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Simple Deformation Modelling Using GNSS GPS Data at Minahasa Subduction

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Abstract. North Sulawesi Trench or Minahasa subduction area is a subduction zone between the oceanic crust of Sulawesi Sea and the North Sulawesi Arm located at the triple junction in Eastern Indonesia. This subduction activity causes the North Arm of Sulawesi as an earthquake-prone area. Tectonic activities in the region can be studied through geodetic monitoring using GNSS GPS observations and by physical modelling from the rate of geodetic geometric results. Yearly GNSS GPS campaign have been conducted in the region from 1997 to 2008 and continuously observed by BIG from 2008 to 2016 using permanent GNSS GPS stasion. The coordinates of monitoring stations realized in ITRF-2008 provide residual RMS values of 3.13 mm, 4.15 mm and 7.26 mm for the northern, eastern and vertical components, where this indicates a high degree of accuracy. A simple estimation profile using GNSS GPS data based on the Okada elastic equation for the subduction zone shows a subduction movement ranging from 4 to 5 cm/yr with a locking depth of about 50 km, a dip 300 and ending in the post-seismic phase due to the sequence of earthquakes occurring in Minahasa since January 1, 1996 Mw 7.9 to 16 June 2002 Mw 5.9.

INTRODUCTION

The convergence between the three major plates in eastern Indonesia: Australia, the Pacific and Eurasia [1] has caused Sulawesi Island in this region become a geologically complex zone [2] (Fig.1A and C). One of the phenomena that resulted was the formation of Minahasa subduction (North Sulawesi Trench), which is a subduction zone between the oceanic seabed of Sulawesi Sea [3] and North Sulawesi Arm. Various studies have been undertaken by previous researchers both geologically, geophysically and geodetically in the region. Geological tectonic reconstruction based on a holistic approach in it including paleomagnetic data indicates that there are two opinions on Sulawesi's development, especially concerning the Southwest Arm and the North Arm [4,5,6]. [4] made a reconstruction that the Southeast Arms and North Sulawesi were part of a long arc from Java-Bali-Nusa Tenggara Timur since Tertiary, and then rotated to the present position. While [5,6] states that the arm has been separated from the Bali group to other Nusa Tenggara Timur or is part of the Sunda Block (including Java) since Tertiary, and the other part merges then to the recent. The reconstructions of Sulawesi tectonic and its surroundings associated with plate boundaries and active tectonics, are driven by [7] and then to be detailed by [8]. For the North Arm region, absorption occurs by the active tectonic structure which is related to the shortening that occurs in the North Sulawesi subduction zone (Minahasa Trench) which is accommodated by the Palu-Koro fault and the Matano faults. These two faults are left lateral fault that act as a "trench-to-trench transform" separates southern and southwestern Sulawesi with northern and northeastern Sulawesi [1, 7, 9, 10, 11, 12, 13]. Paleomagnetic data [14] and geodetic measurements [1, 10, 13, 15] confirm that the Sula Block [16] comprising northern arm - northeastern arm of Sulawesi, Banggai Sula, Buru and the North Banda Sea Basin are separate part of the plates Australia, the Pacific or the Sunda Block. The Sula block rotates clockwise relatively to the Sunda Block at a rate about 4^{o} / Ma with a

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rotational pole located near the northeast end of Sulawesi's Northern Arm [10, 16, 17]. From the geological and geophysical studies of the sea consisting of gravity and seismology, [7] it states that there is a link between Palu-Koro Fault and subduction in Northern Sulawesi, this relationship is the classic pair of plate tectonics between the convergent and accomodated plates, although this relationship within the mapped detail limit is still not visible.

