POSIBILITAS PENENTUAN MAGNITUDE GEMPABUMI REAL TIME MENGGUNAKAN GPS UNTUK SISTEM PERINGATAN TSUNAMI DI INDONESIA

A POSSIBILITY OF REAL TIME EARTHQUAKE MAGNITUDE DETERMINATION USING GPS FOR TSUNAMINWARNING SYSTEM IN INDONESIA

Sulastri[1,*)], Buldan Muslim[2], Bambang Sunardi[1], Supriyanto Rohadi[1], Yusuf Hadi Perdana[1], Muzli[1,3], Susilo[4], Jonny Effendi[4]

[1]*Pusat Penelitian dan Pengembangan BMKG, Jakarta*
[2]*Pusat Sains Atmosfer LAPAN, Bandung*
[3]*Earth Observatory of Singapore, Singapura*
[4]*Badan Informasi Geospasial, Bogor*
[*]email: sulastri@bmkg.go.id

Abstrak

Tulisan berikut merupakan studi awal tentang posibilitas penentuan magnitude gempabumi secara real time dari data GPS di Indonesia untuk sistem peringatan tsunami. Sampai sekarang, penentuan sumber gempabumi di Indonesia menggunakan rekaman seismik. Dengan penelitian kolaborasi dan menggunakan jaringan GPS yang diatur oleh Badan Informasi Geospasial/ BIG, terdapat suatu kesempatan untuk menentukan magnitude gempabumi dengan cara lain, disamping menggunakan jaringan seismograf dan akselerograf. Vektor perpindahan dari pengukuran GPS memegang peranan penting dalam penentuan magnitude gempabumi. Ke depannya, penentuan magnitude gempabumi menggunakan GPS dapat mendukung Sistem Peringatan Dini Tsunami yang dilaksanakan oleh BMKG.

Kata kunci: GPS, magnitude gempabumi, sistem peringatan tsunami.

Abstract

This paper contains preliminary study about the possibility of real time earthquake magnitude determination from GPS in Indonesia for tsunami warning system. Until now, the determination of earthquake sources in Indonesia by using seismic records. By a collaborative research and utilizing the GPS networks managed by Indonesian Geospatial Information Agency (Badan Informasi Geospasial/ BIG), there is a chance to determine the earthquake magnitude in another way, instead of using seismograph and accelerograph networks. The displacement vector from GPS measurements plays important rules in the earthquake magnitude determination. In the future, the earthquake magnitude determination using GPS could support the Indonesia Tsunami Early Warning System conducted by BMKG.

Keywords: GPS, earthquake magnitude, tsunami warning system.

Introduction

The Most tsunamis are generated by earthquakes. The 2004 Sumatra, Indonesia and the 2011 Tohoku, Japan tsunamis were generated by the great earthquakes. The magnitude of earthquake as one of earthquake source is the crucial parameter to be determined rapidly and correctly. After the 2004 Sumatra Earthquake, Indonesia in collaboration with German through the German Indonesian Tsunami Warning System (GITEWS) built a system to handle the earthquakes and tsunamis in Indonesia. Various sensor systems such as seismic, GPS, and tide gauge stations were installed in Indonesia, and the data is merged and integrated at the Tsunami Warning Centre at Badan Meteorology Climatology dan Geofisika, BMKG (Agency for Meteorology, Climatology, and Geophysics) in Jakarta.

The first warning tsunami message has to be issued no later than 5 minutes after the earthquake's origin time. This time limit is too short to provide a set of source parameters and accuracy necessary for a reliable near-filed early warning. Since 2008, a near real time GPS-Shield called GTS (Ground Tracking System) is operated [1]. The GTS provides displacement vector data for locations that send Global Navigation Satellite System (GNSS) raw data. The displacements are calculated as differences between the GNSS-stations coordinates before the earthquake. The time from GNSS to product deliveries is only 1-2 minutes, provided that GNSS raw data is received in real-time. Figure 1 showed example for the display of displacement vectors on the GTS Map View, based on data simulated for an earthquake that occurred on 2005-03-28, M 8.6, at a depth of 30 km, and GNSS-station locations providing input to the GTS [1].

Figure 1. Example for the display of displacement vectors on the GTS Map View [1].

