「海一自然と文化」東海大学紀要海洋学部　第２巻第１号　1-17頁（2004）
Journal of The School of Marine Science and Technology, Vol.2 No.1 pp. 1-17, 2004

# Damage to Abandoned Lignite Mines Induced by 2003 Miyagi-Hokubu Earthquakes and Some Considerations on its Possible Causes

Ömer AYDAN*1

**Abstract**

The seismic response and stability of areas situated above the abandoned lignite mines in Japan due to urbanization in recent years are of great concern. The July 26 2003 Miyagi-Hokubu earthquake (Mj6.2) caused some damage in the area of abandoned lignite mines nearby Yamamoto town, which is just on the epicenter of the earthquake. The author had the chance to visit the damaged area in October, 2003. This article describes several cases of damage to the area of abandoned lignite mines and some peculiar phenomena such as the sinkholes, sloshing-induced sand boiling, the settlement of filled shafts caused by the M6.2 earthquake and its aftershocks, which are of great interest in environmental city planning and new developments in such areas. In addition, some model tests on abandoned lignite mines were performed by using a shaking table to explain peculiar phenomena observed during this earthquake. The ground water in abandoned lignite mines are thought to be contributing to the stability of the abandoned mines under static conditions. However, this earthquake showed that the ground-water may have negative effects on the stability of the abandoned mines under dynamic conditions. Furthermore, if the filling material used to grout underground openings such as shafts, adits, rooms is cohesionless, the settlement and lateral flow of the filling material may occur, which may subsequently cause the settlement in such areas. The sloshing phenomena depend upon the geometry of the abandoned mines and the characteristics of the earthquake. The sloshing phenomena may particularly influence the small mines by nearby in-land earthquakes while the large mines may be influenced by the off-shore earthquakes.

## 1. INTRODUCTION

There is a growing concern on the seismic response and stability of areas situated above the abandoned-lignite mines in Japan due to urbanization in recent years (Aydan et al. 2004). From time to time, some surface depressions or cavings occur as a result of the deterioration of rockmass of pillars and layers spanning over the openings or surcharge loads induced by the construction of super-structures and/or vehicles. Nevertheless, there is almost no available record on damage inflicted in abandoned-lignite mines neither in Japan nor elsewhere except the 1975 Tangshan earthquake in which the causative fault of the earthquake crossed the mine.

Lignite (called ATAN in Japanese) was extensively exploited in the areas of in Aichi, Miyagi, Yamaguchi and Fukuoka prefectures before the Second World War II (Kawamoto et al. 2004). These mines were in operation until the early 1960s. The room and pillar technique was mainly employed during the extraction of lignite. The depth of lignite mines ranges between 5-100m from the ground surface.

The 2003 Miyagi-Hokubu earthquake caused some damage on the abandoned lignite mines and provided a unique opportunity for actual observations on the seismic response and instability problems in such areas. The author as a member of the reconnaissance team of Japan Grouting Society had an opportunity to investigate the damaged area over the abandoned lignite mines in October 2003 (Kawamoto et al. 2004). This report describes the characteristics of damage induced on abandoned lignite mines by the 2003 Miyagi-Hokubu

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＊1　東海大学海洋学部海洋土木工学科（Department of Marine Civil Engineering, School of Marine Science and Technology, Tokai University）

earthquake in relation to its ground shaking characteristics and discuss the possible causes of damage inflicted on the ground surface on the basis of some shaking table model tests in laboratory.

## 2. GEOGRAPHY AND GEOLOGY

Miyagi Prefecture is located in the Tohoku District of Japan on Honshu Island (Figure 1). The prefectural capital is Sendai city. The earthquake epicenter was located in the northern part of the prefecture somewhere between Naruse and Yamoto towns 25km North of Sendai.

Neogenic formations belonging to Pliocene era are Kameoka (Km), Tatsukonokuchi (Tf), Hanaremori, Omotezawa (Ozt), Tawaraniwa (Tw) from bottom to top (Figure 2). Lignite seams are found in Tawaraniwa formation and Omotezawa formation and Kameoka formation. Lignite seams in Tawaraniwa formation were extracted.

Tawaraniwa formation consists of sandy siltstone, fine sandstone and tuff with intercalating lignite seams while Omotezawa formation consists of siltstone, conglomerate and siltstone with lignite seam. The area is covered with alluvial deposits belonging to Quaternary period and they consist of sand, silt and clay.

There is an active fault named "Asahiyama flexure", which has North-South strike, around the focal area shown in Figure 1. It was initially considered that this fault caused these earthquakes (Kawamoto et al. 2004). This earthquake sequence took place around this active fault. The Asahiyama flexure inclines to the west with an 8km length extending from Naruse Town to Kanan Town, and it is a reverse fault with the west side of this fault moving upward. The Asahiyama flexure is located on the eastern wing of the Oshio anticline that deforms the Miocene and Pliocene formations.

## 3. CHARACTERISTICS OF 2003 MIYAGI-HOKUBU EARTHQUAKES

The earthquake occurred at 07:13 AM. local time July 26, 2003 with magnitude Mj6.2 (JMA, 2003). The epicenter is located lat. 38.40 N., long. 141.175 E. (about 25km northeastern Sendai city), with a focal depth 12 km (Figure 1). On the same day, foreshock and aftershock of magnitudes – M5.5 and M5.3 - hit the same area at 00:13 AM and 04:56 PM with epicenters about 3km and 11km north of the mainshock, respectively. The JMA intensity was 6+ at many sites (about 10 in MMI

