EVALUATION OF INTERPOLATION METHODS FOR GNSS VELOCITIES IN CRUSTAL DEFORMATION: A CASE STUDY ON STRAIN RATE CALCULATION IN THE SOUTHERN SUMATRA

(*Evaluasi Metode Interpolasi untuk Kecepatan GNSS dalam Deformasi Kerak: Studi Kasus Perhitungan Laju Regangan di Selatan Sumatra*)

Satrio Muhammad Alif
Department of Geomatics Engineering, Institut Teknologi Sumatera1
Terusan Ryacudu, Way Huwi, Jati Agung, Lampung Selatan, Indonesia, 35365
E-mail: satrio.muhammad@gt.itera.ac.id

Diterima: 21 Agustus 2024; Direvisi: 26 September 2024; Disetujui untuk Dipublikasikan: 27 November 2024

ABSTRACT

This study evaluates three interpolation methods—Inverse Distance Weighting (IDW), Kriging, and Sandwell—for analyzing crustal deformation in southern Sumatra, focusing on the on-site velocity consistency test. This test is crucial for assessing interpolation accuracy by comparing interpolated velocities to actual GNSS velocities at specific sites. Given the region's sparse GNSS network, accurate interpolation is vital for reliable deformation analysis. GNSS data from continuous and campaign sites, collected between 2017 and 2022 with a 30-second sampling interval, were processed to generate velocity. The Sandwell method, particularly with a Poisson’s ratio of 0, demonstrated superior performance, achieving the lowest mean residuals in the on-site velocity consistency test. This method consistently provided accurate interpolated velocities that closely matched original site data. IDW and Kriging methods also showed effectiveness but had different convergence behaviors: IDW required higher interpolation degrees for accuracy, while Kriging excelled in the east-west residuals. The Sandwell method’s velocities were used to calculate strain rates, revealing significant spatial variability. The findings underscore the importance of detailed on-site velocity consistency testing and highlight the need for expanding GNSS networks to improve accuracy and better assess seismic hazards in southern Sumatra.

Keywords: Crustal deformation, GNSS velocities, interpolation methods, on-site velocity consistency, strain rates

ABSTRAK

Penelitian ini mengevaluasi tiga metode interpolasi—Inverse Distance Weighting (IDW), Kriging, dan Sandwell—untuk menganalisis deformasi kerak di Sumatra bagian selatan, dengan fokus pada uji konsistensi kecepatan di titik GNSS. Uji ini penting untuk menilai akurasi interpolasi dengan membandingkan kecepatan interpolasi dengan kecepatan GNSS aktual di setiap titik. Karena jaringan GNSS di area ini tidak padat, interpolasi yang akurat sangat penting untuk analisis deformasi yang baik. Data GNSS dari situs kontinu dan periodik, yang dikumpulkan antara tahun 2017 dan 2022 dengan interval pengambilan sampel 30 detik, diproses untuk menghasilkan kecepatan. Metode Sandwell, terutama dengan rasio Poisson 0, menunjukkan kinerja yang terbaik, mencapai residual rata-rata terendah dalam uji konsistensi kecepatan di titik GNSS. Metode ini secara konsisten memberikan kecepatan interpolasi yang akurat yang cocok dengan data kecepatan GNSS yang asli. Metode IDW dan Kriging juga menunjukkan efektivitas tetapi memiliki perilaku konvergensi yang berbeda: IDW memerlukan derajat interpolasi yang lebih tinggi untuk interpolasi yang baik, sementara Kriging unggul dalam residual komponen timur-barat. Kecepatan dari metode Sandwell digunakan untuk menghitung laju regangan, dan menunjukkan variabilitas spasial yang signifikan. Temuan ini menekankan pentingnya uji konsistensi kecepatan di lokasi yang rinci dan menyoroti kebutuhan untuk memperluas jaringan GNSS guna meningkatkan akurasi dan menilai bahaya seismik di Sumatra bagian selatan.

