CHAPTER 194

MODEL VERIFICATION FOR TIDAL CONSTITUENTS

By

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ABSTRACT

Installation and operation of an automated model data acquisition and control system have made it possible to make a quantum advance in the accuracy and time required for verification of tidal inlet (or estuary) hydraulic models. The flexible sampling rate (usually about 200 samples per model tidal cycle for each gage) and digital recording of these data make them ideal for harmonic analysis and comparison with prototype data defining the coefficients and phase for each tidal constituent at various key locations within the tidal lagoon and at an open-ocean station removed from the immediate influence of the tidal inlet. The concept used is to force the model with the M_2 tidal constituent with the amplitude being correct at the ocean tide gage. A harmonic analysis is performed at all other gage locations corresponding to the prototype measurements, and the amplitude and phase (relative to the ocean tide gage) are calculated and compared with the prototype data. Investigation of the relative phases between various gages quickly shows those areas where either more or less model roughness is required. It is reasonable to expect to be able to have all phases for the M_2 constituent verified within 1 degree. Tidal elevations can almost always be expected to be verified to within a maximum deviation of ±0.1 ft in both tidal height and mean tide level. Upon verification of the M_2 constituent, which practically insures that the proper channel roughness is obtained, a progressive tide can be constructed; and it should be attempted to perform a verification for a 14.765-day (synoptic period for M_2 and S_2 components) progressive tide at east coast locations using the prototype measurements of tidal velocities for the final verification data. Should additional roughness be necessary, it will almost always be on the mud flats or marsh areas. Computations are made to illustrate the energy transfer from the M_2 constituent to higher order harmonics as the wave propagates from the ocean to the back of the estuary, and it is shown that this energy transfer is, at worst, the same order of magnitude in both the model and prototype.

The concept ventured in this paper has been applied to verification of the Murrells Inlet, South Carolina, hydraulic model. Model scales were 1:60 vertical and 1:200 horizontal (a distortion ratio of 3-1/3:1).

Major conclusions are that verification based on the M_2 constituent is feasible and was quite successful in the Murrells Inlet, South Carolina, model, and it is postulated that a method similar to that contained in this paper should be used for the verification of numerical models.

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INTRODUCTION

Design, construction, and operation of hydraulic models of tidal inlets in order to evaluate the effects of planned improvements to inlet-estuary systems are common problems undertaken in the Wave Dynamics Division. Usually the improvement consists of either proposed jetty construction to stabilize and maintain some project depth in an entrance channel or lengthening of existing jetties with an associated deepening of the entrance channel to accommodatelarger and deeper-draft vessels. This type of problem has been common during the past 20 years and is anticipated to continue for the foreseeable future since there are about 340 navigable tidal inlets and river entrances along the east, Gulf, and west coasts of the continental United States.

Tidal inlet models are practically always distorted out of necessity for various reasons which will be mentioned but not discussed. Many times tidal inlets are large and the bathymetry includes flood and ebb tidal deltas which are quite shallow leading to large model energy attenuation and viscous friction scale effects on waves. These effects can be minimized through distortion and at the same time decrease model costs. It is extremely desirable to reproduce the entire tidal estuary for reasons which follow. Inclusion of the tidal estuary in the model results in the flexibility to study the effects of proposed improvements on the tidal prism, tidal circulation, tidal flushing, and salinity of the estuary. In addition, inclusion of the estuary should result in the correct nonlinear energy transfer from various tidal constituents to higher order harmonics. Deletion of a major portion of the estuary leaves reproduction of this phenomenon considerably more uncertain, although its improtance is not well established but should perhaps be investigated on a case-by-case basis.

This paper focuses attention on the problem of model verification and reports on an attempt to verify a model by using the elevation and phase of the M_2 tidal constituent for the principal verification tool. A progressive tide was subsequently used in the final phase of verification. The model being used was of Murrells Inlet, South Carolina; and since this was a project study (not a research study), there are several experimental tests which should be conducted to supplement the knowledge gained in this investigation. These areas are pointed out and will, hopefully, be the subject of future research.

HYDRAULIC MODEL OF MURRELLS INLET, SOUTH CAROLINA, USA

This section gives a brief discussion of model design, instrumentation, and the automated data acquisition system used in the model study. Verification by tidal constituent is practically impossible without an automated data acquisition system which was an integral part of this model study.

Model Design

Murrells Inlet, South Carolina, is an unimproved inlet, Figure 1, with an existing main channel of only about -4.0 ft mlw which meanders and is not stable. The estuary is actually a well-mixed tidal lagoon of ocean salinity with no source of fresh water inflow except for surface runoff from rainfall. Figure 2 illustrates the model layout showing the head bay, wave generator locations, and locations of prototype and model tide gages and velocity ranges. Vertical scale of the model is 1:60 and horizontal scale is 1:200 resulting in a distortion of 3-1/3.

An interesting point to designers of hydraulic models is that a portion of the model bathymetry (seaward of the -22 ft mlw contour) is artificial in order to compensate for refraction due to bathymetric variations seaward of this contour which could not feasibly be installed in the model because of the extremely large distance seaward. This is a typical problem along the east and Gulf Coast of the United States. This represents the first use (at the Waterways Experiment Station) of an artificial bathymetry to correct for refraction seaward of the model limits and will be the subject of a future paper. A thorough discussion of this appears in the final report (Perry, 1976) to be published near the end of this calendar year. The artificial bathymetry was chosen to yield the approximate prototype energy distribution and wave direction at the -22 ft mlw contour from all wave directions of interest in the model study.

