May 17th, 1:50 PM

Historical Storm Surges: Consequences on Coastal Resources and Shoreline Protection in East Coast of Peninsular Malaysia

Norzana Mohd Anuar  
*National Hydraulic Research Institute Malaysia, norzana@nahrim.gov.my*

Ahmad Mustafa Hashim  
*Universiti Teknologi Petronas, mustafa_hashim@utp.edu.my*

Nor Aslinda Awang  
*National Hydraulic Research Institute Malaysia, aslinda@nahrim.gov.my*

Mohd Radzi Abd Hamid  
*National Hydraulic Research Institute Malaysia, radzi@nahrim.gov.my*

Follow this and additional works at: [https://digitalcommons.usu.edu/ishs](https://digitalcommons.usu.edu/ishs)

Recommended Citation


This Event is brought to you for free and open access by the Conferences and Events at DigitalCommons@USU. It has been accepted for inclusion in International Symposium on Hydraulic Structures by an authorized administrator of DigitalCommons@USU. For more information, please contact dylan.burns@usu.edu.
Historical Storm Surges: Consequences on Coastal Resources and Shoreline Protection in the East Coast of Peninsular Malaysia

N. Mohd Anuar¹,², A.M. Hashim², N.A. Awang¹ & M.R. Abd Hamid¹
¹National Hydraulic Institute of Malaysia, Seri Kembangan, Selangor, Malaysia
²Dept. of Civil & Environmental Engineering, Universiti Teknologi PETRONAS, Seri Iskandar, Perak, Malaysia
E-mail: norzana@nahrim.gov.my

Abstract: The storm surge event of 1988 that affected the East Coast of Peninsular Malaysia has produced significantly high water levels that caused severe flooding and destruction to coastal mitigation structures. A 28-year analysis of recorded water level data (1986 to 2013), from the southern coast of Thailand to the south-eastern coast of Peninsular Malaysia, show that the surge level was highest in the 80’s, started to decline in late 90’s, and slowly increased later in the twentieth century. Maximum surge was recorded in 1988 at Paknam Bangnara station in southern region of Thailand (max. storm surge, \( S_{\text{max}} = 1.42 \text{ m} \)) and Goring (\( S_{\text{max}} = 0.93 \text{ m} \)) in the north-eastern region of Peninsular Malaysia which resulted in high erosion rate along these coasts. This paper explores the consequences of storm surge increment on the vulnerability of present coastal resources and shoreline protection structures along the East Coast of Peninsular Malaysia. The study reveals an increasing magnitude of storm surge and mean sea level increment in all the stations over the years which conform with the sea level rise assessment in IPCC AR5. Storm surge trends and the correlation between the stations are also investigated. Storm surge levels corresponding to various return periods are derived as a guideline for engineers and developers to determine the optimum level in their design.

Keywords: Tide level, storm surge level, return period, coastal shelves, Northeast Monsoon.

1. Introduction

Tides generally are the rise and fall of sea levels caused by the combined effects of the gravitational forces exerted by the Moon and the Sun and the rotation of the Earth. Most places in the ocean usually experience two high tides and two low tides each day (semdiurnal tide), but some locations experience only one high and one low tide each day (diurnal tide). Storm surges, however, are caused by strong winds that drive seawater against the shore. In conjunction with certain tidal states, these coastal flooding events can cause significant property damage and loss of life. Despite measures to protect exposed coastline, there is also an increasing risk for severe flooding due to sea level rise (SLR) both from existing natural trends and the global warming impact. The subject of storm surge has been intensively studied worldwide. It is widely accepted that storm surge has increased over the years as a result of an increase in global mean atmospheric temperature. The changes in storm surge are subjected to several combined force, such as strong atmospheric wind, low atmospheric pressure and continental-trapped waves along the coast (Bell et al. 2000; Gönnert 2004). Nicholls (2002, 2003) has estimated that in the past 200 years, more than 2.6 million people have drowned during surge events. In 1997, approximately 1.0 - 2.5 m surge height was generated along the coastline of Gulf of Thailand (GoT) by Typhoon Linda, causing 330 casualties and over 2,000 missing persons in the coastal areas of Thailand and Vietnam (Aschariyaphotha et al. 2011; Wannawong et al. 2010).

