CHAPTER 121

Computation of Storm Surge

RICHARD SILVESTER
Professor of Coastal Engineering
Asian Institute of Technology, Bangkok, Thailand

ABSTRACT

From knowledge of wind resistance coefficients measured over the sea, it is possible to compute the shear stress of a wind field on its surface Where a body of water is relatively shallow, such a shear stress will transport water to the downwind end and so create a high water level or surge Graphs are presented for ready application of the relevant formulae to cases of lakes and Continental Shelves The wind fields of either uniform or triangular horizontal distribution in velocity are included, as well as conditions of stationary or moving fetches Surges from seven typhoons travelling towards Hong Kong are computed and compared to actual records

INTRODUCTION

Wind stress on a water surface is a function of its roughness, particularly in respect to the shorter period waves in the spectrum Hence an enclosed body of water can be hydrodynamically rougher than the open sea where the shorter waves are dissipated with the assistance of the longer ones Formulae available can be put in graphical form for the computation of surge heights These apply to lakes or Continental Shelves With the latter the ratio of fetch length to Shelf width assumes importance, as well as velocity of approach of the fetch and the horizontal distribution of the wind velocity Application of the graphs to a number of typhoons approaching Hong Kong indicates the accuracy of the procedure

WIND STRESS

The shear stress applied by the wind to a water surface depends upon its smaller roughnesses and hence the wave conditions Wu[1] has shown that waves in the order of 0 7 seconds period and 0 1 metre height are the main roughness element The stress thus varies with the wind velocity and the fetch available For this reason it is understandable that optimum values can be reached which are different for enclosed bodies of water of limited size and the open sea The former contain a larger proportion of short waves that are reaching, or are at, their limiting steepness The latter, however, when they approach the fully arisen state, contain less of the short period components and more of the longer period waves[2] For this reason the

sea is slightly smoother as far as wind stress is concerned It can be presumed therefore that the stress of a given steady wind can also vary with duration

The shear stress is given by

$$\tau = \rho_a U^2 \qquad \text{----------(1)}$$

where ρ_a = density of air
U^a = shear velocity near the water surface
this can be expressed as

$$\tau = \rho_a C_y U_y^2 \qquad \text{----------(2)}$$

where C_y = resistance coefficient varying with U_y
U_y = wind velocity at y metres above water surface

Many workers[3][4][5] have evolved relationships for C_y and U_y from measurements over lakes and the sea Wu[6] has summarised these data and discussed their significance, from which Figure 1 has been prepared This shows C_{10} for a range of U_{10}, as most wind measurements have been made at the 10 metre height Within the boundary of the experimental values the relationships presented by various workers is also shown, including the stepped curve of Wu It is now generally accepted that a limiting value of $C_{10} = 2\ 6 \times 10^{-3}$ can be applied to limited water bodies when the 10 metre high wind exceeds 10 metres/sec or 30 knots The optimum for the ocean is $C_{10} = 2\ 4 \times 10^{-3}$ For winds less than this a relationship of

$$C_{10} = 0\ 65\ 10^{-3} U_{10}^{\frac{1}{2}} \qquad \text{----------(3)}$$

would follow Sheppard's curve reasonably well to the aforesaid limits To convert wind velocities from other levels to the 10 metre height, graphs have been provided elsewhere [7]

In storm surge calculations it is more appropriate to use the relationship

$$\tau = k \rho U_{10}^2 \qquad \text{----------(4)}$$

where ρ = density of the water

so that $k = \frac{\rho_a}{\rho} C_y$, which for seawater $= \frac{1}{800} C_{10}$

the limiting values of $k = 3\ 3 \times 10^{-6}$ and $3\ 0 \times 10^{-6}$ apply to lakes and ocean areas respectively

A scale for k is included in Figure 1, together with scales for U_{10} in knots and designations of Beaufort Number and Sea State