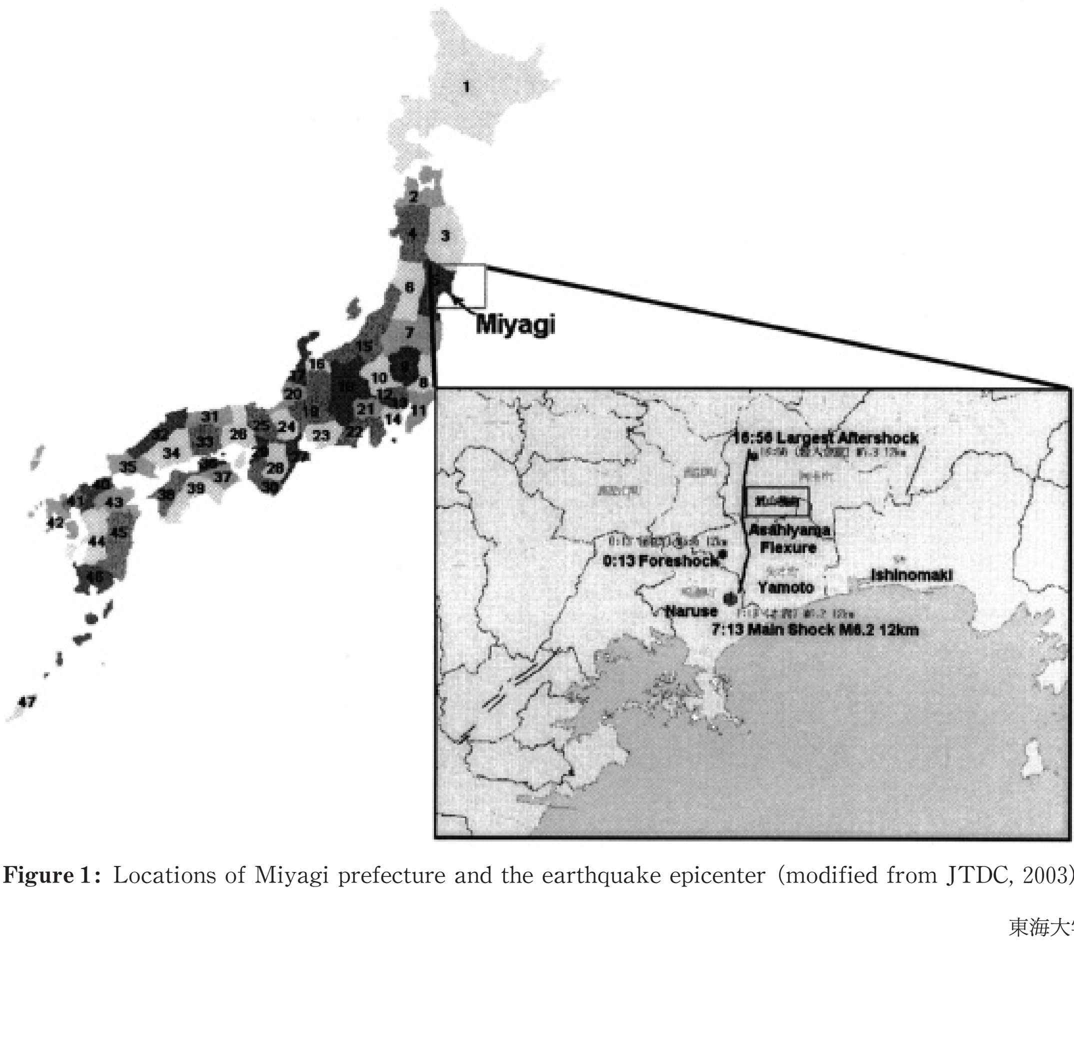



**Figure 1:** Locations of Miyagi prefecture and the earthquake epicenter (modified from JTDC, 2003)

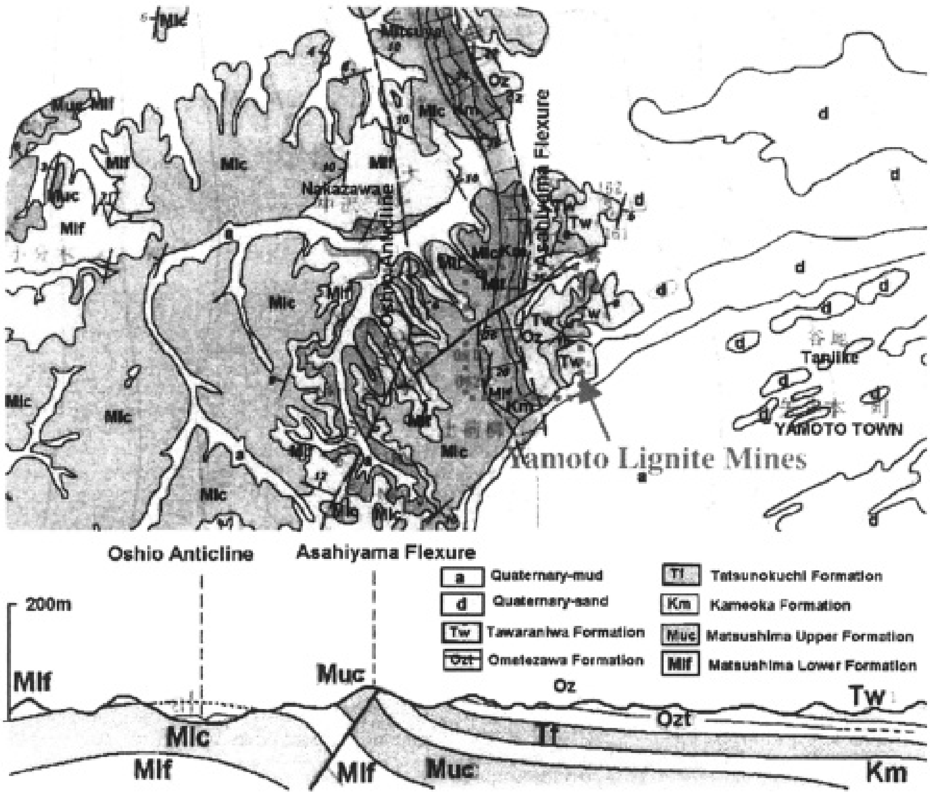



**Figure 2:** Geological map and cross section of the area (modified from JGS (2003)

scale). These earthquakes caused total 676 injuries and 11,341 buildings were damaged, 1,017 of which were collapsed. Fortunately, no death or missing persons were reported. The economic losses due to these earthquakes are 195.4 million dollars.

### 3.1 Faulting Mechanism

The mainshock was caused by a dominantly thrust faulting with a slight sinistral sense. The focal mechanism of the foreshock was similar to that of the mainshock. The epicenters of the main shock and the largest shocks were aligned along the strike of Asahiyama flexure. Nevertheless, the causative fault was not the Asahiyama flexure and it is inferred that the causative fault, which caused no rupture on the ground surface, must be to the east of the Asahiyama flexure in view of aftershock distributions and projections on the ground surface. The main parameters of faulting mechanism are given in Table 1 and the focal plane solutions for the foreshock and mainshock are shown in Figure 3.

### 3.2 Strong Ground Motions

The strong-motion networks deployed by JMA, Local governments and by NIESDP (K-Net and Kik-Net networks by National Research Institute for Earth Science and Disaster Prevention, Japan). The maximum PGA (2005gal) in strong motion records was recorded in the 00:13 event at the Naruse strong motion station of JMA network 3.5km from the epicenter. However, this was caused by a problem associated with the fixation of the accelerometers to the base. However, the highest ground accelerations measured by K-Net and Kik-Net networks were not that high. Figure 4 shows the attenuation of maximum ground acceleration for the mainshock. The ground acceleration at ground surface and bedrock at nearby Ishinomaki strong-motion station indicated that the ground amplification was about 1.7–1.9. Table 2 gives the maximum ground accelerations at Yamoto town, which is the nearest town to the abandoned-lignite mines. It is of great interest that the UD component at Yamoto is very high during the main

**Table 1:** Parameters of July 26 Miyagi-hokubu 2003 earthquakes (computed by NIESDP, 2003)

| Earthquake | Latitude | Longitude | Depth (km) | Magnitude Mj | Width (km) | Length (km) | Strike | Dip | Rake |
|---|---|---|---|---|---|---|---|---|---|
| 00:13 | 38.43 | 141.17 | 11 | 5.5 | 12 | 18 | 197° | 49° | 86° |
| 07:13 | 38.40 | 141.20 | 12 | 6.2 | 15 | 18 | 201° | 42° | 102° |

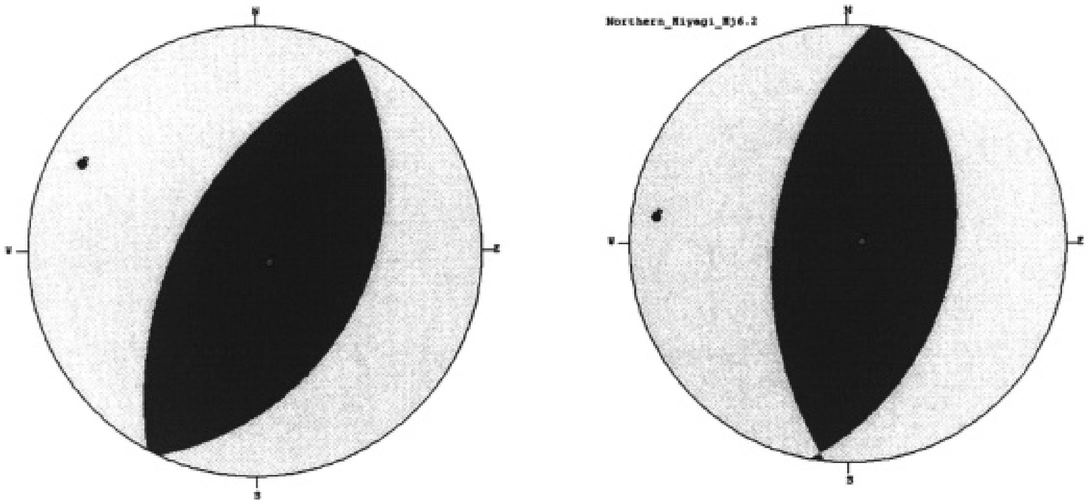


**Figure 3:** Focal plane solutions for the M5.5 foreshock and M6.2 mainshock (drawn by Aydan).

**Table 2:** Maximum Ground Accelerations and Intensity at Yamoto town

| Time (JST) | Magnitude Mj | Epicentral distance (km) | Maximum Ground Acceleration | | | JMA measured Intensity | JMA Intensity |
|---|---|---|---|---|---|---|---|
| | | | NS (Gal) | EW (Gal) | UD (Gal) | | |
| 00:13 | 5.5 | 4.5 | 366.2 | 476.4 | 360.3 | 5.5 | 6-weak |
| 07:13 | 6.2 | 4.2 | 667.1 | 489.5 | 1241.7 | 6.2 | 6-weak |

