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STORM SURGE RISK IN HONG KONG ASSOCIATED WITH SUPER TYPHOON HATO (1713)

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STORM SURGE RISK IN HONG KONG ASSOCIATED WITH SUPER TYPHOON HATO (1713)

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Abstract

Super Typhoon Hato passed around 60 kilometres to the south-southwest of Hong Kong on the morning of 23 August 2017, bringing significant impact to Hong Kong in terms of storm surges and serious coastal flooding. There were general gales over the territory, with up to hurricane force winds over the southern part of the territory. The track taken by Hato was particularly conducive to the occurrence of significant storm surge. The peak surge induced by Hato occurred around the higher high water of the spring tide of the month, with the height of sea level at Quarry Bay inside the Victoria Harbour reaching 3.57 metres above Chart Datum, the highest recorded since Super Typhoon Wanda in 1962.

This paper discusses the application of the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model, the operational storm surge simulation model in use at the Hong Kong Observatory, in assessing the worst case scenario of storm surge in Hong Kong during the approach of Hato. The simulation results were found to be very sensitive to both the distance to Hong Kong at closest approach as well as the storm size. If Hato had taken a track slightly more to the north bringing it even closer to Hong Kong, the peak storm tide at Quarry Bay could reach 4 metres, exceeding that of Wanda in 1962. The paper also reviews the observed storm surge responses over different parts of Hong Kong during the passage of Hato and the implications on the provision of reliable forecast guidance for operating the localized storm surge alerts.

Keywords : Hato; storm surge; SLOSH

1. INTRODUCTION

Hong Kong, located on the coast of southern China, is vulnerable to coastal flooding due to storm surges associated with the passage of tropical cyclones over the northern part of the South China Sea. Historically, storm surges induced by typhoons in 1906, 1937 and Wanda in 1962 have brought severe casualties and damages to Hong Kong (Ng et al., 2014). Storm surges induced by Typhoon Hope in 1979 and Typhoon Hagupit in 2008, even though with no significant casualties, still brought severe flooding and damages to Hong Kong during their passages. Table 1 shows the records of major storm surges in Hong Kong.

Fig. 1 shows that typhoons bringing significant storm surges to Hong Kong follow similar tracks, viz. forming over the western North Pacific, then moving across the Luzon Strait without making landfall over the Philippines or Taiwan, and finally hitting Hong Kong or passing to the south with intensity reaching at least typhoon strength. Typhoons following such a track can gather strength rapidly over the ocean, bypassing major landmasses and generating violent onshore winds that can bring severe storm surges to Hong Kong.

Table 1. Records of major storm surges in Hong Kong.

Typhoon name	Year	Maximum storm surge at Victoria Harbour (above astronomical tide) (m)	Maximum storm tide at Victoria Harbour (above Chart Datum) (m)	Number of deaths
-	1906	1.83^	3.35^	~15,000*
-	1937	1.98^	4.05^	~11,000*
Wanda	1962	1.77	3.96	183
Hope	1979	1.45	2.78	12
Hagupit	2008	1.43	3.53	0
Hato	2017	1.18	3.57	0

* According to press reports.
^ Based on tide pole observations, field surveys or reports by local residents. The tide gauge network only started operation in 1952.

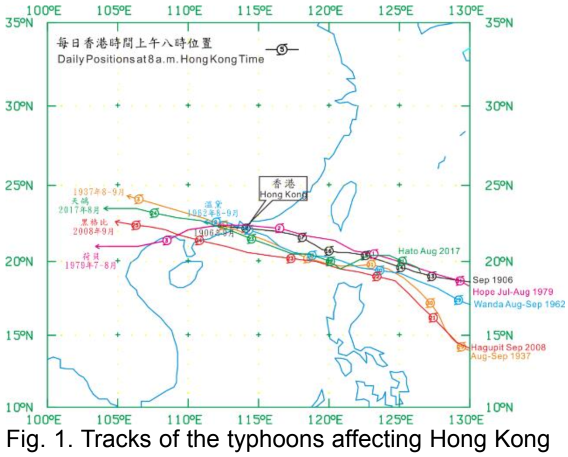

Fig. 1. Tracks of the typhoons affecting Hong Kong in 1906, 1937, Wanda in 1962, Hope in 1979, Hagupit in 2008 and Hato in 2017.

