CHARACTERISTICS AND AMPLIFICATION OF GROUND MOTIONS ABOVE ABANDONED MINES

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ABSTRACT: The authors have been involved with the research on the short and long-term stability of ground above these abandoned mines. In this article, they present the outcomes of their studies on the dynamic characteristics of ground and amplification of ground motions above abandoned mines exploited by room and pillar technique and long-wall mining technique, and discuss their implications. In addition to excavation ratio, depth and geomechanical properties of ground, it is shown that topographic effects may also play important role on ground motions in areas with abandoned mines.

Key Words: Dynamic characteristics, amplification, ground motion, earthquake, abandoned mines

INTRODUCTION

There are many abandoned mines in various parts of Japan and the recent earthquakes showed these mines are quite vulnerable to cause sinkholes and subsidences (Aydan and Tano, 2012a,b). Therefore, there is a growing concern on the safety of areas above such abandoned mines in relation to the anticipated Nankai-Tonankai-Tokai earthquake. Unfortunately, the present seismic risk assessment of Japan does not consider the effect of abandoned mines on ground motions in such areas. The authors have been carrying out researches on the short and long-term stability of ground above these abandoned mines.

There are almost no studies on the dynamic characteristics of ground and amplification of ground motions induced by earthquakes above abandoned mines exploited by room and pillar technique as well as long-wall mining techniques except those by the authors. In this article, the authors present the outcomes of their studies on the dynamic characteristics of ground and amplification of ground motions above abandoned mines and discuss their implications. In addition to the effects of some parameters associated with extraction, some topographic effects on ground motions in areas with abandoned mines are also investigated and results are presented.
CHARACTERISTICS OF ABANDONED COAL AND LIGNITE MINES

The shallow lignite seams are commonly exploited using the room and pillar technique as illustrated in Figures 1(a) together with possible modes of failure. The extraction ratio of lignite seam is generally in the order of 60-80%. Pillars of lignite support roof layers.

The long-wall technique was employed for exploiting the coal/lignite seams as illustrated Figure 2(a). As illustrated in Figure 2(b), The overburden ground would subside into the excavated space following the extraction of coal/lignite seams. Depending upon backfilling state, the overall subsidence would be a fraction of the total height of extraction (Aydan 1994). For longwall mining operations in Japan, Hiramatsu et al. (1979) reports that the overall subsidence would be 70 to 90 percent of the total extraction height due to bulking of the broken overburden layers when no backfilling is employed. However, the broken overburden layers or goaf (gob) might further subside in long-term due to creep, degradation and vibration resulting from earthquakes or other sources. It should be also noted that the geomechanical characteristics of the goaf would be different from the original unbroken ground.

Fig. 1 Illustration of room and pillar method and likely instability modes (Aydan and Tano 2012b)

(a) Room and Pillar Method  (b) Sinkhole due to roof failure
(c) Settlement due to pillar failure

Fig. 2 Illustration of longwall mining method and ground subsidence (Aydan and Tano 2012b)

(a) Longwall Mining Method  (b) Settlement due to extraction of seam
AYDAN ET AL. (2004, 2013) PERFORMED SOME MODEL EXPERIMENTS TO INVESTIGATE THE DYNAMIC CHARACTERISTICS AND AMPLIFICATION OF GROUND MOTIONS USING A SHAKING TABLE. IN THOSE EXPERIMENTS, THE EFFECTS OF EXCAVATION RATIO, DEPTH AND OVERBURDEN THE DYNAMIC CHARACTERISTICS AND AMPLIFICATION OF GROUND MOTIONS AT GROUND SURFACE WERE INVESTIGATED. HOWEVER, IT IS VERY DIFFICULT TO INVESTIGATE THE EFFECTS TOPOGRAPHY AND COMPLEX EARTHQUAKE ACCELERATION IS SUCH MODEL EXPERIMENTS. IN THIS SECTION, THE AUTHORS UTILIZED SOME NUMERICAL TECHNIQUES TO INVESTIGATE THE EFFECT OF DEPTH, LAYER INCLINATION AND TOPOGRAPHIC EFFECTS.

**One-dimensional Shear Layer Modeling of a Mine with Flat Ground**

Aydan et al. (2004, 2007) also developed a shear layer model utilizing the tributary area concept for assessing the shaking characteristics of ground above abandoned lignite mines. The lignite mine was assumed to be 2m thick with excavation ratio of 50%. Table 1 gives the properties of materials used in the finite element analyses. Figure 3(a) shows the acceleration response at ground surface for sinusoidal shaking with various periods. The largest amplification occurs when the period of ground shaking coincides with the natural period of the domain, as expected. Figure 3(b) shows the maximum ground displacement response with respect to the base with a wave period of 0.5s. As expected, large relative displacement occurs at the level of extracted lignite seam. The amplitude of the amplification entirely depends upon the viscous properties of layers and frequency characteristics of the ground motions.