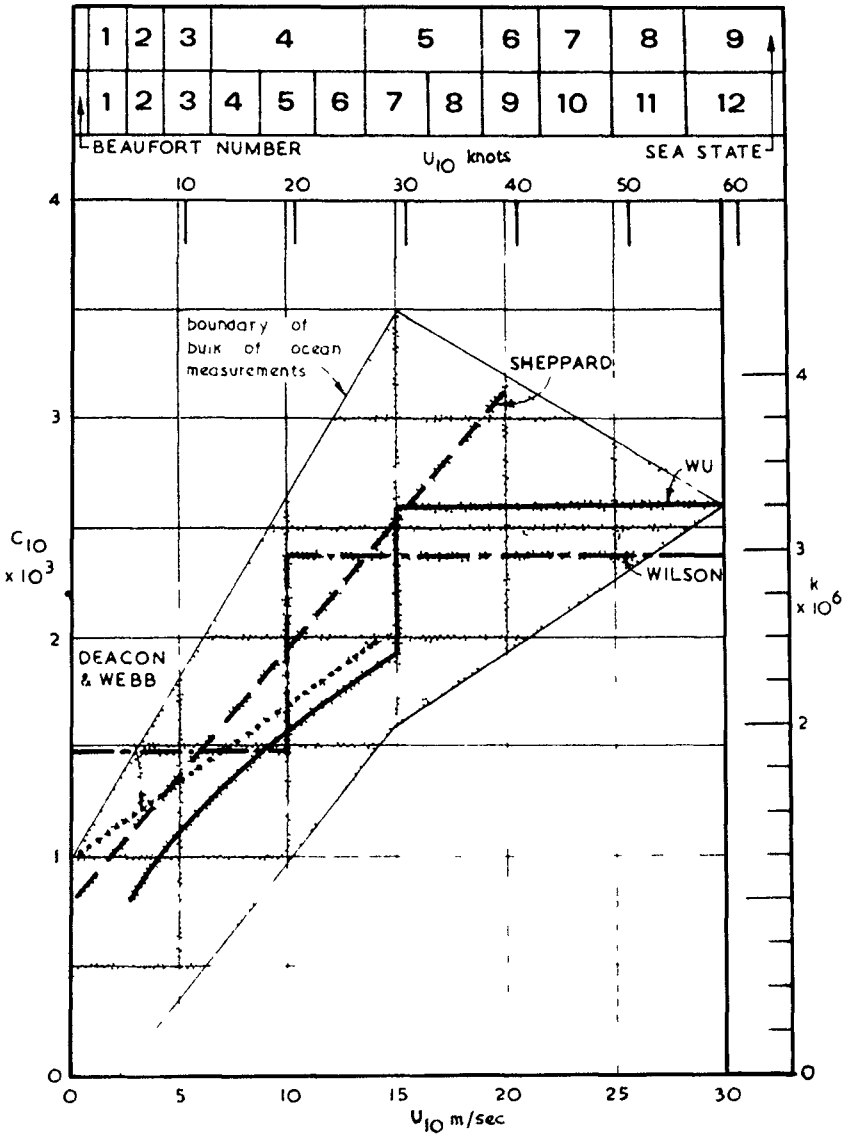


Fig 1 Variation of wind resistance coefficient with wind velocity

ENCLOSED BODIES OF WATER

Considering a lake of rectangular proportions in plan, its longitudinal cross-section can be equated to a rectangular one of equal area, giving an equivalent depth d and length or fetch L The equation for the water surface profile[8][9][10] when a steady wind velocity U_{10} is applied to it is

$$\frac{S}{d} = \frac{k_{10}U_{10}^2 L}{2\,g\,d(d+S)} = \frac{k_{10}U_{10}^2 L}{2\,gd^2} \qquad \text{----------(5)}$$

where S = surge height at the down wind end The last form of the equation assumes S to be small in respect to d Equation (5) also approximates the nodal point at the centre of the length L

The variables in this dimensionless equation must be chosen consistently The values of the fall and rise of the water surface at the upwind and downwind ends of the lake are presented in graphical form in Figures 2 and 3, for the two conditions of bottom exposure at the upwind end The surface passes through the mean depth plane around the centre of the water body[8] even when part of the bed is exposed Lakes of irregular depth can be treated similarly by determining an equivalent rectangular section

In the case of narrow bodies of water such as canals the same value of $k_{10} = 3\ 3 \times 10^{-6}$ is applicable since the optimum roughness is due to waves of about 1 second period[11] reaching their maximum steepness of 1/7

For the case of non-rectangular planar shapes, of uniform depth or sloping bottoms, Keulegan[11] has derived some form factors N by which the values of S/d in equation (5) should be multiplied These are illustrated in Figure 4, where the exponential form analysed by Langhaar for constant depth d, and trapezoidal shapes with uniform depth or uniformly sloping bottom are presented The high values of N resulting from the downwind depth decreasing should be noted The same order of magnification will be observed for similar shoaling on the Continental Shelf

CONTINENTAL SHELF - STATIC WIND FIELD

Where a wind is applied to the Continental Shelf blowing towards the shore, the Shelf width can be taken as half the length of the lake considered previously The water feeding the surge comes from the deep ocean The major difference from the previous situation is the decreasing depth towards the shore For the purposes of surge calculation it is reasonable to assume a uniform variation from a depth d_1 at the Shelf edge to d_2 near the coast (see inset of Figure 5)

Surge problems assume importance on reasonably wide Continental Shelves The majority of these have been constructed by sediment deposition for which waves are the predominant distributing factor

