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2004 SUMATRA EARTHQUAKE AND TSUNAMI RATE OF POSITIONS DISPLACEMENT EXPERIENCED BY MALAYSIA

Submitted by Department of Survey and Mapping Malaysia **

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** Prepared by Mr. Samad Abu, Mr. Chang Leng Hua and Mr. Soeb Nordin, Department of Survey and Mapping Malaysia.

2004 Sumatra Earthquake and Tsunami
Rate of Positions Displacement Experienced by Malaysia

Samad Abu, Chang Leng Hua & Soeb Nordin
Department of Survey and Mapping Malaysia

Abstract

The Sumatran earthquakes that occurred on 26th December 2004 and 28th March 2005 had caused significant deformation to South East Asian region. In Malaysia, this is the first time in history such incident has brought about in the lost of life. Early study (26th December 2004 event) has indicated that the horizontal displacement magnitude in Peninsular Malaysia is between 2 to 18 cm with the greater magnitude shown at the northern part of the Peninsular. The Department of Survey and Mapping, Malaysia (DSMM) has monitored closely the coordinates time series of MASS and MyRTKnet Networks, carried out precise leveling network observation and analyzed the sea level trend in order to determine the physical effect of the events on geodetic infrastructures in Malaysia. The results shown that there were two 'jumps of coordinates' recorded during the event and a strong post-seismic motion in the South-West direction can still be noticed on the northern part of Peninsular Malaysia with gradual easing towards the south. The events do not really affect the existing precise leveling network and has no significant effect on the sea level trend.

1. INTRODUCTION

The Department of Survey and Mapping Malaysia (DSMM) is a government agency under the Ministry of Natural Resources and Environment (NRE) which acts as the technical advisor to the Government of Malaysia on all matters pertaining to surveys and mapping in the country. It is the sole governmental body which maintains the Malaysian Spatial Reference Frame for various works such as for geodesy, mapping, engineering, cadastral, scientific study, geodynamics and creations of Geographical/Land Information Systems. DSMM is responsible for the operational of GPS permanent networks in Malaysia, maintaining of the Precise Leveling Networks (PLNs), and implementation of the gravity survey and tidal observations.

The recent Sumatran earthquakes that occurred on 26th December 2004 and 28th March 2005 had caused significant deformation to South East Asian region. Preliminary study (26th December 2004 event) has indicated that the horizontal displacement magnitude in Peninsular Malaysia is between 2 to 18 cm, and with a greater value on the northern part. The coordinates' time series of the Malaysian GPS Permanent stations from 1999 till now were analyzed with the objectives of determining the relative changes in time of the coordinates with respect to ITRF2000 Reference Frame. Monitoring of the post seismic motion is crucial in order for us to know it's implication on the accuracy of GPS real time positioning services and on other survey and mapping products.

2. GPS PERMANENT STATIONS

2.1 Stations Distribution

MASS and MyRTKnet networks respectively consist of 18 and 27 permanent stations situated through out the country. 10 of the MASS stations and 25 of the MyRTKnet stations are located in the Peninsular. In the coming fiscal year of 2006 to 2008, DSMM will upgrade all the existing MASS stations with real time capability and will add more new stations to cover the whole of Peninsular and the states of Sabah and Sarawak (East Malaysia). DSMM has planned to operate at least 50 MyRTKnet stations in Peninsular and around 25 stations in Sabah and Sarawak by the end of 2008 (**Figure 2**).

2.2 Displacement and Time Series Analyses

By using geodetic technique, the trend and effect of back-to-back earthquake off the Sumatra waters has been modeled. The analyses of the effect on Malaysia Active GPS System (MASS) and Real-Time Kinematic Net (RTK Net) stations have been carried out using the GPS data of these respective stations. The GPS data from 19 December 2004 to 6 January 2005 and from 20 Mac to 2 April 2005 were used for the determination of the displacements magnitude, whereas for the post-seismic motion, GPS data from 1999 till now were used. The processing and analyses were carried out in two stages. The first stage involved the processing and analyses of the MASS and MyRTKnet stations with reference to the International GPS Service (IGS) stations and the second stage involved the analyses on the post-seismic motion.

From the analyses, stations nearer to the epicenter of the first earthquake have shown a significant displacement with a magnitude of 18 cm in the East-West component, for instance in Langkawi and Penang Island and in Arau, Perlis (**Figure 3**). Similar displacement trend also recorded during the second earthquake, with the displacement vectors pointing towards the epicenter of the event (**Figure 4**).

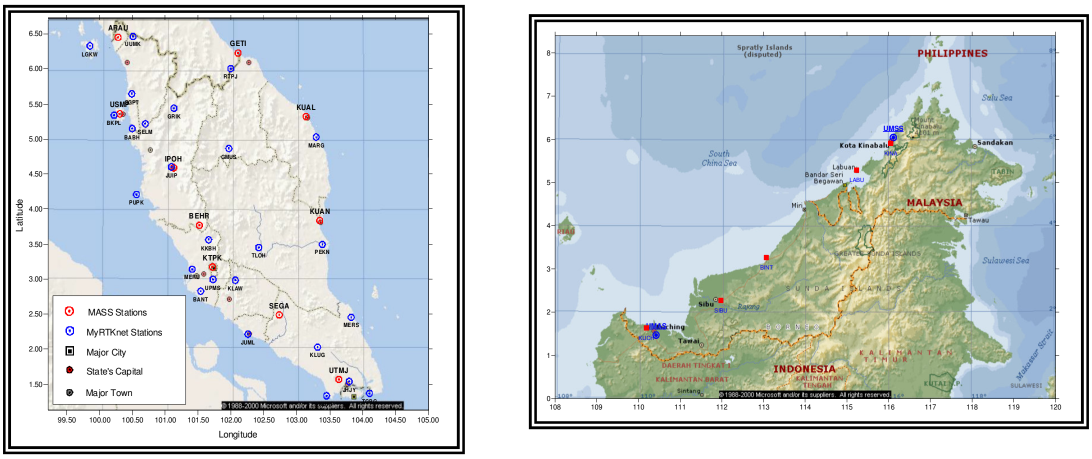

FIGURE 1: Existing MASS & MyRTKnet Networks

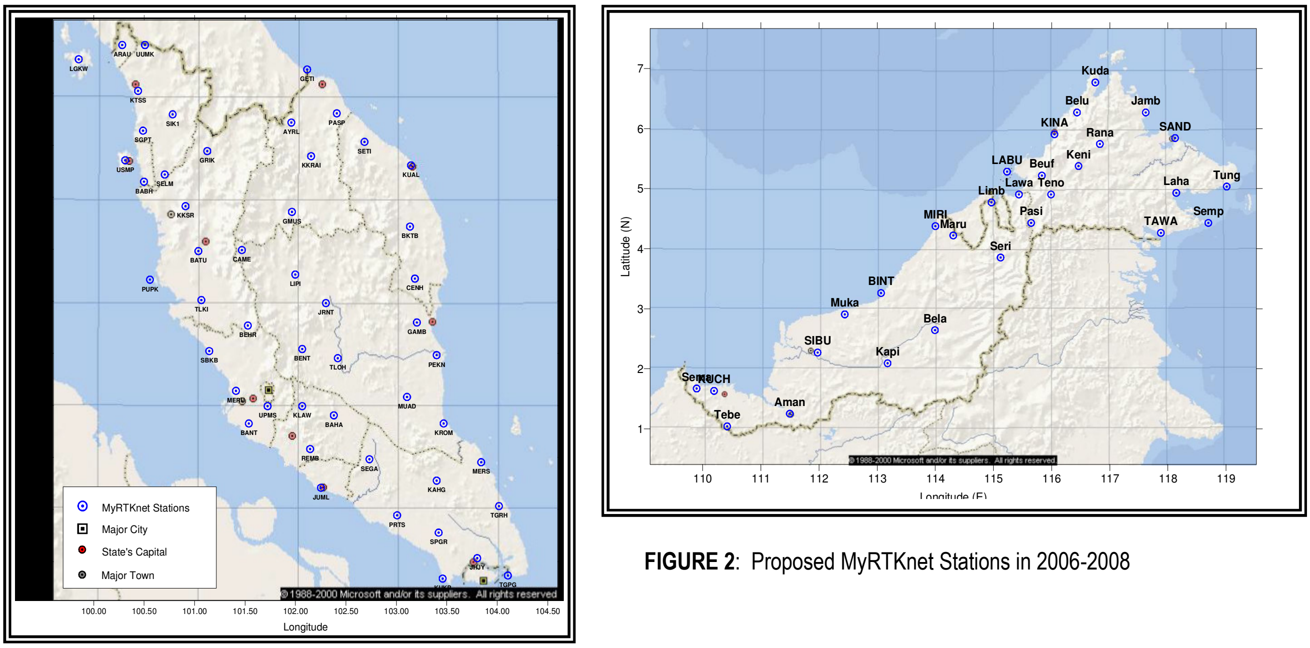

FIGURE 2: Proposed MyRTKnet Stations in 2006-2008

From the figures, it can be seen that the stations in the North of Peninsular suffered a maximum displacement of 28 cm with vectors pointing in the South-West direction. Other stations on the West coast in the state of Selangor, Pahang, Perak and Melaka show a smaller magnitude in the direction of North West. As for the stations in the South of Peninsular, the displacement vector is around 2 cm and the direction of displacement is in the North. This trend of the velocity vector indicates that the existence of a rotation on the earth surface in Peninsular Malaysia. For GPS permanent stations in Sabah and Sarawak (East Malaysia) the displacement magnitude is very minimal.

