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Slip Rate of Kumering Fault in Lampung Province Calculated from GPS Data from 2007 to 2021

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Abstract
Kumering Fault in Lampung Province is a segment of SFZ that was tectonically active region that had generates large earthquakes. The earthquake hazard around Kumering Fault can be estimated by understanding slip rate of Kumering Fault. This research aim is to estimate slip rate of Kumering Fault by using GPS data from 2007 to 2021. GPS data used in this research are 6 periodic GPS sites and 1 continuous Sumatran GPS Array site. GPS data is processed to obtain daily solution coordinates which are used to calculate velocity by using least-square method of linear regression. Fault parallel velocities are calculated to estimate slip rate and locking depth of Kumering Fault. The The process to obtain slip rate is using grid-search method by finding best fit velocities for all GPS sites. The velocities of GPS sites indicate Sundaland Plate movement. Fault parallel velocities shows the typical movement of right-lateral Kumering Fault. The slip rate of Kumering Fault estimated from this study is 18.2 ± 10 mm/year while the locking depth of the Kumering Fault is 17 ± 3 km. It proves that SFZ is rigid block. However, building more GPS sites in area study is mandatory to obtain better result.

Keywords: Kumering Fault; fault; slip rate; locking depth; Sumatran fault zone

Abstrak
Sesar Kumering di Provinsi Lampung merupakan segmen SFZ yang merupakan wilayah aktif secara tektonik yang telah menghasilkan gempa besar. Potensi bencana gempa di sekitar Sesar Kumering dapat diperkirakan dengan memahami slip rate Sesar Kumering. Penelitian ini bertujuan untuk mengestimasi laju geser Sesar Kumering dengan menggunakan data GPS dari tahun 2007 sampai dengan tahun 2021. Data GPS yang digunakan dalam penelitian ini adalah 6 stasiun GPS periodik dan 1 stasiun kontinu Sumatran GPS Array. Data GPS diolah untuk mendapatkan koordinat solusi harian yang digunakan untuk menghitung kecepatan dengan menggunakan metode kuadrat terkecil dari regresi linier. Kecepatan paralel sesar dihitung untuk memperkirakan laju geser dan kedalaman kuncian dari Sesar Kumering. Proses untuk mendapatkan laju geser menggunakan metode grid-search dengan mencari kecepatan yang paling cocok untuk semua stasiun GPS. Kecepatan stasiun GPS menunjukkan pergerakan Lempeng Sundaland. Kecepatan paralel sesar menunjukkan gerakan khas Sesar Kumering lateral kanan. Slip rate Sesar Kumering yang diperkirakan dari penelitian ini adalah 18,2 ± 10 mm/tahun sedangkan kedalaman penguncian Sesar Kumering adalah 17 ± 3 km. Hal ini membuktikan bahwa SFZ adalah blok yang kaku. Namun, pembangunan lebih banyak stasiun GPS di wilayah studi tetap diperlukan untuk mendapatkan hasil yang lebih baik.

Kata Kunci: *Sesar Kumering, sesar, laju geser, kedalaman kuncian, zona sesar Sumatra*

INTRODUCTION

Kumering Fault is 150 km long fault located in Lampung Province. It is a segment of Sumatran Fault Zone that stretched from Aceh Province to Lampung Province (Sieh and Natawidjaja, 2000). Kumering Fault is a segment of Sumatran Fault Zone (SFZ) resulted from subduction of Indian Plate beneath Sundaland Plate (McCaffrey,

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2009). Kumering Fault is dextral strike-slip fault that is located in South Sumatra Province and Lampung Province (**Figure 1**), was tectonically active region that had generates large earthquake in the past. The epicenter of the Mw7.5 Liwa Earthquake occurred in 1933 is located ~60 km east of Kumering Fault in Lampung Province (Hurukawa et al., 2014). The 1994 Mw6.8 Liwa earthquake was also occurred around Kumering Fault and caused severe damage in Liwa, West Lampung Regency (Rasimeng et al., 2020). The earthquake also caused land movement in West Lampung Regency (Alif *et al.*, 2021a). The earthquake hazard around Kumering Fault can be estimated by understanding slip rate of Kumering Fault (Meilano *et al.*, 2012).