***Kata kunci**: Deformasi kerak, kecepatan GNSS, metode interpolasi, konsistensi kecepatan di titik GNSS, laju regangan*

INTRODUCTION

Monitoring crustal deformation is crucial for understanding seismic hazards, particularly in earthquake-prone regions. The Global Navigation Satellite System (GNSS) has become an indispensable tool in this endeavor, providing precise measurements of ground movements that are critical for assessing seismic risks (Raharja et al., 2023). GNSS velocities can be used to analyze deformation throughout the earthquake cycle, including coseismic (Anggara et al., 2024), postseismic (Alif et al., 2016), and interseismic deformation (Takada et al., 2018). Therefore, a dense network of GNSS sites is required to precisely estimate earthquake potential in countries with a high risk of earthquakes. In Indonesia, such networks are established by Badan Informasi Geospasial (BIG) and are known as the Indonesia Continuously Operating Reference Stations (InaCORS) (Aditiya et al., 2014). The network was densified in 2018 on Sumatra Island to complement another pre-existing GNSS network in Sumatra, the Sumatran GPS Array (SuGAr), which is managed by the Earth Observatory of Singapore (EOS) (McLoughlin et al., 2011). Additionally, there are extra campaign GNSS sites managed by BIG in southern Sumatra.

However, this dense network is still too sparse and lags behind those of other countries with similar seismic risks, such as Japan (Sagiya, 2004). The availability of a denser network would allow for more precise identification of earthquake hazards (Shyu et al., 2020), such as fault slip rates (Natawidjaja, 2018), and sources of non-seismic crustal deformation (Meneses-Gutierrez et al., 2020). In southern Sumatra, the currently established sources of earthquake hazard are the subduction zone, beginning at the Sunda Trench as a result of the subduction of the Indo-Australian Plate beneath the Sundaland Plate (McCaffrey, 2009), and the Sumatran Fault Zone, which results from oblique subduction (Sieh & Natawidjaja, 2000). No other seismogenic faults are confirmed in the area of approximately 146.2 km² (BPS, 2024), which might be fewer than the actual sources of hazard. Moreover, the complex deformation from past earthquakes, starting in 2004 and affecting southern Sumatra (Alif et al., 2023), may influence the overall crustal deformation and cannot be properly resolved.

Given the limitations of current GNSS networks, spatial interpolation emerges as a potential solution. However, the accuracy of the interpolation can significantly deteriorate if the wrong method is chosen. This represents a critical gap in current practices, as selecting an inappropriate interpolation method could lead to inaccurate assessments of crustal deformation and, consequently, seismic hazards (Bucher et al., 1995). For spatial interpolation in crustal deformation, well-known methods include Inverse Distance Weighting (IDW) (Myers, 1994), Ordinary Kriging (Oliver & Webster, 1990), and the method introduced by Sandwell (Sandwell & Wessel, 2016). This research aims to evaluate these interpolation methods for GNSS velocities in crustal deformation. By identifying the most accurate method, this study seeks to mitigate the risks associated with improper interpolation and improve the reliability of strain rate calculations in southern Sumatra.

METHOD

GNSS data used in this study were obtained from all available GNSS networks in southern Sumatra, including both continuous and campaign sites (**Table 1**). These data were measured from 2017 to 2022, with a consistent sampling interval of 30 seconds across all networks. These data were processed using Bernese 5.2 (Dach & Walser, 2015), considering relative static positioning. Eight International GNSS Service (IGS) sites (ALIC, COCO, DARW, DGAR, IISC, KARR, PIMO, and YARR) (Johnston et al., 2017) were used as constrained sites during processing to obtain coordinate time series of those 35 GNSS sites in ITRF2014. Additional parameters considered in the GNSS processing included IGS final ephemeris, Earth rotation parameters, and the International Earth Rotation and Reference Systems Service (IERS) Conventions 2010. The general flowchart of this study is shown in **Figure 1**.

Table 1. GNSS data used in this study.

Reference	Classification	Number of Sites
SuGAr	Continuous	4
BIG	Continuous	17
BIG	Campaign	14

GNSS velocities were then calculated from the coordinate time series using classical time series analysis with the least squares method, as no offsets or periodic signals were detected (Feng et al., 2015). For the purposes of strain rate calculation and selecting the best interpolation method, only horizontal velocities (referred to as original GNSS velocities) were used. Additionally, the uncertainty of vertical velocities at campaign sites was statistically significant and could negatively impact the selection of the best interpolation method. These original GNSS velocities was then translated into Sundaland Plate reference frame (Alif et al., 2024).

The three interpolation methods (IDW, Kriging, and Sandwell) were applied, with each method tested under multiple parameter variations. The principle of IDW is the influence of a known data point decreases with increasing distance (Myers, 1994). The interpolation degree, which ranged from 1 to 99 with an interval of 2 resulting in 50 different interpolation options. The principle of Kriging is that the value is predicted by a weighted linear combination of the values at surrounding locations (Oliver & Webster, 1990). The Kriging range, ranging from 1 km to 1000 km, resulting in 5 different options. The principle of method introduced by Sandwell is that the Green's functions of an elastic body subjected to in-plane forces were applied in the interpolation process (Sandwell & Wessel, 2016). The Poisson’s ratio, which ranged from -1 to 1 with an interval of 0.1, was randomly selected, resulting in 21 different options.

