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Hypocenter Determination and Estimation 1-D Velocity Models Using Coupled Velocity-Hypocenter Method

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Abstract— **Hypocenter relocation is performed to obtain a high-precision hypocenter location (accurate earthquake location). An accurate earthquake location is the key problem in seismology. Further information from an accurate hypocenter location can be used for seismicity analysis, velocity structure study, and earthquake prone mapping as one of the earthquake mitigation efforts. In this research, the method used to relocate the earthquake hypocenter was the Coupled Velocity-Hypocenter. Relocations were conducted in the Central Sulawesi region; we located 40 local earthquake events with a magnitude of ≥ 3.8 ML and a depth of ≤ 25 km. The selected P-wave traveltimes were inverted from 5 seismic stations. The variance of initial velocity models used the 1-D Primary wave velocity model of North Sulawesi, Jeffrey-Bullen and Central Sulawesi. The relocation results show that most of the hypocenters are concentrated precisely in minor faults present in the research area, and the hypocenter distribution of the events indicated as destructive shallow earthquakes occurs at depths of about 5-15 km. The residual distributions resulting from the relocation using the initial velocity model of the Central Sulawesi region indicates an improved quality if compared to Jeffrey-Bullen velocity model and the North Sulawesi velocity model, with RMS error value of 0.08 seconds. This research concluded that the 1-D velocity model in the regional (Central Sulawesi Region) reference was suitable for determining the high-precision hypocenter location.**

Keywords— **1-D velocity model; Coupled Velocity-Hypocenter; faults, hypocenter; Sulawesi.**

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I. Introduction

Indonesia is one of the areas prone to earthquakes and volcanic eruptions. This is due to the tectonic conditions of Indonesia, which are located between three major tectonic plates, namely the Indian-Australian, Eurasian and Pacific plates. Most of the world's seismicity occurs along the subduction zones, and most of the largest earthquakes are generated along these active margins. The relative movement of the plates also creates faults which can then develop into the areas of earthquake sources [1], [2]. One of the areas in Indonesia that must be aware of earthquakes is the Central Sulawesi region.

Sulawesi has many active local faults that can trigger earthquakes. One of the active faults is the Palu-Koro fault. The Palu-Koro fault is located in Central Sulawesi, with SSE-NNW direction [3]. Based on the number of earthquake events [4], [5], as shown by the seismicity map above, and active faults in the Central Sulawesi region, awareness of earthquake disasters in the area is needed. That can be used to assist in earthquake mitigation efforts through the further study of seismicity of the earthquake and the identification of local faults that cause earthquakes. One form of awareness is accurately determining the hypocenter's location and estimating the 1-D velocity model accurately.

This research aims to find out the location of the earthquake hypocenter accurately and estimate a one-dimensional Primary wave velocity model that is suitable for determining the high-precision hypocenter location on the Central Sulawesi region. Therefore, this research used Coupled Velocity-Hypocenter Method, which is the relocation of the earthquake hypocenter method, which also produces a new velocity model and station correction simultaneously using the principle of the Geiger method, where the velocity model is updated using the Kissling equation [4]–[6].

Geiger method is one method to determine the location of the hypocenter using the residue of time produced from calculation and observation time. Unfortunately, some errors still occur in this method due to the structure of the seismic wave's velocity, which has not been modeled yet. Hence, the renewal velocity model of a one-dimensional primary wave is very important to reduce the errors from this method. [7], [8]. The renewal can also be done using the Coupled Velocity-

Hypocenter method with Kissling equation [9], [10]. The result of renewal using the Coupled Velocity-Hypocenter method obtained a new velocity model with vp/vs in each layer [4], [11], [12].

Based on those problems, the accuracy of earthquake information parameters (hypocenter) must be improved with the hypocenter relocation. In this research, hypocenter earthquake data in the Central Sulawesi region was relocated using Coupled Velocity-Hypocenter method, with three different one-dimensional Primary wave velocity models, namely the Jeffrey-Bullen velocity, North Sulawesi region velocity, and Sulawesi Central region velocity model. Based on the results of this research, we can conclude which velocity models that produce hypocenter location with higher accuracy and is more appropriate with the seismotectonic condition of the research area (Central Sulawesi). In addition, we can estimate which one-dimensional Primary wave velocity model is suitable for determining the high-precision hypocenter location on the Central Sulawesi region.

