HISTORICAL STORM SURGES AND STORM SURGE FORECASTING IN HONG KONG

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Situated on the coast of southern China facing the South China Sea, Hong Kong is vulnerable to sea flooding due to storm surge caused by approaching tropical cyclones. On average, about 6 to 7 tropical cyclones affect Hong Kong each year. Historically, the storm surges in 1906 and 1937 brought about great casualties. Statistical and dynamical methods have successively been used to forecast storm surges in Hong Kong over the past few decades. In 1994, the Hong Kong Observatory (HKO) adopted the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) storm surge numerical prediction model for operational use. To streamline the storm surge forecasting and warning workflow, SLOSH has recently been integrated with the interactive tropical cyclone graphic tool and the meteorological information dissemination system of HKO. This paper gives a brief account of the history of storm surges and storm surge forecasting in Hong Kong. In addition, the results of a verification of the accuracy of SLOSH based on tide gauge stations in 1994-2006 are also presented. With a root mean square error of 0.31 metre, SLOSH is providing useful operational guidance to forecasters.

Keywords: storm surge; SLOSH; Hong Kong Observatory

INTRODUCTION

With an average number of 6 to 7 tropical cyclones affecting Hong Kong each year, storm surge poses a threat to the local community from time to time and has caused severe damages historically in a number of occasions.

Low pressure and high winds associated with a tropical cyclone are the major cause of storm surge. The extent of the surge also depends on bathymetry and shape of the coastline. Coastal areas on the windward side of a tropical cyclone would invariably have higher surges while bag-shape bays provide more favourable conditions than channels for water to pile up. In Hong Kong, the Tolo Harbour over the northeast is more susceptible to high storm surges than the Victoria Harbour (Cheng, 1967). The various places in Hong Kong referenced in this paper are shown in Figure 1. Table 1 lists the top 20 storm surge events recorded at the Quarry Bay/North Point tide gauge station in the Victoria Harbour from 1947 to 2006. The

corresponding tropical cyclone tracks of the events listed in Table 1 are shown in Figure 2. The water level mentioned in this paper refers to the height above chart datum (CD) which is about 1.4 m below mean sea level.

HISTORICAL STORM SURGES

In the first half of the twentieth century, destructive storm surges were responsible for the heavy causalities in the two deadliest typhoon events in Hong Kong in 1906 and 1937. Over 10,000 people were killed in each incident (Ho, 2003). In the morning of 18 September 1906, the suddenly arrived gales and storm surges of the typhoon brought about a great deal of damage along the sea front in Hong Kong and resulted in heavy loss of life. The death toll of about 10,000 was a shockingly high figure for a small community of less than 450,000 people at that time. 90% of the fatalities were boat people who were drowned in the fury of the "huge waves" (Doberck, 1907; Li, 1976). For the Typhoon of 1937, the villages along the coast of Tolo Harbour were severely flooded by the storm surge of the typhoon. Thousands of lives were lost, mostly fishermen who were living in their boats. The high water mark in the area left by the typhoon was estimated to be about 6 metres above CD, which meant a surge of about 3.8 metres (Jefferies, 1937; Watts, 1959).

After the Second World War, Typhoon Wanda, which killed 183 people in 1962, claimed third place in the hierarchy of the deadliest typhoon in Hong Kong since 1884 (Ho, 2003, HKO, 1962). The storm surge brought by Wanda on 1 September 1962 inundated hundreds of hectares of farmland. Thousands of huts were destroyed or damaged by boats or logs crashing into them from the shore. The tide gauge at Tai Po Kau registered a maximum surge of about 3.2 metres.

In 1979, the visit of Typhoon Hope triggered substantial rise in sea level, causing widespread flooding in the New Territories. The tide gauge at Tai Po Kau recorded a maximum surge of about 3.2 metres (HKO, 1979).