Slip rate of strike-slip Kumering Fault is researched previously by using Global Positioning System (GPS) data up to 2016. The published slip rate from Natawidjaja (2018) is 12 mm/year, while the published slip rate from Meilano *et al.* (2021) is 14 mm/year. Those studies only used the GPS data until the end of 2014. The value shows that SFZ is rigid block since the northest segment and southest segment of SFZ have similar value. Slip rate is the rate at which displacement on a fault occurs on tectonic timescales can be using geological data (Natawidjaja et al., 2017) and/or geodetic data. The geodetic data used to estimate slip rate which is commonly used is the GPS data (Alif *et al.*, 2020a; Lifton et al., 2021).

The GPS data up to 2021 are used to estimate slip rate of Kumering Fault. This study is important since the GPS data especially the data after 2016 have never been researched and published to estimate slip rate of Kumering Fault. All available GPS sites both periodic and continuous sites around Kumering Fault are utilized to estimate the slip rate of fault. The number of sites used in this research is almost similar to the number of GPS sites to monitor SFZ segment south of Kumering Fault, Semangko Fault (Alif et al., 2020b) but it is much less than GPS sites to monitor other faults such as California (Evans, 2018) and Dead Sea Transform (Alchalbi et al., 2010). This research aim is to estimate slip rate of Kumering Fault in Lampung Province by using GPS data from 2007 to 2021.

METHOD

GPS data used in this research are data from GPS sites around Lampung Province in West Pesisir District and West Lampung District. There are 6 periodic GPS sites owned by Geospatial Information Agency of Indonesia (BIG) and 1 continuous Sumatran GPS Array site owned by Earth Observatory of Singapore (McLoughlin et al., 2011). There are 5 to 8 Day of Year (DoY) data used from periodic GPS sites and 1440 DoY data used from continuous GPS site. Location of GPS sites are as follows: 5 sites located in the west of Kumering Fault, 1 site located on the

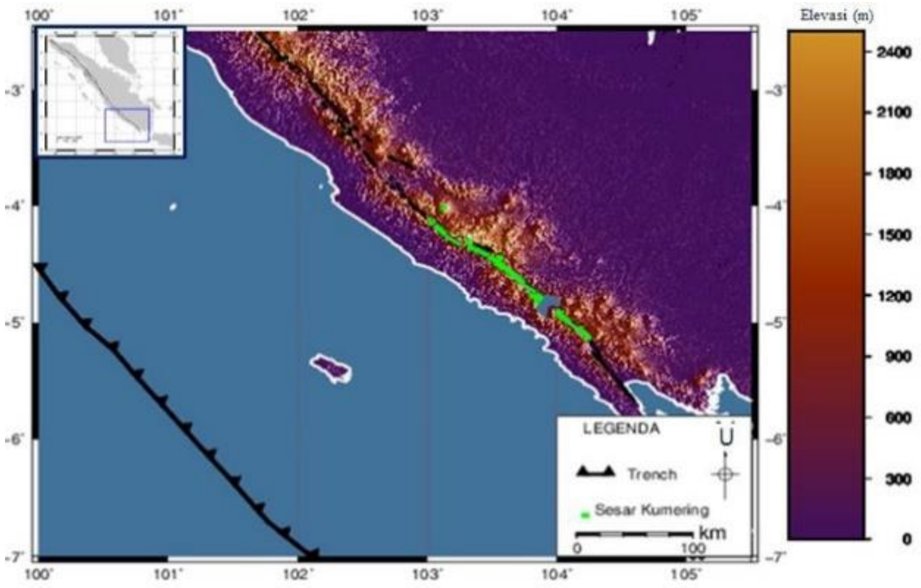

Figure 1. Kumering Fault shown by green lines located in South Sumatra Province and Lampung Province.The terrain model is obtained from SRTM data with 1 arc second spatial resolution (Farr et al., 2007)

Kumering Fault, and 1 site located on the east of Kumering Fault. It is shown on **Figure 2.** The example of GPS site (K602) is shown in **Figure 3**. Most of the periodic sites are measured from 2007 to 2021 (**Table 1**). Data measured in 2007 are recorded after the 2007 M8.5 Bengkulu earthquakes so that the cosesismic displacement due to the earthquake did not affect the GPS sites. The logarithmic trend of postseismic mechanism of earthquakes also did not affect the GPS sites (Alif *et al.*, 2016).

