*2019 Rock Dynamics Summit– Aydan et al. (eds)
© 2019 Taylor & Francis Group, London, ISBN 978-0-367-34783-3*

The effect of cave-filling of abandoned lignite mines in Tokai Region, Japan against an anticipated mega-earthquake

T.Ito & Ö. Aydan
Department of Civil Engineering, University of the Ryukyus, Okinawa, Japan

K.Sugiura & A. Sakamoto
Tobishima Corporation, Nagoya Branch, Nagoya, Japan

ABSTRACT: There is now a great concern how to deal with potential damage resulting from the collapse of abandoned room and pillar mines in relation to the anticipated Nankai-Tonankai-Tokai mega earthquake. The authors have initiated some analytical, numerical and monitoring studies on stability and performance abandoned cavities as well as their performance before and after back-filling. In this study, the authors present the outcomes of a series of experimental studies on the supporting effect of backfilling on the response and stability of abandoned mines. Furthermore, the authors discuss their implications on backfilling against anticipated mega earthquakes through a series of numerical analyses with the considerations of experiments.

1 INTRODUCTION

The Great East Japan Earthquake with a moment magnitude 9.0 caused gigantic tsunami waves, which destroyed many cities and towns along the shores of Tohoku and Kanto Regions of Japan. Besides the structural damage on ground surface, this earthquake caused the collapses abandoned lignite and coalmines and underground stone quarries and associated damage to super structures at 329 localities (Fig. 1). Similar events occurred in the previous 1978 Off-Miyagi earthquake, 2003 Miyagi-hokubu earthquake and 2008 Iwate-Miyagi intraplate earthquake. There is now a great concern in Japan how to deal with potential damage resulting from the collapse of abandoned room and pillar mines and quarries in relation to the anticipated Nankai-Tonankai-Tokai mega earthquake. The anticipated magnitude would be similar to that of the 2011 Great East Japan earthquake occurred along the Tohoku region of Japan (Fig. 2).

The authors have involved with the performance and responses of abandoned mines in Tokai Region of Japan during earthquakes and have initiated a continuous measurement and monitoring program for investigating the stability and performance of several abandoned room and pillar lignite mine in Mitake town since April 2004. The authors have also been carrying out some monitoring studies on the response of abandoned cavities before and after back-filling. In this study, the authors present the outcomes of a series of experimental studies on the supporting effect of backfilling on the response and stability of abandoned mines and quarries and report the results of a series of numerical analyses.

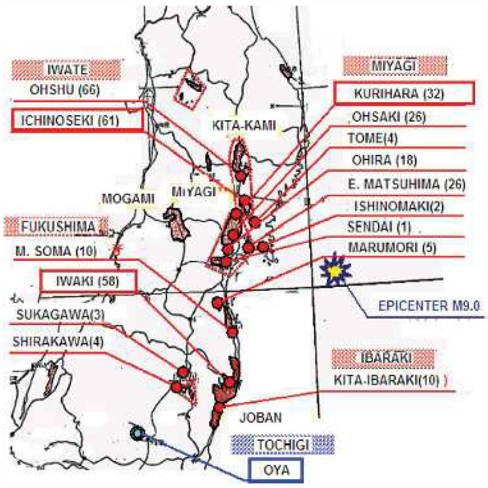


Figure 1. Locations of damage to abandoned mines and quarries after the 2011 Great East Japan Earthquake (from Aydan and Tano, 2012).

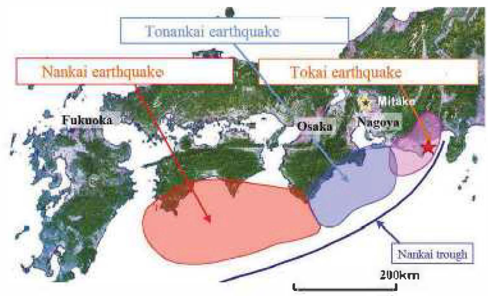


Figure 2. Anticipated M9 Nankani-Tonankai-Tokai earthquake and location of Mitake town.

