# CHAPTER 2

CALIBRATION OF A HURRICANE STORM SURGE PROGRAM

by

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## Abstract

The "Bathystrophic Storm Tide Theory" is used to predict
open-coast storm surge due to major hurricanes.  The model
described here is used to calculate storm-surge effects such
as flood elevations needed for designing nuclear power plant
safety related structures.  In order to establish the model's
viability the numerical techniques have been verified and
the model calibrated using available field data.

Numerical verification was performed for special cases
where the governing equations of the model could be analyti-
cally solved.  Inherent in the governing storm-tide equations
are certain undetermined coefficients that describe the
effects of wind drag and bottom friction.  These coefficients
were determined by correlating computer predicted results to
hurricane storm surge hydrographs of record.

As a result of this study, we find excellent agreement
between computer predicted and analytical results.

## Introduction

Storm surges caused by maximum intensity hurricanes or
"Probable Maximum Hurricanes" (PMH) constitute a major hazard
for nuclear power plants located at coastal sites.  Failure
to design adequately for the effects of such a maximum hurri-
cane on the water level may result in catastrophic consequence
for the power plant.  The Atomic Energy Commission has selected
the PMH storm as the parameter to be considered in designing
structures to ensure adequate safety.

The surge (rise in the water level) and the attendant
wave activity as functions of time and caused by a PMH storm
are used to determine the changing water level at the site of
a proposed plant.  This information is then considered when

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designing sea walls, protective barriers, bulkheads, cooling water suction and discharge pipes, and other coastal structures associated with the plant.

Until recently, hurricane storm-surge calculations were based on a simplified, one-dimensional, pseudo-static model, considering only the effects of the onshore wind drag and the variations in mean water depth. More recent studies (1,2) are based on the so-called "Bathystrophic Storm Tide Theory" and include the Coriolis effects of the time-dependent, alongshore, fluid motion on the water level. These investigations, however, have produced cumbersome computer programs because the dynamic hurricane-wind-field data must be input from graphically constructed isovel and wind vector figures.

The computer program described here solves the basic mathematical equations for the surge problem by using highly accurate numerical techniques. In addition, the inputs necessary to the program are simplified, so that only the basic design hurricane parameters are needed. The hurricane wind field and the barometric pressure variation at any point in the storm, which in previous programs had to be supplied, can now be calculated using the computer program based on the PMH hurricane model (3). This program is being used in most safety analysis reports for nuclear generating plants submitted to the U. S. Atomic Energy Commission.

This paper presents verification of the numerical model used to solve storm tide equations. Also presented are results of a calibration study, correlating computer predicted results to hurricane storm surge of record.

### Storm Surge Model

The model is based on the general equations of horizontal fluid flow simplified to eliminate certain second-order terms and to be quasi-one-dimensional in nature. The model is designed to analyze open-coast storm surge resulting from passage of an ideal PMH.

The basic equations on which the model is based may be written as follows:

$$\frac{df}{dt} = kUU_y - \frac{Kf|f|}{(h+\eta)^2} \tag{1}$$

$$\frac{d\eta}{dx} = \frac{kUU_x + \Omega f}{g(h+\eta)} \tag{2}$$

The x-axis is taken generally perpendicular to the coastal bathymetry contours (shown in Figure 1), with the origin located in deep water (600 to 900 ft.). The other parameters in the above equations are:

f        = flow-flux in the direction of the y-axis
           (perpendicular to the x-axis and along
           constant depth bathymetry contours)
U        = wind velocity
$U_x$, $U_y$ = wind velocity component along the x-axis
           and y-axis, respectively
k        = wind stress coefficient
K        = bottom friction coefficient
η        = surge elevation above stillwater level
h        = stillwater depth at a given instant of time
           (includes the effects of tides, barometric
           pressure effects, and any initial surge
           effects due to meteorological anomalies)
Ω        = Coriolis parameter ≈ 0.5235 sinΦ, rad/hr
Φ        = degrees north latitude
g        = acceleration of gravity taken as
           32.2 ft/sec²

    Equations 1 and 2 result from the basic horizontal flow
equations with the following assumptions:

    1.   Wind gradients and water depth variations in a
         direction normal to the x-axis are assumed to be
         small; thus, the problem becomes essentially
         one-dimensional.

    2.   No flow occurs in the x-direction, and the surge
         elevation occurs instantaneously in time; thus,
         a hypothetical vertical barrier to fluid motion
         normal to the coast is presumed.