The effect of global warming has induced diversity in storm surge characteristics along coastal areas (von Storch and Woth 2008), and storm frequency and intensity are projected to increase globally in the future (IPCC 2014). However, recent scientific insights derived by researchers suggest that storm surges are subject to individuality of coastal areas, such as their local atmospheric condition and coastal geographic. A study performed by Woth et al. (2006) over the North Sea and Norwegian Sea found that storm surge is expected to increase by about 10% under extreme conditions. On the southwest part of the North Sea, Debernard et al. (2002) commented that surge heights are the greatest during autumn time. In the coastline facing the South China Sea (SCS), coastal flood and inundation caused by storm surge are recognized as a major threat to coastal communities populated adjacent to coastal margins and low-lying areas apart from anthropogenic intervention. The frequency and intensity of storms become more significant due to frequent occurrence of tropical typhoons, although tropical typhoons are rarely known to hit the coastal region of Peninsular Malaysia (PM). In 2001 part of the southern coastline of PM was hit by Typhoon Vamei, causing at most a surge of about 1.0 m. Thus, storm frequency is expected to modify the characteristics of storm surges.

Several studies on storm surges along the coast of Gulf of Thailand (GoT) and east coast of Peninsular Malaysia (EPM) have been carried out over the years but usually using satellite altimetry data. However, How et al. (2012) used limited temporal observation data acquired from global mean sea level (MSL) source. Sinha et al.
(2009) in another case used idealized historical typhoon events along the SCS to estimate storm surge. Luu et al. (2015) examined the sea level trend using a combination of tide gauge data, vertical land movement information, and satellite altimetry. Their investigations indicate a variation in trends such that sea level falls coincide with El Niño events while the rises are correlated with La Niña, which indirectly affect storm surge characteristics. Another study on sea level trend variation used two tide gauge stations located in the west coast of PM using Man-Kendall and moving averaged methods (Md Ali and Tan 2015). A study by Vongvisessomjai (2006) and Neelasri et al. (1988) agreed with Woth et al. (2006), where in Ko Lak in western GoT, the trend in SL decreased due to the steep sloping shoreline. Land subsidence rate has varied over the years in Thailand, but the pace has accelerated after 2004 Sumatera earthquake. However, due to the insufficient of GPS data, the effect of land subsidence on sea level and surge in the southwestern coast of GoT and EPM are incomplete and fragmentary (Luu et al. 2015). Md Din et al. (2017), using Permanent Service for Mean Sea Level (PSMSL) data without excluding the vertical land movement (VLM) effect, discovered a linear trend in the relative sea level at PM with positive trend rates. However, it was found to be significantly site-specific, which also agreed by Sojisuporn et al. (2013).

Generally, the investigation on surge characteristics and trends based on local, long term, observational tide level data is still insufficient and incomplete. Although storm surge related researches have been widely explored since the 70’s in various parts of Southeast Asia, there is still a knowledge gap in understanding the characteristics of storm surge, particularly along the PM region. In future, understanding the surge characteristics and trends are important in deriving an empirical formulae and run surge model simulation to predict coastal flood levels. The findings in this paper will hopefully serves as a guideline for effective forecasting for coastal inundation mitigation measures and provide close prediction for crest level design of coastal protection structures against risk of overtopping and structural failure.

2. Data and procedures

Hourly records of five tide gauge stations distributed along the southern-most of the GoT and EPM (Figure 1) are used for this study. The tide gauge stations are facing the GoT and the SCS, which were selected for being influenced by the El Niño and La Niña events and the Northeast Monsoon. The spacing between the stations is not equidistance but almost, especially among the tide stations along the EPM. The water level data is acquired from the Department of Survey and Mapping, Malaysia (DSMM), which is comprised of a 28-year span of hourly observational data from 1985 to 2013. Series of the available data set revealed a missing data (in certain period of time and referred to as ‘gaps’) in most of the stations, but overall, the gaps identified are less than 10% within the specified extreme event period (during Northeast Monsoon; November until March). The missing data were added using a correlation with adjacent data from neighboring tide stations. In investigating the surge trend of each stations, for consistency purposes, only data sets which covered 1986 until 2012 (27 years) is considered for this study.