The method to choose the best interpolation method involved finding the minimum mean residual at GNSS sites. To obtain the residual, the original GNSS velocity at a site was subtracted from the interpolated GNSS velocity at the same site through an on-site velocity consistency test. The interpolated GNSS velocity for a site was obtained by incorporating all other original GNSS velocities, except the original GNSS velocity at the site being calculated. Each scenario and method were iterated across all 35 GNSS sites. The evaluation was based on the east-west component, north-south component, and the resultant of the mean residual.

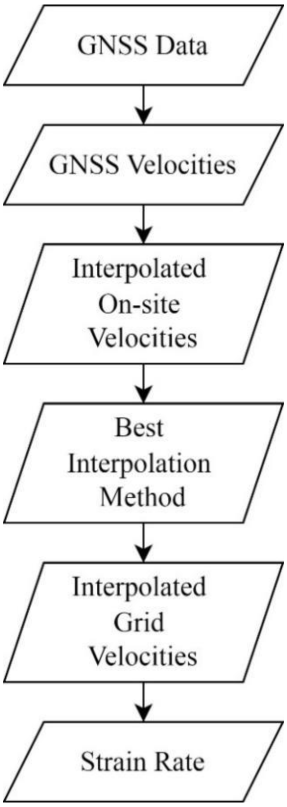

Figure 1. Research flowchart.

Using the best interpolation method, velocities at grid points were calculated from the original GNSS velocities. These grid points were spaced 20 km apart and located within the area encompassed by the distribution of GNSS sites. The interpolated grid velocities were then used to estimate the two-dimensional velocity gradient tensor, which models strain rate as a continuous function using the method of Shen et al. (1996), with a grid spacing of 20 km. It considers the distance between the grid of interpolated points and the grid for strain rate calculation, as well the smoothness radius which is considered as 30 km corresponds to the maximum strain rate variation in the study area. The principal strain rate obtained was then used to interpret the possible existence of other seismogenic faults.

RESULTS AND DISCUSSION

The original GNSS velocities in the Sundaland Plate reference frame generally show a northwestward motion (**Figure 2**). This motion is driven by the elastic component of the northward movement due to the oblique subduction of the Indo-Australian Plate (Alif et al., 2021). The velocities can be distinguished by larger values west of the Sumatran Fault Zone (SFZ) and smaller values to the east. The velocities west of the SFZ are significant, with a maximum value of 25.8 mm/year, due to the rigid motion of the Sliver block located between the SFZ and the Sunda Trench. These velocity results confirm the right-lateral behavior of the SFZ. The distribution of these original velocities is crucial to highlight, as it can influence the selection of the best interpolation method. Denser GNSS velocities are concentrated within 50 km of the SFZ, south of latitude -4.5° (inside the black rectangles in **Figure 2**), with more than 50% of the GNSS sites located in this zone. East of the denser zone, GNSS velocities are sparse and smaller in value. In these sparse zones, the reliability of interpolated velocities decreases (Wang et al., 2017).

The interpolation of on-site velocities, conducted 76 times across three different methods, is compared to the original GNSS velocities. The interpolated velocities generally appear smoother and more consistent than the original GNSS velocities (**Figure 3**). Away from the denser zone, the interpolated velocities are larger in magnitude, moving seaward and northwestward. East of the denser zone, the interpolated velocities are much smaller in magnitude, similar to the original GNSS velocities, with some moving southeastward. Within the denser zone, the random directions observed in the original GNSS velocities are not present in the interpolated on-site velocities.

Different interpolation methods exhibit distinct behavior in the on-site velocity consistency test (**Table 2**). The IDW method yields a smaller resultant mean residual as the interpolation degree increases, but it converges when the interpolation degree exceeds 80. This convergence results in a mean residual of 0.42 mm/year at an interpolation degree of 99. The Kriging method, in contrast, shows a different convergence trend, where the resultant mean residual decreases as the Kriging range decreases. The Kriging method produces a smaller resultant mean residual than the IDW method, achieving as low as 0.31 mm/year. Additionally, the Kriging method yields the best east-west component mean residual (<0.1 mm/year). On the other hand, the Sandwell method does not exhibit any convergence pattern, and the resultant mean residual is the smallest among all the interpolation methods, at 0.2 mm/year.