Instrumentation

The principal information required in the verification process is tidal elevation data. Various types of tidal height sensors are in use; however, the Murrells Inlet model used a "bubbler system" or gage which measures small hydrostatic pressure changes associated with changes in model tidal elevations. The "bubbler system" consists of a high precision pressure transducer, a scanivalve device for sequencing input ports, and 48 pressure inputs. Durham et al. (1976) gives a thorough discussion of the model sensors. Wave gages also were installed in the model but are not discussed here since those data were not essential to the verification process. Velocities of tidal currents were measured with minature Price-type current meters and with two electromagnetic velocity meters. Most data were acquired with the minature Price meters, but the electromagnetic current meters seem to be quite promising for future model use.

Data Acquisition

An automated data acquisition and control system (acronym ADACS) has been designed, procured, installed, and is operational on wave and tidal inlet models at WES. Durham, et al. (1976) describes the system. The principal functions of ADACS are to provide automated acquisition of wave and tide data in a format compatible for digital reduction and analyses and automated control of model sensor calibration and of wave and tide generators.

Figure 1. Murrells Inlet, South Carolina.

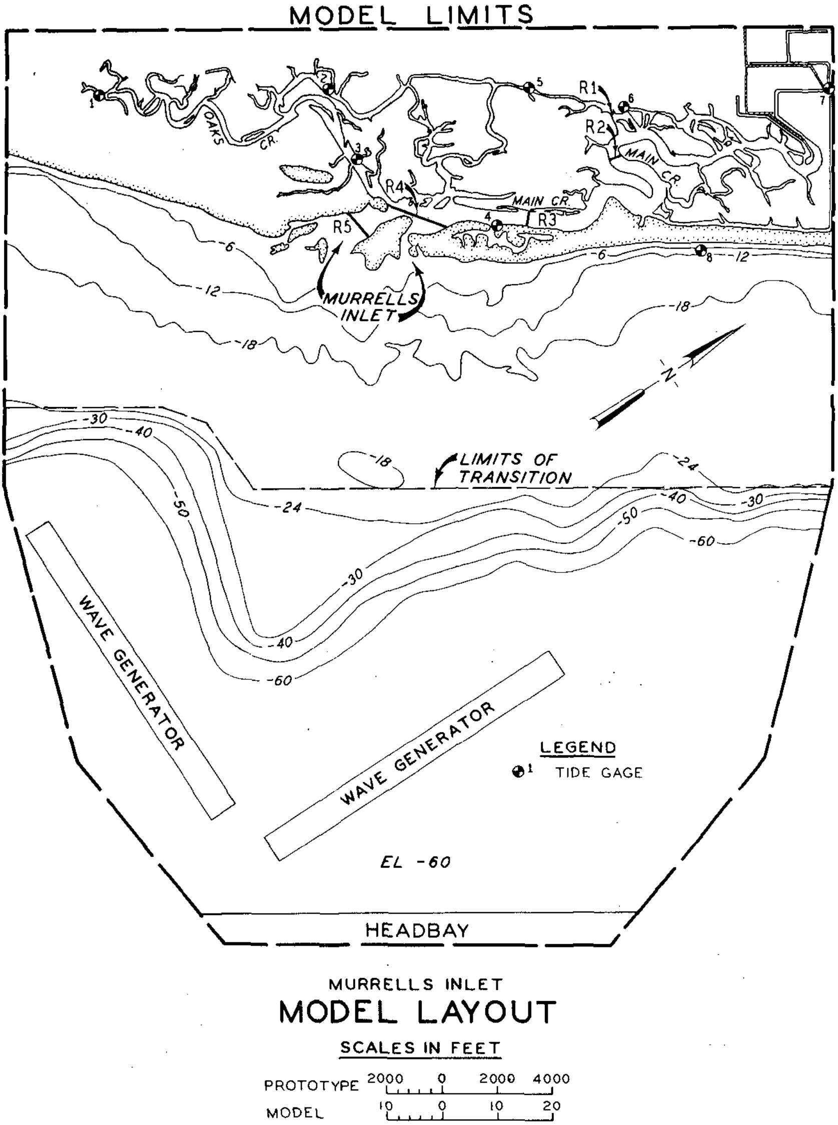


Figure 2. Model Layout.

Tidal elevation data for a programmed tide condition are collected from a specified number of tide sensors, digitized and recorded on magnetic tape or disc for future analysis. A flexible sampling scheme is used and is only limited in sampling rate by the scanivalve multiplexing rate. The sampling scheme used for this study consisted of the following (a) increment the scanivalve to the first data channel, (b) delay a specified time interval (usually 0.5 sec) to allow input pressure stabilization, (c) collect a specified number of samples (10 in this case), (d) average the voltage samples, (e) store the discrete sample in memory, (f) increment to the next channel, (g) repeat the above procedure, and (h) continue sequentially through the remaining channels. Using input parameters, the minicomputer calculates (1) the required timing interval between scanivalve multiplexing scans to provide the correct sampling rate, (2) the delay interval at each channel, and (3) the number of voltage samples to be digitized and averaged and initializes counters for determining completion of tidal tests. In addition, it provides an analog command signal through the digital to analog converter to the tide generator and lags the beginning of data acquisition by a specified number of tide cycles after starting the generator.

Due to thermal effects (zero drift) on the transducer output over a tidal test of 2-3 hours duration, the pressure transducer is calibrated prior to and at selected time intervals during each tidal test to provide accurate, update calibration data for scaling voltage (pressure) to tidal elevations. Durham et al. (1976) give a complete discussion of the calibration procedure.

A limited number of channels of tidal velocity can be measured by miniature, electromagnetic current meters which are monitored by ADACS. The collection of tidal velocities using ADACS has not been fully implemented at this time and is pending the completion of transducer evaluation which should be within the next year. Until such time, the majority of tidal velocity measurements are obtained manually by using a modified version of the miniature Price meters.

