Surface subsidence due to underground mining operation under weak geological condition in Indonesia

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Abstract

Subsidence analysis and prediction with measured data have been conducted and applied to local strata and mining conditions worldwide. Underground coal mines chose the most suitable analysis and prediction method for them. However, there was no study based on the measured data of subsidence induced by underground mining operation in Indonesia. This paper describes the condition of underground coal mine in Indonesia and then discusses the subsidence behavior due to longwall mining operation based on measured data in Balikpapan coal-bearing formation in Indonesia.

1. Introduction

Indonesia produced 400 Mt of saleable coal in 2013 with rapid increase in production by almost 99% of surface mining year by year as shown in Fig. 1 (BP, 2013; Indonesia Coal Mining Association, 2014). On the other hand, the rapid increase in production has brought strong concerns on sustainable supply of coal with current quality level in future, due to deepening mining location with increasing stripping ratio, decreasing coal reserve with high quality in the currently operating mines, and constraints on development of surface mine by environmental impact (Matsui et al., 2010). Under this circumstance, the importance of developing underground mines has been recognized in Indonesia, and recently several projects of underground mines have been implemented. However, there is no study based on measured data of surface subsidence induced by underground coal mining in Indonesia. Moreover, the overburden rocks of underground mines in Indonesia are very weak and deteriorated due to water. Therefore, the behavior of subsidence might be different from that in other countries such as Europe, US, Australia, etc. Hence, understanding the behavior of surface subsidence due to underground mining operation is the most important for the assessment of its environmental impact and appropriate underground mine design.

This paper describes the condition of underground coal mines and mining technology in Indonesia firstly, and then discusses the subsidence behavior due to the longwall mining operation based on the measured data in Balikpapan coal-bearing formation in Indonesia.

2. Characteristics of coal measures rocks in Indonesia

Most of the coal deposits in Indonesia are concentrated in Sumatra and Kalimantan. The strata are composed of sediments that are typically found in deltaic and shallow marine depositional environments, such as sandstone, clays and shale. These fresh formations are weak, with the measured rock strengths being much lower than those of most mined coal measures in the world. Coal measures rocks consists of silt stone, mudstone, shale, clay stone, sandstone, etc., and its mechanical properties are generally weak and deteriorated due to water. Especially, the rock containing smectite is very sensitive to water. Fig. 2 shows the histogram of uniaxial compressive strength (UCS) of recovered core (saturated) in KPC coal mine. This figure shows that the coal measures rock is very weak. Fig. 3 represents the slaking characteristics scored by means of the evaluation method of Sadisun et al. (2004). It can be observed from this figure that the slaking index increases with the increasing smectite content. From these results, it can be concluded that the deformation/closure behaviors of roadways are affected not only by ground pressure but also by weathering/slaking phenomenon due to groundwater and moisture supplied by ventilation. Generally speaking, the strength of coal in Indonesia is larger...
than that of coal measures rock, and it is about 10–20 MPa, which is almost the same as that in Japan.

3. Underground mining technologies in Indonesia

3.1. Privage and support system

Drivage and support system for roadways is one of the important factors for underground coal mine. As drill and blast method is generally applied in small-scale mine, mechanized drivage system is applied in some of the middle-to-large scale coal mines. For example, in Ombilin coal mine, roadheader was used for drivage of entries and roadways in soft rocks, and Dosco-MKII and AM50 were applied for drivage of entries for a longwall panels. Originally, the steel/wooden sets and/or steel arch have been used as support systems. Bolting system has been introduced from Australia since 1994. However, deformation and/or failure behaviors of roadways cannot be controlled only by bolting system in case that development rate is slow and the roadways/entries has to be maintained for longer time, and then additional support have to be installed. Now, the steel arch becomes a major support system again instead of bolting system, indicating that the term of maintaining roadways/entries has an obvious impact on the stability of roadways supported by bolts.

3.2. Mining system

In Indonesia, Ombilin coal mine had introduced a fully mechanized longwall mining system. However, the productivity is much lower than that expected. This is because of the dramatic change of coal seam conditions and unfixable face control. Prop and cap mining system has been introduced into the other underground coal mines as shown in Fig. 4. From the points of view of productivity, safety and economics, usual fully mechanized longwall mining system or room-and-pillar mining system by using continuous miner or roadheader should be considered for their introduction. Drivage system with a continuous miner and roof bolt support system has been introduced in Indominco Mandiri by Australian contractor, and coal extraction has been conducted by means of room-and-pillar mining system with BLS (Garcia et al., 2010). In the future, as this mining system may be introduced in small-to-middle scale underground coal mines, the advantage of this kind of fully mechanized mining system may be canceled in case that the dip of coal seam is very steep and the characteristic strength of floor rock is very low.

