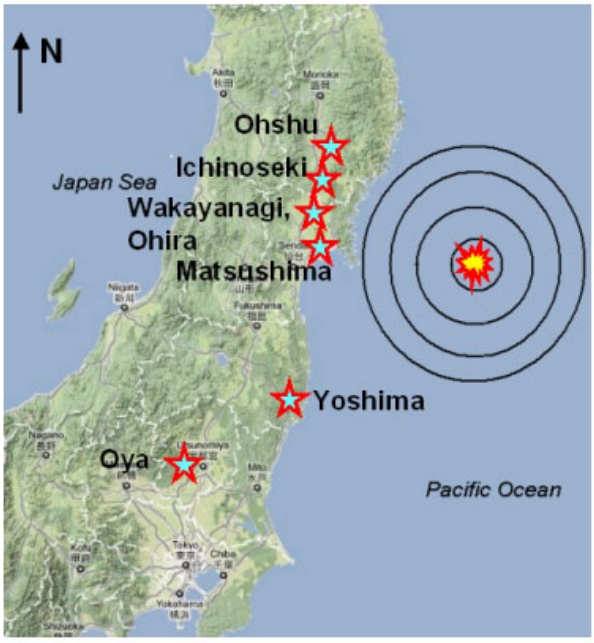

Fig. 1 Investigation locations

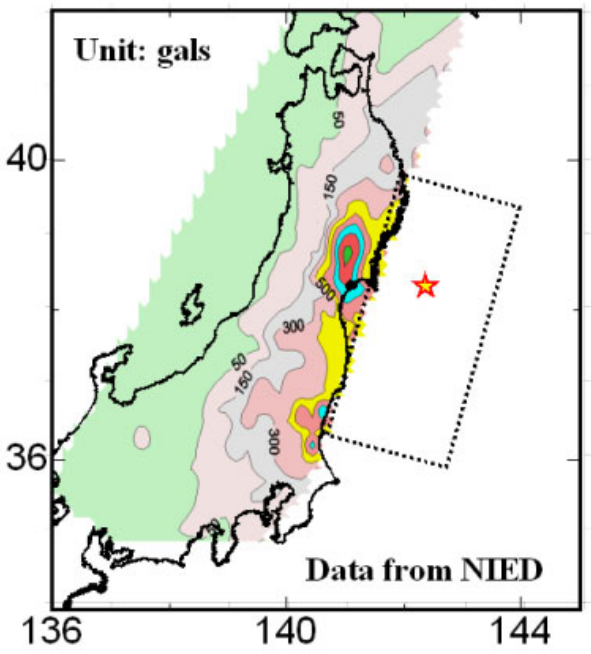

Fig. 2 Maximum acceleration contours

ABANDONED COAL AND LIGNITE MINES

Figure 3 shows the distributions of coal and lignite (brown coal) fields in Tohoku Region and the locations and number of sinkhole damage at each locality. The number of sinkhole formation or related events are from the news release of the Ministry of Economy, Trade and Industry (METI) on July 25, 2011. The number of sinkholes and related event were 5 locations in Iwaki City in Fukushima Prefecture, 11 locations in Kurihara City, 7 locations in Osaki, 11 locations in Higashi Matsushima and 3 locations in Kurogawa in Miyagi Prefecture 11 locations in Ichinoseki City and 10 locations in Oshu City in Iwate Prefecture in the News Release of the METI on March 30, 2011 and the number has become more than 10 times in the News Release of the METI on July 25, 2011. It is also reported that the number of abandoned lignite mine damage events become 20 times that every year in the southern part of Iwate Prefecture.

The shallow lignite seams are commonly exploited using the room and pillar technique connected to ground through inclined shafts and vertical shafts. The long-wall technique was employed for exploiting the coal seams. The coal fields are Jobando coal field and Shirakawa coal field. The authors explain the observations of damage to abandoned mines investigated by the authors in this section.

