NON-LINEAR CRUSTAL DEFORMATION MODELING FOR DYNAMIC REFERENCE FRAME: A CASE STUDY IN PENINSULAR MALAYSIA

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Key words: Crustal Deformation, Peninsular Malaysia, Non-linear, Dynamic Reference Frame

SUMMARY

Series of major big earthquakes struck the Sundaland platelet since December 2004 due to convergence between Indian and Australian plates along its western and southern boundaries. Consequently, the plate has been undergoing significant co-seismic and post-seismic afterslip deformation effecting national geodetic reference frame for countries in the region such as Malaysia. The deformation is causing errors in Global Navigation Satellite System (GNSS) satellite measurements due to incompatibility between ground and satellite coordinates. In addition, the afterslip deformation exhibits on-going non-linear motion of land mass which further complicates the maintenance of the geodetic frame. This paper investigates spatio-temporal crustal deformation due to Mw >7.9 earthquakes that is affecting geocentric reference frame and geospatial accuracy in Peninsular Malaysia. The fundamental work was modelling the co-seismic and post-seismic deformation to account for time dependency of reference frame. The study has found that afterslip deformation model has minimized the effect of non-linear motion on geodetic network in the order of better than 2cm. The work is significant in view of improving the stability of reference frame in Malaysia.

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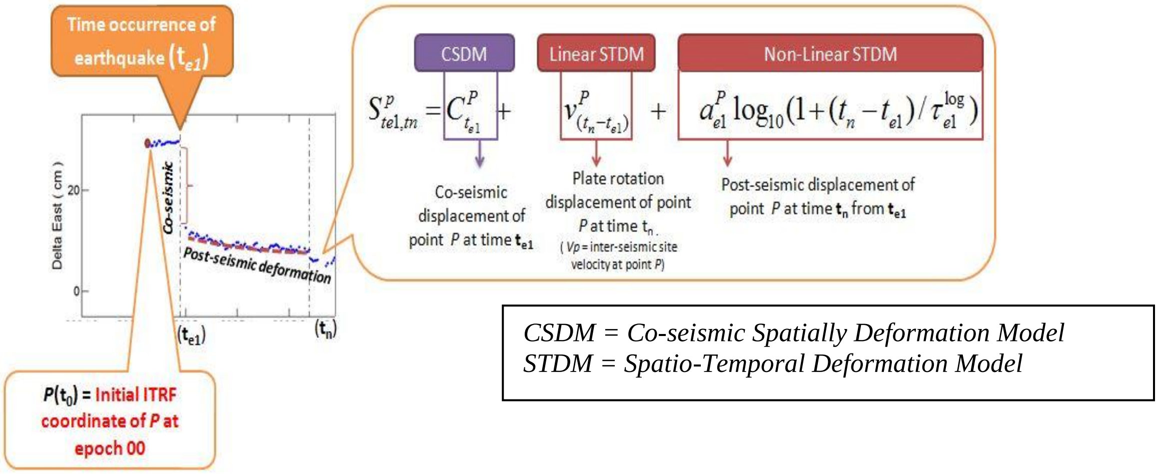
1. INTRODUCTION

Positioning activities such as national boundary determination, oil and gas field exploration, and high precision surveying applications require a stable geodetic reference frame. In the advanced space positioning, linear and non-linear crustal deformation due to the earth seismicity have become additional observable for the establishment of reference frame (Bevis and Brown, 2014; Gomez *et al.*, 2016). Peninsular Malaysia is very much effected by the regional seismics and it has experienced spatial and temporal crustal deformations due to four earthquakes (>7.8Mw); 2004 Sumatra Andaman at 9.2Mw, 2005 Nias Simeulue (8.5Mw), 2007 Bengkulu (7.9Mw) and 2012 Indian Ocean (8.6Mw) which lead to a maxiumum of 39cm/year seismic deformation (Aris *et al.*, 2016).

The region crustal deformation also exhibits non-linear motion due to significant crustal relaxation causing more problems to the present geodetic reference frame. Latest realization of the IERS namely ITRF2014 has included co-seismic and post-seismic logarithmic functional deformation model (Altamimi *et al.*, 2016). Previously, crustal deformation was being modelled by piecewise linear fitting which may not be fitted well causing some errors in instantenous position correction. This paper discusses crustal deformation model in Peninsular Malaysia that caters for distribution of non-linear co- and post-seismic signals due to major earthquakes (>7.9Mw). The paper is devided into sections. Section 2 describes conceptual linear and non-linear crustal deformation in the present-day reference frame, Section 3 describes crustal deformation modeling, Section 4 presents the assessment of the model and finally, Section 5 is for conclusion and recommendations.