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Hato (1713) formed as a tropical depression over the western North Pacific about 740 km east-southeast of Gaoxiong of Taiwan on the night of 20 August 2017 (Hong Kong Observatory, 2017). After moving westwards across the Luzon Strait, Hato entered the South China Sea on 22 August, intensified into a typhoon and tracked west-northwest towards the south China coast. On the morning of 23 August, Hato intensified further into a super typhoon over the seas south of Hong Kong, reaching its peak intensity with an estimated sustained wind of 185 km/h near its centre. Hato finally made landfall over the coast near Macao shortly after midday.

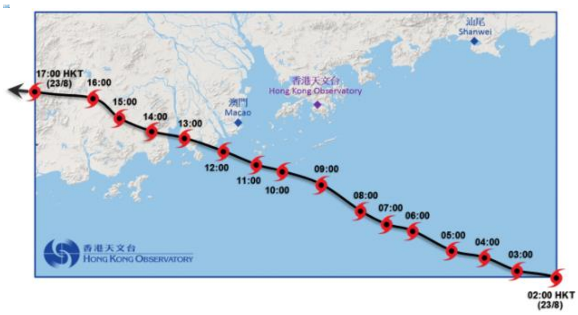

Fig. 2. Track of Super Typhoon Hato.

Hato took a track similar to other historical typhoons in Fig. 1 that brought significant storm surges to Hong Kong. It passed around 60 kilometres to the south-southwest of Hong Kong on the morning of 23 August (Fig. 2). In addition to a rise of sea level due to the low pressure near Hato's centre, the hurricane-force southeasterly winds blowing over the sea surface piled up the sea water along the coastal waters of Hong Kong. Moreover, it was also the spring tide of the month that day with the highest astronomical tide of 2.39 m at 10:17 HKT (8 hours ahead of UTC) at the tide gauge location in Quarry Bay inside the Victoria Harbour, and 2.44 m at 11:00 HKT at Tai Po Kau over the northeastern part of Hong Kong (Fig. 3). As the peak storm surge brought by Hato occurred around the time of the highest astronomical tide, the aggregated effect resulted in the inundation of many low-lying areas in Hong Kong. The water level in Hong Kong rose generally by one to two metres, reaching a maximum of 3.57 m (above Chart Datum, same for all references to tide level hereafter) at Quarry Bay, the second highest since instrumental records began in 1954 and only lower than the record of 3.96 m set by Super Typhoon Wanda in 1962. It was even higher at Tsim Bei Tsui over the northwestern part of Hong Kong where a maximum water level of 4.56 m was recorded, the highest since records began in 1974. Table 2 lists the peak storm tide and storm surge recorded by the six tide gauge stations operated by the Hong Kong Observatory (HKO) during the passage of Hato.

Fig. 3. Locations of the tide gauge stations in Hong Kong.

Table 2. Recoded peak storm tide and peak storm surge during the passage of Super Typhoon Hato on 23 Aug 2017.

Station	Peak storm tide above Chart Datum (m)	Peak storm surge above astronomical tide (m)
Quarry Bay	3.57	1.18
Shek Pik	3.91	1.54
Tai Miu Wan*	3.14	1.05
Tai Po Kau	4.09	1.65
Tsim Bei Tsui	4.56	2.42
Waglan Island*	2.97	0.76

* Derived from incomplete data.

Despite the improvement in the accuracy of numerical weather prediction models bringing a substantial improvement in the tropical cyclone track forecasts over the years, there still exist considerable uncertainties in the forecast positions of tropical cyclones even within the next 24 hours. Fig. 4 shows that the T+24h forecast position error of HKO was about 64 km in 2016. With Hato passing about 60 km to the south-southwest of Hong Kong and considering the forecast uncertainties mentioned above, an even closer encounter with Hato could have led to very different storm surge scenarios in Hong Kong.

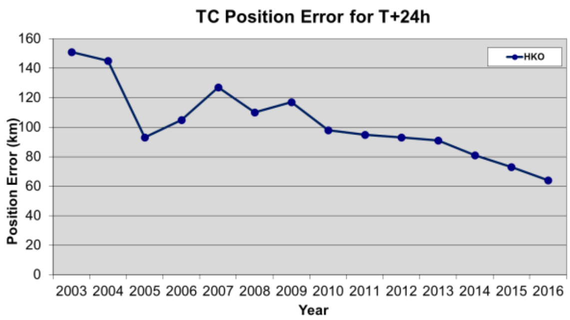

Fig. 4. Tropical cyclone position error of HKO for T+24h from 2003 to 2016.

