HYDROLOGIC ENGINEERING SUMMARY AND EVALUATION OF THE HURRICANE VERIFICATION STUDIES AND DESIGN BASIS HURRICANE
CRYSTAL RIVER NUCLEAR GENERATING PLANT
DOC. NO. 50-302

The staff and our consultant, the U.S. Army Coastal Engineering Research Center (CERC), have independently undertaken the verification of the CERC model for the 1949 hurricane and hurricanes Carla, Camille, Audrey, and Carol.

Both models numerically integrate the differential equations of horizontal flow. The equations are quasi-two-dimensional and are first or second order approximations of the equations for wind-induced flow. The significant differences in the two models are the numerics used to solve the flow equations and the form of the wind stress coefficient equation.

The form of the D&M equation is given in their documentation and on page 3 of "Summary of Applicant's Hurricane Studies," a companion enclosure. The CERC version of the wind stress coefficient is as follows:

$$K = C(A + B(1 - 16/U)^2)$$

where;

K = wind stress coefficient

A and B = 1.1 $\times 10^{-6}$ and
2.5 $\times 10^{-6}$, respectively

ENCLOSURE 2

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based upon Van Dorn's relation
for wind stress

U = wind speed in mph

C = multiplier, based upon reconstitutions of historical hurricane surges = 1.1 for Crystal River

From a practical standpoint, the staff believes that the wind stress and bottom friction coefficients used in both models actually represent model calibration coefficients which include more than the physical effects of wind and friction. The models are intended to describe only the surge levels (and not waves) caused by severe storms, such as hurricanes, when the physical situation may be highly turbulent. Therefore, the so-called bottom and wind stress relationships are considered to be representative of all the remaining unknowns.

Basic data preparation was divided between CERC and the AEC. CERC developed the basic bathymetry data for all traverses and wind field digitization for hurricanes Camille and Carol, and AEC digitized wind field data for the 1949 hurricane and hurricanes Carla and Audrey. In addition, the staff reviewed the numerics of both the CERC and Dames & Moore models, the Dames & Moore hurricane surge reconstitutions and test cases, and made comparisons between the two models.

The staff compared the independently developed Dames & Moore and staff digitized wind field data for hurricanes Carla (Galveston traverse) and Audrey (Eugene Island traverse) to determine whether there were significantly different interpretations of the basic sequential, synoptic hurricane wind field charts developed by NOAA. There were no differences of consequence for hurricane Audrey. For hurricane Carla, however, the wind speed and wind angles for two time periods near the maximum surge showed significant differences in wind field interpretations. The staff double-checked the interpretation of the NOAA wind field charts and concluded the Dames & Moore interpretations are incorrect. The consequences of the Dames & Moore Carla wind field interpretation are that their verification is somewhat lower than it should be and, accordingly, this would have some effect on the selected calibration coefficients.

The attached table summarizes initial conditions used and results obtained by both models for historical hurricane surge reconstitutions, test cases and probable maximum hurricane (PMH) surge estimates for Crystal River.

Locations for which sufficient hurricane data was available to make meaningful surge reconstitutions were limited, since both models are only valid for open coast locations. The staff has concluded that only surges for hurricane Carla at Galveston and hurricane Audrey at Eugene Island were sufficiently "open coast" to be meaningful.

In comparing the results from both the CERC and Dames & Moore models for the two storms, the staff has concluded that reconstitutions with both models are equally good, but that two reconstitutions are insufficient to judge which is the better model. Further, the "adjustment" of recorded surge hydrographs by D&M (see attached table) reduces the confidence which may be placed in the various coefficients used in their verifications.

The staff believes that because of the coupled nature of the bottom friction coefficient, wind stress correction factors and initial rise in both models, the results of the verification studies using both models have not established values of these parameters which can be readily transferred or extrapolated to PMH conditions at locations for which no historical surge records exist without utilizing conservative estimates for each parameter. In comparing only the two forms of wind stress coefficients, values for historical hurricane wind speeds can yield similar results. When extrapolated to PMH conditions, however, significant differences result.

As previously noted, D&M stated that effect of the truncation errors in CERC's model pr~vented an accurate solution of the test cases and would produce errors in the CERC estimate of a PMH. However, in reviewing the Dames and Moore verification study, and the test cases analyzed therein using both models and analytical solutions, the staff determined the CERC model would yield closer approximations to the analytical solutions than indicated by Dames and Moore when closely spaced traverse points (bathymetry) and small time increments are used; thus, preventing any significant truncation errors. The comparative results of the test cases are considered inconclusive by the staff in judging which model may be better.