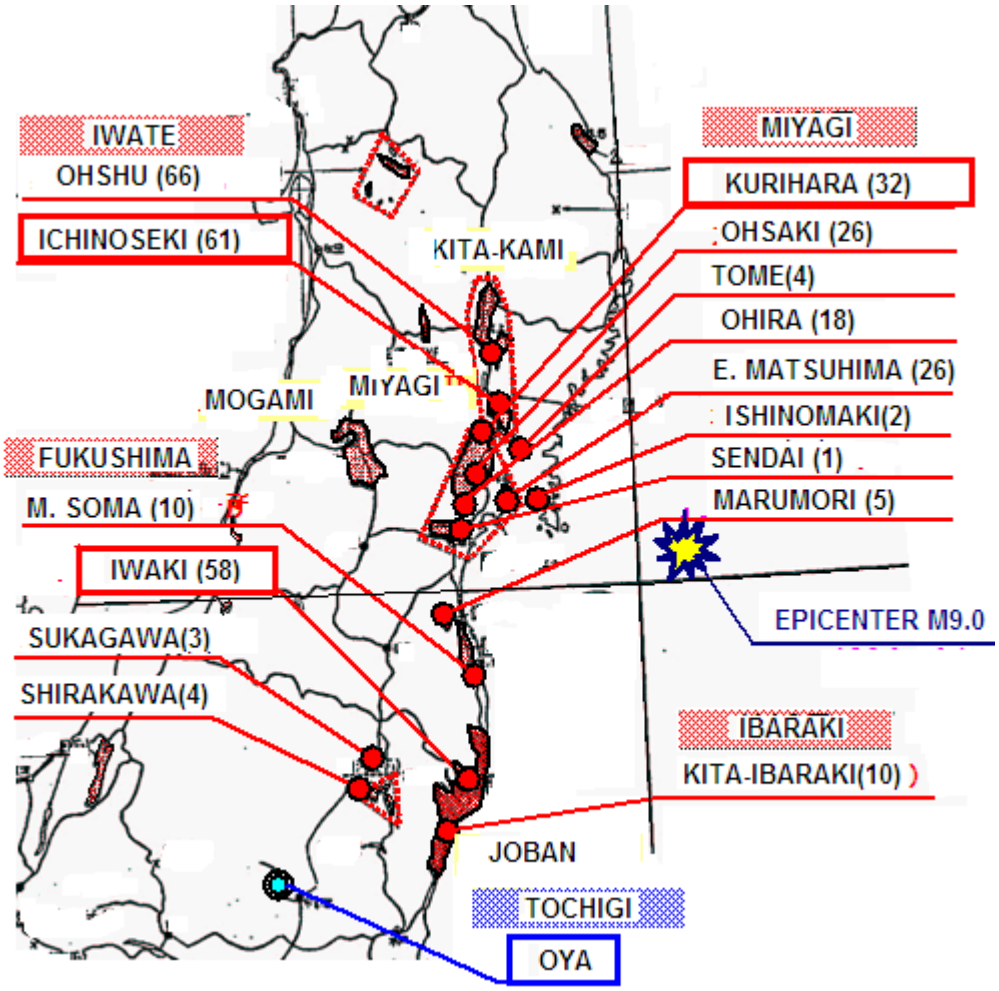

Fig 3 Locations of sinkhole damage (number in parenthesis is the number of damage event)
The numbers are quoted from the New Release of METI on July 25, 2011