The MASS and MyRTKnet GPS networks stations began their continuous GPS observations from 1999 and the third quarter of 2004 respectively. For the time series analyses, GPS processing were carried out by using Bernese GPS Processing Software Version 4.2. Two step analysis strategies have been employed with the inspection of weekly coordinate's variation and baseline length.

Figure 5 – 8 depicted the coordinate's time series of the selected MASS stations located on different parts of Peninsular Malaysia. As expected, two big jumps of stations coordinates were found during the 26th Dec 2004 and 28th March 2005 earthquakes. Coordinates time series before Sumatran Earthquake (26th December 2004) clearly show the motions of MASS stations were going towards South-East direction with magnitude around 3 cm/year. This was similar to the direction and magnitude of Sunda Block motion. The station's coordinates variation between first and second event of Sumatran earthquake shows mix directions and magnitudes of the stations motion. The results were somehow influenced by noisy data and due to a short span of times; it's difficult to see the real trend of the station's motion.

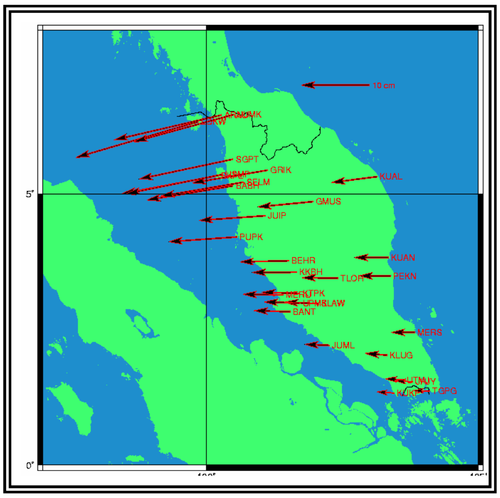

FIGURE 3: Displacement Vector from 26th December 2004 Earthquake

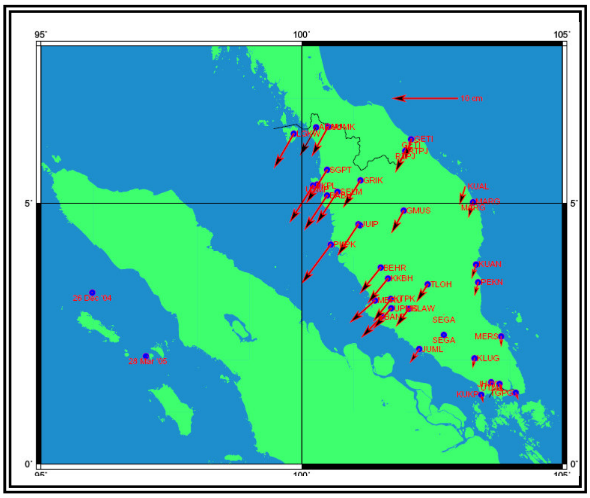

FIGURE 4: Displacement Vector from 28th Mac 2005 Earthquake

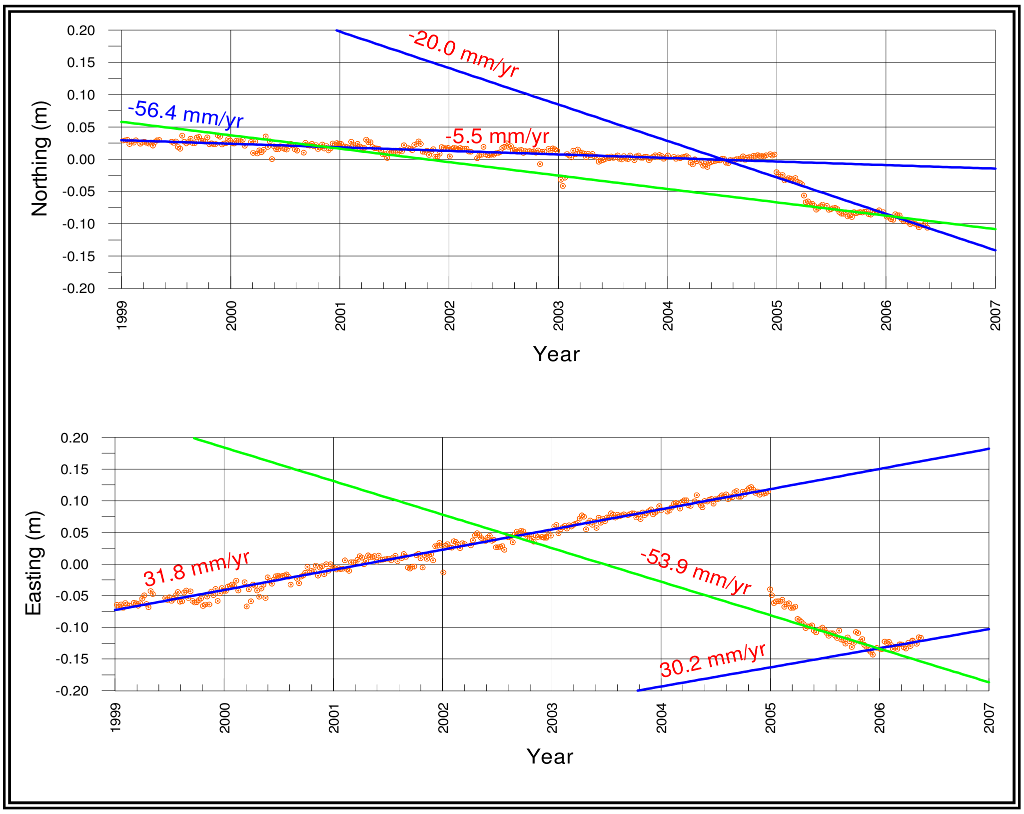

FIGURE 5: Coordinates Time Series for ARAU

The post-seismic motion after the second earthquake in Nias is what we really want to monitor in the first hand. From the coordinate's time series trend, it is clearly show that a strong motion was recorded in stations coordinates but varies from one station to another. The motion rate of ≈ 8 cm/year in South-West direction was recorded in ARAU and is easing towards south-east of Peninsular. The summary of post-seismic motion for selected stations is tabulated in Table 1. However, another trend that can be noticed from the time series is the reverse direction of station's motion in the east-west component.