2. LINEAR AND NON-LINEAR TREND IN SPATIAL CRUSTAL DEFORMATION MODEL

In order to account for co-seismic and post-seismic caused by significantly major earthquakes, pragmatic approach by fitting logarithmic and/or exponential functions to the site-specific coordinate time series is necessary. Figure 1 demonstrates temporal change of coordinate over time t due to linear and non-linear trend of crustal deformation. From the figure, coordinate point P at time t_n is the displaced position from initial coordinate at t_0 after occurrence of earthquake e^1. In traditional way, the displacement of coordinate topocentric (*north* or *east*) $S^{p}_{te1,tn}$ is computed by assuming that the crustal deformation depicts linear trend after the occurrence of earthquake as in Equation 1;



CSDM = Co-seismic Spatially Deformation Model
STDM = Spatio-Temporal Deformation Model

Figure 1: Demonstration of crustal deformation model for Peninsular Malaysia as applied by ITRF (Altamimi *et al.*, 2016).

$$S^p_{te1,tn} = C^P_{t_{e1}} + [v^P_{(t_n-t_{e1})} \text{ or } \bar{v}^P_{(t_n-t_{e1})}] \qquad (1)$$

where; t time; $C^P_{t_{e1}}$ is co-seismic displacement at point P after earthquake e^1, $v^P_{(t_n-t_{e1})}$ is total velocity displacement at point P from time t_{e1} to t_n, and $\bar{v}^P_{(t_n-t_{e1})}$ is plate rotation deformation at point P from time t_{e1} to t_n.

Meanwhile, in the current practice of high precision ITRF, the $S^p_{te1,tn}$ is computed by assuming that the crustal deformation refers to plate rotation and post-seismic trend after the occurrence of earthquake as in Equation 2 which depicts a non-linear trend.

$$S^p_{te1,tn} = \bar{v}^P_{(t_n-t_{e1})} + C^P_{t_{e1}} + a^P_{e1}\log_{10}(1+(t_n-t_{e1})/\tau^{\log}_{e1}) \qquad (2)$$

where, a^{e1} and $\tau^{e1}_{\log}$ is post-seismic amplitude and logarithmic decay rate, respectively for earthquake e^1 at point P. For the case of multiple earthquake events, variable terms of deformation model (co-seismic, amplitude and logarithmic decay rates) can be imposed in Equation 1 or 2. It is noted that, the application of high precision ITRF will be more practical when the $S^p_{te1,tn}$ can be predicted at non-GPS CORS sites (*i.e.*, passive network). This is possible when the terms $C^P_{t_{e1}}$, a^{e1}, $\bar{v}^P_{(t_n-t_{e1})}$ and $v^P_{(t_n-t_{e1})}$ are spatially modeled for *north* and *east* components separately. In this study, Co-seismic Spatial Deformation Model (CSDM) refers to spatial co-seismic displacement, $C^P_{t_{e1}}$ for each major earthquake. Meanwhile, Spatio-Temporal Deformation Model (STDM) can be divided into three (3); Sunda Linear (SuLin-STDM), Velocity Linear (VeLin-STDM) and Post-seismic Non-Linear (PosNoLin-STDM) referring to the distribution of $\bar{v}^P_{(t_n-t_{e1})}$, $v^P_{(t_n-t_{e1})}$ and a^{e1} respectively. For the case of CSDM and STDM, this study has generated national grid namely Quasi Network (Q1- Q144) with spatial resolution 0.3°×0.3°, as shown in Figure 2-(a). The information of $C^{P}_{t_{e1}}$, a^{e1}, $\bar{v}^{P}_{(t_n-t_{e1})}$ and $v^{P}_{(t_n-t_{e1})}$ at Quasi Network point were predicted from the knowledge of actual $C^{P}_{t_{e1}}$, a^{e1}, $\bar{v}^{P}_{(t_n-t_{e1})}$ and $v^{P}_{(t_n-t_{e1})}$ signals as quantified by MyRTKnet stations (by Department of Survey and Mapping Malaysia) that records the 9 years of crustal deformation trend since 2004 Sumatra Andaman earthquake, as shown in Figure 2-(b).