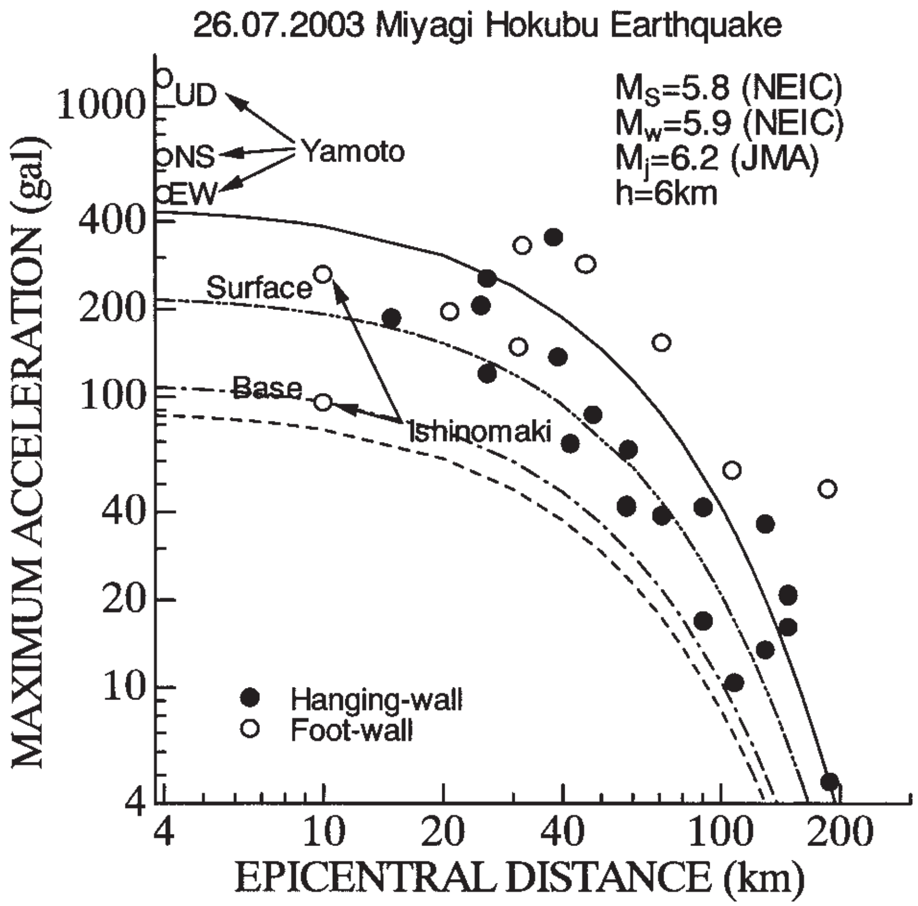



**Figure 4:** The attenuation of maximum ground accelerations

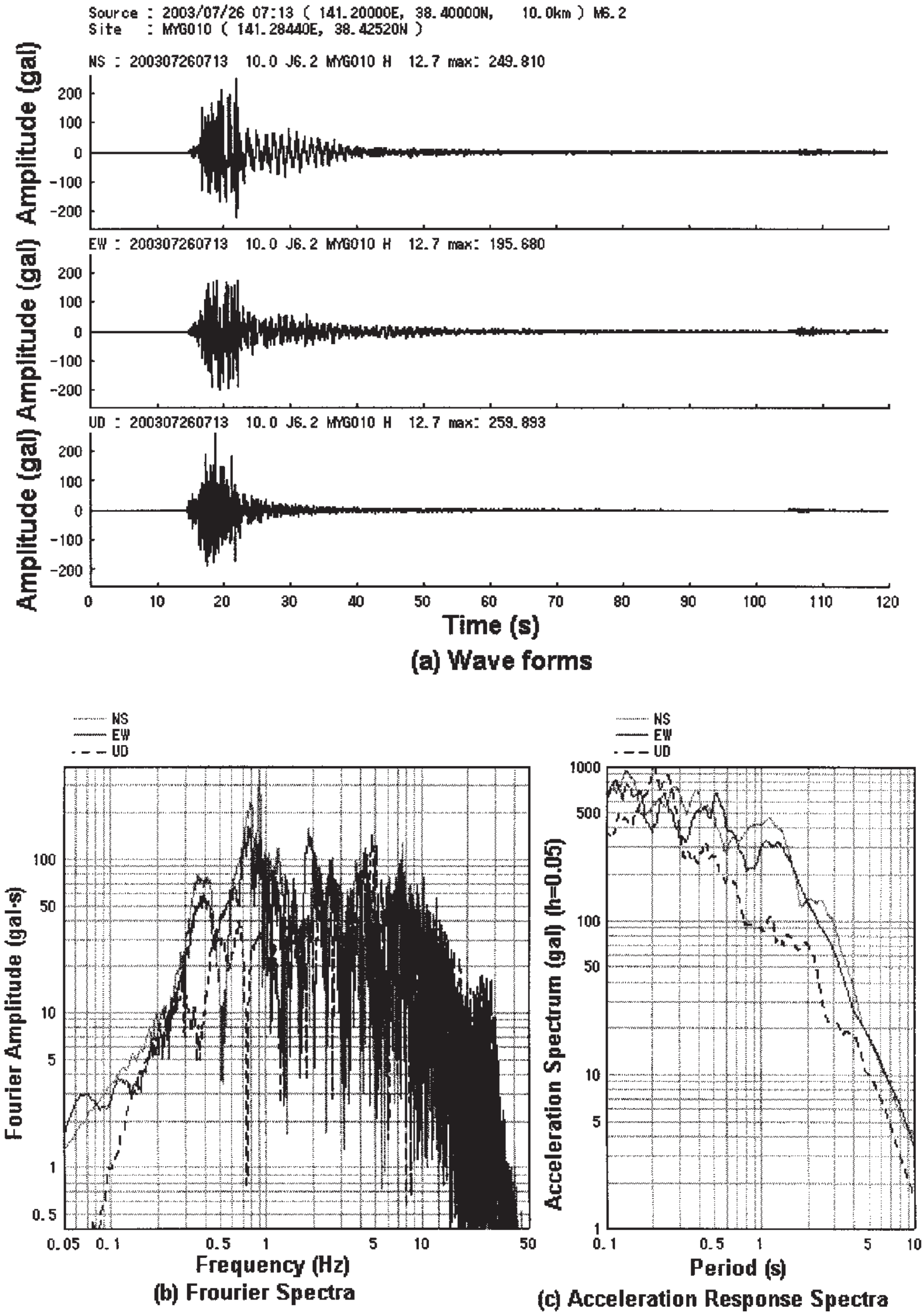



**Figure 5:** The acceleration records recorded at Ishinomaki station of KikNet and their Fourier spectra and acceleration response spectra (modified from JTDC, 2003)

shock since it was situated on the overhanging wall side of the causative fault. Since the records at Yamoto station of JMA was overwritten, the strong motion records could not be available. Nevertheless, the acceleration records recorded at Ishinomaki station of KikNet and their Fourier and acceleration response spectra are shown in Figure 5. However, it should be noted that Ishinomaki station is on the foot-wall of the causative fault. Therefore, the response at Yamoto station, which is on the overhanging of the fault, might be quite different than that at Ishinomaki station.

## 4. CHARACTERISTICS OF DAMAGE TO ABANDONED LIGNITE MINES

The damage surveys on abandoned lignite mines are restricted to surface damage. Although there is no doubt that some damage in the form of roof collapse and pillar failure may take place underground, it is very difficult to observe those damage due to the limitation of access to abandoned workings. The local authorities (Yamoto Town) identified 28 locations where the surface damage was observed. The damages were in the form of caving (sink-hole) and water discharge. Figures 6 and 7 show some examples of damage observed. Some of water discharge was associated with sand and silty soil boiling as seen in Figure 6. Although some reports associated with this sand-boiling phenomenon with liquefaction of subsoil, it is quite difficult to contemplate such a phenomenon of the ground, which generally consists rocky layers. Some soil sampling was done at the location shown in Figure 6 and their grain-size distributions were determined as shown in Figure 8. The grain-size distributions of soil samples fall within the liquefiable soil limits. The same figure also shows the grain-size distributions of overlaying weakly cemented sandstone layer just above the lignite seam. The grain-size distributions of boiled sand and sandstone layer are remarkably similar to each other. This simply implies that the sand accumulated on the floor of the abandoned lignite workings due to collapse of the overlaying sandstone layer may be ejected to ground surface during the sloshing of the ground water in the abandoned-lignite mines as a result of ground shaking caused by the earthquake. The local people showed that some wells adjacent to damaged locations had very high water level, implying that the abandoned-mine workings are fully submerged with ground water. Furthermore, it is reported that the water discharge from caving locations continued for a considerable period of time. This also imply that the motion of the ground water may breach submerged abandoned mining workings at higher elevations and flow towards the abandoned mine workings at lower elevations since such events generally took place at locations with lower elevations.

A peculiar liquefaction phenomenon was observed at the site shown in Figure 6. The liquefied ground at a rice-paddy over the abandoned-lignite mine workings looked like a do-nut. The local authorities informed that the pillar at abandoned-lignite mines had a square shape with a side length of 1.5-2m. The shaking table tests on room & pillar mines by the author indicated that the shaking was higher on the ground surface above pillars than the ground surface above the openings (Aydan et al. 2003). Therefore, the local differences in the shaking characteristics of the ground surface may play some roles on the peculiar form of ground liquefaction.

A peculiar settlement of filled sinkhole with a diameter of 2.5m occurred on a road in Komatsu-danchi, which is a bed-town for people working in Sendai City and it was filled with 120 tons of a mixture of sand and gravel (Figure 9). The filling material in the sinkhole was settled due to an aftershock with a magnitude of 3.6 at 22:54 on September 4. This aftershock was very close to the site and the maximum acceleration at Ishinomaki of K-Net strong motion network, which is 11 km away from the epicenter, was 48.5gal. Although the aftershock was small, very high ground accelerations observed during this small aftershock.

## 5. PHYSICAL AND MECHANICAL PROPERTIES OF IN-SITU ROCKS

Some chunks of in-situ rocks in the vicinity of damaged site were collected. Some samples were prepared in the form of prismatic blocks having a height/width ratio of 2. Some physical and mechanical properties of rock samples are listed in Table 3 and typical uniaxial compression strain-stress relations are shown in Figure 10. While lignite and loam samples show a brittle behaviour, sandstone, siltstone and claystone samples exhibit an elastic-perfectly plastic behaviour for a great range of uniaxial strain. The uniaxial compressive strength ($\sigma_c$) of rocks is remarkably low. This was thought to be weathering of rocks since rock blocks collected were on the ground surface being subjected to atmospheric conditions for a considerable period of time. Figure 11 compares the needle penetration index (NPI) versus uniaxial strength of Yamoto rocks together with other soft rock samples from different parts of the world.