In addition to tide data, most tidal inlet studies require wave information. Generation and acquisition of wave data at specific tidal phases (normally high, low, and mean tide levels) are provided by ADACS. While controlling the tide generator and collecting tidal data, ADACS uses in-core timers to determine the occurrence of specified tidal phases at which times (1) the wave generators are turned on, (2) wave data at a specified sampling rate for a predetermined number of wave periods are collected at various locations in the model, (3) the completion of wave test for that tidal phase is detected, (4) the wave generators are turned off, and (5) in-core timers initialized to determine the next specified tidal phase for wave tests. These wave tests are performed normally during the middle cycle of a three-cycle tidal test. The instrumentation and procedure for collecting wave data are the same as described in Durham and Greer (1975).

At completion of the acquisition mode, the calibration, wave, and tide data have been recorded in binary form on magnetic tape or disc. Schematically, the automated procedures for analyzing tidal data are as follow:

I. Program Initialization

  (1) Input test parameters and option flags.
  (2) Read and decode data tape or disc file.
  (3) Demultiplex data files and scale data.

II. Tidal Data Analyses

  (1) Harmonic analysis using Least Squares techniques.
    (a) Amplitude and phases of tidal constituents.
    (b) Relative phases between gages.

  (2) Analyses of residual variances.
    (a) Original versus Least Square estimate.
    (b) Prototype tide versus model tide.
    (c) Model base test versus model plans.

  (3) Graphic output of above results.

In addition to the above automated procedures, manual and photographic techniques are employed in tidal models to study general patterns of tidal circulation and to qualitatively define littoral transport and deposition patterns. Analyses of wave data are discussed by Durham and Greer (1975) and are basically auto-spectral and cross-spectral analyses, statistical analyses for wave heights and periods of wave signals at selected locations throughout the model, and computation of response functions or amplification factors from wave energy within the harbor or tidal inlet relative to incoming wave energy.

PROTOTYPE DATA

Model verification can be no better than the prototype data available for verification. Recent improvements and advances in acquisition of hydraulic model data (ADACS) have resulted in the situation where model data are almost invariably more accurate than the prototype data. The method of verification discussed in this paper was selected subsequent to collection of the prototype data (of course after evaluation of these data to ascertain their adequacy for such an approach). As a result the tidal elevation data are completely satisfactory, but the velocity data are not adequate to extract components of the various tidal constituents. Nonetheless, they are satisfactory for velocity verification during a portion of the progressive tide. The verification method described makes primary use of tidal elevation data.

Tidal Elevations

Prototype data on tidal elevations were obtained at seven locations in the tidal lagoon and one location on the open coast north of the inlet. The gages were installed, operated, and analyzed by personnel of National Ocean Survey (NOS) of the National Oceanographic and Atmospheric Administration for a period of approximately 6 months. Gage locations are shown in Figure 2, and results of the NOS analysis of these data for the tidal constituents at the open-coast gage are shown in Table 1. As indicated in Table 1, the Murrells Inlet tidal regime is dominated by the principal lunar semidiurnal constituent M_2. The M_2 variance represents approximately 90 percent of the tidal variance in Murrells Inlet.

Table 1: PROTOTYPE TIDAL CONSTITUENTS

Component	H(ft)	κ(deg)	Component	H(ft)	κ(deg)
J_1	.0175	106.75	L_2	.0673	214.91
K_1	.2623	112.04	N_2	.5628	187.69
M_1	.0157	117.33	S_2	.3635	214.63
O_1	.2209	122.62	S_4	.0342	49.64
P_1	.0868	112.04	S_6	.0083	356.56
Q_1	.0429	127.91	P_2	.0029	214.63
ρ_1	.0084	127.17	T_2	.0214	214.63
M_2	2.4020	201.30	ν_2	.1092	189.51
M_4	.0106	23.13	2N	.0749	174.08
M_6	.0065	152.89	2Q	.0057	133.20
M_8	.0109	311.58	00	.0095	101.46
K_2	.0989	214.63	λ	.0168	207.49

Tidal Velocities

Prototype tidal velocities were measured for a 14-hr period on 1 May 1974 at the ranges illustrated in Figure 2. Depending on the channel width and depth, currents were measured every 30 minutes for 1 to 3 stations (marked by buoys) on each range at 1 to 3 water depths per station (surface, mid-depth, and bottom). Bottom and surface measurements were 3 ft above the bottom and 3 ft below the surface, respectively. Price current meters were used with a direct readout on boat for both speed and direction. A hand-operated winch was installed on the boat for raising and lowering the current meters. These velocity data are summarized in their entirety in Perry (1976).

Bathymetry

Bathymetric data required for model construction were obtained by the U. S. Army Engineer District, Charleston, and consisted of a survey of the offshore area at 500-ft intervals normal to the shore established baseline out to the 30-ft contour where the topography was taken directly from existing C&GS survey charts. The channels also were surveyed. Aerial photography (color infrared and black and white) was obtained at low water (while the gages were installed) from which the preceding high water line could be clearly distinguished. Spot elevations in the tidal lagoon also were obtained after inspection of the aerial photography in order to insure a good tie in between the prototype survey with the aerial photography.

MODEL VERIFICATION

Upon completion of construction of the Murrells Inlet hydraulic model the ADACS described previously had just been installed and became operational for Wave Dynamics Division models of harbors and tidal inlets. Availability of this new capability for acquisition and analysis of large quantities of model data led to the plan to attempt verification of Murrells Inlet model by using the M_2 tidal constituent and proceeding to use a progressive tide.