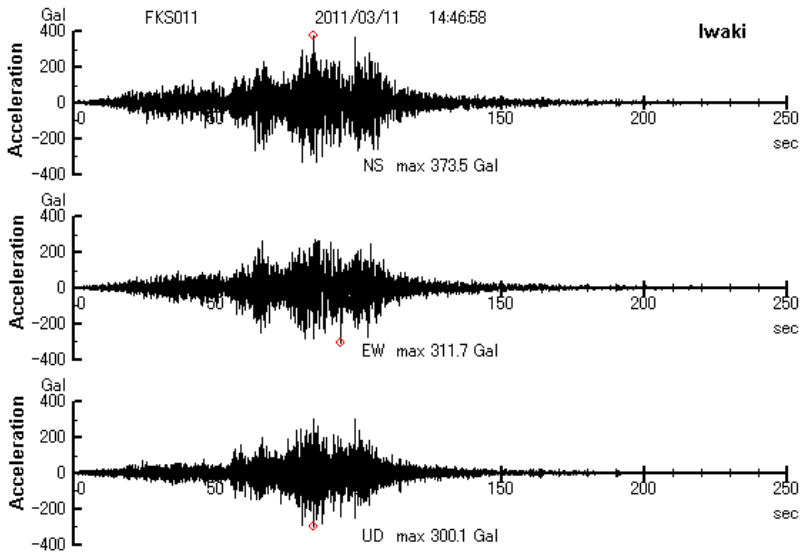

Fig. 4 Acceleration records at Iwaki station

Figure 4 shows the acceleration record at Iwaki strong motion station of KIKNET. The maximum ground acceleration at Iwaki strong motions station of KIKNET was 481 gals at the ground surface. There were 5 sinkholes at the abandoned Yoshima mine of Jobando coal field as shown in Figure 5. The collapses were associated with inclined shafts. The sloshing of the underground water in inclined shafts caused the failure of roof rock resulting in sinkholes as seen in Figures 6 and 7.