II. Materials and Method

The earthquake hypocenter relocation using Coupled Velocity-Hypocenter method used 40 events of earthquake in Central Sulawesi region with coordinates of 0.53˚-1.52˚S and 119.71˚-120.12˚E, with magnitude of ≥ 3.8 ML and a depth of 0-25 km. Seismic stations used in this research were SDTA, PMBB, BASE, LBAN, and PCI. Table I shows the coordinates of seismic stations that were used in this research. For our purposes, we selected only well-located events that matched the minimum requests concerning the location quality, that is, the event with at least five well-readable P and S arrivals.

TABLE I
THE DATA OF THE SEISMIC STATION USED IN THIS RESEARCH

Code	Location	Coordinate
SDTA	Sadaunta, Sigi district	01° 22’ 31.7”S – 119° 58’ 21.2”E
PMBB	Pombeve, Sigi district	00° 58’ 51.1”S – 119° 57’ 13.3”E
BASE	Baluase, Sigi district	01° 12’ 22.4”S – 119° 53’ 20.7”E
LBAN	Labuan Toposo, Donggala district	00° 37’ 13.3”S – 119° 51’ 34.5”E
PCI	Palu Geophysical Station	00° 54’ 18.7”S - 119° 50’ 12.3”E

There are three initial velocity models used in this research, ie Jeffrey-Bullen velocity, North Sulawesi region velocity, and Central Sulawesi region velocity model, as shown in Table II. Then, relocation using the Coupled Velocity-Hypocenter method was done as in Fig. 1. The relocation of earthquake hypocenter using Couple Velocity-Hypocenter method is a simultaneous relocation of earthquake hypocenter using travel time data [6], where the travel time data was obtained from local earthquake data derived from the Agency for Meteorology, Climatology, and Geophysics of Indonesia (BMKG) catalog.

TABLE II
1-D OF PRIMARY WAVES VELOCITY MODEL USED IN THE RESEARCH. (A) NORTH SULAWESI VELOCITY MODEL [13], (B) CENTRAL SULAWESI REGION VELOCITY MODEL [14], (C) JEFFREY-BULLEN VELOCITY MODEL [15]

Velocity Model			
North Sulawesi		**Central Sulawesi**	
Depth (km)	**P waves Velocity (km/s)**	**Depth (km)**	**P waves Velocity (km/s)**
0.00-1.00	3.28	0.00-1.00	3.30
1.00-3.00	3.46	1.00-3.00	4.80
3.00-6.00	3.18	3.00-6.00	4.80
6.00-10.00	2.95	6.00-10.00	5.18
10.00-15.00	5.59	10.00-15.00	6.53
15.00-20.00	5.10	15.00-20.00	6.53
20.00-25.00	6.68	20.00-25.00	7.12
25.00-30.00	6.98	25.00-30.00	7.49
30.00-36.00	9.07	30.00-36.00	9.63

(A) (B)

Velocity Model Jeffrey-Bullen	
Depth (km)	**P waves Velocity (km/s)**
0-34	6.03
34-67	7.82
67-100	7.93
100-150	8.00
150-200	8.21
200-250	8.34
250-300	8.52
300-350	8.69
350-400	8.84
400-450	9.07
450-500	9.50
500-550	9.86
550-600	10.14
600-650	10.41
650-700	10.62

(C)

The data were selected to determine the arrival time of the primary waves. Hypocenter relocation is done by entering parameters such as latitude, longitude, depth, magnitude, origin time, travel time, one-dimensional primary wave velocity model, and seismic station coordinate, which were then processed using Coupled Velocity-Hypocenter relocation method.