Table 1. List of selected stations and its location. Years of data are the years used in the study

<table>
<thead>
<tr>
<th>Station</th>
<th>Name of stations</th>
<th>Location</th>
<th>Stn. id</th>
<th>Year</th>
<th>Max. surge (m)</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Geting</td>
<td>6.23°N, 102.10°E</td>
<td>GT</td>
<td>1986 - 2012</td>
<td>0.93</td>
<td>22/11/88 11am</td>
</tr>
<tr>
<td>3</td>
<td>Chendering</td>
<td>5.27°N, 103.18°E</td>
<td>CH</td>
<td>1985 - 2011</td>
<td>0.63</td>
<td>23/12/99 12pm</td>
</tr>
<tr>
<td>4</td>
<td>Tg. Gelang</td>
<td>3.98°N, 103.43°E</td>
<td>TG</td>
<td>1984 - 2012</td>
<td>0.68</td>
<td>22/12/99 1pm</td>
</tr>
<tr>
<td>5</td>
<td>Tioman</td>
<td>2.80°N, 104.13°E</td>
<td>TIO</td>
<td>1986 - 2008</td>
<td>0.71</td>
<td>23/12/99 6pm</td>
</tr>
</tbody>
</table>

The paper consists of four parts: the first involves the analysis of storm surge height trends throughout the collective years. The surge height is determined by subtracting the observed tide gauge data with a predicted tide for all stations. The present study focuses on positive surges during extreme events during the Northeast Monsoon (NEM). It should be noted that the stations’ reference systems used in this study (EPM stations) have already converted to a common datum, known as the National Geodetic Vertical Datum (NGVD), which was established by DSMM in 1983. It is presented here in reference to MSL in Port Klang. The second part extends the trend analysis on MSL variations over the 27 years span of data for the five stations to investigate the range of level rises with respect to latest SLR projection. The third part uses correlation analysis to investigate if there is any statistical dependency between the storm surge height at each station. This is to understand the characteristics of surge trends and the possibilities of concurrent events. The fourth part uses the Gumble
An analysis of recorded tide data was carried out for the five standard tide stations. The storm surge is defined as a variation in sea level resulting from the action of meteorological forces. The surge height was calculated in the usual way by subtracting harmonic tidal predictions from the observed tide level. In analysing the surge and MSL trends, several methods can be used. In present study, the least square method was employed to analyse the trends on the 27-year data. The best fitting regression line was determined with the sum of the squared residuals is minimized as much as possible. Based on the trend line plotted, the fitted linear regression model was determined. The equation demonstrates whether the trend has increased or decreased over time. The decrease or increase trend indicates how quickly or slowly the change occurred.

To further understand the surge height trends and its development along the coastline of GoT and EPM, the relationship between two surge height of paired stations; PB-GT, GT-CH, CH-TG and TG-TIO were determined using the Pearson Correlation Coefficient (PCC) developed by Pearson (1895). The strength of association between the paired surges were determined by calculating their correlation coefficient $r$ given as follows:

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{(n(\sum x^2) - (\sum x)^2)(n(\sum y^2) - (\sum y)^2)}}$$