This study examines the application of the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model (Jelesnianski, 1992), the operational storm surge simulation model in use at HKO, in assessing the worst case scenario of storm surge in Hong Kong during the approach of Hato, based on the forecast uncertainties in the track of Hato 24 hours before its closest approach to Hong Kong and assuming no change in cyclone intensity.

Among the six tide gauge stations operated by HKO (Fig. 3), the station at Quarry Bay (QUB) measures the sea level inside the Victoria Harbour, where the most populated regions of Hong Kong are located on both sides. Another tide gauge station at Tai Po Kau (TPK) has been monitoring the sea level inside the Tolo Harbour for over 50 years. Historically, the Tolo Harbour is most susceptible to storm surges pushed on by the northeasterly winds during the approach of tropical cyclones and is one of the flood prone areas in Hong Kong due to its unique geographical location and bathymetry. This study mainly focuses on the storm surges recorded at QUB and TPK.

2. Storm surge simulation for Hato using SLOSH

The SLOSH storm surge model, developed by the National Oceanic and Atmospheric Administration (NOAA) of USA, has been used by HKO to support its tropical cyclone warning operation since 1994. The model operates on a polar grid, with a grid size ranging from 1 km near the centre around Hong Kong increasing to about 7 km in the open sea. SLOSH is a parametric storm surge model, with input parameters including 6-hourly positions of the tropical cyclones and the corresponding values of central minimum pressure and storm size from 48 hours before to 24 hours after the time of closest approach to Hong Kong. The storm size is defined as the distance from the centre of a tropical cyclone to the location of the storm's maximum winds. In a well-developed tropical cyclone, the radius of maximum winds is generally found near the eyewall.

Table 3. Input parameters used for storm surge simulation of Hato.

Date	Time (UTC)	Intensity category	Estimated minimum central pressure (hPa)	Lat. (N)	Lon. (E)	Storm size (km)
21/8	03	TS	994	20.1	124.8	31
	09	TS	994	20.4	123.8	31
	15	TS	990	20.3	122.3	37
	21	TS	988	19.7	120.7	37
22/8	03	STS	982	20.2	119.4	36
	09	T	975	20.5	117.8	27
	15	T	965	20.8	116.6	37
	21	T	965	21.2	115.2	32
23/8	03	SuperT	950	21.85	113.7	24
	09	T	970	22.4	112.0	37
	15	TS	988	22.8	109.9	42
	21	TS	994	23.1	107.6	61
24/8	03	TS	996	23.4	107.0	61

TS: Tropical storm
STS: Severe tropical storm
T: Typhoon
SuperT: Super typhoon

In this study, the 6-hourly positions and values of the central minimum pressure of Hato were adopted from the provisional best track of HKO from 03 UTC on 21 August 2017 to 03 UTC on 24 August 2017 as tabulated in Table 3. As storm size information was not directly available from the best track dataset, the storm sizes of Hato, except for 03 UTC on 23 August 2017 during the closest approach, were determined based on the maximum winds near the storm centre and the gale radius using the empirical formula defined in SLOSH.

Around the time of closest approach to Hong Kong and just before landfall, Hato developed briefly into a super typhoon with a clear eye shown on both satellite and radar imageries. The storm size could be more accurately estimated based on the wind observations recorded by land or island stations nearby. Fig. 5 shows the radar picture at 11:00 HKT when the inland station of Huangmao Zhou (HMZ) was located near the eastern inner edge of Hato's eyewall and experiencing the strongest winds associated with the storm. The storm size of Hato was thus estimated to be around 24 km at 03 UTC on 23 August 2017.

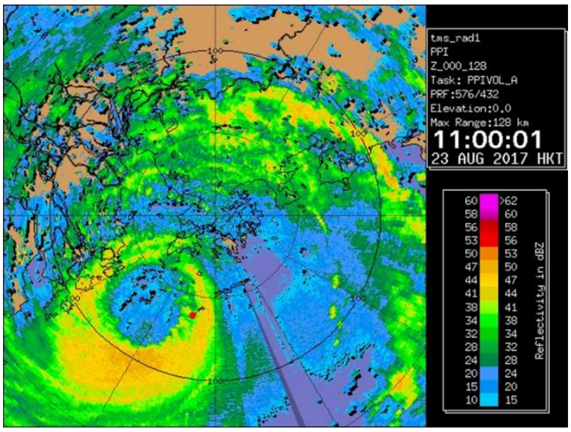

Fig. 5. Huangmao Zhou (red dot) was near the eastern inner edge of eyewall of Hato at 11:00 HKT on 23 August 2017.

