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Effect of Geometry and Number of Seismic Stations on Micro-Earthquake (MEQ) Hypocenters in Geothermal Fields

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Abstract: Micro-earthquake (MEQ) distribution describes subsurface conditions that can contribute to monitoring the dynamics of geothermal reservoirs. Thus, the distribution of MEQ hypocenter locations with high accuracy becomes extremely important. Experiments were conducted with 3 variations of geometry and number of seismic stations, while Geiger and Coupled Velocity-Hypocenter methods were used to determine the location of MEQ. Experimental results show that in determining the location of the MEQ, the geometry and number of seismic stations played an important role. Increasing the number of stations with relatively long distances can result in less accurate locations of MEQ, error and bias in determining the location of MEQ will be greater when the azimuth gap value is greater. This is shown by the distribution of MEQ that are more spread out in variations 4A and 4B (4 seismic stations) compared to the distribution of MEQ hypocenters using data from 8 seismic stations. The azimuth gap variations of stations 4A and 4B are 283° and 267°, and 8 stations have a value of 222°. The large value of the azimuth gap is due to the distribution of stations only on one side so that there are horizontal angles that are not covered by seismic stations.

Keywords: Geiger; Geometry; Geothermal; Micro-earthquake (MEQ); Seismic Station.

Introduction

Geothermal is one of the natural resources formed from high-temperature materials from under the surface of the earth that is used by humans to provide for their daily needs (Aneke & Menkiti, 2016; Bertani, 2016; Cheng, 2022; Lund et al., 2011; Rahmaningtyas et al., 2020). Some geothermal energy uses as power generation to heating necessity (Jouhara et al., 2020; Moya et al., 2018). Geothermal energy is included in environmentally friendly energy (Anderson & Rezaie, 2019; Østergaard et al., 2020). The utilization of geothermal energy is included in the Sustainable Development Goals (SDGs) as stated in point 7 (related to clean and affordable energy), point 9 (related to industry, innovation, and infrastructure), point 11 (related to sustainable cities and communities), point 13 (related to climate action), and point 17 (related to partnerships for goals).

The existence of geothermal energy is generally found in the volcanic zone, which is a weak zone in geology (Cheng, 2022; Farhan et al., 2019; Geoffroy et al., 2022; Mahwa et al., 2022). In this zone, there are many faults formed due to geological activity (Geoffroy et al., 2022; Riziq Maulana et al., 2019; Zaini et al., 2022). The faults that are formed open a fluid migration path (generally groundwater) to approach the heat source and or migrate to the geothermal reservoir zone (Anderson & Rezaie, 2019; Chen & Huang, 2018; Cheng, 2022; Geoffroy et al., 2022). Fault planes will generally increase porosity and permeability due to fractures formed between one fault plane and another (Chen & Huang, 2018; Geoffroy et al., 2022; Riziq Maulana et al., 2019; Yang et al., 2021). The presence of faults that cause

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this fracturing can be identified based on the release of seismic waves generated when the fault is formed (Barbosa et al., 2020; Farhan et al., 2019; Firdaus Al Hakim et al., 2019; Küperkoch et al., 2018; Riziq Maulana et al., 2019).

The Micro-Earthquake (MEQ) method can be used to identify the presence of faults, where the distribution of MEQ hypocenters with a relatively low magnitude scale, i.e. with a strength of less than 3 Richter Scale (SR) can indicate the presence of faults (Kato et al., 2021; Toledo et al., 2020; Utama et al., 2021; Wildan Perdana et al., 2020). MEQ is used to identify subsurface dynamics related to the presence of faults and weak zones in geothermal field reservoirs, MEQ hypocenter determination is carried out based on seismic data recorded by seismic stations which are then processed by the inversion method and then analyzed to describe the subsurface conditions of the geothermal field (Pennington et al., 2022; Utama, Ardhya, et al., 2022). Generally, after the identification of the hypocenter is carried out, analysis and validation of the suitability with geological data of the geothermal field area or research area are carried out (Halim et al., 2020; Intani et al., 2020; Sicking & Malin, 2019; Utama & Garini, 2022).

Based on the results of previous studies, the quality of reliable MEQ location with a high level of precision and accuracy depends on several factors, including the availability of good quality (low noise) data recorded by the cluster network, the measurement error of the observed arrival time (quality of seismic phase determination, number and distribution of seismic stations, subsurface seismic velocity structure in the cluster region), the quality of seismic phase determination, the number and distribution of seismic stations, and the accuracy of MEQ subsurface seismic velocity in the unknown cluster region (Karasözen and Karasözen 2020; Kianimehr et al. 2018; Midzi et al. 2020; Sevilla et al. 2020; Zhang et al., 2019; Utama, Garini, and Lansa 2022).

Research on the effect of the number of seismic stations on the estimation of the earthquake Centroid Moment Tensor (CMT) has been widely conducted, where the number of seismic stations affects the estimation of the earthquake CMT (Fahntalia & Madlazim, 2017). The influence of the number and distribution of seismic stations on the identification of MEQ hypocenter locations in geothermal fields is something that has been studied (Bidang, 2020; Cheng, 2022; Fahntalia & Madlazim, 2017; Pennington et al., 2022). There are indications that the number and geometry of seismic stations influence the distribution of MEQs, thus affecting the analysis results obtained. Therefore, some MEQ data processing software applies a minimum number of stations used for processing, in order to obtain a more representative MEQ hypocenter model (Kissling, 1998; Kissling et al., 1995; Nishi, 2005). When the number of stations used does not reach the minimum limit, it will produce a relatively large error value, resulting in less accurate identification of the hypocenter (Bondár et al., 2004; Huang et al., 2018; Küperkoch et al., 2018; Siddiq et al., 2020).

