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ROYAL OBSERVATORY, HONG KONG

TECHNICAL NOTE NO. 26

STORM SURGES IN HONG KONG

BY

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C O N T E N T S

INTRODUCTION

Storm surges are some of the most destructive natural calamities. Harris [1] has stated that "more than half of the fatalities in hurricanes and other tropical storms have been drownings either in floods from excessive rainfall or in tidal waves coming in from the sea", and that "a large fraction of the property loss has been due to the same causes".

Several tropical cyclones that have affected Hong Kong have generated disastrous storm surges, two of the best known occurring on September 2, 1937 and on September 1, 1962 (Typhoon Wanda). The former destroyed several villages around Tolo Harbour [2] while the latter claimed 127 lives and damaged or destroyed 3,000 huts in addition to wrecking numerous fishing boats and inundating hundreds of acres of farm land with sea water. [3]

The present trend towards the development of new residential and industrial areas on reclaimed land greatly increases the potential dangers from flooding by storm surges. Therefore, it follows that storm surge forecasts should occupy an important role in the Colony Tropical Cyclone Warning Service.

DEFINITION OF STORM SURGE

A storm surge is defined as the difference between the observed water level and that which would have occurred at the same place and time in the absence of the storm.

CAUSES OF STORM SURGE

Storm surges are generated by the following factors:-

(i) The Pressure Effect

In accordance with the laws of hydrostatics, the water level in the ocean will rise in regions of low atmospheric pressure and fall in regions of high pressure so that the total pressure remains constant. This is also known as the inverted barometer effect and one millibar of pressure difference causes a difference of approximately one centimetre in sea level.

The above equilibrium can be achieved only under the following conditions: -

(a) There are no rapid changes in the intensity of the atmospheric pressure system,

(b) the pressure systems are not moving, and

(c) the ocean is sufficiently deep and large so that there will be no restriction to the flow of water in attaining equilibrium.

Proudman[4] showed that a pressure disturbance travelling along a uniform channel of depth h would cause a wave of amplitude ζ given by the following equation: -

$$\zeta = \frac{\bar{\zeta}}{1 - \frac{u^2}{gh}} \qquad \text{..............(1)}$$

where $\bar{\zeta}$ is the equilibrium surface elevation when u = 0, and

g is the acceleration due to gravity.

Harris[5] modified the equation to obtain the effects of a disturbance moving over a large expanse of water but his expression still contains the term $\left(1 - \frac{u^2}{gh}\right)$ in the denominator. This means that when the pressure disturbance moves at the speed of the long wave (i.e. when $u^2 = gh$), resonance will occur and a very large storm surge will be generated.

Resonance does not occur over deep seas because h is so large there that the term $\frac{u^2}{gh}$ will be very small. It is over shallower waters that the term $\left(1 - \frac{u^2}{gh}\right)$ approaches zero.

Over the continental shelf off the South China coast, tropical storms have to move at speeds well above 40 knots before resonance can occur. As tropical storms in the South China Sea seldom move at speeds above 20-25 knots, the risk of a gigantic storm surge due to resonance is very small indeed. However it should be noted that fast moving storms bring bigger surges than slow moving ones.

(ii) The Effect of Wind Stress

The intensity of the frictional stress produced by winds blowing over a water surface depends on the wind speed and the roughness of the sea surface. The roughness of the sea surface is itself a function of the wind speed. It is generally accepted that wind stress can be expressed in the form: -

$$\tau_s = \rho_A \; K \; V^2 \qquad \text{........................(2)}$$

where τ_s = surface shear stress
ρ_A = density of the air
K = a constant
V = wind speed.

Over shallow waters this wind stress generates a current the direction of which is almost parallel to the wind. Any obstruction to the flow of this current will cause the water to become "piled up". Consequently the coastal sea level will tend to rise with onshore winds and fall with off-shore winds.

(iii) The Effect of the Earth's Rotation

As stated in (ii) above, winds over shallow waters generate a current parallel to the wind direction. Due to the geostrophic effect, any current in the northern hemisphere will have an acceleration directed towards the right of its course. A consequence of this geostrophic effect is that tropical storms that bring winds with a strong easterly component to Hong Kong should produce bigger surges.

Tropical storms that have crossed the coast to the east of Hong Kong have never brought any big surges to the Colony whereas severe surges in Hong Kong have invariably been caused by storms that have passed over or to the south of Hong Kong. This is because storms on the coast to the east of Hong Kong cause northwesterly winds whereas those to the west cause southeasterlies.

(iv) The Effect of Waves

Waves approaching shallower waters tend to break and this tendency increases as the depth of the water into which the wave is advancing decreases. The water from waves that break may have sufficient momentum to run a considerable distance up a sloping beach and affect areas which are much higher than the average sea level.

(v) The Rainfall Effect

Tropical storms are usually accompanied by torrential rainfall and run-off will cause a significant increase in the water level if it is directed into an almost enclosed bay or into a lake.

(vi) The Resonance Effect

Every body of water has its own periods of free oscillation. If a storm surge causes a disturbance with a period approaching that of the free oscillation, the intensity of the surge will be enchanced.

During Typhoon Wanda of 1961, the tide gauge at Tai Po Kau recorded a series of maxima at intervals of approximately $3\frac{3}{4}$ hours. Examination of tide records from the same station shows that oscillations of similar periods were common when the Tolo Harbour was affected by storm surges.

(vii) The Effect of the Shape of Shore Lines

If an estuary or bay has a wide and deep mouth but becomes progressively narrower towards its head, the effect of convergence as a storm surge propagates further upstream may amplify the surge several times.

Moreover, if the head of the estuary or bay is also the leeward end, the piling up of water due to wind stress may render the surge even more intense.

These effects probably explain why Tai Po and Sha Tin (Fig. 1) are so vulnerable to storm surges.

STORM SURGE DATA

Watts(6) found that the tides recorded at the North Point Tide Station (Fig. 1) were representative of the tides in the Hong Kong Harbour. Consequently storm surges obtained by analyzing the tide records from this station may be taken to be representative of conditions in the Harbour during storms.

To obtain storm surges from the tide records, a sine curve is fitted between the predicted high and low tides and the difference between this curve and the actual record is taken as the storm surge. Figure II illustrates how the storm surge associated with Typhoon Ida was obtained.