3. Performance of storm surge model

According to the SLOSH simulation results, a peak storm surge of 1.37 m, about 0.29 m higher than the observed value, would occur at 12:10 HKT on 23 August at QUB. As the predicted peak storm surge occurred later than observed and did not coincide with the occurrence of the astronomical high tide earlier on at 10:17 HKT, the predicted peak storm tide was 3.53 m, slightly lower than the observed value. At TPK, a peak storm surge of 1.62 m, about 0.03 m lower than the observed value, would occur at 11:20 HKT on 23 August. The predicted peak storm surge occurred coincidently with the astronomical high tide at 11:00 HKT, and the predicted peak storm tide was 4.04 m, about 0.05 m lower than the observed value. The time series of the predicted storm surge and storm tide at QUB and TPK are given in Figures 6 and 7, and Table 4 compares the predicted and actual peak storm surge and storm tide at the two stations and at Waglan Island (WGL), an offshore island to the southeast of Hong Kong (see Fig. 3). The prediction results generally agreed with the observed values, suggesting that SLOSH was able to predict reasonably well the storm surge impact to Hong Kong induced by Hato.

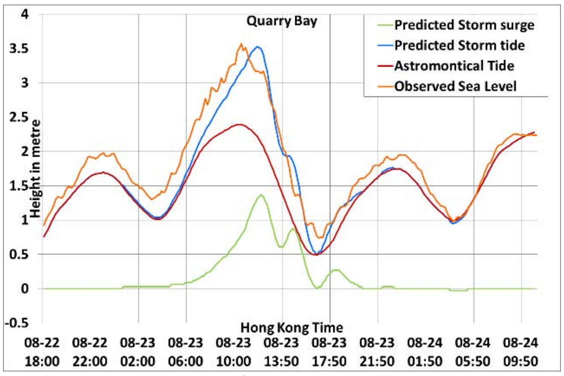

Fig. 6. Time series of predicted storm surge and storm tide, along with observed sea level and astronomical tide at Quarry Bay during the passage of Hato.

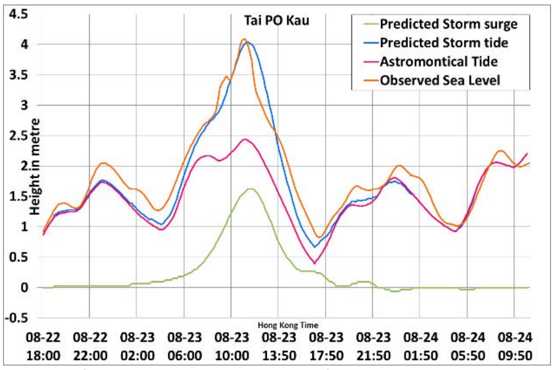

Fig. 7. Same as Fig.6, except for Tai Po Kau.

Table 4. Predicted and actual peak storm tide and storm surge.

Station	Predicted peak storm tide (m)	Actual maximum sea level (m)	Predicted peak storm surge (m)	Actual storm surge (m)
Quarry Bay	3.53	3.57	1.37	1.18
Tai Po Kau	4.04	4.09	1.62	1.65
Waglan Island*	3.56	2.97	1.10	0.76

* Derived from incomplete data.

Since SLOSH is a parametric storm surge model, a reliable representation of the storm wind field is essential for accurate prediction of storm surge. To verify the wind field generated from the input parameters for Hato, the output wind field was checked against actual observations. Fig. 8 to Fig. 10 show the time series of the generated wind speed and direction at QUB, TPK and Waglan Island. The observed wind speed at QUB and TPK were generally smaller than the simulated values generated by SLOSH. However, the simulated wind speed at WGL was in close agreement with the observed values. This can be explained by the fact that WGL is an outlying island in a more exposed environment, whereas QUB and TPK are located within the urban areas with a more sheltered environment. Similar agreement between the generated wind field and actual observations was also found for another outlying island Cheung Chau (time series omitted). As such, the input parameters used in the SLOSH simulation in this study were considered to be generally adequate.