It is not surprising, therefore, that most of these Shelf edges occur at around 65 fathoms[12], or the reach of the 12-14 second waves, which are the most persistent swell waves of the oceans[13] Thus, unless more specific information is available the depth d_1 may be taken as 400 feet (120 metres) On sandy shorelines the beach profile is parabolic from the breaker line, which produces depths of 5 fathoms very close to shore It is such depths, rather than zero values at the beach, that are more effective in the surge phenomenon Where a large tidal range occurs, or sediment of silt character exists, large tidal flats will necessitate the use of much smaller values of d_2

The width of the Shelf will be designated as L, which can be different from the fetch length F of the wind zone As seen in Figure 5 the depth ratio d_1/d_2 can be equally expressed by L/x where x is distance inland where the plane of the bed meets the mean water level

Where a storm zone has a fetch length (F) in excess of the Shelf width (L), only that portion across the relatively shallow zone is effective in producing surge, thus F = L This is likely to be the case in extra-tropical cyclones, where wide expanses of ocean can suffer winds of uniform speed and direction In tropical cyclones the fetch lengths are smaller and are more likely to be less than the Shelf width This case is discussed later, together with the problem of velocity of advance (V) of the wind field

(a) Uniform Wind Velocity (V=0)

For a wind of steady and uniform speed applied to a Continental Shelf the following formula has been derived[14]

$$S = \frac{k\,U^2 L}{g(d_1-d_2-S)}\,\ell n\,\left(\frac{d_1}{d_2+S}\right) \qquad \text{----------(6)}$$

Since S is small compared to d_2 equation (6) can be rewritten

$$\frac{S}{d_1} = \frac{k\,U^2}{g d_1}\left(\frac{L}{d_1-d_2}\right)\ell n\,\frac{d_1}{d_2} \qquad \text{----------(7)}$$

so that

$$\frac{S}{d_1} = \frac{k\,U^2 L}{g d_1^2 (1-d_2/d_1)}\,\ell n\,\frac{d_1}{d_2} \qquad \text{----------(8)}$$

Values of S/d_1 versus $k\,U^2L/gd_1^2$ have been graphed in Figure 5 for the range of $L/x = F/x = 0.01$ to 1000 or $d_1/d_2 = 1.01$ to 1001 (the latter approximating $d_2 = 0$)

(b) Triangular Wind Velocity (V=0)

The wind in a tropical cyclone is circular in character, but is deflected towards the centre such that it is around 45° to the radii