3.3. Safety and environment issues in underground coal mines in Indonesia

A plenty of accidents had occurred and a great number of lives were lost in underground mining operation. It can be said that the current ground control technique is developed with great loss of life. Today, although many advanced technologies have been introduced in underground coal mining industry, many fatal accidents still occur.
Even though the advanced and/or high capacity support systems and monitoring systems have been introduced, roof/rib falls in the face and roadway have still been one of the greatest hazards in underground coal mines. This is because of the poor/weak mechanical properties of surrounding rocks and high ground pressure.

In Indonesia, the characteristics of coal measure rocks which include silt stone, shale, sand stone, and clay stone are very weak and lower than that of coal (Takamoto et al., 2012). As mentioned above, their characteristics are deteriorated dramatically due to water, and some of them represent the slaking phenomena. In underground coal mines, the deterioration of characteristics of surrounding rocks may occur due to groundwater and/or inflow of rainfall from portal. This may cause a severe deformation of roadways and roof/rib falls. Especially, this phenomenon occurs remarkably in the case of deep mining operation or increasing ground pressure due to mining operation.

The in-situ stress condition has to be known for appropriate mining plan or design of roadway and support system. Unfortunately, as the data of in-situ stress condition in Indonesia are not sufficient enough, the investigation should be conducted rapidly.

Generally speaking, the impact of underground mining operation on the environment is smaller than that of surface one. However, the impact of underground mining operation on the surrounding environment cannot be disregarded in case of wide extraction area. Surface subsidence due to mining operation often becomes a big issue in underground coal mines. Cave-in due to mining operation often occurs at shallow mining depth, especially this phenomenon occurs remarkably during the rainy season. In the case that the longwall mining operation is conducted at relatively deep mining depth, the subsidence basin is formed at the surface (Peng and Chiang, 1984), as shown in Fig. 5. If the magnitude of subsidence is large, it has an obvious impact on the surface buildings. The prevention of the environmental disruption caused by mining is a responsibility of mining engineers.

4. Overview of underground coal mine targeted in this research

The measurement of subsidence has been carried out at Fajar Bumi Sakti (FBS) coal mine, located in Kutai Kartanegara regency in East Kalimantan, Indonesia, approximately 50 km far from Samarinda which is a capital city of East Kalimantan, as shown in Fig. 6. Fig. 7 shows the monitoring points on the surface with a longwall panel layout in this underground mine.

A seam was mined by semi-mechanized retreat longwall mining method using hand pick hammers for cutting, and hydraulic props and link bars for support. The gob was caved in by rocks above the roof without material packing. The longwall panel monitored was the first panel in seam A. Therefore, it was not affected by adjacent longwall excavation, but room-and-pillar mining operation had been carried out along the tailgate roadway before the longwall panel excavation.

The monitoring points were located at the middle of the face A, the edge of the faces B, C and D in the extension direction in lines 1 and 2, as shown in Fig. 7. The extraction of the longwall started on July 5th, 2005 and finished on April 15th, 2006. Key factors of the longwall panel were described as follows:

2. Mining coal seam: seam A.
3. Working thickness: 1.8–2.0 m.
4. Dip of the coal seam: almost level.
5. Length of the longwall face: 83 m.
6. Length of the gate road: 266 m.
7. Advance of the longwall per day: 1.4 m.

Fig. 8 shows the standard procedure of the longwall mining operation in this mine. The mine uses removable wooden chocks for supporting behind a face conveyor. Fig. 9 shows the distribution of rock strata obtained by a borehole near the longwall panel. Coal seams of the mine are of Balikpapan coal-bearing formation. Seam A was mined firstly before commencing the development of the underground mine. Seams A and B were extracted by underground mining method. The surface over the longwall panel is the floor of seam A. The cover depth of seam A is generally 50 m, and the overburden rocks consist of mudstone and siltstone. The UCSs of the rocks around the mining panel area are 3 MPa for siltstone and 1–4 MPa for mudstone. This result indicates that the strength of the rocks in this mine is very weak compared to that of rocks in other countries such as US and Australia, but it is typical in Indonesian coal mines.

5. Measurement and analysis of surface subsidence

5.1. Measurement of surface subsidence

Fig. 10 shows the time histories of surface subsidence along lines 1 and 2. Only vertical subsidence was measured and the horizontal movement was not done.

The working thickness in both lines 1 and 2 was 1.9 m, and the cover depth was 40 m in line 1 and 50 m in line 2. Unfortunately, the subsidence at the center of the panel such as points 1A and 2A could not be monitored from the date on or before starting longwall extraction due to the existence of water pool formed during rainy season. The subsidence of those points was measured from 28 September 2005. Therefore, the total subsidence of those points was predicted by the following method.

