Widespread ground deformation over the Palu Basin caused by the 2018 Sulawesi, Indonesia Earthquake

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Key Facts
- Hazard Type: Earthquake
- Date of disaster: Sept. 28th, 2018
- Location of Survey: Palu, Central Sulawesi, Indonesia
- Date of the field survey: Not Applicable
- Survey tools: Digital Terrain Models, InSAR
- Key findings:
  1) Pre and Post-earthquake Digital Terrain Models (DTMs) covering Palu Basin suggested that the entire stretch of the basin, mainly west of the irrigation canal, seemed to have deformed, not to mention the large flow slide sites.
  2) Line-of-sight (LOS) deformations over the Palu Basin obtained from ALOS 2/PALSAR 2 at two different days after the earthquake (October 12, 2018, and January 4, 2019) showed that the flat land has slowly and steadily been deforming over the three months.

Key Words : *2018 Sulawesi Earthquake, long-lasting ground displacement buildup, lateral slides*

1. INTRODUCTION

A devastating M_w 7.5 earthquake struck Central Sulawesi, Indonesia, on September 28, 2018, resulting in over 4,000 fatalities and severe damage to several areas in and around Palu City. Sulawesi is a vast island of Indonesia with four spindly arms spinning outward. Palu city is at the inner-most part of Palu Bay that cuts in the northernmost arm joint. The south-north trending Palu Basin that extends straight to Palu Bay features the unique terrain of the epicentral area. The epicentral area is a typical pull-apart tectonic basin with a thick alluvial deposit filling the valley. This earthquake's most spectacular and devastating aspect was lateral slides of the almost flat alluvial soil deposit along the west and east bounds of the basin. Lateral spreads were the most serious in Balaroa, Petobo, Jono Oge, and Sibalaya (Rohit, D.[1)], Kiyota et al.[2)]). The maximum flow distance at each site was reportedly several hundred meters or more. As of October 9, 2018, at least 671 were on the list of missing, but the National Disaster Management Agency said the mudflows may have swallowed up many more people when the flows engulfed houses in these villages (Aprilia, K.[3)]). Though the administration's final count of victims has finally reached 4,340 (United Nations Office for the Coordination of Humanitarian Affairs, OCHA[4)]), the actual death toll due to the combined effects of the earthquake and tsunami might never be known (Aprilia, K.[3)]).

There are various theories for the lateral-spread initiations and motions discussed by many researchers (Kiyota et al.[2)], Rohit, D.[1)]). They have a common opinion that liquefiable deposits and multiple capping layers might have triggered the flow slides. Bradley, K.[5)] reported that aqueduct-supported cultivation, primarily of wet rice, raised the water