Procedure

In the past, verification of tidal inlet and estuary models has consisted of first matching model and prototype tide curves (recorded on a strip chart) at key locations within the estuary and on the open coast. This matching process was either performed by visual means or by a least squares analysis of a discrete (but relatively small) number of points during a tidal cycle. Adjustments in model roughness are made primarily on the basis of the tidal amplitude comparison but also considering the phase if there is an obvious disparity between model and prototype curves. It is difficult to visually detect relatively small phase differences if the relative phase of the tidal constituents is not known for either the model or prototype curves. Subsequent to verification of the tidal elevations, a tidal velocity verification is conducted where additional model friction adjustments are made. In the past, prototype data usually consist of a tide curve for several days (almost never an analysis of the amplitude and phase of the tidal constituents and their harmonics) and 13 or 25 hrs of velocity data at several stations along pertinent ranges in the inlet and estuary.

Upon considering the capabilities of the newly operational ADACS and the availability of prototype data on the amplitude and phase of the tidal constituents, it became apparent that we had the opportunity to possibly improve our model verification procedure with no increase in model testing cost (and potentially a decrease in future model testing costs). Considering the previous verification procedure, it was hypothesized that the time usually spent in velocity verification was probably really performing model roughness adjustments in order to make the tidal phases (model to prototype) agree. The basis for this hypothesis was that it is difficult to detect up to a 30-minute variation in phase when model and prototype data only consist of strip chart information which must be digitized and compared. Furthermore, the usual prototype velocity data consist of discrete velocity measurements every 20 to 30 minutes. A 5 to 20 minute variation in phase can, in some instances, make a large difference in velocity fields, especially at some critical locations near channel intersections and large flooding marshes. Therefore, it was concluded that any new verification procedure should focus on adjustments in model roughness to verify both tidal amplitudes and phases throughout the estuary as closely as possible.

The desired verification procedure can be summarized as follows:

a. Adjust the tide generator to reproduce M_2, M_4, M_6, and M_8 at the open-coast gage.

b. Calculate the amplitude and phase of M_2 at each gage in the inlet and estuary and tabulate the phases relative to the open-coast gage and relative to adjacent gages in the estuary and compare these calculations with one another. Also calculate the mean tide level at all gages and compare with that for the prototype.

c. Readjust model roughness (preferably between two gages only), conduct another test, and again calculate the amplitude and relative phases at all gages for the M_2 constituent.

d. Repeat Step c until a satisfactory verification has been achieved.

e. Construct a progressive tide and perform a velocity verification for that portion of the progressive tide for which prototype data are available. This should be near the middle of the model progressive tide.

It should be noted that the desired procedure described above was not precisely followed due to various reasons such as problems with the tide controller and time constraints on the project schedule. Actually the time generator was adjusted to reproduce the M_2 component at the open-ocean gage; however, the energy in M_4, M_6, and M_8 was not reproduced for this gage. Consequently, the energy in the overtides is not precisely what it should be; however, it is the correct order of magnitude. This will be discussed later in the paper in connection with energy transfer to higher order harmonics. The remainder of the procedure described above was followed. For emphasis, the parameter used to estimate the distribution (horizontal) of roughness elements is the relative phase of the M_2 tidal constituent and the mean tide level at different locations along a tidal channel relative to some reference location in the channel.

Elevation of the prototype tide at a specific location can be represented by

$$h(t) = H_o + \sum_{i=1}^{N} f_i H_i \cos\left[\alpha_i t + (V_o + \mu)_i - \kappa_i\right]$$

The harmonic analysis performed by NOS provided H_o, and H_i, and κ_i for each tide gage. Other coefficients f_i, α_i, $(V_o+\mu)_i$ can be obtained from tables (Schureman, 1940). The above equation can be rewritten in the form

$$h(t) = H_o + \sum_{i=1}^{N} A_i \cos(\omega_i t + \phi_i)$$

which is used for model control and analyses of the hydraulic model data. A harmonic function composed of M_2, M_4, M_6, and M_8 was used as the initial command signal to the model tide generator, and tidal heights were recorded simultaneously at all model tide gages. The model tidal elevation can be represented as

$$h_M(t) = \hat{h}_M(t) + \varepsilon(t) \equiv a_o + \sum_{i=1}^{N} [a_i \cos(\omega_i t) + b_i \sin(\omega_i t)] + \varepsilon(t)$$

where $\hat{h}_m (t)$ is the calculated tidal elevation represented by a harmonic series of known frequencies and $\varepsilon(t)$ is noise. Since the noise level is unknown, the method of least squares is used to solve for the unknown coefficients (amplitudes and phases) for the M_2, M_4, M_6, and M_8 tidal constituents by minimizing the variance of the sum of the squared difference between the measured model tidal elevation and the assumed form for the model tidal elevation.

Therefore, the harmonic coefficients for the model tidal height at each tide gage can be used to calculate the phases of the tidal constituents at each gage relative to tidal Gage 8 on the open ocean and the differences in the model and prototype relative phases can be determined.

The above procedure should, in principle, lead to an excellent verification including that for tidal velocities. It was decided to attempt to verify the tidal amplitudes within ±0.1 ft and the phase of M_2 within ±1.0 degree.

It appeared that the primary problem which might not be solved by the M_2 verification procedure enumerated above would be the situation where a spring tide caused a considerable amount of flow to occur over relatively flat marsh areas which might have little or no flow over them for the M_2 constituent of smaller amplitude. If such were the case, there would have been a lack of adjustment of model roughness in these areas. A minor problem somewhat analogous also could occur for a neap tide if there were too much roughness in relatively shallow channels. However, for tidal regimes dominated by M_2 variance, this procedure with emphasis placed on mean tide level verification as well as the M_2 constituent throughout the inlet should minimize this problem.

Consequently, the velocity data, practically always taken during a spring tide (if only one set is acquired), should be used for this final verification using a progressive tide in the model and making velocity measurments at the stage corresponding to that for which prototype data are available. Since the progressive tide should run for 15 or 30 days, depending on the location, this test will be quite long in the model and should be performed after all other verification tests.