This research applies the Geiger Method with Adaptive Damping (GAD) and Coupled Velocity Hypocenter (CVH) to identify MEQ hypocenters in geothermal fields, related to the influence of the number of seismic stations and their location distribution. Variations in the number of seismic stations used in this study are 4 and 8 seismic stations. The subsurface rock model in this study is considered a homogeneous model, so that the variation of rock physical properties as a medium for MEQ seismic wave propagation is considered isotropic. This research aims to support the 7th point of SDGs in realizing clean and affordable energy, through geothermal energy applications that require detailed fault conditions and locations, which can be identified from the studied MEQ hypocenter.

Method

The number of stations used in the analysis of the influence of the number of seismic stations and distribution on the identification of MEQ hypocenter locations are 4 and 8 seismic stations, namely ULI, ZPN, ZUI, BRB, BUT, BRK, ZTO, and BUA seismic stations. In analyzing the influence of hypocenter distribution, 3 types of variations are used, namely 4A, 4B and 8 to get an overview of the differences between the two approaches. The first variation 4A consists of 4 stations which are ULI, ZPN, ZTO, and BUT. The 4B variation consists of stations ZUI, BRK, BRB, and BUA, and the third variation consists of all stations namely ULI, ZPN, ZTO, BUT, ZUI, BRK, BRB, and BUA. There are several input data needed to identify the location of MEQ using the inversion method including the arrival time of Primary (P) and Secondary (S) waves, seismic station coordinates, magnitude, origin time, and 1D velocity model. The inversion methods used are Geiger method to identify the initial MEQ location and the Coupled Velocity-Hypocenter (CVH) method to relocate the MEQ and determine the 1D velocity model of the cluster region, the framework can be seen in Figure 1.

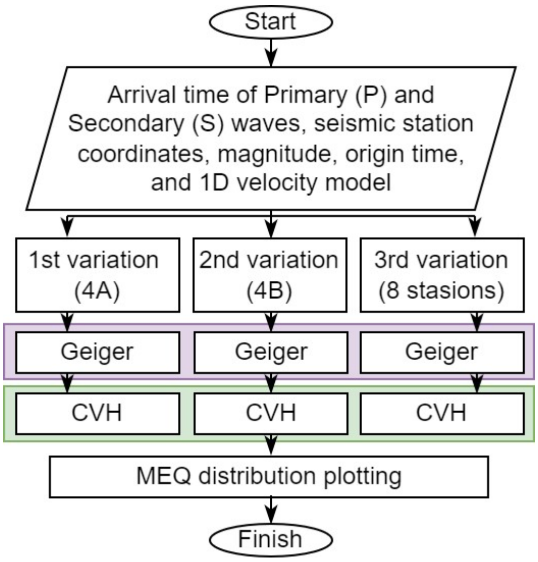

Figure 1. Research flowchart (purple box represents the step of identifying the initial MEQ and and the green box represents the step of relocation of the MEQ hypocenter)

Geiger Method

Geiger Method is one of the inversion methods for determining the initial MEQ hypocenter (Madrinovella, 2012; Midzi et al., 2020; Nishi, 2005). The Geiger method is applied in determining a single hypocenter by using residual time data, where this data is the difference between the observation time and the calculation time (Chen & Huang, 2018; Riziq Maulana et al., 2019; Utama et al., 2021). The GAD method control is the seismotectonic state suitability of the research as indicated by the RMSE value. Smaller RMSE value (close to zero), generally indicates the better or more accurate MEQ hypocenter determination. The RMSE value in this method is obtained from the residual observation time and the earthquake occurrence time.

Coupled Velocity-Hypocenter Method

Coupled Velocity Hypocenter (CVH) Inversion Method is an earthquake hypocenter testing method with simultaneous station correction using the Geiger method (Kianimehr et al., 2018; Kissling, 1995, 1998; Sevilla et al., 2020; Utama, Garini, & Indrianii, 2022). The CVH method is a travel time inversion method, where the intended travel time is the difference between the seismic wave arrival time and the earthquake event time. The CVH inversion results are the earthquake hypocenter locations in the form of coordinates, depth, RMSE value, and azimuth gap.

Result and Discussion

The data has been processed with variations in the different station distributions using the CVH and GAD inversion methods, showing the MEQ hypocenters distribution results from 8 seismic stations. It is known that many MEQ hypocenter locations distribution is identified in zones that are relatively close to the presence of seismic stations. This is shown in Figure 2, where the MEQ hypocenters determined by the 8 seismic stations are clustered in the zone around the 8 stations, and the distance between hypocenters are increasingly stretched as the hypocenter are further away from the stations. This is supported by the hypocenter distribution pattern, when viewed from the top as shown in Figure 3. The hypocenter cluster has a high concentration in the zone relatively close to the seismic station and is increasingly tenuous when the hypocenter position is relatively far from the station.