The approach of Typhoon Utor on 6 July 2001 brought significant storm surges to Hong Kong. Both the tide gauges at Tsim Bei Tsui and Quarry Bay (previously North Point tide gauge) registered a maximum surge of about 1.1 metres. Coupled with the astronomical high tide, sea levels reached 3.4 metres at Quarry Bay in that morning. The reading was the highest sea level recorded in the Victoria Harbour since Typhoon Wanda in 1962 (4 metres). Storm surges caused severe flooding in numerous places in the northwestern New Territories. Some villagers sustained serious economic loss (HKO, 2002).

Over the past few decades, continuous improvement in tropical cyclone forecasting and warning services, building design of infrastructures and public awareness towards destructive typhoons in Hong Kong have greatly reduced the threat posed by tropical cyclones with respect to loss of lives. Figure 3 shows a plot of the total number of deaths and missing reported during tropical cyclone events in Hong Kong from 1960 to 2006. A clear declining trend in death toll can be observed.

STORM SURGE PREDICTION AND WARNING

For the destructive typhoons in 1906 and 1937 as well as Typhoon Wanda in 1962, a major cause of death is the abnormal rise in sea level due to storm surges which drowned a lot of people living along the coast. In view of the dire consequence of storm surges, the protection of the population and property from sea flooding through the provision of storm surge information is therefore an important activity of the Hong Kong Observatory (HKO).

(i)   Storm Surge Monitoring

Since the first automatic recording tide gauge installed in North Point in 1952, tide gauges have been successively installed in different places of Hong Kong for monitoring sea levels. Currently, HKO operates six tide gauges at locations shown in Figure 1. They provide information for tidal prediction, storm surge advisories, tsunami mornitoring and mean sea level analysis. In the early years, tidal predictions of daily high/low waters for Hong Kong were computed by the U.K. Institute of Oceanographic Sciences. In 1983, a computer program for the analysis and prediction of tides was acquired from the Institute of Ocean Sciences, Canada and subsequently modified for application in Hong Kong in 1986 (Cheng, 1987).

(ii)   Storm Surge Prediction

Prior to the formulation of numerical modelling, empirical regression equations (Cheng, 1967) and joint probability methods (Peterson, 1975) were used to estimate storm surge height and assess the risk of high water levels in Hong Kong in 1960s and 1970s. They are simple from the computation point of view but give no information on the time profile of the surge.

In 1979, an operational method was devised to compute the peak storm surge and the accompanying peak storm tide levels in the Victoria Harbour and Tolo Harbour during the approach of tropical cyclones (Lau, 1980a). It made use of nomograms derived from results of computer runs performed with NOAA's SPLASH (Special Program to List the Amplitude of Surge Heights) storm surge model for historical and hypothetical tropical cyclones (Jelesnianski, 1972). The sum of the forecast surge height and the predicted astronomical tide is given as the predicted water level. To support the engineering departments and consultants on the assessment of storm surge risk, HKO also carried out several investigations with the use of a single layer vertically integrated hydrodynamic bay model (Lau, 1980b, Chan, 1983).

In 1994, the "Sea, Lake and Overland Surges from Hurricanes" (SLOSH) which was developed by NOAA for real-time forecasting of hurricane storm surges replaced the SPLASH nomograms in forecasting storm surges in Hong Kong (Jelesnianski et al, 1992; Tam, 1996). SLOSH operates from grids of 1 kilometre in bays and near coasts and of

around 7 kilometre to the open sea. An in-house program has also been developed to combine the forecast storm surge from SLOSH with the predicted astronomical tide to obtain the forecast storm tide profile.

(iii)   Forecast Operation and Warning Services

To streamline the operation of storm surge forecasting and information dissemination, SLOSH has recently been integrated with the Tropical Cyclone Information Processing System (TIPS) developed by HKO (Figure 4).   TIPS is an interactive tropical cyclone graphic tool which provides a one-stop-shop platform for forecasters to handle tropical cyclone forecasting information and prepare forecasting tracks (Ng et al, 2003).   Tropical cyclone information and forecasts required for storm surge computation are automatically ingested into SLOSH via TIPS and the storm surge forecast outputs in both table and graphic forms are generated on-the-fly and disseminated to different users through the internet and the Meteorological Information Dissemination System (MINDS) of HKO.