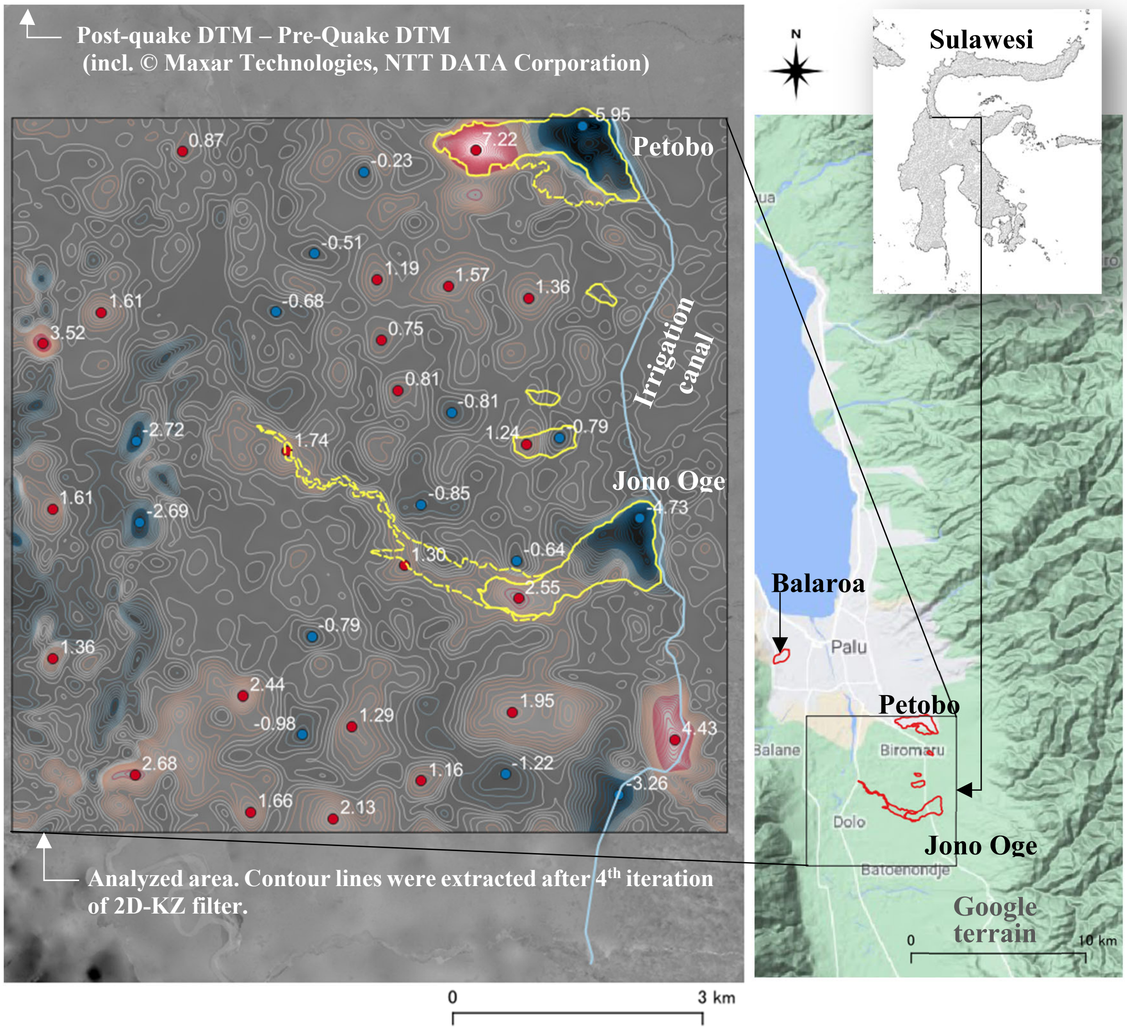

Fig. 1 Difference in the digital terrain models (incl. © Maxar Technologies, NTT DATA Corporation) before and after the earthquake: The Two-Dimensional (2D) Kolmogorov–Zurbenko (KZ) filter was applied to the image to smear the rapid intensity changes and draw smoother contour lines. The contour lines are drawn with the unit and the interval set at the "meter" and "0.2 m," respectively. Yellow polygons show locations of extensive flow slides.

table near ground level, saturating sandy alluvial soils. Thus, the devastating lateral spreading in the Palu Valley could have been a direct consequence of irrigation. However, the cause of flow-slide cannot be determined solely by the presence of the irrigation channel because there was no primary irrigation channel in Balaroa, the west side of Palu Valley (Kiyota et al.[2]).

For a thorough discussion of the impact of soil spreading, it is essential to look at the big picture of the soil spreading over the whole Palu Basin. We also need to keep a watchful eye on if the ground has been deforming since the devastating events. Though the post-quake movements of the land can be small, the deformation buildups may have affected lifeline restoration operations in these areas. For this purpose, we use two sets of topographic data; (1) Digital Terrain Models of the Palu Basin before and after the earthquake and (2) Line-of-sight (LOS) deformations over the Palu Basin obtained from ALOS 2/PALSAR 2 on two different days after the earthquake (October 12, 2018, and January 4, 2019). This article describes the preliminary results of our analyses of the two topographic data sets.