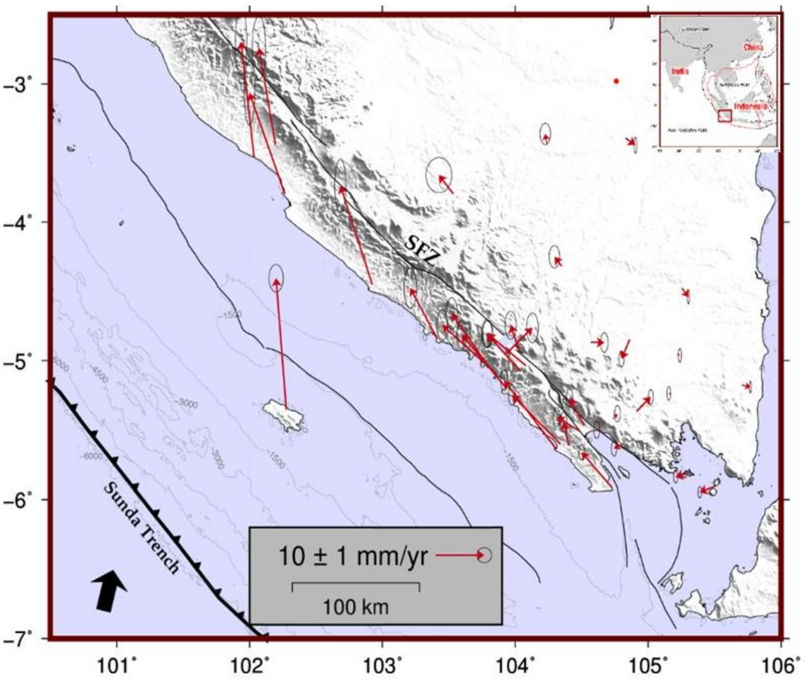

Figure 2. Original GNSS velocities.

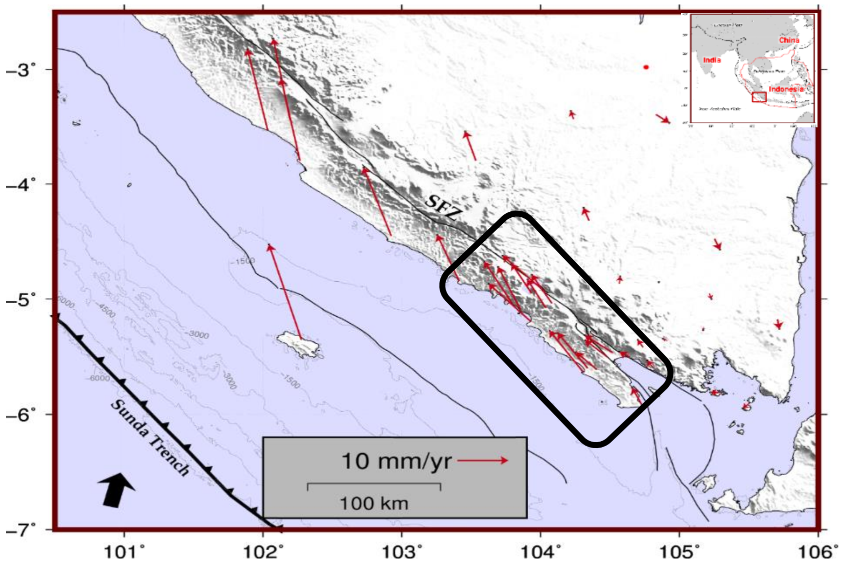

Figure 3. Interpolated on-site velocities of the best interpolation method.

Table 2. On-site velocity consistency.