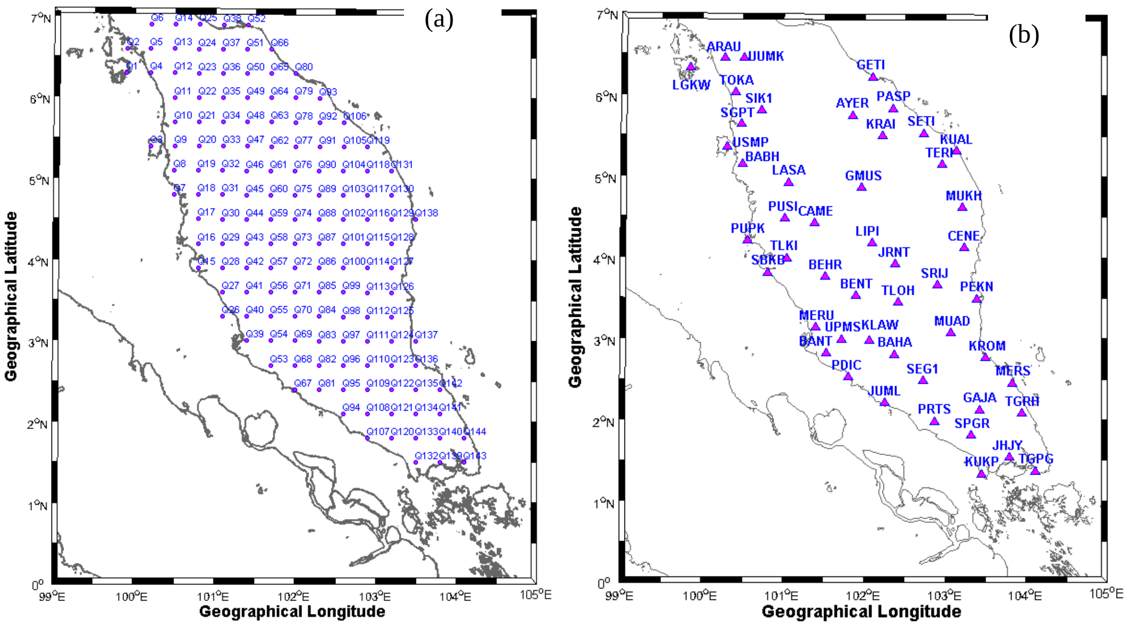


Figure 2: (a) Quasi-Network grid (Q1-Q144) with spatial resolution 0.3°×0.3° ; and (b) distribution of MyRTKnet in Peninsular Malaysia.

The prediction of crustal deformation signals can be made through least square collocation which can be expressed by Moritz, (1962) and Moritz, (1980). The predicted signal *S* (*i.e.*, intra-plate grid velocity to be predicted) at the nearest point is given as;

$$S = C_{SL} C_{LL}^{-1} L \tag{3}$$

where C_{SL} is empirical covariance functional matrix between signal *L* (*i.e.*, co-seismic deformation, velocity fields and post-seismic amplitudes) at the observation points (*i.e.*, GPS sites). While, C_{LL} is the covariance matrix of signal *L* between observation points. The crustal deformation signals at Quasi-Network is assumed to be a random field which comprises only one random function with a number of independent variables. Therefore, one can define a covariance function that depends only on the distance between the points. The empirical value is used to compose the covariance function C_{SL} in order to estimate the signal *S*. The derivation of local empirical covariance function is extracted from a local data set. The computation of the variance and covariance from the given local data set is demonstrated in Equation 4 and 5, respectively (El-Fiky *et al.* 1997; Mikhail and Ackermann, 1976);

$$C_{LL}(0) = \frac{1}{n}\sum_{i=1}^{n} L_i L_i \tag{4}$$

$$C_{LL}(d_p) = \frac{1}{n_p}\sum_{i<1}^{n_p} L_i L_i \tag{5}$$

where distance between location of MyRTKnet stations (*i* and *j*) are divided into finite discrete intervals *P*. The models were applied to predict both linear and non-linear motion for both *north* and *east* components to allow for determination of coordinate at specific epoch.