Verification for the M_2 Constituent

Since this was the first time such a verification procedure was attempted, it required more tests than originally contemplated to verify the M_2 constituent. However, the total time for verification was normal or less than that for similar models using the usual procedure. A total of 73 test runs were made leading up to the verified condition. This number included all runs, some of which were made to determine optimum sump water level and to repair the model tide generator which malfunctioned twice during the process. When testing was ongoing, two tests were conducted per day. Total elapsed time from initiation to completion of verification was about 4 months. With hindsight, it appears that 6-8 weeks might be sufficient on a similar future model study.

Tables 2, 3, 4, and 5 show some results of the M_2 constituent verification procedure after Runs 1, 36, and 73. Run No. 1 represents the first test, No. 36 an intermediate test, and No. 73 the verified condition.

For Run No. 1, Table 2 shows all model tidal amplitudes are too high (most by 0.3 ft) and Table 3 indicates the tide reaches all estuary gages too fast (relative to Gage 8 the phase differences range from about 6 degrees to 18 degrees). Table 4 shows there is about the correct amount of roughness between Gage 4 and 7, there is too much roughness or something is restricting the flow too much between Gages 6 and 7, there is too little roughness elsewhere, and the most roughness should be added between Gages 1 and 2 (a little but not much is needed between Gages 2 and 3). Actually there was an error in molding the channel between Gages 6 and 7, which did not allow enough flow through the channel. Table 5 illustrates that the mean tide level is too high everywhere except at Gage 3. It is readily apparent that an enormous amount of information has been gained by merely looking at Tables 2 through 5 for Run No. 1.

Table 2: M_2 CONSTITUENT TIDAL AMPLITUDES (FT)

		Run No. 1		Run No. 36		Run No. 73	
Station	Prototype	Model	Difference	Model	Difference	Model	Difference
1	1.788	2.150	+0.362	1.804	+0.016	1.716	-0.072
2	1.834	2.140	+0.306	1.922	+0.088	1.789	-0.045
3	1.866	2.070	+0.204	1.916	+0.050	1.797	-0.069
4	1.919	2.260	+0.341	1.974	+0.055	1.878	-0.041
5	1.885	2.220	+0.335	1.957	+0.072	1.838	-0.047
6	1.936	2.270	+0.334	1.986	+0.050	1.872	-0.064
7	1.865	1.950	+0.085	1.885	+0.020	1.819	-0.066
8	2.402	2.430	+0.028	2.412	+0.010	2.396	-0.006

Table 3: M_2 CONSTITUENT PHASE DIFFERENCES (DEG*)

		Run No. 1		Run No. 36		Run No. 73	
Station to Station	Prototype	Model	Difference	Model	Difference	Model	Difference
8-1	48.23	30.50	-17.73	45.14	-3.09	49.24	+1.01
8-2	33.40	26.50	- 6.90	32.20	-1.20	34.20	+0.80
8-3	19.52	13.80	- 5.72	19.20	-0.32	20.20	+0.68
8-4	20.69	13.80	- 6.89	21.40	+0.71	20.30	-0.39
8-5	32.66	23.90	- 8.76	32.30	-0.36	33.10	+0.44
8-6	33.23	21.20	-12.03	32.00	-1.23	32.50	-0.73
8-7	47.09	41.00	- 6.09	44.46	-2.63	46.80	-0.29

* 1 Degree = 2.07 minutes of prototype time.

Table 4: M_2 CONSTITUENT PHASE DIFFERENCES (DEG*)

Station to Station	Prototype	Run No. 1		Run No. 36		Run No. 73	
		Model	Difference	Model	Difference	Model	Difference
2-1	14.83	4.60	-10.23	12.94	-1.89	15.04	+0.21
3-1	28.71	17.30	-11.41	25.94	-2.77	29.04	+0.33
3-2	13.88	12.70	- 1.18	13.00	-0.88	14.00	+0.12
4-5	11.98	10.10	- 1.88	10.90	-1.08	12.80	+0.82
4-6	12.54	7.40	- 5.14	10.60	-1.94	12.20	-0.34
4-7	26.38	27.20	+ 0.82	23.06	-3.32	26.50	+0.12
5-6	0.57	-2.70	- 3.27	-0.30	-0.87	-0.60	-1.17
6-7	13.84	19.70	+ 5.86	12.46	-1.38	14.30	+0.46

* 1 Degree = 2.07 minutes of prototype time

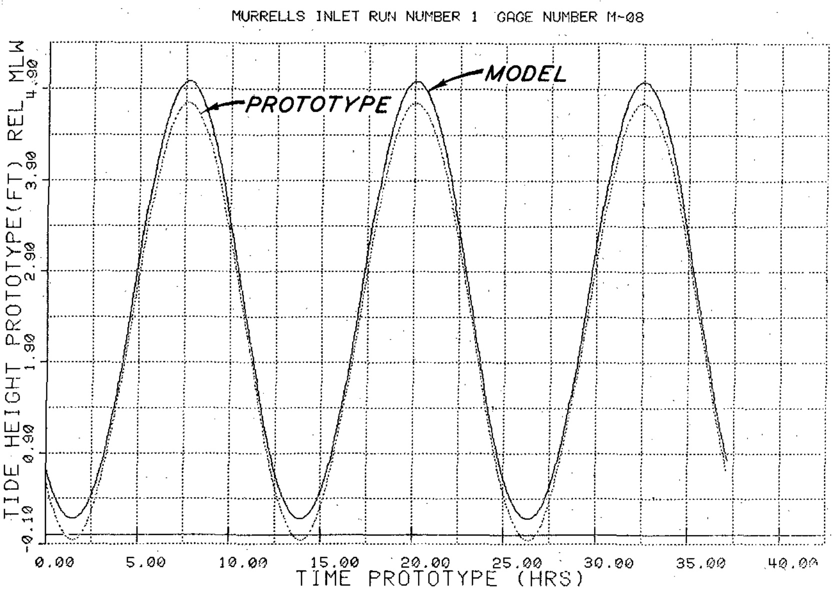
Table 5: M_2 CONSTITUENT MEAN TIDE LEVELS (FT ABOVE MLW)