5.2. Evaluation of the complete subsidence

The measured data shown in Fig. 10 have to be evaluated whether the data show the complete subsidence or not before predicting the final subsidence of lines 1 and 2. Fig. 11 shows the relationship between the amount of subsidence and the elapsed time after passing longwall face in Japanese coal mines (Bureau of Economy, Trade and Industry in Kyushu Branch, 1975). It can be seen that in the cases of longwall mining panels with gob caved without packing, the deeper the longwall panel is, the longer the time to reach the final subsidence is. However, it also can be found that the subsidence is completed within 6 months even though the depth of longwall panel is greater than that in FBS mine such as...
case E (cover depth 90—130 m) and case M (cover depth 70—140 m). Moreover, the data shown in Fig. 10 were measured after 8 months. From the measured data of lines 1 and 2 shown in Fig. 10, it can be seen that the subsidence was completed within approximately 3 months in line 1 (cover depth of 40 m), and approximately 6 months in line 2 (cover depth of 50 m). From these conditions, it can be considered that the measured data shown in Fig. 10 have been already the final subsidence. Besides, the time to reach the final subsidence due to the longwall mining operation in this area is similar to that in the cases in Japan. It is considered that this similarity is caused by similar longwall panel width and weak rocks above the roof which falls soon after the longwall passes. Thus, it can be thought that Fig. 10 may be used for prediction of the time to subsidence completion before subsidence data are collected under various conditions in Indonesia.

5.3. Subsidence profile along line 1

The measured data of the final subsidence along line 1 are plotted in Fig. 12.

Since the subsidence of the center of the panel (1A) was not measured from the beginning due to the existence of water pool, it was predicted by the following methods.

(1) Case 1: Room-and-pillar gob has an effect on the measured data

In case that the measured data were affected by room-and-pillar gob which was made prior to longwall mining, since the measured data of points 1B, 1C and 1D cannot be used to predict the subsidence only induced by longwall mining, the maximum subsidence at the center of the panel is predicted by using the National Coal Board (NCB) model which uses the monograph to show the relationship among the subsidence, longwall panel width and depth, together with the table which shows the subsidence profiles at each ratio of longwall panel width/depth as shown in Fig. 13 (NCB, 1975). The predicted profile by this method is shown as NCB_Line 1 in Fig. 12. In this case, the mining at line 1 can be classified as a critical subsidence based on NCB SEH's rule of critical subsidence as the ratio of advance/depth equals 0.7. Then 10% reduction of subsidence was applied due to the mining in the virgin area according to the recommendation by NCB SEH. The subsidence of the point 1A is 1.45 m.

(2) Case 2: Room-and-pillar gob has no effect on the measured data

In case that the measured data were not affected by room-and-pillar gob, the measured data of points 1B, 1C and 1D can be used to predict the subsidence only induced by longwall mining. Two methods were applied for predicting the final subsidence at the point 1A.

(i) Application of NCB SEH monograph and the influence function proposed by Bals (Kratzsch, 1983)

The subsidence at the point 1A was predicted by the combined method of NCB SEH model mentioned above and the influence
function method proposed by Bals since the subsidence becomes subcritical with 34° of limit angle as shown in Fig. 14. The edge of the subsidence was found by the linear approximation from the point 1D, applying the straightline of the same subsidence range of NCB profile. The calculated coefficient of influence was 0.85 resulting from 5 parts of divided areas by Bals formula (Fig. 15). Table 1 shows the influence factors calculated by Bals formula. Therefore, the subsidence of the point 1A was predicted to be 1.23 m by multiplying the critical subsidence of 1.45 m by 0.85.

(ii) Application of the subsidence prediction formula.

Karmis et al. (1984) proposed a formula to predict the surface subsidence as

$$S(x) = S_{\text{max}} \frac{1 - \tanh(c x / B)}{2}$$

where $S_{\text{max}}$ is the maximum subsidence in the subsidence profile; $x$ is the horizontal distance from the inflection point; $B$ is the distance from the center of the subsidence profile to the inflection point; $c$ is a coefficient, which is 1.4 for subcritical panels and 1.8 for critical and supercritical panels. The relationships among these parameters are shown in Fig. 16.

The distance $B$ was calculated by inputting the data of points 1B, 1C and 1D with $c$ (1.4) due to subcritical subsidence, then $S(x)$ was calculated. The result is shown as Calc_Line 1 (Karmis et al., 1984) in Fig. 12. The profile matches the subsidence of points 1B, 1C and 1D well. The subsidence of the point 1A is predicted to be 1.09 m.