Table I lists in chronological order the storm surges recorded by the North Point Tide Gauge in the period 1954 - 1964.

After the North Point recording tide gauge was installed late in 1952, it had to be reset from time to time to make allowance for the settling of the sea-wall. Watts(7) found that a correction of -0.6 feet should be applied to all records during the period October 24, 1952 to September 12, 1956. The surges in Table I for the period 1954 to September 12, 1956 have been adjusted accordingly. Since no major resetting was necessary after September 12, 1956, no correction was applied to surges after this date.

Another recording tide-gauge was installed at Tai Po Kau (Fig. 1) in 1961 and the storms surges recorded at this station are tabulated in Table II.

CORRELATION OF STORM SURGES WITH VARIOUS METEOROLOGICAL PARAMETERS

It is seen from the discussion given in the previous sections that the various forces which bring about a storm surge are complex and a forecast of each one in order to obtain the total effect is impossible at present. In order to provide guidance for forecasting storm surges, the surge of 1936 and those of 1954 - 1964 were correlated with certain meteorological parameters as measured at the Royal Observatory, namely, the maximum gust, the maximum 10-minute mean wind, the maximum 60-minute mean wind and the minimum sea level pressure and the following regression equations were obtained:-

(i) $S = 0.045\,G - 0.43$ ....(3)

coefficient of correlation = 0.85

where S = storm surge in feet, and

G = maximum gust in knots recorded by the Royal Observatory Dine's Anemometer.

(see Fig. III)

(ii) $S = 0.087W_{10} - 0.61$ ....(4)

coefficient of correlation = 0.88

where S = storm surge in feet, and

W_{10} = maximum 10-minute mean wind in knots recorded by the Royal Observatory Dine's Anemometer.

(see Fig. IV)

(iii) $S = 0.089W_{60} - 0.45$ ....(5)

coefficient of correlation = 0.88

where S = storm surge in feet, and

W_{60} = maximum 60-minute mean wind in knots recorded by the Royal Observatory Dine's Anemometer.

(see Fig. V)

(iv) $S = -0.085P + 87.16$ ....(6)

coefficient of correlation = -0.73

where S = storm surge in feet, and

P = instantaneous minimum sea level pressure in millibars recorded at the Royal Observatory.

(see Fig. VI)

Surges caused by storms that landed to the east of Hong Kong were not used to compute the regression equations but they are plotted on the respective scatter diagrams. Surges associated with a minimum sea level pressure higher than 1005 millibars were not used in obtaining Equation (6).

PROPOSED PROCEDURE FOR FORECASTING STORMRSU GES IN THE HONG KONG HARBOUR

(1) Forecast the following elements for the Royal Observatory for each storm : -

(a) the maximum gust

(b) the maximum 10-minute mean wind

(c) the maximum 60-minute mean wind.

(d) the instantaneous minimum sea level pressure

If there are difficulties in forecasting any of these elements then they may be omitted.

(2) Substitute the above forecast values into Equations (3), (4), (5) and (6) respectively to obtain the surge and use the mean of the predicted values as the forecast surge.

(3) In Fig. VII are plotted the isopleths of surges produced by typhoons at various distances and bearings from Hong Kong. Plot the forecast track of the typhoon on Fig. VII. The surge thus obtained can be used as a check on the value obtained by (2) above.

(4) It has been found that on occassions when surges exceeded two feet the maximum gusts were usually recorded at the Royal Observatory before the maximum surge occurred in the Harbour.

Hence, if a gust of say 80 knots has just been recorded one can be fairly certain that a surge at least as high as that corresponding to a maximum gust of 80 knots will occur.

PROCEDURE FOR FORECASTING STORM SURGES AT TAI PO KAU

The storm surges recorded during 1962-64 by the recording tide gauge at Tai Po Kau were correlated with those recorded by the North Point Tide Gauge and the following equation was obtained:-

$$S_{T.P.} = 2.18\, S_{N.P.} - 1.46 \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

coefficient of correlation = 0.96

where $S_{T.P.}$ = surge recorded by the Tai Po Kau tide gauge

and $S_{N.P.}$ = surge recorded by the North Point tide gauge (see Fig. VIII)

To obtain the surge at Tai Po Kau, substitute the forecast surge for the Hong Kong Harbour into Equation (7).

However, it must be borne in mind that the equation was obtained from records made before the Plover Cove Dam was constructed. It is possible that because of the reduced capacity of the Tolo Harbour as a result of the construction of the dam, bigger surges may affect this area in future.

FLOODING DUE TO STORM SURGES

Not all storm surges result in flooding because not every surge coincides with the astronomical high water and even it did flooding would not occur unless the surge and/or the astronomical tide were sufficiently large.