Station	Prototype	Run No. 1		Run No. 36		Run No. 73	
		Model	Difference	Model	Difference	Model	Difference
1	2.668	2.833	+0.165	2.499	-0.169	2.734	+0.046
2	2.674	2.831	+0.157	2.427	-0.247	2.695	+0.020
3	2.696	2.632	-0.062	2.249	-0.447	2.546	-0.150
4	2.715	2.733	+0.018	2.380	-0.335	2.663	-0.052
5	2.696	2.794	+0.098	2.432	-0.273	2.682	-0.014
6	2.680	2.755	+0.075	2.387	-0.293	2.655	-0.025
7	2.676	3.012	+0.336	2.523	-0.153	2.762	+0.086
8	2.344	2.557	+0.213	2.128	-0.216	2.365	+0.021

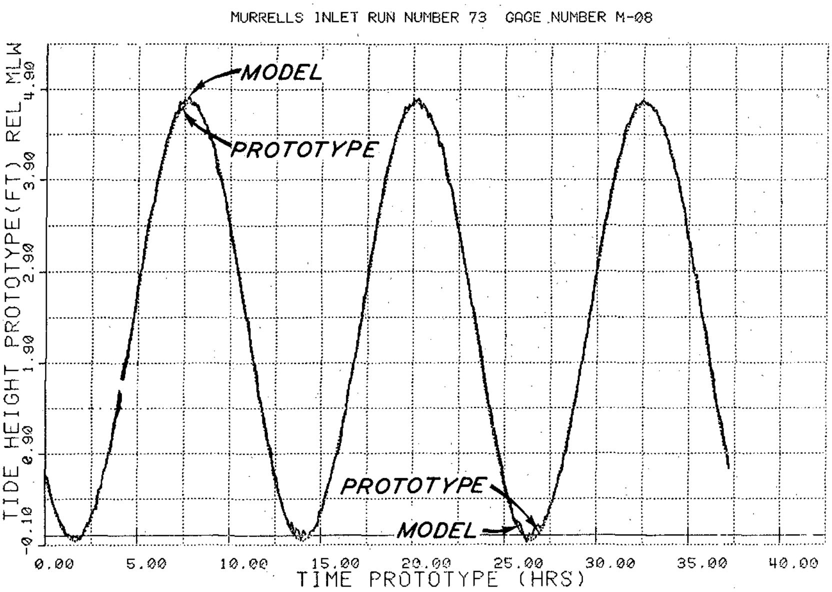
For Run No. 36, Table 2 shows that all tidal amplitudes are still too high but within 0.1 ft of the prototype, and Table 3 indicates the tide still reaches all gages except No. 4 too fast (relative to Gage 8), however, the largest phase difference has been reduced to 3 degrees. Table 5 shows more roughness is needed between all gages, but the most is needed between Gages 1 and 2 and 4 and 6. Table 5 illustrates that the mean tide level is too low at all model gages and by nearly 0.5 ft at Gage 4.

For Run No. 73, the verified condition, Table 2 shows that all model tidal amplitudes are less than the prototype but by only a few hundredths of of a foot (the largest difference is 0.07 ft). Table 3 also indicates that about half of the phase differences are positive and half negative (relative to Gage 8) with the largest being 1 degree. Table 4 shows that the largest phase difference is 1.17 degrees and that is between Gages 7 and 8. Table 5 illustrates that the mean model tide level is larger than the prototype at about half the gages and smaller at the other half. The largest difference in the mean tide level is 0.086 ft. Figures 3 and 4 illustrate model and prototype tide curves for M_2 at Run No. 1 and Run No. 73 for Gage 8 and Gage 2, respectively.

To summarize the M_2 constituent verification, we have been successful in verifying the M_2 tidal amplitude to within ±0.1 ft, the mean tide level