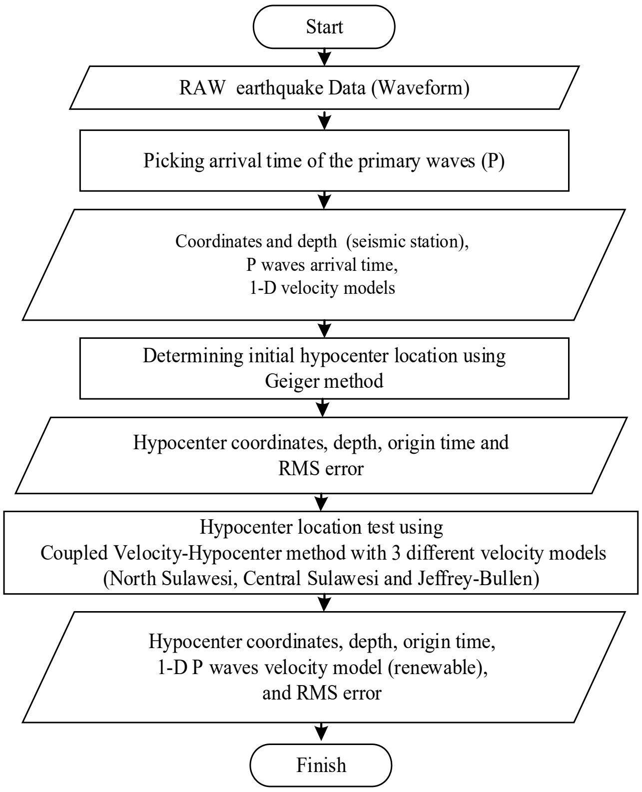

Fig. 1 Research flowchart

In this research, the hypocenter relocation was conducted three times with different velocity models, i.e., Jeffrey-Bullen velocity model, North Sulawesi region velocity model, and Central Sulawesi region velocity model. Therefore, the precise hypocenter locations and error estimations demand the solution of all unknowns in the coupled inverse problem, namely the hypocentral parameters and the velocity field. The minimum 1-D model can be achieved by simultaneously inverting the hypocenter and velocity parameters. The minimum 1-D velocity model obtained by this trial and error process represents the velocity model that most closely reflects the a priori information obtained by other studies, for example, refraction studies, and that leads to a minimum average of RMS error values for all earthquakes [12], [5].

The results of the relocation of the three velocity models can be analyzed to conclude which one velocity model that produces hypocenter location with higher accuracy and is more appropriate with the seismotectonic condition of the research area (Central Sulawesi).

III. Result and Discussion

The Coupled Velocity-Hypocenter method can be used to update the velocity model. The Root Mean Square (RMS error) value in each relocation result is the residual between the observation time (t_{obs}) and the calculation time (t_{cal}) of the hypocenter relocation processing. The preliminary data required to process this method are initial hypocenter data, arrival time recorded on the geophysical station, primary and secondary waves travel time, earthquake station coordinates, and initial velocity model [6].

A. Hypocenter Relocation Using Coupled Velocity-Hypocenter Method

The earthquake data used in this research was the earthquake that occurred in January 2012 - December 2013, with a magnitude of ≥3.8 ML and hypocenter depth between 0-25 km, which is a shallow earthquake. The arrival time of each earthquake was recorded at at least 5 seismic stations because of the assumption that earthquakes recorded at many seismic stations have good seismic parameter solutions [16].

The seismic waves used in this study were the 1-D Primary waves, assuming that it is easier to choose the arrival time because these waves are the first waves recorded on the seismic earthquake station, and these waves can propagate in three mediums, i.e., solid, liquid and gas medium. [17]. There were three initial velocity models in this research, i.e., Jeffrey-Bullen velocity, North Sulawesi region velocity, and Central Sulawesi region velocity model.

Most of the epicenter earthquakes after relocation did not shift significantly; they formed clusters in the minor faults at north Lindu Lake and partly west of Lindu Lake. Therefore, when looking at the results of epicenter earthquake mapping before and after relocation, it is suspected that the earthquake activity originated from minor faults located around Lindu Lake. Several epicenter earthquakes were near the Palu-Koro fault, allegedly due to the activity of the Palu-Koro fault. Palu-Koro fault is active at a shift of about 25-30 mm/year, extending from north (Palu) to south to Bone bay. This fault is also related to the Matano-Sorong and Lawanoppo faults, while at the northern end of the Makassar Strait intersects the subduction zone of the Sulawesi Sea Plate.

After relocation using three initial velocity models, as shown in Fig.3 and in addition to the epicenter shift layout of the earthquake, the depth of hypocenter relocation results also changed as shown in Fig. 2.