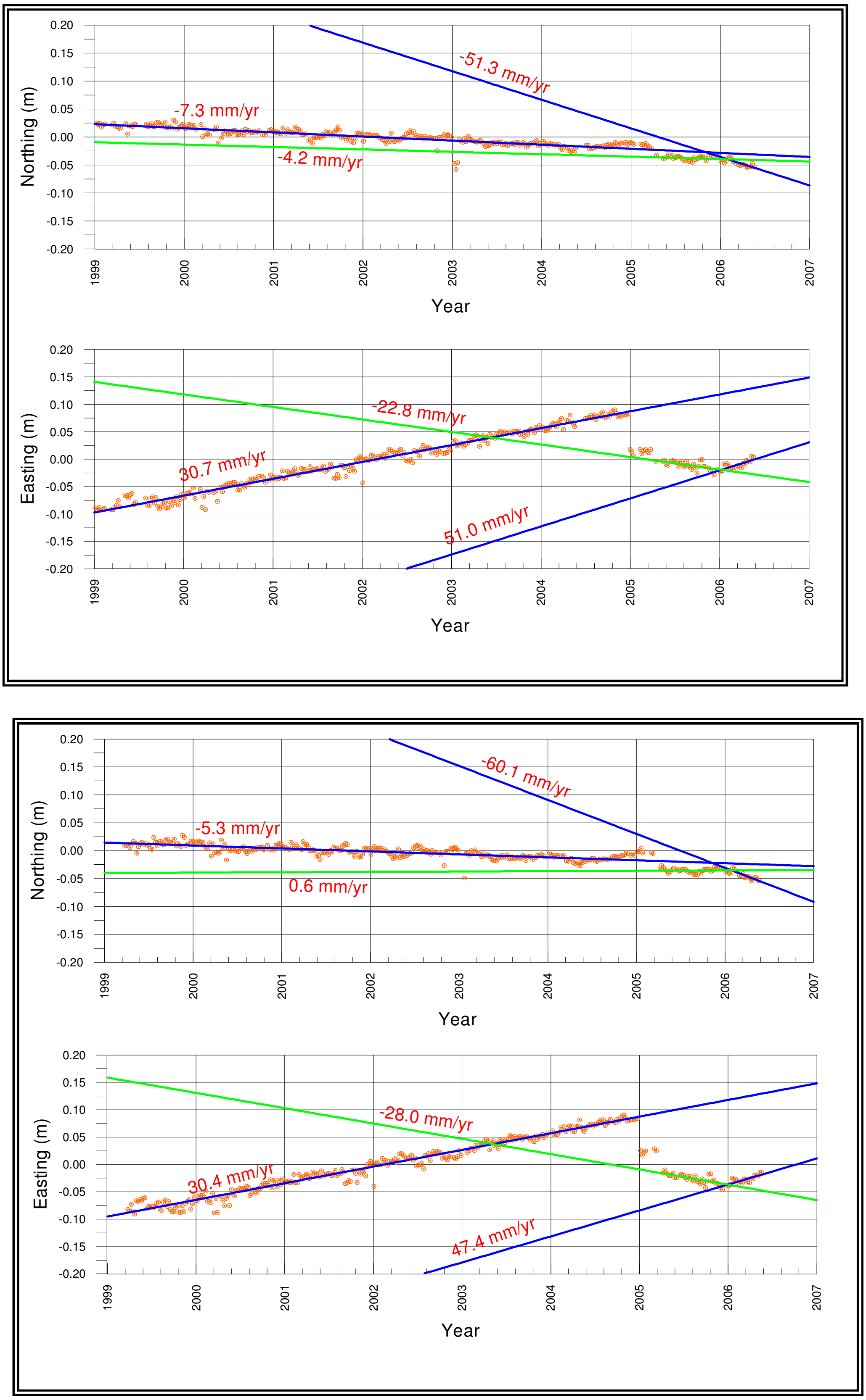

FIGURE 7: Coordinates Time Series for KTPK

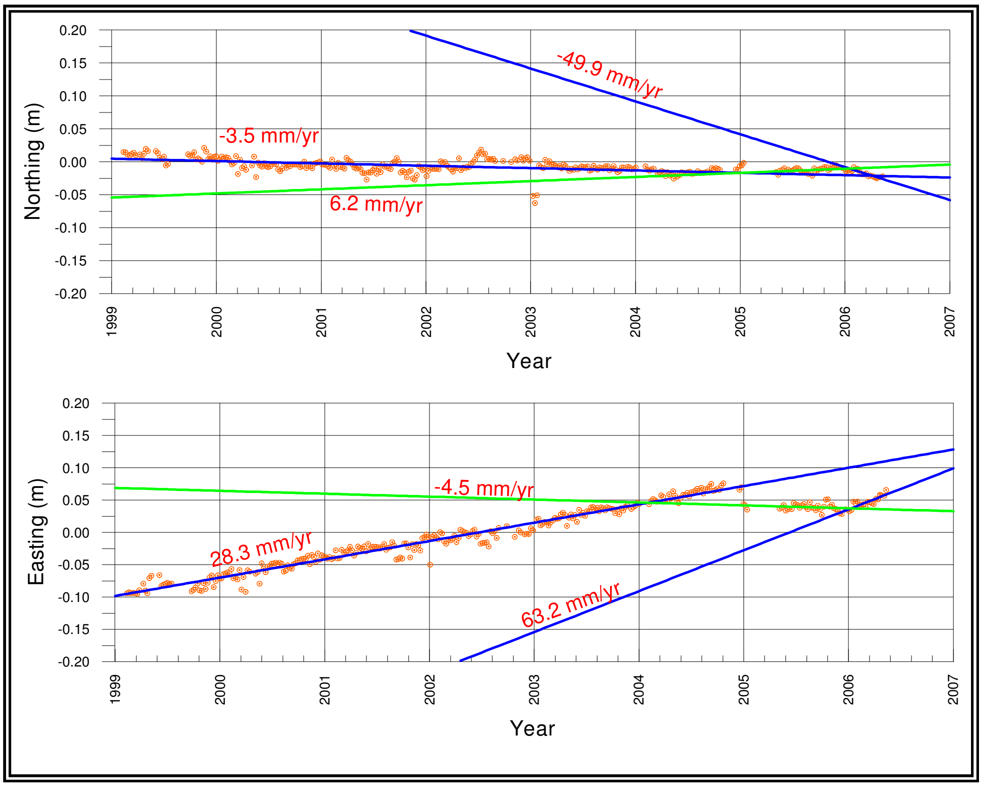

FIGURE 8: Coordinates Time Series for UTMJ

Beginning of year 2006, all stations show similar trend that can be described as an early indication that the Indo-Australian plate has been locked-up with the Sunda block and started to push the latter back to it's original direction. The station's motion trend that was modeled with 20 weeks of GPS data starting from GPW Week 1356 started to show that the motion is in a same direction as a motion prior to Sumatran earthquake, but with a different magnitude. With a short time span, it is difficult to model the stations motion correctly and DSMM will continue with the station coordinates time series monitoring in order to understand the station's behavior before any decision made on re-definition of geodetic reference frame in Malaysia.

Table 1: Pre and Post Seismic Motion

No.	Station	1999 – 2004		28th March '05 – 31st Dec '05		1st Jan '06 – 20th May '06	
		N (mm/yr)	E (mm/yr)	N (mm/yr)	E (mm/yr)	N (mm/yr)	E (mm/yr)
1.	ARAU	-5.5	31.5	-56.4	-53.9	-20.0	30.2
2.	LGKW	-	-	-22.4	-57.2	-61.5	28.5
3.	UUMK	-	-	-19.5	-47.4	-50.5	25.2
4.	SGPT	-	-	-16.9	-44.0	-56.2	35.3
5.	USMP	-6.5	34.1	-22.4	-57.8	-50.6	74.6
6.	BABH	-	-	-15.5	-40.0	-60.4	37.1
7.	GRIK	-	-	-13.5	-39.4	-51.1	31.5
8.	PUPK	-	-	-15.2	-37.4	-57.0	44.7
9.	IPOH	-4.6	30.4	-6.7	-37.4	-56.5	38.4
10.	BEHR	0.3	31.0	-6.4	-33.4	-61.0	52.0
11.	KTPK	-5.3	30.4	0.6	-28.0	-69.1	47.4
12.	KLAW	-	-	1.7	-20.9	-46.9	56.8
13.	SEGA	-4.5	27.8	1.7	-10.9	-48.5	50.0
14.	KLUG	-	-	6.4	-5.1	-48.6	56.1
15.	KUKP	-	-	7.6	-1.8	-50.2	59.6
16.	UTMJ	-3.5	28.3	6.2	-4.5	-49.9	63.2
17.	TGPG	-	-	2.0	1.9	-57.7	66.4
18.	MERS	-	-	4.8	-6.3	-53.6	61.9
21.	KUAN	-5.6	30.5	1.4	-17.2	-42.3	70.0
22.	KUAL	-7.3	30.7	-4.2	-22.8	-51.3	51.0

23.	GETI	-6.4	31.2	-7.6	-33.3	-55.5	40.4
26.	KUCH	-11.1	27.5	-8.7	12.4	-6.0	54.3
27.	BINT	-12.0	26.7	4.2	3.4	-68.3	63.9
28.	MIRI	-10.8	25.9	-4.3	15.0	-45.3	40.9
30.	KINA	-12.4	24.7	-5.9	14.2	-56.0	45.0
31.	SAND	-15.0	26.4	-9.7	12.5	-55.4	30.2
32.	MTAW	-15.1	22.2	-10.5	11.1	-68.6	31.7

3. TIDAL OBSERVATIONS

3.1 Stations Distribution

The establishment of the Tidal Observation Network (TON) in Malaysia commenced in 1983. This project was initialized with the cooperation of the Japan International Cooperation Agency (JICA). By the end of 1995, twenty-one (21) tide stations (**Figure 9**) were established and in operation, in which nine (9) were located around Sabah and Sarawak and the rest in the Peninsular. However, the tide station located in Miri, Sarawak was damaged since December 1998 due to an unforeseen accident and subsequently re-establish in 2006.