Advice on storm surge is included in tropical cyclone warning bulletins if the forecast water level exceeds specific thresholds.   Moreover, to cater for the need of people living in some of the low-lying areas where are prone to flooding due to seawater backflow, the Drainage Services Department (DSD) of the Hong Kong Government launched a local flood message dissemination service for the concerned communities in 2006 (DSD, 2007).   To support this service, HKO provides DSD with the latest weather and warning information, real-time tidal observation, storm surge prediction and astronomical tidal prediction which are transmitted automatically to DSD via MINDS and the internet.   A Short Message Service (SMS) or voice message will be sent to residents and shop operators who have subscribed to the service to remind them to take precautionary measures against any flood damage when any one of the preset criteria is met.

SLOSH VERIFICATION RESULTS

The accuracy of the predictions from the SLOSH model is verified against the measured sea levels recorded at HKO tide gauge stations from 1994 to 2006 when the SLOSH model is put into operational use in Hong Kong.   The input parameters for SLOSH are based on the post-analysis tropical cyclone tracks prepared by HKO.   The SLOSH forecast error is defined as follows:

SLOSH forecast error = SLOSH storm surge – actual storm surge

The statistics of the verification is shown in Table 2.   In total, 99 cases were verified. The absolute mean error and root mean square error are 0.25 and 0.31 metre respectively.

The data are fit to a simple linear regression equation by the least square method (Figure 5) and the result is as follows :

$$y = 1.00\, x - 0.10$$

where x is the actual peak storm surge height in metre and y is the value forecast by SLOSH. The correlation coefficient between the two variables is 0.66 and is significant at the 1% level.

The error statistics show that SLOSH is capable of providing useful operational guidance for forecasters.

CONCLUSION

Since 1960s, empirical regression equations, SPLASH nomograms and SLOSH numerical storm surge model have been successively adopted by HKO for predicting storm surges during tropical cyclone scenarios. Recently, the SLOSH model has also been integrated with other tropical cyclone information processing and dissemination system to improve the forecasting and warning workflow. In 2006, a new flood watch service utilizing SMS and voice messages was introduced to alert special users living in low-lying areas against flood damages. The forecast verification using the storm surge data from 1994 to 2006 suggests that SLOSH is able to provide useful guidance for operational storm surge forecasting.

TABLE 1 – TOP 20 STORM SURGES RECORDED AT QUARRY BAY/NORTH POINT TIDE GAUGE STATION IN VICTORIA HARBOUR (1947-2006)

Year	Month	Day	Name of tropical cyclone	Maximum storm surge at Quarry Bay (m)
1962	9	1	Typhoon Wanda	1.77
1954	8	29	Typhoon Ida	1.68
1949	9	7	No name	1.49
1964	9	5	Typhoon Ruby	1.49
1979	8	2	Typhoon Hope	1.45
1957	9	22	Typhoon Gloria	1.34
1993	6	27	Typhoon Koryn	1.34
1964	8	8	Typhoon Ida	1.31
1974	10	12	Typhoon Bess	1.23
1989	7	17	Typhoon Gordon	1.20
1954	11	6	Typhoon Pamela	1.16
2001	7	6	Typhoon Utor	1.12
1960	6	8	Typhoon Mary	1.10
1968	8	21	Typhoon Shirley	1.09
2003	7	24	Typhoon Imbudo	1.02
1965	7	14	Typhoon Freda	1.01
1997	8	2	Typhoon Victor	1.01
1978	8	27	Severe Tropical Storm Elaine	0.99
1971	7	22	Typhoon Lucy	0.97
1964	5	28	Typhoon Viola	0.94