Daily solution of GPS sites are obtained from GPS scientific processing. Data from GPS sites are process using AUSPOS Online GPS Processing Software version 2.3 (Hu et al., 2014) utilizing Bernese 5.2 software (Dach and Walser, 2015). It uses the model of solid earth tide, atmospheric loading, tropospheric and ionospheric parameter and earth orientation. The reference sites to produce daily solution refer to ITRF2014 are COCO, DARW, KAT1, NNOR, PERT, XMIS, YAR2 IGS GPS sites in ITRF2014 (Altamimi *et al.*, 2016). Those reference sites selection is based on reference sites with minimum standard deviation (Alif *et al.*, 2021b). The velocity of each GPS sites are calculated from those daily solution. The velocities and its standard deviation are calculated by doing linear regression with the least square method (Alif *et al.*, 2020c).

Figure 3. One of GPS sites used in this study (K602) measured in 2014.

Table 1. GPS sites used in this study.

Site Name	Latitude (°)	Longitude (°)	Location	Data Period
K602	-5.0758	104.0377	Balik Bukit	2007.72-2021.32
K603	-5.0356	104.0812	Balik Bukit	2007.72-2021.32
K604	-4.9373	104.0329	Sukau	2007.72-2021.32
K608	-4.6182	104.0534	Buay Rawan	2014.89-2021.32
K609	-4.94645	103.9332	Lombok Seminung	2014.88-2021.32
K610	-5.0438	103.7991	Pesisir Utara	2014.9-2021.32
KRUI	-5.0902	103.8546	Karya Penggawa	2016.01-2019.99

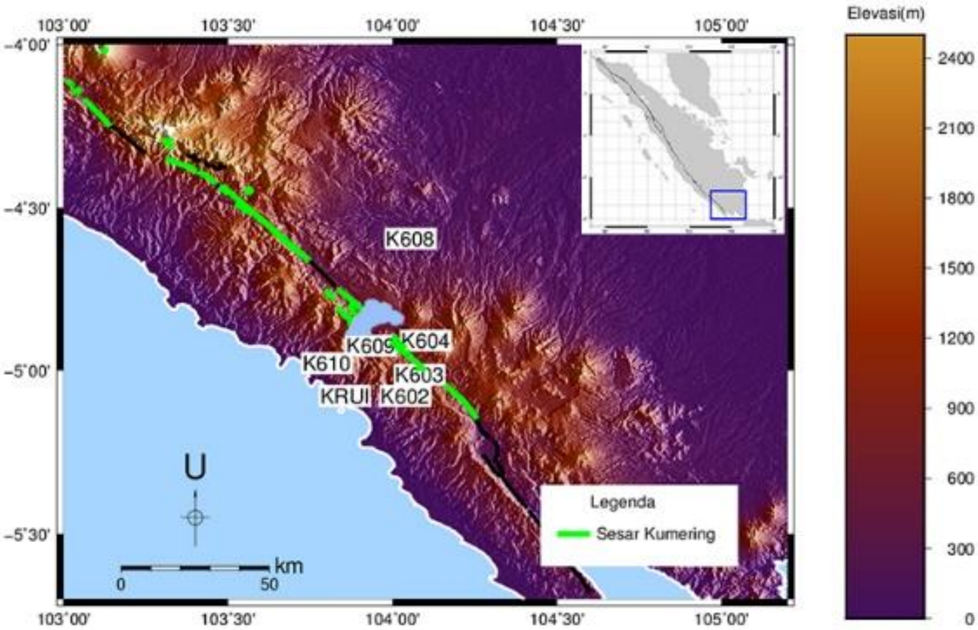

Figure 2. GPS used in this study to estimate slip rate of Kumering Fault. The terrain model is obtained from SRTM data with 1 arc second spatial resolution (Farr et al., 2007)

Horizonal component of GPS velocities are used to calculate slip rate of Kumering Fault. The reference for the calculated velocities from GPS data processing are altered from ITRF2014 to Kumering Fault since the velocities are used to analyze Kumering Fault movement. The process is conducted by substracting north-south component and east-west component of each GPS sites with north-south component and east-west component of K604 site since it is located on Kumering Fault. Up-down component or vertical component is not used for analysis since Kumering Fault is strike-slip fault that only accomodates horizontal movement. Moreover, the standard deviation of vertical velocities are usually large especially on the data from periodic GPS sites (Aktug *et al.*, 2009)

Velocities used to estimate the slip rate of Kumering Fault of fault parallel velocities. It is calculated from velocities that refer to K604 site. Since KRUI use much more DoY than the other GNSS site, KRUI has greater weighting in slip rate calculation. Fault parallel component is obtained by calculating the azimuth of Kumering Fault and applying to each GPS sites. The fault parallel velocities are used to estimate slip rate by using Formula 1 (Hidayat et al., 2012).

$$S = \frac{D}{\pi}\tan^{-1}\frac{y}{w} \quad (1)$$

where D is slip rate of the fault, w is locking depth of the fault, y is closest distance between GPS sites and the fault, and S is the fault-parallel velocity on the GPS sites.

