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Seismic Deformation Analysis of the 28th September 2018 Palu Earthquake (7.5 Mw) Using InaCORS Station Data and Okada Model

Nurdin[1], Marzuki[1*], Deasy Arisa[2], Vira Friska[1]

[1] Department of Physics, Universitas Andalas, Padang, Indonesia.
[2] Research Center of Geotechnology, National Research and Innovation Agency (BRIN), Bandung, Indosesia.

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Corresponding Author:
Marzuki
marzuki@sci.unand.ac.id

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Abstract: This study employs the Okada Method to analyze the horizontal seismic deformation of the Palu earthquake on September 28, 2018, with a magnitude of 7.5 Mw. Data from InaCORS stations (WATP, CPRE, CPAL, TOBP, and CMLI) strategically positioned near the earthquake epicenter were processed using Gfortran software, and deformation was mapped using GMT software. The analysis focuses on the 100 Days of Year (DOY) period from August 6 to November 28, 2018. Results indicate that during the co-seismic phase (DOY 272), InaCORS stations experienced deformations ranging from 477.130 mm to 7.7852 mm. The magnitude of deformation varied based on station proximity to the epicenter, with the largest displacement observed at TOBP and the smallest at CPRE. Station movements were divergent, with northern stations shifting northward and southern stations moving southward. Subsurface slip reached 1449.23 mm, affecting an area measuring 145 km by 76 km at a depth of 8 km, dip of 65˚, strike of 351˚, and rake of -46˚. These findings contribute valuable insights into the seismic impact on the Earth's crust, aiding seismic hazard assessments in the region.

Keywords: Coseismic; Deformation; Eartquake; Okada model and palu koro fault

Introduction

The island of Sulawesi is part of Indonesia and lies at the convergence of three major tectonic plates: Indo-Australian, Pacific, and Eurasian. The movement of these plates involves the Indo-Australian plate moving from the south at an average rate of 7 cm per year, the Pacific plate moving from the east at a rate of about 6 cm per year, and the Asian plate moving relatively passively to the southeast at ± 3 cm per year. The seismic activity resulting from the interaction of these plates makes the Sulawesi region prone to high seismic activity, including earthquakes, tsunamis, ground movements, and volcanic eruptions, creating a complex tectonic framework. This seismic activity and tectonic complexity are due to various manifestations such as volcanoes, subduction zones, faults, and fractures (Kaharuddin M S et al., 2011). Several active faults are scattered across Sulawesi, contributing to its high seismic activity. These faults include the Walannae Fault (South Sulawesi), the Palu-Koro Fault (Palu to Makassar Strait), the Gorontalo Fault, the Batui Fault (Central Sulawesi), the Makassar Strait Uplift Fault, and the Matano, Lawanopo, and Kolaka Faults (Southeast Sulawesi) (Ismullah et al., 2015).

Central Sulawesi is a region of high seismic activity. The Central Sulawesi region has experienced at least 22 damaging earthquakes from 1910 to 2018 (Supartoyo et al., 2018). Some of these damaging earthquakes were centered inland around the Palu Koro Valley and are thought to be related to the activity of the Palu Fault. On 28 September 2018, activity on the Palu Koro fault resulted in an earthquake with a magnitude of 7.5 on the Richter scale. The earthquake's epicenter was located at a depth of 10 km, approximately 26 km north of Donggala. It triggered a tsunami that hit the city of Palu and surrounding areas, with a maximum height of 10 m in the village of Tondo, East Palu, and liquefaction in the Petobo and Balaroa areas (BMKG,

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2018). The epicenter of the 2018 Palu earthquake is shown in Figure 1A.

The 2018 Palu earthquake has raised awareness of the importance of earthquake hazard mitigation in Central Sulawesi. One earthquake disaster mitigation method is conducting geodynamic and deformation studies by analyzing Global Navigation Satellite System (GNSS) observations. InaCORS (Indonesian Continuously Operating Reference Station) is one such GNSS-based technology owned by Indonesia and operated by the National Geospatial Information Agency (BIG), with stations distributed throughout Indonesia (BIG, 2019). It can be used to analyze the geodynamics and horizontal deformation of the 2018 Palu earthquake.