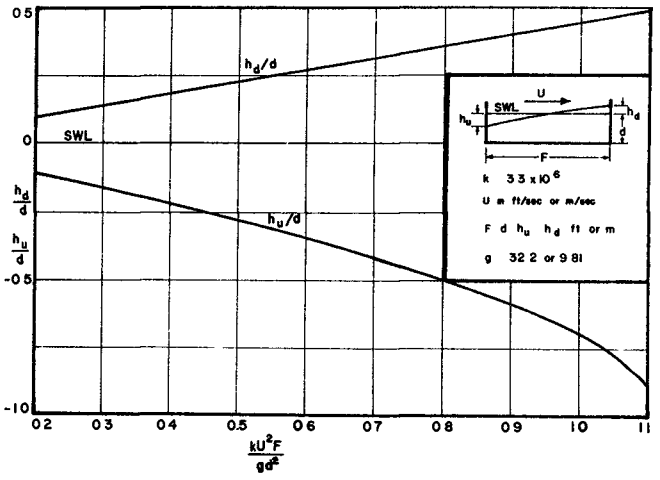


Fig 2 Upwind and downwind surge levels in a lake of uniform depth

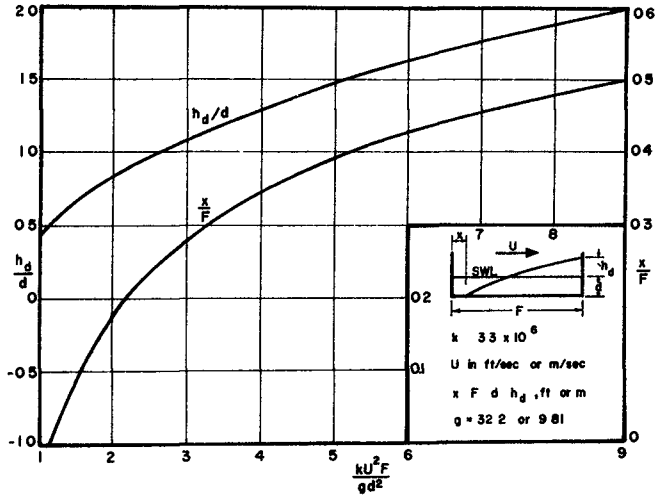


Fig 3 Surge levels in a lake when the upwind bed is exposed

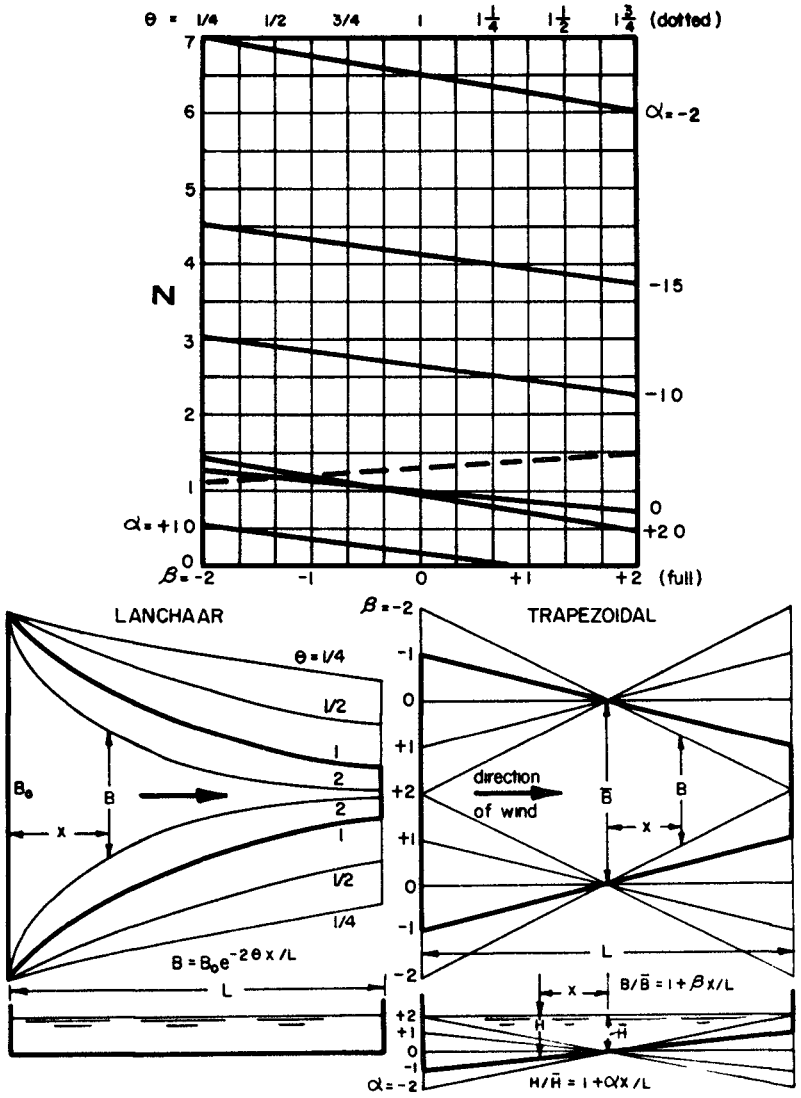


Fig 4 Amplification factor N for Langhaar shaped and trapezoidal lakes

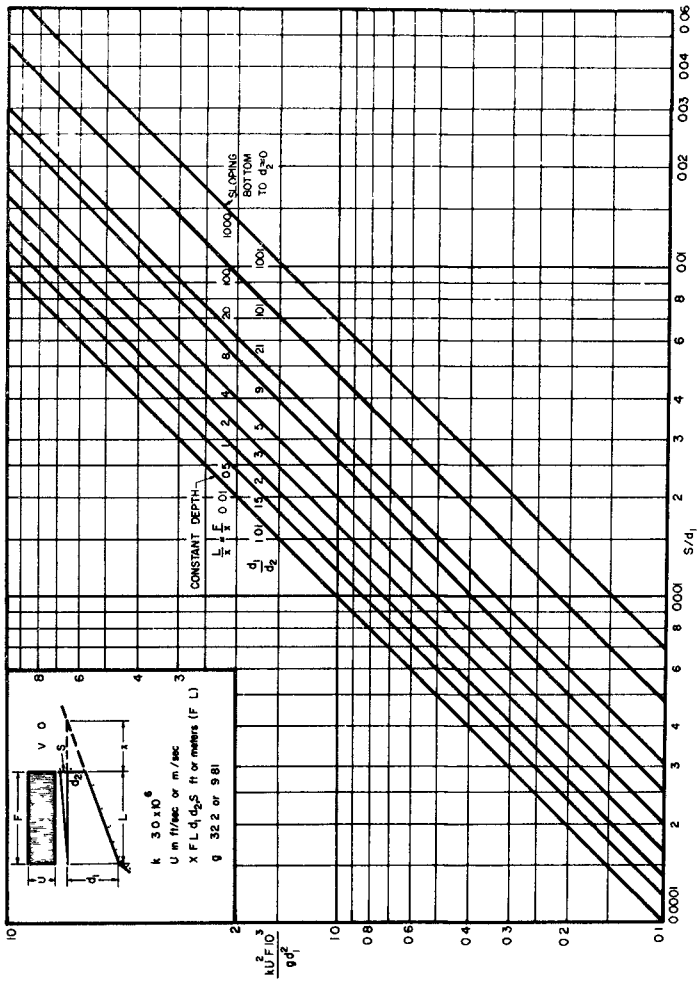


Fig 5 Surge produced by a static uniform wind field extending across the Continental Shelf

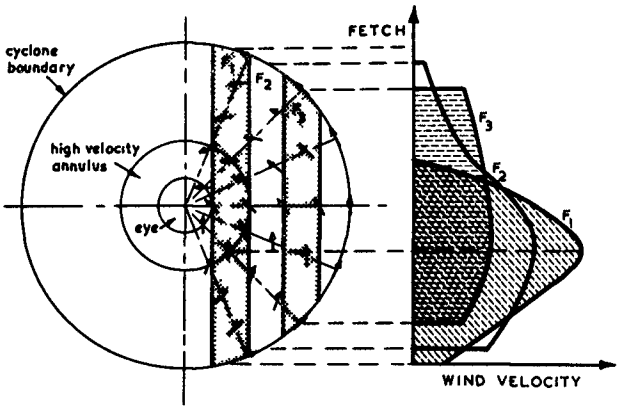


Fig 6 Typical surface wind structure inside a tropical cyclone

(See Figure 6) As the cyclonic centre moves forward the critical conditions as far as surge as well as wave generation is concerned are contained in the quadrant for which the centre and wind vectors are in same direction The cyclone depicted in Figure 6 represents air circulation for the northern hemisphere in which the right rear quadrant contains the critical conditions for surge generation The worst affected coastal zone will be that in line with fetch F_1 passing through the high velocity annulus The assessment of wind components along this alignment will result in a triangular distribution of velocity (See Figure 6), the shape of which depends greatly on the radial distribution of the wind around the centre

For a triangular wind distribution of more-or-less isosceles shape Reid[15] has derived the following surge formula

$$S = \frac{k\,U^2 T}{C_1}\left(\frac{d_1}{d_2}\right)^{\frac{1}{4}} Z \qquad \text{----------(9)}$$

where T = mean time for surge wave to traverse the Shelf