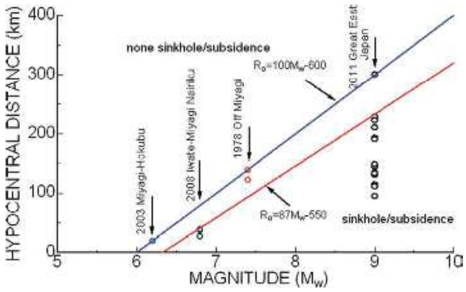


Figure 3. Comparison of case history data with an empirical relations for assessing the possibility of sinkhole/subsidence occurrence as a function of earthquake magnitude (from Aydan and Tano, 2012)

Aydan and Tano (2012) evaluated the seismic vulnerability of abandoned lignite mines with the consideration of the recent earthquakes and they plotted the case history data described in the previous section together with those from other earthquakes occurred in Tohoku region in the space of earthquake moment magnitude versus hypocentral distance of the locality where sinkhole or large subsidence occurred as shown in Fig. 3. The data was fitted to a linear function whose coefficients are shown in the same figure. The line in the figure should be interpreted as a limiting line between surface damage and non-damage on the ground surface. This figure may serve as a guideline to assess the risk of sinkhole or large subsidence due to abandoned mines and quarries exploited using the room and pillar method as a function of earthquake magnitude.

2 GEOLOGY AND CHARACTERISTICS OF ROCKS OF TOKAI REGION

2.1 *Geology*

The geological age of soft rocks associated with lignite deposits differ from location to location. Fig. 4 shows the distribution of lignite deposits in Tokai region. While the age of lignite field within Nakamura unit of Mizunami formation at Mitake belongs to the Miocene era, the lignite field belonging to Yadagawa unit of Seto formation at Nagakute does to Pliocene. Therefore, rocks of Mitake are older than those at Nagakute. There are four lignite seams in Mitake and the second and the third seams were extracted. The thickness of the third seam is 1-3m thick. Although the number of lignite seams at Nagakute is four, the seams are much thinner (less than 1m). Sedimentary rocks at Mitake are broadly classified as lignite, sandstone, siltstone and mudstone with conglomerate layers at the base of the formation above the pre-Tertiary rocks. Although sedimentary rocks of Nagakute can be geologically classified in the same manner, the cementation is poor and sometimes non-cemented sand layers are found below lignite seams. Rock samples were obtained through boring at Mitake town.

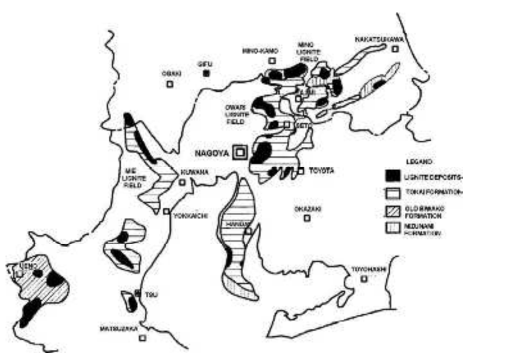


Figure 4. Lignite deposits in Tokai region and locations of sites.

2.2 *Characteristics of Rocks*

Rock samples were obtained from Tokai Region, mainly in Mitake town, Nagakute and Akaike City. Various short term experiments were carried out. Table 1 gives major properties of rocks in Mitake town.

The mechanical properties of soft sedimentary rocks are influenced by the water content. The compressive strength and elastic modulus of soft rocks generally decrease with the increase of water content. During some experiments, electric potential, electrical resistivity, magnetic force, acoustic emission (AE) were measured besides conventional load and displacement. The main purpose of such measurements was to establish some experimental bases for the real-time monitoring of multi-parameters for the stability assessment of an abandoned mine in Mitake (Aydan et al. 2005a,b).

The experiments were mainly carried out by using specially designed creep-loading devices. Fig. 5 shows the responses of sandstone sample measured in one of the creep tests. Fig. 6 shows the long-term strength of rocks of Mitake town together with other rocks.