3. CSDM & STDM

Nine years of high precision daily GPS-derived coordinate time series (CTS) in *north* as *east* components has been generated by using GPS data as recoreded by MyRTKnet stations since December 2004. The GPS-derived CTS at these CORS were utilised to estimate information of $C_{t_{e1}}^{P}$, a^{e1}, and $v_{(t_n - t_{e1})}^{P}$. Meanwhile, $\bar{v}_{(t_n - t_{e1})}^{P}$ were extrapolated from the knowledge of Sunda plate motion model by Mustafar *et al.* (2016). These estimated values were then utilised to generate CSDM and STDM at Quasi Network points using least-square collocation as in Equation 3-5. Figure 3 presents CSDM vectors at Peninsular Malaysia during the occurance of four great earthquakes. The vector of CSDM^{2004} was predicted from the knowledge of $C_{t_{e1}}^{P}$ (*north* and *east*) during the 2004 Sumatra Andaman earthquake (9.2Mw) which was detected by 14 MyRTKnet stations. These vectors were headed to earthquake's epicenter (northern part of Sunda trench) at azimuth N256^{o} (southwestward) in northern part and decreased to N264^{o} (northwestward) in southern part of the region. Large predicted co-seismic displacements (*north* and *east*) was found with the highest magnitude of 185 mm at point Q1 (northwestern part of the region) and decreased to 24 mm at Q144 (southeastern part of the region). Similar to CSDM^{2004}, the vector of CSDM^{2005} was predicted from the knowledge of $C_{t_{e1}}^{P}$ during the 2005 Nias Simeulue earthquake (8.5Mw) by using 14 detected MyRTKnet stations. It can be inspected that, the pattern of CSDM^{2005} vectors varies over Quasi Network points. The predicted vectors were found to be headed to the earthquake's epicenter with azimuth varying from ~N216^{o} to ~N238^{o}. Large predicted co-seismic displacements were found at Quasi Network points near to site PUPK at predicted displacement of 67 mm. Meanhwhile, CSDM^{2007} vectors was predicted from the knowledge of co-seismic deformation during the 2007 Bengkulu earthquake (7.9Mw) as observed by twenty-eight (28) MyRTKnet sites. As seen from the figure, the magnitude and direction of CSDM^{2007} significantly vary over latitudinal direction. Heterogeneous co-seismic displacement can be seen from east to southeast direction and headed to the earthquake's epicenter (in Mentawai trench, Indonesia) with azimuth that varies from ~N145^{o} to ~N246^{o}. Large predicted $C_{t_{e1}}^{P}$ were found with highest magnitude of 31 mm at Quasi Network points near to site KUKP (southern part).