The staff has also analyzed the development of the CERC model finite difference technique to determine whether any refined numerical solution would allow reduction or elimination of potential truncation errors. The results indicated a direct solution (definite integral) may be made of one differential equation. This direct solution (see attached) was incorporated in a modified version of the CERC program and tested using data for hurricanes Carla and Audrey. The results indicated differences of less than 2 percent in the basic CERC model, the modified model computing higher surge levels.

In reconstituting historical surges, the staff found difficulty in establishing values for initial surge. The normally accepted definition of initial surge is the elevated water level that is evident in the tide gage record before the arrival of strong hurricane winds. Furthermore, the selection of appropriate bottom friction coefficients and the selected initial surge value are coupled (dependent) to estimates of the wind stress relationship.

In reviewing the technical bases for the CERC model, the staff determined that the finite difference technique (for both time and space) being employed in the CERC model could indeed lead to relatively large errors if the model is not carefully employed as recommended by CERC. To overcome potential truncation errors with the CERC program, it is generally necessary to use time steps between wind field orientations of an hour or less, and to define the bathymetry close to shore with a spacing between computational traverse locations of a mile or less. In addition, a number of textual errors were observed in CERC TM No. 35 (see attached).

In comparing the Dames & Moore (29.4 feet MLW) and CERC (33.4 feet MLW) PMH estimates for Crystal River, the staff noted two basic differences as follows:

a) The Dames & Moore bathymetry contains two near-shore underwater shoals, but the CERC estimated bathymetry does not. The staff estimated that use of the Dames & Moore traverse profile would reduce the peak surge estimate by up to a foot. There appears to be no evidence to support the inclusion of the shoals, since the profiles should represent general area bathymetry, and not local anamolies. The attached figure shows the two traverse profiles.

b) The form of the wind stress coefficient as discussed herein.

Both the staff and CERC have recomputed a PMH surge level for the Crystal River site, and believe a design bases water level of 33.4 feet above mean low water provides a suitably conservative design basis water level.

In conclusion, the staff has independently concluded that both the CERC and Dames & Moore hurricane surge models can be used to predict open coast hurricane surges if conservative estimates of bottom friction and wind stress are employed to assure the estimated surge level represents the case dictated by the PMH definition -- the worst reasonably possible. Because the wind stress coefficient used in the CERC estimate of the Crystal River PMH may be used in the reconstitution of historical surges with as much confidence as the Dames & Moore wind stress coefficient, the staff concludes the CERC stillwater estimate of 33.4 feet MLW should be used as a hurricane design bases to assure the safety of the plant. Furthermore, since insufficient historical data exists to conclusively establish transferrable (both in location and for high wind speeds) bottom friction and wind stress relationships, and since there is little likelihood of accumulating sufficient hurricane data to do so, the staff also concludes that further research is desirable to analytically, experimentally and firmly establish acceptable working values. Pending the outcome of any future research, the staff concludes the CERC form of the wind stress equation (as indicated on page 1 herein) and conservative bottom friction coefficients should be used in PMH estimates.

DIRECT INTEGRATION OF ALONG-SHORE FLUX EQUATION

I

equation 12 $$\frac{\partial V}{\partial t} = kW^2 \text{ Sin}\theta - KV^2D^{-2}$$ 1

equation 18+1 $$B = kW^2 \text{ Sin}\theta$$ 2

substitute 2 in 1

$$\frac{\partial V}{\partial t} = B - KV^2 D^{-2}$$ 3

let $$\frac{\partial V}{\partial t} = \frac{V^{n+1}_{i+1/2} - V^{n}_{i+1/2}}{\Delta t}$$ 4

substitute 4 in 3

$$\frac{V^{n+1}_{i+1/2} - V^{n}_{i+1/2}}{\Delta t} = B - KV^2D^{-2}$$ 5

let K be a constant

let $$B = 1/2\left[\left(\frac{B_i + B_{i+1}}{2}\right)^n + \left(\frac{B_i + B_{i+1}}{2}\right)^{n+1}\right]$$

$$= 1/2\left[\left(\overline{B_i + B_{i+1}}\right)^n + \left(\overline{B_i + B_{i+1}}\right)^{n+1}\right]$$ 6