Table 1. Physical and mechanical properties of soft rocks from Mitake site

Rock	UW (kN/m^3)	UCS (MPa)	EM (GPa)	Vp (km/s)
Lignite	10.6-14.1	4.0-6.0	1.8-1.9	1.6-2.3
Sandstone	16.8-19.2	2.3-7.0	0.3-0.5	1.6-2.7
Mudstone	15.6-16.5	1.0-1.5	0.1-0.3	1.3-1.5

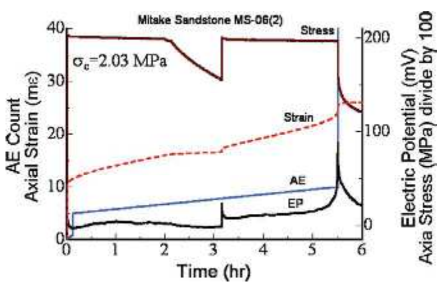


Figure 5. Creep test result on sample MS-06.

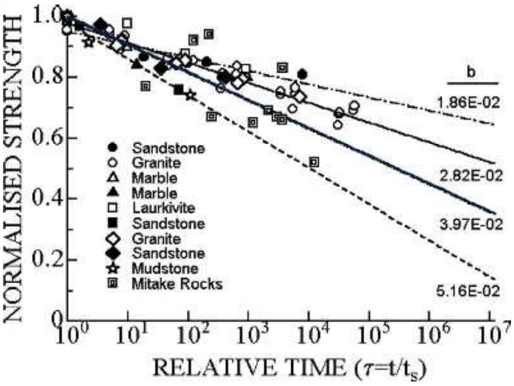


Figure 6. Comparison of normalized long term strength of Mitake soft rocks with other rocks.

Figure 7. Examples of disintegration of soft rocks of Mitake.

2.3 *Degradation of Lignite and Surrounding Rocks*

The surrounding rocks and lignite itself in abandoned lignite mines are sedimentary rocks and very prone to degradation due to cyclic variations of water content during absorption and desorption. Such variations cause flaking of surrounding rocks from roof and pillars of lignite seam and results in the reduction of the support area of pillars and thinning of roof layers. Soft rocks in Mitake exhibit such behavior as seen in Fig. 7. The same phenomenon observed in abandoned mines.

3 EXPERIMENTS ON BACKFILLING OF ABANDONED LIGNITE MINES

Aydan et al. (2013a) have carried out large-scale short-term experiments on lignite samples of abandoned mines of Nagakute and Mitake towns and of Oya tuff under both unfilled and back-filled state using granular backfilling and cohesive backfilling materials (Fig. 8). Cohesive backfilling material is a mixture of clayey and sandy residue from ceramic factories and cement. Experiments were carried out at the age of 28 days with the consideration of hydration process of cement. This backfill material is commonly used in the backfill of abandoned lignite mines in Tokai Region in Japan and it is named as NSK backfilling material. These experiments repeated recently and performed both under static and dynamic conditions. Figs. 9-11 show results of some experiments carried out under static condition. Figs. 9, 10 and 11 compares the average strain

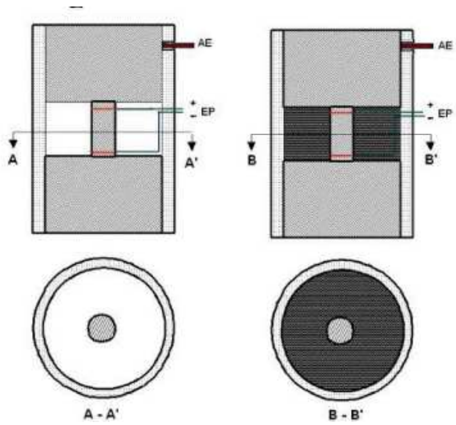


Figure 8. Set-up unfilled and backfilled samples.

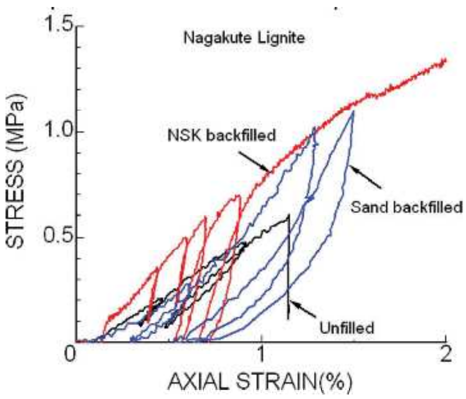


Figure 9. Comparison of strain-stress responses of unfilled pillar, backfilled pillars with granular and cohesive backfill materials during cyclic compression.