(1)

where $n$ is the number of data pairs. Values of $r$ range from 1.0 to -1.0, which indicates perfect and strong correlation between data pairs. A confidence level of 95% is used and probability, $p$-value is also determined. This study also attempts to predict future projection of peak surge height at the desired return period using the Gumble distribution method (Gumble 1954). The Gumble distribution equation for peak surge estimation at return period, $T$, is:

$$x_T = \bar{x} + K\sigma$$

(2)

where: $x_T$ denotes the magnitude of the return period, $T$-year surge event, $K$ is the frequency factor, $\bar{x}$ and $\sigma$ are the mean and standard deviation of the peak surge respectively. The frequency factor $K$ is expressed as:

$$K = \frac{Y_T - \bar{y}}{s_x}$$

(3)
In which $\bar{y}$ is the reduced mean, $S_r$ is the reduced standard deviation and reduced variate, $Y_r$ is expressed as:

$$Y_r = -\left(\{\ln \left(\ln \frac{r}{r-1}\right)\}\right)$$  

(4)

3. Results and discussion

The analysis of the 27-year of surge level records for GoT and EPM exposed that most of the peak surge occurred before the high-water level or at the rising tide (Figure 2). The timing between high tide and peak surge agrees with the investigations and findings established by Rossiter (1961), Prandle and Wolf (1978), and Wolf (1981). Horsburgh and Wilson (2007) confirmed that the surge generation is decreased as it approaches the high water based on a long duration surge events analysis. In this paper however, the analysis of the timing of peak surge with respect to the timing of high water was not investigated in detail.

![Figure 2. Maximum surge level, observed and predicted sea level at five standard tide stations](image-url)

Using the linear regression method, the plots in Figure 3 exhibit a distinct downward and upward trend with significant fluctuations observed between the stations. Stations located on the northern side of SCS, PB, and GT, showed a downward trend, while the southern stations, CH, TG, and TIO, showed an upward trend on average under long term observation. All stations showed an increment in surge height and the surge rising trend is likely because of the location of the stations. The up-rush effect from the mass of water from Sunda Shelf towards the mouth of GoT during a tropical cyclone, or NEM, amplified the surge height on the northern coast. Whereas on the west of SCS, the wide span of SCS has distributed to the up-rush flow energy and dampened the surge height at CH, TG, and TIO stations under similar climatic conditions. The downward trend was from 1986 to 2005, but it increased in later years with varying rates of increments. At PB, the dip trend halted in the year 2001 and started to rise the following year. The distinct transition was likely due to the La Niña event in 2001. However, the dampening effect of La Niña in 2001 was not significant in other stations in EPM. The GT surge trend showed a dip in 2005, and CH, TG, and TIO all showed an abrupt turn in surge changes in 1997, with surges recorded at less than 0.3 m. The low surge heights at CH, TG, and TIO were largely because of warmer
El Niño event in 1997-1998 (which has been considered by scientists as the strongest warm event in 50 years) compared to El Niño event in 1982-1983 (NOAA 2007). However, the reason of the small surge at GT in 2005 is unclear. Nevertheless, the highest surge height identified in 1999 in all stations was likely due to the strong La Niña event (Table 2).

![Graphs showing trend analysis for annual maximum surge](image)

**Figure 3.** Trend analysis for annual maximum surge for PB, GT, CH, TG and TIO stations from 1986 – 2012

<table>
<thead>
<tr>
<th>Normal Year</th>
<th>El Niño</th>
<th>La Niña</th>
</tr>
</thead>
</table>