The process to obtain slip rate is using grid-search method (Wan, 2015; Alif, 2021c). It is conducted by alternating two unknown parameters of the formula (slip rate and locking depth) to get best fit known parameter (fault parallel velocities). The 7 GPS velocities used in this study makes the formula works with 5 degrees of freedom. Alternate fault parameters used in generating fault models are as follows: the slip rate is ranging from 0 to 50 km, the locking depth is ranging from 0 to 50 mm/year. The deepest estimation of Kumering Fault to Benioff Zone is 120 km (Sieh and Natawidjaja, 2000). The best slip rate is determined by finding minimum $\chi 2$ or best fit velocities for all GPS sites.

RESULT AND DISCUSSION

The velocity of GPS sites coordinates daily solution in ITRF2014 indicate Sundaland Plate movement. The velocities of GPS sites refer to ITRF2014 is shown on **Figure 4** while the coordinate daily solution time series is shown on **Figure 5**. The GPS sites move eastward, the similar direction to Sundaland Plate movement (Kuncoro et al., 2019). It is also shown in the time series that all GPS sites move upward in east-west component. In the north-south component, the GPS in the east side of the fault, move downward, while GPS in the west side the fault, move upward. It typically indicates right-lateral movement of Kumering Fault. The K604 site, which is located on the fault, move slightly downward in north-south component.