reduce 3

$$\frac{\partial V}{\partial t}\left(\frac{1}{B - KV^2D^{-2}}\right) = 1 \cong \frac{dV}{dt}\left(\frac{1}{B - KV^2D^{-2}}\right)$$

$$\frac{dV}{B - KV^2D^{-2}} = dt$$

ATTACHMENT

$$1/B \quad \frac{dV}{\frac{1-KV^2D^{-2}}{B}} = dt \qquad 7$$

let B, K & D be constants over small dV & dt and integrate 7

$$1/B \int_{V_1}^{V_2} \frac{dV}{1-\frac{K}{B} V^2 D^{-2}} = \int_{t_1}^{t_2} dt$$

$$\frac{B}{D^{-2}K}\frac{1}{B} \int_{V_1}^{V_2} \frac{dV}{\frac{B}{KD^{-2}} - V^2} = t_2 - t_1$$

$$\frac{1}{D^{-2}K} \int_{V_1}^{V_2} \frac{dV}{\frac{B}{KD^{-2}} - V^2} = \frac{1}{D^{-2}K}\left[\frac{1}{2\sqrt{\frac{B}{KD^{-2}}}} \log\left(\frac{\sqrt{\frac{B}{KD^{-2}}} + V}{\sqrt{\frac{B}{KD^{-2}}} - V}\right)\right]_{V_1}^{V_2}$$

$$= \frac{D^2}{2K}\frac{K^{1/2}}{B^{1/2}\,D}\left[\log\left(\frac{D\left(\frac{B}{K}\right)^{1/2} + V}{D\left(\frac{B}{K}\right)^{1/2} - V}\right)\right]_{V_1}^{V_2} = t_2 - t_1$$

$$\log\left[\frac{D\left(\frac{B}{K}\right)^{1/2} + V_2}{D\left(\frac{B}{K}\right)^{1/2} - V_2}\right] - \log\left[\frac{D\left(\frac{B}{K}\right)^{1/2} + V_1}{D\left(\frac{B}{K}\right)^{1/2} - V_1}\right] = M$$

$$= 2(t_2 - t_1)\,\frac{K^{1/2}\,B^{1/2}}{D} \qquad 8$$

let $\frac{D\left(\frac{B}{K}\right)^{1/2} + V_1}{D\left(\frac{B}{K}\right)^{1/2} - V_1} = N$ 9

substitute in 8

$$\log\left[\frac{\left(D\left(\frac{B}{K}\right)^{1/2} + V_2\right)}{\left(D\left(\frac{B}{K}\right)^{1/2} - V_2\right)}\right] - \log N = M$$

$$\frac{D\left(\frac{B}{K}\right)^{1/2} + V_2}{D\left(\frac{B}{K}\right)^{1/2} - V_2} = N\text{antilog } M$$

$$= P$$ 10

$$D\left(\frac{B}{K}\right)^{1/2} + V_2 = P\left(D\left(\frac{B}{K}\right)^{1/2} - V_2\right)$$

$$V_2\ (1 + P) = D\left(\frac{B}{K}\right)^{1/2} (P - 1)$$

$$V_2 = D\left(\frac{B}{K}\right)^{1/2} \frac{(P - 1)}{(1 + P)}$$

$$= D\left(\frac{B}{K}\right)^{1/2} \frac{(N\text{antilog } M - 1)}{(1 + N\text{antilog } M)}$$ 11

let $D\left(\frac{B}{K}\right)^{1/2} = Q$ 12

substitute 12 in 11

$$V_2 = Q \frac{(N\text{alog } M - 1)}{(1 + N\text{alog } M)} \quad 13$$

substitute 9 & 12 in 13

$$V_2 = \frac{Q\left(\left(\frac{Q + V_1}{Q - V_1}\right) \text{alog } M - 1\right)}{\left(1 + \left(\frac{Q + V_1}{Q - V_1}\right) \text{alog } M\right)} \quad 14$$

substitute 8 in 14

$$V_2 = Q \frac{\left[\left(\frac{Q + V_1}{Q - V_1}\right) \text{alog } 2(t_2 - t_1) \frac{B}{Q} - 1\right]}{1 + \left(\frac{Q + V_1}{Q - V_1}\right)\left(\text{alog } 2(t_2 - t_1) \frac{B}{Q}\right)} \quad 15$$

limited to small Δt when wind speeds are changing and to small $\Delta \ell$ when the bathymetry changes