Application of double-difference method for relocating aftershocks hypocenters in Opak Fault Zone

Y Nurbaiti1, E Ibrahim2, M U Hasanah1 and B Wijatmoko1
1Geophysics Departement, Padjadjaran University, Jl. Raya Bandung-Sumedang Km 21, Jatinangor, Sumedang 45363, Indonesia
2Research Division, Institute Technology of Sumatra, Jl. Terusan Ryacudu, Way Hui, Jati Agung, Lampung 35364, Indonesia
E-mail : yasminnurbaiti@gmail.com

Abstract. The 6.4 Mw earthquake occurred in Yogyakarta on 27th May 2007 has been renowned as a manifestation from Opak fault activity. Double-Difference (HypoDD) method was implemented to relocate hypocenters location, due to its poor accuracy caused by un-modeled velocity structure. The relocation was carried out on aftershocks data from 15th June to 19th June 2006. This method relocated 296 out of 303 aftershock events. Seismicity map after relocation showed concentrated epicenters by the east side of Opak fault. Distribution of the hypocenters which previously ranged from 0 to 40 km significantly shifted to the range of 10-20 km. RMS values obtained after relocation reduced close to 0 which indicated an outstanding improvement of hypocenters location in Opak fault zone.

1. Introduction
On 27th May 2006, a 6.4 Mw earthquake occurred in Yogyakarta for 60 seconds and followed by approximately 750 aftershocks [1]. Based on coseismic deformation research and GPS survey done by Geodetic Engineering Team of ITB, the earthquake originated from a sinistral fault existed 3-4 km by the east side of Opak Fault. However, the aftershocks data recorded 3 months after showed that the earthquake was generated 10-20 km by the east side of Opak Fault [2]. Both theories not only referred that Opak Fault has shifted from its initial position in Geologic Maps, but also revealed the likelihood of the existence of another unknown fault. The contradiction nevertheless requires a validation from seismicity analysis of earthquake data.

Seismicity analysis demands hypocenters location for identifying the fault zone and micro-fractures orientation accurately. The main problem of seismic analysis is the uncertainty hypocenters location caused by the un-modeled velocity structure that many times larger from the source dimension of event itself [3,4]. Waldhauser and Ellsworth established Double-Difference algorithm implemented in

*To whom any correspondence should be addressed.
Hypocenters Double-Difference (HypoDD) program to increase the accuracy. This method utilizes the fact that if the hypocenter separation between two earthquakes is small compared to event-station distance and the scale length of velocity heterogeneity, then the ray paths between the source region and common station are similar along almost the entire ray path. The bottom line is the difference in travel times for two earthquake events observed in one station can be attributed to the spatial offset between the events with high accuracy [4]. Therefore, Double-Difference relocation method was carried out to enhance hypocenter location. Aftershocks events which recorded by BMKG and GFZ stations in Yogyakarta and Surakarta region were used for relocation. Through data processing, improved accuracy hypocenters were achieved and effectively able to delineate tectonically active zone in fault area.

2. Regional Geology of Survey Area
According to gravity research, this fault lied along the Opak river that extends from Prambanan to its estuary by the west side of Parangtritis (Depok beach) [5]. Geology Map of Yogyakarta showed the sedimentation deposit of research area divided in several rock formations, respectively from old to young [6,7]:

- **Semilir Formation**
  Consisted of tuff tuck, breccia, dacitic tuff and andesite tuff, tuff and clay tuff. This formation was deposited at the end of Lower Miocene and the oldest rocks unfolded in research area.

- **Nglangrran Formation**
  Consisted of volcanic breccia with andesitic fragment, breccia, conglomerate, and lava. This formation in several places was seen as a development of andesite-basaltic rock that gradually changed to pillow structure auto-clastic breccia, hialoclastic, and eventually became andesitic-sanctuary. This formation aged at Middle Miocene and lied parallel to Semilir Formation.

- **Sambipitu Formation**
  The Miosen aged formation consisted of sandstone and clay, silt, tuff, and conglomerate. This formation was deposited above Nglanggran Formation.

- **Wonosari Formation**
  This formation consisted of limestone and calcarenite. This formation aged Middle Miosen to Upper Miosen and deposited parallel to Sambipitu Formation.

- **Kepek Formation**
  The Upper Miosen aged formation consisted of limestone stack and napal. This formation was deposited parallel to Wonosari formation.