**Figure 6:** Caving and sand boiling in the area of Yamoto-town caused by the earthquake

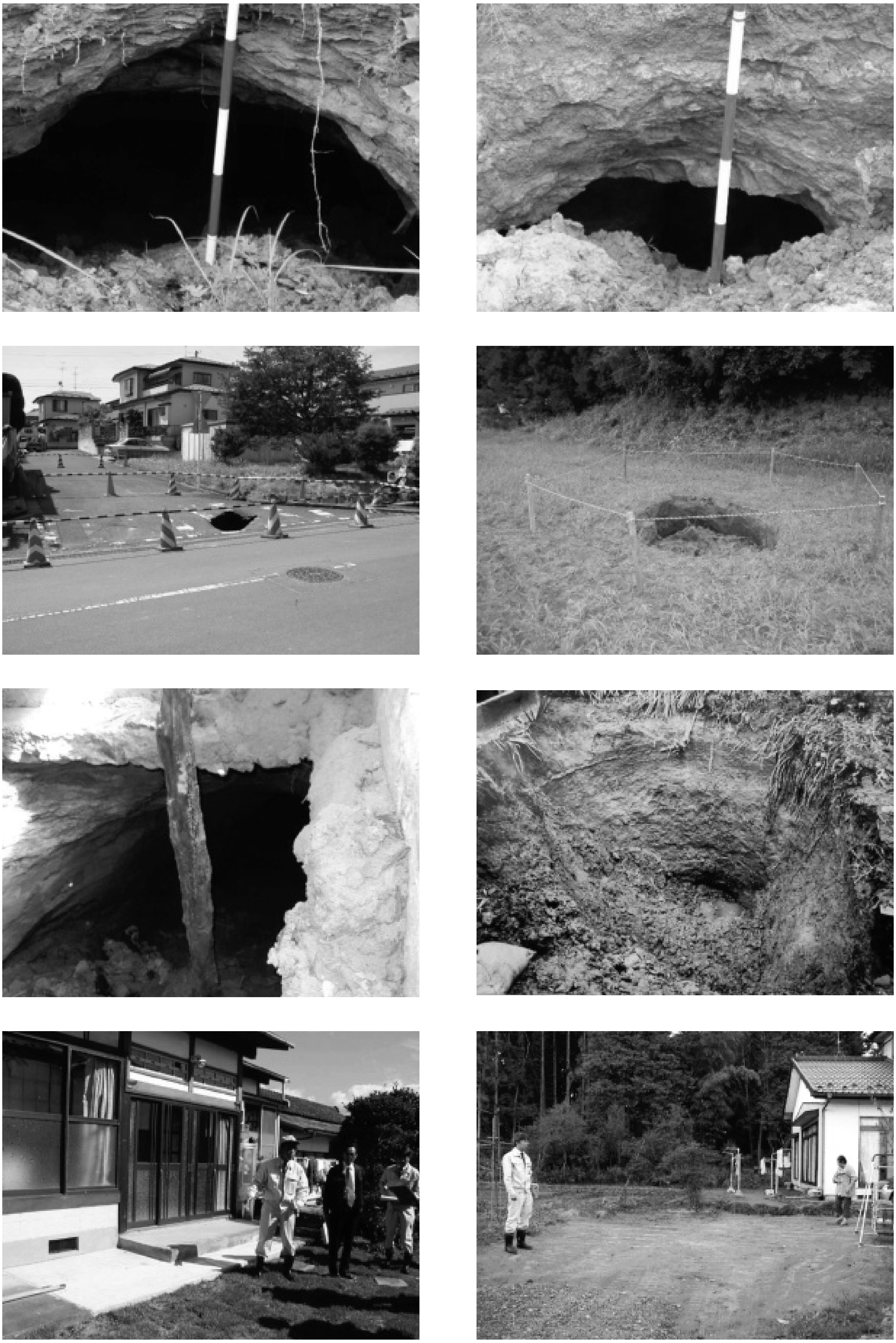


**Figure 7:** Caving and restoration

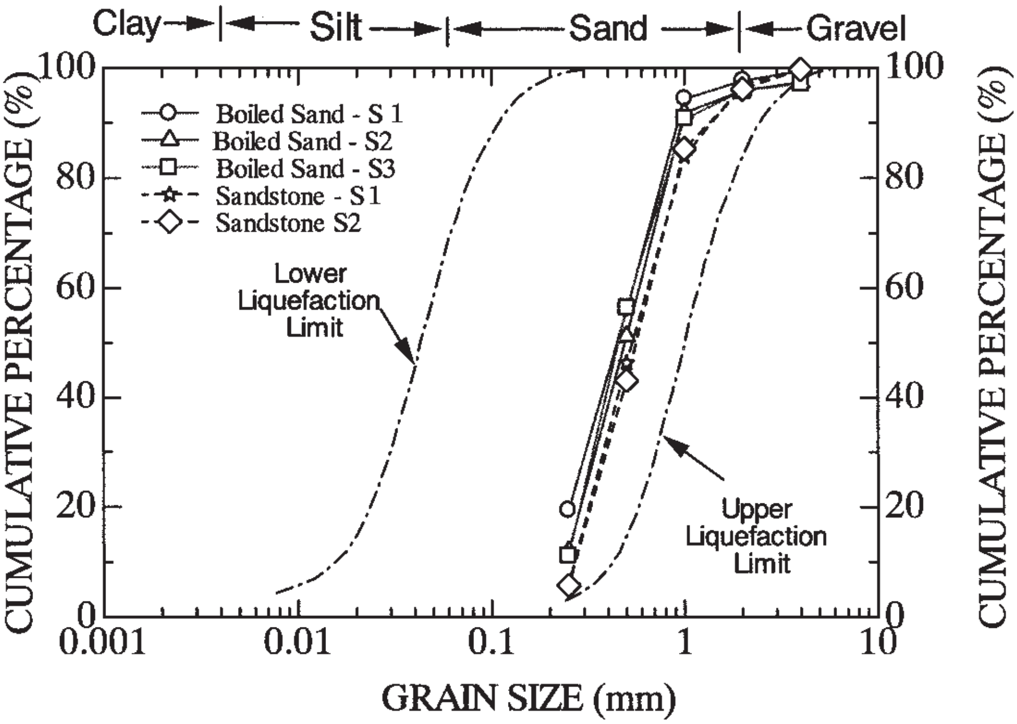



**Figure 8:** Grain-size distribution of boiled sand and sandstone at location No17.

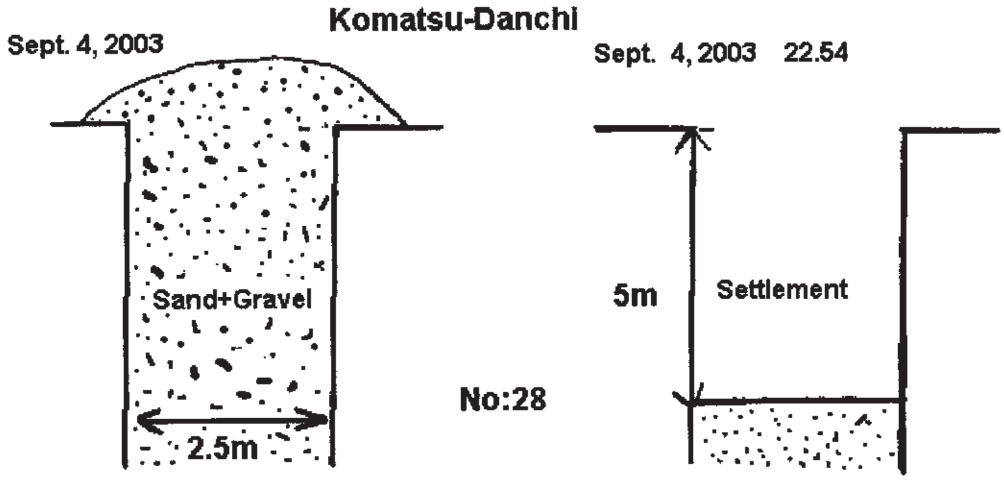



**Figure 9:** An illustration of the settlement of the filling material in a sinkhole

**Table 3:** Physical and mechanical properties of rocks from Yamoto area

| Sample No. | Unit weight [kN/m³] | Wave Velocity [m/s] | Uniaxial Compressive strength $\sigma_c$ [kPa] | NPI [kN/mm] |
|---|---|---|---|---|
| Sandstone | 15.8-16.9 | 480-783 | 9.4-11.5 | 0.5-1.2 |
| Loam | 15.5-16.6 | 965-1453 | 143-230 | 2.1-3.0 |
| Sandy claystone | 16.1-17.9 | 1111-1339 | 33-50 | 0.9-1.0 |
| Siltstone | 14.1-15.9 | 641-1007 | 24-67 | 1.6-2.8 |
| Atan (lignite) No.5 | 13.2-16.3 | 556-1224 | 89-198 | 1.8-4.2 |
| Atan (lignite)-No.17 | 14.2-15.3 | 693-1344 | 173-259 | 2.0-4.0 |