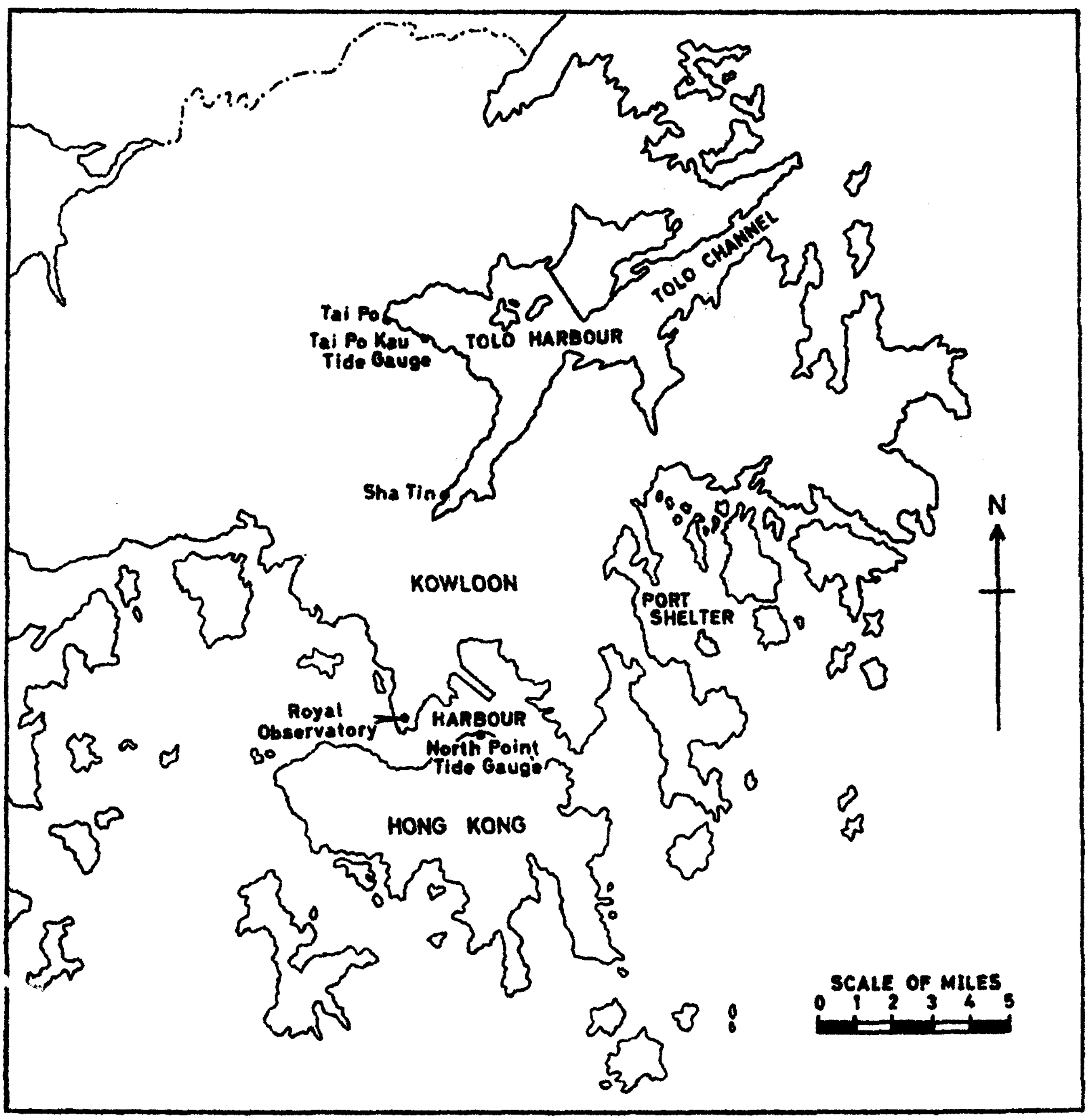
The resultant sea level, being the sum of the astronomical tide and the storm surge, can be obtained by first plotting the astronomical tide and then adding the expected surge to the curve.

The normal tides in the Hong Kong Harbour sometimes rise as high as about 8.8 feet above chart datum, therefore if the resultant water level during the approach of a tropical cyclone is not expected to reach this height, no general flooding from the sea is likely to occur.

EXTREME SURGES

By means of Gumbel's method, Bell [8] obtained the maximum gusts, maximum hourly mean winds as well as the minimum hourly sea level pressures for the various return periods. Assuming that the regression equations are still valid for these extreme values, the maximum surges for the corresponding return periods can be obtained. By means of Equation (7), the extreme surges at Tai Po Kau can also be computed. The extreme values are tabulated in Tables IV and V.