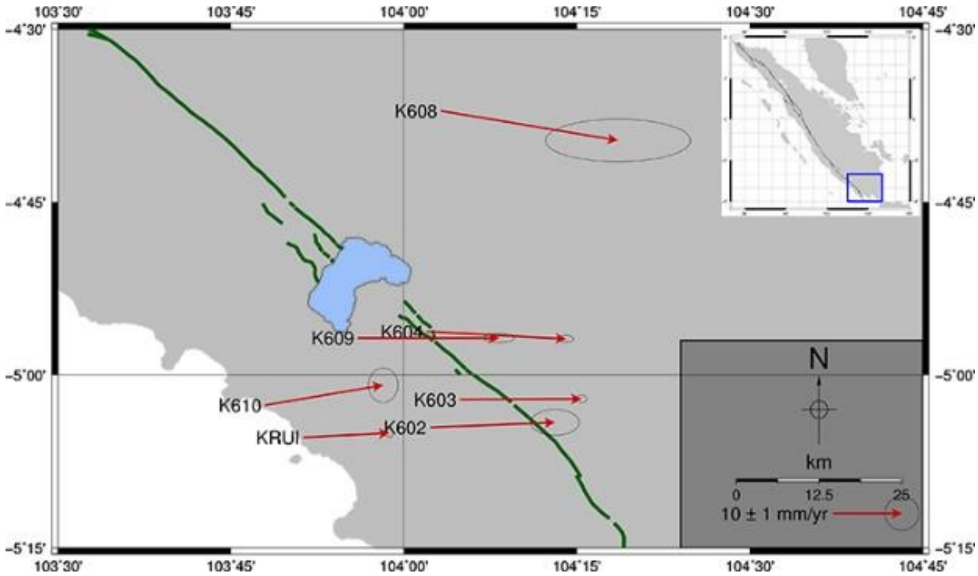

Figure 4. Velocities of GPS sites refer to ITRF2014

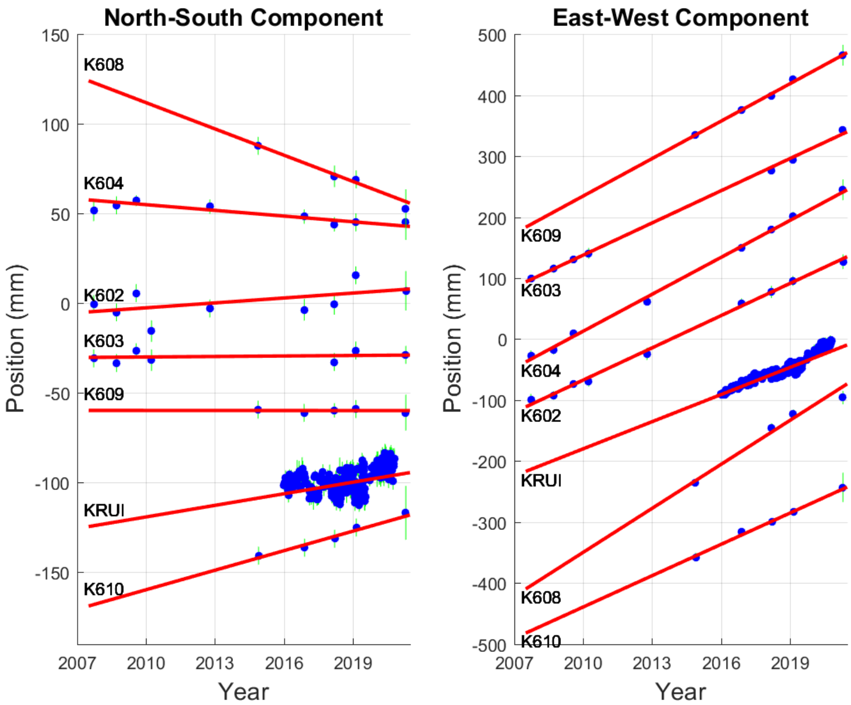

Figure 5. Coordinate time series of GPS sites. Blue points are observations data. Red lines indicate linear fitting of GPS data. Green lines within the blue points are deviations of points.

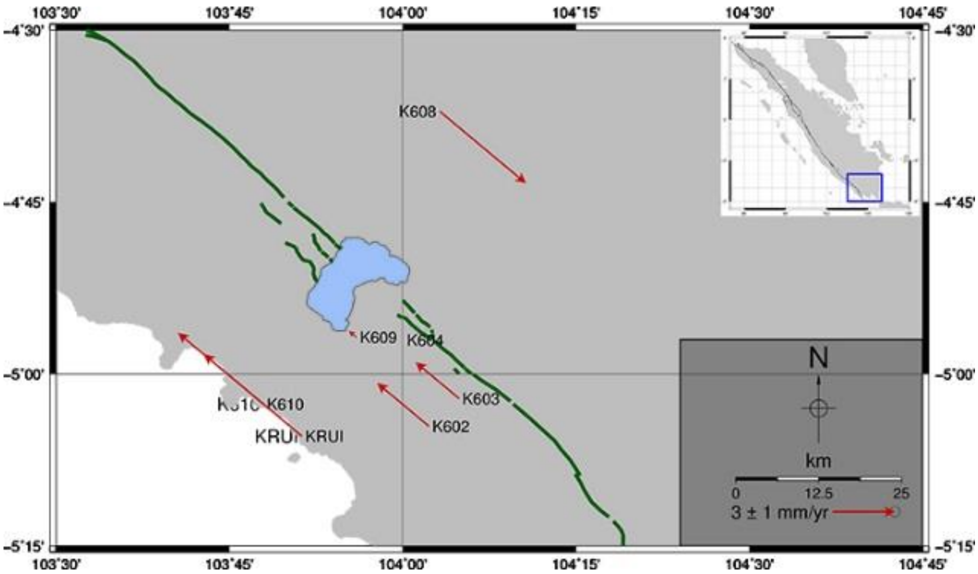

Figure 6. Fault parallel velocities of GPS sites shown by red arrows.

Fault parallel velocities obtained from the processing shows the typical movement of right-lateral Kumering Fault. GPS sites in the east side of the fault move southeastward while GPS sites in the west side of the fault move northwestward. The fault parallel velocities refer to the K604 site on the Kumering Fault. It is shown on Figure 6. The distance to the Kumering Fault affects the value of fault parallel velocities. The resultant value, the direction of the fault parallel velocities, and the distance to the fault is shown on Table 2.

Table 2. Fault Parallel Velocties of GPS Sites

Site Name	Distance to the Fault (km)	Resultant Value (mm/year)	Direction
K602	11.54	3.6	Northwestward
K603	4.25	3.1	Northwestward
K608	26.91	5.0	Southeastward
K609	7.44	0.9	Northwestward
K610	25.69	5.8	Northwestward
KRUI	25.30	6.6	Northwestward

K608, K610, KRUI site which is further to the fault (>25 km) have the largest resultant value of fault parallel velocities. The GPS site which moves with minimal value and in the west side of the fault is K609. It is further than K603 site yet the fault parallel velocity is lower. It is located close to Ranau Lake and is probably affected by water body of Ranau Lake (Saleh et al., 2018).