Several researchers have conducted studies on the 2018 Palu earthquake. Data from InaCORS stations (GPS stations operated by BIG) in the horizontal direction show that stations in the northern part moved northwards, while southern stations moved southwards (Muttaqin, 2019). This movement is attributed to the sinistral or left-lateral displacement of the Palu Koro fault. Other research shows that the magnitude of movement during the interseismic and postseismic phases reached the centimeter scale. In contrast, during the coseismic phase, it reached the meter scale, especially at stations in Palu city (Wihikan & Heliani, 2020).

Although previous studies have addressed the deformation due to the activity of the Palu Koro fault in 2018, they have not thoroughly investigated the movement of InaCORS stations, especially in estimating the subsurface slip and the extent of the deformed area. Therefore, this study aims to provide a more in-depth analysis of the seismic deformation resulting from the activity on the Palu Koro Fault during the 2018 Palu earthquake, focusing on the horizontal coseismic deformation. In addition, surface deformation values obtained from InaCORS station observations will be used to calculate deformation using the Okada method. The observed and calculated deformation values will then be used to model subsurface deformation with the Okada model to obtain earthquake slip parameters and estimates.

Method

Data

The data used in this study are a time series of InaCORS station position observations from 6 August to 28 November 2018, namely the day of the year (DoY) 218-317. The InaCORS stations used are CPRE (Parepare), CMLI (Malili), CPAL (Palopo), WATP (Watatu) and TOBP (Toboli). The distribution of stations used is shown in Figure 1B. The selection of InaCORS stations was based on the distance between the epicenter of the earthquake and the research area where the InaCORS station is located, as well as the availability of the required data at the time needed for the research.

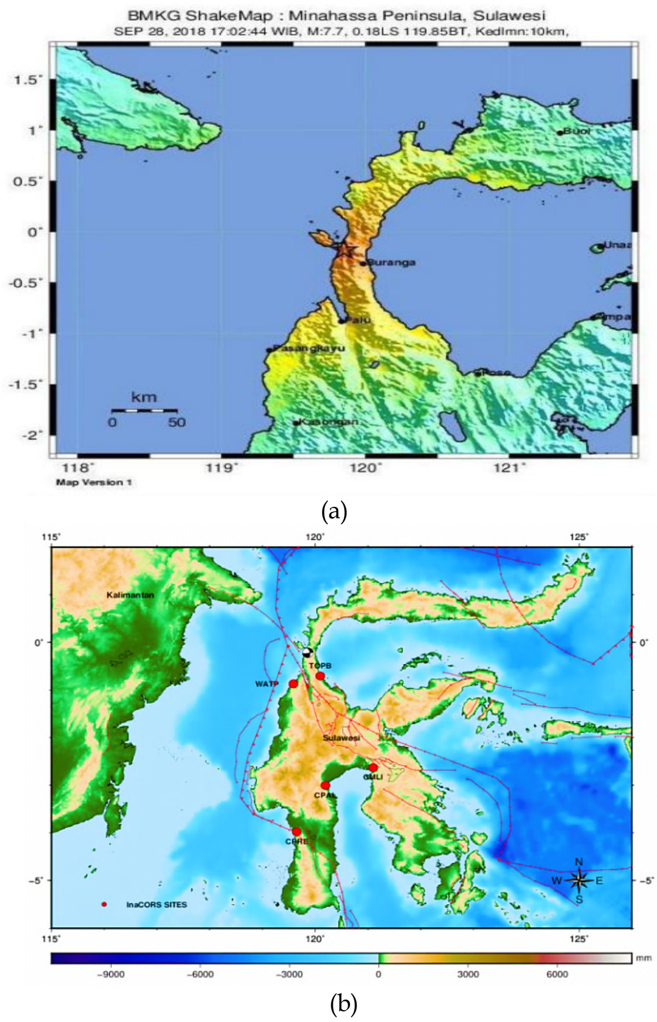


Figure 1. a. Epicenter of 7.5 SR Palu eartquake; b. Distribution of InaCORS stations used in this study

Methods

In this study, observational data from GPS stations was meticulously processed using the GAMIT/GLOBK software (version 10.74) to derive precise insights into geodetic phenomena. GAMIT, an acronym denoting GPS Analysis Massachusetts Institute of Technology, was employed as a robust and fully automated scientific tool developed by the esteemed Massachusetts Institute of Technology (MIT) for the comprehensive analysis of GPS data. The GAMIT processing methodology involved the estimation of station coordinates to discern deformation patterns during seismic events, requiring eight distinct input data types: raw data, l-file, station.info, session.info, navigation, sestbl, sittbl, and the GPS ephemeris file. The resultant output of GAMIT processing encompassed h-files, q-files, and an autcl.summary file.