3. Methods
3.1 Earthquake Data and Recording Stations
This research aimed to investigate aftershocks data taken from 16 BMKG and GFZ recording stations in Yogyakarta and Surakarta region. The aftershocks data ranged for a period of 15th June to 19th June 2006 where the seismic activity was moderately active. Figure 1 shows recording stations in research area. The blue dots represent earthquake recording stations.

3.2 Model Parameter
Initial hypocenters location were obtained by using Grid-Search method applied in Nonlinloc program. The Grid Search method principle was based on nested grid with fixed size, number of nodes, and location. The location of the grid will be set automatically in the x, y, z directions. Location quality (misfit) can be specified in each location grid. Thus travel time observation results can be obtained on each nodes of the corresponding travel time grid file [8].
AKA135 velocity model with depth over 120 km was used as reference model. The model used consisted of maximum 7 (seven) layers as shown in Table 1. The Vp/Vs Ratio is constant at 1.71. Vp/Vs ratio is important for locating hypocenters location but does not significantly affect relative velocity variation in tomography inversion [9].

3.3 Relocation with HypoDD

Inversion in HypoDD divided into two types namely SVD (Singular Value Decomposition) and LSQR (Conjugate Gradient Least Squares). SVD inversion is generally used to process data in a small system with 100 earthquake events. This research thus used an LSQR inversion that can provide complete earthquake event relocation processes on larger systems [5]. LSQR can resolve the damped least square problem. DAMP is a damping factor that affects the hypocenters adjustment if the adjustment vector becomes broad or unstable. Determination of damping factor is highly dependent on the condition of the system. In data with large clusters, large attenuation can be determined freely, but if damping factor is too high it will result in a moveable hypocenters location unable to move [3]. The damping value of the solution vector provides control of the convergence velocity in obtaining solutions that can affect the number of iterations (NITER). In general, the first iteration contributed to a change in hypocenters location position. The subsequent position changes will be arranged sequentially after the first iteration corresponds to the uncertainty on the location in the catalogue data. Iterations can be stopped when the hypocenter or residual RMS positioning has reached below the noise level of the data.

![Figure 1. BMKG and GFZ earthquake recording stations plotted in Yogyakarta and Surakarta Geology Map. The blue dot represents recording stations](image-url)
Table 1 AKA135 Velocity Model (Kennett, Engdah & Buland, 1995)

| Depth (km) | Vp (km/s) | Vs (km/s) |
|-----------|-----------|-----------|
| 0         | 1.45      | 0         |
| 3         | 1.45      | 0         |
| 3         | 1.65      | 1         |
| 8         | 1.65      | 1         |
| 8         | 5.8       | 3.2       |
| 10        | 5.8       | 3.2       |
| 10        | 6.8       | 3.9       |
| 18        | 6.8       | 3.9       |
| 18        | 8.0355    | 4.4839    |
| 43        | 8.0379    | 4.4856    |
| 80        | 8.040     | 4.480     |
| 80        | 8.045     | 4.490     |
| 120       | 8.050     | 4.500     |
| 120       | 8.050     | 4.500     |

4. Results and Discussion

Figure 2. (a) Shows epicentres distribution using Grid-Search method, (b) shows epicentres distribution after relocation with HypoDD program. The red dots represent epicentres meanwhile the blue line is A-B incision line to delineate hypocentres distribution in subsurface.
Figure 3. (a) Showed hypocenters distribution using Grid-Search method in the sub-surface below A-B incision line, (b) showed hypocenters distribution after relocation using HypoDD program in the subsurface below A-B incision line.

Figure 4. Shows RMS Residual Comparison between before relocation and after relocation process. Red bar represents after relocation RMS data and Blue bar represents before relocations RMS data.

5. Data Interpretation
HypoDD program has relocated 296 out of 303 earthquakes by using high value of NITER and Damping factor. Post-relocation seismicity map in figure 2(a) showed concentrated aftershocks event by the east section of Opak fault in direction of North-East and South-West. This hypocenter distribution was allegedly caused by contrast lithology difference between east and west section of Opak fault. Based on geology map of Yogyakarta region, the eastern section of Opak fault was composed of Nglanggran Formation, Wonosari Formation, and Kepek Formation; whereas the western section was composed of Semilir formation.