FIGURE 1
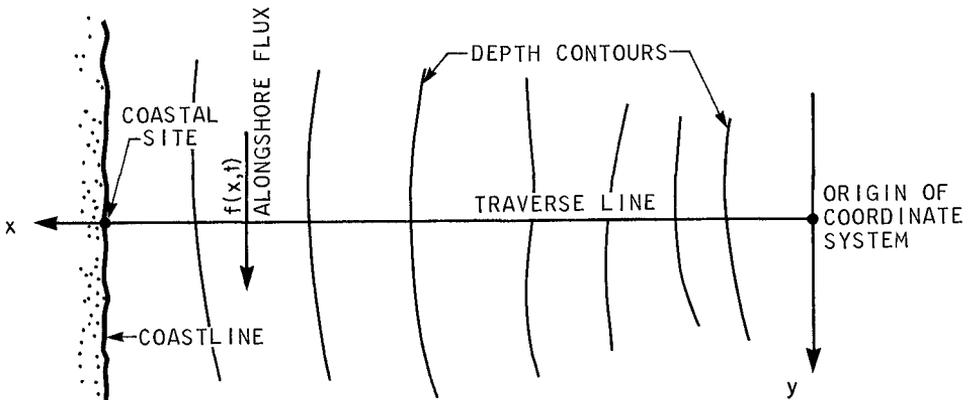
The relationship governing wind stress, $T_0$, is usually in the following form:

$$\frac{\vec{T_0}}{\rho_\omega} = \frac{\rho_a}{\rho_\omega} C_D U^2 \frac{\vec{U}}{|U|} = k |U| \vec{U} \qquad (3)$$

where
$C_D$ = drag coefficient
$\rho_\omega$ = density of fluid
$\rho_a$ = density of air
$U$ = wind velocity  (at the 10-meter level)

Several studies (4,5,6) indicate that the drag coefficient, $C_D$, has the form:

$$C_D = A + B (1-U_0/U)^2 \qquad (4)$$

where
$A$  = constant
$B$  = constant
$U_0$ = critical wind velocity, below which $C_D$ = A

In comparing the four equations above, the wind stress coefficient obtains the form:

$$k = \rho_a/\rho_\omega \left[ A+B (1-U_0/U)^2 \right] \qquad (5)$$

Wilson (4) correlates the work of numerous investigators in an attempt to determine the value of the coefficients A and B.  From the above investigation, the following values for A and B are indicated:

$$A = 1.0 \text{ to } 1.1 \times 10^{-3}$$
$$\qquad \qquad \qquad \qquad \qquad (6)$$
$$B = 1.2 \text{ to } 1.8 \times 10^{-3}$$

The critical wind velocity, $U_0$, is between 13 and 16 miles per hour.  The density ratio, $\rho_a/\rho_\omega$, for standard conditions (20°C and 29.92 in. Mercury) and for sea water is taken to be:

$$(\rho_a/\rho_\omega)_{STP} = 1.17 \times 10^{-3} \qquad (7)$$

The density ratio is affected by changes in the barometric pressure, the dewpoint temperature, and the air temperature.  In the case of a PMH hurricane acting on coastal waters, the greatest variation in this ratio is caused by local barometric pressure changes.  Assuming a linear relationship between air density and barometric pressure, the density ratio becomes:

$$(\rho_a/\rho_\omega) \approx 1.17 \times 10^{-3} \times \frac{P}{29.92} \qquad (8)$$

where
$P$ = local barometric pressure in inches Mercury

The local pressure, P, in the presence of a hurricane (3) may be taken as:

$$P = P_\eta - (P_\eta - P_o) \left[ 1 - \exp(-R/\rho) \right] \tag{9}$$

where

$P_\eta$ = asymptotic pressure of hurricane
$P_o$ = central pressure of hurricane
$R$ = radius of maximum winds
$\rho$ = radial distance from hurricane center

Thus, the pressure is determined from Equation 9, and the wind-stress coefficient takes the form of:

$$k = \left[ CSK1 + CSK2 \, (1-U_o/U)^2 \right] \times 1.17 \times \frac{P}{29.92} \tag{10}$$

The coefficients CSK1 and CSK2 obtain values of $10^{-3}$ times those shown for A and B values, and the critical velocity, $U_o$, is taken as 15 miles per hour.

The bottom-friction factor, K, is largely dependent on the bottom condition. There is evidence (2) that K depends on the prevailing slope of the sea bottom and on the length of the traverse line (distance of the deep water origin from shore). Most evidence indicates that K has a value in the range of 0.002 to 0.005 for the form of the bottom-friction effect assumed in Equation 1.

The numerical scheme used to solve Equations 1 and 2 will not be described here. Details of the numerical program are described in another study (7). Also described in that study is the hurricane model used to define the input wind field.