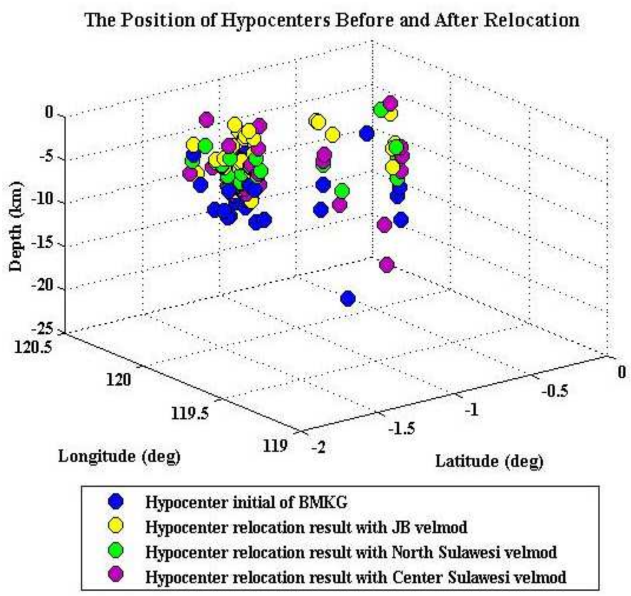

Fig. 2 Location of hypocenter before relocation and hypocenter after relocation by Coupled Velocity-Hypocenter method using three different velocity models.

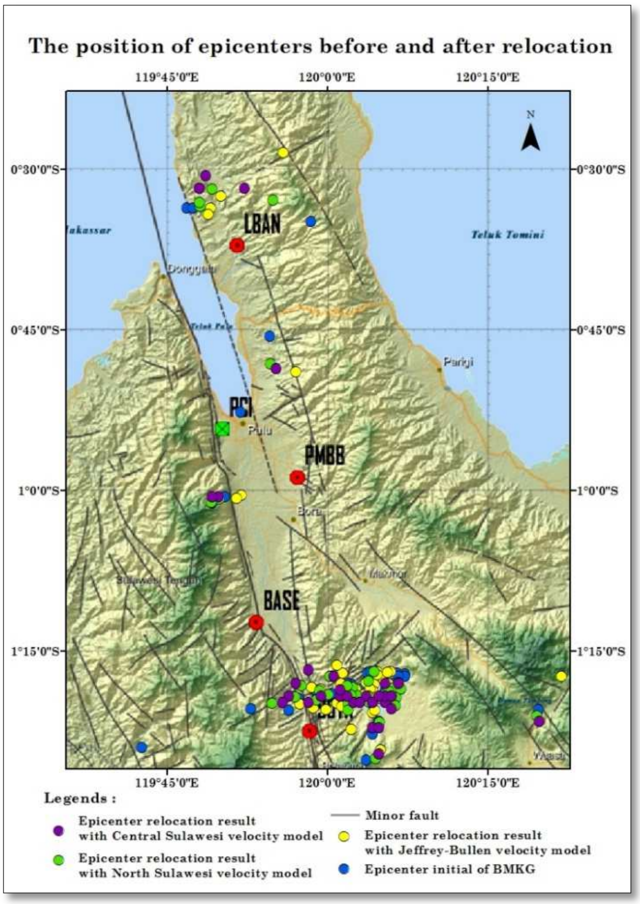

Fig. 3 Initial epicenters location and location of the epicenters after being relocated by Coupled Velocity-Hypocenter method using three different velocity models

The controls of this method were the suitability of the hypocenter distribution with the seismotectonic conditions of the research area and the minimum error value (RMS error), where the smaller (near zero) RMS error value is a better solution. The Root Mean Square (RMS error) value in each relocation result is the residual between the observation time (t_{obs}) and the calculation time (t_{cal}) of the hypocenter relocation processing.

On the other hand, the incorrectly selected arrival time at a seismic station actually denotes a significantly mislocated hypocenter. To overcome this error, we can plot that arrival time in a Wadati diagram and eliminate phases that are too far from the min trend [8], [18].