C_1 = celerity of the surge wave at the Shelf edge ($= \sqrt{gd_1}$)
Z = factor, (= 0 56 for F = L and V = 0)

Substituting $T = \dfrac{L}{\frac{1}{2}(\sqrt{gd_1} + \sqrt{gd_2})}$ into equation (9) gives

$$\frac{S}{d_1} = \frac{k\,U_{max}^2}{gd_1^2}\,L\left[\frac{1\ 12}{1 + \sqrt{d_2/d_1}}\left(\frac{d_1}{d_2}\right)^{\frac{1}{4}}\right] \qquad \text{----------(10)}$$

Equation (1) has been graphed in Figure 7 in a similar manner to Figure 5 for a similar range of $\frac{d_1}{d_2}$ or $\frac{L}{x} + 1$.

CONTINENTAL SHELF - MOVING WIND FIELD

In the case of the storm centre travelling towards the coast the initial surge wave is being reflected as later portions are still approaching. The interaction of these establishes a new surge system which Reid[15] has analysed for various ratios of F/L and $V/\bar{C}$

where $$\bar{C} = L/T = \tfrac{1}{2}(\sqrt{gd_1} + \sqrt{gd_2}) \qquad \text{----------(11)}$$

From the graphs so presented the ratio R of maximum surge (S_{max}) to that for static storm conditions (S)(i e F = L and V = 0) has been plotted as in Figure 8, for both uniform and triangular wind distributions To find S_{max} it is necessary first to compute S for a hypothetical shelf whose width L equals the fetch length F (not the reverse) With this noted, then R is obtained from the combination of F/L and $V/\bar{C}$ It is seen that the influence of the storm-centre speed differs in the two wind distributions Reid's analysis[15] also provides information on the timing of the maximum surge in respect to the location of the fetch, but this has not been included