The slip rate of Kumering Fault estimated from this study is 18.2 ± 10 mm/year. The locking depth of the Kumering Fault is 17 ± 3 km. Those values produce fault parallel velocities with minimum χ^2 (1.15). The model of Kumering Fault movement resulted from this study by considering slip rate and locking depth is shown on **Figure 7**. The process of finding minimum χ^2 from Kumering Fault parallel velocities is shown on **Figure 8.** The estimated slip rate is higher than the parameter used in Alif *et al.* (2016) which is 14 mm/year. The locking depth is deeper which is 16 km. The slip rate of Kumering Fault is slighty higher than slip rate of SFZ segment south of Kumering Fault, Semangko Fault or West Semangko Fault which is 16.5 mm/year (Alif *et al.*, 2020a). However, the locking depth of Kumering Fault is slightly shallower than Semangko Fault which is 18.5 km although it is still in the interval of uncertainties.

The result supports the idea that SFZ is rigid block. The slip rate estimated from Natawidjaja (2018) which is 8-12 mm/year is in the interval of uncertainties of slip rate estimated from this study which is 8.2-28.2 mm/year. Furthermore, the slip rate of of SFZ segment north of Kumering Fault, near Lake Toba in North Sumatra and near Lake Maninjau in West Sumatra is 14-15 mm/year which is also in the interval of uncertainties of slip rate estimated from this study. It agrees with the SFZ system which is a rigid block instead of much stretched. The large uncertainties of slip rate is mainly caused by small number of GPS sites used to estimate the slip rate especially in the east side of the fault, the similar problem to estimate the slip rate of Semangko Fault. The increasing number of GPS sites to monitor Kumering Fault also assists study to monitor the other probable fault in the area study such as Pauh Fault (Djarwadi *et al.*, 2019) or sub-segment of Kumering Fault (Aribowo et al., 2017). The fault study should be conducted by using GPS data since record the most recent motions, and geological data simultaneously since it is used as constraint and to assess long-term hazard (Petersen *et al.*, 2014).

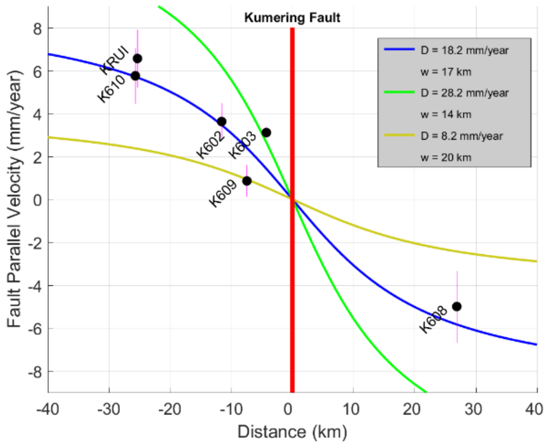

Figure 7. The model of Kumering Fault with its uncertainties. The red thick line shows Kumering Fault. Black points are fault parallel velocities. Red lines within the blue points are deviations of points. Blue line is the best fit model. Green line and yellow line are the deviation of model.

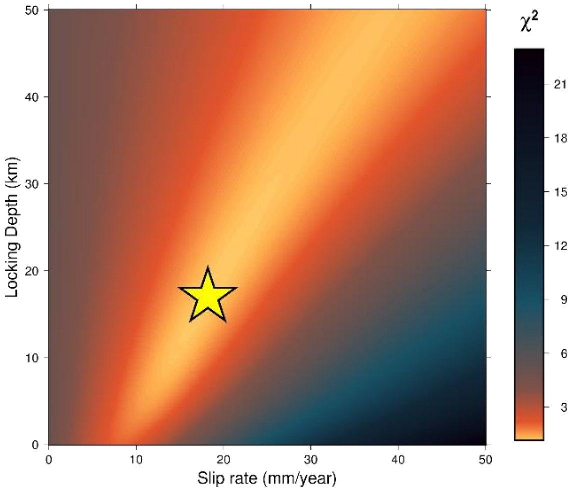

Figure 8. The process of finding minimum χ2 from Kumering Fault parallel velocities. The yellow star represents minimum χ2.

CONCLUSION

Slip rate of Kumering Fault estimated from this study is 18.2 ± 10 mm/year with 17 km locking depth. The large uncertainty is mainly caused by small number of GPS sites used in the study. 6 periodic GPS sites and 1 continous GPS sites are used to estimate the slip rate. However, it proves that SFZ is rigid block since the slip rate from northest segment to southest segment, Semangko Fault which is south of Kumering Fault, have somewhat similar value. Building more GPS sites in area study is mandatory to obtain better result and monitor the other probable fault in the study area.

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