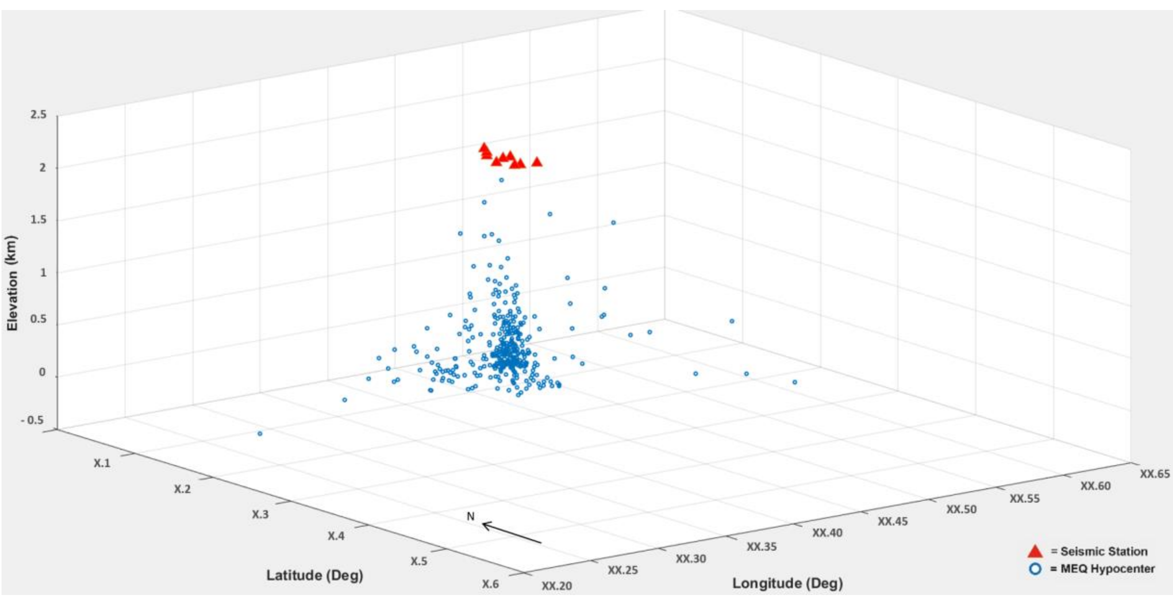

Figure 2. CVH inversion data plot results for 8 stations in 3D model

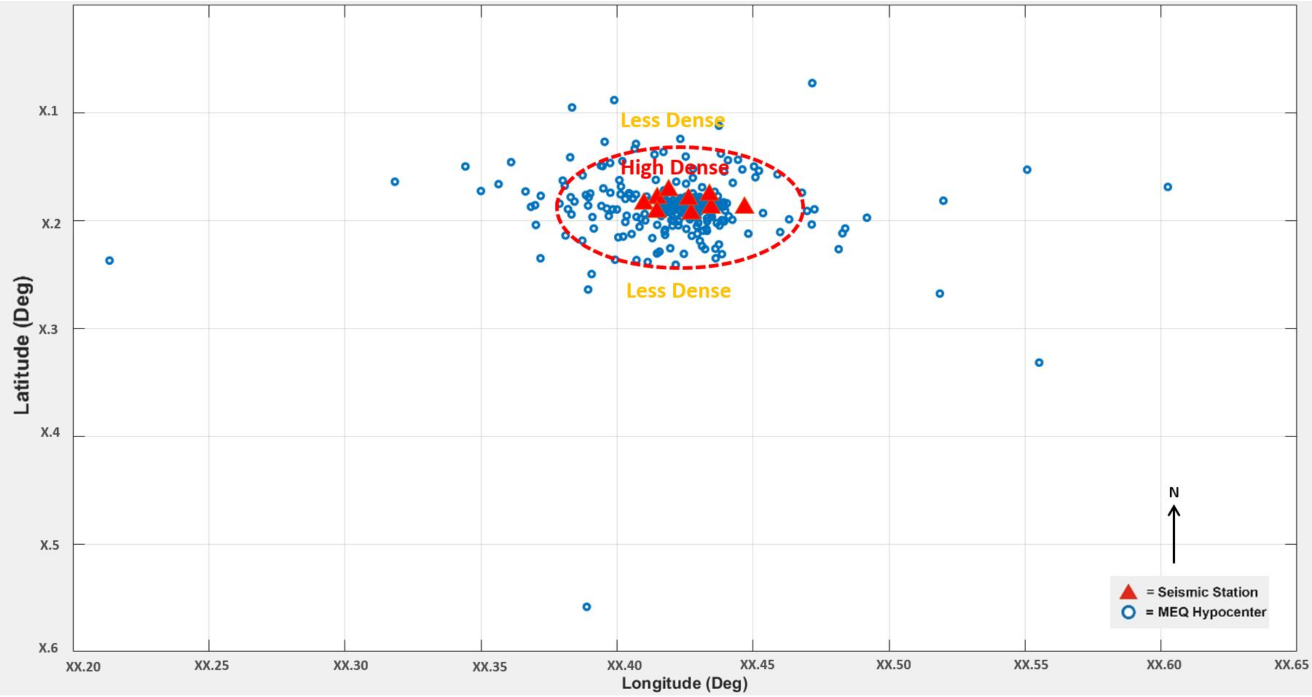

Figure 3. CVH inversion data plot results for 8 stations in bird view

Hypocenter distribution pattern from the cross-section is also interesting to discuss. In the latitude coordinate section as shown in Figure 4, it is known that the hypocenter point density has a high concentration just below the station located at a depth of 1.5 to 2 kilometers below the seismic station. The relatively dense hypocenter point has no effect spatially vertically, but is affected spatially horizontally. This is also shown in Figure 5, which displays latitude coordinate incisions, where the MEQ hypocenters distribution pattern forms a "triangle-shape", showing the depth effect does not significant on the hypocenter location identification, but the hypocenter distribution in horizontal axis gave more significant effect on the hypocenter point identification. In other words, if the MEQ hypocenter is closer to the seismic station, there are more hypocenters will be detected by the seismic station.

After knowing the relationship between MEQ hypocenters distribution and the seismic station location, to determine the seismic stations number effect on the MEQ hypocenters distribution, seismic stations will be divided, which originally consisted of 8 stations into 2 groups of stations, each group consist of 4 stations. The data below station position, with horizontally spaced intervals, that are relatively close to the station zone, tends to lower RMSE value. This support by analysis results in the previous section, where the hypocenter point will be “more identified” in the relatively close to the station zone horizontally. It is known that the depth factor does not have a significant influence on the MEQ hypocenters distribution identified by seismic stations.

Average RMSE values obtained from stations 4A and 4B were 0.159 and 0.105, respectively. This result is lower than the result from 8 stations simultaneously, which has an average RMSE value of 0.26. It is known that the less number of seismic stations in MEQ hypocenter measurement impacts the lower RMSE value. This is inseparable from the station's location influence and the amount of hypocenter data used, where is farther hypocenter from the seismic station and the more hypocenter data calculated will potentially produce a larger RMSE value.