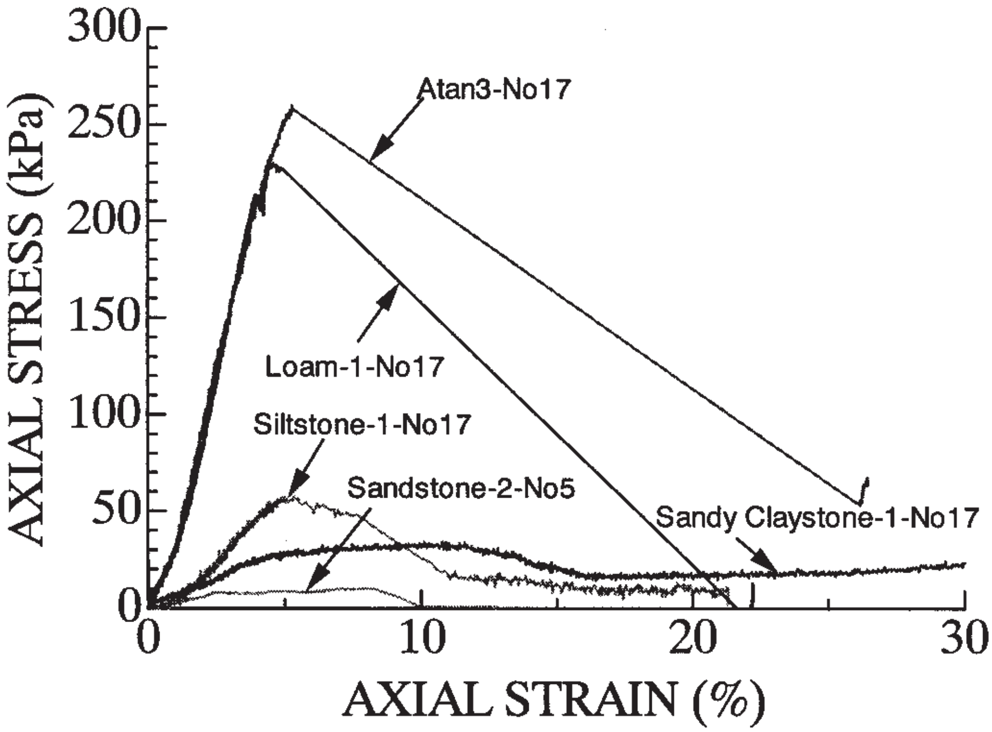



**Figure 10:** Typical uniaxial compression strain-stress relations for each rock group

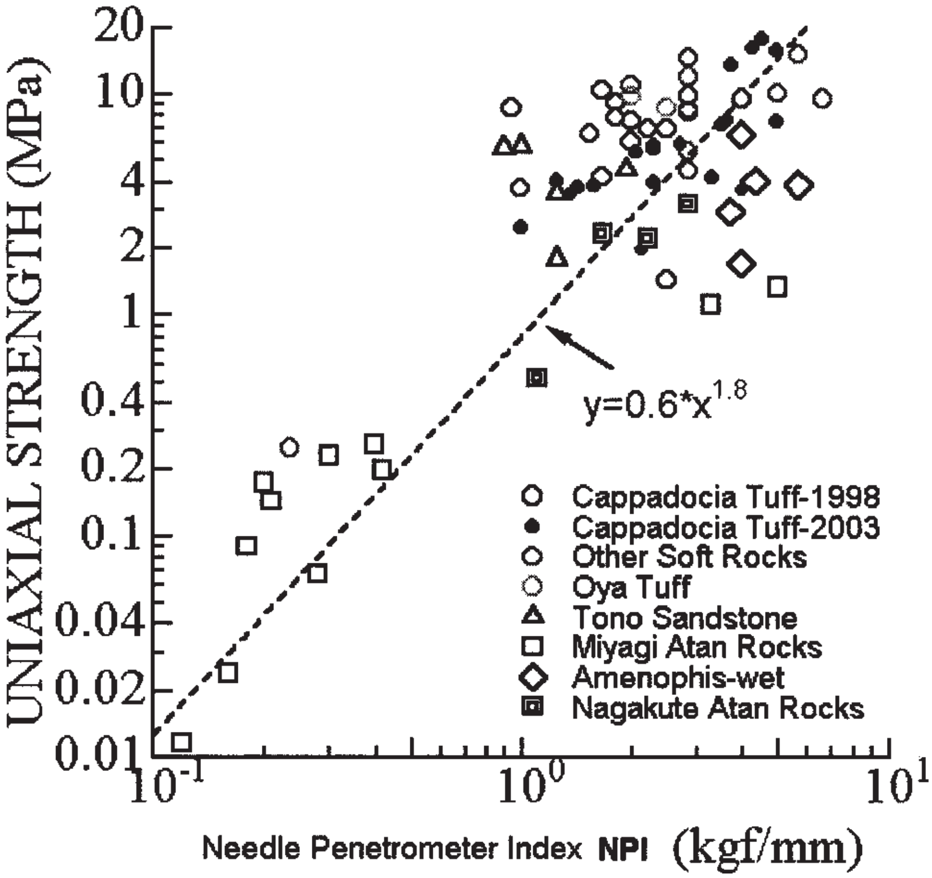



**Figure 11:** Needle-penetration index versus uniaxial strength of Yamoto rocks

## 6. MODEL TESTS ON POSSIBLE CAUSES OF DAMAGE

Several model tests were performed in order to understand the possible causes of damage observed in abandoned lignite mines around Yamoto town. The tests were carried out on a shaking table and concerned with water discharge from the abandoned mines and the settlement of a filled shaft due to ground shaking during an aftershock.

### 6.1 Sloshing Models

Since ground-water appeared on the ground surface at several locations in the abandoned lignite mine area soon after the earthquake, two series of model tests having connected openings submerged with water together with vertical and / or inclined shafts were prepared and subjected to horizontal shaking up to 600–900 gals (Figure 12 and Figure 13). In the first series of the model tests, the model underground openings with vertical shafts shown in Figure 12 were prepared. The underground model opening made plastic was placed in a transparent container and the space between the model and the container was filled with dry sand as seen