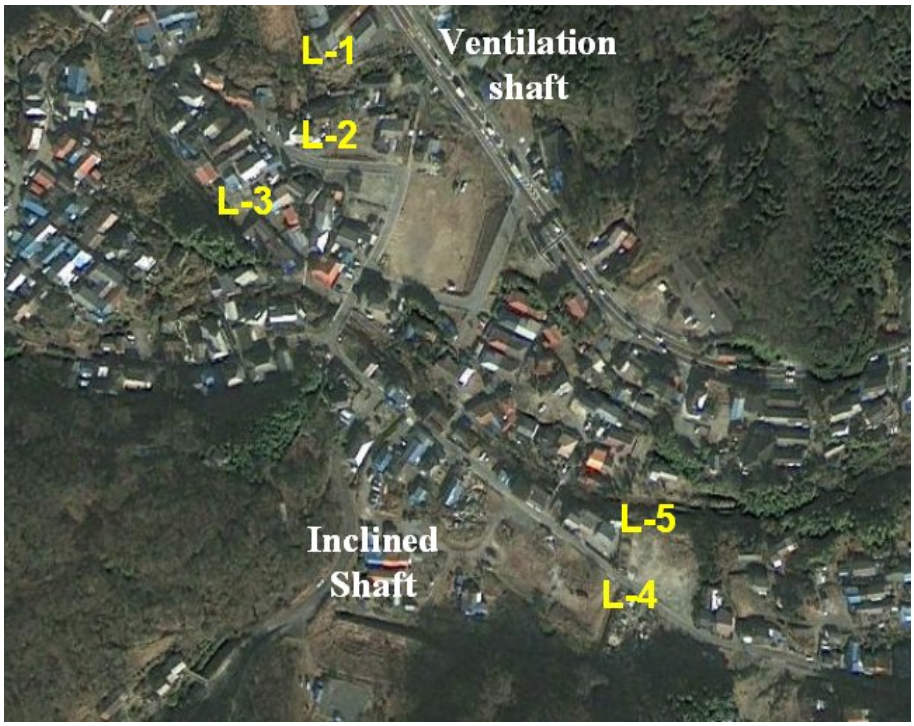

Fig. 5 Locations of sinkholes at the abandoned Yoshima Coal mine

Fig. 6 Views of sinkholes locations L1-L3

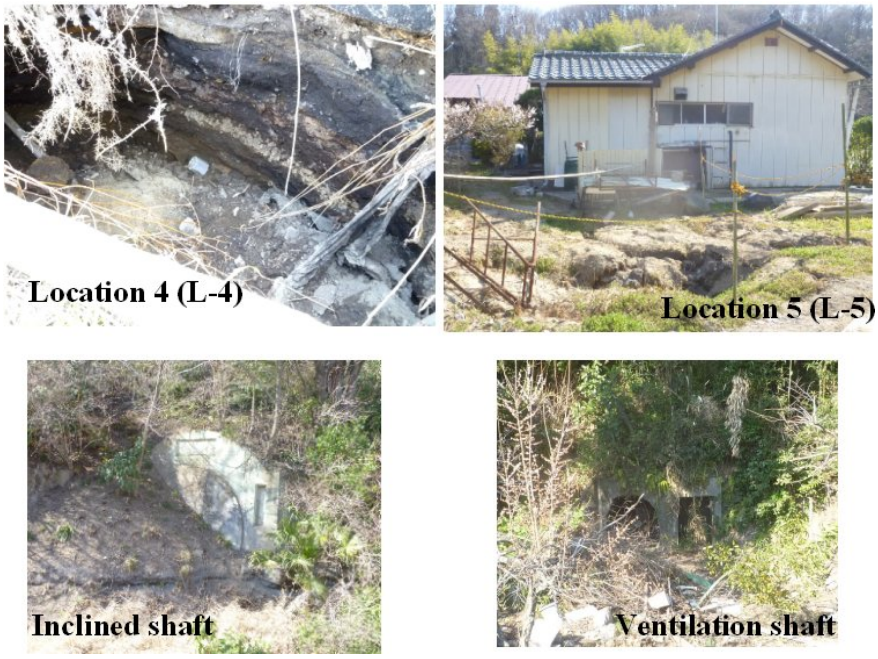

Fig. 7 Views of sinkholes locations L4-L5

The Ministry of Economy, Trade and Industry of Japan (2011) reported that collapses occurred at 32 locations in Miyagi Prefecture and 21 locations in Iwate Prefecture in the News Release of March 30, 2011. The section responsible with abandoned mines incidents in Miyagi Prefecture did not released the locations of sinkholes to the authors and the sites were located by the own efforts of the authors together with the generous help of the local people suffered from this earthquake.

The ground motions records differ from place to place. The largest ground motions were recorded at the Tsukidate strong motion station of KNET. Except top 1 m thick clay layer, this station is based on sedimentary rocks, which are commonly observed in lignite mine areas. Figure 8 shows the acceleration record at the Tsukidate strong motion station of KNET. The maximum ground acceleration at Tsukidate strong motion station of KIKNET was 2933 gals at the ground surface.

In Wakayanagi town of Kurihara City, 5 sinkholes occurred in residential area as seen in Figure 9. Luckily , these sinkholes did not cause the collapse of the residential houses on the ground surface. However, the fracturing of the base concrete occurred and one corner of the building was overhanging with a slight tilting. The overburden of the sinkholes ranged between 1 m to 3 m at this locality.

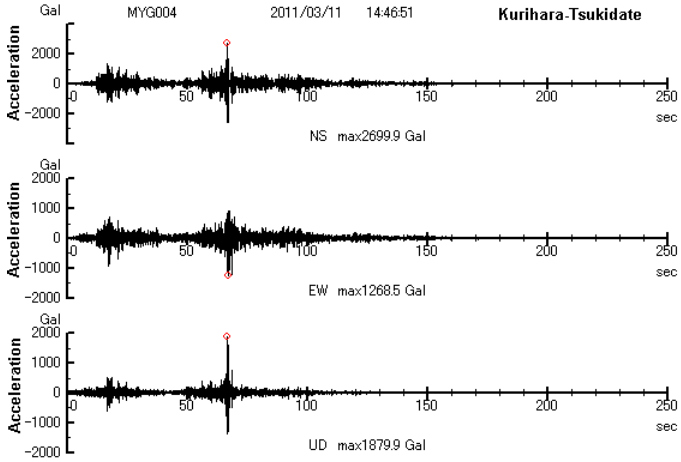

Fig. 8 Acceleration records at Tsukidate station

Fig. 9 Views of sinkholes and related damage in Wakayanagi town

In a large rice field near Ohira Village of Kurihara City, more than 10 sinkholes with a diameter ranging from 1 m to 5 m were observed as seen in Figure 10. Besides ground shaking, the sloshing phenomenon of ground water in the underground openings abandoned lignite mine areas contributed to the collapse of the roof layers. As a result of this phenomenon, sandy material together with fragments of rocks and lignite appeared on the ground surface and this ejected sandy material is sometimes misinterpreted as ground liquefaction by soil-mechanics researchers and engineers. The overburden of the sinkholes ranged between 2 to 4 m at this locality.

