

# THE DAMAGE TO ABANDONED QUARRIES AND MINES BY THE M 9.0 EAST JAPAN MEGA EARTHQUAKE ON MARCH 11, 2011

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The East Japan Mega Earthquake with a moment magnitude 9.0 occurred on March 11, 2011. There are many abandoned lignite mines in the close vicinity of the epicentral area such as Miyagi and Iwate Prefectures. The Ministry of Economy, Trade and Industry of Japan reported that collapses occurred at 32 locations in Miyagi Prefecture and 21 locations in Iwate Prefecture. In addition some collapses occurred in Oya of Tochigi Prefecture and in Yoshima coal field in Iwaki City of Fukushima Prefecture. The authors present their investigations results and discuss their implications in short and long-term performance of abandoned mines and quarries in this article.

**Key Words :** collapse, 2011 East Japan Mega Earthquake, abandoned mines, quarries.

## 1. INTRODUCTION

The East Japan Mega Earthquake with a moment magnitude 9.0 took place at 14:46 (JST) on March 11, 2011<sup>1</sup>. The earthquake was a subduction plate-boundary earthquake and the rupture area was 450 km long and 200 km wide<sup>2</sup>. 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<sup>3</sup>. 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<sup>4</sup> and KiKNET<sup>5</sup>. 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.



Figure 1. Investigation locations

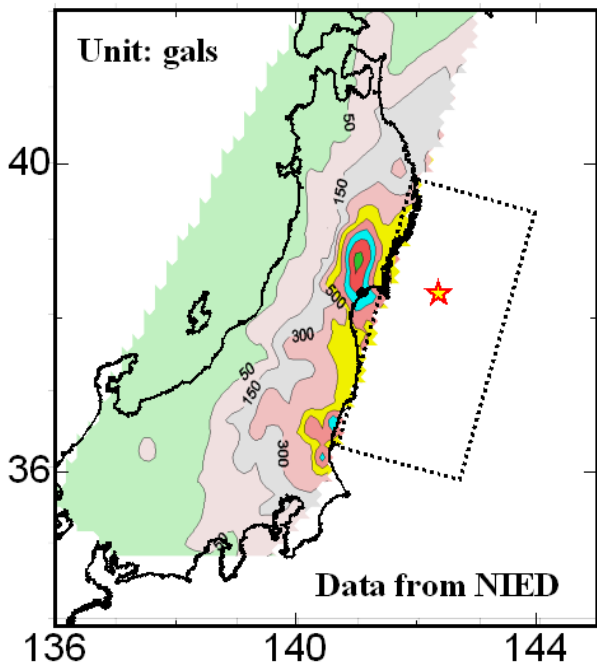


Figure 2. Maximum acceleration contours<sup>3)</sup>

## 2 ABANDONED QUARRIES

Damage to abandoned underground quarries occurred in Oya (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 is about 295km away from the earthquake epicenter.

Although ground motions recorded in the vicinity of abandoned underground quarries in Oya, the instruments are mainly velocity based and they do not measure three components of the ground motions. Figure 3 shows the acceleration record at Utsunomiya strong motion station of KNET near Oya. The maximum ground acceleration at Utsunomiya strong motions station of KNET was 358 gals at the ground surface.

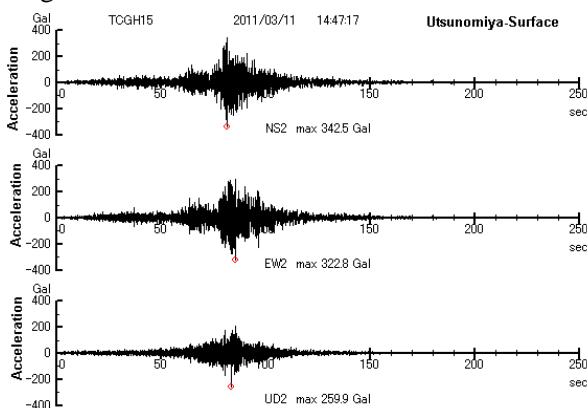


Figure 3. Acceleration records at Utsunomiya

Total or partial collapse of semi-underground quarries occurred as seen in Figures 4 and 5. The toppling of pillar (P1) caused the collapse of thin roof of the abandoned quarry as seen in Figure 4. In some cases, partial collapses of the overhanging parts occurred as seen in Figure 5.



Figure 4. Totally collapsed semi-underground opening



Figure 5. Partially collapsed semi-underground opening

The settlement of back-filling material of three shafts of abandoned quarries occurred. In the example shown in Figure 6, 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 7. 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 during the 2003 Miyagi-Hokubu earthquake<sup>6,7)</sup>.





Figure 6. the settlement of back-filling material of the shaft



Figure 7. The settlement of back-filling material of the shaft and the fall of the hut and car into the shaft

### 3 ABANDONED COAL AND LIGNITE MINES

Figure 8 shows the distributions of coal and lignite (brown coal) fields in Tohoku Region. The shallow lignite seams are commonly exploited using the room and pillar technique. The long-wall technique was employed for exploiting the coal seams. The coal fields are Jobando coal field and Shirakawa coal field.

The earthquake caused sinkholes at 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 Ichonseki City and 10 locations in Oshu City in Iwate Prefecture<sup>8)</sup>.

Figure 9 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 10. 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 11 and 12.