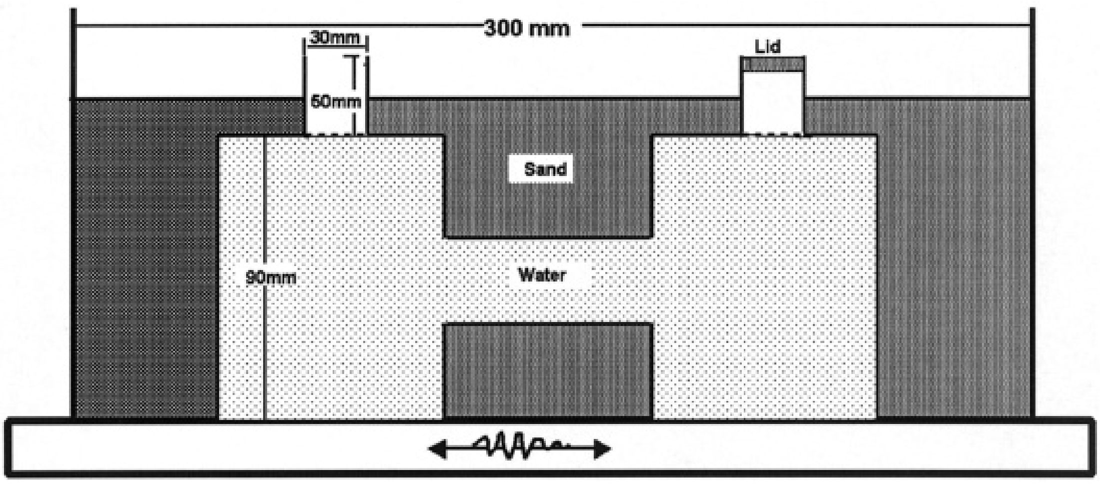



**Figure 12:** Sloshing (splashing) test model

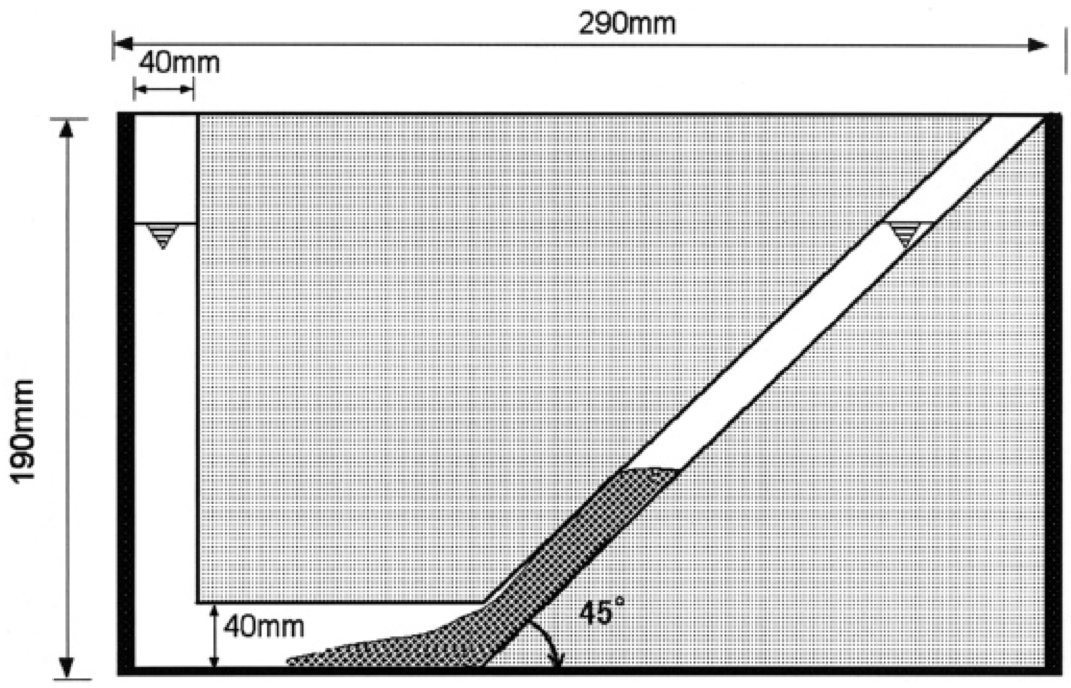
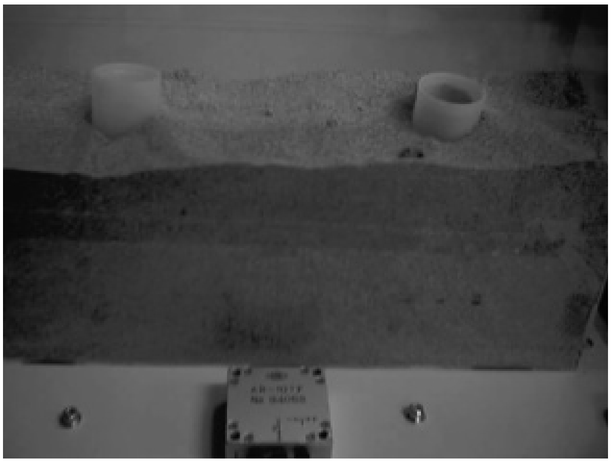
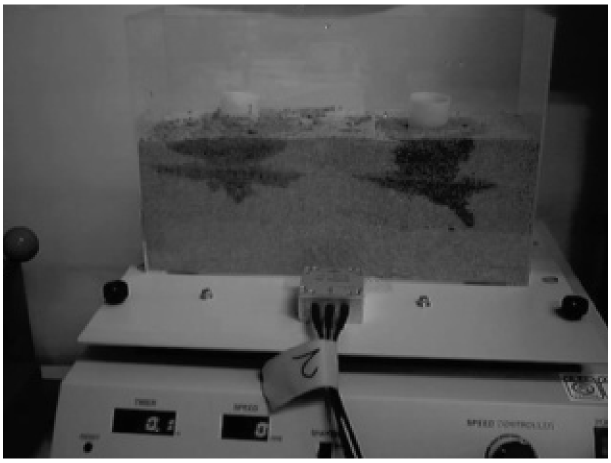