## Verification of Model

The numerical scheme was verified by comparing computer predicted results to simplified, known analytical solutions. The first hypothetical case tested was for a rectangular basin of constant depth. The basin had vertical sides over which a wind, constant in time but variable in space, acts. The wind distribution was assumed to be Gaussian, with a maximum value occurring at the end of the basin. The geometry for this test case is shown in Figure 2 below.



FIGURE 2
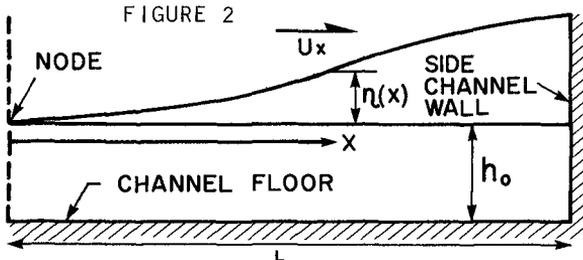
The value of the surge is assumed to be zero at the
origin of coordinates (x = 0). It is further assumed that
the wind acts along the x-axis. Thus, if the effects of
bottom friction are ignored, Equation 2 may be used to
determine the steady-state solution for the surge amplitude.
The detailed analytical solution is shown in an earlier
study (7).

Figure 3 shows the analytical solution for the surge
amplitude as well as the results obtained from the computer
program. Figure 3 indicates that the output of the program
shows negligible deviation from the theoretical results.
Additional analytical cases were studied, and they indicate
comparable agreement with computer predicted results (7).

The computer program was correlated to historical hurri-
cane data of record primarily to determine the two constants
(CSK1 and CSK2) appearing in the wind-stress coefficient taken
from Equation 10. Recorded hydrographs at known shoreline
locations and recorded meteorological and oceanographical data
were obtained for several severe historical hurricanes. Much
of this data was obtained from the National Oceanic and
Atmospheric Administratioñ (NOAA). The following data of
record were used:

1.  Hurricane Carla (1961)--Galveston and Sabine Pass,
    Texas, hydrographs
2.  Hurricane of 1949--Brazos Port, Texas, traverse
3.  Hurricane Carol (1954)--Newport, Rhode Island,
    traverse
4.  Hurricane Audrey (1957)--Eugene Island, Louisiana,
    traverse
5.  Hurricane Camille (1969)--Peak surge at Biloxi,
    Mississippi

The hurricane data were digitized and used as input to
the computer model in order to generate a surge hydrograph.
The computer-generated hydrographs were then compared with
the hydrographs of record to obtain appropriate wind-stress
coefficients.

Three comparison methods were used to judge the accuracy
of calculated hydrographs relative to recorded hydrographs.
In the first method, a point-by-point comparison was made by
looking at the percentage difference between the two hydro-
graphs at each time-step. The time-steps were defined by the
times given for the hurricane-wind-field data.

The second method takes an overview of the hydrograph
while emphasizing the maximum surge. With this method, the
sum of the squares of the differences between the two hydro-
graphs were computed for the duration of the hydrograph. Also,
a percentage difference at the point of maximum surge was
calculated.