2. IMMEDIATE GROUND DEFORMATION

The Digital Terrain Models (AW3D DTMs, 2 m resolution, NTT Data, RESTEC[6]) before and after the earthquake are random gatherings of various source data sets at different times. The DTM before the earthquake covers the period from January 1, 2010, to September 27, 2018, while the post-quake DTM covers the period from September 28, 2018, to November 20, 2018. Differences in spatial coverage and levels of detail often create discontinuities within the overlapping areas of the source DTMs and along

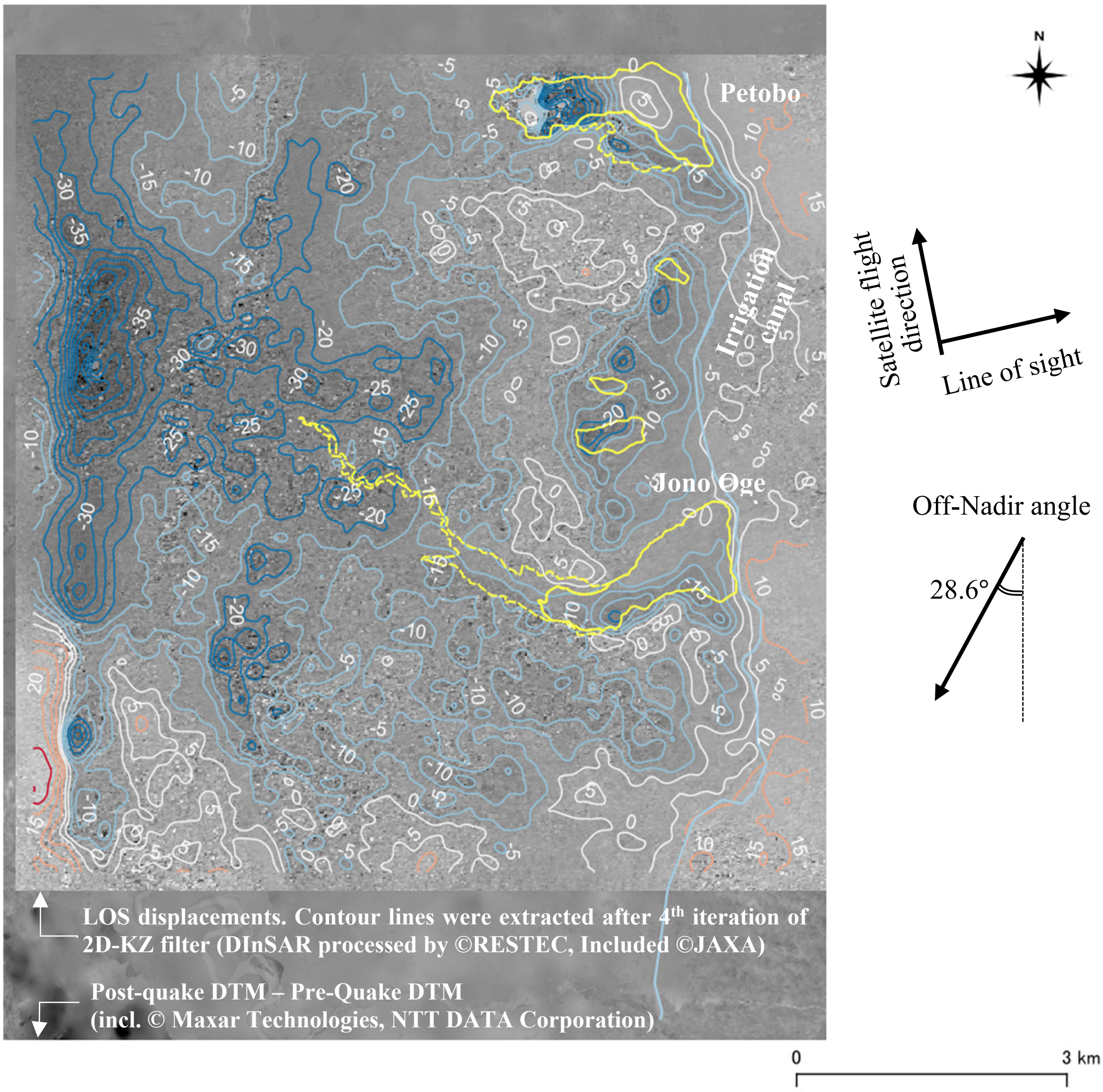

Fig. 2 Line-of-sight (LOS) deformations over the same area as Fig. 1 from ALOS 2/PALSAR 2 on two different days after the earthquake (October 12, 2018, and January 4, 2019): DInSAR processed by ©RESTEC, Included ©JAXA. The Two-Dimensional (2D) Kolmogorov–Zurbenko (KZ) filter was applied to the image to smear the rapid intensity changes and draw smoother contour lines. The contour lines are drawn with unit and interval set at the "millimeter" and "5 mm," respectively. Yellow polygons show locations of extensive flow slides.

their boundaries. Therefore, calibration was supposed to have been made with precise reference points given on the ground. However, amid the COVID-19 pandemic, which did not allow any field works, we subtracted the pre-quake DTM from the post-quake DTM to evaluate the vertical components of the quake-induced ground displacement. To avoid rapid scatters in the image intensity, the difference of the DTMs was first resampled for a burred image of 10 m resolution. Then, the Two-Dimensional (2D) Kolmogorov–Zurbenko (KZ) filter (Zurbenko[7], Yang, W.[8]) was applied to the image to smear the rapid intensity changes further. The 2D-KZ filter is a series of iterations of a moving average square filter $(2L+1)\times(2L+1)$, where L is a positive integer. It has thus two parameters, the half-length L of the square window and the number of iterations k of the moving average operation. Since the resampled DTM has a 10 m resolution and L was set at 5, the moving average window is 110-m square.