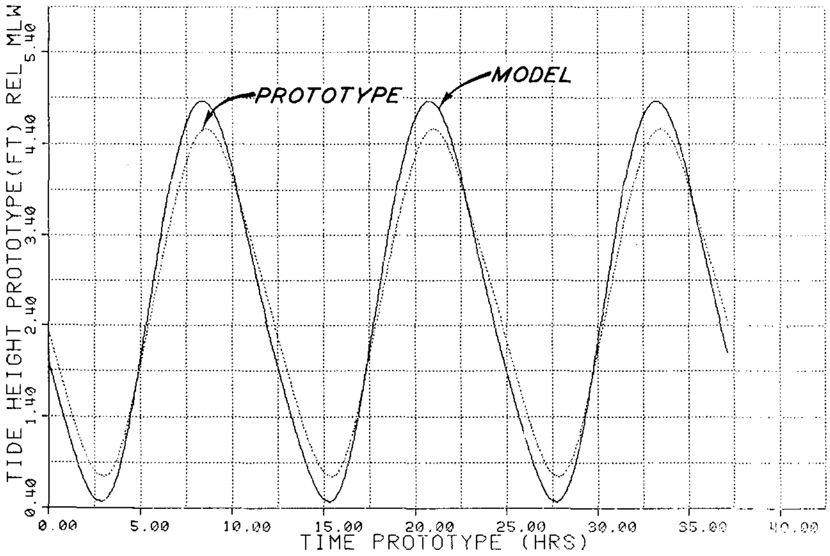


BEFORE VERIFICATION



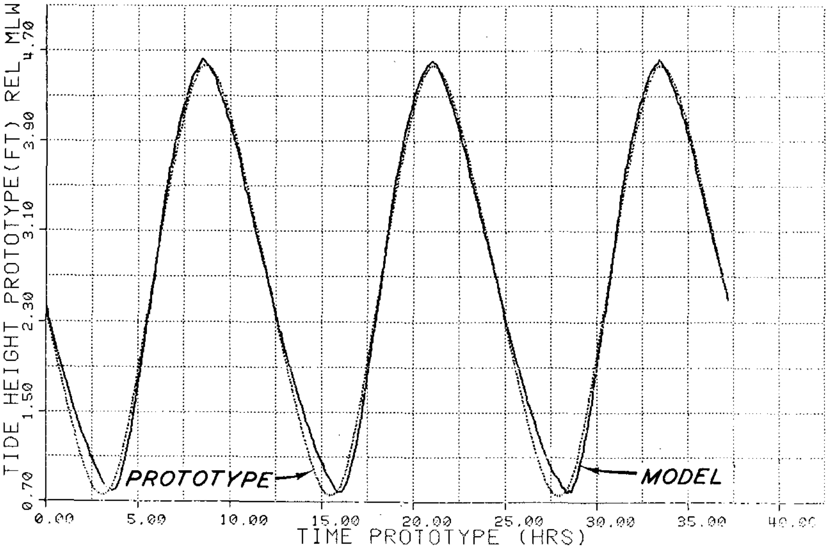
AFTER VERIFICATION

Figure 3. M_2 Tidal Elevation Near Mouth of Murrells Inlet.



BEFORE VERIFICATION

MURRELLS INLET RUN NUMBER 1 GAGE NUMBER M-02



AFTER VERIFICATION

MURRELLS INLET RUN NUMBER 73 GAGE NUMBER M-02

Figure 4. M_2 Tidal Elevation in Back Reach of Estuary.

to within ±0.1 ft, and the phase of the M_2 constituent to within 1 degree relative to the phase at the open-ocean gage. This is considered to be an excellent M_2 constituent verification.

Verification for Progressive Tide

Due to the lack of prototype constituent velocity data, this portion of the verification was limited. A 15-day progressive tide consisting of the M_2, S_2, and their overtide constituents was generated in the model and velocities were measured at the 4 ranges for which prototype data were available. The velocity verification was considered adequate, and no adjustments in model roughness were made or additional verification tests conducted. Figure 5 illustrates a sample of the velocity verification.

DISCUSSION OF OTHER PERTINENT DATA

A brief discussion follows on the significance of other data acquired during the verification processes of the model study. Although these data have not been analyzed to glean their full potential some interesting and quite important information has been obtained.

Energy Transfer to Higher Order Harmonics

Table 6 shows a comparison of the model and prototype amplitudes for M_2, and its overtides M_4, M_6, and M_8. Gage 8 is the open-ocean gage and the model and prototype M_2 amplitudes are identical for all practical purposes. Unfortunately, sufficient time was not available to adjust the amplitudes of the overtides (M_4, M_6, and M_8) to coincide with the prototype data at Gage 8. However, the information contained in Table 6 is interesting and can be quite informative. The difference between amplitudes of the overtides in the estuary (Gages 1 to 7) and the open coast (Gage 8) represents a nonlinear transfer of energy from the principal lunar component M_2 to its harmonics M_4, M_6, and M_8. Obviously this is occurring at a non-negligible rate in the prototype. It has often been questioned whether or not such nonlinear energy transfers occur in hydraulic models and to what degree. Unfortunately, this question cannot be answered completely from the data contained in Table 6 since the energy in M_4, M_6, and M_8 was not precisely adjusted at Gage 8. However, it is obvious that nonlinear energy transfer is occurring in the model and in more or less the correct proportion. Thus, the information in Table 6 is interpreted as preliminary confirmation that such nonlinear effects are occurring in approximate similitude (at least within the correct order of magnitude) in the hydraulic model. Several additional model tests should be conducted to confirm this indication and to unequivocally determine the relative degree of similitude of these nonlinear energy transfers.