In principle, the national GPS CORS network of Indonesia, officially is the one that is established by Bakosurtanal [2, 3]. Usually, this network is termed as the Indonesian Permanent GPS Station Network (IPGSN). The primary purpose of the IPGSN is to maintain an accurate and precise geodetic reference frame over Indonesian region, and also to support a wide range of scientific and practical applications such as geodynamics and deformation monitoring, meteorological and ionospheric studies, sea level monitoring, intelligent transportation systems, and real-time based surveying and mapping applications. After the 2004 Sumatra earthquake, the IPGSN network was rapidly developed as part of the development of the Indonesian Tsunami Early Warning System (Ina TEWS). In December 2017, the network had consisted 134 stations, which is depicted in Figure 2.

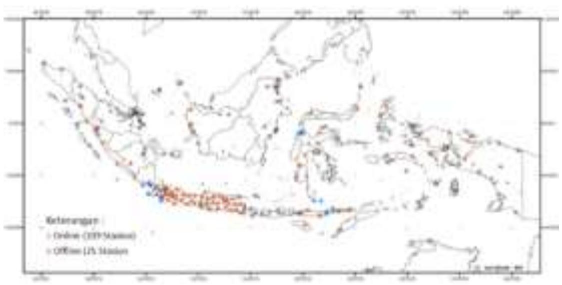

Figure 2. GPS CORS stations over Indonesia (source: BIG).

To support the early warning system to be given less than 5 minutes, it is needed the determination of earthquake magnitude in another way, instead of using the seismic network. As stated above, the displacements could be delivered in 1-2 minutes by using the GNSS, so it is possible to determine the earthquake magnitude by using the GNSS data less than 5 minutes. An alternative determination of magnitude instead of using seismogram is needed, because for large earthquake the current warning tends to be underestimated. The purpose of this paper is to determine whether there is any possibility to make real time earthquake magnitude determination using GPS to support tsunami warning system in Indonesia At the first step, this study was focused in the review of some previous researches related to the earthquake magnitude determination as a preliminary study.

Reviews of Earthquake Magnitude Determination

Richter in 1935 introduced earthquake magnitude scale as a log function of the amplitude of the seismogram record and distance. The magnitude of any shock is taken as the logarithm of the maximum trace amplitude, expressed in micron, with which the standard short-period torsion seismometer ($T_0 = 0.8\ sec$, $V = 2800$, $h = 0.8$) would register that shock at an epicentral distance of 100 kilometers [4].

Guteberg (1945) deduced empirical relationship between peak displacement (*A*), distance (Δ), and magnitude (*M*) as below [5]:

$$M = \log A + 1.66 \log \Delta + 2.0 \quad (1)$$

Hanks and Kanamori formed the relationship between seismic moment M_0 and the magnitudes M_L, M_s and M_w, which is uniformly valid for $3 \lesssim M_L \lesssim 7$, $5 \lesssim M_s \lesssim 7\frac{1}{2}$ and $M_w \gtrsim 7\frac{1}{2}$ as equation below [6]:

$$M = \frac{2}{3} \log M_0 - 10.7 \quad (2)$$

It is possible to determine earthquake magnitude using the displacement amplitude. Hara [7] applied earthquake magnitude determination using high frequency energy radiation and displacement amplitude to tsunami earthquakes, included 1994 and 2006 Java earthquakes. The high frequency energy radiation duration could be determined from a time series of squares of band-pass (2-4 Hz) filtered seismogram. The earthquake magnitude then determined by the following formula:

$$M = 0.79 \log A + 0.83 \log \Delta + 0.69 \log t + 6.47 \quad (3)$$

Where *M* is an earthquake magnitude, A is the maximum displacement (m) during the estimated duration of high-frequency energy radiation from the arrival time of a P-wave, Δ is the epicentral distance (km), *t* is the estimated duration (*s*) of high-frequency energy radiation. The estimated magnitudes by this method were significantly larger than M_s, and close to M_w for tele-seismic events.