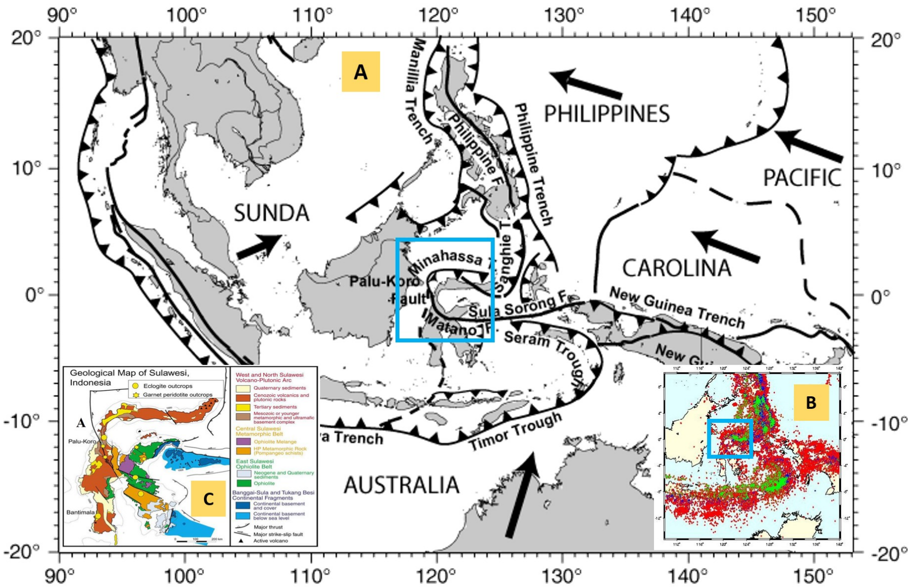
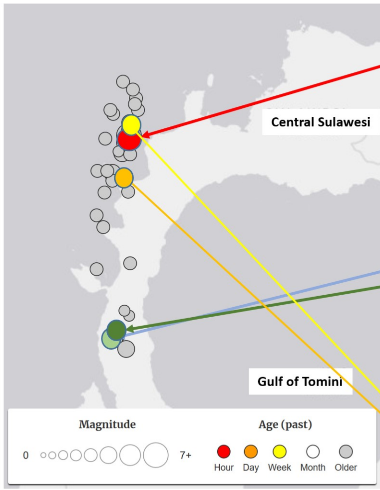


Figure 1. A. Indonesian Tectonics Map [1], B. Earthquake activity from NEIC Catalog and C. Geological Map of Sulawesi [2]

This north-south trending shortening causes the North Sulawesi Arm region have a high earthquake activity as shown in Figure 1.B. The North Sulawesi subduction segment represents a seismotectonic segment [12] in the direction of σ1: N3560E and N3510E, with an intraplate-type deformation, and a slab slope of about 150SW, at a rate of 20 - 54 mm / yr. This segment extends westward and is active both in the west and east with poles around the east, or according to [7] active in the north. The end of the segment lies in the subduction zone. Since the period of 1990 to 2016, there have been several earthquakes in related areas, ie there was 45 earthquakes with 9 large earthquakes above the Mw 5 in the period 1996 to 2002, ie 96/1/1 Mw 7.9-5.6- 5.5, 96/3/1 Mw 5.5, 98/10/10 Mw 6-5.9, 2000/12/28 Mw 5.4, 2002/5/3 5.3 Mw and 2002/6/16 Mw 5.9. Major earthquakes occur again in 2012 until 2015 ie 2012/2/8 Mw 5.1, 2013/4/30 Mw 5.3-5.3, 2014/7/15 Mw 5.3 and 2015/1/15 Mw 5.12. In order to know the deformation status due to the related seismicity, a study was conducted using a simple model based on the Okada elastic model [18] from continuous and episodic GNSS GPS observation data organized by Geospatial Information Agency (Badan Informasi Geospasial/BIG) Indonesia, TU Delft and Institut Teknologi Bandung (ITB) cooperation since 1996-2008 and for the subsequent time duration only continuous data from BIG station until 2016.