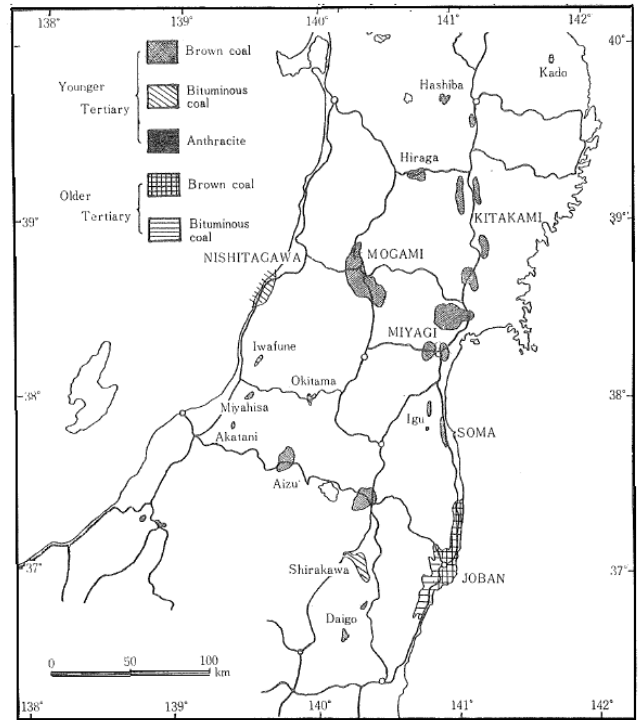


Figure 8. Coal and lignite fields in Tohoku Region<sup>9)</sup>

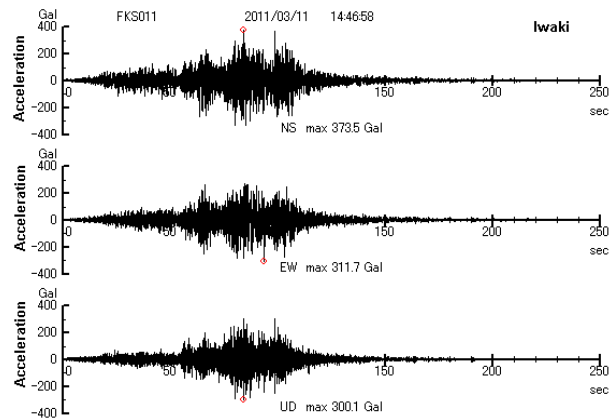


Figure 9. Acceleration records at Iwaki station



Figure 10: Locations of sinkholes at the abandoned Yoshima Coal mine



Location 1 (L-1)



Location 2 (L-2)

Location 3 (L-3)

Figure 11. Views of sinkholes locations L1-L3



Location 4 (L-4)

Location 5 (L-5)



Inclined shaft

Ventilation shaft

Figure 12. 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. 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 mines. Figure 13 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 14. 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.

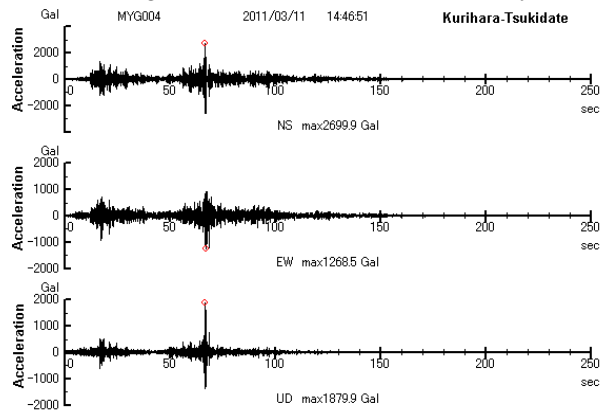


Figure 13. Acceleration records at Tsukidate station



Figure 14: Some views of sinkholes 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 15. 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 mis-interpreted as ground liquefaction



by soil-mechanics researchers and engineers. The overburden of the sinkholes ranged between 2 to 4 m at this locality.



Figure 15. Views of sinkholes in a rice field near Ohira Village

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 16. The overburden of the sinkholes with a diameter of 2-3 m ranged between 1 to 2 m at this locality. The collapse was caused by the ground shaking.



Figure 16. Views of sinkholes along a roadway and parking lot near Ohira Village

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.

A number of sinkholes in both residential areas and fields caused in Ichinoseki by the 2011 East Japan Mega Earthquake. The sinkholes were enlarged in size after each large aftershock. Figure 17 and 18 shows the sinkholes beneath or close vicinity of houses in Ichinoseki City. Figure 19 shows a sinkhole along a roadway in Ichinoseki City. In addition to these there were sinkholes in rice fields.



Figure 17: A sinkhole beneath a house in Ichinoseki. (L1). The size of the sinkhole enlarged after the April 7, 2011 aftershock.



(a) A large sinkhole extending below the storage room and the main building



(b) Cracking of the concrete base and walls in the main building.

Figure 18: A sinkhole beneath a house in Ichinoseki. (L2).



Figure 19. Sinkhole beneath the roadway in Ichinoseki (L3)

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.

#### 4 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 effect 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 during the 2003 Miyagi Hokubu earthquake<sup>6,7)</sup>.
- 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.

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### 2011年3月11日東日本巨大地震による亜炭廃坑および地下採石場跡地における陥没とその被害について

藍檀オメル、田野久貴

2011年3月11日にマグニチュード9の巨大地震が東北沖に発生し、2011年東日本大震災と名づけられた。宮城および岩手県に数多くの亜炭廃坑、旧鉱山が存在している。また、栃木県の大谷町に数多くの旧地下採石場が存在している。経済産業省は宮城県で32箇所岩手県で21箇所陥没が発生したと報告した。栃木県の大谷町の地下採石場跡地と福島県いわき市の石炭跡地でも陥没が発生した。本論文で著者らはこれらの地域で発生した陥没現象に対する調査結果を報告し、今後廃坑や地下採石場跡地の短期および長期的な観点からその意味合について論じている。