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Rotation and Strain Rate of Sulawesi from Geometrical Velocity Field

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Abstract. One of methods that can be used to determine the tectonic deformation status is rate estimation from geometric rotation and strain using quantitative velocity data from GPS observations. Microplate Sulawesi region located in the zone of triple junction (Eurasia, Australia and Philippine Sea Plates) has very complex tectonic and seismic condition, which is why become very important to know its recent deformation status in order to study neo-tectonic and disaster mitigation. Deformation rate quantification is estimated in two parameters: rotation and geodetic strain rate of each GPS station Delaunay triangle in the study area. The analysis in this study is not done using the grids since there is no rheological information at location that can be used as the interpolation-extrapolation constraints. Our analysis reveals that Sulawesi is characterized by rapid rotation in several different domains and compression-strain pattern that varies depending on the type and boundary conditions of microplate. This information is useful for studying neo tectonic deformation status and earthquake disaster mitigation.

BACKGROUND

Microplate Sulawesi region located in the zone of triple junction (Eurasia, Australia and Philippine Sea Plates) has very complex tectonic and seismic condition, which is why become very important to know its recent deformation status in order to study neo-tectonic and disaster mitigation. Sulawesi and surrounding tectonic reconstruction associated with active tectonic plate boundaries as well [1 - 2], especially for the areas of Banda. In the western region of eastern Indonesia, the process of shortening trending EW that occurred in SW Sulawesi and Makassar Strait is expected active since the Middle Miocene [3] or the Early Pliocene [4]. This compression caused by collisions between Sulawesi with the westward migration of the micro-continent Tukang Besi and Banggai-Sula [1, 3, 5] and still be active based on observation seismological and geodetic [6, 7, 8, 9 10].

One of methods that can be used to determine the tectonic deformation status is rate estimation from geometric rotation and strain using quantitative velocity data from GPS observations. Deformation rate quantification is estimated in two parameters: rotation and geodetic strain rate of each GPS station Delaunay triangle in the study area. The analysis in this study is not done using the grids since there is no rheological information at location that can be used as the interpolation-extrapolation constraints. We use 1994-2015 GNSS-GPS velocity rates at ITRF-2008 from [11] to deduce the latest deformation rate of Sulawesi Area.

METHOD AND DATA

The type of data obtained using GPS-GNSS observations are in the form of discrete values of a position. Known from two sets of observations at two different epochs, wewill get displacement vector magnitude or

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velocity vectorof the station observed. Since vertical componentprecision of GNSS-GPS observations is 3 to 5 times lower than the horizontal component, so in this geometric modelingwe will only use the horizontal component (2-dimensional). The time series example of continuous station data and campaign station data are shown in Figure 1 and the 1994 to 2015 velocity rate at ITRF-2008 of Sulawesi Area [11]that we use in this research are shown in Figure 2.