The MEQ hypocenter results plot based on the grouping of 4 stations produce a relatively wide distribution of hypocenter points compared to the inversion results at 8 stations. Figure 6 shows the data distribution from the CVH inversion results from station groups 4A and 4B. The hypocenter points relatively high concentration emergence in the zone that relatively close to the station location. This is supported by the top view plot results shown in Figure 7, where the fewer number of stations (4 seismic stations) results in a relatively more spread-out hypocenter points distribution, although the denser zones of hypocenter points are still in a zone that is relatively close to the station locations.

The MEQ hypocenter points distribution in the 4 station grouping is more spread-out as an small number effect of seismic stations, it turns out that it does not only occur horizontally, but also vertically. This is shown in Figure 8 and Figure 9, where the latitude and longitude plots results will identify the MEQ hypocenter points distribution which are increasingly spread out as there are fewer number of seismic stations. Even though there is also a distribution of hypocenter points that spread more vertically, it is still possible to identify dense zones from the MEQ hypocenter point, where the location of the dense zone is relatively right below the seismic station. This is related to the azimuth gap where the average value of stations 4A and 4B is 283 and 267, whereas when using 8 stations the azimuth gap average value is 222. High azimuth gap value in the data analysis results is caused by the stations distribution which are only on one side, not scattered around the earthquake epicenter. The MEQ hypocenter plot results from the CVH inversion results with the grouping of 4 stations show a tendency towards a certain direction. The direction orientation formed from the MEQ hypocenter plot is influenced by the location of the seismic station. Station 4A which is relatively in the western part, records more hypocenters in the western cross-sectional area, while station 4B which is relatively in the eastern part records more hypocenters in the eastern cross-sectional area. This shows MEQ hypocenter distribution pattern indication from data which tends to follow the location of the seismic measurement station.