Following GAMIT processing, the data underwent further analysis and refinement through the GLOBK (Global Kalman filter VLBI and GPS analysis program) software package. The h-files generated by GAMIT served as crucial input for GLOBK processing, yielding daily position data in both topocentric coordinates (north, east, up) and geocentric coordinates (X, Y, Z). Additionally, GLOBK produced a comprehensive time series graphic featuring error bars to visually represent station movement. To enhance the visualization and interpretation of the shift vector derived from GPS observation data, the GMT 5.4.5 software (Generic Mapping Tools) was employed. The resulting GLOBK output, comprising daily position data in topocentric coordinates (N, E) and deformation velocity (Ve and Vn) for both networks, was then judiciously utilized in subsequent analyses, graphical representations, and map plotting, ensuring a robust and thorough exploration of the geodetic dynamics under investigation.

The seismic data utilized for the Okada model analysis in this study were obtained from the USGS Catalog. The monitoring of fault zone phenomena was designed using a three-dimensional elastic dislocation model that takes into account fracture parameters such as dip, depth, width, and length of the fault plane. By varying the locking depth and dip of the fault zone, the expected station placement can be estimated to detect motion patterns in both horizontal and vertical directions (Okada, 1992). The Okada model produced in this research will depict three-dimensional internal deformation during the co-seismic phase of the 2018 Palu earthquake. The accuracy of the model concerning GPS observation data is assessed based on the Root Mean Square (RMS) values, where a smaller RMS value indicates a better-fitting model.

Upon obtaining deformation values and displacement directions, a map illustrating the displacement pattern of the Palu-Koro Fault will be created using GMT 5.4.5. This map aims to visually represent the spatial distribution of fault movements based on the developed model. The data processing methodology used in this study aligns with previous research (Wihikan & Heliani, 2020; Monica et al., 2022a; Monica et al., 2022b; Ramadhan et al., 2022; Friska et al., 2022; Nurdin et al., 2022).