The tide stations were evenly distributed along the coast and the locations selected to show typical characteristics of tides of the adjacent sea. The stations were constructed on a rigid shore or on a stable structure extended into the sea. The Geodesy Section, DSMM is responsible for the monitoring of the tide gauge stations which involves regular maintenance of the gauges as well as the collection, processing, analysis and distribution of observed tidal data. The observed tidal data and other related values are published annually in two reports by DSMM, namely *The Tidal Observation Record* and *The Tidal Prediction Table*.

FIGURE 9: Tide Gauge Stations Distribution in Malaysia

3.2 Tidal Analyses on 26th December 2004

Tide observation at all the tide stations in Malaysia is observed at 10 seconds sampling rate and the data is stored in IC memory chip. The data set was averaged at every 5 epochs (50 seconds interval) after it was downloaded to PC before further computation taken place at Tidal Processing Center in Geodesy Section. For the purpose of 26th December analyses, data set of 50 seconds interval has been used in order to determine the tidal wave's approximate time of arrival. All 21 tidal stations have been analyzed and only few stations have shown the present of the tidal wave. Analyses of tide stations located on the West Coast of

Peninsular Malaysia and some selected stations in East Coast of Peninsular and in Sabah and Sarawak were carried out for the purpose of this study.

Tide station in Langkawi Island is the northern most station in Peninsular Malaysia and was the first station being hit by the tidal wave. **Figure 10**, shows the arrival of the killer wave at 12:13 pm when the sea level was supposed to be at high tide, was suddenly being drove away until the level of 1.79 m above Zero of Tide Gauge (ZTG) at 12:30 pm.

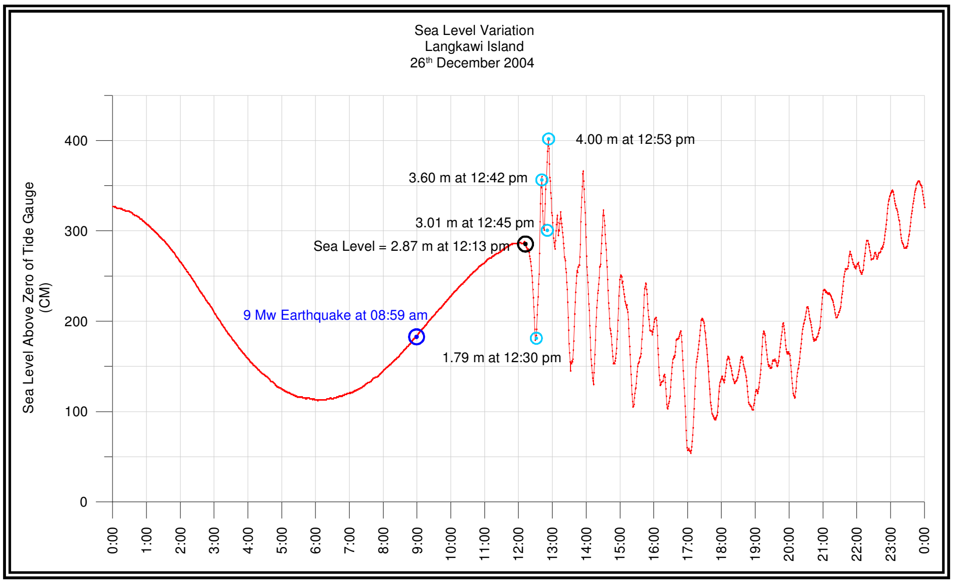

Figure 10: Sea Level Variation (50s Interval) at Langkawi Island

The first high wave recorded at 12:42 pm with the sea level at 3.60 meter high above ZTG, before went down to 3.01 m three minutes later. The second arrival of high wave is the highest at 4.00 meter above ZTG which hit at 12:53 pm and followed by another high wave at 01:55 pm at the level of 3.66 meter. The following wave patterns show that the tidal force decreased for the next 14 hours (**Figure 11**).

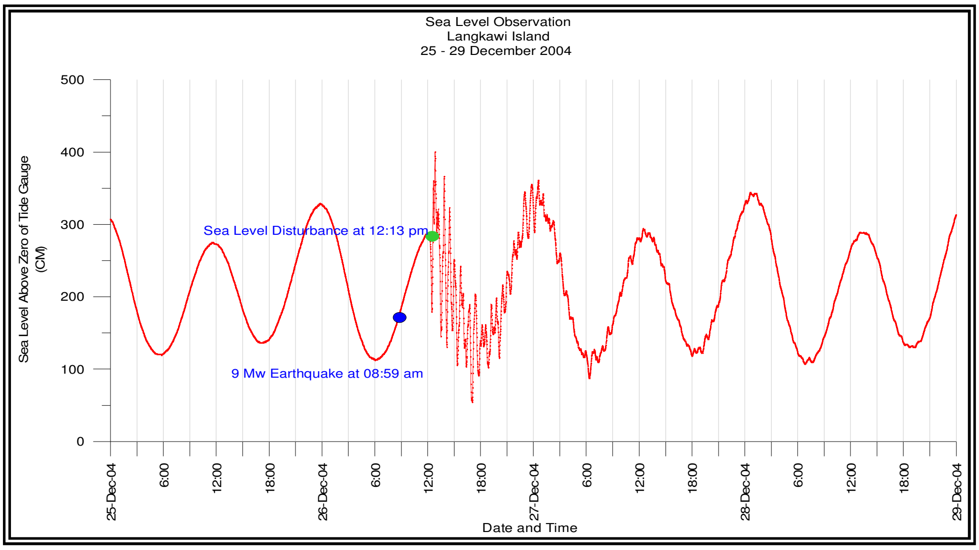

Figure 11: Sea Level Variation (25 – 29 Dec.) at Langkawi Island

The second tide station being hit by the tidal wave was Penang Island, followed by Lumut, North Klang Port and then the tidal force started to loose its energy towards the South. Penang's tide station recorded the water disturbance at 01:28 pm (**Figure 12**) when the sea level (3.12 m) started going down until 2.44 meters above ZTG at 01:48 pm. At 02:04 pm the first high wave arrived at 3.31 meter before it decreased to 3.07 m one minute later. The highest wave hit at 02:18 pm with 3.86 m high before the tidal energy is reduced.

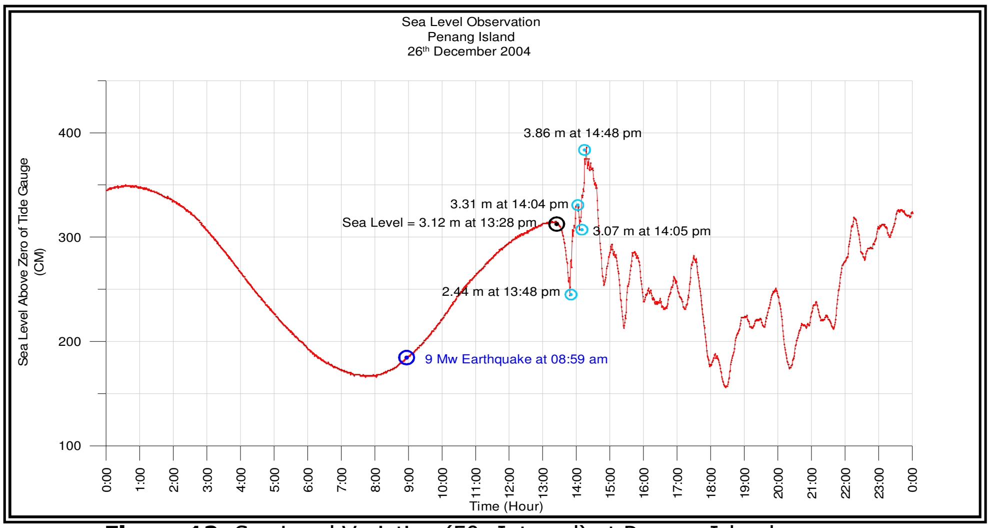

Figure 12: Sea Level Variation (50s Interval) at Penang Island

Figure 13 – 16 show the characteristic of the tidal wave from Lumut to Kukup. The waves reached North Klang Port at 4:40 pm before it faded away. Tide stations at Tg. Keling, Kukup, stations in East Coast of Peninsular Malaysia and in Sabah and Sarawak did not record any arrival of the waves for the next 48 hours after the earthquake. **Figure 17** shows the tidal direction and approximate time the tidal wave reached the tide stations.