Interpolation Method*	Mean Residual (mm/year)		
	East-West	North-South	Resultant
Sandwell (1)	0.36	-0.21	0.41
Sandwell (11)	0.14	-0.15	0.20
Sandwell (21)	0.41	-0.18	0.45
Kriging (1)	0.31	-0.01	0.31
Kriging (5)	-0.43	0.05	0.44
IDW (1)	-0.37	-0.37	0.51
IDW (10)	-0.21	-0.44	0.49
IDW (50)	-0.12	-0.40	0.42

**Number inside the bracket of the interpolation method is the option employed in the interpolation.*

The Sandwell interpolation method is identified as the best interpolation method for southern Sumatra based on the on-site velocity consistency test. The optimal setting is at option 11, corresponding to a Poisson's ratio of 0. As the Poisson's ratio deviates from this value, the resultant mean residual consistently increases. At a Poisson's ratio of 0, the resultant mean residual is 0.2 mm/year. While a Poisson's ratio of 1 and 0.5 indicates incompressible and highly elastic materials, respectively, a Poisson's ratio of 0 suggests that the material is relatively rigid (Ji et al., 2009). This ratio indicates that the GNSS velocities point predominantly in one direction across all regions, aligning closely with the original GNSS velocities, particularly in the denser zone. However, this analysis is only applicable to the current distribution of GNSS sites. With the establishment of additional GNSS sites, velocities could potentially point in multiple directions, leading to a different optimal Poisson's ratio or possibly a better fit with a different interpolation method. Nevertheless, given the current GNSS site distribution, the Sandwell interpolation method with a Poisson's ratio of 0 is employed to calculate the interpolated grid velocities used for strain rate calculation.

The interpolated grid velocities fill the gaps in areas without GNSS sites (**Figure 4**). These areas are mostly located outside the denser zone, such as the vast water body and the far east of the Sumatran Fault Zone (SFZ). The grid velocities over the vast water body are around 25 mm/year in a northwestward direction, while those in the far east of the SFZ are less than 3 mm/year in a southeastward direction. These interpolated grid velocities were then used to calculate strain rates (**Figure 5**). The principal strain rates and the dilatation rate are key components analyzed to understand the implications of the interpolated grid velocities (Dermanis, 2009). The maximum extension and maximum shortening in southern Sumatra are 17.1 μstrain/year and 11.9 μstrain/year, respectively. The analysis reveals significant spatial variability in strain rates, which is crucial for assessing tectonic activity and potential seismic hazards in the region. Additionally, the less reliable interpolation in sparse zones highlights the need for caution when interpreting strain rates in these areas. Future research and monitoring should focus on improving GNSS coverage and validating interpolated data to enhance the accuracy of strain rate assessments and better understand regional tectonics.

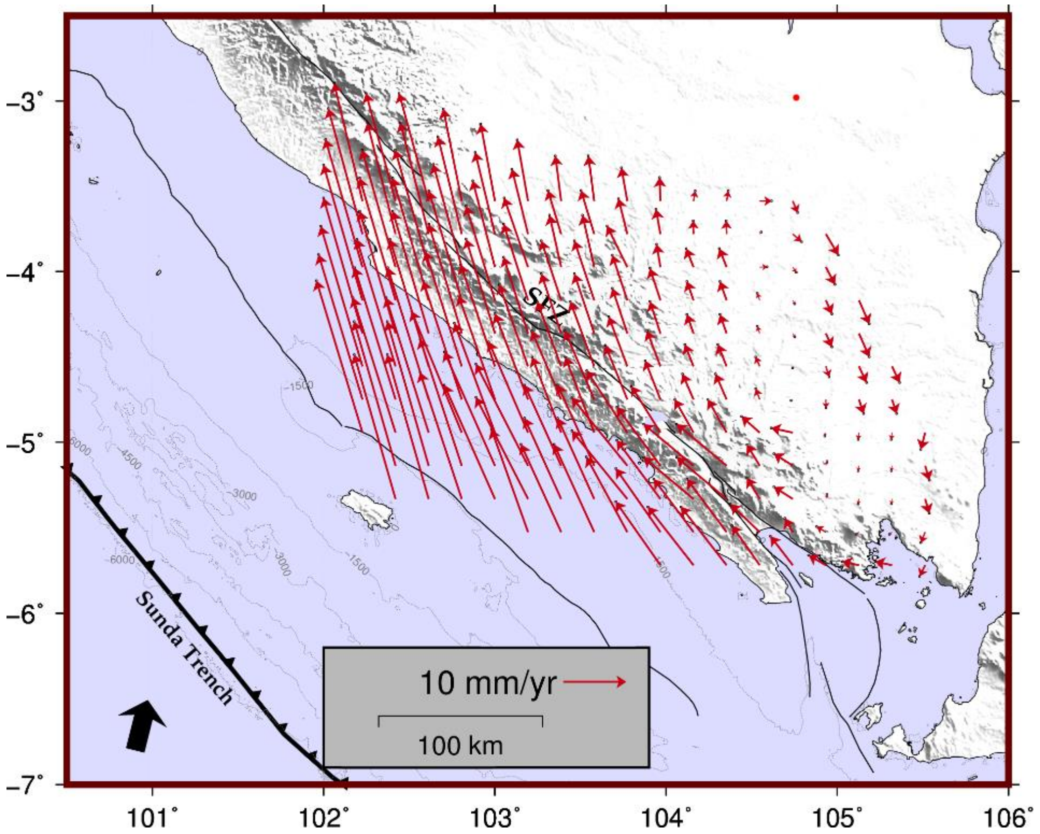

Figure 4. Interpolated grid velocities based on the best interpolation method.