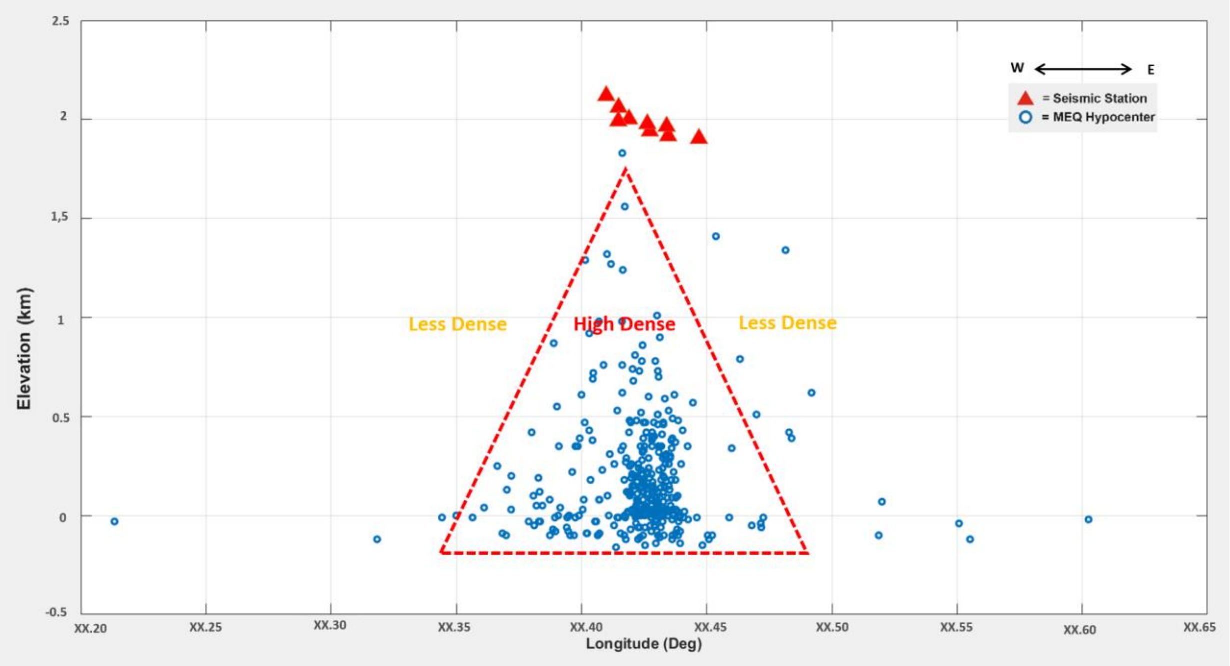

Figure 4. CVH inversion data plot results for 8 stations in longitude coordinate section

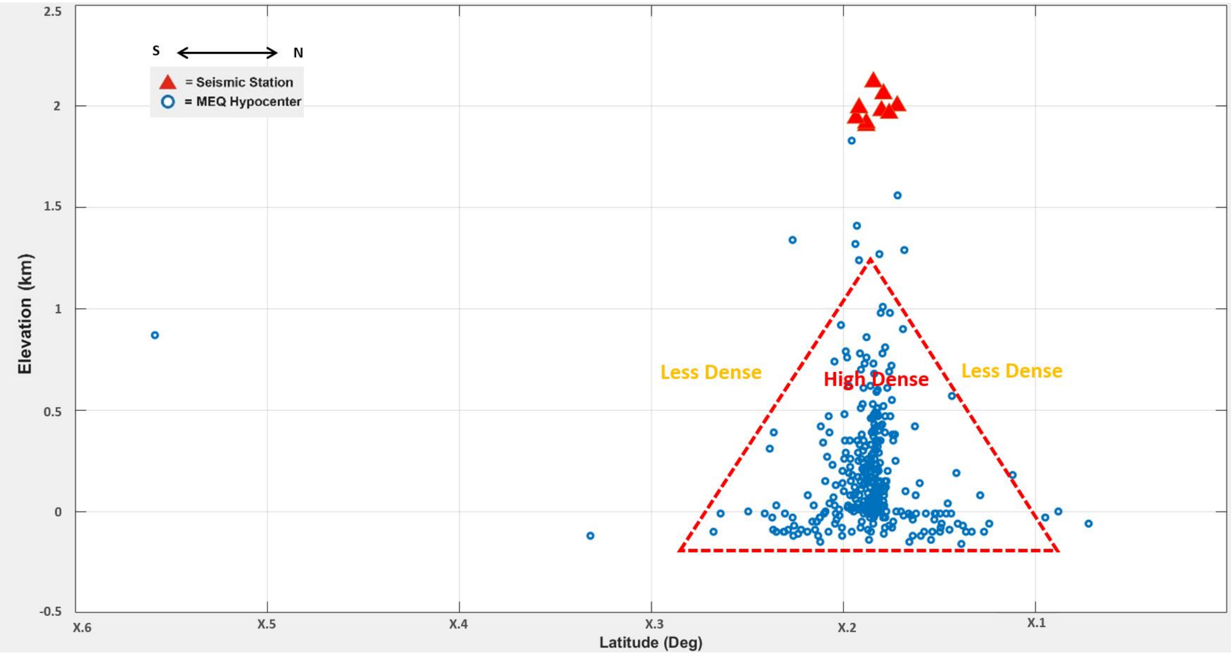

Figure 5. CVH inversion data plot results for 8 stations in latitude coordinate section