The assessment of the surge levels among the five stations seems to agree with findings from Jelesnianski (1973). Along with wind forcing, shelf geometry also has significant impact on storm surge formation, where, at wide continental shelves, peak surge can reach three times those at narrow shelves. Literally it is the shallowness and shape of the ocean floor that influence the storm surge height. As for the annual MSL trend, all stations indicated an upward trend which agreed with the global SLR assessment (IPCC 2014) and Malaysia SLR projection (NAHRIM 2017) as shown in Figure 4. Sea level trends analysis adjacent to PM and GoT, has been investigated by Trisirisatayawong et al. (2011), and the SCS (Peng et al. 2013) and SLR will not be uniform. By the end of 21st century, more than 95% of ocean area will be subjected to SLR and about 70% global coastline are projected to experience respective changes (IPCC 2014). The projected rise will definitely influence the surge magnitude, which conforms with the surge height trends in this paper. As of present, the characteristics of the MSL are inclined to increase over time due to SLR-induced depth changes, which alter frictional damping and shallow water effects (Coles and Tawn 2005; Müller et al. 2011; Arns et al. 2015; Mawdsley et al. 2015), both of which can amplify (Famikhalili and Talke 2016) or diminish the surge height. In general, the storm surge rise is in correlation with the increment in MSL but not in uniformity.
In light of the projected increment in mean SLR in year 2040 and 2100 at 0.15 m and 0.47-0.49 m at PM (NAHRIM 2017), the surge height will likely to increase in the future and further exaggerate the risk faced on coastal resources and shore protection. The MSL from north, at PB, to south, along EPM at GT, CH, TG, and TIO, have shown an increased in level over 27 years. The increment ranges from 1 cm to 6 cm with rapid rise estimated at CH at 5.62 cm, compared to PB at 1.1 cm. At GT, TG, and TIO, the increment estimation is 1.1 cm, 5.0 cm, and 3.8 cm, respectively. The increment rate is lower in EPM than in West Coast of PM, due to the disperse effect by the mass surface area in SCS compared to the narrow channel of the Strait of Malacca (SM). In a similar period, the increase in SLR at Tg Keling and Kukup were estimated to be 7 cm and 10 cm, respectively (Md. Ali and Tan, 2015). Another possible cause is the vertical land movement (VLM) effect, which has not been taken into account in the processing of the tidal data. Currently, VLM measurements and regional network of GPS station were sparse which causes uncertainty in estimating the sea level trend from tidal records. Thus, more VLM data and an improved computing technique are needed to enhance this approach and estimation.

![Figure 4. Mean Sea Level variations from 1986 to 2012](image)

The surge trend analysis is further tested in this study. The peak surge along the GoT and EPM mostly occurred within the duration of the NEM event. The possibility that each station will experience similar wind forces, which resulted in higher surge within a few hours of observation, is investigated. The surge magnitude may vary, but the coincidence probability of two stations in neighboring locations encountering similar heights is determined using the Pearson’s correlation analysis. The scatter diagram for the paired stations are shown in Figure 5, and the analysis results are tabulated in Table 3. In the plot between the paired stations, PB-GT (Figure 5a), the surge height at GT is not dependent on surge at PB in terms of surge magnitude, but they showed positive strong correlation with respect to the surge population between the two stations where \( r = 0.61 \); thus, there is an association between the surges at PB and at GT. For GT-CH, the correlation is weak with \( r = 0.13 \), meaning that the probability that a surge at CH will occur at GT is low. The coastal shelves condition in the northern EPM is wider and likely to have significant alteration on the surge magnitude. The coastal shelves along CH coastline have steeper slopes, where strong wave conditions and serious erosion have been frequently reported to occur during NEM (EPU1985). But the rate of erosion is dependent on site-specific factors apart from offshore bathymetry and sheltering effect from nearby islands (Husain et al. 1995). Wider coastal shelves can also be seen along the coast adjacent to TG and TIO station (Figure 1). Analysis of CH-TG and TG-TIO showed strong PCC values of \( r = 0.88 \) and 0.95, respectively. The \( r \) values indicated that there is a strong association in observed surge height between the paired stations. Note that the \( p \)-values are calculated between immediate neighboring stations.