Fig. I HONG KONG AND NEW TERRITORIES



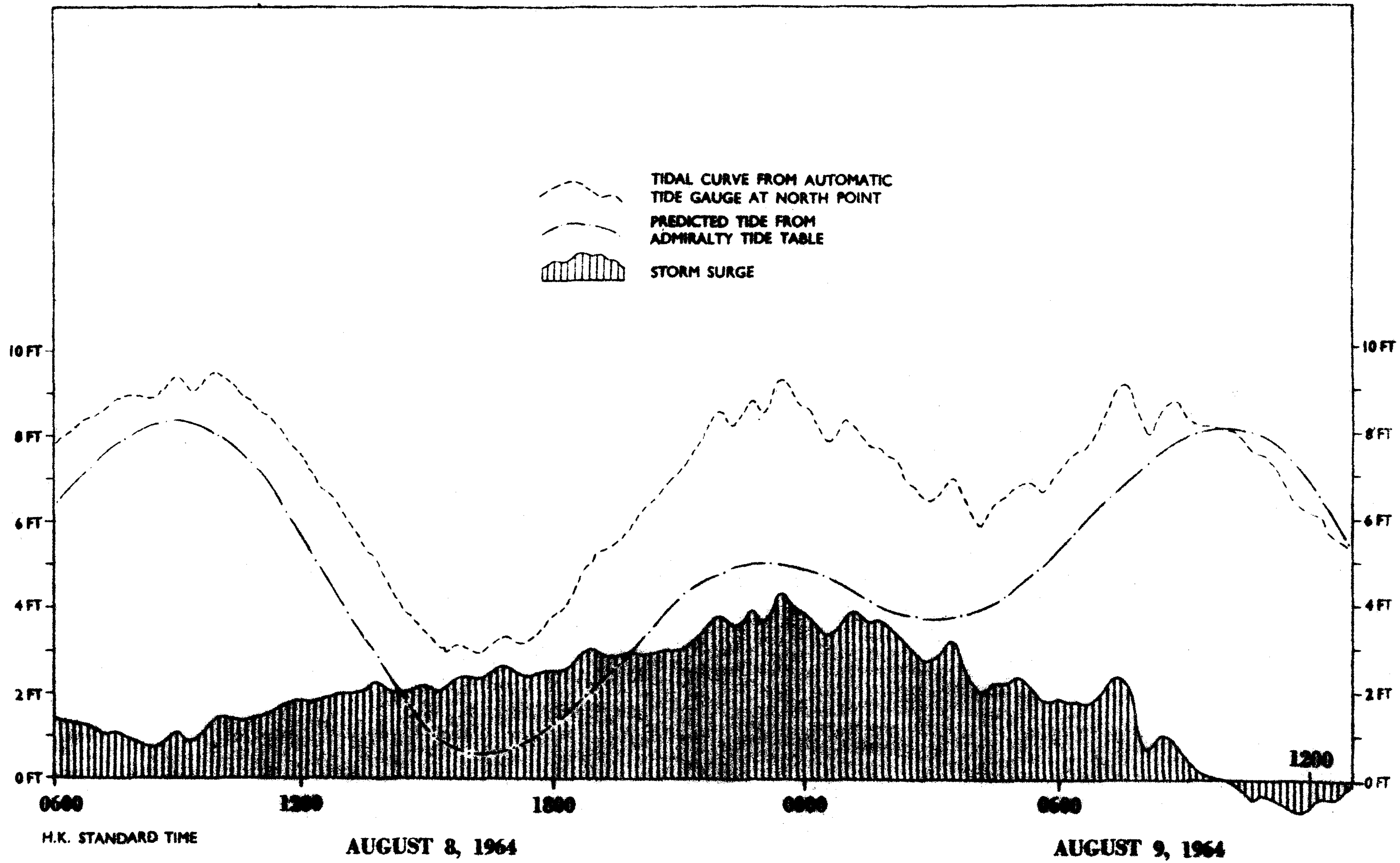


Fig. II STORM SURGE OF TYPHOON IDA

Fig. III RELATION BETWEEN STORM SURGE AND MAXIMUM GUST

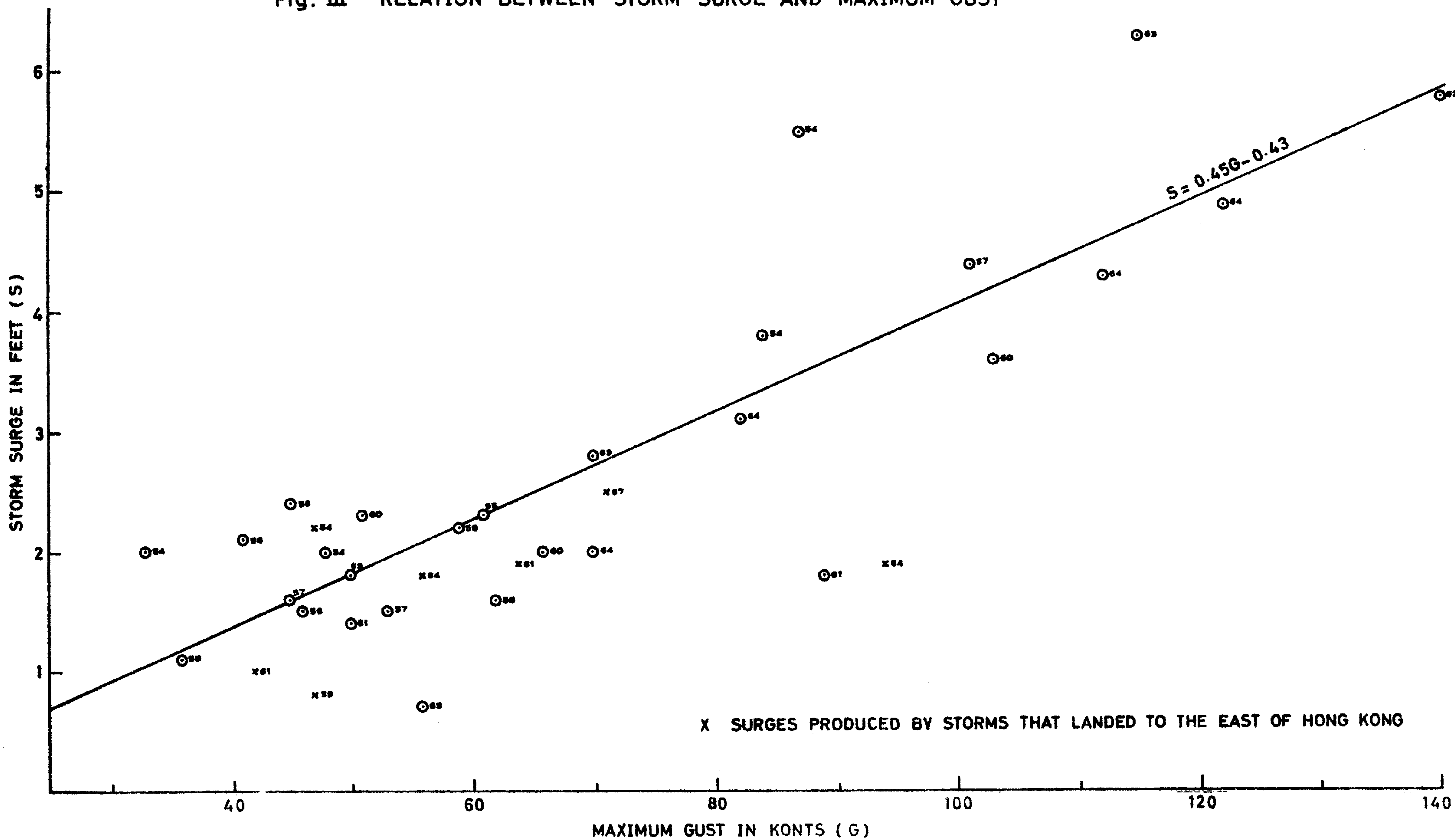