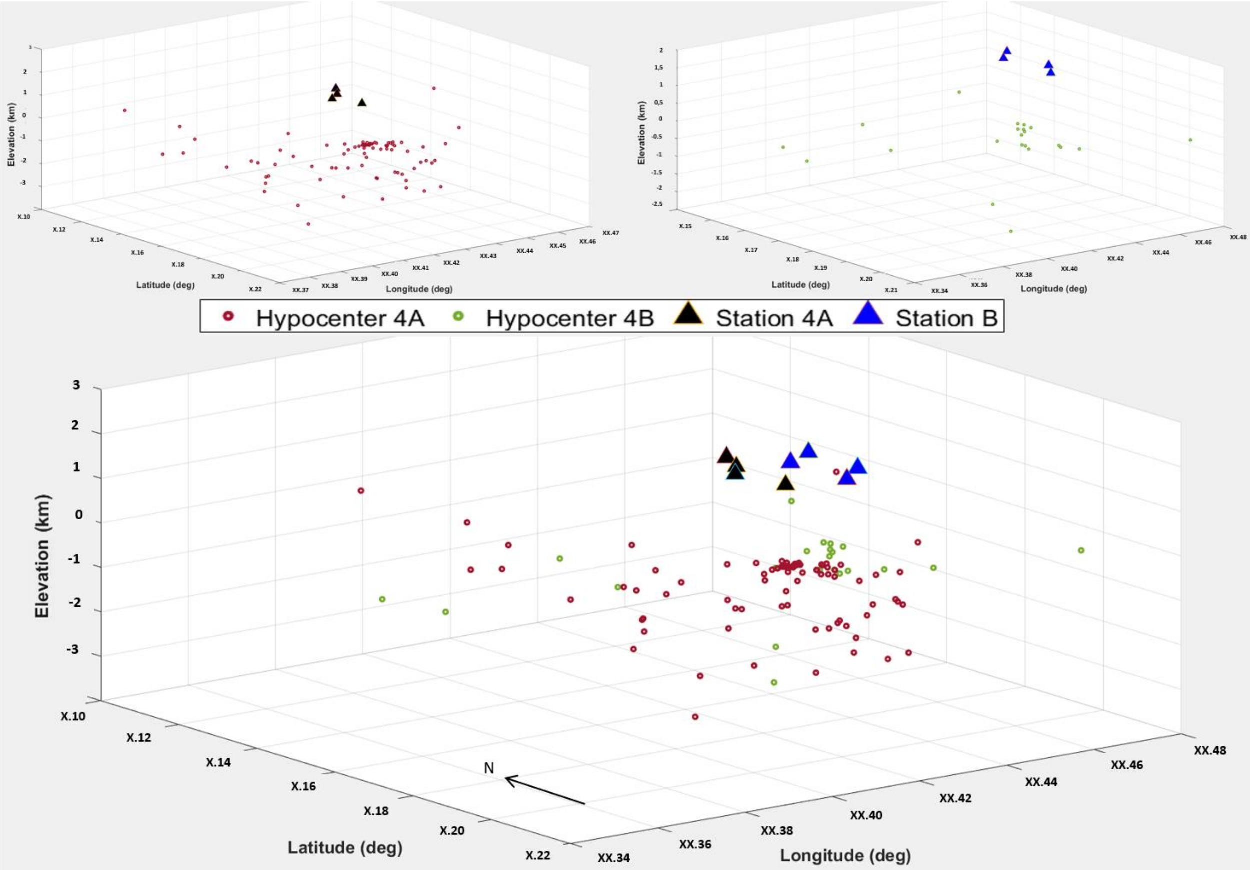

Figure 6. CVH inversion data plot results for 4 stations grouping in 3D model

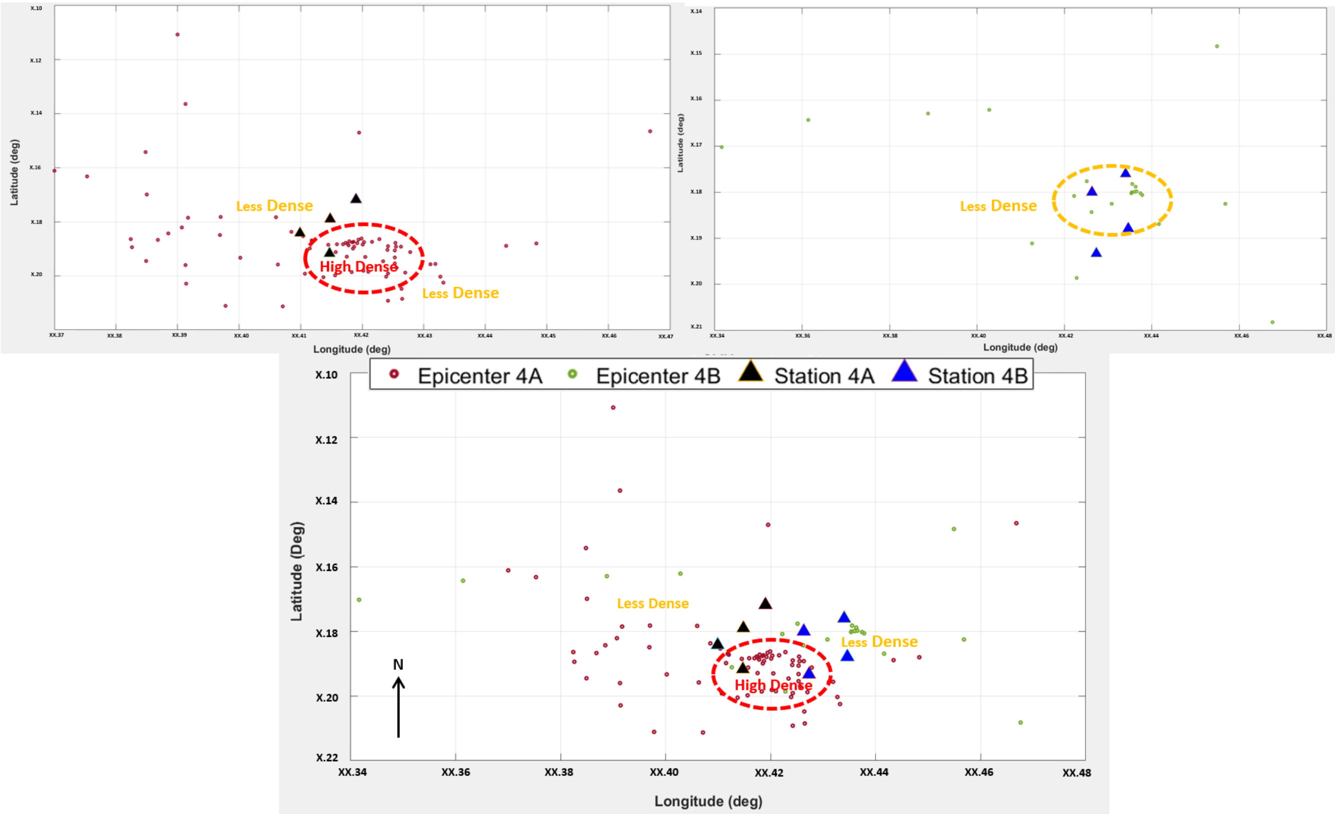

