Surface deformation and earthquake potential in Surabaya from GPS campaigns data

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Abstract. Study by the National Centre for Earthquake Studies suggests the presence of two segments of Kendeng active fault, namely Surabaya fault and Waru fault in Surabaya. This study aims to investigate the surface deformation and earthquake potential in Surabaya that possibly related to the activities of those two faults. We use GPS campaigns data conducted in March 2017, September 2017, May 2018, and October 2018 and five GGPS CORS stations around Surabaya provided by the Indonesian Geospatial Information Agency. In total, 21 GPS stations data were processed to obtain horizontal and vertical displacement velocities in each station. The results showed almost all stations move toward southeast with the velocity rates range from 1.034 cm/yr to 5.674 cm/yr, except BM33 and SB07 that moves northeast with the velocity rates 4.065 cm/yr and 3.312 cm/yr respectively. For the vertical displacements, almost all stations subject to subsidence with the rates range from -0.190 cm/yr to -5.769 cm/yr. Only three stations subject to uplift namely BM23 with the rate of 0.234 cm/yr, BM24 with the rate of 2.844 cm/yr, and BM29 with the rate of 3.33 cm/yr. The strain analyses showed large shortenings in the area between two faults with the values up to 11.95 μstrain. From the results, we can conclude that the surrounding area of the two faults have different deformation patterns, and by confirming with geological data, we suggest that Surabaya has an earthquake potential due to the active faults.

1. Introduction
Indonesia is situated on the boundaries of four major active plate tectonics, namely the Eurasian Plate, the Indo Australian Plate, the Philippine Sea Plate, and the Pacific Plate. The plates are actively moving against each other and making Indonesia prone to tectonic activities induced disasters such as earthquakes, tsunamis, and active volcanoes eruptions. In the south of Java island, the confluence between the Indo Australian and Eurasian Plates is forming a subduction zone called the Java Trench. The tectonic activities on the Java Trench subduction zone had affected the geological formation in Java island such as the formation of faults and active volcanoes range.

Surabaya is the largest city in Indonesia located in Java island. The city is the capital of East Java Province and one of an essential government and business activities center in Indonesia. According to the Central Bureau of Statistics, in 2018, Surabaya City has a total area of 326.36 km² with the population
of 2.87 million [1]. Study by the National Centre for Earthquake Studies suggests the presence of two segments of Kendeng active fault, namely Surabaya fault and Waru fault in Surabaya [2]. The activities of these two faults have made the city threaten by earthquakes and surface deformation. Therefore, monitoring surface deformation and studying the earthquake potential in Surabaya become crucial.

Surface deformation monitoring can be performed using extraterrestrial Geodetic techniques such as Global Positioning System (GPS) survey and Interferometry Synthetic Aperture Radar (InSAR). This study aims to examine the surface deformation in Surabaya using GPS campaigns data and use the results to analyse the earthquake potential over the city related to the presence of the active faults.

2. Study area, data and methodology
The study took place in Surabaya which is located on the latitude of 7°11’00”S to 7°21’00”S and the longitude of 112°36’00”E to 112°51’00”E. The northern and eastern shores are on the Madura strait, whereas the western and southern boundaries are adjacent to Gresik and Sidoarjo respectively (Figure 1).

Figure 1. The study area. Surabaya is shown by the orange color

In this research, three types of GPS data were used. Namely, the GPS campaigns data, the GPS CORS stations data, and IGS (International GNSS Service) stations data. The GPS campaigns were conducted four times during 2017 and 2018, which the detail can be seen in Table 1. The total number of GPS campaign stations that at least have been observed in three campaigns were 16 stations (Figure 4). Five GPS CORS stations around Surabaya provided by the Indonesian Geospatial Information Agency were used (Figure 2) to complement the GPS campaigns data. As the references to tie the coordinates to the International Terrestrial Reference Frame 2014 (ITRF2014), we used thirteen IGS stations with distributions that can be seen in Figure 3.

| Campaign # | Date            | doy     |
|------------|-----------------|---------|
| 1          | 10-13 March 2017| 069-072 |
| 2          | 11-15 September 2017 | 254-258 |
Figure 2. The distribution of GPS CORS stations around Surabaya

Figure 3. The distribution of IGS stations used in this study

Figure 4. The Geological setting of Surabaya and its surroundings (modified from [3]). The distribution of GPS campaign stations are shown as black triangles. The faults are shown as brown dashed lines.