<table>
<thead>
<tr>
<th>Layers</th>
<th>$\rho$ (m/s$^2$)</th>
<th>$\eta$ (m$^2$/s)</th>
<th>$b$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1 (30-40m)</td>
<td>320</td>
<td>32</td>
<td>10</td>
</tr>
<tr>
<td>Layer 2 (28-30m)</td>
<td>160</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Layer 3 (0-28)</td>
<td>320</td>
<td>32</td>
<td>10</td>
</tr>
</tbody>
</table>

Fig. 3. The acceleration response at ground surface and maximum displacement response of lignite pillars

The same numerical model was used to assess the shaking characteristics of ground above the abandoned mine located at a depth of 16 m in Mitake town for an exploitation ratio of 70%. Results are shown in Fig. 4 for the abandoned lignite subjected to the base acceleration obtained according to the method proposed by Sugito (2000) for the anticipated M9 Nankai-Tonankai-Tokai earthquake. The material properties used in the analyses are given in Table 2. The maximum amplitude of the base
acceleration is about 250 gals. The ground motions are amplified up to 3.7 times at the ground surface. This implies that the ground motions above the abandoned lignite mines can reach very high level of shaking, which may be critical for surface structures.

![Graph showing acceleration response at ground surface and lignite seam](image)

**Table 2. Parameters used finite element analyses.**

<table>
<thead>
<tr>
<th>Layers</th>
<th>$(G/\rho)^{1/2}$ (m/s)</th>
<th>$\eta/\rho$ (m$^2$/s)</th>
<th>$(b/\rho)$ (m/s$^2$)</th>
</tr>
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<tr>
<td>Layer 1 (36-31m)</td>
<td>900</td>
<td>45</td>
<td>19</td>
</tr>
<tr>
<td>Layer 2 (18-31m)</td>
<td>600</td>
<td>30</td>
<td>19</td>
</tr>
<tr>
<td>Layer 3 (16-18)</td>
<td>400</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>Layer 4 (5-16m)</td>
<td>500</td>
<td>25</td>
<td>19</td>
</tr>
<tr>
<td>Layer 5 (0-5)</td>
<td>300</td>
<td>15</td>
<td>19</td>
</tr>
</tbody>
</table>

**Three-dimensional Analyses of Mine with Flat Ground and Inclined Lignite Seam**

The dynamic response of an actual abandoned lignite mine with a flat ground surface and inclined lignite seam in Mitake town was chosen and its dynamic response is analysed using the strong motion due to the M9 anticipated Nankai-Tonankai-Tokai earthquake. The strong motion estimation was obtained according to the method proposed by Sugito et al. (2000). Fig. 5 shows a three-dimensional perspective view of the mine and a cross section. The material properties used in the analyses are given in Table 3. The method is based on the finite difference technique utilizing silent boundary conditions and Rayleigh type damping of 5%. The details of the numerical method can be found in a publication by Geniş and Aydan (2008). Fig. 6 shows the computed ground acceleration at the surface normalized by that of the base at the middle section denoted in Fig. 5. The amplification of the ground motion is about 2.2 times that of the base.

**Table 3. Parameters used numerical analyses.**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Vs (m/s)</th>
<th>$\rho$ (kN/m$^3$)</th>
<th>E (MPa)</th>
<th>Poisson</th>
<th>Damping</th>
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<tr>
<td>Soil</td>
<td>300</td>
<td>19</td>
<td>270</td>
<td>0.35</td>
<td>5</td>
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<tr>
<td>Mst-Sst</td>
<td>500</td>
<td>19</td>
<td>750</td>
<td>0.30</td>
<td>5</td>
</tr>
<tr>
<td>Lignite</td>
<td>400</td>
<td>14</td>
<td>400</td>
<td>0.30</td>
<td>5</td>
</tr>
<tr>
<td>Mst-Sst</td>
<td>600</td>
<td>19</td>
<td>1073</td>
<td>0.30</td>
<td>5</td>
</tr>
<tr>
<td>Chert</td>
<td>1000</td>
<td>19</td>
<td>3647</td>
<td>0.30</td>
<td>5</td>
</tr>
</tbody>
</table>
Three-dimensional Analyses of Abandoned Mine with Flat Ground Adjacent to Cliff

The dynamic response of abandoned lignite mine is chosen as an actual example and its dynamic response is analysed. Figure 7 shows a three-dimensional perspective view, geometry and geology of the abandoned mine. The material properties used in the analyses are given in Table 4. The input ground motion is first assumed to be sinusoidal with a chosen period. Figure 8(a) shows the selected points of observation. The acceleration responses of the selected points are shown in Fig. (b). The method is based on the finite difference technique utilizing silent boundary conditions and Rayleigh type damping was 5%. As noted from the figure, the ground motion is amplified to 3 times at the seam level near the cliff and 5 times at the cliff crest. This example also shows the importance of ground amplification due to topography.