DATA AND METHODOLOGY

One difficulty in realizing the deformation monitoring network to be ideally suited in the Okada model, is that not all areas of the North Arm are land areas and only the southern part of the subduction zone can be accommodated by GNSS GPS measurements. Distribution of GNSS GPS observation stations is elongated from DGLA that located in the Donggala region to the north up to SNTG. Campaign/episodic monitoring was conducted once a year in the framework of cooperation between BIG-TU Delft and ITB using static methods and data processing performed using GAMIT / GLOBK 10.6 by applying a multi-baseline-processing method with precision orbits and mapping into ITRF - 2008. As for the approach local, is done relative to the Sunda Block from [13]. The mapping into local reference which is considered stable is done to prevent deformation signal bias due to error propagation at the time of transformation into global reference system. Daily solution is calculated in a 24 hour session with sampling every 30 seconds. For each session, modeling the theoretical values of phase and pseudorange observations was performed. Observational data were calculated by applying an ionosphere-free (LC) combination, the determination of double-difference for clock error elimination and troposphere parameters was estimated using a 60-minute model for each station. The multi-session solution of the obtained free network adjusment is then analyzed using Kalman Filtering to determine the positioning solution and its covariance variance.



no	time		latitude	longitude	depth	mag	
1	1/1/1996	22:41:58	0.692	119.912	33	5.5	mw
2	1/1/1996	9:14:34	0.523	119.838	33	5.6	mb
3	1/1/1996	8:05:11	0.729	119.931	24	7.9	mw
4	1/3/1996	12:06:43	0.64	119.87	33	3.9	mb
5	1/3/1996	11:23:43	0.633	119.896	33	5.5	mw
6	1/3/1996	5:09:52	-0.014	119.752	57.7	4.6	mb
7	1/5/1996	21:25:27	0.875	119.982	33	4	mb
8	1/10/1996	0:15:00	1.031	119.902	33	4.7	mb
9	1/20/1996	0:23:17	0.851	119.843	33	4.2	mb
10	2/4/1996	3:28:32	0.762	119.925	10	4.5	mb
11	2/5/1996	4:52:21	0.874	119.83	33	4.7	mb
12	7/11/1996	18:23:15	0.94	119.97	33	4.8	mb
13	7/28/1996	11:29:33	0.991	119.952	33	4.7	mb
14	10/22/1996	16:54:55	0.22	119.789	33	4	mb
15	5/24/1997	7:46:13	0.41	119.794	33	4.4	mb
16	10/10/1998	19:55:51	-0.277	119.933	33	3.9	mb
17	10/10/1998	16:32:19	-0.403	119.84	33	6	mwc
18	10/10/1998	16:29:08	-0.384	119.859	33	5.9	mwc
19	10/24/1998	7:44:32	-0.246	119.904	33	3.8	mb
20	5/14/1999	19:04:03	0.415	119.925	33	4.3	mb
21	5/29/2000	23:20:00	0.284	119.753	59	4.5	mb
22	5/29/2000	6:01:59	0.019	119.936	33	4.7	mb
23	12/28/2000	21:06:54	-0.46	119.917	33	5.4	mwc
24	11/9/2001	10:41:21	0.533	119.756	33	4.5	mb
25	11/27/2001	20:24:49	0.48	119.838	33	4.4	mb
26	1/8/2002	18:08:46	0.625	119.936	33	4.5	mb
27	3/5/2002	15:40:49	0.8	119.938	33	5.2	mwc
28	6/16/2002	0:00:26	0.495	119.901	34.8	5.9	mwc
29	6/3/2003	18:39:29	0.908	119.967	33	4.7	mb
30	2/9/2004	11:13:23	0.715	119.798	40.3	4.6	mb
31	3/4/2005	4:49:21	0.533	119.809	54.4	4.4	mb