Besides sinkholes in the rice field, some sinkholes were observed along the roadway and in the parking lot next to residential buildings as seen in Figure 11. The overburden of the sinkholes with a diameter of 2-3 m ranged between 1 to 2 m at this locality. The ground shaking caused the collapse.

Two sinkholes in residential areas and one sinkhole in rice field occurred in the Tsukidate town of Kurihara City. Although there was no casualty in these events, it causes some anxiety in the people living in such areas.

Fig. 10 Views of sinkholes in a rice field near Ohira Village

Fig. 11 Views of sinkholes along a roadway and parking lot near Ohira Village

The 2011 East Japan Mega Earthquake caused a number of sinkholes in both residential areas and fields caused in Ichinoseki. The sinkholes were enlarged in size after each large aftershock. Figure 12 and 13 shows the sinkholes beneath or close vicinity of houses in Ichinoseki City. Figure 14 shows a sinkhole along a roadway in Ichinoseki City. In addtion to these there were sinkholes in rice fields.

Fig. 12 A sinkhole beneath a house in Ichinoseki. (L1). The size of the sinkhole enlarged after the April 7, 2011 aftershock

In addition to the sinkholes explained in this article, there were also some sinkholes formations in abandoned lignite mine areas in Oshu City (Iwate Prefecture) and Matsushima City (Miyagi Prefecture) . Sinkholes were observed in both residential areas and fields. However, there was no casualty in any incident.

Fig. 13. A sinkhole beneath a house in Ichinoseki. (L2)

Fig. 14 Sinkhole beneath the roadway in Ichinoseki (L3)

ABANDONED QUARRIES

Damage to abandoned underground quarries occurred in Oya Town (Tochigi Prefecture). Oya tuff or Oya stone, has been quarried in the Oya region, Utsunomiya, Japan. Over 200 underground quarries have been exploited for more than 100 years and some of those are below residential areas. Oya town is about 295 km away from the earthquake epicenter.

Although ground motions recorded in the vicinity of abandoned underground quaries in Oya, the instruments are mainly velocity based and they do not measure three components of the ground motions. Figure 15 shows the acceleration record at Utsunomiya strong motion station of KiKNET near the Oya town. The maximum ground acceleration at Utsunomiya strong motions station of KiKNET was 358 gals at the gound surface.

Total or partial collapse of semi-underground quarries occurred as seen in Figures 16 and 17. The toppling of pillar (P1) caused the collapse of thin roof of the abandoned quarry as seen in Figure 16. In some cases, partial collapses of the overhanging parts occurred as seen in Figure 17.

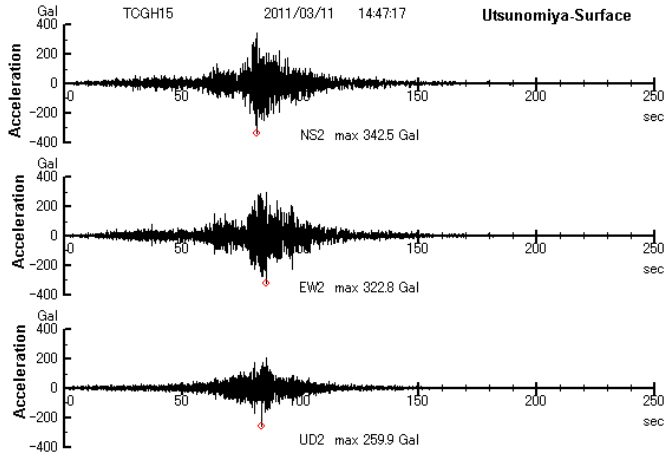

Fig. 15 Acceleration records at Utsunomiya

Fig. 16 Totally collapsed semi-underground opening

Fig. 17 Partially collapsed semi-underground opening

The settlement of back-filling material of three shafts of abandoned quarries occurred. In the example shown in Figure 18, the settlement of back-filling material was more than 5 m and the diameter of the shaft was about 7 m. The back-filling material was non-cohesive.

The back-filling material of the abandoned shaft settled more than 3 m as seen in Figure 19. There was a hut on top of this shaft. The hut and the car parked next to the hut was fallen into the settled shaft. These observations are very similar to those observed in Yamoto town (re-named as Higashi-Matsushima) during the 2003 Miyagi-Hokubu earthquake.