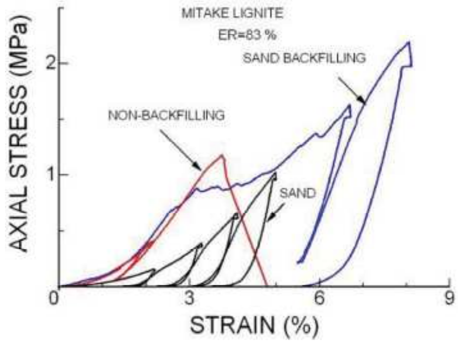


Figure 10. Comparison of strain-stress responses of unfilled pillar, backfilled pillars with granular backfill materials during cyclic compression.

stress relations for unfilled and pillars backfilled with granular and cohesive backfill materials for lignite samples. It is interesting to note that the bearing capacity of backfilled pillars is increased about 1.3-1.5 times compared with that of the unfilled sample at the same strain level. Furthermore, the behavior of backfilled pillars

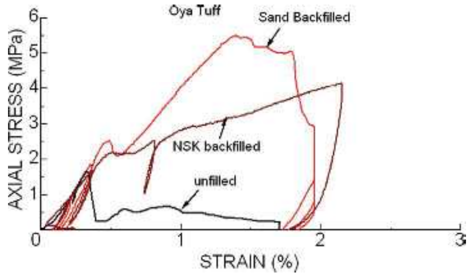


Figure 11. Comparison of strain-stress responses of unfilled pillar, backfilled pillars with granular and cohesive backfill materials during cyclic compression.

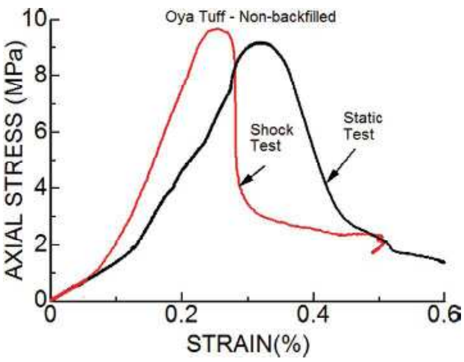


Figure 12. Effect of loading condition on strain-stress responses of the pillars for non-backfilled situation.

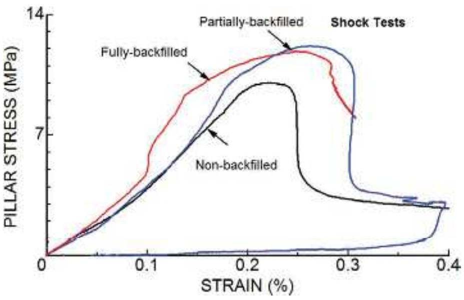


Figure 13. Strain-stress responses of the pillars for different backfilling condition subjected to shock loads

is elasto-plastic without any softening even after the failure of the pillars. Furthermore, the bearing capacity of the backfilled pillars was of great significance. The bearing capacity of the pillar backfilled with NSK backfill material is greater than that of the pillar backfilled with granular backfill material.

Fig. 11 compares the average strain stress relations for unfilled and Oya tuff pillars backfilled with granular and cohesive backfill materials for lignite samples. It is interesting to note that the bearing capacity of backfilled pillars is increased about 1.3-2.5 times compared with that of the unfilled sample at the same strain level. Furthermore, the behavior of backfilled pillars is elasto-plastic without any softening even after the failure of the pillars. The bearing capacity of the pillar backfilled with NSK backfill material is greater than that of the pillar backfilled with granular backfill material.

4 SHOCK TESTS

Aydan et al. (2018) reported a new series of experiments to investigate the response of Oya tuff pillars under three different backfilling state under shock tests. The back-filling situation were the same as those of the second series experiments, which were:

i. Non-backfilled,
ii. Partially-backfilled up to 70% of the pillar height,
iii. Fully backfilled.