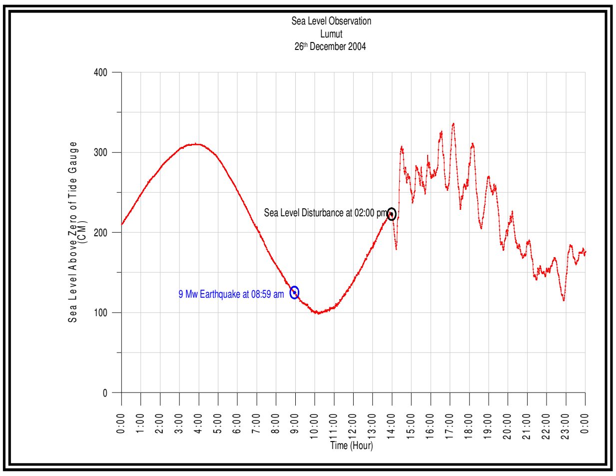

Figure 13: Sea Level Var. (50s Int) at Lumut

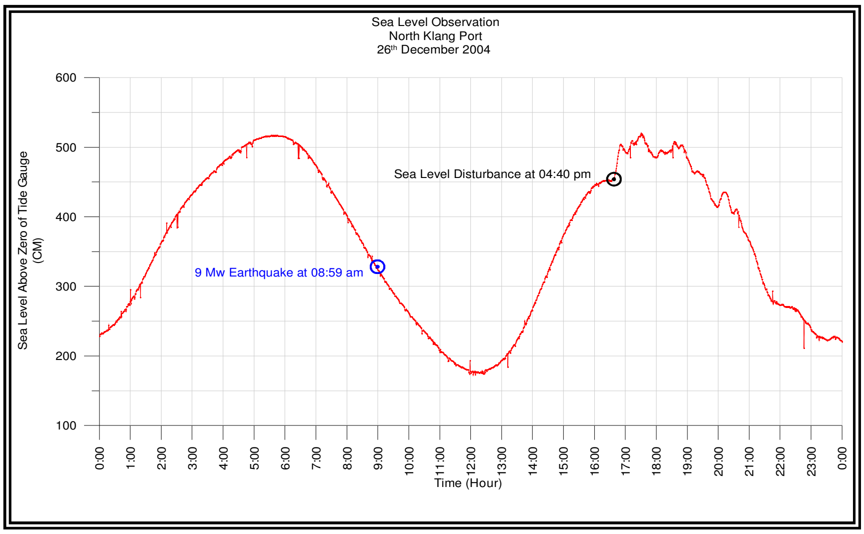

Figure 14: Sea Level Var. (50s Int) at P. Klang

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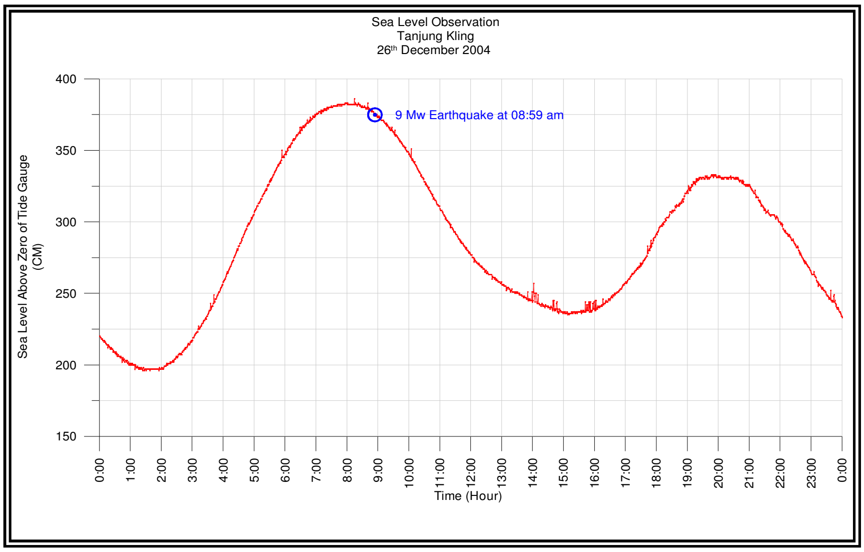

Figure 15: Sea Level Var. (50s Int) at Tg. Keling

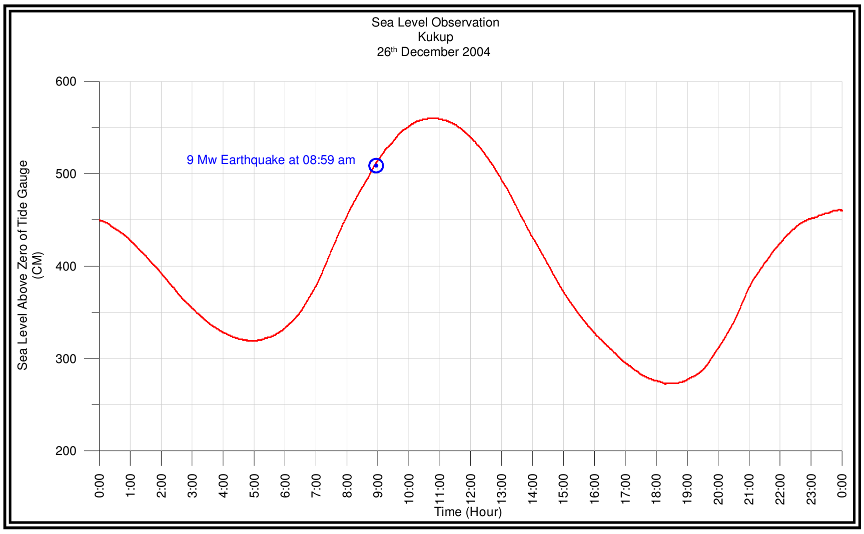

Figure 16: Sea Level Var. (50s Int) at Kukup

3.3 Pre and Post Tsunami Trend Analyses

In order to determine if there is any long term effect of the tsunami such as a sudden and continuous sea level rise in Malaysian waters, the sea level time series has been maintained routinely to monitor the tide stations. The hourly, daily, monthly and yearly mean sea levels were computed and analyzed in Geodesy Section, DSMM to monitor the sea level trend.

For pre and post tsunami tidal analyses, tide station in Langkawi Island which is situated in northern part of the island and facing the Andaman Sea, has been used in this study. The Tide station in Langkawi has been operating since 1985 (December) until now. During that period, the station has failed only in two occasions to observe the sea level for more than two weeks due to equipment failure.

Figure 18 shows the monthly mean sea level for Langkawi for the past 20 years. The brown linear trend line is representing the monthly mean sea level until November 2004, the green trend line represents the whole data set (until May 2006) and the black trend line is based on 18.6 years observation. The linear trend lines show that Langkawi station has recorded the sea level rise with the average of 24 mm/year (Brown line) prior to the Sumatran Earthquake and 18 mm/year when using all data sets.