Figure 7. CVH inversion data plot results for 4 stations grouping in bird view

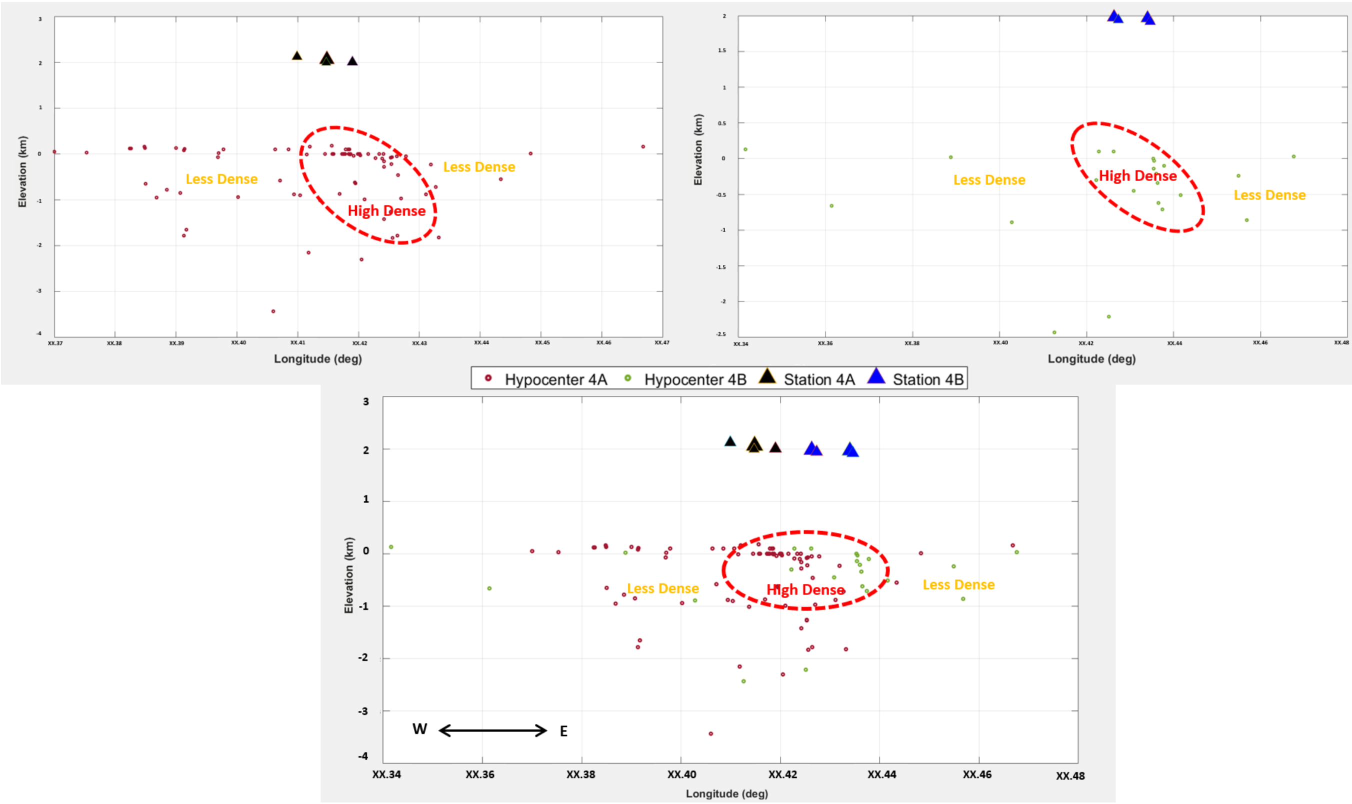

Figure 8. CVH inversion data plot results for 4 stations grouping in longitude coordinate system