The relocation result using this Coupled Velocity-Hypocenter method was relatively good, as shown in Fig. 4. The average RMS error of relocation results using Jeffrey-Bullen initial velocity model was 0.18 seconds. When viewed on the histogram of the relocation result, as many as 33 data have a range of RMS error value from 0-0.24 seconds. The average RMS error of relocation results using the North Sulawesi region initial velocity model was 0.35 seconds. When viewed on the histogram of the relocation results, as many as 36 data have a range of RMS error value from 0.25-0.50 seconds. The average RMS error relocation result using the Central Sulawesi region initial velocity model was 0.08 seconds. When viewed on the histogram of the relocation results, as many as 39 data have a range of RMS error value from 0-0.24 seconds.

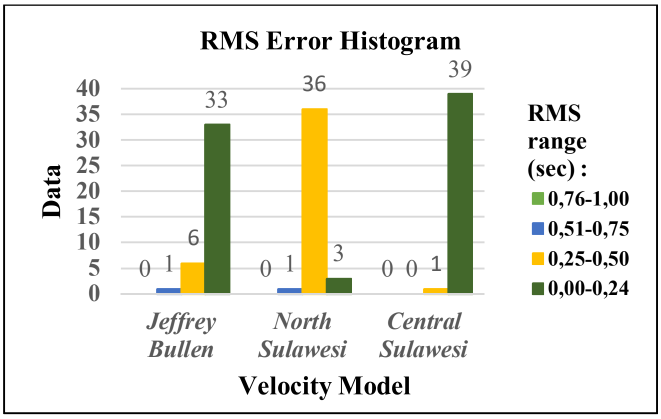

Fig. 4 RMS error residual histogram of relocation result using different velocity models.

From these results, it can be seen that the hypocenter result of relocation using the initial velocity model of the Central Sulawesi region was better than the results of relocation using the initial velocity model of Jeffry-Bullen and the velocity model of North Sulawesi region. It is indicated by the average RMS error value of relocation using the initial velocity model of Central Sulawesi region, which is smaller than the other two models, that is 0.08 seconds (near zero).

B. Updated Velocity Model

The earthquake wave velocity structure model used in Indonesia in general is Jeffrey-Bullen velocity model [15]. Velocity structure model was created assuming ideal spherical earth models. The results of the earthquake hypocenter relocation using Jeffrey-Bullen's initial velocity model show that the velocity model after the relocation is faster than the initial velocity model (Jeffrey-Bullen). However, at a 200-700 km depth, it has the same velocity as the initial model. Table III shows the comparison between the Jeffrey-Bullen initial velocity model with the result of the relocation velocity model using the Coupled Velocity-Hypocenter method.

TABLE III
THE COMPARISON BETWEEN THE JEFFREY-BULLEN INITIAL VELOCITY MODEL WITH RESULT OF THE RELOCATION VELOCITY MODEL USING THE COUPLED VELOCITY-HYPOCENTER METHOD

Velocity Model Jeffrey-Bullen			
Before Relocation		**After Relocation**	
Depth (km)	**P waves Velocity (km/s)**	**Depth (km)**	**P waves Velocity (km/s)**
0-34	6.03	0-34	6.03
34-67	7.82	34-67	7.93
67-100	7.93	67-100	8.00
100-150	8.00	100-150	8.21
150-200	8.21	150-200	8.21
200-250	8.34	200-250	8.34
250-300	8.52	250-300	8.52
300-350	8.69	300-350	8.69

Velocity Model Jeffrey-Bullen			
Before Relocation		After Relocation	
Depth (km)	P waves Velocity (km/s)	Depth (km)	P waves Velocity (km/s)
350-400	8.84	350-400	8.84
400-450	9.07	400-450	9.07
450-500	9.50	450-500	9.50
500-550	9.86	500-550	9.86
550-600	10.14	550-600	10.14
600-650	10.41	600-650	10.41
650-700	10.62	650-700	10.62