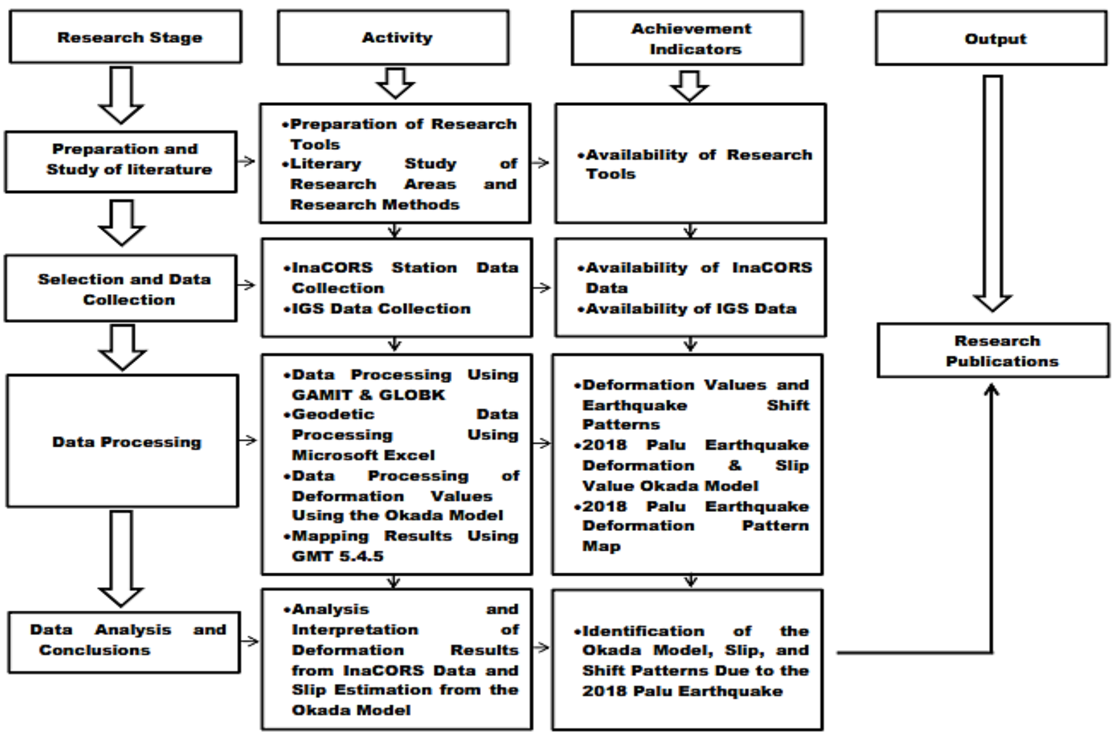


Figure 2. Research flow chart

Result and Discussion

Time Series of InaCORS data

Figure 3 depicts a time series graph covering 100 days of observation for all InaCORS stations used, including WATP, CPRE, CPAL, TOBP, and CMLI. Dashed lines indicate the day of the earthquake or the coseismic phase (Day of Year 271). During this phase, the accumulated energy resulting from preseismic movement is released in the form of vibrations or an earthquake. The movement has exceeded the elastic limit of the rocks in the area around the earthquake epicenter, causing the surrounding rocks to deform (Anggriani et al., 2020).