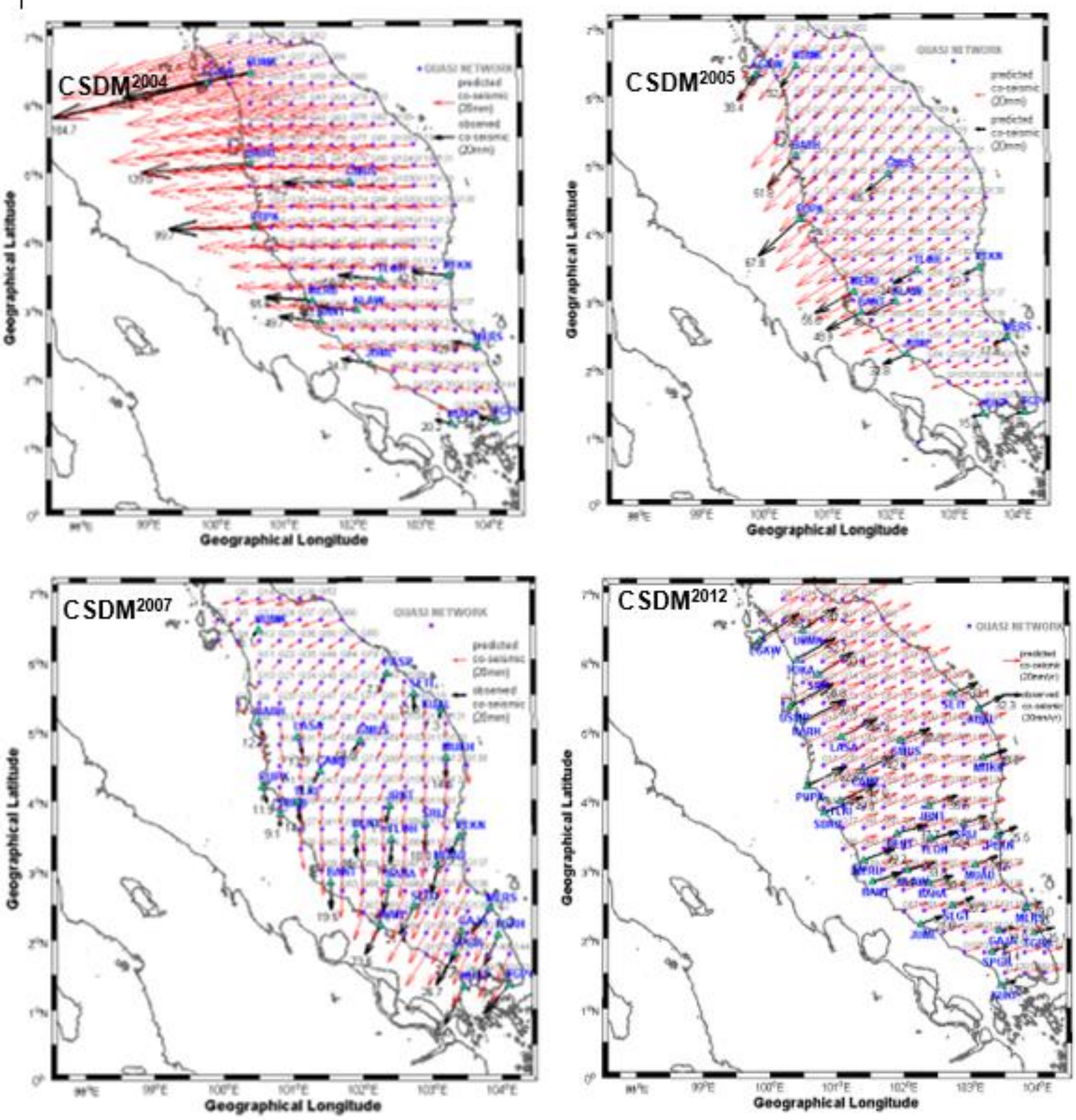


Figure 3: CSDM vectors, $C_{t_{e1}}^{P}$ in Peninsular Malaysia during great earthquakes occurances.