Figure 2. Earthquake activity at Minahasa area from USGS and NEIC Catalog

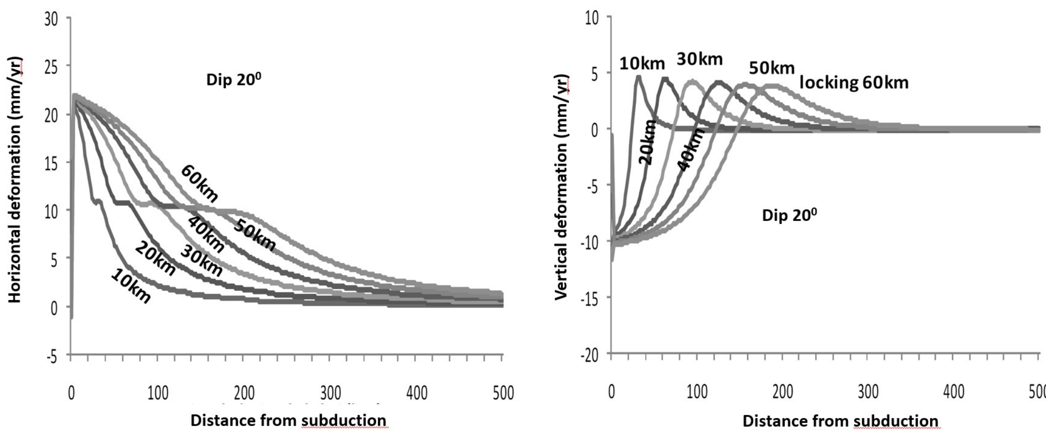


Figure 3. Horizontal (left) and vertical (right) deformation using simple elastic modelling from Okada for subduction zone

The seismic data used for the Okada model analysis [18] was obtained from the NEIC and USGS Catalog as shown in Figure 2. While the subduction zone phenomenon monitoring was designed using a 3-dimensional elastic dislocation model that takes into account the fault parameters of dip, depth, width and length of the fault plane. By varying the depth of the locking and dip of the subduction zone, it can be estimated that the station laying position is expected to be used to detect motion patterns in both horizontal and vertical directions. Figure 3 shows that with the a priori information in the subduction locking zone to a certain depth, the smaller of the dip will create the greater horizontal deformation at the same distance for larger dips, also for the vertical deformation. As for the same dip value the effect of both horizontal and vertical deformation will be further away from the subduction zone with the deeper the locking distance. Thus, ideally the observation station is installed extending along the perpendicular plane of the subduction zone with minimum distance as close as possible to the initial position of subduction up to about 300-400 km (for constant dipped case 20^0 and 30 km constant locking case with 30 mm/yr) minimum number of 4 stations.

RESULT

The coordinates of monitoring stations realized in ITRF-2008 provide residual RMS values of 3.13 mm, 4.15 mm and 7.26 mm for northern, eastern and vertical components, where this indicates a high degree of accuracy, Figure 4 is an example of a time series analysis is used to estimate the velocity rate of GNSS GPS station, ie. analysis of 1996-2008 using TOMI campaign or episodic type station and analysis of 2008-2016 using continuous CTOL type station. In order to facilitate the analysis, the velocity rate in ITRF-2008 (Figure 5 (left)) is calculated relative to the the Sunda Block (Figure 5 (right), this is done to eliminate the velocity effect of other adjacent blocks. The velocity rate of the Minahasa Subduction ranges from 4 to 5 cm/yr. In general the velocity from DGLA to the north up to SNTG is strongly influenced by the Northern Sulawesi block movement but mixes with the seismic pre-co-post rate of Minahasa Subduction activity in the north and left lateral activity of Palu-Koro Fault located on the left side of the monitoring network. Basically, monitoring by episodic method due to limited coverage of the duration of monitoring time, it is rather difficult to define in detail the section of the seismic cycle. And since from 2008 until 2016, we only have one stasion CTOL to monitor it, it will become difficult to have geometrically precise analysis result. Therefore, the analysis done in this paper is only using Okada's best-fitting elastic model deformation.