The abandoned mine was subjected to ground shaking due to 2004 Tokaido-oki earthquake (Mj 7.2) (236 km away) and 2005 Komaki earthquake (Mj 4.7) (25 km away). The accelerations recorded at Mino-kamo strong motion station of K-NET as base accelerations. Figs. 9 and 10 show the acceleration responses at the same selected points normalized by the maximum value of the base ground acceleration. Far-distant earthquakes induce larger ground motions in the vicinity of the cliff crest above the abandoned mines compared to those by the near-field earthquakes.
Table 4. Rock material properties used in numerical analyses.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Unit weight (kN/m³)</th>
<th>Elastic modulus (MPa)</th>
<th>Shear modulus (MPa)</th>
<th>Damping Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lignite</td>
<td>20</td>
<td>557</td>
<td>229</td>
<td>5</td>
</tr>
<tr>
<td>sandstone</td>
<td>20</td>
<td>257</td>
<td>103</td>
<td>5</td>
</tr>
<tr>
<td>Mudstone</td>
<td>20</td>
<td>76</td>
<td>30</td>
<td>5</td>
</tr>
</tbody>
</table>

Fig. 7 Mesh, geology and geometry of abandoned lignite mine

(a) Locations

(b) Acceleration responses

Fig. 9 Locations and acceleration responses of selected points

Fig. 9 Acceleration responses of selected points during the 2004 Tokaido-oki earthquake
CHARACTERISTICS AND AMPLIFICATION OF GROUND MOTIONS ABOVE ABANDONED MINES WITH LONGWALL MINING TECHNIQUE

As mentioned in the introduction, long-wall mining is one of the commonly used extraction technique for coal and lignite seams. The ground above the coal seam is forced to fail following the extraction of the coal. The broken rock mass above the mined areas is called goaf or gob and its properties are reduced greatly with respect to virgin ground. There are few reports on the in-situ investigations of the characteristics of the goaf such as by Fujii et al. (2011). The in-situ investigations showed that the reduction of wave velocity of goaf can be between 30% to 65% of the virgin ground. As pointed out by Aydan et al. (2013), there is no report about the possible ground amplifications above the goaf of old mine workings. The authors have been now performing three dimensional ground response analyses for such grounds in addition to preliminary shear layering dynamic analyses. In this article, we just report the results of analyses using the shear layering dynamic analysis method. Analyses were carried out for two ideals situations, namely, virgin ground and ground with goaf with a depth of 30 m, which is relatively shallow (Fig. 11). Material properties are shown in Table 5 and the ground motion was assumed to be due to the M9 anticipated Nankai-Tonankai-Tokai earthquake as used in the previous sections.

Fig. 11 Illustration of ground conditions of old mine workings with longwall mining technique
Fig. 12 shows the computed acceleration responses for ground surface for old mine workings without/with long wall mining. As expected, ground amplification occurs due to free surface even there is no mining. However, the ground amplification on the ground surface above the goaf becomes much larger when it is compared with that of the virgin ground.

Table 5. Parameters used finite element analyses.

<table>
<thead>
<tr>
<th>Layers</th>
<th>$(G/\rho)^{1/2}$ (m/s)</th>
<th>$\eta/\rho$ (m$^2$/s)</th>
<th>$(b/\rho)$ (m/s$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin ground</td>
<td>900</td>
<td>45</td>
<td>25</td>
</tr>
<tr>
<td>Goaf</td>
<td>300</td>
<td>15</td>
<td>18</td>
</tr>
</tbody>
</table>

(a) Acceleration responses for virgin ground (VGA)

(b) Acceleration responses for mined ground (BGA)

Fig. 12. Acceleration response of ground surface for virgin ground and the mine ground
CONCLUSIONS

Although there are many abandoned mines in various parts of Japan and the recent earthquakes showed these mines are quite vulnerable to cause sinkholes and subsidence, the present seismic risk assessment of Japan does not consider the effect of abandoned mines. The outcomes of the numerical studies on the dynamic characteristics of ground above abandoned mines showed that ground amplifications may be quite large on the abandoned mines where extraction is carried out by room and pillar or long-wall mining technique. The ground amplifications may be 3-5 times that at the base. Particularly these amplifications may be quite large particularly near steep cliffs. Furthermore, the frequency content of ground accelerations may have some pronounced effects on ground amplifications when the responses induced by nearby and far distant earthquakes are compared. Further studies on the effect of multiple seam extraction or of new large underground excavations beneath abandoned mines on the ground motions and their amplifications should be carried out.

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REFERENCES


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