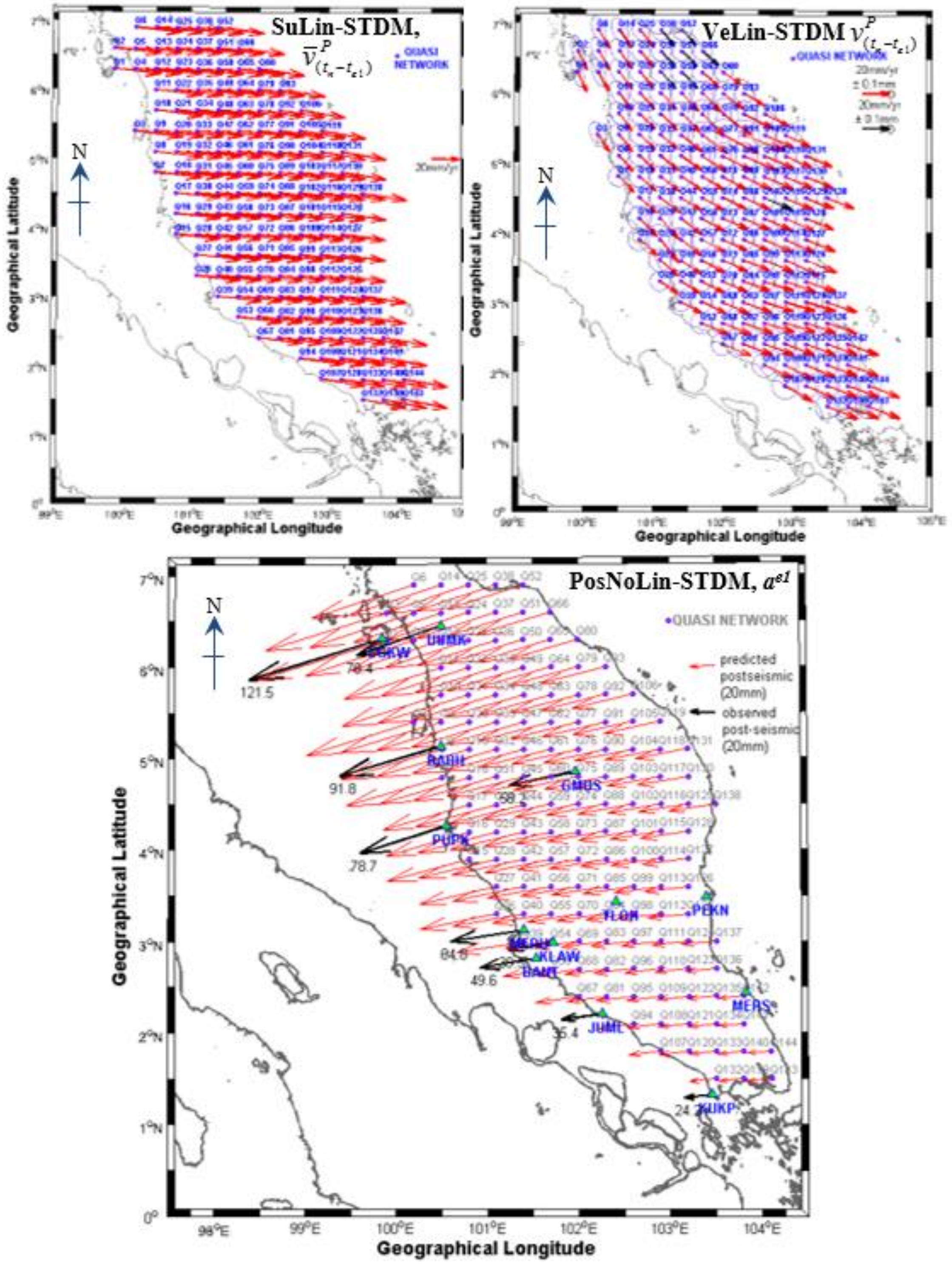


Figure 4: SuLin-STDM, VeLin-STDM and PosNoLin-STDM at Quasi Network points.

Finally, vectors of CSDM^{2012} represents spatial distribution of $C_{t_{e1}}^{P}$ during the 2012 Indian Ocean earthquake (8.6Mw). The model was determined from the knowledge of estimated $C_{t_{e1}}^{P}$ from 34 MyRTKnet sites. One can inspect that the vector of CSDM^{2012} headed to northeastward (azimuth from ~N145^{o} to ~N246^{o}) and depicted different co-seismic pattern as compare to the other CSDMs. This can be explained due to the internal deformation of the diffused plate boundary between India and Australia plates that caused the Peninsular Malaysia to be co-seismically displaced away from the earthquake's epicenter.

The velocity vector of SuLin-STDM, VeLin-STDM and PosNoLin-STDM are presented in Figure 4. The SuLin-STDM vectors appeared to be consistent at all Quasi Network points. This indicate the tectonic motion depicted as rigid but follow the rotation of Sunda plate. The region moves southeastward (in range of azimuth N95^{o} – N101^{o}) with slow variation of magnitude at 31.713 mm/yr in the southern part and 33.212 mm/yr in the northern part of the region. From the figure, one can inspect inhomogeneous direction of intra-plate velocities from sites in northern to southern part that moved horizontally southeastward (in range of azimuth N130^{o} – N150^{o}) with average magnitude of 15.389 mm/yr. The magnitude increased gradually over longitudinal and latitudinal with average magnitude of 22.989 mm/yr and moved southeastwardly (in range of azimuth N110^{o} – N122^{o}). Finally, the pattern of PosNoLin-STDM indicates that the region is being driven by a single afterslip mechanism since the day of the 2004 Sumatra Andaman and subsequent earthquakes. The decay rate of post-seismic, $\tau_{\log}^{e1}$ was found at 148.5 and 204.1 days for *north* and *east* components. From the analysis, these decay rates were also found to be consistent for all sites, however, the post-seismic amplitudes of the afterslip tends to varies over the region in spatial sense. Large post-seismic amplitudes can be noticed at Quasi Network points situated in the northwestern part of Peninsular Malaysia with magnitude ~121.5 mm. The post-seismic amplitudes, a^{e1} decreased over latitudinal of the region with minimum magnitude of 24.2 mm within southern part of the region.

4. ASSESSMENT OF CSDM AND STDM IN RESOLVING REFERENCE FRAME DISTORTION

Experimental works has been conducted to test the efficacy of both STDM and CSDM models. Crustal deformation trends were predicted based on three assumptions; *Assumption 1*, *Assumption 2* and *Assumption 3* and its descriptions are tabulated in Table 1. Prediction tests were made at testing point, PN1 as shown in Figure 5. The PN1 is situated closer to existing MyRTKnet stations in the northern part of Peninsular Malaysia namely SGPT and it is noted that GPS positioning from this site is independent from STDM and CSDM modeling. The assessment result is shown in Figure 6.