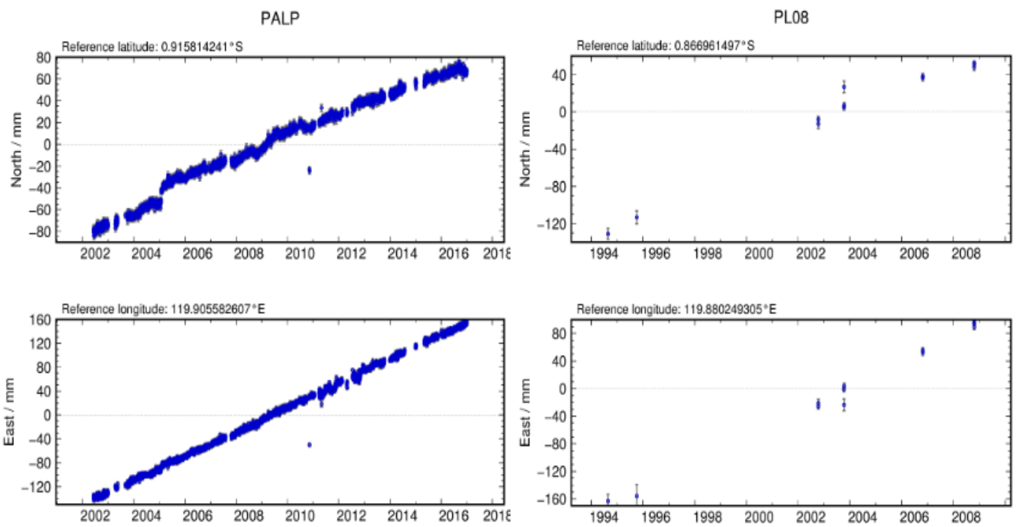

FIGURE 1. North-East components of station time series position for PALP-continuous type (left) and PL08-campaign type (right)

If ai set stationsare known to have horizontal velocity components: V_n (northern component of velocity) and V_e (eastern component of velocity) relatively to a reference point j which has a velocity as well, then the velocity gradient tensor L obtained from the following equation

$$\begin{bmatrix} Ve \\ Vn \end{bmatrix}_i = \begin{bmatrix} Ve \\ Vn \end{bmatrix}_j + \begin{bmatrix} \frac{\partial Ve}{\partial e} & \frac{\partial Ve}{\partial n} \\ \frac{\partial Vn}{\partial e} & \frac{\partial Vn}{\partial n} \end{bmatrix} \begin{bmatrix} de_{ij} \\ dn_{ij} \end{bmatrix} \tag{1}$$

or

$$Ven_i = Ven_j + L\, den_{ij} \tag{2}$$

$dn_{ij}$and $de_{ij}$are the difference between the coordinates of the station$i$ to reference station j in the northern and eastern component. $Ven_{ij}$and den_{ij} is the velocity matrix and coordinates difference matrix between station$i$ to reference station j. Furthermore, to determine the continuously velocity field, it were estimated using interpolation-extrapolation method of discrete velocity values mentioned above. There are various interpolation methods such as collocation; interpolation based on basic functions and interpolation method of finite elements for each triangle. This research applies finite element method to perform linear interpolation in a triangle drawn by Delaunay triangle criteria. The characteristics Delaunay triangle is no one side of a triangle which is truncated by the other side of a triangle and each triangle has three points compilers that are unique and not to be duplicated that identical in other triangles [12].

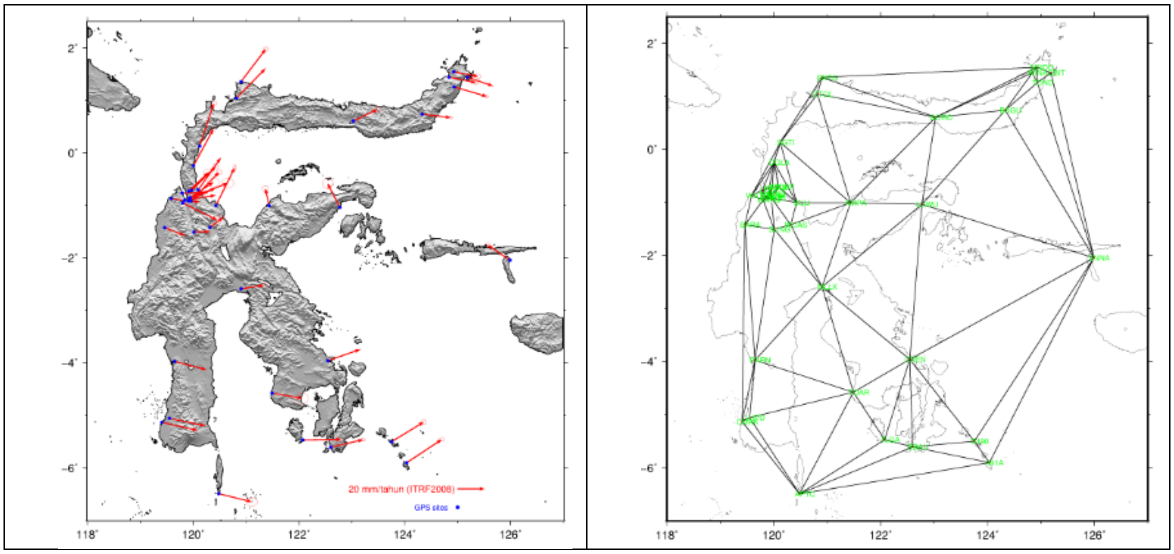

FIGURE 2.1994 to 2015 velocity rate of Sulewesi Area at ITRF-2008(Left) and Delaunay design (Right)