The load was imposed as shocks on samples. Fig. 12 compares the response of Oya tuff without backfilling under static and shock loads. As noted from the figure, the overall stiffness and the strength of the pillar sample subjected to shock loading are slightly higher than those of the sample tested under static loading. Furthermore, the residual strength of the sample subjected to shock loading is also slightly higher than that of the sample tested under static condition.

Fig. 13 shows the strain-stress responses of the Oya tuff pillar samples with different degree of backfilling subjected to shock loads. It is also noted that the overall stiffness increases as a function of degree of backfilling similar to those of samples tested under static case.

The acceleration response of samples at the time of failure for non-backfilled and fully-backfilled situations are shown in Fig. 14. As noted from the figures, the accelerations are higher for the non-backfilled sample as compared with that of the fully-backfilled sample. The maximum amplitude of the acceleration is almost four times that of the fully-backfilled sample. Furthermore, the accelerations are not symmetric with respect to time axis as noted previously by Aydan et al. (2011).

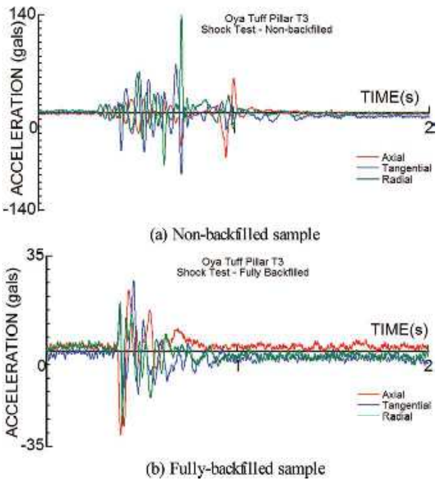


Figure 14. Acceleration responses of the non-backfilled and fully-backfilled samples.

5 ASSESSMENT OF EFFECT OF BACK-FILLING DURING MEGA EARTHQUAKES

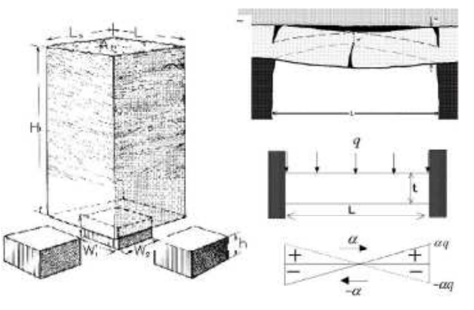
Aydan (Aydan 2017; Aydan et al. (2006, 2011, 2013b) proposed a practical method for evaluating the stability of pillars and roof of abandoned room and pillar lignite mines using the seismic coefficient approach. Fig. 15(a,b) shows the assumed models for the dynamic stability of pillars and roofs. In this approach, the pillar was assumed to fail under the maximum compressive stress. The load condition under horizontal shaking is assumed to consist of gravitational load inducing the bending stresses and linearly varying axial stress along the roof axis from tension to compression due to horizontal shaking. On the basis of this assumption, the seismic coefficient at the time of roof layer failure by bending is obtained. Fig. 16 shows computed diagrams for the relation between overburden ratio and seismic coefficient for various failure modes for the chosen parameters shown in the same figure. These results indicate that the shallow mines are prone to roof failure while the deeper mines are prone to pillar failure for actual strong ground motions during earthquakes.

As shown in Sections 3 and 4, the backfilling drastically increases the resistance of the pillars against collapses. In other words, the resistance of the backfilled abandoned mines is the same as that under unexploited condition, provided that the abandoned mines are fully backfilled. If the abandoned mines are partially backfilled, the resistance of the backfilled abandoned mines against earthquakes would be also partial.

Another approach was also proposed by Aydan et al. (2012) to evaluate the response and stability of abandoned room and pillar mines with the use of dynamic tributary area concept. Fig. 17 shows the basic concept of this method. One can evaluate the safety of pillars subjected to ground shaking due to earthquakes.