Table 1: Three assumptions of crustal deformation trends in Peninsular Malaysia

Assumption	Explanation	Trend of Crustal Deformation	Crustal Deformation Models
Assumption 1	After the occurrence of major earthquakes in Sundaland, crustal deformation in Peninsular Malaysia still induced by similar rotation of Sunda plate only.	Linear (Equation 1)	SunLin-STDM + CSDMs
Assumption 2	After the occurrence of major earthquakes in Sundaland, crustal deformation in Peninsular Malaysia has changed and continually moving as different plate entity apart from Sunda plate rotation.	Linear (Equation 1)	VeLin-STDM + CSDMs
Assumption 3	After the occurrence of major earthquakes in Sundaland, crustal deformation of Peninsular Malaysia still induced by the similar rotation of Sunda plates at it was before, but undergoing significant afterslip deformation *(i.e.,* co-seismic and post-seismic).	Linear and Non-Linear (Equation 2)	SuLin-STDM + PosNoLIn-STDM + CSDMs

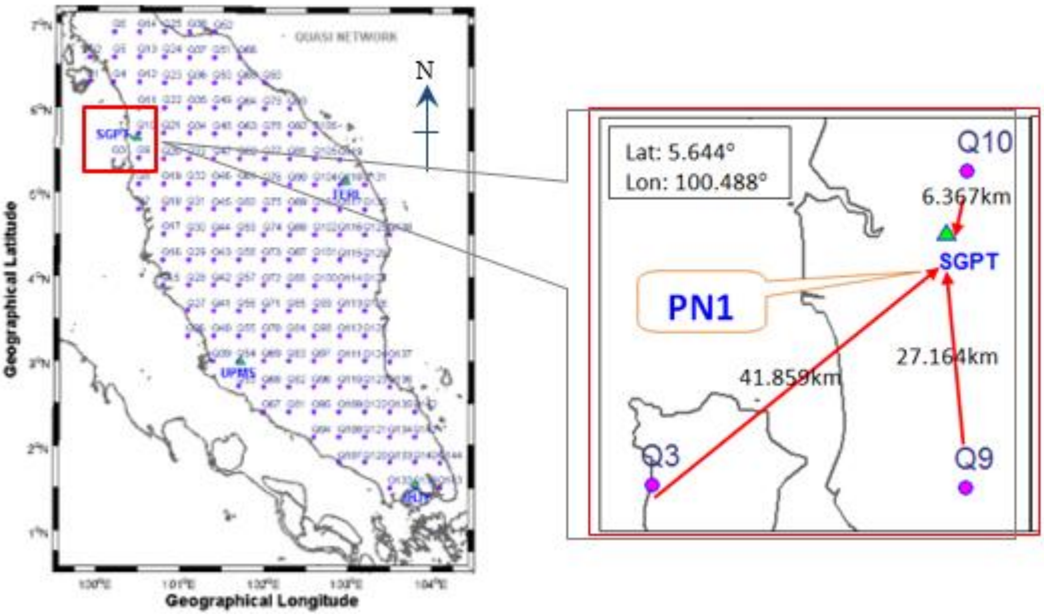


Figure 5: Locations of PN1 situated in northern part of Peninsular Malaysia.

As seen in Figure 6, the simulated CTS at PN1 based on *Assumption 1* led to significantly large difference in RMSe of about 59.2 mm and 181.4 mm in *north* and *east* components respectively. The simulated CTS from *Assumption 2* were different from actual GPS-derived CTS in *north* component with RMSe value of 22.889 mm. However large RMSe was depicted in easting components reaching to 77.227 mm. Simulated CTS from *Assumption 3* was in good agreement with the GPS-derived CTS in *north* and *east* components with averaged RMSe of 9.984 mm, and excellent corelation factor R^2 of 0.918.