Gradient tensor of velocity rate are calculated at the center of each triangle Delaunay by

$$\begin{bmatrix} Ve_1 \\ Vn_1 \\ Ve_2 \\ Vn_2 \\ Ve_3 \\ Vn_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & de_1 & dn_1 & 0 & 0 \\ 0 & 1 & 0 & 0 & de_1 & dn_1 \\ 1 & 0 & de_2 & dn_2 & 0 & 0 \\ 0 & 1 & 0 & 0 & de_2 & dn_2 \\ 1 & 0 & de_3 & dn_3 & 0 & 0 \\ 0 & 1 & 0 & 0 & de_3 & dn_3 \end{bmatrix} \begin{bmatrix} de_j \\ dn_j \\ \frac{\partial Ve}{\partial e} \\ \frac{\partial Ve}{\partial n} \\ \frac{\partial Vn}{\partial e} \\ \frac{\partial Vn}{\partial n} \end{bmatrix} \tag{3}$$

The velocity gradient tensor can be furtherdecomposed into two components, namely the symmetric strain rate tensor $S$and not symmetric strain rate tensor$A$.

$$S = \frac{1}{2}(L + L^T) = \begin{bmatrix} \frac{\partial Ve}{\partial e} & \frac{1}{2}\left(\frac{\partial Ve}{\partial n} + \frac{\partial Vn}{\partial e}\right) \\ \frac{1}{2}\left(\frac{\partial Vn}{\partial e} + \frac{\partial Ve}{\partial n}\right) & \frac{\partial Vn}{\partial n} \end{bmatrix} = \begin{bmatrix} \epsilon_{ee} & \epsilon_{en} \\ \epsilon_{ne} & \epsilon_{nn} \end{bmatrix} \tag{4}$$

and

$$A = \frac{1}{2}(L - L^T) = \begin{bmatrix} 0 & \frac{1}{2}\left(\frac{\partial Ve}{\partial n} - \frac{\partial Vn}{\partial e}\right) \\ \frac{1}{2}\left(\frac{\partial Vn}{\partial e} - \frac{\partial Ve}{\partial n}\right) & 0 \end{bmatrix} = \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix} \tag{5}$$

From the strain rate tensor matrix$S$ and Acan be furtheranalyze about how large the effect from normal strain of eastern component $\in_{ee}$, normal strain of northern component $\in_{nn}$, the shear strain $\in_{en}$and rotation $\omega$from any point of the triangle center Delaunay.

RESULT AND DISCUSSION

Two types of GPS measurement are used to quantify motion at the interest region since 1994 to 2015 at ITRF 2008. After velocity field estimation, deformation rate quantification is derived into two parameters: rotation and geodetic strain rate of each GPS station Delaunay triangle in the study area.The results shown in Figure 2.

In outline from Figure 2, showed that Sulawesi is still characterized by a pattern of rapid rotation in 5 different domains. North Arm has a pattern rate of velocity that is slower from west to east, it causes changes in the rate of clockwise rotation increasingly faster from the west toward the east from 1,250 / My around TOLI to

3,750 / My in KEMA with linear evolution trend. In the western part of the region is the Central Sulawesi is cleaved by Palu-Koro Fault. The area is dominated by a different pattern with North Arm, namely counter-clockwise rotation pattern, where this indicates that both of these areas lie in different blocks. The rotation rate in the Central Sulawesi is divided into two parts where the northern part rotates much faster than in its southern region (from 120 / My becomes 2.50 / My). It is made possible by the activity of Palu-Koro Fault that can move faster in the north than in the south due to the constraints of the collision and friction with blocks in the southern part. Compression of the northern part of Central Sulawesi, namely along the neck connecting with the North Arm, indicating subduction Minahasa role in curbing the rate of rotation of Tomini Gulf region.