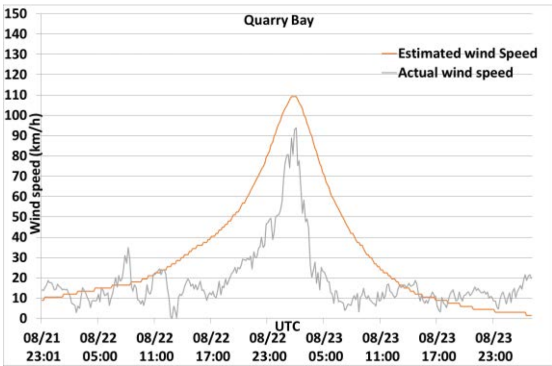

Fig. 8. Estimated wind speed compared with actual wind speed at Quarry Bay.

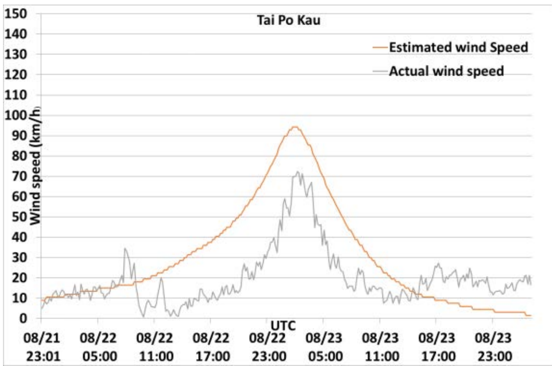

Fig. 9. Same as Fig. 8, except for Tai Po Kau.

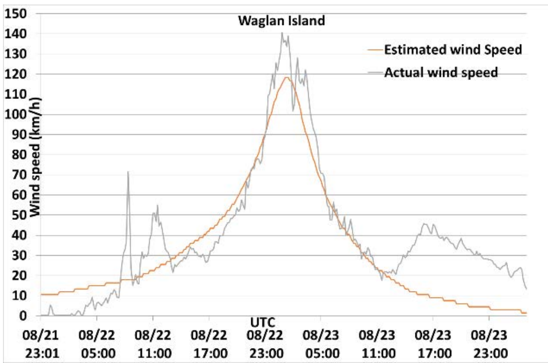

Fig. 10. Same as Fig. 8, except for Waglan Island.

4. Potential Storm Surge Risk brought by Hato

The distance of closest approach to Hong Kong and the storm size are the two major uncertainties in forecasting storm surges. Sensitivity tests of these two parameters were conducted to assess the potential storm surge risk of Hato. For this purpose, a number of hypothetical tracks of Hato were constructed to simulate different storm surge scenarios. Considering that the time of closest approach of Hato was around 10 HKT on 23 August, the hypothetical tracks were constructed starting from the position at 11 HKT the day before, and passing through each forecast position at T+24h (valid at 11 HKT on 23 August) with resolution of 0.1 degree in latitude and longitude within an area of uncertainty circle with a radius of 64 km, i.e. HKO's T+24h forecast position error in 2016. Fig. 11 shows a total of 128 hypothetical tracks thus generated. In constructing these hypothetical tracks, no perturbations were applied to the intensity or storm size and their values were taken to be the same as those given in Table 3.

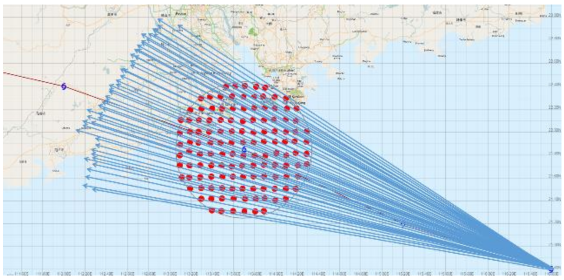

Fig. 11. Hypothetical tracks passing through an area of forecast uncertainty.

Figures 12 and 13 plot the predicted peak storm surge and storm tide at QUB against the distance of closest approach of each hypothetical track. The predicted storm surge could reach 2 m or above when the distance of closest approach was between 12 km and 38 km. A maximum of 2.23 m would even be reached at the closest approach of 34 km. On the other hand, if Hato moved further away from Hong Kong with a closest approach of 120 km, the storm surge would be reduced to 0.73 m. There was a rate of +2.5 cm in storm surge per kilometre for closest approach distance less than 65 km; the rate of change would decrease to +1.1 cm per kilometre for closest approach distance greater than 65 km.