TABLE 2 – STATISTICS ON FORECAST ERRORS OF SLOSH STORM SURGE MODEL

Mean error	- 0.10 m
Absolute mean error	0.25 m
Standard deviation	0.30 m
Root mean square error	0.31 m
Maximum positive error	0.76 m
Maximum negative error	-0.72 m
No. of data	99
Regression equation **y: SLOSH forecast value** **x: Observed value**	$y = 1.00x - 0.10$
Correlation coefficient	0.66
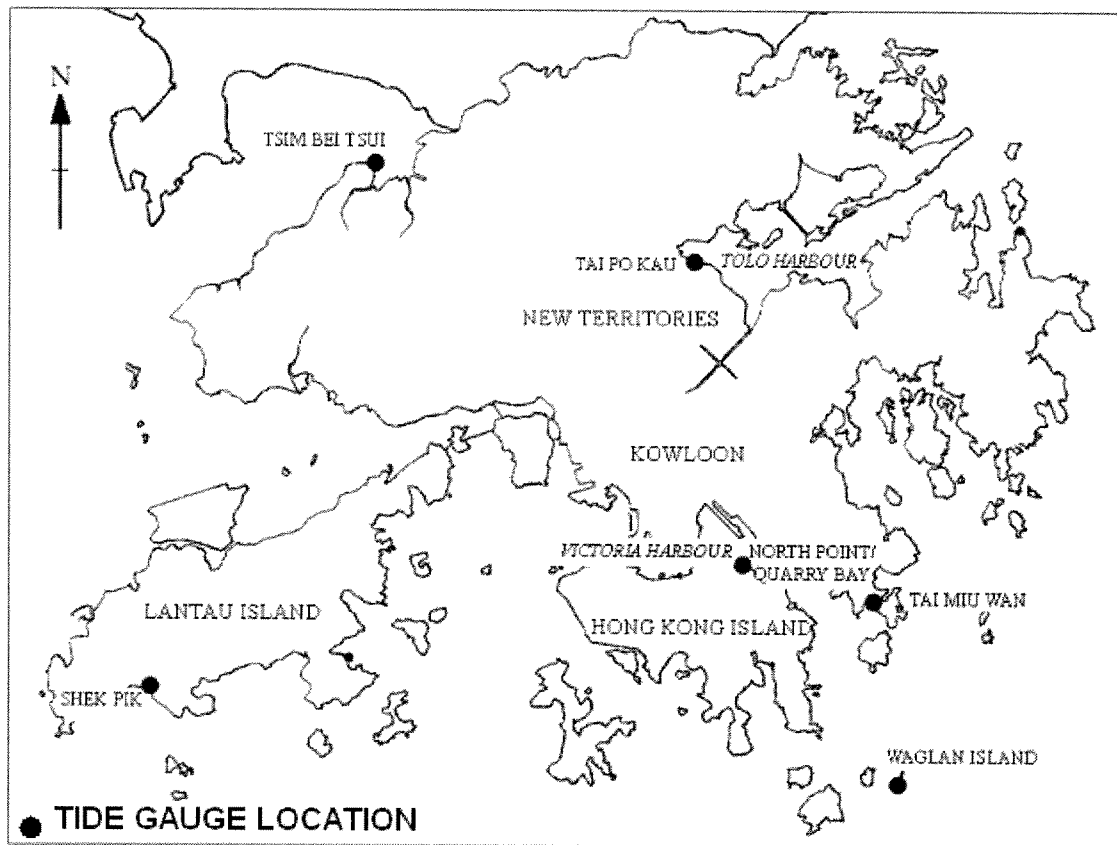
FIGURE 1 – LOCATION MAP FOR HONG KONG PLACES AND TIDE GAUGE STATIONS OPERATED BY THE HONG KONG OBSERVATORY
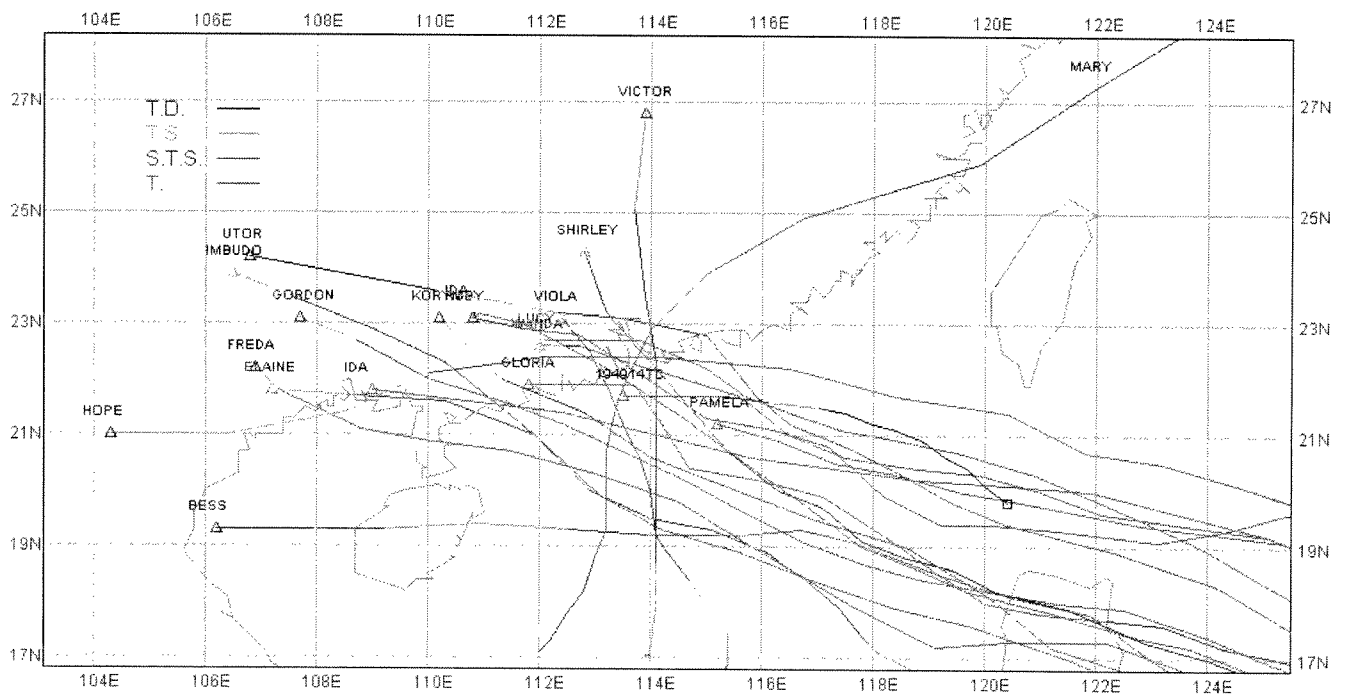