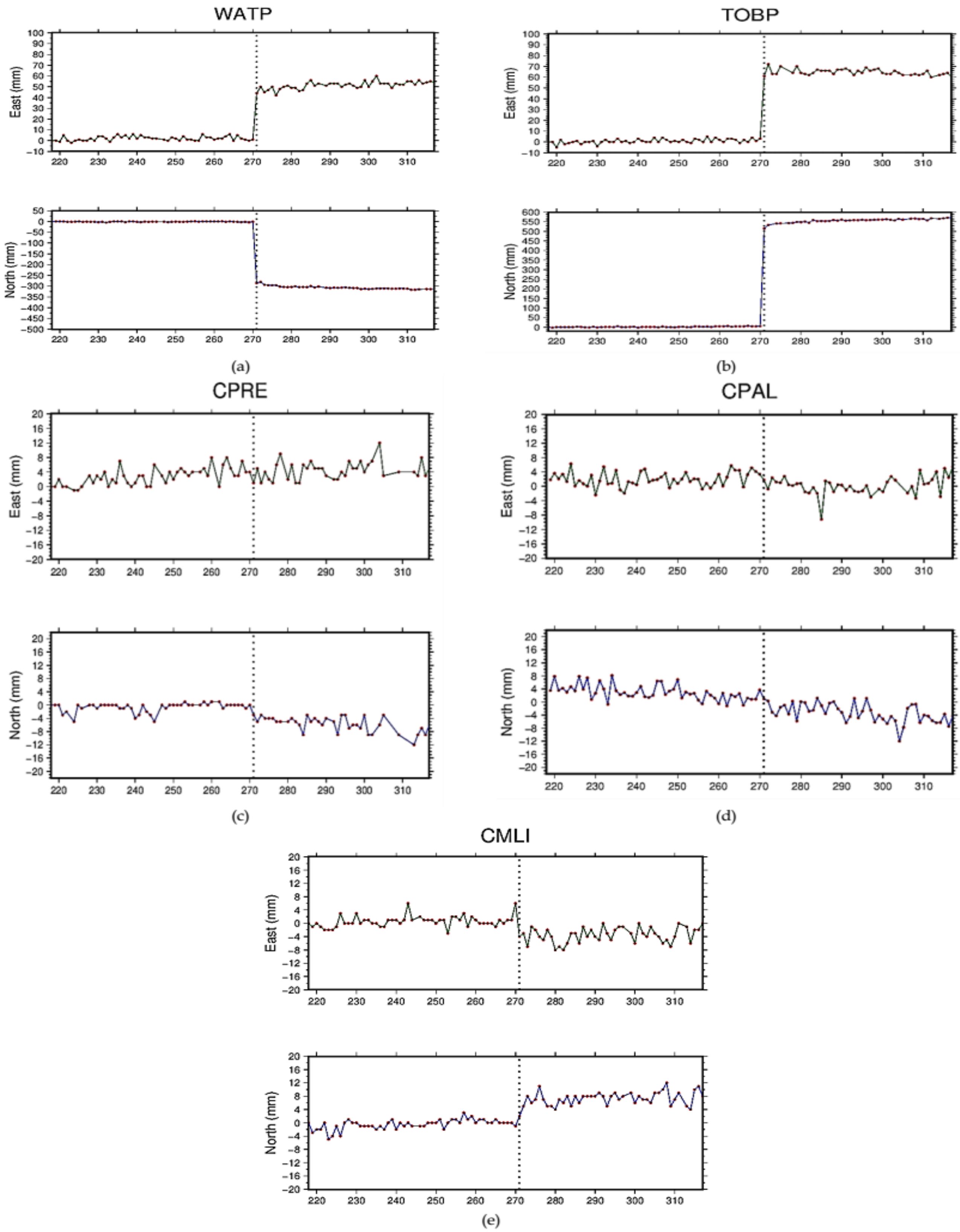


Figure 3. Time series graph of (a) WATP, (b) TOBP, (C) CPRE (d) CPAL (e) CMLI InaCORS station during co-seismic phases. X-axis is the DOY observation and Y-axis is horizontal shift. The dottet line show the day the earthquake occurred

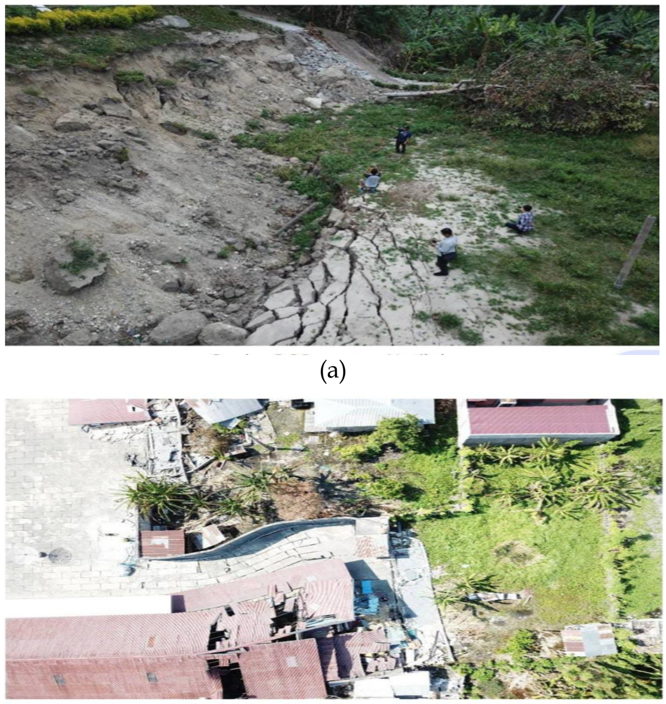
The coseismic jump in Figure 3 is clearly observed, particularly at the WATP and TOBP stations. Although the deformation magnitudes at these two stations differ, they exhibit a similar pattern of movement in the eastward direction, where the displacement increases. However, there is a difference in the northward direction, with the displacement value increasing for the TOBP station and decreasing for the WATP station. This is because the TOBP station is located to the north of the Palu Koro Fault, while WATP is situated to the south, opposite each other. Additionally, this difference may also be attributed to the varying distances between the earthquake epicenter and the station locations, where closer stations experience greater deformation.

The time series for InaCORS stations CPAL and CPRE, located on the south side of the Palu Koro Fault, is less pronounced. For CPAL, during the coseismic phase, there is minimal movement with a deformation pattern involving a reduction in values in the east and north directions. At the CPRE station, there is a decrease in deformation values during the coseismic phase in the east and north directions. As for the CMLI station, deformation is observable in the north and east directions, but it is not particularly significant. From the analysis of the InaCORS time series data above, it can be observed that the closer the station is to the earthquake epicenter, the greater the deformation.

