Analysis of Hypocenter Relocation by Using Double Difference Method in a Deep Underground Mining

Wahyu Hidayat\textsuperscript{1,4}, David P. Sahara\textsuperscript{3}, Sri Widiyanto\textsuperscript{3}, I Putu Raditya Ambara Putra\textsuperscript{2}, Nabil H. Shihab\textsuperscript{2}, Rizka Amalia\textsuperscript{2}, Azhar Harisandi\textsuperscript{2}, and Suharsono\textsuperscript{4}

\textsuperscript{1}Doctoral Program of Geophysical Engineering, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung
\textsuperscript{2}Master Program of Geophysical Engineering, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung
\textsuperscript{3}Global Geophysics Research Group, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung
\textsuperscript{4}Geophysical Engineering, Faculty of Mineral Technology, UPN “Veteran” Yogyakarta

Corresponding author: hidayat18@gmail.com

Abstract. Hypocenter relocation is one of the keys to success in the analysis of seismicity induction in underground mines. Overburden thickness, topography, geological complexity, and mining activities can result in newly induced seismicity that can endanger the safety of underground mine workers. The relatively narrow underground mine area requires the most accurate hypocenter location information possible. The double-difference algorithm approach is one of the keys to overcoming this problem. The double-difference method is a relative location method that tries to minimize the residuals between the observed and calculated travel time differences for pairs of microseismic events at each station, by adjusting the differences between all pairs of events at each station repeatedly. In this study, we utilized microseismic measurement data in the deepest underground mine in Indonesia. A total of 1783 seismic events were successfully relocated. The relocation results show the rock mass stress which is illustrated by the distribution of events around the cave, especially the abutment area and underground mining tunnels.

Keywords: Induced Seismicity, Double-difference method, Underground mining

1. Introduction

Microseismic monitoring is a method of underground seismic investigation based on the detection of the location of earthquakes with small magnitudes that occur in rocks due to natural or artificial processes [2]. Underground mining seismic monitoring system can explain the process of damage to rock mass and rock failure due to mining-induced and geological structures as well as monitoring tunnel development evolution and cave evolution [1]. Monitoring of seismic activity in underground mining areas is very necessary so that the evacuation and handling process carried out when a seismic event that is dangerous to the safety of workers can be carried out quickly and measured.

The determination of the hypocenter location is the first step in seismological studies [2]. Determination of the location of an earthquake hypocenter with high accuracy is required to analyze velocity structures, identify fault zones, microfracture distribution, and orientation as well as to analyze
both global and local seismicity. For these purposes, the relocation of an earthquake hypocenter is very important. To get an accurate location, especially a local scale in underground mines, an efficient and accurate location determination algorithm is required. The Double-Difference method is a method that can relocate earthquakes simultaneously [4] [5] [6]. This method works by pairing earthquakes and utilizing the time difference between the two events to obtain a more accurate hypocenter location. The principle of this method is that if the distance between the two events (a pair of events) that are paired is relatively small compared to the distance to the observing station, then the ray path and waveform of the two events can be considered almost the same. With this assumption, the difference in travel time between the two events recorded at the same station is considered a function of the distance between the two hypocenters [6].

2. Data and methodology
The data used in this research is microseismic catalog data for one month (January 2019) that was recorded by 74 stations from the underground mining in Indonesia. The microseismic catalog data consists of the date, time of occurrence, station, magnitude, depth, and uncertainty of each of these parameters. Total microseismic events were 1783 microseismic events with magnitudes from -1.3 to 1.5 Mw. The microseismic catalog data then calculated the travel time and determined the pair event using ph2dt. Based on the results of ph2dt, 1765 events were selected with a total phase of 2994. The P-wave phase selected pairs as many as 49910 out of 57991 or 86%, while for the S-wave phase, 24943 pairs were selected out of 28752 (86%). There is 1 cluster, the microseismic event is around the mine operation (cave). The initial velocity model used is a 3-Dimensional velocity model. 3-Dimensional velocity model is obtained from geological information. The distribution of the magnitude of the research area is shown in Figure 1.

![Figure 1. Distribution of the magnitude of the seismic event at research area](image)

The double-difference method assumes that if the distance between two adjacent event sources is much smaller than the distance to the station and has a heterogeneity of velocity which is considered the same,
then the waves from both sources are considered almost the same [4]. Figure 2 shows an illustration of two event sources $i$ and $j$ which are close and relatively far from the recording sensors $k$ and $l$.