FIGURE 2 – TROPICAL CYCLONE TRACKS FOR THE TOP 20 STORM SURGE RECORDS AT QUARRY BAY/NORTH POINT TIDE GAUGE STATION (1947-2006)
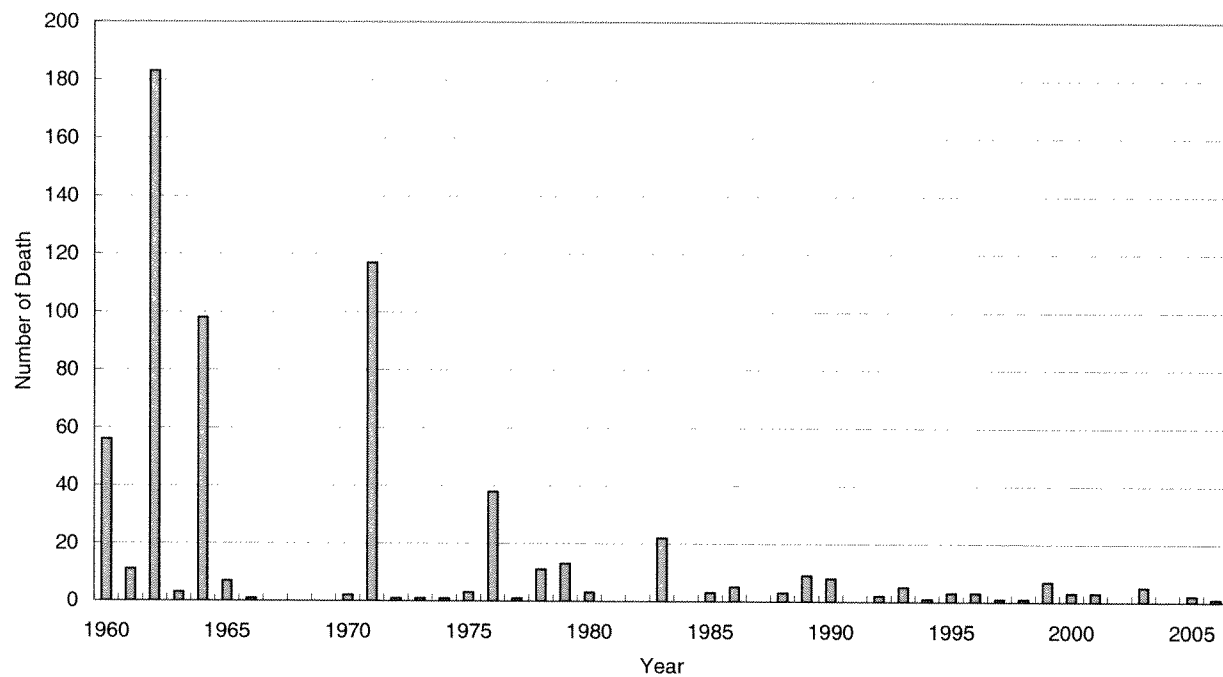
FIGURE 3 - DEATH TOLL (DEATHS AND MISSING) REPORTED DURING TROPICAL CYCLONE EVENTS IN HONG KONG FROM 1960 TO 2006
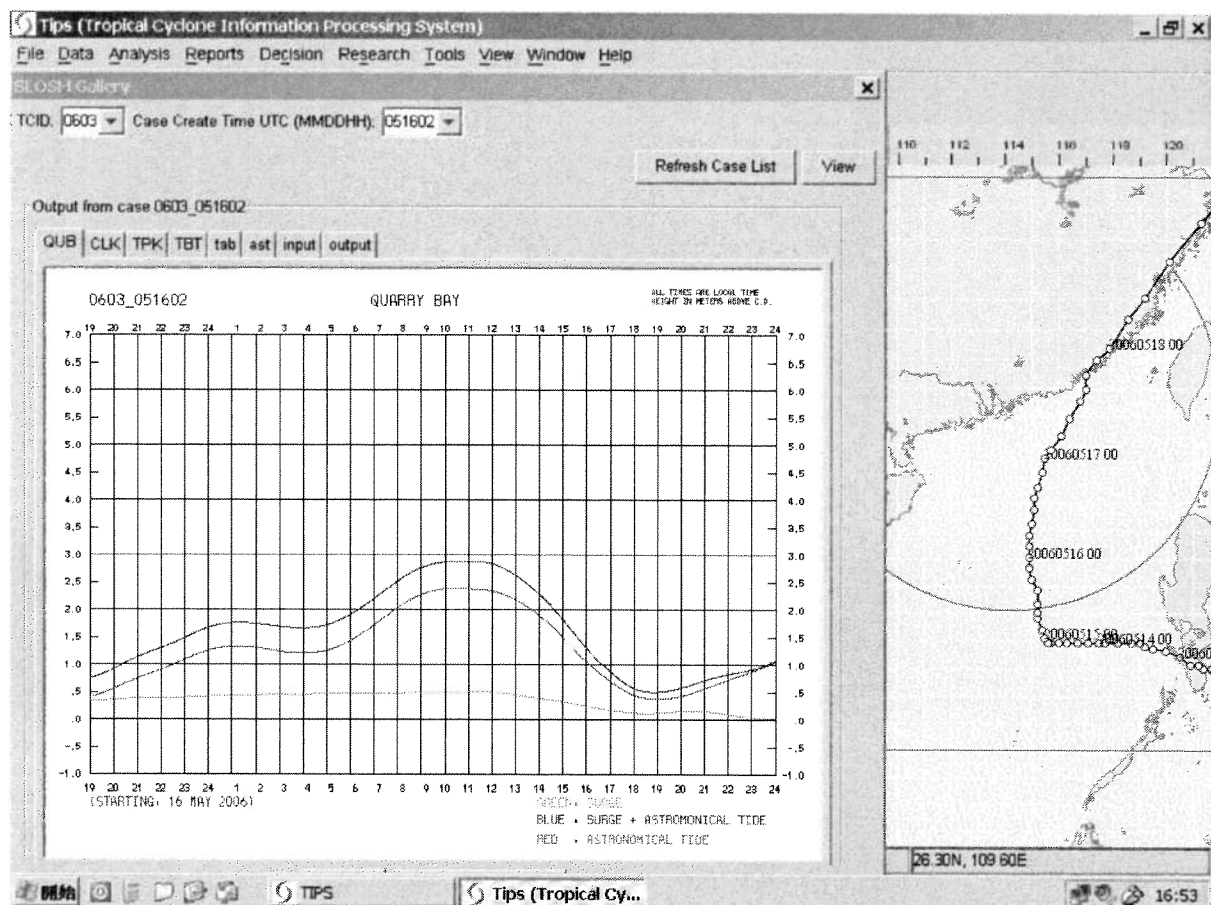