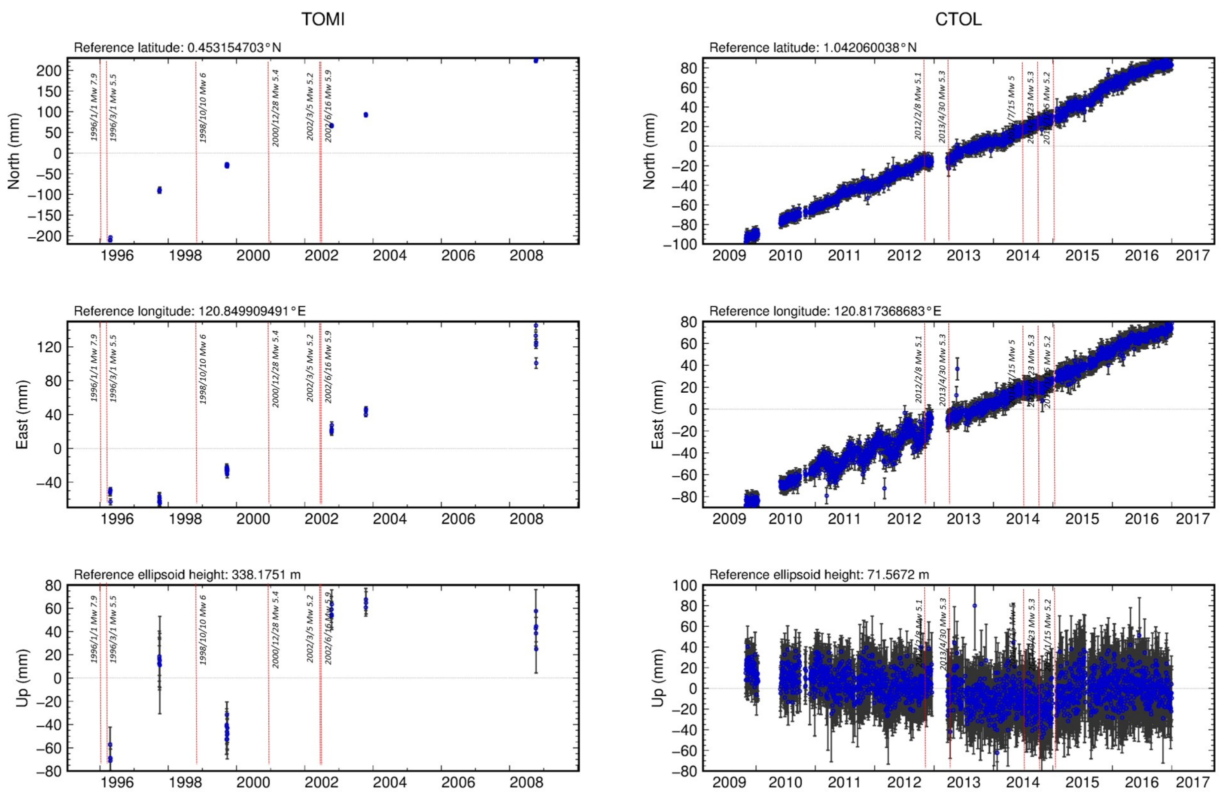


Figure 4. GNSS GPS time series of TOMI station (left) for 1996-2008 analysis and CTOL station (right) for 2009-2016 analysis, with red line as earthquake co seismic event

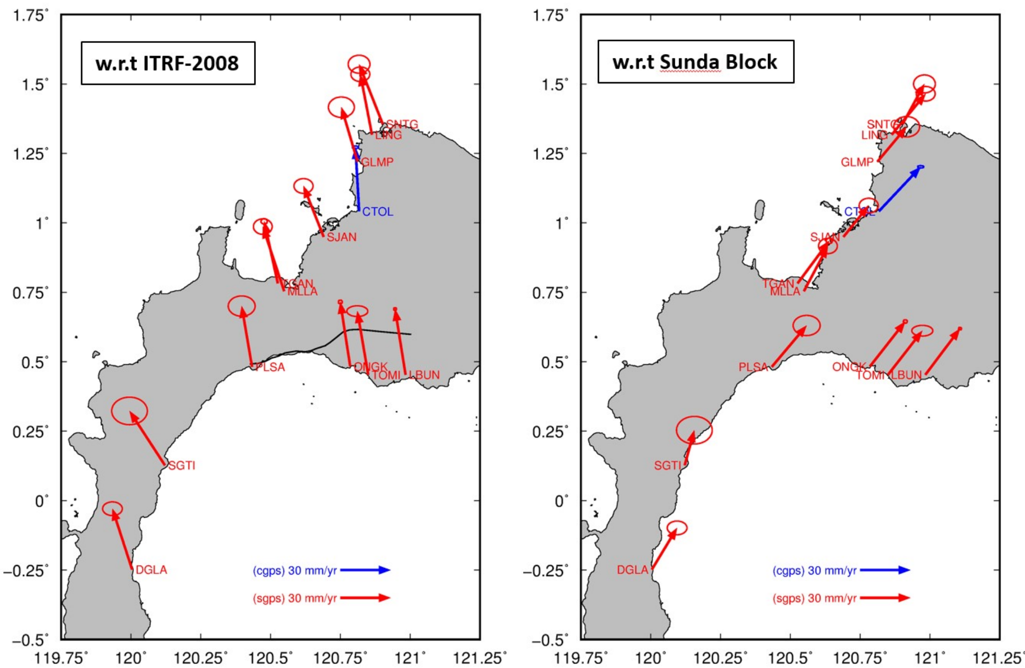


Figure 5. Horizontal velocities of research area w.r.t ITRF 2008 (left) and w.r.t Sunda Block (right)