Deformation in the Coeseimic phase based on the Okada Model

Table 1 represents the deformation values obtained from the parameters of the Palu earthquake on September 28, 2018, calculated using the Okada method. The deformation values obtained have an RMS (Root Mean Square) value of 2.25 horizontally concerning the observation data from InaCORS stations. A smaller RMS value indicates a closer approximation to the actual results (Ikram et al., 2023). Therefore, this data can be considered accurate, and the processing results using the Okada method for the direction of displacement align with the deformation observed at BIG stations. Stations in the northern part generally move northward, while those in the southern part move southward, consistent with the characteristic left-lateral shift of the Palu Koro Fault (Muttaqin, 2019; Nurdin et al., 2022).

Based on a surface offset survey of the 2018 Palu earthquake, interferometry data verified using ALOS-2 and JAXA satellite data by the Japan Geospatial Information Authority (GIA) revealed horizontal surface deformation (Daryono et al., 2018; GIA, 2018). INSAR data indicate a rise in ground elevation in the Donggala area (Elliot, 2018). Landsat-8 USGS/NASA images further confirm that the 2018 Palu earthquake caused horizontal deformation with a left-lateral shift, supported by field surveys conducted by the PuSGeN team, as depicted in Figure 4 (Daryono et al., 2018; Elliot, 2018).



(a)

(b)

Figure 4. Seismic Deformation based on Survey by PuSGeN team a. Vertical b. Horizontal (Daryono et al., 2018).

Table 1. Horizontal Co-seismic Deformation of the 20187.5 SR Palu Earthquake Using the Okada Model

Station	Deformation Vector		Horizontal Deformation (mm)	Direction
	DN (mm)	DE (mm)		
WATP	-287.16	43.47	245.81	South east
TOBP	508.83	54.19	477.13	North east
CPAL	-3.35	-7.69	8.32	South west
CPRE	-4.18	-4.47	7.79	South west
CMLI	4.47	-6.67	10.44	North west

The highest deformation value is found at the TOBP station in the northern part of the Palu Koro Fault. Its horizontal movement shows a deformation value of 508.83 mm to the east and 54.19 mm to the north, resulting in a total horizontal deformation of 477.13 mm, with movement in the northeast direction. The smallest deformation values are exhibited by the CPRE station, with a horizontal shift of -4.18 mm to the north and -4.47 mm to the east, resulting in a total horizontal displacement of 7.7852 mm to the southwest. Moving to stations south of the Palu Koro Fault, the WATP station undergoes successive shifts of -287.156 mm and 43.47 mm in the north and east directions, leading to a horizontal movement toward the southeast of 245.809 mm. Other stations situated to the south of the Palu Koro Fault, namely CMLI and CPAL, experience displacements of -4.47 mm and -6.67 mm for CMLI and -3.35 mm and -7.69 mm for CPAL in the north and east directions. These result in horizontal movements toward the northwest and southwest, respectively.

The deformation values obtained from the USGS Okada model parameters are illustrated in Figure 5. The arrow lengths indicate the deformation values, while the arrow colors represent horizontal movements based on observations (red) and the Okada model (green). Figure 4 also illustrates the subsurface areas that experienced slip during the earthquake, with the slip indicated by pink-colored arrows. Data processing using the Okada model reveals a subsurface slip magnitude of 1449.23 mm, covering an area with dimensions of 145 km by 76 km. The earthquake parameters include a depth of 8 km, a dip angle of 65˚, a strike of 351˚, and a rake of -46˚. Spatial Coulomb Stress analysis in previous research obtained earthquake parameters with a magnitude of Mw 7.48, strike 350˚, dip angle of 67˚, and rake of -9˚, with a maximum slip of 1.65 meters (Wulur et al., 2021). Meanwhile, using Inversion Teleseismic Body waves, earthquake parameters were found to be a strike of 353˚ ± 5˚, dip of 65˚ ± 5˚, rake of -4˚ ± 5˚, with dimensions of 150 km by 45 km and a slip of 1.5 meters (Yolsal-Çevikbilen & Taymaz, 2019). According to the earthquake parameter data released by USGS, the reported values include a magnitude of Mw 7.5, strike of 358˚, dip of 66˚, depth of 10 km, rake of -17˚, and a maximum slip of 1.8 m (United States Geological Survey, 2018).