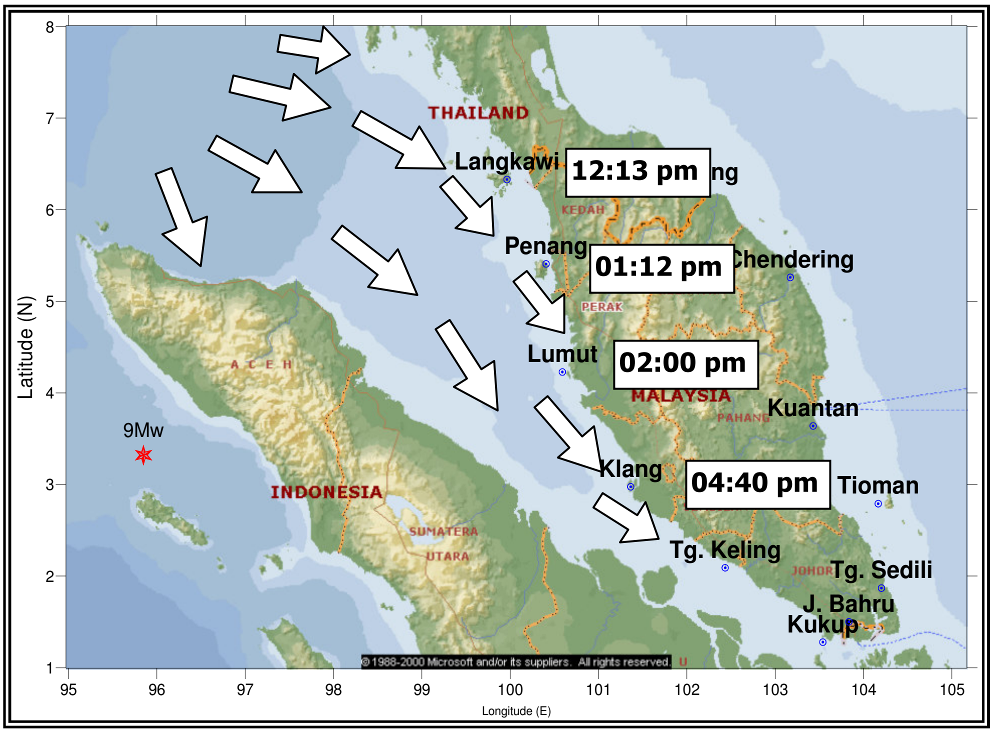

Figure 17: Tidal Wave Direction and Time it Reached Tide Stations

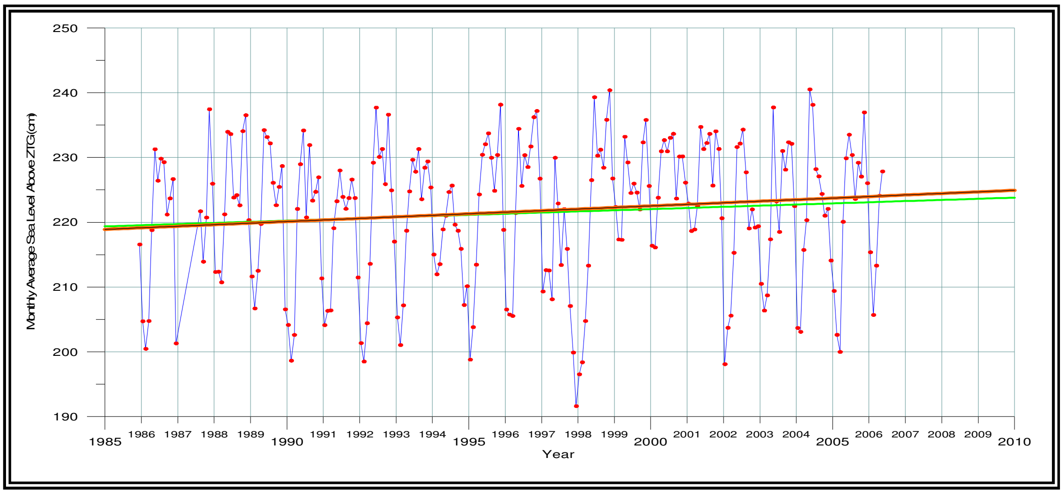

Figure 18: Monthly Mean Sea Level

The small discrepancy of 6mm/year recorded between those two trend lines does not mean the changes cause by the tsunami but more on contribution of noisy data such as loss of data for two weeks in February 2005. Year to year monthly sea level trend since 2001, have also been plotted (**Figure 20**) in order to see if any abnormal trend exists in the sea level data.

In **Figure 19**, comparison between the monthly sea level trend in yearly basis show that the trends direction are relatively similar but with a different magnitude. In fact the sea level trends of 2002, 2003 and 2005 are closely identical, and it can be concluded that the tsunami did not contribute significant effect on the sea level rise.

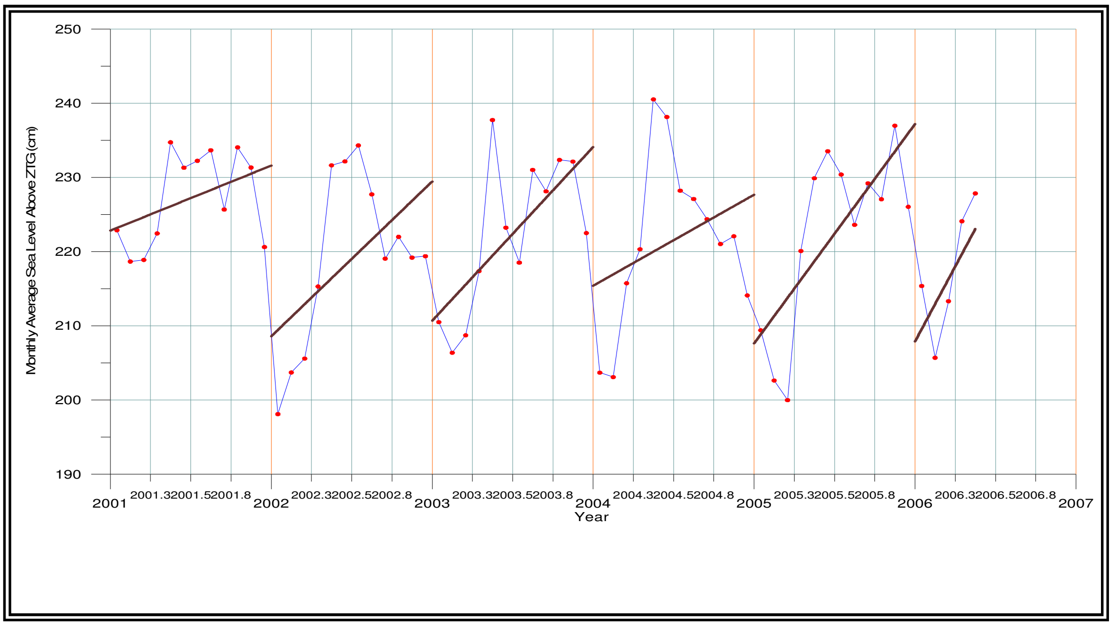

Figure 19: Monthly Mean Sea Level Since 2001

4. TREND ANALYSES ON PRECISE LEVELLING NETWORK

Bench Mark value is one of the products of the Department of Survey and Mapping Malaysia (DSMM) to support various activities in the field of geodetic, mapping, engineering surveys and other scientific studies. In 1983, DSMM began to re-determine the precise MSL value in conjunction with the establishment of the new Precise Leveling Network for Peninsular Malaysia. This was carried out by the setting-up of a Tidal Observation Network that consists of 12 tidal stations. Subsequently, Port Klang was selected as a reference level for the National Geodetic Vertical Datum (NGVD), based on a 10-year tidal observation (1984-93). The existing Precise Levelling Network (PLN) in Peninsular Malaysia (**Figure 20**) was adjusted in 1998 using Geolab 2.4c adjustment software.

Figure 20: Precise Levelling Network (PLN)

For the purpose of studying the Sumatran earthquake implication on the PLN, two close loop leveling line have been selected in the North-West of Peninsular. The first leveling loop covering the whole of Langkawi Island, and the second loop is on the main land that connecting Alor Star, Kangar, Padang Besar, Padang Sanai and Naka (**Figure 21**).

The strategy for data analyses focused on relative comparison to study the trend line to find out if there is any tilt in leveling lines for the two areas. Geolab 3.9 network adjustment package has been used to adjust the leveling lines with a standard modeling of a priori errors of 1 mm/km. All adjustments have passed the statistical criteria and error ellipses for the networks are as in **Figure 22**, **23**, **24**, and **25** respectively.

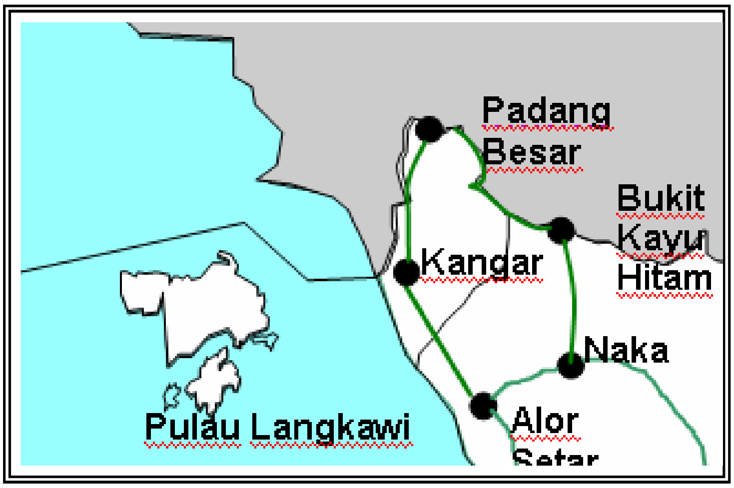

Figure 21: Study Area (North East of Peninsular)