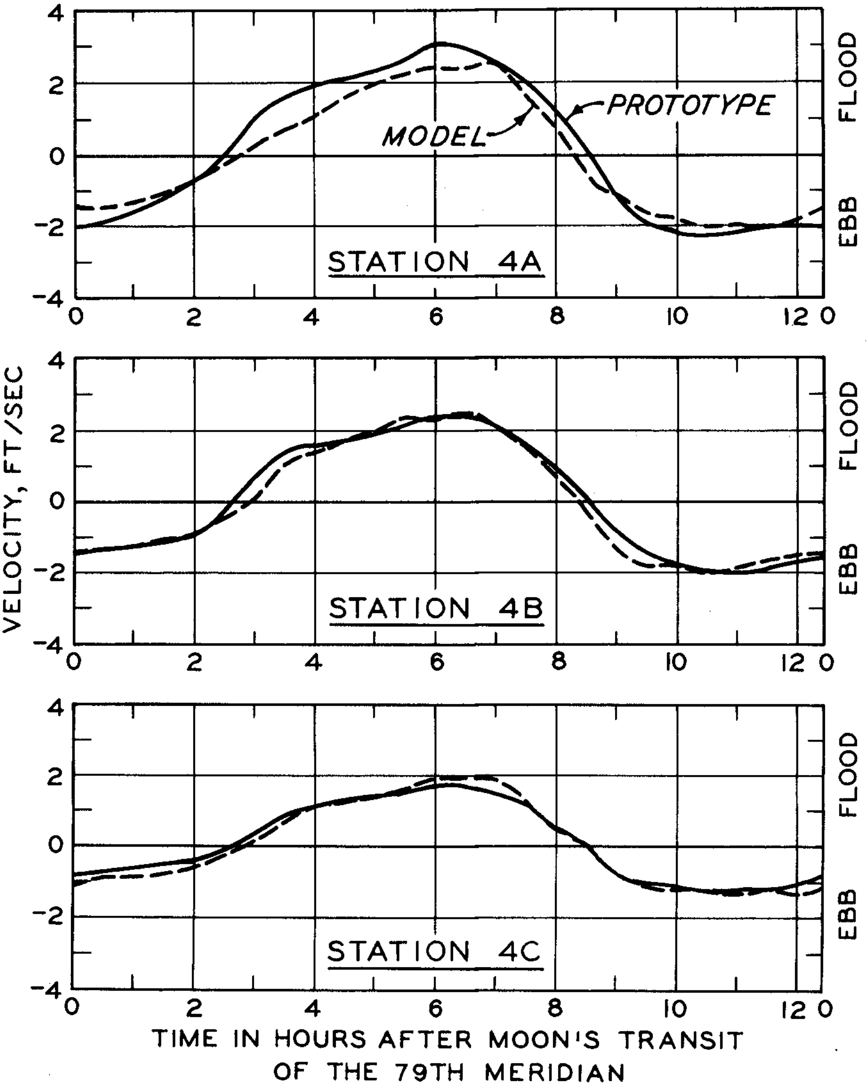


FIGURE 5. VERIFICATION OF MODEL VELOCITIES - MID-DEPTH

Table 6: ENERGY IN HIGHER ORDER HARMONICS (RUN NO. 73)

	M_2 ft		M_4 ft (10^{-2})		M_6 ft (10^{-2})		M_8 ft (10^{-3})	
Gage	Prototype	Model	Prototype	Model	Prototype	Model	Prototype	Model
1	1.7875	1.72	16.36	21.60	8.36	5.32	18.9	62.61
2	1.8344	1.79	15.43	20.77	4.74	4.00	15.9	33.96
3	1.8655	1.80	11.95	24.99	6.33	9.16	13.8	44.51
4	1.9192	1.88	16.75	33.23	4.10	6.91	12.2	26.61
5	1.8849	1.84	15.38	26.75	6.20	5.58	22.6	43.99
6	1.9363	1.87	10.49	23.63	8.74	5.00	31.7	33.15
7	1.8649	1.82	17.60	17.49	8.61	4.55	28.3	52.35
8	2.4020	2.40	1.06	3.54	0.65	1.02	10.9	5.93

Energy in Other Harmonics

A plot of the residual energy as a function of frequency was performed for each gage after each test in order to insure that a large residual energy was not present or that energy was not showing up in some characteristic frequency band which might be indicative of a malfunctioning tide control, sump, or pump, or perhaps an undesirable model resonance. No such problems were detected and the residual energy was always low.

NUMERICAL MODEL IMPLICATIONS

It is believed that results of this study have wide-ranging implications, in particular for numerical models. Recent advances (Butler and Raney, 1976) in numerical modeling of inlet-estuarine systems have finally made numerical modeling of well-mixed systems a viable engineering tool for the early stages of an inlet or estuarine improvement plan. While still having resolution disadvantages relative to a physical model, a numerical model may be a viable alternative in the planning stage to evaluate the relative adequacy of numerous plans while a physical model may and probably should be used as the principal tool for final design.

Since numerical models must be verified in much the same manner as physical models, it is hypothesized that the M_2 constituent verification is a superior method of numerical model verification. This brings many interesting numerical experiments immediately to mind. For instance, will the numerical model predict the nonlinear energy transfer to higher order harmonics as well as the physical model? Will the velocity verification, which is critical to numerical models, be essentially disposed of upon verification of both the amplitude and phase of the M_2 constituent?

It will be practically impossible to verify the numerical model (even the much faster implicit model of Butler and Raney, 1976) for a progressive tide due to computer time and cost limitations. However, the next generation of computers should solve this limitation. While advances in numerical modeling are taking place quite fast, more serious applications work is needed for them to realize their full potential and to complement physical hydraulic model studies to the fullest possible extent.

RECOMMENDATIONS FOR ADDITIONAL RESEARCH

Information emanating from the study reported herein has perhaps led to more questions than answers; however, it is believed a new set of questions have been raised and that our knowledge of model verification has advanced accordingly. As a result of the work performed, the following recommendations for additional research are made:

a. Additional prototype velocity data should be collected at Murrells Inlet to define the velocity constituents. These data would form the basis for further physical model and numerical model verification experiments.

b. Investigate the velocity constituent verification in the physical model of Murrells Inlet using both the M_2 tide and a progressive tide.

c. Attempt to verify a numerical model for Murrells Inlet (Butler and Raney, 1976, appears to be the most applicable model) by use of the M_2 tidal constituent.

d. Perform more physical model experiments specifically designed to investigate nonlinear phenomena occurring. In particular, adjust the model to open-coast gage and analyze the nonlinear energy transfer in model and prototype.

e. Perform detailed numerical model experiments of the nonlinear phenomena present comparing these findings with both the physical model data and the prototype data.

f. It may be possible to experimentally relate and quantify the number of roughness elements needed to relative phase lags.

CONCLUSIONS

The following conclusions are formulated as a result of this study:

a. It is feasible to verify a physical hydraulic model by using tidal constituents.

b. Verification by the M_2 constituent can be expected to be achieved within ±0.1 ft in amplitude, within ±0.1 ft in mean tide level, and ±1 degree in phase.

c. Verification by the M_2 constituent should be followed by verification for a spring tide to insure correct marsh and overbank roughness and a check for a neap tide condition would be wise. It is preferable to perform this verification with a progressive tide of at least 15 days duration which contains 1 spring and 1 neap tide.

d. Prototype verification data collection should be designed to define the principal tidal constituents and their overtides for both the tidal elevation stations and the tidal velocity stations (i.e. a month of record is required as a minimum).