A rapid moment magnitude estimation using static surface displacement from single strong motion data also had been done by Muzli et al., 2015 [8]. They calculated moment magnitude by using a certain model. The model uses finite rectangular faults and calculates deformations due to shear and tensile faults in half space. The input parameters are: the centroid location (latitude, longitude, and depth), fault geometry (strike, dip, rake and rupture's area) and average slip of the earthquake. Static deformation could be predicted and then compared with the observation data at the same coordinate. Using a grid search method, all possibilities of moment and centroid position near hypocenter location were searched iteratively over the magnitude range between 6.0 to 9.5 at intervals of 0.1. For each magnitude iteration, the moment magnitude is calculated using the equation

$$\log(M_o) = 1.5\, M_w + 9.1 \quad (4)$$

Then by assuming the commonly used elastic shear modulus $\mu = 30\, GPA,$ the slip value os calculated by equation

$$M_o = \mu\, D\, A \quad (5)$$

Where *D* is the slip average of the whole rupture area (*A*). The rupture area os calculated using empirical relation of magnitude-area scaling laws. Length (*L*) and Width (*W*) of the rupture area are calculated from equations bellow:

$$\log(L) = 0.63\, M_w - 2.86 \quad (6)$$

$$\log(W) = 0.41\, M_w - 1.61 \quad (7)$$

For the misfit calculation between observation and prediction displacements data, the vertical displacements were weighted 25% relatively to the horizontal components. The rake can be approximated to be close to 90 degrees or by optimum search that is at the minimum misfit value. The result of the method for 2004 Sumatra earthquake using rake of 90 degrees could be seen as Figure 3 [6].

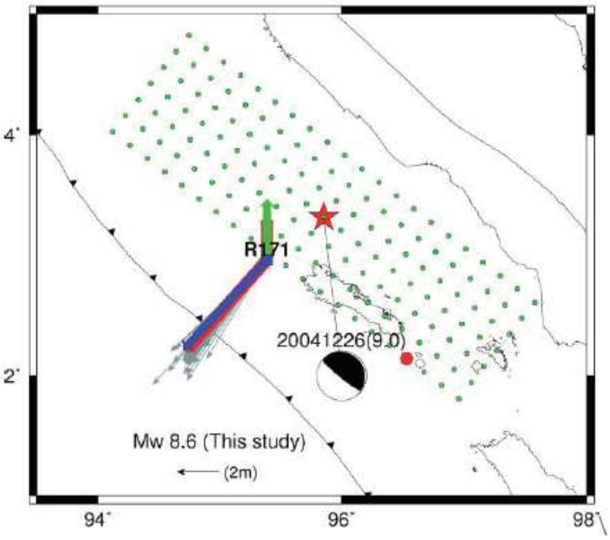

Figure 3. Result of a rapid moment magnitude determination of 2004 Sumatra earthquake using static surface displacement from strong motion data [8].

The magnitude determination by Hara and Muzli et al., above used the seismogram and also accelerogram respectively. Now, we will search another magnitude determination using GPS data. The 26 December 2004 Sumatra Earthquake was the first event to be recorded by seismic and also Global Positioning System (GPS) networks. Also, the event could be said as a starting point when the researches about earthquakes and tsunamis variously increased. The spatial pattern, magnitude, and timing of permanent displacement of GPS stations are keys so that it can be inverted for the earthquake source. The horizontal displacement of GPS station corresponds with ocean bottom displacement. Permanen displacements of the Earth's surface determined by GPS can be used to constrain earthquake models from which the magnitude (M_0 and M_w) can be computed. When using GPS, M_0 is often called "the static moment", which equals the seismic moment if the fault rupture entirely seismically. The magnitude of the 2004 Sumatra earthquake could be determined using only GPS data within 15 min after origin time [9].

The GPS could estimate the seismic moment magnitude (M_w) with some fundamental requirements, that are the GPS network has sufficient near-field stations (within 1 rupture length) to capture the permanent displacement signal, GPS network has sufficient far-field stations to provide a reference frame and an upper bound on the seismic moment, GPS station transmit their data in (near) real time, and GPS analysis systems are in place to handle near real-time data, including the precise estimation of GPS orbits, as well as the estimation of GPS displacement. Figure 4 illustrate the GPS permanent displacements observed during the M_w 9.2 2004 Sumatra earthquake, with $\sim$ 10 mm accuracy [10].