FIGURE 4 – A SCREEN CAPTURE SHOWING SLOSH GRAPHIC OUTPUTS INTEGRATED WITH THE TROPICAL CYCLONE INFORMATION PROCESSING SYSTEM (TIPS) DEVELOPED BY THE HONG KONG OBSERVATORY
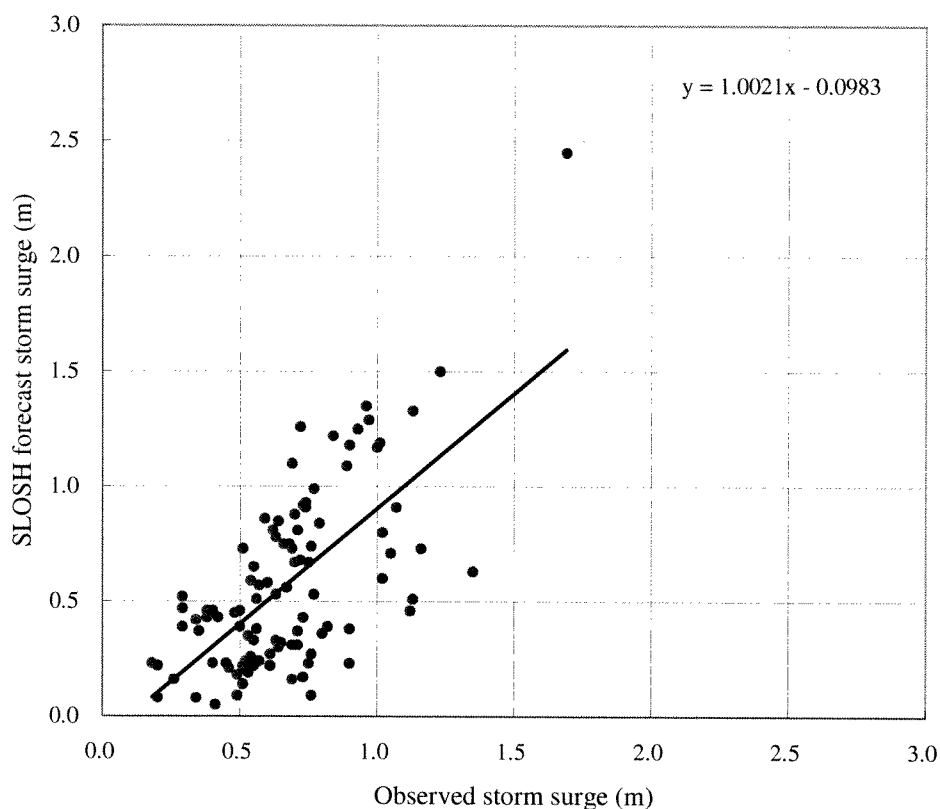
FIGURE 5 – REGRESSION EQUATION OF OBSERVED STORM SURGES AND SLOSH
FORECAST VALUES (1994-2006)

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