Semilir Formation is composed of tuff rock, breccia, andesite and tuf andesite which can be classified as volcanic igneous rocks. Volcanic frozen-rock deposits in the Semilir formation originated from the eruption of young Merapi volcano. On the other side; Nglanggran, Wonosari, Kepek Formation which mostly composed by limestone and tuff were considered to have sedimentary lithology.

The large number of aftershocks occurred at the east section of the fault can be interpreted that sedimentary rocks have greater energy compared to igneous rock. The earthquake energy depends on the characteristics of existing rocks and the amount of stress contained within [10]. Areas with fragile rock, the stress contained is not large because it is immediately released through the occurrence of many small earthquakes. As for stronger rocks, small earthquakes rarely or even never occur so that the stress contained is very large and when the rocks are no longer able to withstand stress, there will be earthquakes with a large magnitude. Strong rocks can be associated as compact igneous rocks and have
very small porosity because of the pressure below the earth's surface. Meanwhile, fragile rocks can be associated as sedimentary rocks that have greater porosity and compaction due to transport and sedimentation processes. In this case, the east section of the fault which mostly consisted of sedimentary rocks caused more aftershocks than the west section did.

6. Conclusion
The NITER and Damping parameters applied to the relocation process affected the quality of the hypocenters location. The greater value of NITER and Damping factor used, the lower the RMS value obtained. The relocation results show the tendency of the event to form one cluster on the east section of the Opak fault with the direction of North-East Southeast. Residual RMS values after the relocation process indicated an improvement of the hypocenters location affected by the eastern section Opak Fault which is composed of sedimentary rocks.

Epicenters distribution after relocation shows that the eastern section of the Opak fault tectonically active than the western section due to its composition of sedimentary lithology. Sedimentary rocks that have large porosity will store more earthquake energy resulting in the occurrence of many earthquakes with small magnitude.

Acknowledgement
We acknowledge the support from Department of Geophysics, Faculty of Mathematics and Science, University of Padjadjaran.

References
[1] Abidin Z H, Andreas H, Meliano I, Gamal M, Usuma M A, Imata F and Ando M 2007 Deformasi Seismik Gempa Yogyakarta dari Survei GPS Jurnal Geofisika Indonesia Edisi 2007 No 1
[2] Walter T R, Wang R, Leuher B G, Wassermann J, Behr Y, Parolais, Anggaini A, Gunther E, Sobiesek M, Grosser H, Wetzel H U, Mikereit C P J, Sri Broto, Puspito K, Harjadi P and Zschau J 2008 The 26 May magnitude 6.4 Yogyakarta Earthquake south of merapi Vulvano: did lahar deposit amplify ground shaking and thus lead to the disaster? AGU and The Geochecimal Society 9 (5) 1-9
[3] Dunn M Meredith 2004 Relocation of Eastern Tennessie Earthquakes using HypoDD Master Thesis, Virginia Polytechnic Institute and State University, Blackburg
[4] Waldhauser F and Ellsworth W L 2000 A Double-difference earthquake location algorithm: Method and Application to the Northern Hayward fault, California, Bull. Seismology Soc. Am. 90 1353-1368
[5] Sudarno I 1997 Petunjuk Adanya Reaktivasi Sesar Di Sekitar Aliran Sungai Opak, Perbukitan Jiwo Dan Sisi Utara Kaki Pemungunan Selatan Media Teknik No.1 Tahun XIX Edisi Februari 1997
[6] Rahardjo W and Sukandar Rumidi Rosidi H 1995 Peta Geologi Lembar Yogyakarta P3G Bandung
[7] Surono Budi Toha and Sudarno 1992 Peta Geologi Lembar Surakarta - Giritingtong, Jawa, Skala 1:100.000 Pusat Penelitian dan Pengembangan Geologi Bandung
[8] Lomax A, J Virieux, P Volant and C. Berge 2000 Probabilistic Earthquake Location In 3D And Layered Models: Introduction Of A Metropolis-Gibbs Method And Comparison With Linear Locations, In Advances In Seismic Event Location Thurber C H and N Rabinowit (eds.), Kluwer, Amsterdam, 101-134.
[9] Koulakov I et al 2007 P- and S-velocity structure of the crust and the upper mantle beneath Central Java from local tomography inversion J. Geophys. Res. 112B08310, doi:10.1029/2006JB004712
[10] Ibrahim Gunawan and Subardjo 2004 Seismologi Jakarta : BMKG