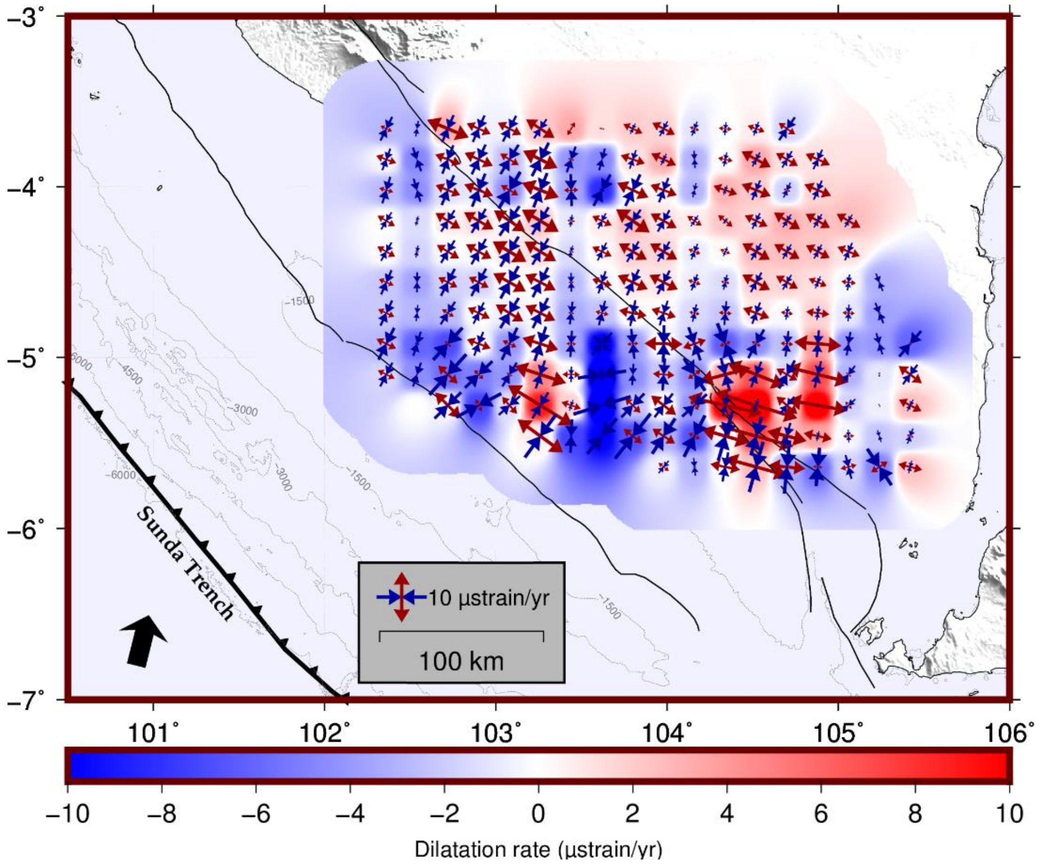

Figure 5. Strain rates in the southern Sumatra.

The strain rates in this area are significantly larger compared to those in other parts of the world, such as the Himalayas (Sharma et al., 2020) and Japan (Hashimoto, 1990). The large strain rates result from velocities across the Sumatran Fault Zone (SFZ) with a high slip rate (~18 mm/year) (Alif et al., 2022). However, large strain rates do not always indicate a high risk of earthquakes, as there is a possibility of non-seismic crustal deformations, such as mud diapirism observed in southern Taiwan (Ching et al., 2016). Non-seismic crustal deformation could occur in the far east of the denser zone, where there is no evidence of a capable fault or earthquake hazard. The high shortening west of the denser zone is due to the convergence behavior of the subduction zone, while the high extension around the SFZ within the denser zone results from the branchiation of the SFZ (Alif et al., 2020). Overall, these strain rates should be reevaluated in the future with a denser GNSS network to improve accuracy and better understand the region's tectonic dynamics. Building more GNSS sites would enhance the precision of strain rate measurements and provide a clearer picture of the region's deformation characteristics.