FIGURE 3
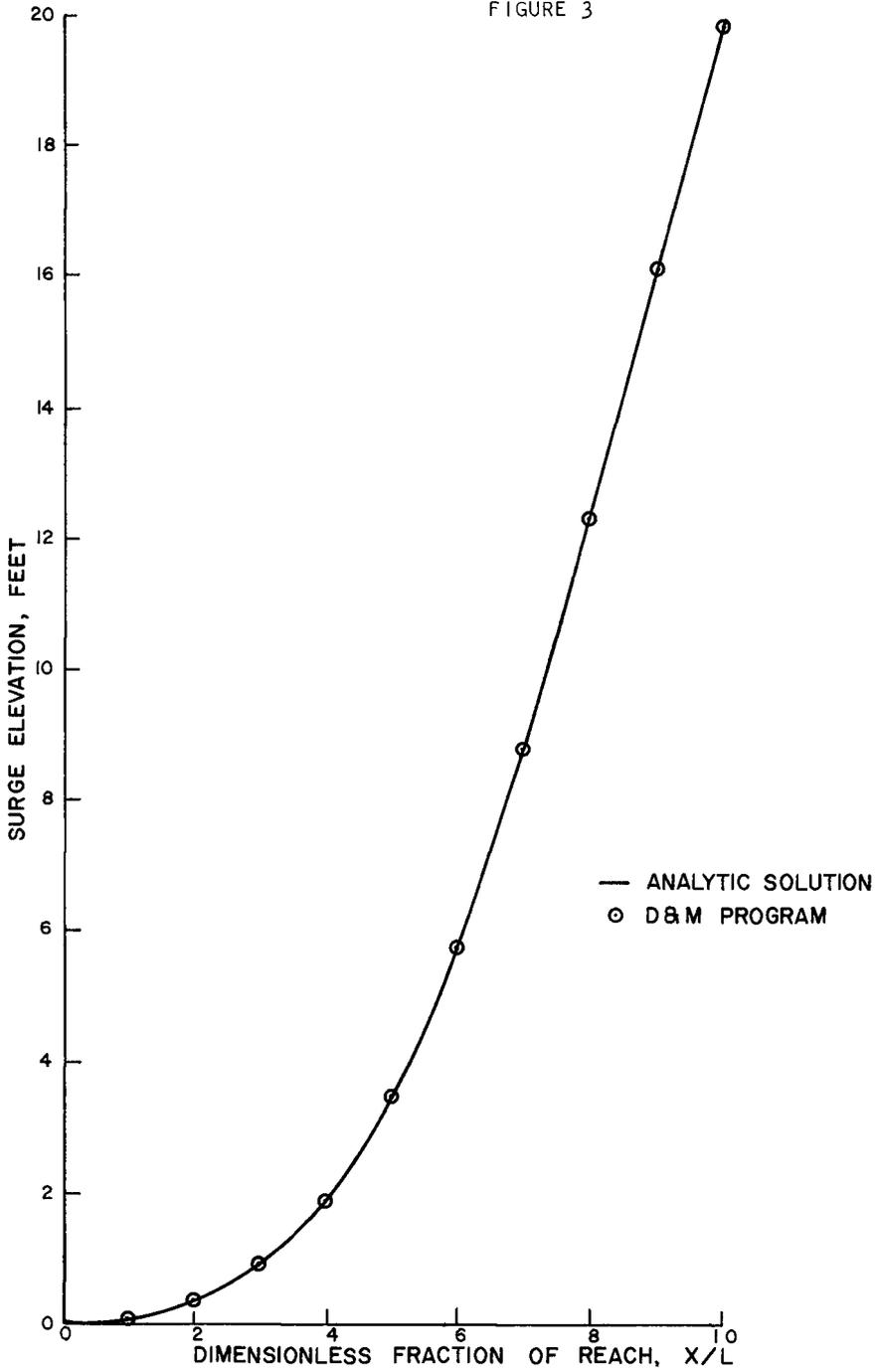
The final comparison method showed the average percentage difference, for each one-third portion, between the two hydrographs. The "fit" of the critical middle-third of the hydrograph was then analyzed. This section is considered critical because it exhibits a rapid rise in water elevation and shows the maximum water levels.

The above described methods of comparison resulted in a four "best fit" correlation criteria. These criteria, in order of importance, were taken to be:

1.    The maximum calculated surge must be greater or equal to that observed.
2.    The middle third of the calculated hydrograph must, on the average, be greater than the corresponding portion of the observed hydrograph.
3.    The deviation between the calculated hydrograph and the observed hydrograph (exemplified by the sum of squares of differences) should be a minimum.
4.    The beginning and end thirds of the calculated hydrograph relative to the observed hydrograph should exhibit a minimum skewness, with a minimum error being desirable.

The limits between which the calibrating input parameters (for wind and bottom friction) were allowed to vary have been discussed previously. Using these limits in conjunction with the criteria for "best fit," the input parameters were handled in the following manner:

1.    A value of CSK1 was held constant while values of CSK2 were varied between the limits previously discussed. This procedure was followed for the full range of CSK1 values.
2.    The bottom friction factor for each pair of CSK1 and CSK2 was varied until the "best fit" condition was reached.

Hurricane Carla hydrographs (Galveston and Sabine Pass stations) exhibited strong correlation with computer predicted results. The Eugene Island hydrograph exhibited fair correlation; while the Freeport and Narragansett Bay cases exhibited poor correlation. Based on an overall assessment of the study results, the following wind-stress coefficient values were selected:

$$CSK1 = 1.0 \times 10^{-6}$$
$$CSK2 = 1.4 \times 10^{-6} \tag{11}$$

A strong correlation between bottom friction coefficients and predicted hydrographs was not observed in this study. However, bottom friction coefficients appear to lie within the range of 0.002 to 0.005.

For example, a bottom-friction coefficient of about 0.003 was indicated for the Sabine Pass traverse, which is relatively long.  The Galveston traverse, which is shorter, has a bottom-friction coefficient of about 0.002.