The absolute resultant is determined also by the depression of atmospheric pressure, which may precede or be concurrent with S_{max} from the wind alone The surge due to air pressure is given by

$$S_a = \left(\frac{1013-p_c}{34}\right)\frac{13\ 59}{12\ 1\ 003} = (1013-p_c)0\ 033 \qquad \text{--------(12)}$$

where S_a = storm surge in feet of seawater
and h_c = pressure at the storm centre in millibars (34 millibars = 1" mercury)
This value should be added to that obtained in the previous equations

EXAMPLES OF HONG KONG TYPHOONS

Since 1962 the Department of Public Works in Hong Kong has collated some valuable data on typhoons approaching the vicinity of the island These have been summarised in a data sheet for each event, in which rainfall, wind speed, wind direction, atmospheric pressure, and sea-level are plotted against time in hours On the sealevel graph is traced the normal tide curve as predicted in tide tables, from which the surge level can be obtained The chronological relationship between the variables listed provides sufficient information to draw a plan of the cyclone and to determine its diameter A geographic plan of the ocean area with the typhoon path traced on it with time markings, permits the speed of travel to be assessed The distance across the Continental Shelf that the typhoon has traversed can also be measured The wind speed trace indicates whether a triangular or rectangular distribution has produced the surge A modified reproduction of one PWD data sheet is illustrated in Figure 9

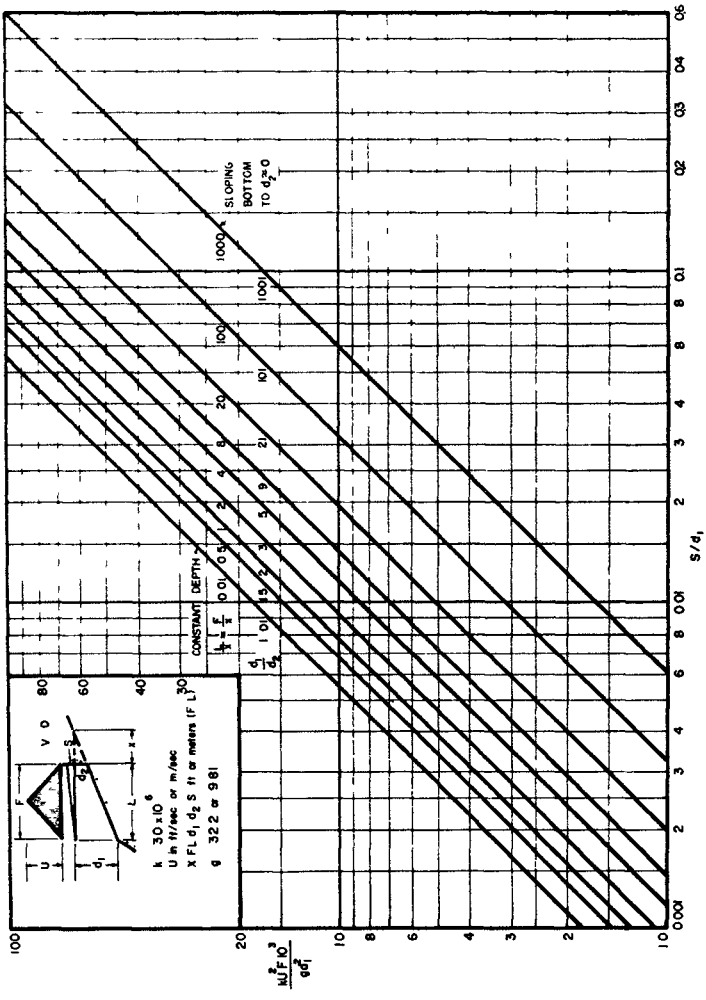


Fig 7 Surge produced by a static triangular wind field extending across the Continental Shelf