CONCLUSION

This study successfully evaluated various interpolation methods—Inverse Distance Weighting (IDW), Kriging, and Sandwell—for assessing crustal deformation in southern Sumatra. The analysis demonstrated that the Sandwell interpolation method, particularly with a Poisson's ratio of 0, provides the most accurate results in terms of on-site velocity consistency, achieving the lowest mean residual. The IDW method, although effective, converged at higher interpolation degrees, while Kriging showed superior performance in the east-west component of mean residuals. The interpolated velocities from the Sandwell method were used to calculate strain rates, revealing significant strain variations across the region. The study highlighted the importance of GNSS site distribution in influencing interpolation accuracy and strain rate calculations. Future research should focus on expanding the GNSS network to improve interpolation reliability and gain a more comprehensive understanding of regional tectonics and seismic hazards.

ACKNOWLEDGMENT

Thanks are given to BIG-ITERA collaboration GPS campaign survey team. Figures were drawn using Generic Mapping Tools (GMT) software (Wessel et al., 2013).

REFERENCES

Aditiya, A., Efendi, J., & Syafii, A. (2014). *InaCORS: Infrastructure of GNSS CORS in Indonesia*. In FIG Congress.

Alif, S. M., Meilano, I., Gunawan, E., & Efendi, J. (2016). *Evidence of postseismic deformation signal of the 2007 M8. 5 Bengkulu earthquake and the 2012 M8. 6 Indian Ocean earthquake in Southern Sumatra, Indonesia, based on GPS data*. Journal of Applied Geodesy, 10(2), 103-108.

Alif, S. M., Ardiansyah, M. I., & Wiyono, S. (2020). *Segmentation of Sumatran Fault Zone in Tanggamus District, Lampung based on GPS displacement and SRTM data*. In IOP Conference Series: Earth and Environmental Science (Vol. 537, No. 1, p. 012002). IOP Publishing.

Alif, S. M., Sauri, M. S., & Perdana, R. S. (2021). *Perubahan Kecepatan Subduksi Lempeng Indo-Australia terhadap Lempeng Sundaland akibat Gempa Bumi Samudera Hindia tahun 2016*. Jurnal Geosains dan Teknologi, 4(3), 159-167.

Alif, S. M., Cahyani, P. F., Anggara, O., & Rizqiansyah, A. (2022). *Slip Rate of Kumering Fault in Lampung Province Calculated from GPS Data from 2007 to 2021*. Jurnal Geosains dan Teknologi, 5(2), 83-90.

Alif, S. M., Siagian, J. M., & Anggara, O. (2023). *Present-day Crustal Deformation in West Sumatra After Series of Sumatran Great Earthquake from 2004-2010*. Journal of Earth and Marine Technology (JEMT), 3(2), 59-68.

Alif, S. M., Ching, K. E., Sagiya, T., & Wahyuni, W. N. (2024). *Determination of Euler pole parameters for Sundaland plate based on updated GNSS observations in Sumatra, Indonesia*. Geoscience Letters, 11(1), 16.

Anggara, O., Alif, S. M., Pratama, A. W., & Hutabarat, W. M. (2024). *Uji Signifikansi Stasiun GPS Kontinu dan Periodik dalam Identifikasi Pergerakan Koseismik*. Jurnal Fisika Unand, 13(1), 89-95.

Badan Pusat Statistik (BPS). (2024). Pedoman Pendataan Survei Penduduk Antar Sesus 2024. Lampung: Badan Pusat Statistik.Bucher, F., & Včkovski, A. (1995). *Improving the selection of appropriate spatial interpolation methods*. In International Conference on Spatial Information Theory (pp. 351-364). Berlin, Heidelberg: Springer Berlin Heidelberg.

Ching, K. E., Gourley, J. R., Lee, Y. H., Hsu, S. C., Chen, K. H., & Chen, C. L. (2016*). Rapid deformation rates due to development of diapiric anticline in southwestern Taiwan from geodetic observations*. Tectonophysics, 692, 241-251.

Dach, R., & Walser, P. (2015). *Bernese GNSS Software* Version 5.2.

Dermanis, A. (2009). *The Evolution of geodetic methods for the determination of strain parameters for earth crust deformation*, Terrestrial and Stellar Environment, Volume in honor of Prof. G. Asteriadis. Publication of the School of Rural & Surveying Engineering, Aristotle University of Thessaloniki, 107-144.