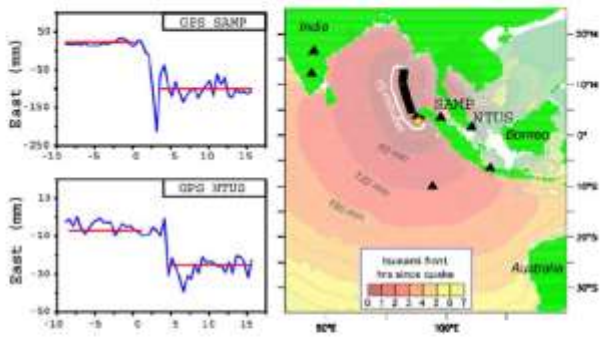

Figure 4. GPS permanent displacements observed during the 2004 Sumatra earthquake. The right one is the ocean-wide tsunami that be generated by the Sumatra earthquake [10].

The real time and reliable magnitudes for large earthquakes could be determined from 1 Hz GPS precise pint positioning. A simple static inversion on a subset of stations was used to determine the portion of the fault that slipped and the earthquake magnitude [11]. Fang et al. [10] used a real-time precise point positioning (RTPPP) system, and estimating the magnitude based on GPS displacement waveforms derived from RTPPP. High accuracy satellites orbits and clocks must be provided to implement RTPPP, which based on the real time data streams. The RTPPP system based on PANDA (positioning and navigation data analysis) software package, developed by GNSS Research Center, Wuhan University. After the orbit and clock products was estimated and then transmitted to the user, the high rate GPS data on observations can be processed in RTPPP mode. Zero differenced ionosphere free observations are used to eliminate the ionosphere delays, and the Saastamoinen model with the global mapping function is used to correct tropospheric delays. To estimate residual tropospheric zenith path delay, receiver clock errors, ambiguity and station coordinates, the SRIF approach is used.

The RTPPP displacement waveforms are consistent with IRP in the horizontal components, whereas the vertical are not exactly consistent. The horizontal displacement waveforms then to be used to estimate the earthquake magnitude. The horizontal peak displacement was defined by equation $\sqrt{E^2 + N^2}$, where *E, N* are east and north components of displacements from RTPPP results. As the investigation result, the peak displacement derived from GPS is a surface wave rather than a P wave. In this method only focused on how GPS displacements can be used for rapid determination of earthquake magnitude. The assumption used in this method is that the earthquake is a point source event or that the epicentral distance of GPS site is enough long to approximate the earthquake as a point source event. The Guteberg equation (Eq. 1) is still appropriate for magnitude based on the near field GPS peak displacement. Only stations with epicentral distance less than 300-500 km are selected, in order to improve the signal to noise ratio (SNR). A point distance was assumed to calculate the epicentral distance and magnitude. The magnitude can be estimated as soon as peak displacement arrived at GPS site, that is it need tens of seconds or a few minutes after an event using a few GPS stations close to epicenter [12].

Melgar et. al [11] used the scaling of peak ground displacement (PGD) from high rate GPS networks to calculate earthquake magnitude. The used GPS at near-source regional distances ($\sim$ 10 – 1000 km), from earthquake between M_w 6 and 9. PGD is the peak dynamic displacement on the unfiltered GPS seismogram. The PGD value from the three component seismogram extracted as [13]:

$$\mathrm{PGD} = \max\left(\sqrt{[N(t)^2 + E(t)^2 + U(t)^2]}\right) \quad (8)$$

where *N(t)*, *E(t)*, and *U(t)* are the north, east, and up displacement seismograms. The scaling law proposed by Crowell et al., (2013) for PGD which includes magnitude-dependent attenuation to account for the relative strengths of the near, intermediate, and far field seismic radiation terms then applied [13]:

$$\log(\mathrm{PGD}) = \mathrm{A} + \mathrm{B} \cdot \mathrm{M_w} + \mathrm{C} \cdot \mathrm{M_w} \cdot \log(R) \quad (9)$$

where *A*, *B*, and *C* are the regression coefficients, M_w is moment magnitude, and *R* is the source to station distance. From the 1321 PGD measurements, and using the earthquake magnitudes for each event determined from finite fault inversions or centroid moment tensor (CMT), the regression for coefficients *A*, *B*, and *C* was performed using an L1-norm minimizing solver that does not have strong sensitivity to outliers. In this way each earthquake is weighted equally in the regression. The procedure was repeated 1000 times to estimate the variance of the coefficients. The regression coefficients computed are $A = -4.434 \pm 0.141$, $B = 1.047 \pm 0.022$, $C = -0.138 \pm 0.003$, and the standard error of the magnitude residuals is 0.27 magnitude units. This result implied the Eq. 9 become [13]:

$$\log(\mathrm{PGD}) = -4.434 + 1.047 \mathrm{M_w} - 0.138\, \mathrm{M_w} \cdot \log(R) \quad (10)$$