Fig. IV RELATION BETWEEN STORM SURGE AND MAXIMUM 10-MINUTE MEAN WIND

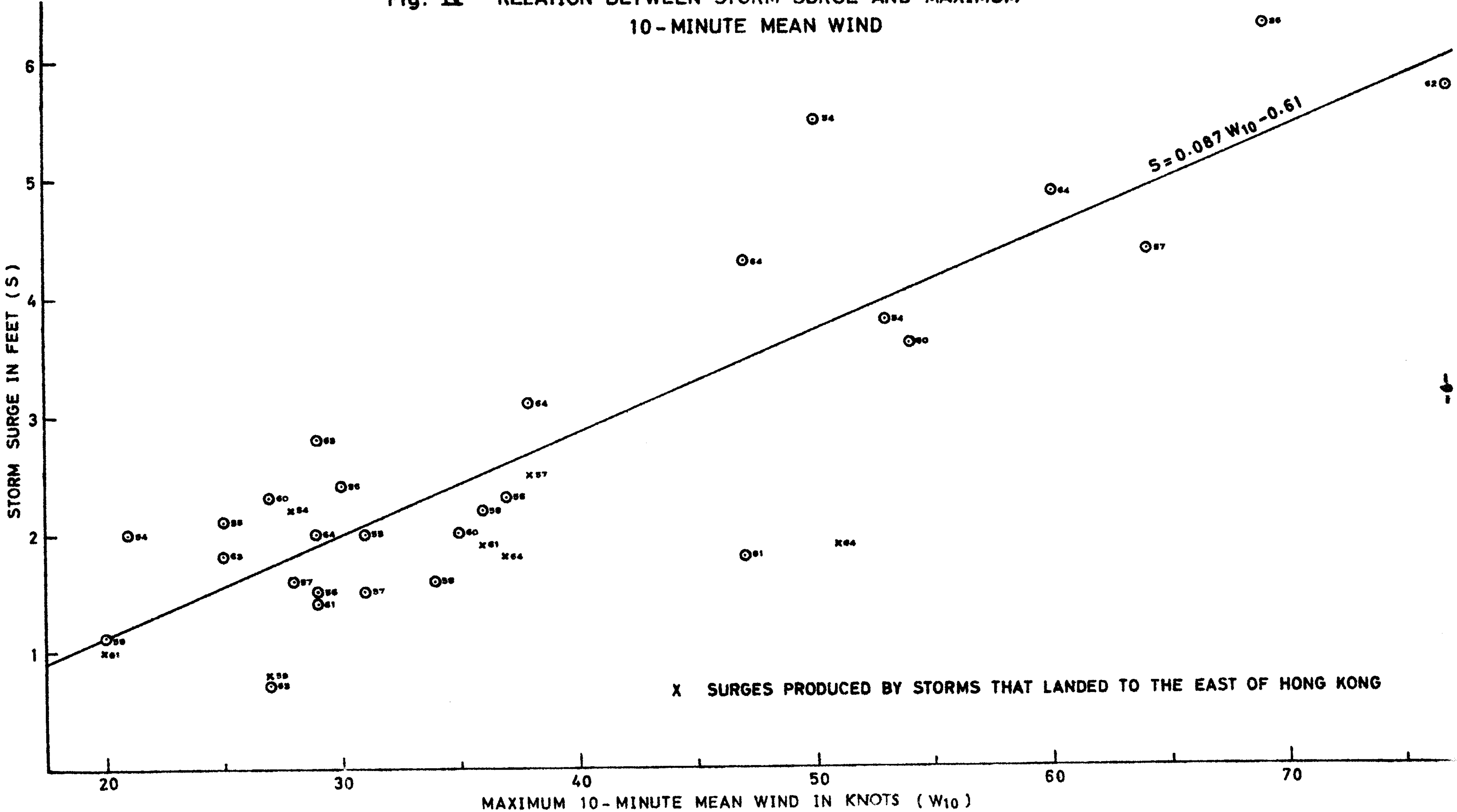


Fig. V RELATION BETWEEN STORM SURGE AND MAXIMUM 60-MINUTE MEAN WIND