As shown in Fig. 13, the storm tide at QUB would be over 4 m when the closest approach distance was between 3 km and 52 km and could even reach a maximum of 4.53 m at 23 km. It also shows that the variation of storm tide could be rather large for the same closest approach distance. The maximum variation of storm tide was found to be 1.34 m at the closest approach of 34 km and the corresponding storm tide could vary from 3.15 m to 4.49 m. Since the storm tide should reflect a combined effect of the storm surge and astronomical tide, the storm tide would be smaller if the storm surge did not coincide with the astronomical high tide. The rate of change in storm tide was found to be +2.2 cm per kilometre for closest approach distance less than 65 km, and +0.6 cm per kilometre for closest approach distance greater than 65 km.

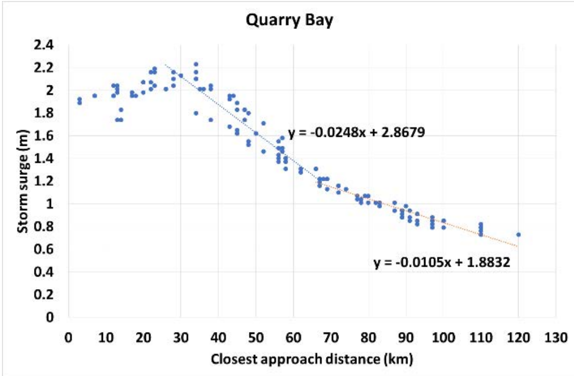

Fig. 12. Heights of storm surge at Quarry Bay for different closest approach distances.

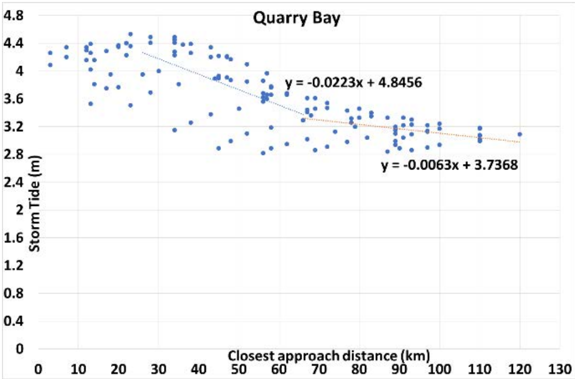

Fig. 13. Heights of storm tide at Quarry Bay for different closest approach distances.

As shown in Fig. 14, the storm surge at TPK would be over 2 m when the closest approach was between 3 km and 57 km with a maximum of 3.93 m at 12 km. If Hato moved further away from Hong Kong with a closest approach of 120 km, the storm surge would be reduced to 0.91 m. There was a rate of +4.2 cm in storm surge per kilometre for closest approach distance less than 65 km and the rate would decrease to +1.4 cm per kilometre for closest approach distance greater than 65 km. As shown in Fig. 15, the storm tide at TPK would reach 4 m or above when the closest approach distance was less than 66 km. It could even exceed 6 m when the closest approach was between 3 km and 18 km with a maximum value of 6.28 m at 12 km. The maximum variation of storm tide at the same closest approach distance was 1.06 m at 34 km, and the corresponding storm tide could vary from 4.34 m to 5.4 m depending on the timing of the astronomical high tide. There was a rate of change of +4.3 cm in storm tide per kilometre for closest approach distance less than 65 km, and the rate would decrease to +1.3 cm per kilometre for closest approach distance greater than 65 km.

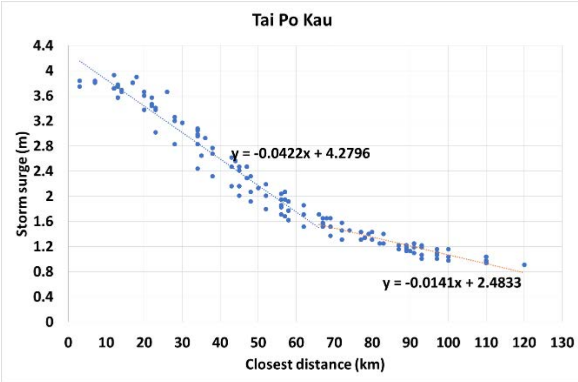

Fig. 14. Same as Fig. 12, except for Tai Po Kau.

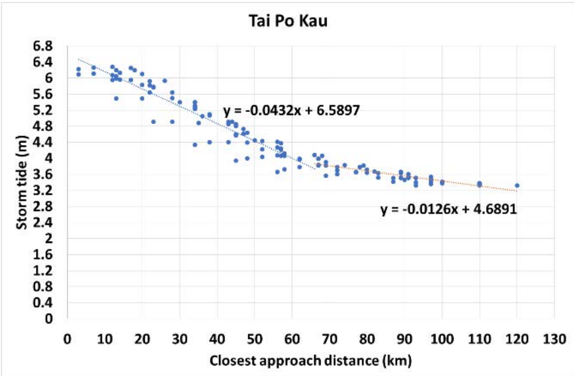

Fig. 15. Same as Fig. 13, except for Tai Po Kau.