Topographically, Surabaya is dominated by lowlands with elevation varies from 1 to 10 meters above mean sea level (MSL) in the northern, eastern, southern, and central part. The western areas are low hills.
with the elevation up to 40 meters above MSL. The lowlands are formed from alluvial river and coastal sediments. The central part of Surabaya is formed by the Brantas River sediments and its river branches and also the Asemrowo River sediments. The Brantas River sediments originated from the eruption of volcanoes that were in the upper reaches. These deposits are usually in the form of sand and gravel. The eastern and northern parts which are along the Madura Strait shore are formed by coastal deposits in the forms of silt and silts clay that enter inland up to 5 km.

Geologically, the low hills over western area of Surabaya are formed by sedimentary rocks of Miocene to Pliocene age. The sedimentary rocks are part of the Kendeng zone that consist of Sonde, Lidah, Pucangan and Kali Pucang formations. The bedrock in Surabaya is a Pliocene (pre-tertiary) Lidah formation. This formation is at a depth of 250 - 300 meters. In addition, the Surabaya area is in the form of young alluvial deposits resulting from sea and river deposits, tuffs and sandstone.

Kendeng Fault is a fault zone that extends from west-east of Central Java to the western part of East Java. This active fault consists of a collection of blind faults that can be observed from the Bouguer anomalies in this area[4]. Study by Koulali et al. (2017) suggested that the Kendeng fault is actively moving with the rate of 0.23 cm/year[5]. In Surabaya, the Kendeng fault is segmented into two faults, namely Waru fault and Surabaya fault. The Waru fault extends from the Waru area (Karangpilang) in Surabaya, Jombang, Nganjuk to Saradan in Madiun whereas the Surabaya fault extends from the hills of Wonokitri, Mayjen Sungkono in Surabaya to Cerme area in Gresik.

To examine the surface deformation in Surabaya using GPS data, we use two approaches, namely the displacement analyses and strain analyses. For the displacement analyses, we use GAMIT/GLOBK software [6] to process the GPS observation data from 2017 to 2018. The results from GAMIT/GLOBK processing are horizontal and vertical velocity rates of each GPS stations. The velocities then be used as input for strain analysis. To calculate the principal strains (extension and compression), we use Delaunay triangle of triangle segments method. In total, the principal strains were computed in 20 triangle segments.

Table 2. Displacement velocity rates of the GPS campaign and CORS stations

| Station name | Longitude degree | Latitude degree | $v_x$ cm/yr | $v_y$ cm/yr | $v_{hor}$ cm/yr | $v_u$ cm/yr |
|--------------|------------------|-----------------|-------------|--------------|----------------|-------------|
| CSMP         | 112.25195        | -7.19545        | 2.202       | -1.016       | 2.425          | -0.607      |
| CPAS         | 112.90104        | -7.65141        | 2.509       | -0.728       | 2.612          | -0.249      |
| BITS         | 112.79345        | -7.28198        | 1.571       | -0.382       | 1.617          | -1.709      |
| KENJ         | 112.77794        | -7.22198        | 2.738       | -1.926       | 3.348          | -2.513      |
| CSBY         | 112.72437        | -7.33433        | 2.436       | -1.349       | 2.785          | -0.190      |
| SB03         | 112.77590        | -7.34026        | 4.179       | -0.083       | 4.180          | -0.920      |
| BM16         | 112.77120        | -7.26778        | 0.827       | -0.620       | 1.034          | -3.448      |
| RGKT         | 112.75705        | -7.32690        | 1.635       | -0.680       | 1.771          | -3.418      |
| WONO         | 112.73740        | -7.29924        | 3.610       | -0.984       | 3.742          | -3.402      |
| WARI         | 112.72926        | -7.34504        | 2.323       | -0.936       | 2.504          | -3.002      |
| BSBY         | 112.72363        | -7.21104        | 4.177       | -1.751       | 4.259          | -3.578      |
| SB07         | 112.70883        | -7.30564        | 3.282       | 0.441        | 3.312          | -0.345      |
| BM08         | 112.69277        | -7.26396        | 3.079       | -2.384       | 3.894          | -2.187      |
| SB15         | 112.67959        | -7.22596        | 2.108       | -1.221       | 2.436          | -4.727      |
| BM33         | 112.67897        | -7.32842        | 3.204       | 2.502        | 4.065          | -3.076      |
| BM24         | 112.66252        | -7.29075        | 2.762       | -2.678       | 3.847          | 3.330       |
| BM29         | 112.63466        | -7.31278        | 4.363       | -2.653       | 5.106          | 2.844       |
| BM23         | 112.63398        | -7.26108        | 4.979       | -2.720       | 5.674          | 0.234       |
3. Results and discussions