<table>
<thead>
<tr>
<th>Paired Stn.</th>
<th>PB</th>
<th>CH</th>
<th>TG</th>
<th>TIO</th>
<th>GT</th>
<th>CH</th>
<th>TG</th>
<th>TIO</th>
<th>TG-TIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>( r )</td>
<td>0.611</td>
<td>0.210</td>
<td>0.161</td>
<td>0.155</td>
<td>0.126</td>
<td>0.055</td>
<td>0.055</td>
<td>0.815</td>
</tr>
<tr>
<td>( r^2 )</td>
<td>0.373</td>
<td>0.044</td>
<td>0.026</td>
<td>0.024</td>
<td>0.16</td>
<td>0.003</td>
<td>0.003</td>
<td>0.78</td>
<td>0.68</td>
</tr>
<tr>
<td>( p )-value</td>
<td>&lt;0.001</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&gt;0.05</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
The peak storm surge height with different recurring intervals were computed and are shown in Table 4. The return period for each respective peak surge over the 27-years event was determined using the Gumble distribution method following the above methodology shown in Figure 6. Based on the analysis, the mean surge height for PB, GT, CH, TG, and TIO was found to be 0.65 m, 0.55 m, 0.40 m, 0.39 m, and 0.35 m, respectively. Using the Gumbel’s distribution analysis, the above results showed that the 27-year mean surge height for each station was about 2-yr RP as shown in Table 4. This means that the prediction of surge height along the GoT and EPM is nearly accurate and follows the Gumbel’s distribution.

**Table 4.** Predicted storm surge height, $x_T$ in various return periods, $T$

<table>
<thead>
<tr>
<th>Return Period, $T$</th>
<th>PB</th>
<th>GT</th>
<th>CH</th>
<th>TG</th>
<th>TIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.60</td>
<td>0.52</td>
<td>0.39</td>
<td>0.37</td>
<td>0.33</td>
</tr>
<tr>
<td>5</td>
<td>0.94</td>
<td>0.73</td>
<td>0.51</td>
<td>0.50</td>
<td>0.48</td>
</tr>
<tr>
<td>10</td>
<td>1.17</td>
<td>0.87</td>
<td>0.59</td>
<td>0.59</td>
<td>0.58</td>
</tr>
<tr>
<td>50</td>
<td>1.68</td>
<td>1.19</td>
<td>0.76</td>
<td>0.79</td>
<td>0.80</td>
</tr>
<tr>
<td>100</td>
<td>2.11</td>
<td>1.32</td>
<td>0.84</td>
<td>0.88</td>
<td>0.89</td>
</tr>
<tr>
<td>200</td>
<td>2.23</td>
<td>1.45</td>
<td>0.91</td>
<td>0.96</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Not much could be said in the extreme event analysis through hydrodynamic simulation, as the storm surge effect has not been duly researched, and the design height is generally accepted as it is. This resulted in CH in Terengganu experienced Category I (C1) erosion, whilst GT, TG, and TIO which was located in Kelantan and Pahang are C2 erosion. The rate of erosion increased within 21 years from 0.3 - 4 km to 5 – 20 km (EPU 1985, DID 2006), as shown in Figure 7, and is still increasing. The increase rate is portrayed the severity of the coastal erosion along EPM, which is mostly sandy beaches, and will further exacerbate if immediate action is not taken by the respective agencies.
Figure 6. Reduced variate vs peak surge for station – PB, GT, CH, TG and TIO

Figure 7. Distribution of coastal erosion and erosion categories in PM (EPU 1985, DID 2006)
4. Conclusion

In this paper, the historical tide gauge records have been analysed, and an overview on the trends in MSL and storm surge in 27 years at stations along GoT and EPM has been provided. Both levels showed an upward and downward pattern over the years. Also, correlation of surge events between neighboring stations indicates a strong dependency probability which is expected. The computed projected surge levels in various return periods may significantly alter risk assessment related to high water levels and should be considered a relevant result for stakeholders and policy makers involved in coastal infrastructure and environmental protection decisions. Moreover, the possibility of surge increment in the next decades depends on the location and coastal shelves alterations (i.e. dredging and reclamation activities). In view of the current design approaches, the procedures are adequate under present-day conditions, but fail to account for future climate change in storm surge and MSL increment. There is a possibility that the design may be overly-conservative if flooding, high tides, and storm surge are all assumed to be coincidental. In practice, there is a slightly higher probability that they are associated, but the assumption of coincidence is generally too conservative and need to be proven through detail hydrodynamic simulation under various extreme climate conditions.

5. References


DID (2006). Coastal Erosion Inventory, Coastal Engineering Division, Department of Irrigation and Drainage Malaysia, Ministry of Natural Resources and Environment.