The predicted storm surge at QUB corresponding to each storm position at 11 HKT on 23 August 2017 of the hypothetical tracks are plotted in Fig. 16. If Hato had moved about 25 km closer, the storm surge would be over 2 m at QUB and the corresponding storm tide would exceed 4 m (Fig. 17). At TPK, the storm surge and storm tide would be over 3.2 m and 5.6 m respectively (Figures 18 and 19). The worst case scenario would be if Hato had taken a track crossing Hong Kong Island and northern Lantau (see Fig. 3). The storm surge could then exceed 3.6 m and the storm tide over 6 m.

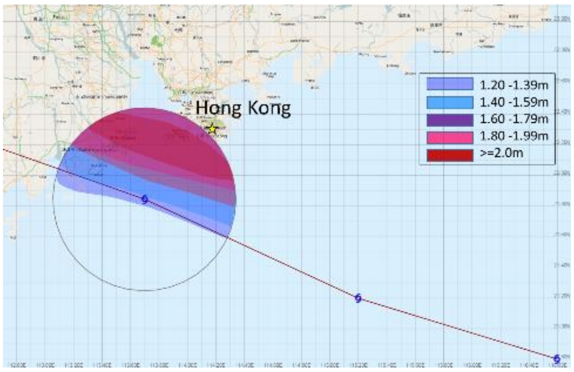

Fig. 16. Contour plot of predicted peak storm surge at Quarry Bay corresponding to each storm position at 11 HKT on 23 August 2017 of the hypothetical tracks. The red line indicates the actual track of Hato.

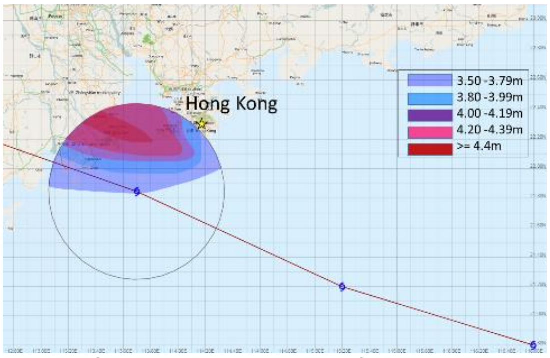

Fig. 17. Same as Fig. 16, except for predicted peak storm tide at Quarry Bay.

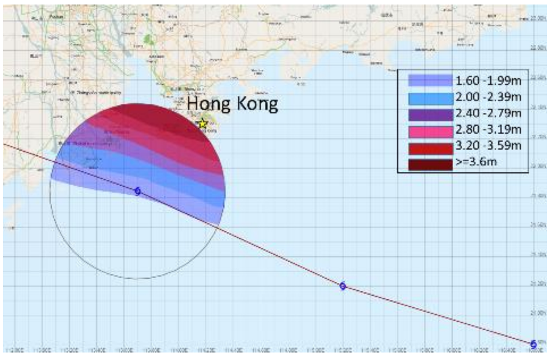

Fig. 18. Same as Fig. 16, except for predicted peak storm surge at Tai Po Kau.

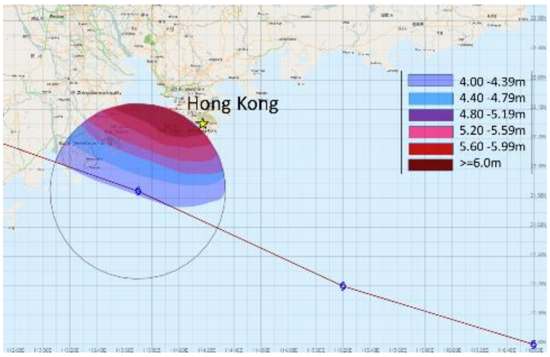

Fig. 19. Same as Fig. 16, except for predicted peak storm tide at Tai Po Kau.