Fig. 18 The settlement of back-filling material of the shaft

Fig. 19 The settlement of back-filling material of the shaft and the fall of the hut and car into the shaft

IMPLICATIONS

The 2011 Great East Japan earthquake caused damage to structures and collapses of abandoned mines in Iwate and Miyagi prefectures where the mining activity was intense about 40 years ago. There are several locations with similar characteristics in Japan. The observations in this earthquake may have important implications on areas with abandoned lignite and coal mines where extraction was done by room and pillar method. Besides the possibility of caving of abandoned mines during earthquakes due to either pillar failure and/or roof failure, the ground water may present additional effects on the submerged abandoned mines. These effects may be observed as sloshing, which may weaken the rockmass and cause additional collapses.

The sand ejection or sand boiling from the abandoned mines are mistakenly mis-interpretted as the ground liquefaction by people having soil mechanics background. Although there is no doubt that the sand having similar characteristics to liquefied soil is ejected, it is the sand which accumulated at the bottom of mine adits and were ejected to ground surface through vertical and inclines shafts or collapsed openings connected to ground surface.

When shafts of abandoned mines and quarries are not deep, they may be filled up using gang material or debris, the behaviour of which may be similar to that of a non-cohesive granular material. When ground motions are sufficient enough to cause the yielding of filling material, the filling material would flow into the adjacent openings and result in the settlement of filling material in the shafts as observed in th shafts of abandoned quarries of Oya during the 2011 Great East Japan earthquake and in abandoned lignite mines of Yamoto area (presently Higashi-Matsuhima City) during the 2003 Miyagi Hokubu earthquake.

The fallen material from the roof or collapse of sidewalls may block adits and inclined shafts in abandoned mines and quarries. When these underground openings are fully or partially submerged with ground water, earthquakes may cause the relative movement of ground water similar to the sloshing phenomenon. When ground motions are strong enough, the ground water may cause the breach of blocked sections and the collapse of the roof and subsequent ejection of accumulated material in underground openings (Aydan and Kawamoto, 2004). This behavior was observed in abandoned coal mines of Yoshima in Fukushima Prefecture, Ohira and Wakayanagi in Miyagi Prefecture during the 2011 Great East Japan Earthquake.

Besides the problems mentioned in this article, the stability of spoils from mining works and tailing dams, the outflow of acidic underground water in mines and outburst of explosive gases due to earthquakes may cause some problems to the environment. Undoubtedly, the 2011 Great East Japan earthquake caused such problems to some extent and such cases histories should be also well documented and potential problems should be addressed.

CONCLUSIONS

The following conclusions can be drawn from the observations reported in this study as follow:

1) Strong ground shaking induced the collapses of semi-underground openings in the abandoned Oya quarries, which are relatively high and having overhanging configurations.

2) Besides the possibility of caving of abandoned mines during earthquakes due to either pillar failure and/or roof failure, the ground water may present additional effects on the submerged abandoned mines. These effects may be observed as sloshing, which may weaken the rockmass and cause additional collapses. Sinkholes are thought to be due to the rupture of ground by the sloshing of ground water in inclined shafts. This phenomenon is the same as that observed in the abandoned lignite mines of Yamoto Town (presently Higashi-Matsushima City) during the 2003 Miyagi Hokubu earthquake (Aydan and Kawamoto, 2004; Aydan et al. 2006).

3) When the filling material of shafts of abandoned mines is non-cohesive, the filling material would settle in the shafts due to its flow into adjacent openings when ground shaking is strong enough to induce the flow of filling material particles.

4) This earthquake clearly showed that the abandoned mines and underground stone quarries exploited using the room and pillar technique are very vulnerable to cause sinkholes and associated collateral damage to super structures on the ground surface.

ACKNOWLEDGMENTS

The authors sincerely acknowledge Mr. K. Sugiura and A. Sakamoto of Tobishima Corporation and Miss T. Ono from Iwaki City Council and Mr. K. Sugawara from Wakayanagi town for joining the authors in some of field investigations reported in this article when it was still difficult to access some sites following the earthquake.

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