3.1. Displacements analyses

The results from GAMIT/GLOBK processing, which are the coordinate velocity rates, for GPS campaign and GPS CORS stations are presented in Table 2. The horizontal displacements \((v_{\text{hor}})\) were obtained from the resultant of the easting \((v_e)\) and northing \((v_n)\) components of the coordinate velocities. The direction of the horizontal displacements were also obtained from those two components. The horizontal velocity rates of the GPS campaign stations in Surabaya and their displacement directions are shown in Figure 5. From the figure we can see that the GPS campaign stations in Surabaya are predominantly moving toward south-east direction with the values are ranging from 1.034 cm/year to 5.674 cm/year. The smallest displacement occurs at BM16 while the biggest one at BM23. The direction of the displacements are predictable because we tied the GPS coordinates to the ITRF2014 so that the movement of the stations are in the same direction with Eurasian plate. However, we found that two stations, namely BM33 and SB07, were moving toward different direction which are northeast. The location of those two stations are close to the suspected Waru and Surabaya faults.

![Figure 5. Horizontal displacement rates of the GPS campaign stations](image)

For the vertical displacement, as can be seen from Figure 6, fifteen (15) GPS campaign stations are subject to subsidence, and three (3) are uplift. The velocity rates of the subsidence are ranging from -0.190 cm/year to -5.769 cm/year. From Figure 4 and Figure 6, we can see that the distribution of the stations that experiencing subsidence are on the alluvial plains. On the other hand, the stations that were experiencing uplift (BM23, BM24, and BM29), are located in the area between two faults. These results are in agreement with the studies by Anjasmarra et al. (2017 and 2018) on the subsidence in Surabaya urban area using DInSAR [7] and time-series InSAR [8] techniques.
3.2. Strain analyses

The principal strains were derived from the horizontal velocity rates using the Delaunay Triangle method. In total, they were twenty (20) triangular segments with the calculated values of extension ($\varepsilon_1$), compression ($\varepsilon_2$), and their orientation ($\theta$). The results are presented in Table 3.

![Figure 6. Vertical displacement rates of the GPS campaign stations](image)

Figure 7 shows the principal strains plot over Surabaya. From the figure, it can be seen that Surabaya, especially the western, southern, and central parts, is dominated by compression or shortening (shown by the arrows). The significant shortenings occurred in the segments formed by BM24-BM33-SB07 and BM33-SB07-WARU the value of 11.950 $\mu$strain and -11.950 $\mu$strain, respectively. This situation illustrates that over this area, there is an accumulation of energy which could be released by the time (i.e., earthquake). From Figure 7 we can see that those significance shortenings are located on the area between the suspected Waru and Surabaya faults. Because of the presence of the shortenings, and based on [9], it is confirmed that those two faults exist. Furthermore, because the compressional strain on Waru fault is higher, it is also assumed that the Waru fault is more active that Surabaya fault.