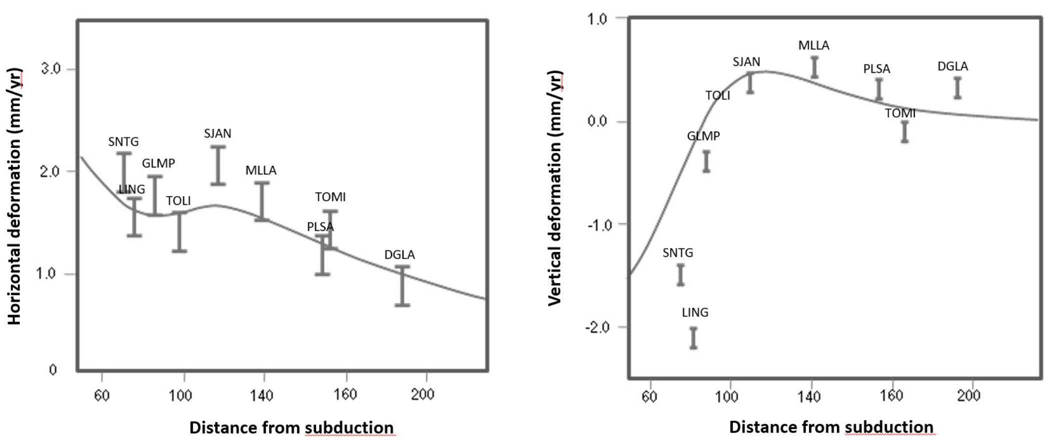


Fig 6. Best-fitting horizontal deformation (left) and vertical (right) with 50 km depth, dip angle 30^0 and subduction velocity 4 cm/yr

Through the separation of horizontal and vertical velocity components thereafter, several estimation models including dip angle and locking depth are applied. From this model both for the speed in the horizontal direction (Figure 3 (left)) and vertical direction (Figure 3 (right)), the best-fitting value of 30-degree angle dip and locking depth is 50 km for subduction rate 4 cm/yr. Based on the rate decreasing that occurs every year in LING, SNTG, TOLI and TOMI is estimated that at the moment is in the final phase of post-seismic phase due to the 9 earthquakes during 1996-2008. The largest deviation lies in the SJAN station measured only 3 times (2003, 2006 and 2008) at considerable time intervals from the first major earthquake of 1996 and subsequent quakes, which is expected to cause considerable extrapolation. A more detailed analysis is rather difficult given the unavailability of observational data prior to the earthquake and episodic measurements not coincided with earthquake events, making it difficult to know the value of the co-seismic shifts occurring for the interpolation-extrapolation of modeling.

CONCLUSION

Simple deformation study of Minahasa Subduction using episodic GPS data provides best-fiting results in 30-degree angle and locking depth of approximately 50 km, and the current status is estimated as the final phase of the post-seismic phase due to the January 1, 1996 earthquake of Mw 7.9 occurred in North Arm area and followed by 8 large earthquakes above Mw 5 scale, (96/1/1 Mw 5.6-4.5, 96/3/1 Mw 5.5, 98/10/10 Mw 6-5.9, 2000/12/28 Mw 5.4, 2002/5/3 5.3 Mw and 2002/6/16 Mw 5.9. To obtain more detailed results on the status and stages occurring due to the complexity of the seismistas area, it is still necessary to filter the velocity of motion using fixed station TOLI and CTOL, the use of GNSS-GPS data measured prior to the year of the earthquake and the use of post-seimic physical models that divide the Minahasa subduction zone into sections based on their seismic activity.

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