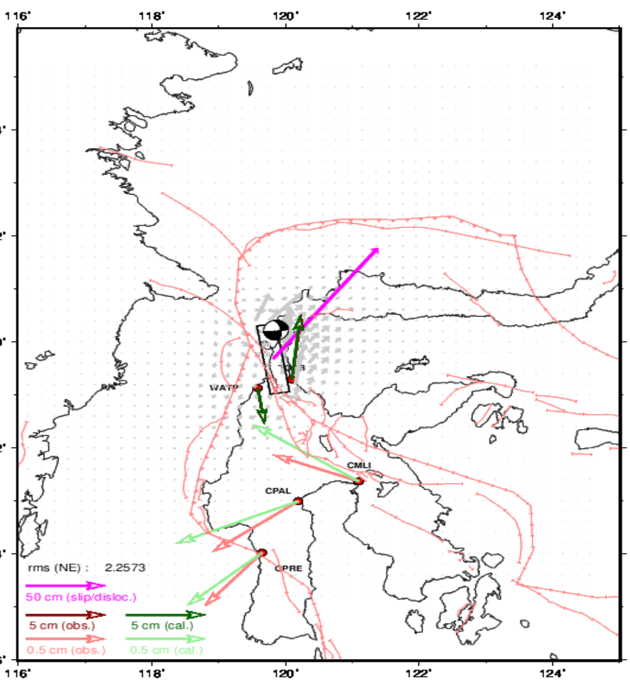


Figure 5. Horizontal co-seismic deformation of the 2018 7.5 SR Palu earthquake using the okada method

The Okada model generally provides results that closely approximate the actual conditions. However, there are some differences in specific parameters compared to research using other methods, particularly in the Rake angle, which typically ranges from -17 to -9˚, whereas the obtained value is -47˚. This discrepancy might be attributed to the limited number of observation stations used and their uneven distribution in the southern and northern regions of the Palu Koro Fault, resulting in less-than-optimal results for the Rake angle. Nevertheless, the research findings align with those of other researchers using different methods.

The deformation directions are different for some stations (Figure 5). The most notable difference in direction is for the TOBP and WATP stations. This difference is because these two stations are directly separated by the Palu Koro fault, whose mode of movement is strike-slip, where the northern part tends to move northwards while the southern part moves southwards (Bellier et al., 2001; Hui et al., 2018; Song et al., 2023; Ulrich et al., 2019). The southern part of the Palu Koro fault, specifically at stations WATP, CPRE, and CPAL, also has different directions of movement. This difference in movement may be due to the influence of other fault activity near the CPRE and CPAL stations, namely the Mamuju fault, while the WATP station is right on the south side of the Palu Koro fault. In the north, the movement of the TOBP and CMLI stations have different directions in east and west, and this difference is due to the movement of the CMLI station also being affected by other nearby faults, namely the Matano and Lawanopo faults.

Conclusion

In summary, the analysis of the 2018 Palu earthquake, combining time series observations and the Okada model, reveals key insights. The coseismic phase, marked by a distinct jump in time series of InaCORS data, indicates significant deformation, especially at WATP and TOBP stations. The Okada model, validated by a small RMS value, accurately captures the horizontal movements consistent with the left-lateral shift of the Palu Koro Fault. Satellite data further confirms the observed horizontal deformation and subsurface slip. Variations in deformation directions highlight the influence of multiple faults. Overall, the study provides a comprehensive understanding of the earthquake's impact, emphasizing the need for multi-method approaches in seismic analysis.

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Author Contributions
Conceptualization, N. N and D. A, M. M.; methodology, N. N. and D. A.; software, N. N. and D. A.; validation, N. N. and D. A; formal analysis, N. N. and D. A.; investigation, N. N. and D. A.; data curation, N. N. and D. A.; writing—original draft preparation, N. N. and M. M.; writing—review and editing, M. M. and V. F.; visualization, N. N. and D. A.; supervision, M. M.

and D. A.; project administration, M. M.; funding acquisition, M. M.

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Conflicts of Interest
No conflict interest.

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