The following results can be drawn from the above analysis:

1. If the subsidence is affected by room-and-pillar mining, the amount of predicted subsidence is 1.45 m.
2. If the subsidence is not affected by room-and-pillar mining, the amount of predicted subsidence is 1.09–1.23 m with the difference of only 7.4%. Both results of Karmis and NCB models are in good agreement, considering NCB suggestion of 10%
However, the profiles are different for both models, because the NCB model was proposed with about 55° of limit angle based on the subsidence data measured in UK. The measurement data of the panel show 34° of limit angle and are different from the NCB model.

5.4. Subsidence profile along line 2

The measured data of the final subsidence along line 2 are plotted in Fig. 17. The subsidence of the point 2A started from the date when the longwall face passed 2.8 m through the line 2. Then the subsidence at the point 2A from the beginning of the longwall was predicted by NCB monograph which represents the relationship between the amount of subsidence at an observation point and the position of longwall face as shown in Fig. 18 (NCB, 1975), where s is the subsidence that already occurred before measurement, and S is the final subsidence. Based on the face advance (2.8 m), h (50 m) and $S_s$ (39 cm) obtained from the measurement, S is found to be 49 cm. The subsidence profile was predicted by using NCB table which represents the subsidence profile at each ratio of longwall panel width/depth monograph shown as NCB_S 0.49 m in Fig. 17. And also the subsidence profile was predicted by using the NCB model. This profile with the maximum depth of 1.4 m is shown as NCB_S 1.4 m in Fig. 17.
According to the above analyses, the following conclusions can be drawn:

(1) The subsidence of line 2 is considered as the critical one with the limit angle of $55^\circ$, because the profile from point 2B to point 2C is almost the same as the NCB profile.

(2) There is a big difference in subsidence at the center of the panel between the measurement (0.49 m) and the predicted one by the NCB model (1.4 m). There is a possibility that the difference is caused by the cut through roadway for ventilation located 12 m ahead of line 2 as about 1.5 m of convergence in the height of the roadway occurred before the longwall panel passed through line 2.

5.5. Summary

The following points are summarized by the analyses of subsidence at lines 1 and 2:

(1) The time for reaching the final subsidence

The time for reaching the final subsidence of longwall mining in Indonesia is similar to the cases in Japan, dependent on the depth of cover. It is considered that this similarity is caused by similar longwall width and weak rocks on the roof which falls soon after longwall passes.

(2) Limit angle

The measured data show a limit angle of $34^\circ$ at line 1 and $55^\circ$ at line 2, respectively. It is known that in general the weaker the overburden is, the larger the limit angle of subsidence is. It is hard to consider that the limit angle of subsidence at line 1 is $34^\circ$ taking into account its low rock strength, e.g. 1–4 MPa of UCS. Thus, it can be considered that the subsidence at line 1 was affected by the gob of room-and-pillar mining which has been conducted before longwall mining. It can be expected that the limit angle of the subsidence is around $55^\circ$ in the area such as line 2 and this is similar to that in Japan and UK.

(3) Subsidence profile

Since the subsidence at the center of the panel at both lines 1 and 2 could not be measured from the beginning of the longwall mining, the predictions of the profile were made by several methods. However, the predicted profile could not be verified due to the lack of the most important subsidence data at the center of
the panel. Whether the NCB model can be applied to predict the subsidence in Indonesia or not, it should be evaluated by accumulating the subsidence data through mining practices in future.

6. Conclusions

Subsidence analysis and prediction with measured data have been conducted worldwide to be applied to local strata and mining conditions. Underground coal mines apply the analysis and prediction method which are most suitable for these mines. However, there was no study based on the measured data of subsidence induced by underground mining in Indonesia as long as the authors know. This paper analyzes the subsidence behavior in Balikpapan coal-bearing formation in Indonesia based on the measured data.

As a result of the analysis, it is expected that the time for reaching the final subsidence agrees well with that in Japan, and the limit angle is around 55° which is the same as that in Japan and UK. However, the predicted subsidence profile could not be evaluated because of the lack of the most important data at the center of the panel.

Overburden rocks of underground mines in Indonesia are very weak and deteriorated due to the water compared with those in other countries. Therefore, the behavior of subsidence might be different from that in other countries.

The analysis with measured data in this paper seems to be the first study. Although this paper gives the basic understanding in some aspects of subsidence, the data are not enough to predict the behavior of subsidence in Indonesia on a proven basis.

Under the circumstance that development of underground mines is expected and environmental impact for the development is paid much attention to, subsidence data due to the underground mining operation should be accumulated in order to develop the prediction method of the behavior of subsidence in Indonesia.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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References


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