Fig. 1 shows the 2D-KZ filtered image of the elevation change over the 8,600 m × 8,600 m flat-land area south of Palu City. Note that the 4th iteration of the moving average with the half-length of the window set at 50 m conservatively truncates the original target area of 9,000 m × 9,000 m by 400 m and 400 m in north-south and east-west directions. The area includes two extensive flow slides at Petobo and Jono Oge. The ground deformation is not exclusive to these large flow slide sites. Surprisingly, almost the entire analyzed area, particularly west of the irrigation canal, shows a checkerboard elevation change pattern. The pattern shows alternating positive and negative values of elevation change ranging over about -1.0 m or below to + 1.0 m or more prominent. Though the calibrations of the DTMs are needed, these peak values are substantially large enough to acknowledge the statistical significance of the 2D-KZ filtered image of the elevation change. The positive and negative peaks appear periodically at an average interval of about 1 km. This pattern can reflect the subsurface soil profile that can include liquefied layers.

3. POST-QUAKE CREEPING GROUND DEFORMATION

If the widespread subsurface layer liquefies, the layer can remain soft for an extended period causing the ground surface to deform gradually (Kiyota et al.[9]). For confirmation purposes, the authors have obtained Line-of-sight (LOS) deformations over the same area from ALOS 2/PALSAR 2 on two different days after the earthquake (October 12, 2018, and January 4, 2019). The 2D-KZ filter was applied to the image of LOS deformations to smear the rapid intensity changes and extract smooth contour lines (Fig. 2). Fig. 2 shows during the three months that the widespread area west of the irrigation canal had been deforming with ridges developing about 15 mm high and troughs sunken about 20 to 30 mm deep. The troughs drawn with blue contour lines seem to have developed on the depositional areas of the extensive flow slides and along the meandering trace of Palu River.

This pattern of LOS displacements contains errors arising from the uncertainty of estimated orbit or topography and the delay caused by the disturbance of water vapor in the atmosphere. However, the LOS displacements are remarkable, mainly on the western side of the irrigation canal. Thus, this pattern triggers us to acknowledge the statistical significance of the 2d-KZ filtered image of the LOS displacements.