In the eastern part of Central Sulawesi, which is in the Gulf of Tomini, rapid clockwise rotation pattern seen that may indicate the involvement of Tomini Gulf Fault that conveniently accommodate differences among them. Rotation in Tomini Gulf itself changed significantly from 8,750 / My at the end of the southwest became 2.50 / My at the eastern end above the Batui Thrust. This suggests that the reduced rotational rate in the eastern Gulf of Tomini accommodated by Batui Thrust. Batui Thrust itself is located in East Arm that the entire area is experiencing a counter-clockwise rotation rate from 50 / My diminished toward the west that is expected to connect Palu-Koro Fault and Bone Gulf.

Southeast Sulawesi Arm and South Sulawesi Arm is still characterized by a pattern of counter-clockwise rotation. From rotation pattern, can be seen small differences of rotational rate between both blocks that divided by Bone Gulf. This indicates the possibility of involvement of the Bone Gulf as boundary zones, considering the geological structures and reconstruction studies paleo-tectonics that the Bone Gulf is boundary between Western Ophiolite Belt of Sulawesi and continental terrain in eastern Sulawesi.

The largest extension pattern is located in Central Sulawesi zone precisely at Palu-Koro Fault and Tomini Fault. This pattern is due to the dominance of fault activity of left lateral Palu-Koro Fault and the possibility of Tomini fault activity. The pattern ofthese extensions in the south decreases as the turning east direction approaching toward the Matano fault, and in the northern part of the shrinking follow Palu-Koro Fault lines prediction in the direction of Minahasa subduction zone.

In this last part, the pattern changed rapidly in a narrow zone near the Toli-toli area with northeast-southwest compression and peaked in the middle zone of the North Arm as a result of compression from Minahasa subduction. Compression pattern looks back transformed into an eastwards extension towards Halmahera double subduction zones. For the record to the zone, this extension dilatation pattern in this study are likely due to its minimal effect GNSS-GPS station in the eastern part of this zone used in the interpolation process, the only station are : AMBO, TERN and SANA. Thus further analysis to double subduction zones Halmahera in this study cannot be done.

Extensions zone are formed in the Gulf of Tomini only covers part of the southern region of the gulf and ended up in the middle of the gulf. This pattern turns into a north compression toward Minahasa subduction and east toward Batui Thurst. Compression in Batui Thurst zone (East Arm) continues to the south at Tolo Thurst (East Arm). Compression pattern is clockwise further toward the South Arm and then increased toward Lawanopo fault, Kolakafault and rift zones in the southern part of Makassar Strait. Highest compression rate in South Arm and East Arm is precisely formed in the Bone Gulf with northwest-southeast direction. In the northern part of the Bone Gulf, showed visible changes in the pattern of compression to the extension in the narrow space toward spatial extension zone in Poso (Tomini bay).