| Triangle Segment | $\varepsilon_1$ $\mu$strain | $\varepsilon_2$ $\mu$strain | $\theta$ degree |
|------------------|----------------------------|----------------------------|----------------|
| BM02-BM23-SB15   | 6.086                      | -2.283                     | -3.420         |
| BM23-SB15-BM08   | 2.951                      | -3.238                     | -4.684         |
| BM23-BM24-BM08   | 1.808                      | -4.276                     | 33.130         |
| BM23-BM24-BM29   | 0.134                      | -6.196                     | 41.736         |
| BM29-BM24-BM33   | -2.330                     | -11.900                    | 12.508         |
| SB15-SBSY-BM08   | 5.682                      | 1.458                      | 31.890         |
| BM08-WONO-SB07   | 1.374                      | -6.823                     | -11.604        |
| BM24-BM08-SB07   | 1.685                      | -6.105                     | -7.341         |
| BM24-BM33-SB07   | 0.830                      | -11.950                    | -3.512         |
| BM08-WONO-BM16   | -0.910                     | -3.486                     | 42.770         |

| Triangle Segment | $\varepsilon_1$ $\mu$strain | $\varepsilon_2$ $\mu$strain | $\theta$ degree |
|------------------|----------------------------|----------------------------|----------------|
| BM08-BSBY-KENJ   | 1.872                      | -2.552                     | 40.880         |
| KENJ-BM08-BM16   | 0.474                      | -6.174                     | 2.073          |
| BM33-SB07-WARU   | 2.750                      | -2.259                     | -14.706        |
| WARU-SB07-WONO   | 2.600                      | -0.190                     | 26.903         |
| WARU-RGKT-WONO   | 0.867                      | -5.716                     | 34.849         |
| KENJ-BM16-BITS   | 4.895                      | -2.376                     | -36.556        |
| BM16-WONO-RGKT   | -0.012                     | -8.478                     | 40.869         |
| BM16-BITS-RGKT   | 2.067                      | -0.495                     | 42.691         |
| WARU-RGKT-SB03   | 7.364                      | -4.660                     | 36.019         |
| BITS-RGKT-SB03   | 8.697                      | -2.574                     | 42.270         |
3.3. Earthquake potential

Surabaya and Waru faults can be assumed originate from the activities of those two faults. This results is supported by [4] which state that the Kendeng Fault consists of a collection of fold-thrust faults that can be seen from Bouguer anomalies in this area. Marliyani [10] also suggests that the evidence of the movement of the Kendeng fault can be seen with the presence of river terraces which are lifted through the movement of faults over the area. The results of strain analyses showed that in the area between Surabaya and Waru faults, there is an energy accumulation indicated by the significant shortening rates. This accumulated energy could be released as earthquakes in the future so that we can conclude that Surabaya has an Earthquake potential.

4. Conclusions and future works

The surface deformation in Surabaya, especially the horizontal one, was mainly affected by the Eurasia plate movement toward southeast with the values of velocity rates range from 1.034 cm/year to 5.674 cm/year. However, this study found that two stations located in the area between Waru fault and Surabaya fault were moving toward northeast with the value of 3.312 cm/year and 4.065 cm/year respectively. As for the vertical deformation pattern, Surabaya were dominated by subsidence with the velocities range from -0.190 cm/year to -5.769 cm/year. Even so, three stations located in the area between two active faults were experienced uplift with the velocities range from 0.234 cm/year to 3.330 cm/year. We assumed that these different patterns of horizontal and vertical deformation were related to the active faults.

From the analysis of the principal strain, it could be seen that the Surabaya area was dominated by compression with the significant values up to 11.950 µstrain. The area with the shortening patterns was mainly found over the area between the Surabaya and Waru faults. Therefore, we suggest that Surabaya would has earthquake potential due to the activities of these two faults. Nevertheless, more studies need to be done to examine the exact position of the faults and their behavior.

5. References

[1] Badan Pusat Statistik 2018 Surabaya Municipality in Figures 2018 (Surabaya: BPS - Statistics of Surabaya Municipality) p 452
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