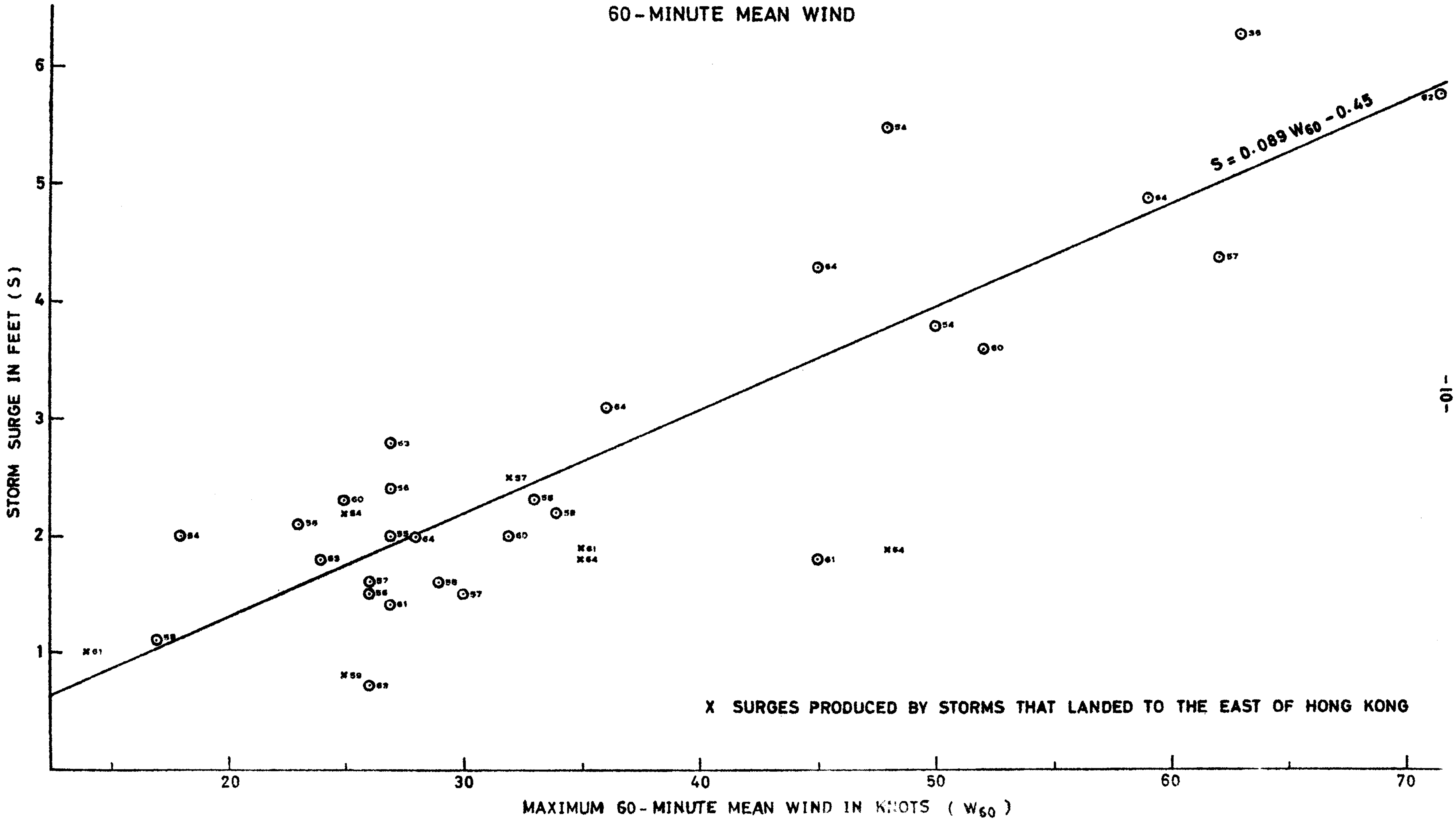


Fig. VI RELATION BETWEEN STORM SURGE AND MINIMUM SEA LEVEL PRESSURE

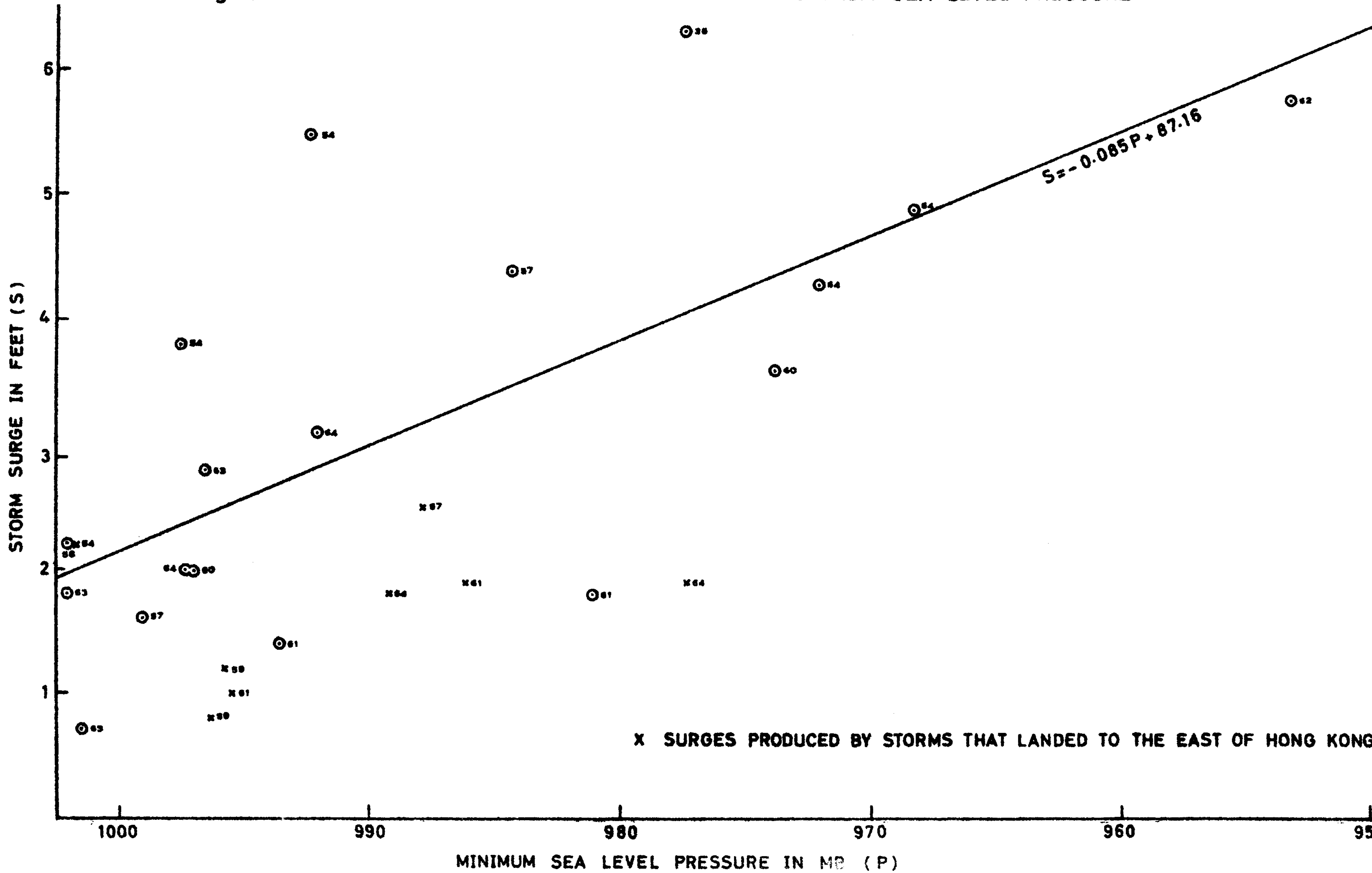
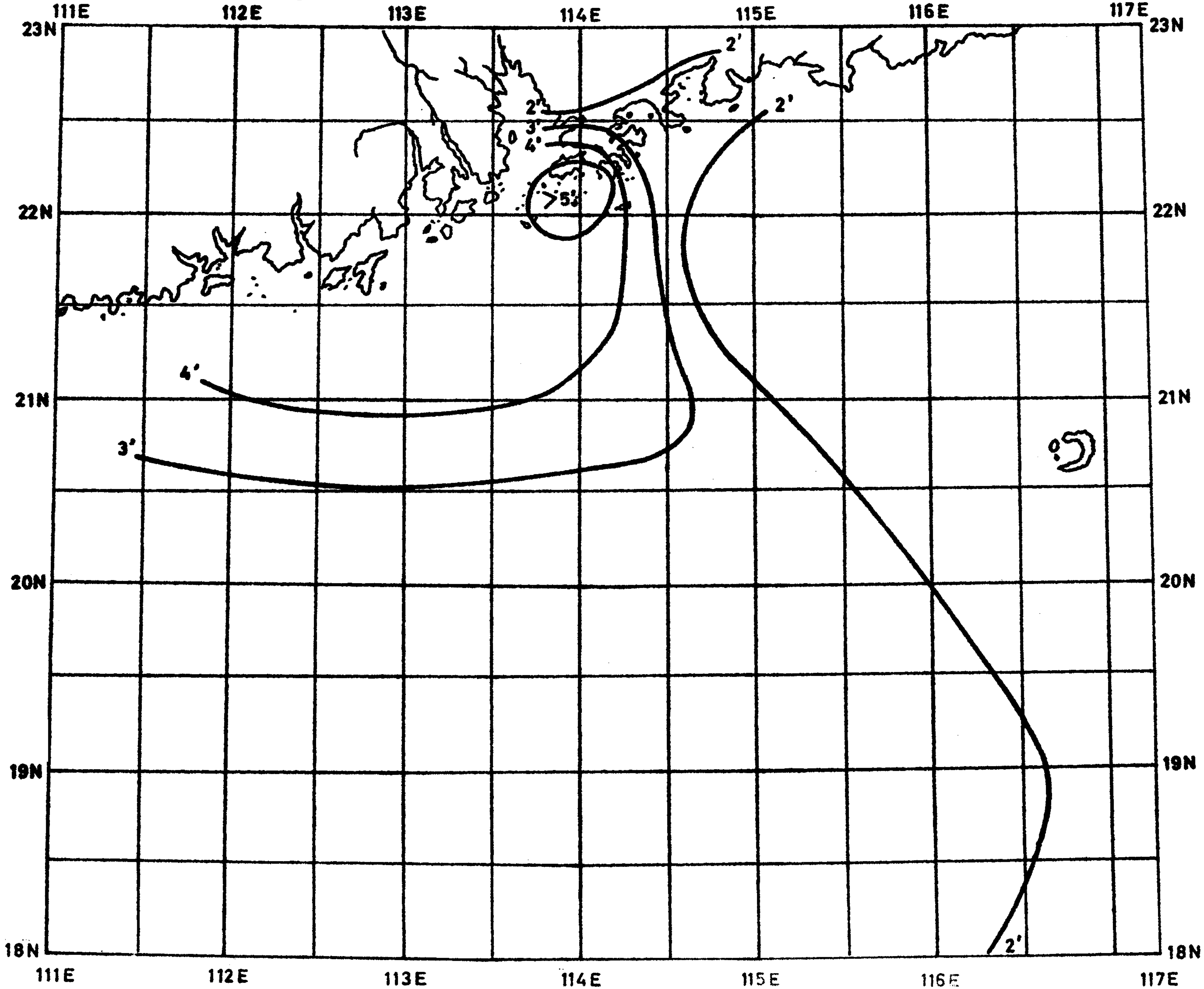