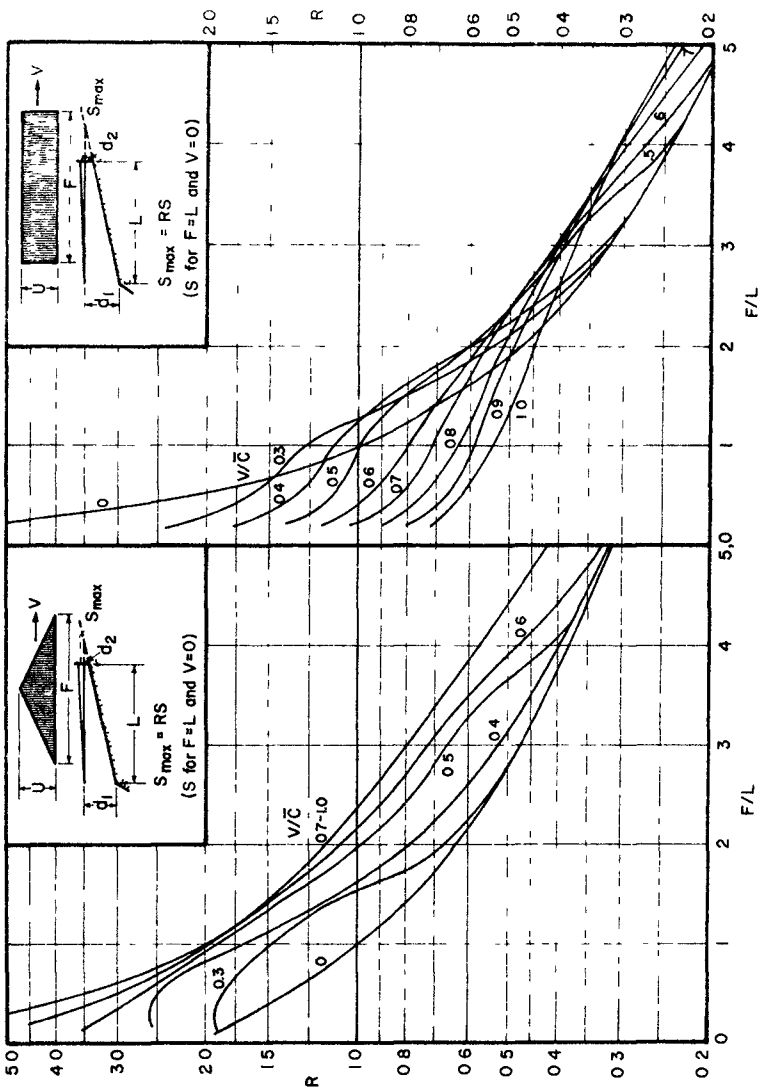
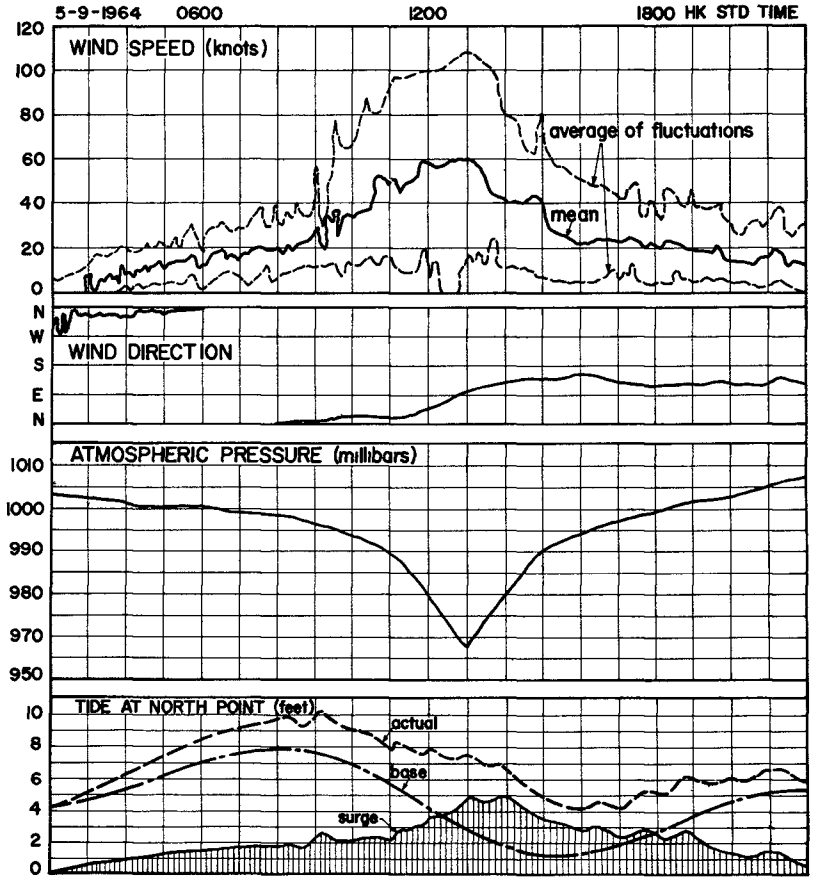


Fig 8 Optimum surge resulting from various fetch lengths and velocities of advance