**Figure 13:** Model for blockage breach by sloshing (splashing)

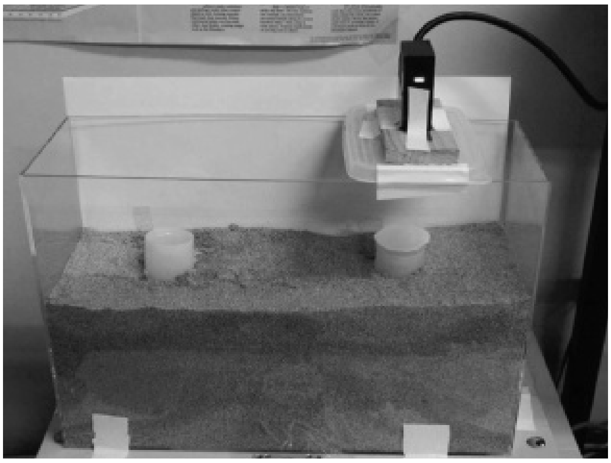


(a) Model before shaking

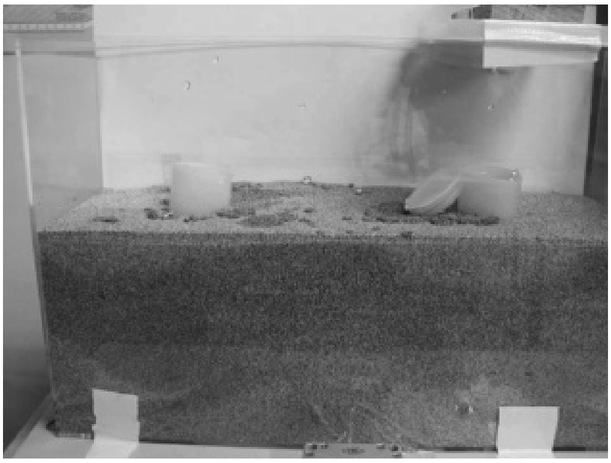


(b) Model after shaking

**Figure 14:** Views of the model preparation and after shaking in the first sloshing experiment



(a) Model before shaking



(b) Model after shaking

**Figure 15:** Views of the second experiment and instrumentation before and after shaking

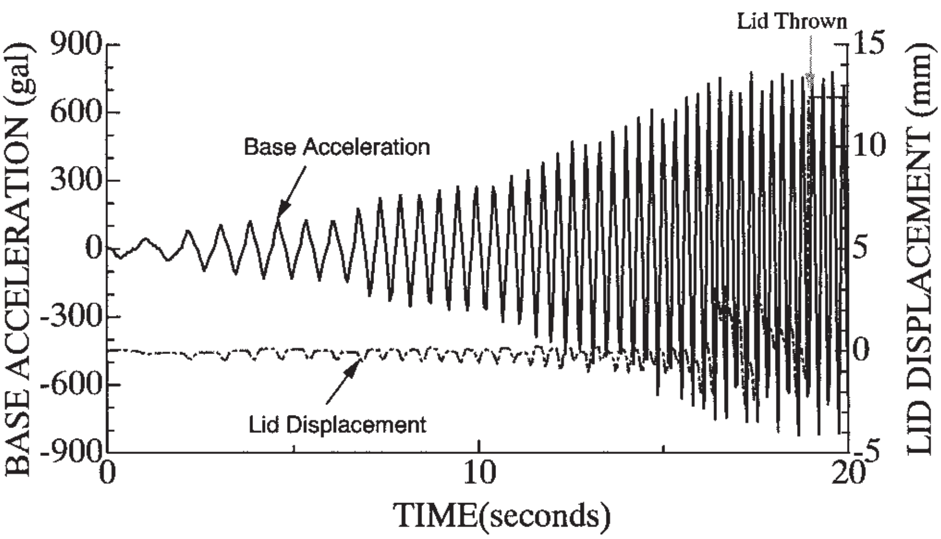
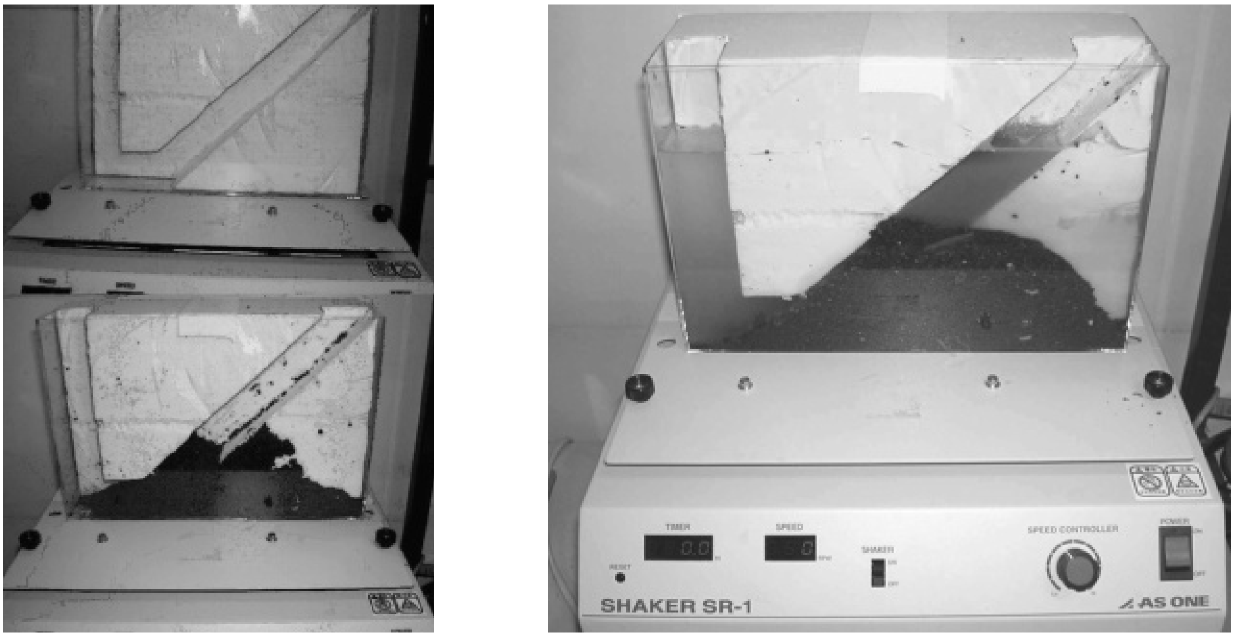
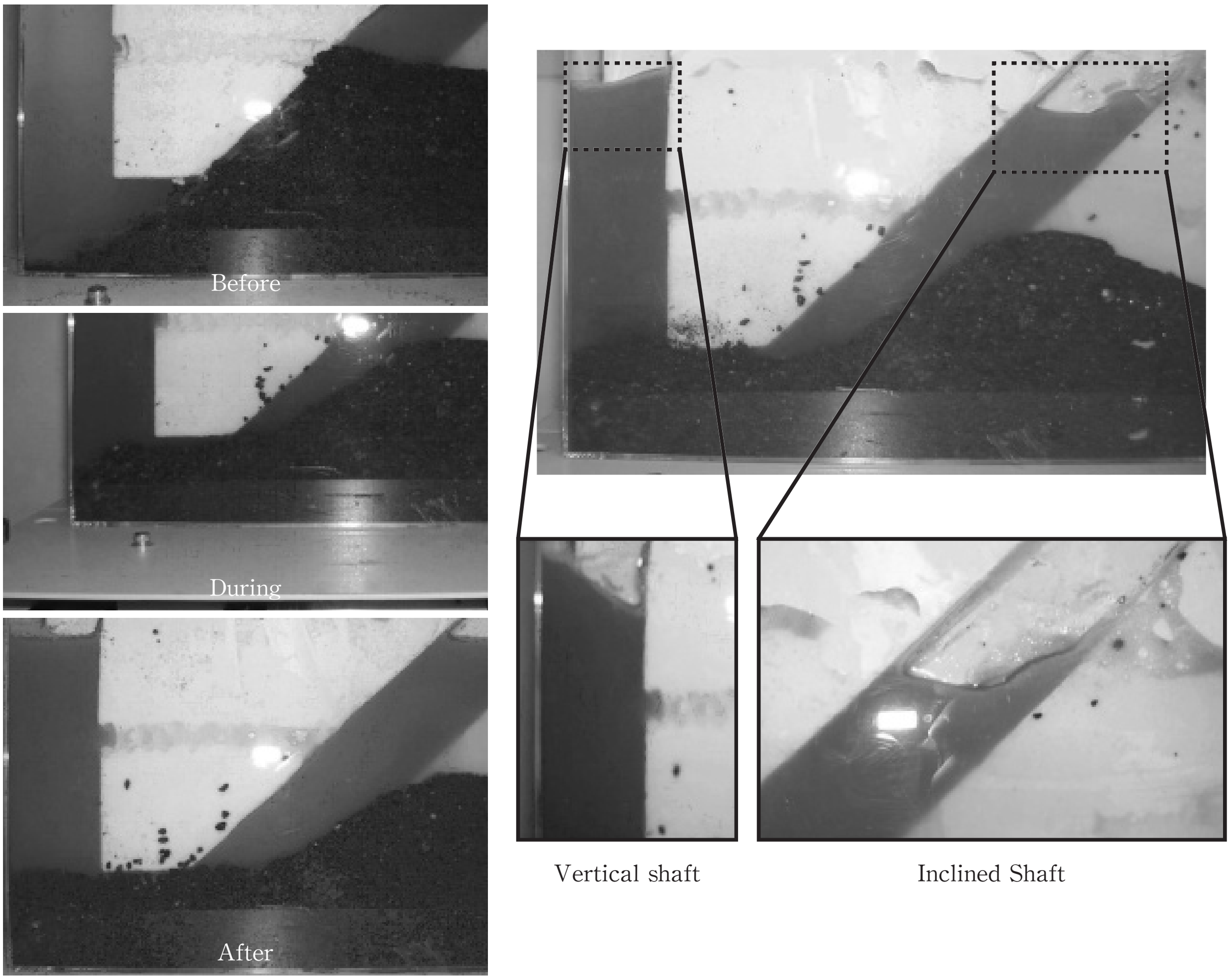



**Figure 16:** Measured base acceleration and the vertical displacement of the lid




(a) Views of model test on blockage breach before shaking




(b) Views of model test on blockage breach during and after shaking

**Figure 17:** Views of the model test on blockage breach before, during and after shaking

in Figure 14(a). The shaking was horizontal. In the first experiment, no instrumentation was used and the main aim was to see if sloshing phenomenon could occur or not. Figure 14(b) shows a view of the model after shaking. The experiment clearly indicated that sloshing phenomenon did take place and ground water was ejected to the ground surface through the vertical shafts.

Then the second experiment was designed to measure applied acceleration on the model. In addition, one of the vertical shaft had a lid and the motion of the lid was also measured during shaking (Figure 15). Figure 16 shows the base acceleration and vertical displacement of the lid. The motion of the lid starts when the base acceleration exceeds 300 gals and the lid was thrown by sloshing ground water in the vertical shaft when the acceleration level was about 900 gals. Figure 17(b) shows a view of the model after the shaking. Therefore, it can be firmly said that one of the causes of the appearance of the ground water nearby damaged areas is the sloshing (splashing) of ground water in submerged abandoned lignite mines.

The second series of experiments was concerned with the breach of the blockage of the fallen material in the underground opening (Figure 13). Figures 17 shows several views of the model before, during and after shaking. The experiment clearly showed that the motion of ground water can breach the blockage in the opening. This may imply that the ground water will appear on the ground surface at abandoned mines at lower elevations when the blockage in the abandoned mines with higher elevations having higher ground water table is breached.

### 6.2 Settlement of A Filled Sink-hole

This section describes a model test on a peculiar settlement phenomenon of the filling material in a sink-hole in an abandoned lignite mining site. Sandy gravel was used as filling material to represent the filling material used on the site. The friction angle of gravel is about 33-36°. Its repose angle is almost the same as the friction angle. Figure 18 shows the Mohr-Coulomb yield function for this material. The model consists of a vertical sinkhole and horizontal opening with a cross section of 3×3 $cm^2$. The sinkhole was 6cm deep. The repose angles ranged between 33-38° after the filling process was completed as seen in Figure 19.

To obtain the acceleration at the base of the model, the displacement response was measured using laser displacement transducers. Then, displacement responses were numerically derivated to obtain the acceleration response. Another laser displacement transducer was used to measure the settlement of the filling material in the sinkhole during the test. The displacement records were logged and stored using a lap-top computer.

The model was subjected to shaking after the filling and set-up of the instrumentation. Figure 19 shows a view of the model after shaking. As noted from the figure, the filling material settled and flowed into opening. The settlement was almost the half of the sinkhole depth. Furthermore, the fine sand used for marking purposes flowed along a curved path. The final slope of the spreaded filling material was about 18-20°. The slope