Fig. VII ISOPLETHS OF SURGES PRODUCED BY TYPHOONS



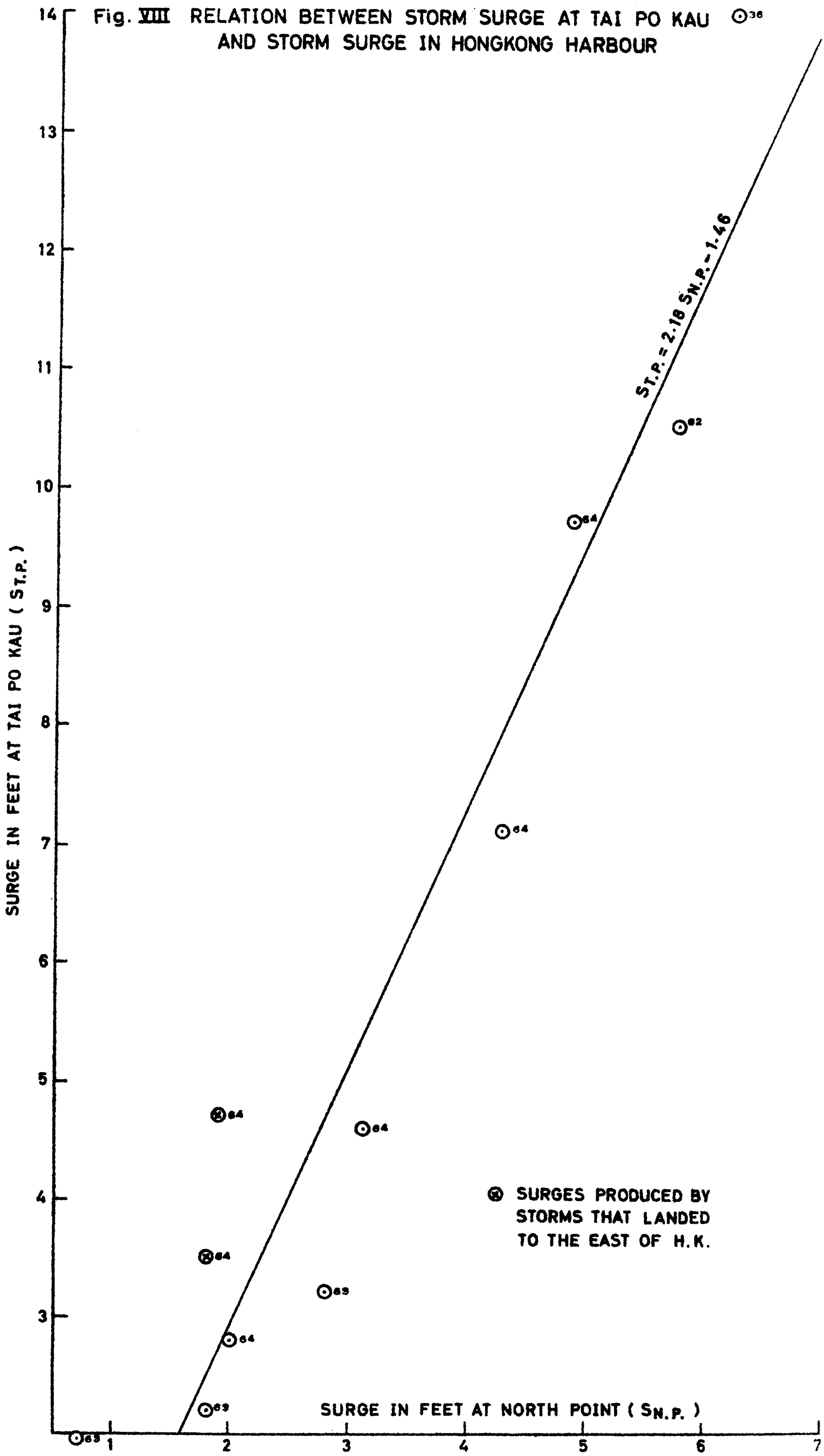


Fig. VIII RELATION BETWEEN STORM SURGE AT TAI PO KAU AND STORM SURGE IN HONGKONG HARBOUR
SURGE IN FEET AT TAI PO KAU (ST.P.)
SURGE IN FEET AT NORTH POINT (SN.P.)
ST.P. = 2.18 SN.P. - 1.46
SURGES PRODUCED BY STORMS THAT LANDED TO THE EAST OF H.K.
14
13
12
11
10
9
8
7
6
5
4
3
1
2
3
4
5
6
7
36
62
64
64
64
64
64
63
64
63
63