The last method of computing magnitude from GPS come from Psimoulis et al. [12]. They focused on the predominant period methodology and identify three reasons for the limited performance of EEW during large earthquake. Firstly, the overlap of the predominant period with microseismicity. This noise contributes to limitations of EEW systems in terms of both response time and magnitude determination accuracy. Secondly, processing step, such as de-trending and high-pass filtering, may remove long-period signals that are necessary to capture the size of large events. Thirdly, potentially remaining errors in the acceleration record will affect the recursive procedure of the τ_p computation. The use of narrow-width windows, within which τ_p is computed, makes τ_p non-sensitive to long period signals and therefore may be inappropriate to capture the seismic source spectrum of events of $M_w > 7.0$, causing underestimation of event magnitude [14].

The predominant period (τ_p) of a seismic signal is computed by the recursive relation [14]:

$$\tau_{p(i)} = 2\pi \sqrt{\frac{X_i}{D_i}} \quad (11)$$

where X_i and D_i are the smoothed squared ground velocity and acceleration, respectively, at time *i*, given by the relationships $X_i = \alpha X_{i-1} + {x_i}^2$ and $D_i = \alpha D_{i-1} + \left(\frac{dx}{dt}\right) i^2$, with α being a smoothing constant, taken as $\alpha = 0.99$ for 100 Hz sampling rate.

For the computation of τ_g, it can be used the same recursive relation of τ_p, with the GPS displacement time series being differentiated once and twice to velocity and acceleration, respectively. The mean trend of τ_g increases with the M_w, while the noise level of $\tau_g$max is rather stable, regardless of the earthquake magnitude. By applying linear regression, for $\alpha = 0.99$ and $M_w \geq 6$,

$$\tau_g = 0.176 M_w + 2.150 \quad (12)$$
$$(r^2 = 0.98, n = 42, and\ p = 1.84 \times 10^{-5})$$

And for $\alpha = 0.36$ and $M_w > 6.5$

$$\tau_g = 3.050 M_w - 16.812 \quad (13)$$
$$(r^2 = 0.98, n = 30, and\ p == 2.03 \times 10^{-3})$$

where *r*, *n*, and *p* are the regression coefficient, the number of the data and the p-value of the regression analysis.

Method

Various methods could be conducted to calculate the earthquake magnitude as above. We plan to develop a methodology to calculate earthquake magnitude from real time GPS data as in Figure 5:

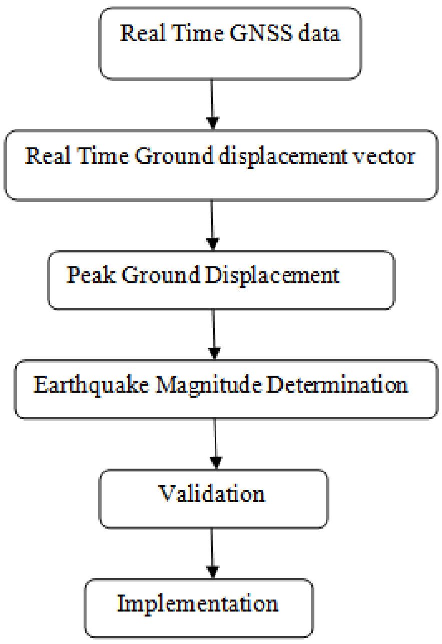

Figure 5. A methodology developed to calculate earthquake magnitude from GPS data.

Conclussion

The earthquake magnitude also could be determined by using the ground displacement from GPS data. By implementing the GPS displacement method as an operational real-time system, GPS could be incorporated into tsunami warning system. GPS data could then be used to rapidly model the earthquake and thus initialize parameters for real-time modeling of tsunami generation.

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