![Figure 2. Double-difference methodology illustration [4].](image)

The arrival time of the $T$ wave from the event source $i$ to an event station is expressed by the wave-ray theory,

$$ T_k^i = \tau^i + \int_{x_1^i}^k u \, ds $$

(1)

where $\tau^i$ is the event occurrence time from the source $i$, $u$ is the slowness vector, and $ds$ is the partition of the wave raypath. The relationship between the arrival time and the source location is not very linear, therefore linearization is carried out by calculating the misfit between the observed data and the predicted arrival time $r_k^i$.

$$ r_k^i = \sum_{l=1}^3 \frac{\partial T_k^i}{\partial x_l^i} \Delta x_l^i + \Delta \tau^i + \int_{x_1^i}^k \delta u \, ds $$

(2)

Equation 2 is substituted with the occurrence of source $j$ received by station $k$, then it is obtained:

$$ r_k^i - r_k^j = \sum_{l=1}^3 \frac{\partial T_k^i}{\partial x_l^i} \Delta x_l^j + \Delta \tau^i + \int_{x_1^j}^k \delta u \, ds - \sum_{l=1}^3 \frac{\partial T_k^j}{\partial x_l^j} \Delta x_l^j - \Delta \tau^j - \int_{x_1^j}^l \delta u \, ds. $$

(3)

By assuming the two sources are so close that the light lines of the waves are nearly equal and cancel each other out, equation 3 can be simplified to:

$$ r_k^i - r_k^j = \sum_{l=1}^3 \frac{\partial T_k^i}{\partial x_l^i} \Delta x_l^j + \Delta \tau^i - \sum_{l=1}^3 \frac{\partial T_k^j}{\partial x_l^j} \Delta x_l^j - \Delta \tau^j $$

(4)

where $r_k^i - r_k^j$ is a double – difference [4]. Double - difference is the time difference between the observed data and the calculated data between two adjacent event sources which can be written as [6]:

$$ r_k^i - r_k^j = (T_k^i - T_k^j)_{\text{obs}} - (T_k^i - T_k^j)_{\text{calculation}}. $$

(5)

The difference in arrival time $(T_k^i - T_k^j)_{\text{obs}}$ can be obtained through waveform cross-correlation or from absolute time difference from event catalog data.
3. Results and discussion
The data used in data processing in this study include data absolute travel time at each station, difference time data for each pair of events (cross-correlation difference time or catalog difference time), station coordinate data, earthquake catalog data, and initial velocity model. Determination of the initial velocity model is carried out by utilizing geological data information based on the results of logging and coring of rocks in underground mines vertically and horizontally in 3 dimensions. Data selection is done by making a plot between the travel time and the distance traveled and based on rock velocity information from rock test results in the laboratory. The difference time data for each pair of event events is in the form of cross-correlation difference times or catalog difference times which are then used in the inversion process using the TomoDD program package. Figure 3a is a histogram of the residual travel time before being relocated, while figure 3b is a histogram that has been relocated. The residual RMS distribution before being relocated was in the range of -3 ms to 2 ms. The histogram after relocation shows a high-frequency distribution value and is close to 0 with a value range of -2 ms to 2 ms, which shows that the microseismic relocation is statistically better than before the relocation. To determine the distance of the shifting of the microseismic before and after being relocated, a histogram of the shift versus the amount of data and a rosette diagram was made to determine the dominant direction of distribution (Figures 4 and 5).

![Figure 3a. Histogram of microseismic residual RMS before being relocated. Figure 3b. Histogram of microseismic residual RMS after being relocated.](image)

![Figure 4. Histogram of shifting before and after being relocated.](image)
The shift of the hypocenter before and after being relocated shifted from 0.01 to 13 meters (Figure 4). This shows that the event relocation in the mine needs better accuracy because the mining area has a relatively narrow supporting utility. The distance between panels and certain levels is in the order of meters. The result of the event shift histogram was then made a reset diagram. The distribution of the microseismic shown by the rosette diagram spreads in all directions, but dominantly in the NE-SW direction (Figure 5).

![Figure 5. Rosette diagram.](image)

The distribution of the hypocenter of the event using the Double - Difference method before relocation and after the relocation is shown in Figure 6. The distribution of the hypocenter of the event before the relocation (blue color) is more spread out, on the other hand, after the relocation of the hypocenter is more congested (orange color). The relocation results show the rock mass stress which is illustrated by the distribution of events around the cave, especially the abutment area and underground mining tunnels.

![Figure 6. The results of the micro event relocation, a blue circle before being relocated, and an orange color after being relocated](image)
4. Conclusion
The double-difference method has succeeded in increasing the accuracy of local scale microseismic relocation. The results of the relocation indicated a shift in the location as far as an average of ± 0.01 to 13 meters from the initial location.

5. References
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