TABLE I

STROM SURGES IN THE HONG KONG HARBOUR

Year	Month	Tropical Cyclone	Storm Surge in H.K. Harbour in ft	Minimum sea-level pressure in mb	Maximum gust in kt	Maximum 10-minute mean wind in kt	Maximum 60-minute mean wind in kt	Remarks
1936	AUG		6.3	977.4	115	69	63	From P27 of "The Effect of Meteorological conditions on tide height at Hong Kong" by I.E.M. Watts
1954	AUG	IDA	5.5	992.3	87	50	48	
	OCT	NANCY	2.0	1012.7	33	21	18	
	NOV	PAMELA	3.8	997.5	84	53	50	
	NOV	RUBY	2.2	1001.8	47	28	25	*
1955	JUN	BILLY	2.0	> 1005.0	48	31	27	
	SEP	KATE	2.3	1007.5	61	37	33	
1956	JUL	VERA	1.5	1005.5	46	29	26	
	AUG	CHARLOTTE	2.4	1003.5	45	30	27	
	OCT	JEAN	2.1	1008.3	41	25	23	
1957	JUL		1.6	999.0	45	28	26	
	JUL	WENDY	2.5	987.7	71	38	32	*
	SEP	GLORIA	4.4	984.3	101	64	62	
	OCT		1.5	1004.2	53	31	30	
1958	MAY		2.2	1001.9	59	36	34	
	AUG		1.6	1004.0	62	34	29	
	AUG		1.1	1003.9	36	20	17	
1959	JUL	WILDA	1.2	995.7	NO	RECORD		*
	SEP	NORA	0.8	996.2	47	27	25	*
1960	JUN	MARY	3.6	973.8	103	54	52	
	JUN	OLIVE	2.0	997.0	66	35	32	
	OCT	KIT	2.3	> 1005.0	51	27	25	
1961	MAY	ALICE	1.8	981.1	89	47	45	
	JUL	ELSIE	1.0	995.4	42	20	14	*
	SEP	OLGA	1.9	986.1	64	36	35	*
	SEP	SALLY	1.4	993.5	50	29	27	
1962	SEP	WANDA	5.8	953.2	140	78	72	Surge height from C.M. Gilford's unpublished report.
1963	JUL	AGNES	1.8	1002.1	50	25	24	
	AUG	CARMEN	0.7	1001.4	56	27	26	
	SEP	FAYE	2.8	996.5	70	29	27	
1964	MAY	VIOLA	3.1	991.9	82	38	36	
	JUL	WINNIE	2.0	997.1	70	29	28	
	AUG	IDA	4.3	972.0	112	47	45	
	SEP	RUBY	4.9	968.2	122	60	59	
	SEP	SALLY	1.8	989.1	56	37	35	*
	OCT	DOT	1.9	977.3	94	51	48	*

* Tropical Cyclone landed to the east of Hong Kong.

TABLE II

STORM SURGES RECORDED BY THE TAI PO KAU GAUGE

Year	Month	Tropical Cyclone	Storm Surge at Tai Po Kau in ft	Minimum sea level pressure in mb	Maximum gust in kt	Maximum 10-minute mean wind in kt	Maximum 60-minute mean wind in kt	Remarks
1936	AUG		14.0	977.4	115	69	63	From P26 of "The Effect of Meteorological Conditions on Tide Height at Hong Kong" by I.E.M. Watts.
1962	SEP	WANDA	10.5	953.2	140	78	72	From C.M. Gilford's unpublished report.
1963	JUL	AGNES	2.2	1002.1	50	25	24	
	AUG	CARMEN	1.9	1001.4	56	27	26	
	SEP	FAYE	3.2	996.5	70	29	27	
1964	MAY	VIOLA	4.6	991.9	82	38	36	
	JUN	WINNIE	2.8	997.1	70	29	28	
	AUG	IDA	7.1	972.0	112	47	45	
	SEP	RUBY	9.7	968.2	122	60	59	
	SEP	SALLY	3.5	989.1	56	37	35	*
	OCT	DOT	4.7	977.3	94	51	48	*

*** Tropical Cyclone landed to the east of Hong Kong.**

TABLE III

Extreme values of maximum gust, maximum 60-minute mean wind and minimum sea level pressure

Return period in years	Maximum gust in knots	Maximum 60-minute mean winds in knots	*Minimum mean sea level pressure in mb
10	109	63	979
20	123	71	975
50	141	80	970
100	155	88	966
200	168	95	962
500	186	105	957
1000	199	112	953

* Hourly values and not instantaneous values.

TABLE IV

Extreme surges in Hong Kong Harbour obtained from extreme values in Table III

Return Period in years	Extreme surges (in feet) expected in Hong Kong Harbour		
	Obtained from extreme gusts	Obtained from extreme 60-minute mean winds	* Obtained from extreme hourly minimum mean sea-level pressures
10	4.5	5.1	3.9
20	5.1	5.9	4.3
50	5.9	6.7	4.7
100	6.5	7.4	5.0
200	7.1	8.0	5.4
500	7.9	8.9	5.8
1000	8.5	9.5	6.1

* Surges in this column are smaller because hourly values instead of instantaneous values have been used.

TABLE V

Extreme surges expected at Tai Po Kau obtained from extreme values in Table III

Return Period in years	Extreme surges (in feet) expected at Tai Po Kau		
	Obtained from extreme gusts	Obtained from extreme 60-minute mean winds	*Obtained from extreme hourly minimum mean sea-level pressure
10	8.4	9.7	7.0
20	9.7	11.4	7.9
50	11.4	13.2	8.8
100	12.7	14.7	9.4
200	14.0	16.0	10.3
500	15.8	18.0	11.2
1000	17.1	19.3	11.8

* Surges in this column are smaller because hourly values instead of instantaneous values have been used.

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