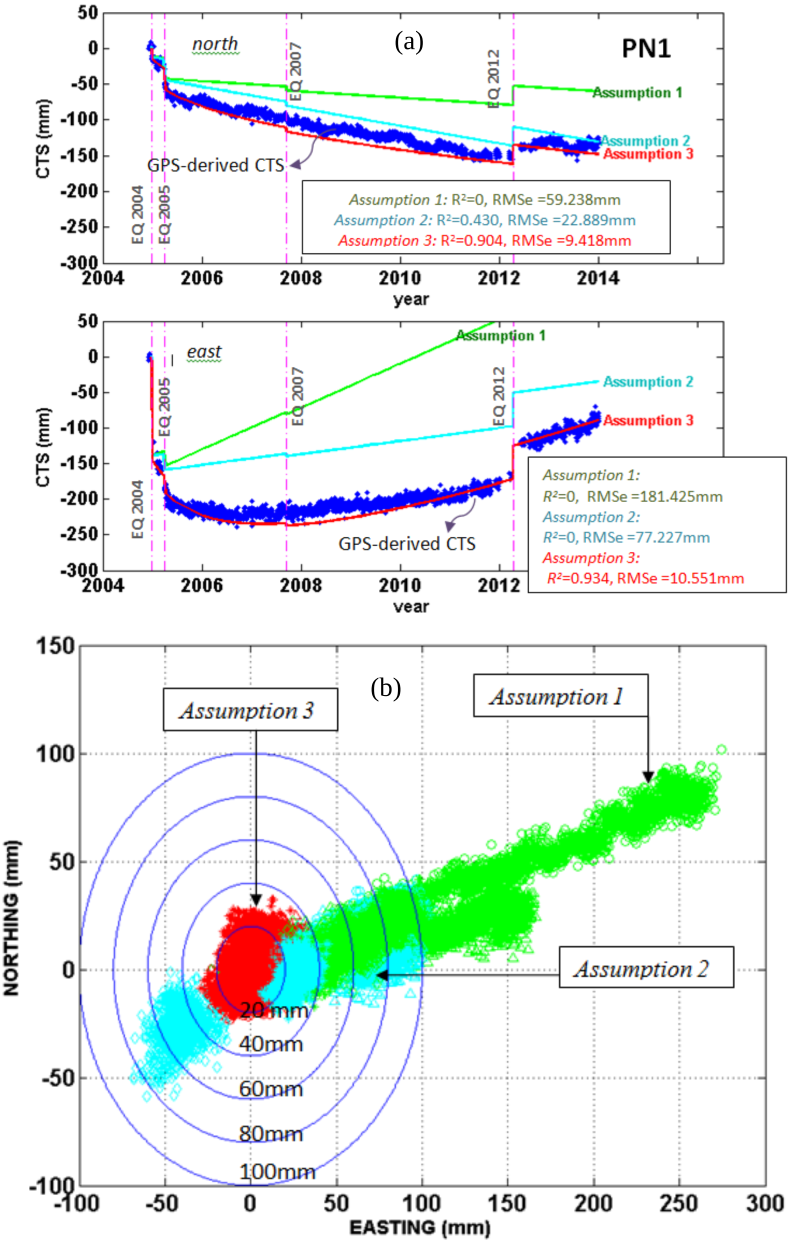


Figure 6: Misfit between the simulated CTS and observed GPS-derived CTS at four locations. Green, cyan and red represents residual simulated CTS based on *Assumption 1*, *Assumption 2* and *Assumption 3*, respectively.

From Figure 6 (a), the resutls from *Assumption 1* and *2* do not provide accurate deformation trend thus resulting large coordinate dispute over the time with RMS of residual of 114mm. Results from *Assumption 3* seems to provide accurate deformation trend with average RMS of residual of 11.538mm. In overall, the use of CSDMs works-well to re-compute the co-seismic displacement during the day of major earthquake's occurrences. However, large post-seismic amplitudes were observed in the northern of Peninsular Malaysia which is responsible for the inability of VeLin-STDM to determine the actual trend of crustal deformation within the region. It is expected that the used of SunLin-STDM and PosNoLin-STDM are efficient to resolve such distorted geodetic network and adequately describe the non-linear trend of post-seismic deformation. Further analysis on residual coordinate was made between predicted CTS and GPS-derived CTS. The green, cyan and red nodes in scatter plot of Figure 6 (b) represent residual from simulated CTS based on *Assumption 1*, *Assumption 2,* and *Assumption 3* respectively. It can be inspected that ~83% of simulated CTS from *Assumption 1* fall inside the 2cm limit, and ~17% fall between 2 and 4 cm. Meanwhile, 22% of simulated CTS from *Assumption 2* fall within 2 cm limit, and the other 78% were distributed from 2 to 10 cm. Nevertheless, simulated CTS from *Assumption 1* signify the presence of systematic bias. The results from this assessment indicates that after the occurrence of major earthquakes in Sundaland, crustal deformation of Peninsular Malaysia is still induced by the similar rotation of Sunda plates as it was before, but undergoing significant afterslip deformation (*i.e.*, co-seismic and post-seismic), that agree with *Assumption 3*.

5. CONCLUSION

This paper has presented proper modelling of linear and non-linear time dependency of seismic deformation for Peninsular Malaysia due to Sundaland plate motion and recent major earthquakes. The model may be used to update modern geodetic reference frame for precise 3D coordinates definition and determination. The coordinate time series analysis reveals that the post seismic deformation model yield position accuracy improvement of 1-2 cm while co - seismic model contributed to position accuracy of +- 5mm. With this, the new concept of dynamic reference frame can be realized in Malaysia.

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