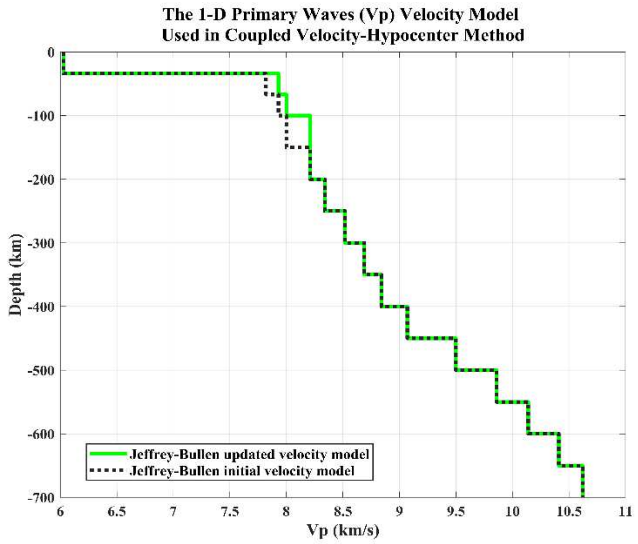

Fig. 5 The Jeffrey-Bullen 1-D Primary waves (Vp) velocity model used in Coupled Velocity-Hypocenter Method

TABLE IV
THE COMPARISON BETWEEN THE NORTH SULAWESI REGION INITIAL VELOCITY MODEL WITH RESULT OF THE RELOCATION VELOCITY MODEL USING THE COUPLED VELOCITY-HYPOCENTER METHOD

Velocity Model North Sulawesi			
Before Relocation		After Relocation	
Depth (km)	P waves Velocity (km/s)	Depth (km)	P waves Velocity (km/s)
0.00-1.00	3.28	0.00-1.00	3.31
1.00-3.00	3.46	1.00-3.00	4.73
3.00-6.00	3.18	3.00-6.00	4.73
6.00-10.00	2.95	6.00-10.00	5.18
10.00-15.00	5.59	10.00-15.00	6.51
15.00-20.00	5.10	15.00-20.00	6.51
20.00-25.00	6.68	20.00-25.00	7.09
25.00-30.00	6.98	25.00-30.00	7.40
30.00-36.00	9.07	30.00-36.00	9.52

The relocation results using the initial velocity model of the North Sulawesi region and the Central Sulawesi region are similar, where the velocity model after the relocation is faster than the initial model. Figures 6 and 7 show the comparison between the initial velocity model of the North Sulawesi region and the Central Sulawesi region with the velocity model from relocation using the Coupled Velocity-Hypocenter method. The three relocation results have similarities: the deeper the location, the greater the velocity of the Primary wave. The closer the location is to the inner core, the layers of the earth will get closer.

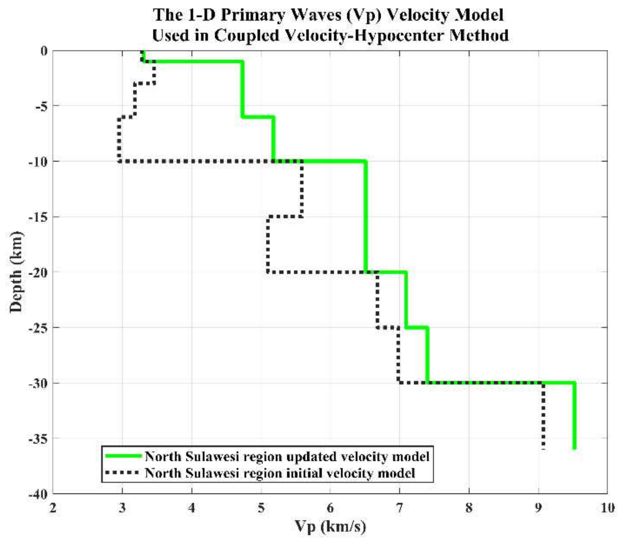

Fig. 6 The North Sulawesi 1-D Primary waves (Vp) velocity model used in Coupled Velocity-Hypocenter Method

The relocation results using the initial velocity model of Central Sulawesi region were better than the results of relocation using the initial velocity model of Jeffry-Bullen and the velocity model of the North Sulawesi region. It is indicated by the average RMS error value of relocation using the initial velocity model of Central Sulawesi region, which is smaller than the other two models, that is 0.08 seconds (near zero).