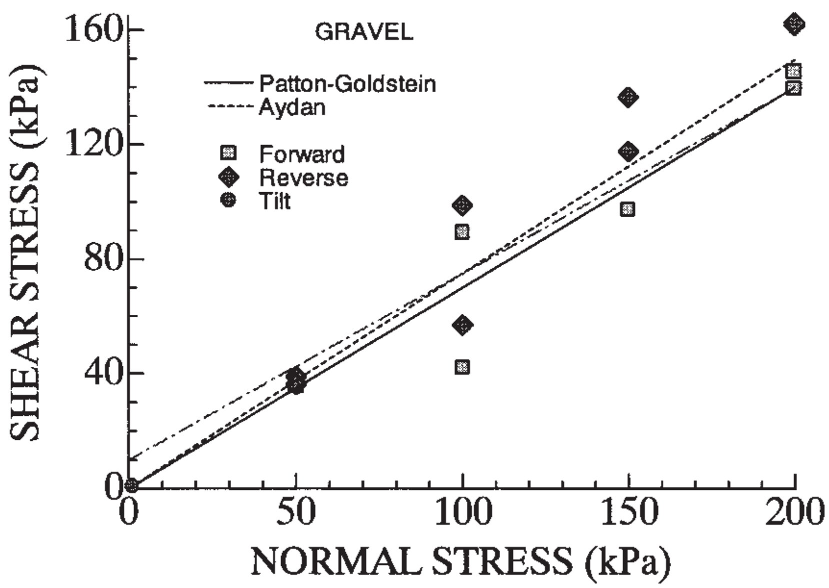
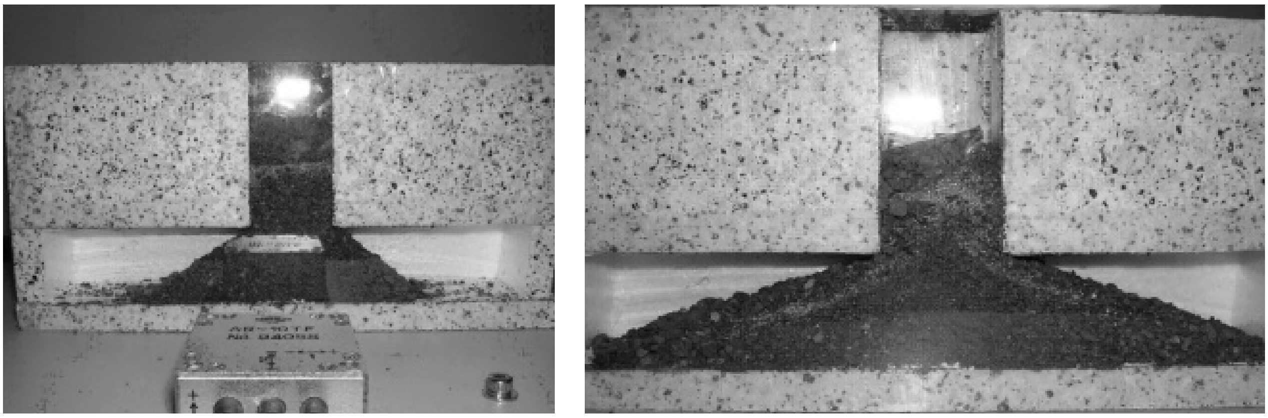



**Figure 18:** Mohr-Coulomb yield function for sandy-gravel



(a) Model before shaking (b) Model after shaking

**Figure 19:** Views of the model before and after the shaking test

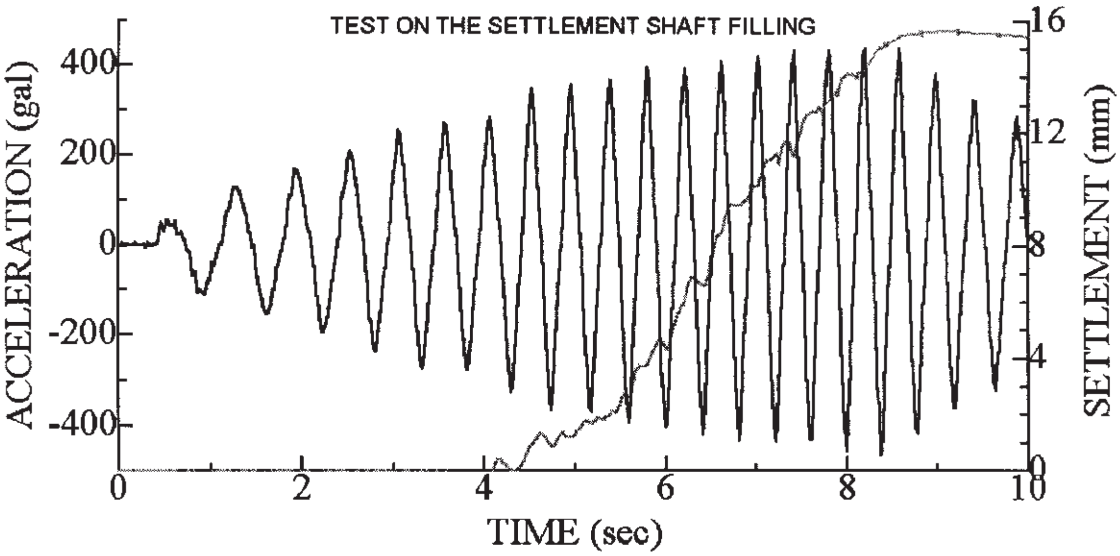



**Figure 20:** Measured base acceleration and the settlement of the filling material

angle seems to be in accordance with the stable slope angle for the applied maximum amplitude of the base acceleration.

Figure 20 shows the measured base acceleration and settlement response of the filled sinkhole. Due to some reflection problems, the laser displacement transducer at some intervals could not measure properly the settlement response. Nevertheless, the measured responses are sufficient to illustrate the overall behaviour of the filling material during shaking. Furthermore, the settlement was initiated when the acceleration was greater than 325gal. The observed behaviour of the filling material was quite similar to the observations at the actual site and can explain the physical background of the settlement problem. The amount of the settlement of the filling material depends upon the frictional properties of filling material, the maximum ground acceleration and its duration as well as the geometry of sinkhole and the size of openings associated with the sinkhole.

## 8. CONCLUSIONS

Miyagi-hokubu earthquake on July 26, 2003 caused damage to structures and collapses of abandoned mines and water discharge in Yamoto area 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 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 boiling from the abandoned mines were 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 was ejected, it was the sand which accumulated at the bottom of mine adits and were ejected to ground surface through vertical and inclined shafts or collapsed openings connected to ground surface.

## ACKNOWLEDGEMENTS

The author would like to Emeritus Prof. Dr. T. Kawamoto, who is presently the chairman of Japan Grouting Society for giving the chance to the author to participate in the reconnaisance trip to Yamoto on the behalf of Japan Grouting Society and local authorities of Yamoto-town and Economics and Industry Department of Sendai City for providing first-hand information on some of pictures on the damaged areas in the close vicinity of Yamoto-town.

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## 要　旨

2003年７月26日宮城北部連続地震による亜炭採掘跡地における陥没被害とその要因に関する考察

アイダン・オメル
海洋土木工学科

2003年７月26日０時13分頃のM5.5の地震から始まって，震度５弱〜６強の地震が連続して宮城県北部地方（主に宮城県鳴瀬町，矢本町，鹿島台町，南郷町，河南町の５町を中心とした地域）に発生した．この地震は典型的な内陸直下型地震であり，しかも震度６弱以上の地震が一日の間に３回発生したという特異なケースである．被害の点でも５月26日に発生した宮城県沖地震を大幅に上回るものであった．　筆者が特に注目したのは，矢本町小松地区で民家内や水田で噴砂跡が見られたと陥没である．更に東北経済産業局から得られた情報により，亜炭採掘跡に関連して発生した陥没被害が矢本町だけで28ヶ所，河南町２ヶ所，松山町１ヶ所に及んだことが判明した．日本充てん協会の調査団のメンバーとして，宮城県北部地震による亜炭採掘地域の地盤変状の実態を調査・検討するため，2003年10月７日に宮城県矢本町における一部の陥没地および噴砂の現場調査と，関係亜炭鉱業の資料収集を行った．本論分で入手した地質・地震および災害速報や，現地での聞取り調査，記録写真等をとりまとめ，さらに調査結果の検討・考察と模型実験を行い陥没や噴砂現象の要因について考察した．

陥没被害は32ヶ所に及び，池の内，上前柳，鷹の池，堰の内および館前などの数カ所に分かれて集中的に分布している．特に目立つのは鷹の池から堰の内の西部を挟み，更に池の内へかけて，北北西〜南南東に伸びる線に沿って断続しながら18ヶ所で陥没が発生していることである．陥没部は大部分深度2m以下のもので，採掘跡の空洞も地下の比較的浅い所に存在した可能性が大きい．陥没部が断続して分布する北北西〜南南東の方向はほぼ亜炭層の走向と一致し，この方向は，旭山撓曲の方向と平行に近い．

低地で地震直後に庭の作業小屋の隅から大量の水が噴出し巨大な穴が発生し，地下水が一時は高さ2m以上まで上がり，約10分間にわたって噴出して大量の土砂が周囲に堆積したと報告されている．また，別な位置で陥没に伴って砂が噴出し，砂は家屋内および軒先から庭にかけて散乱していた．

陥没の原因としては，亜炭空洞の天盤の崩壊が直接原因であるが，空洞内の地下水の水圧変化は考えられるが，土被り約2mという浅所では，地下水が高い被圧を受けていたとは考えられない．崩壊に伴って大量の砂が噴出したことは，地震により地下水が大きく揺れてスロシング（sloshing）現象が起きたことを示唆するように思われる．これらの現象の可能性を検証するため，振動台を用いて亜炭廃坑の模型実験を実施した．振動によってスロシング現象が発生することと坑内の地下水が地表面に噴出されることが明確になった．斜坑内が堆積物で封鎖されていると考えて行った模型実験で振動によって封鎖していた堆積物が崩壊し，スロシング現象が発生すること明確になった．

矢本町小松台における通用路で直径2.5mの土砂で充てんされた陥没がM3.6の余震でその充てん土砂は5m分の沈下し，その沈下現象の機構は模型実験を用いて明らかにした．

本論分の内容は亜炭採掘跡地空洞の地震に対する挙動や耐震性の評価に資することである．