DATA SHEET FOR TYPHOON RUBY PREPARED BY PORT WORKS OFFICE (PWD) HONG KONG

INFORMATION OMITTED FROM ORIGINAL

RAINFALL

TIDES AT OTHER LOCATIONS

PLAN OF HONGKONG & VICINITY

DATA PRIOR TO & SUBSEQUENT TO

5 TH SEPTEMBER

TRACK OF TYPHOON

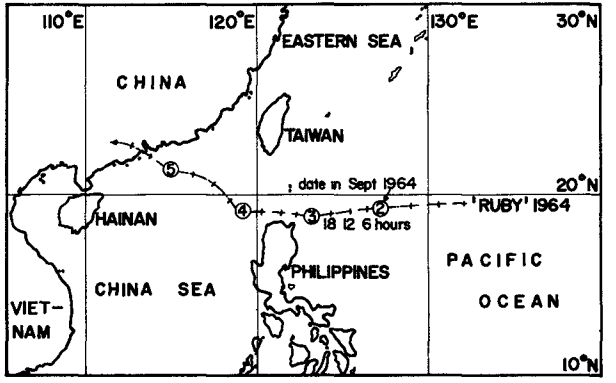


Fig 9 Limited reproduction of a typhoon data sheet produced by the Department of Public Works, Hong Kong

Data as above are available for seven typhoons, as listed in Table I, where relevant parameters leading to the final surge (S_t) are included Comparison of the computed and measured values indicates the accuracy of the procedure presented

To determine a surge prior to its arrival, the possible path in respect to the site must be assessed The maximum wind speed at the boundary of the eye is a function of the atmospheric depression at the centre Kraft[16] provides an equation for Atlantic hurricanes as follows

$$U_{max} = 14\sqrt{1013-p_c} \qquad \text{----------(13)}$$

where U_{max} is expressed in knots for p_c in millibars

Equation (13) may not be applicable to typhoons or more modest tropical cyclones

From table I the only typhoon which was centered on Hong Kong, and for which values could be used for verification, is that of Wanda when U_{max} = 80 knots for 1013-952 = 61 millibars This would indicate a relationship of

$$U_{max} = 10\ 3\sqrt{1013-p_c} \qquad \text{----------(14)}$$

The overall diameter of typhoons in the Western Pacific is around half of those normally recorded for Atlantic hurricanes It is not unreasonable, therefore, to expect lower wind velocities for any given atmospheric depression Such data should be compiled for a region under study, when optimum storm surges are required to be calculated

The optimum water level to be expected can be computed from a knowledge of the most severe tropical cyclones known to exist in the area The fetch for this should then be traversed across the Continental Shelf at the critical speed, to hit the coast just to the left (northern hemisphere) or right (southern hemisphere) of the port under study This maximum surge should then be added to MHWS level which can occur during the cyclone period of the year Should the harbour be located near the head of a funnel shaped inlet, or one that has a shoaling approach channel, an amplification factor[17] may have to be determined for the surge level computed for the mouth

ACKNOWLEDGEMENTS

Appreciation is expressed to the Department of Public Works, Hong Kong, who supplied copies of their typhoon data sheets and gave permission for publication of this material

Table I Comparison of computed and measured surges at North Point, Hong Kong harbour

Name Date	Wanda Sept 62	Faye Sept 63	Viola May 64	Ida Aug 64	Ruby Sept 64	Sally Sept 64	Shirley Aug 68
Δp (mb)	61	17	21	38	45	24	44
S_a (feet)	2 02	0 57	0 70	1 27	1 50	0 80	1 47
U_{max} (knots)	80	25	30	45	60	35	42
Distribution	Δ	▭	▭	Δ	Δ	Δ	Δ
F (NM's)	55	220	110	210	166	107	90
d_1 (feet)	400	400	400	400	270[1]	400	400
$k\ U^2F\ 10^3/gd_1^2$	3 55	1 4	1 0	4 3	13 7	1 32	1 6
$S/d_1 \times 10^3$ (Figs 5 & 7)[2]	5 5	3 8	2 7	6 5	20 0	2 0	2 5
S (feet)	2 2	1 52	1 08	2 6	5 4	0 8	1 0
L (NM's)	180[3]	240[4]	120	120	80[1]	120	120
F/L	0 3	0 92	0 92	1.75	2 08	0 89	0 75
V (knots)	12	10	8	15	12 8	13 3	9 1
$V/\bar{C}$	0 280	0 234	0 187	0 350	0 348	0 312	0 213
R (Fig 8)	1 9	1 3	1 4	0 9	0 7	1 6	1 5
S_{max} (= RS)	4 18	1 98	1 51	2 34	3 78	1 28	1 5
$S_t (= S_a + S_{max})$	6 20	2 55	2 21	3 61	5 28	2 08	2 97
S (measured)	4 6[5]	2 8	3 0	4 0	5 0	1 8	3 0

(1) Typhoon changed direction part way across Shelf where d_1 = 270 feet and L = 80 NM's

(2) Assuming d_2 = 30 feet

(3) Approach was from ESE, equivalent L = 180 NM's

(4) Approach was from east, equivalent L = 240 NM's

(5) Tide gauge out, water mark observations only

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