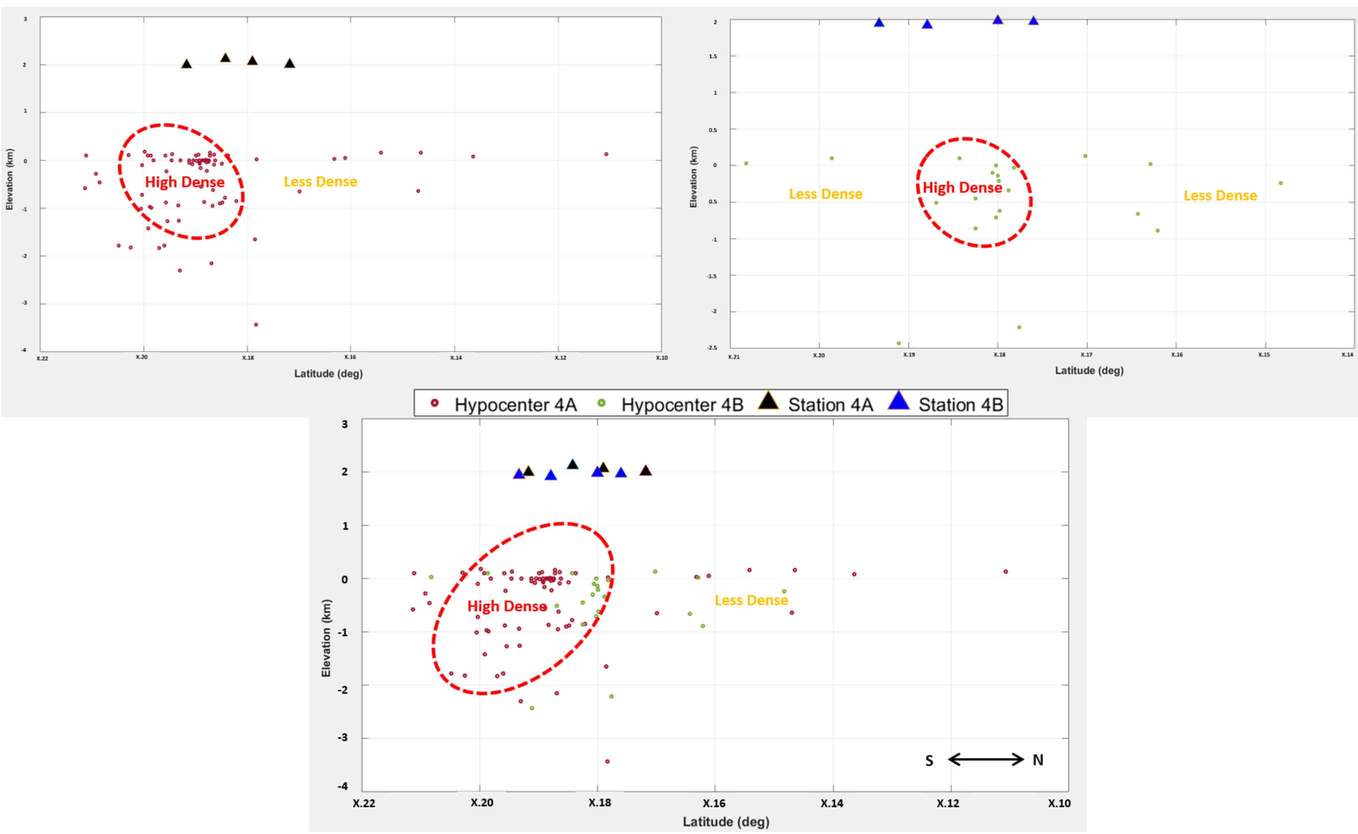

Figure 9. CVH inversion data plot results for 4 stations grouping in latitude coordinate system

The approach that can be taken as an effort to minimize the MEQ location bias is to increase the number of seismic stations 360° around the earthquake event in the study area, so the azimuth gap can be below 120° (Bidang, 2020; Bondár et al., 2004; Fahntalia & Madlazim, 2017). Even though each method is given a minimum limit for the use of seismic stations, it would be nice to increase the number of seismic stations beyond the minimum standard. If this is not possible, then with the number of existing stations, an initial study is carried out regarding the history of the existing reservoirs so that the placement of seismic stations can be efficient and can produce a good picture of the subsurface of the reservoir.

Conclusion

MEQ hypocenter data processing using the CVH and GAD methods results show a different micro-earthquake hypocenter locations distribution for each type of station distribution. MEQ hypocenter distribution was mostly identified in zones relatively close to seismic stations, with the intervals between hypocenters stretching further as the hypocenters move away from the station. Experimental results show that in determining the location of the MEQ, the geometry and number of seismic stations played an important role. Increasing the number of stations with relatively long distances can result in less accurate locations of MEQ, error and bias in determining the location of MEQ will be greater when the azimuth gap value is greater. This is shown by the distribution of MEQ that are more spread out in variations 4A and 4B (4 seismic stations) compared to the distribution of MEQ hypocenters using data from 8 seismic stations. The azimuth gap variations of stations 4A and 4B are 283° and 267°, and 8 stations have a value of 222°. The large value of the azimuth gap is due to the distribution of stations only on one side so that there are horizontal angles that are not covered by seismic stations. An approach that can be taken to minimize MEQ location bias is to increase the number of 360° seismic stations around earthquake events in the study area, so that the azimuth gap can be below 120°.

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Author Contributions
The author’s contributions include Widya Utama, Sherly A. Garini, Dwa D. Warnana, and Wien Lestari: focus on methdology and review on writing, and so on. Sherly A. Garini, Dhea P. N. Putra, and Merry C. Hutapea: data collection, data processing, data analysis, and writing the original manuscript.

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Conflicts of Interest
The authors declare no conflict of interest regarding the publication of this paper.

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