Sensitivity tests were also conducted to evaluate how the storm size would affect the storm surge heights in Hong Kong. As shown in Figures 20 and 21, both the storm surge and storm tide at QUB and TPK would increase with the storm size. For QUB, the predicted storm surge and storm tide would increase at a rate of 4.8 cm and 4.4 cm per kilometre increase in storm size respectively for storm size less than 40 km. The rate would be reduced to 0.4 cm and 0.7 cm respectively for storm size larger than 40 km. The height of storm surge and storm tide would fall when the storm size was greater than 70 km. For TPK, the predicted storm surge and storm tide would increase at a rate of 4.8 cm and 4.4 cm per kilometre increase in storm size respectively for storm size less than 55 km. The rate would be reduced to 2.0 cm and 2.3 cm respectively for storm size greater than 55 km.

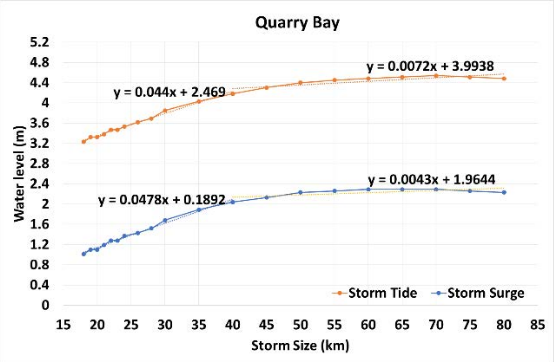

Fig. 20. Predicted storm surge and storm tide under different storm sizes at Quarry Bay.

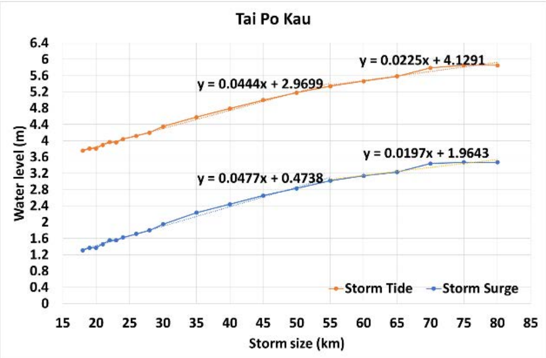

Fig. 21. Same as Fig. 20, except for Tai Po Kau.

5. Discussion and Conclusion

Based on the provisional best track of HKO for Super Typhoon Hato, SLOSH performed reasonably well in reproducing the extreme sea levels at selected strategic locations in Hong Kong during the closest approach of the storm.

Given the forecast uncertainties, the potential storm surge risk in Hong Kong as assessed using SLOSH one day before closest approach was also evaluated. The results suggested that the predicted heights of storm surge would be very sensitive to the closest approach distance and the storm size.

The predicted storm surge induced by Hato could vary from 0.73 m to 2.23 m at QUB (actual value 1.18 m) and 0.91 m to 3.93 m at TPK (actual value 1.65 m). This indicates that the forecast error could range from 38% to 89% for QUB and 45% to 138% for TPK. For the storm tide, the predicted values could vary from 2.74 m to 4.53 m at QUB (actual value 3.57 m) and 3.32 m to 6.28 m at TPK (actual value 4.09 m), equivalent to a forecast error ranging from 23% to 27% for QUB and 19% to 54% for TPK. With respect to the closest approach distance, the storm surge and storm tide predictions were found to be more sensitive at TPK than at QUB. Maximum storm tides of 4.53 m and 6.28 m could occur inside the Victoria Harbour (QUB) and the Tolo Harbour (TPK) in the worst case scenarios, surpassing the severity of storm surge induced by Typhoon Wanda in 1962 and the typhoon in 1937.

At HKO, a default storm size of 56 km is normally adopted in operation for tropical cyclones over the oceans far away from Hong Kong where observations are sparse. However, if this default storm size had been used in the case of Hato, the predicted storm surge and storm tide would be grossly over-estimated. The predictions would be particularly sensitive to a storm size smaller than 40 km for QUB and 55 km for TBK. Such sensitivity would gradually decrease and level off as the storm size increased. The location of peak storm surge height would be near the radius of maximum winds of the storm.

For tropical cyclones passing in the vicinity of Hong Kong like Hato, the accuracy of storm surge prediction based on one single operational track would be subject to forecast uncertainties and the extent of impact to Hong Kong could be quite different, depending on the distance of closest approach, the storm size, as well as the translation speed of the storm which would affect whether the timing of peak storm surge would coincide with the astronomical high tide. Alternative tracks constructed based on forecast uncertainties should therefore be taken into account in the formulation of warnings or advisory messages. A probabilistic approach should be further developed so that the general public and stakeholders can take early and appropriate precautionary measures against the range of possible alternative scenarios in consideration of their own risk profiles.

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