Aydan et al. (2012) used this model to evaluate the response of the abandoned mines in Mitake town with the use of ground acceleration due to M9 class anticipated mega earthquake. Fig. 18 shows the acceleration responses of the abandoned mines at ground surface and lignite seam together with the input base acceleration. As noted from the figure, the amplification of the ground acceleration at the ground surface is very high above the abandoned mines and it may be up to 5 times while the amplification at the lignite seam level is 3 times.

Fig. 19 shows the safety factor and shear stress variation at the lignite seam level (19m below the ground surface) for abandoned lignite mines in Mitake town subjected to anticipated base acceleration of the mega earthquake. As noted from the figure, when short term strength is considered the safety factor is about 1.5. On the other hand, the safety factor may be drastically reduced for long-



(a) Pillar (b) Roof

Figure 15. Mathematical models for stability assessment of pillars and roof layers under dynamic conditions

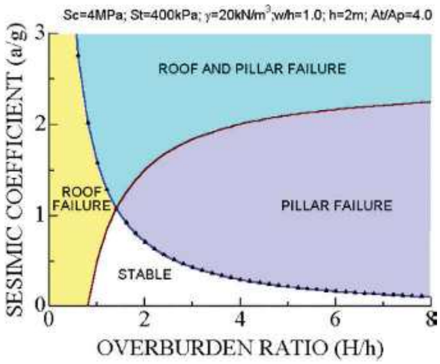


Figure 16. An example of computation for the stability of pillars and roof layers under dynamic conditions.

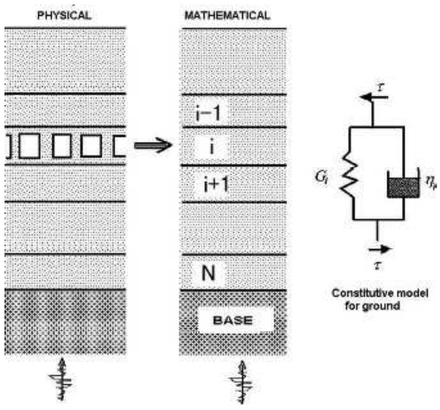


Figure 17. Mathematical model for dynamic response of pillar during earthquakes (from Aydan et al. 2013b).

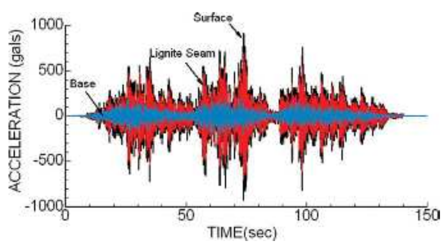


Figure 18. Computed acceleration responses at lignite seam level and ground surface for the anticipated M9 class mega earthquake.

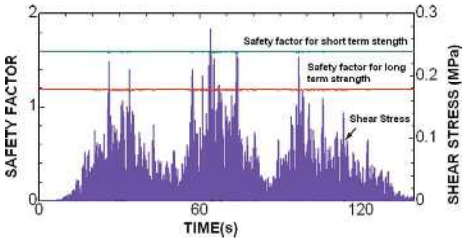


Figure 19. Variation of the safety factor and shear stress at the lignite seam level of the abandoned room and pillar during the mega earthquake shaking.

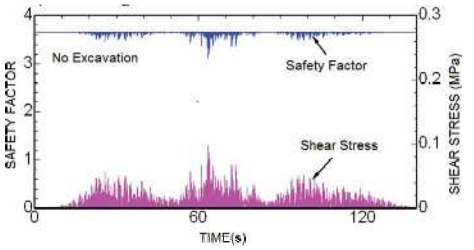


Figure 20. Variation of the safety factor and shear stress at the virgin lignite seam level during the mega earthquake shaking.

term strength of the lignite pillar. As discussed in Sections 3 and 4, the backfilling increases the pillar strength and the ground condition would be quite close to the unexploited state. For such case, the variation of the safety factor would be quite close that under virgin state as shown in Fig. 20. The safety factor of the lignite seam level under backfilled state is expected to be more 3.6.