The detailed correlation analysis is contained in reference 7.  An example of a correlation computer run for the case of Hurricane Carla (Galveston traverse) is shown in Figure 4.

A hydrograph of record was not available for Hurricane Camille.  However, peak surge elevations could be estimated from debris lines indicating high water marks near Biloxi, Mississippi.  This surge elevation, along with Hurricane Camille data, was used to cross-verify correlation results.

The wind-stress coefficient values used were obtained from the correlation study.  A bottom-friction coefficient of 0.002 was chosen due to the comparable length of the Biloxi and Galveston traverses.  The numerical model indicated a peak surge that closely matched the observed high-water debris marks.

## Conclusions

It is extremely important when designing coastal structures, especially nuclear power plants, to properly assess the magnitude of hurricane storm surges.  Simplified one-dimensional models are the currently accepted means of calculating hurricane storm surge.  The model discussed here was verified and correlated with historical hurricane data.  Although reasonable correlation was obtained, it is apparent that reliable hurricane data is severely limited.

As additional hurricane data is received, a more refined storm-surge model can be considered.  Such a model should include the effects of convective transport, coastal flooding, and two-dimensional aspects.

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FIGURE 4
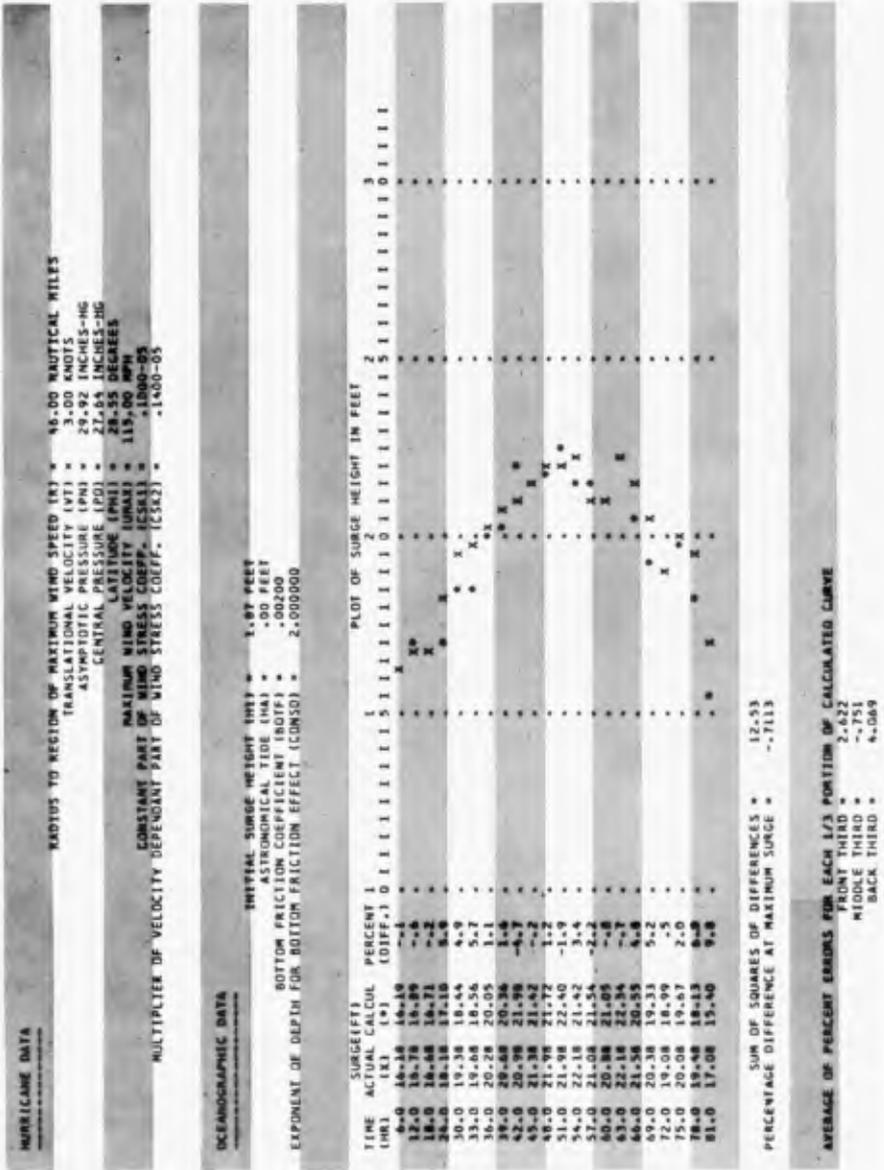


"BEST FIT" CONDITION FOR GALVESTON TRAVERSE

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