Feng, L., Hill, E. M., Banerjee, P., Hermawan, I., Tsang, L. L., Natawidjaja, D. H., & Sieh, K. (2015). *A unified GPS-based earthquake catalog for the Sumatran plate boundary between 2002 and 2013*. Journal of Geophysical Research: Solid Earth, 120(5), 3566-3598. https://doi.org/10.1002/2014JB011661

Hashimoto, M. (1990). *Horizontal strain rates in the Japanese Islands during interseismic period deduced from geodetic surveys Part 1, Honshu, Shikoku and Kyushu*. Zisin;(Japan), 43(1).

Ji, S., Wang, Q., & Salisbury, M. H. (2009). *Composition and tectonic evolution of the Chinese continental crust constrained by Poisson's ratio*. Tectonophysics, 463(1-4), 15-30.

Johnston, G., Riddell, A., & Hausler, G. (2017). *The international GNSS service*. Springer handbook of global navigation satellite systems, 967-982.

McCaffrey, R. (2009). *The tectonic framework of the Sumatran subduction zone*. Annual Review of Earth and Planetary Sciences, 37, 345-366.

McLoughlin, I. V., Wong, K. J., & Tan, S. L. (2011*). Data collection, communications and processing in the Sumatran GPS array (SuGAr)*. In Proceedings of the World Congress on Engineering (Vol. 2, pp. 6-8).

Meneses-Gutierrez, A., & Nishimura, T. (2020). *Inelastic deformation zone in the lower crust for the San-in Shear Zone, Southwest Japan, as observed by a dense GNSS network*. Earth, Planets and Space, 72, 1-10.

Myers, D. E. (1994). *Spatial interpolation: an overview*. Geoderma, 62(1-3), 17-28. https://doi.org/10.1016/0016-7061(94)90025-6

Natawidjaja, D. H. (2018). *Updating active fault maps and slip rates along the Sumatran Fault Zone, Indonesia*. In IOP conference series: earth and environmental science (Vol. 118, p. 012001). IOP Publishing.

Oliver, M. A., & Webster, R. (1990). *Kriging: a method of interpolation for geographical information systems*. International Journal of Geographical Information System, 4(3), 313-332.

Raharja, R., Ito, T., & Meilano, I. (2024). *Evaluation of earthquake potential using a kinematic crustal block motion model in Java, Indonesia, based on GNSS observation*. Journal of Asian Earth Sciences: X, 11, 100171.

Sagiya, T. (2004). *A decade of GEONET: 1994-2003 The continuous GPS observation in Japan and its impact on earthquake studies*. Earth, planets and space, 56(8), xxix-xli.

Sandwell, D. T., & Wessel, P. (2016). *Interpolation of 2-D vector data using constraints from elasticity*. Geophysical Research Letters, 43(20), 10-703. https://doi.org/10.1002/ 2016GL070340

Sharma, Y., Pasari, S., Ching, K. E., Dikshit, O., Kato, T., Malik, J. N., & Yen, J. Y. (2020). *Spatial distribution of earthquake potential along the Himalayan arc*. Tectonophysics, 791, 228556.

Shen, Z. K., Jackson, D. D., & Ge, B. X. (1996). *Crustal deformation across and beyond the Los Angeles basin from geodetic measurements*. Journal of Geophysical Research: Solid Earth, 101(B12), 27957-27980.

Shyu, J. B. H., Yin, Y. H., Chen, C. H., Chuang, Y. R., & Liu, S. C. (2020). *Updates to the on-land seismogenic structure source database by the Taiwan Earthquake Model (TEM) project for seismic hazard analysis of Taiwan*. Terr Atmos Ocean Sci, 31(4), 469-478.

Sieh, K., & Natawidjaja, D. (2000). *Neotectonics of the Sumatran fault, Indonesia*. Journal of Geophysical Research: Solid Earth, 105(B12), 28295-28326. https://doi.org/10.1029/ 2000JB900120

Takada, Y., Sagiya, T., & Nishimura, T. (2018). *Interseismic crustal deformation in and around the Atotsugawa fault system, central Japan, detected by InSAR and GNSS*. Earth, planets and space, 70, 1-12.

Wang, Y., Akeju, O. V., & Zhao, T. (2017). *Interpolation of spatially varying but sparsely measured geo-data: A comparative study*. Engineering Geology, 231, 200-217.