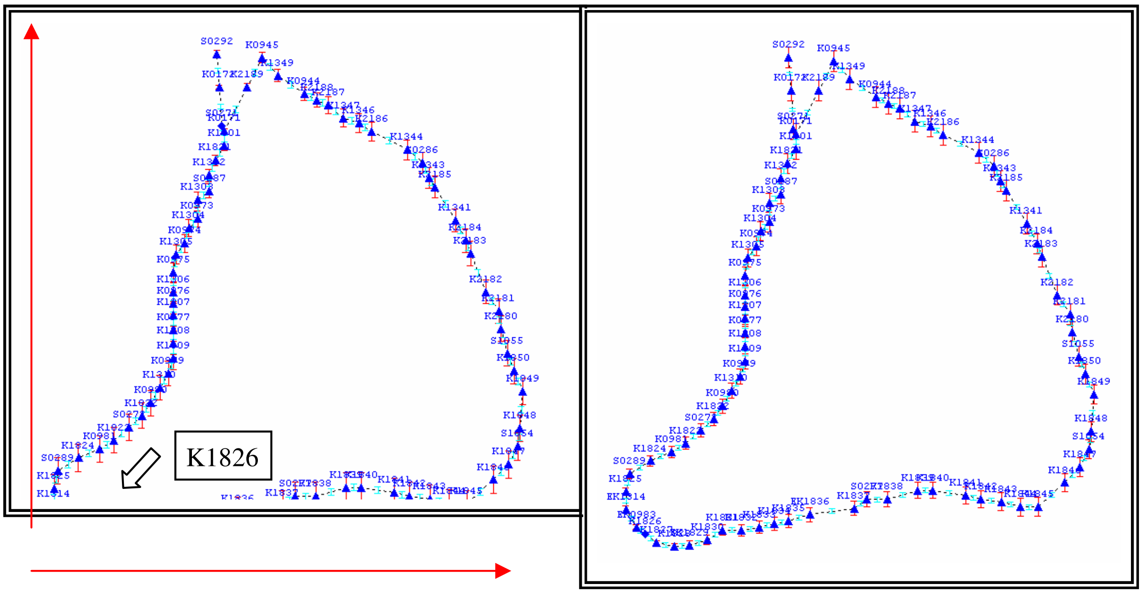

Figure 22 & 23: Error Ellipses for Langkawi Levelling Networks (Before on Left)

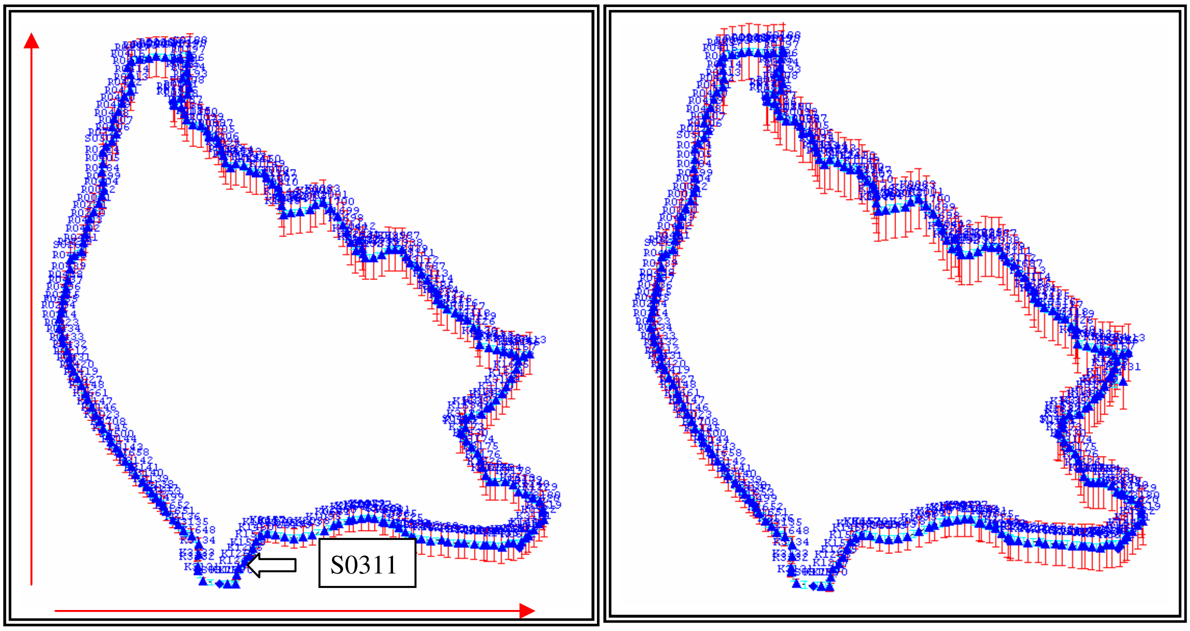

Figure 24 & 25: Error Ellipses for Main Land Networks (Before on Left)

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In Langkawi Island, Benchmark K1826 was used as a reference and in the mainland, Standard Benchmark (SBM) S0311 was the reference. The leveling line extension in Langkawi is 20 and 30 km for East-West and North-South components respectively.

Figure 26 (unfiltered) and **Figure 27** (Filtered) show the height differences with respect to K1826 that extent from east to west of Langkawi Island. The slope of the trend line is 0.34 and 0.2 mm/km for the unfiltered and filtered data set. The value is insignificant to confirm if, there is a tilt in leveling line when the error estimates being used in the adjustment is 1 mm/km.

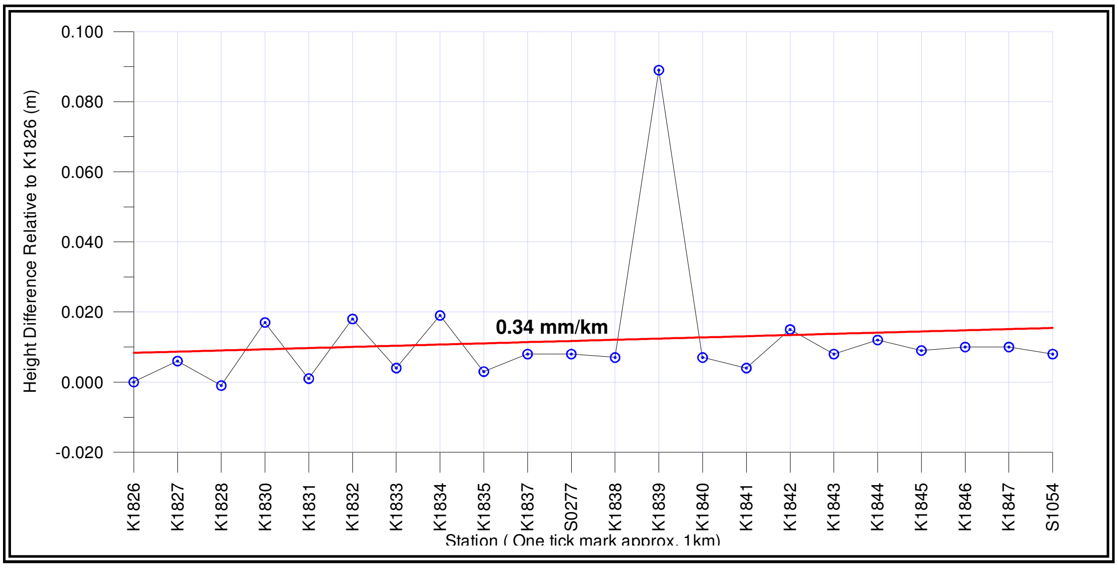

Figure 26: Height Difference in East-West Component (Unfiltered)

For the South-North component as shown in **Figure 28**, the trend is much smaller at -0.08 mm/km. Based on the findings, it can be concluded that leveling network in Langkawi Island is not deformed due to the mega thrust earthquake in Sumatra on 26 December 2004.

For the mainland leveling network, the leveling line extension is 40 and 65 km for East-West and North-South components respectively. **Figure 29** shows the height difference with respect to S0311 that extent from east to west of the network. The slope trend line is -1.2 mm/km for the whole data set, where the value is insignificant to confirm if, there is a tilt in leveling line when the error estimates being used in the adjustment is 1.5 mm/km. However there is a 4 cm jump in height difference between Benchmarks K0666 and S0176 that needs further clarification and investigation.