6 CONCLUSIONS

There are many abandoned mines in various parts of Japan and the recent earthquakes showed these mines are quite vulnerable to the formation of sinkholes and subsidence. Therefore, there is a growing concern on the safety of areas above such abandoned mines in relation to the anticipated Nankai-Tonankai-Tokai earthquake. The authors have been involved with the research on the short and long-term stability of ground above these abandoned mines. In this study, the authors present the results of a series of experimental studies on the supporting effect of backfilling on the response and stability of abandoned mines under static and dynamic situations. Furthermore, the authors discussed their implications on backfilling against anticipated mega earthquakes in view of the experimental and numerical studies. It is shown that the backfilling has a great stabilizing effect on the abandoned room and pillar mines provided that the fully backfilled.

REFERENCES

Aydan, Ö., 2017. Rock Dynamics. CRC Press, Taylor and Francis Group, 462p, ISRM Book Series No. 3, ISBN 9781138032286.

Aydan, Ö., 2004. Damage to abandoned lignite mines induced by 2003 Miyagi-Hokubu earthquakes and some considerations on its possible causes. J. of School of Marine Science and Technology, Vol. 2, No.1, 1-17.

Aydan, Ö., 2007. Monitoring. In Mine Closure and Post-Mining Management – International State of Art, C. Didier (Ed.). International Commission on Mine-Closure, ISRM, 111–123.

Aydan Ö, Kawamoto T., 2004. The damage to abandoned lignite mines caused by the 2003 Miyagi-Hokubu earthquake and some considerations on its causes. *3rd Asian Rock Mechanics Symposium*, Kyoto, 525–530, 2004.

Aydan, Ö., Geniş, M., 2007. Assessment of dynamic stability of an abandoned room and pillar underground lignite mine, 23–44. Turkish Journal of Rock Mechanics Bulletin, Turkish National Rock Mechanics Group, ISRM, No. 16,

Aydan, Ö., Tano, H. 2012. The observations on abandoned mines and quarries by the Great East Japan Earthquake on March 11, 2011 and their implications. Journal of Japan Association on Earthquake Engineering, Vol.12, No.4, 229–248.

Aydan, Ö., Sakamoto, A., Yamada, N., Sugiura, K. and Kawamoto, T., 2005a. The characteristics of soft rocks and their effects on the long term stability of abandoned room and pillar lignite mines. Post Mining 2005, Nancy.

Aydan, Ö., Sakamoto, A., Yamada, N., Sugiura, K. and Kawamoto, T., 2005b. A real time monitoring system for the assessment of stability and performance of abandoned room and pillar lignite mines. Post Mining 2005, Nancy.

Aydan, Ö., Daido, M., Ito, T., Tano, H. and Kawamoto, T., 2006. Instability of abandoned lignite mines and the assessment of their stability in long term and during earthquakes. 4th Asian Rock Mechanics Symposium, Singapore, Paper No. A0355 (on CD)..

Aydan Ö, Ohta, Y., Genis, M., Tokashiki, N., Ohkubo, K., 2011. Response and Stability of Underground Structures in Rock Mass during Earthquakes. Rock Mech Rock Eng (2010) 43:857–875

Aydan Ö, Genis, M., Sakamoto, S. and Sugiura, K., 2012. Characteristics and amplification of ground motions above abandoned mines. International Symposium on Earthquake Engineering, JAEE, 75–84.

Aydan Ö, Tokashiki N, Tano H, 2013a. An experimental study on the supporting effect of back-filling on abandoned room and pillar mines, quarries and karstic caves, and its in-situ verification. ARMA 13-379. 47th US Rock Mechanics/Geomechanics Sym., San Francisco, 10pages.

Aydan Ö, K. Sugiura, A. Sakamoto 2013b. Dynamic characteristics of ground above abandoned mines. 13th *Japan Rock Mechanics Symposium*, 519–524 (in Japanese).

Ito, T., Ö. Aydan: Abandoned Lignite Mines in Mitake and Issues 2019. Post-Mining and Environmental Issues Themed Issue, Environmental Geotechnics, Institute of Civil Engineers (in press).

Aydan, Ö., Sugiura, K., Sakamoto, A. 2018. The quality of backfilling of abandoned lignite mines on ground settlement under static and dynamic conditions. AusRock2018, 134–141.