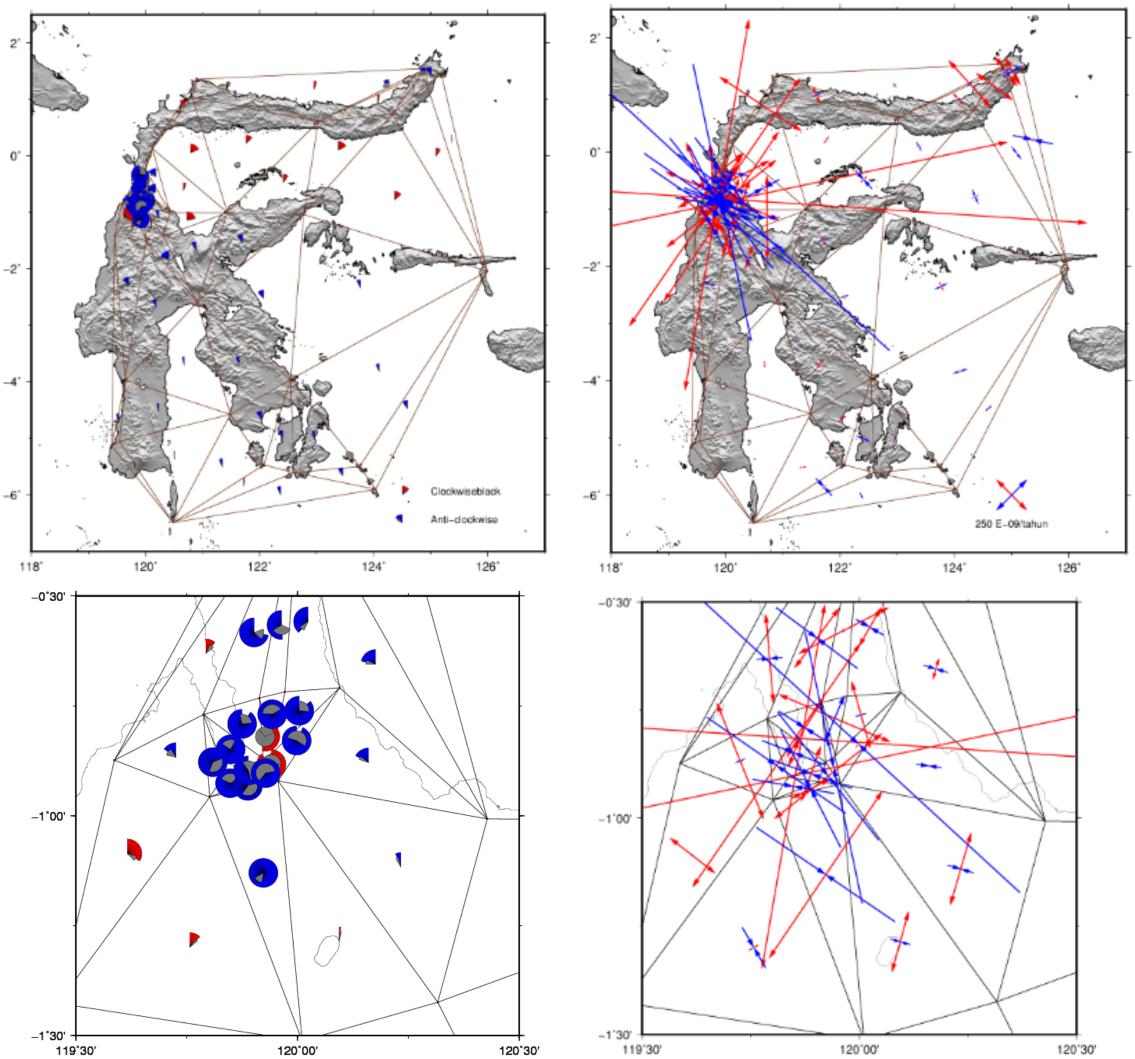

FIGURE 3. Rotation Rate (Left -Up) with its zoom at Palu-Koro Fault (Left-Bottom), and Strain Rate (Right) with its zoom also at Palu-Koro Fault (Right-Bottom) from geometric modeling

CLOSING REMARKS

Two types of GPS measurement are used to quantify motion at the interest region since 1994 to 2015. After velocity field estimation, deformation rate quantification is derived into two parameters: rotation and geodetic strain rate of each GPS station Delauney triangle in the study area. The analysis in this study is not done using the grids since there is no rheological information at location that can be used as the interpolation-extrapolation constraints. Our analysis reveals that generally Sulawesi is characterized by rapid rotation in several different domains: counter clockwise rotation in the western and southern part, and rapid clockwise rotation at northeast part. In central Sulawesi, very complex rotation pattern came from Palu-Koro Fault activity that observed using specific transect monitoring network. Compression-strain pattern that varies depending on the type and boundary conditions of microplate. Western part of Sulawesi shows smaller compression from north to south direction. Palu Koro Fault System also shows the same complex pattern as combination from high compression and high extension.

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