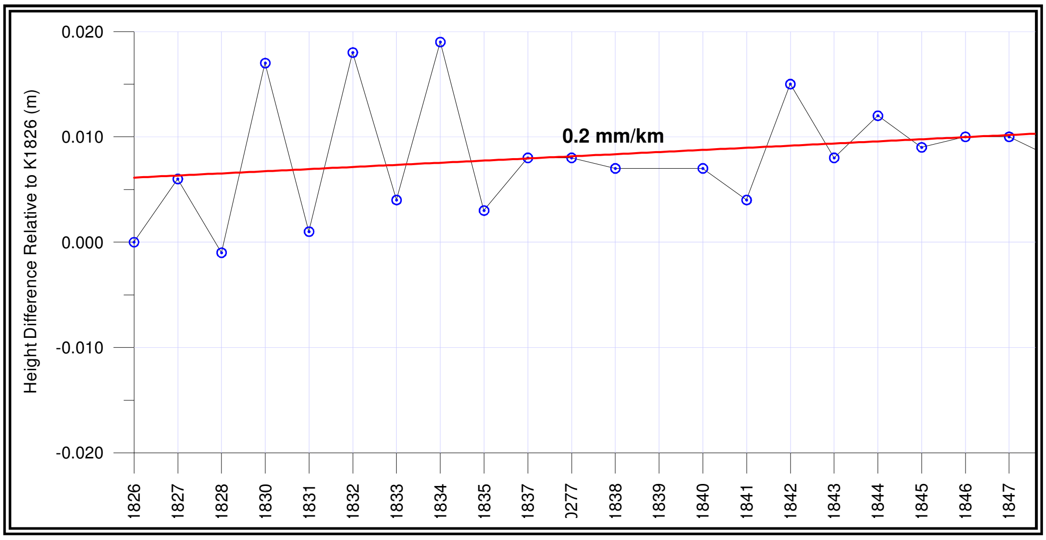

Figure 27: Height Difference in East-West Component (Filtered)

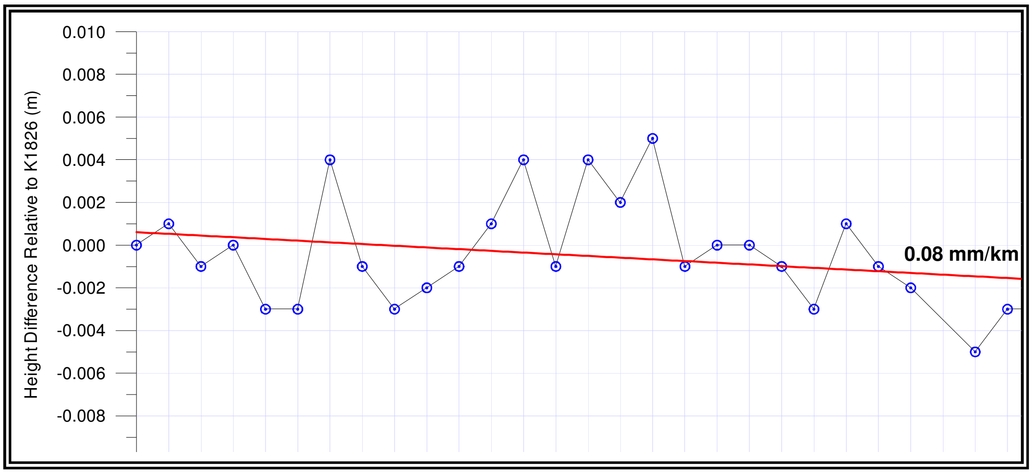

Figure 28: Height Difference in South-North Component (Filtered)

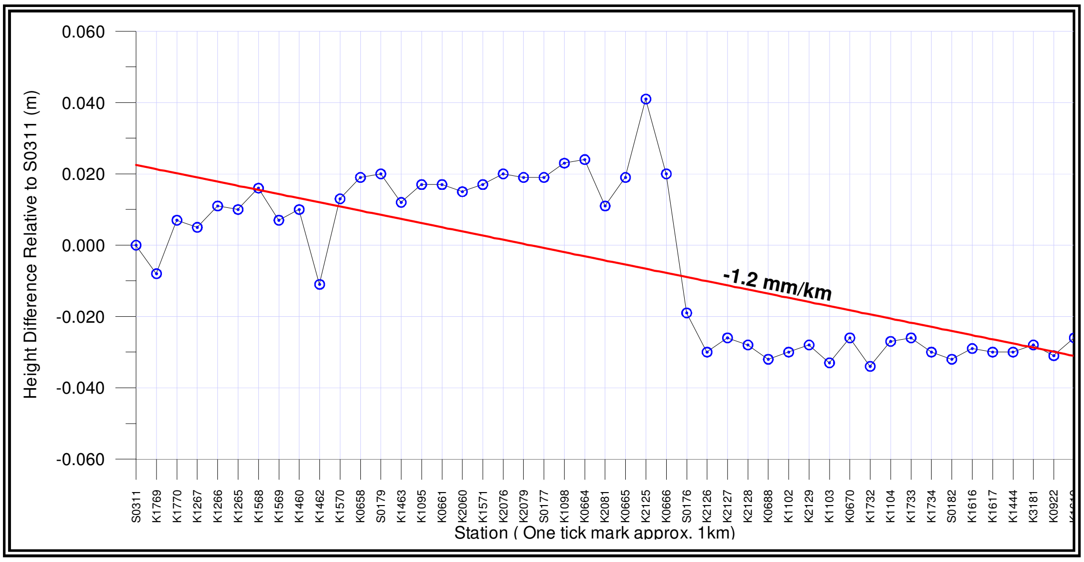

Figure 29: Height Difference in East-West Component

The slope trend line for South-North component is smaller with 1.1 mm/km. Similar with the East-West component, there is a noisy signal at the beginning of the leveling line (**Figure 30**) with a magnitude of 8 cm that can confirm several of the Benchmarks have been disturbed.

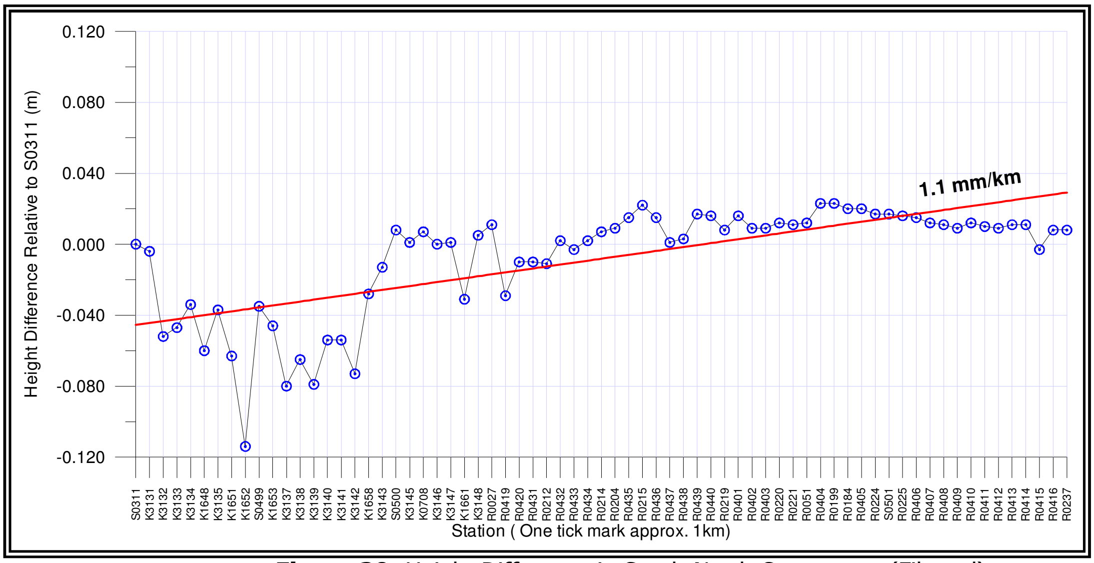

Figure 30: Height Difference in South-North Component (Filtered)

5. SUMMARY

From the analyses on the movement of the MASS and RTK Net stations it shows that there is a maximum total displacement of 24 cm in the South-West direction on the Northern Peninsular and its magnitude decreases towards the South and the East due to back-to-back Sumatran earthquake. When post-seismic motion was taken into consideration with a maximum rate of 8 cm/year, stations located in Northern Peninsular was displaced more than 32 cm at the end of 2005. Analyses from tidal and precise leveling data do not show any significant long term effect of the events on the sea level and height.

6. IMPLICATION DUE TO THE MOVEMENT

This movement and the effect of tsunami have brought about the following implications:

a. GDM2000 Coordinates

The movement will changed the GDM2000 reference frame. By using the coordinates of MASS and RTK Net stations and the GPS Control points, the GPS users will realize the existence of an offset whenever baseline computation are carried out. This effect could be negligible in a local survey when the baseline is short, but it will become significant when longer baseline is involved. Therefore, detail investigation need to be carried out after these stations have become stabilized and the GDM2000 could possibly need to be redefined.

b. Mapping

The total displacement difference of the movement between Johor Bahru and Arau is approximately 28 cm over a distance of about 1000 km, and this means the error will be only be 1 mm over 3.5 km and the maximum angular change will be 0.06 second. With this small change, the maps in Malaysia need not be revised and the existing mapping programme and activities could be continued.

c. Cadastral

Due to the fact that the cadastral survey is carried out in a relative mode, the movement has very little effect on the area and land title. In general, if a land owner has a plot of land stretching from North to South for 3.5 km; it will only experience 1 mm difference in distance. The existing survey instrument will not be able to detect this difference.

d. Precise Levelling Network

From the investigation on precise leveling network, it has not indicated a significant movement in the height component, therefore it can be certified that the precise leveling network has not been distorted.

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