4. SUMMARY

The devastating M_w 7.5 Palu Earthquake and Tsunami struck northwestern Sulawesi, Indonesia, on September 28, 2018. This earthquake's most spectacular and catastrophic aspect was lateral slides of the almost flat alluvial soil deposit along the west and east bounds of the basin. To get a perspective on the extensive ground deformation of Palu Basin, we used two sets of topographic data. Namely, (1) Digital Terrain Models (DTMs) of the Palu Basin before and after the earthquake and (2) Line-of-sight (LOS) deformations over the Palu Basin obtained from ALOS 2/PALSAR 2 on two different days after the earthquake (October 12, 2018, and January 4, 2019). The obtained images suggested that the entire stretch of the basin, mainly west of the irrigation canal, seemed to have deformed, not to mention the large flow slide sites. If the widespread ground deformation is attributed to soil liquefaction, the liquefied layer can remain soft, causing the ground to deform gradually for an extended period. The observed pattern of Line-of-sight (LOS) deformations over the Palu Basin shows that the flat land has slowly been deforming over the three months (from October 12, 2018, to January 4, 2019), backing up the hypothesis. These findings teach us essential lessons to enter the immediate and following stages of rehabilitations of liquefaction-devastated areas. We need to take necessary measures considering the liquefied ground can remain soft for an extended period. Further studies will be necessary for more quantitative discussions.

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REFERENCES

1) Rohit, D., Hazarika, H., Maeda, T. et al.: Forensic investigation of flowslides triggered by the 2018 Sulawesi earthquake. *Prog Earth Planet Sci*, 8, Article No. 60, 2021. https://doi.org/10.1186/s40645-021-00452-5.
2) Kiyota, T., Furuichi, H., Hidayat, R.F., Tada, N., Nawir, H.: Overview of long-distance flow-slide caused by the 2018 Sulawesi earthquake, Indonesia, *Soils and Foundations*, Vol. 60, Issue 3, 722-735, 2020, ISSN 0038-0806, https://doi.org/10.1016/j.sandf.2020.03.015.
3) Aprilia, K.: Death Toll in Indonesia’s Quake, Tsunami Climbs Past 2,000, *Benar News*, Radio Free Asia, October 9, 2019, https://www.benarnews.org/english/news/indonesian/indonesia-quake-10092018170604.html. (Accessed March 1, 2022).
4) United Nations Office for the Coordination of Humanitarian Affairs, OCHA: Central Sulawesi disasters killed 4,340 people, final count reveals, *Relief-web*, Jan. 31, 2019, https://reliefweb.int/report/indonesia/central-sulawesi-

disasters-killed-4340-people-final-count-reveals (Accessed March 1, 2022).
5) Bradley, K., Mallick, R., Andikagumi, H. et al.: Earthquake-triggered 2018 Palu Valley landslides enabled by wet rice cultivation. *Nat. Geosci*. 12, 935–939, 2019, https://doi.org/10.1038/s41561-019-0444-1.
6) NTT Data, RESTEC: The world's first 3D global map with 5M resolution AW3D: Global High-resolution 3D Map, https://www.aw3d.jp/en/about/ (Accessed March 1, 2022).
7) Zurbenko. I.: The Spectral analysis of time series, *North-Holland Series in Statistics and Probability*, Elsevier, Amsterdam, 1986.
8) Yang, W., Zurbenko, I.: Kolmogorov-Zurbenko filters, *Wiley Interdisciplinary Reviews: Computational Statistics*, 2 (3): 340–351, 2010, https://doi.org/10.1002/wics.71.
9) Kiyota, T., Ikeda, T. Yokoyama, Y. and Kyokawa, H.: Effect of in-situ sample quality on undrained cyclic strength and liquefaction assessment, *Soils and Foundations*, Vol. 56, Issue 4, 691-703, 2016. https://doi.org/10.1016/j.sandf.2016.07.009.
10) Japan International Cooperation Agency (JICA): Project for Development of Regional Disaster Risk Resilience Plan in Central Sulawesi, updated on Jan. 13, 2022. https://www.jica.go.jp/project/english/indonesia/020/index.html (Accessed March 1, 2022).

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