TABLE V
THE COMPARISON BETWEEN THE CENTRAL SULAWESI REGION INITIAL VELOCITY MODEL WITH RESULT OF THE RELOCATION VELOCITY MODEL USING THE COUPLED VELOCITY-HYPOCENTER METHOD

Velocity Model Central Sulawesi			
Before Relocation		After After relocation	
Depth (km)	P waves Velocity (km/s)	Depth (km)	P waves Velocity (km/s)
0.00-1.00	3.30	0.00-1.00	3.44
1.00-3.00	4.80	1.00-3.00	5.41
3.00-6.00	4.80	3.00-6.00	5.41
6.00-10.00	5.18	6.00-10.00	5.82
10.00-15.00	6.53	10.00-15.00	6.91
15.00-20.00	6.53	15.00-20.00	7.05

Velocity Model Central Sulawesi			
Before Relocation		After After relocation	
Depth (km)	P waves Velocity (km/s)	Depth (km)	P waves Velocity (km/s)
20.00-25.00	7.12	20.00-25.00	7.14
25.00-30.00	7.49	25.00-30.00	7.52
30.00-36.00	9.63	30.00-36.00	9.67

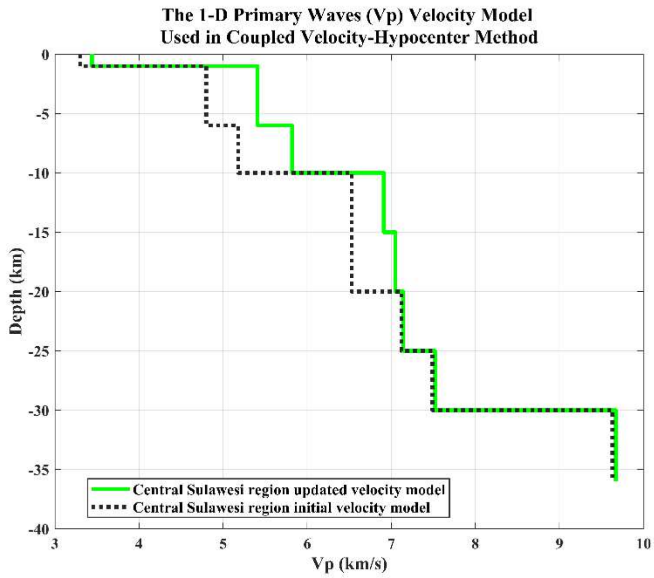

Fig. 7 The Central Sulawesi 1-D Primary waves (Vp) velocity model used in Coupled Velocity-Hypocenter Method

The second indication is the suitability between the distribution of epicenter relocation results with seismotectonic conditions of the research area. Based on the analysis, the one-dimensional Primary wave velocity model of Central Sulawesi region can be used to improve the quality of earthquake relocation by using Coupled Velocity-Hypocenter method. This shows that an unsuitable velocity model can cause systematic errors in the hypocenter location. Therefore, precise hypocenter locations and error estimates require the simultaneous solution of both velocity and hypocentral parameters.

IV. Conclusion

The relocated epicenters indicated similarities, shown by the clusters formed on minor faults at the north of Lindu Lake and partly west of Lindu lake. Upon viewing the results of epicenter earthquake mapping before and after relocation, the earthquake activity is suspected of starting originally from minor faults located around Lindu Lake. The Palu-Koro fault's activity allegedly caused the appearance of several epicenter earthquakes near the Palu-Koro fault. Moreover, the hypocenter relocation results using different velocity models showed similarities as well. Most of the hypocenters form clusters at the depths of 5-15 km, indicating that the earthquakes can be classified as destructive shallow earthquakes and have a depth characteristic of fewer than 60 km. The relocation results using the initial velocity model of Central Sulawesi region were better than the results of relocation using the initial velocity model of Jeffry-Bullen and the velocity model of North Sulawesi region. It is indicated by the average RMS error value of relocation using the initial velocity model of the Central Sulawesi region, which is smaller than the other two models with 0.08 seconds (near zero). The second indication is the suitability between the distribution of epicenter relocation results with seismotectonic conditions of the research area. Thus, the one-dimensional Primary wave velocity model of Central Sulawesi region can be used to improve the quality of earthquake relocation using Coupled Velocity-Hypocenter method. Therefore, it can be concluded that the 1-D velocity model in the regional (Central Sulawesi Region) reference was suitable for determining the high-precision hypocenter location.

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