THE CORPS OF ENGINEER'S GENERAL INVESTIGATION OF TIDAL INLETS

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Introduction

During the past decade the U.S. Army Corps of Engineers has been conducting a General Investigation of Tidal Inlets (GITI). The GITI was an applied research program through which a wide range of inlet phenomena relating to Corps responsibilities for coastal navigation and recreation, prevention of beach erosion, and control of coastal flooding were investigated. The program was managed by the U.S. Army Coastal Engineering Research Center (CERC); specific research projects were conducted by CERC, the U.S. Army Waterways Experiment Station (WES), private consultants, and universities.

The various GITI research efforts can be divided into five categoies: 1) field studies of the hydraulics and sedimentary dynamics of selected inlets, 2) analysis of historic field data, 3) numerical models of inlet hydraulics, 4) movable and fixed-bed physical inlet models, and 5) other miscellaneous inlet studies. Research results are being published in a special report series. The number, title, author and date of each report are listed in the Appendix - GITI Reports.

The intent of this paper is to summarize GITI research efforts and, based on key results of this research as well as recent Corps field experience, to recommend new areas for research.

Field Studies of Tidal Inlets

Corpus Christi Water Exchange Pass in Texas is a two mile long prismatic channel (8 ft by 120 ft) with short entrance jetties that was dredged across the barrier island to connect Corpus Christi Bay and the Gulf of Mexico. Field studies of the pass and adjacent beaches were conducted from the time of channel construction in 1972 to 1975 (GITI 8, 9).

Water levels were continuously measured at each end of the channel and twenty tidal-cycle discharge surveys were conducted over the three-year study period to document tidal cycle, lunar, seasonal and longterm changes in channel hydraulics. During the first year of pass operation, average channel frictional resistance increased by approximately 50 percent and even greater resistance variability was observed during individual tidal cycles. This is demonstrated by typical plots of Manning's n and water level differential versus time (Figure 1). At times there was a strong progressive increase in resistance as flood or ebb flow

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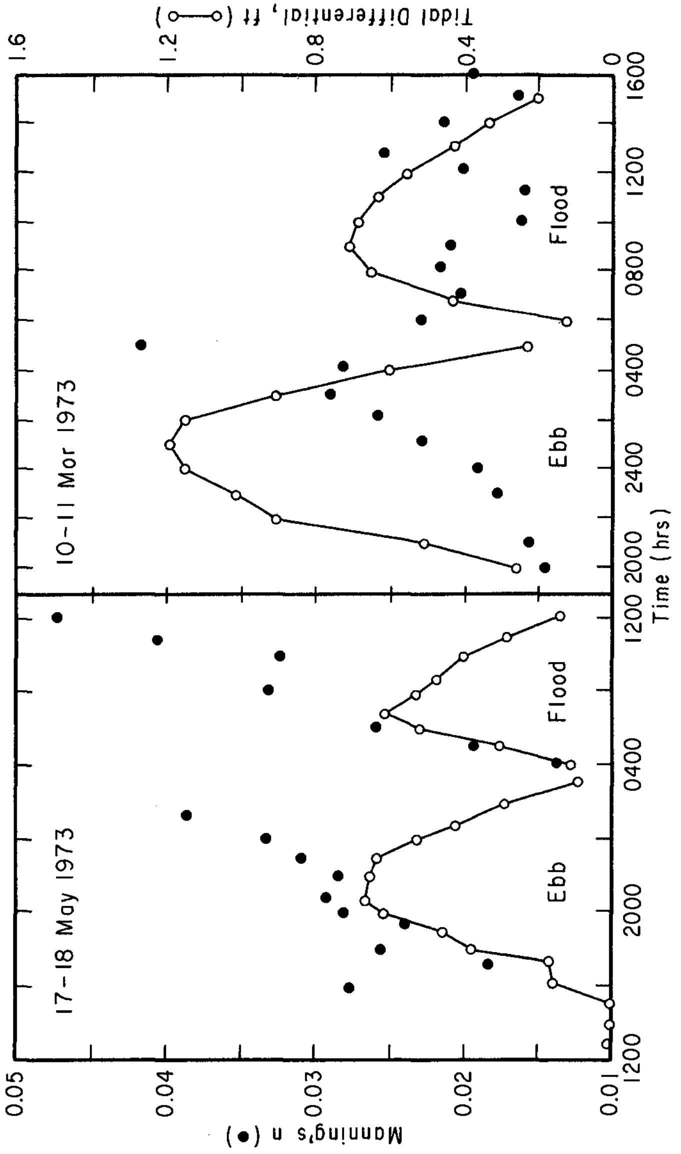

Figure 1 Temporal variation of Manning's n and tidal differential, CCWEP, Texas (GITI 10)

developed followed by a rapid drop as flow reversed; at other times no trend in channel resistance was observed.

Temporal flow resistance variations of the magnitude demonstrated in Figure 1 will have a significant impact on inlet flow regimes as well as on our ability to accurately predict inlet hydraulic response by applying physical and numerical models. There is a strong need for additional field and possibly laboratory investigations to define the causes for this resistance variation and the field conditions under which it can occur.

Periodic bathymetric surveys of the bay and gulf entrances, the pass, and adjacent beaches were also made and results related to wave climate (visual observations), gulf tide levels, local winds, channel discharge, and estimated longshore transport rates. Inlet stability analyses proposed by O'Brien (1931, 1969), Escoffier (1940), and Bruun and Gerritsen (1960) concur with the continuing channel shoaling observed during the field study period.

The other GITI field study involved a two-year program of data collection at North Inlet, a natural tidal inlet in South Carolina (GITI 10, 16). Water level differentials and inlet discharge were measured, visual wave observations were made to determine longshore energy flux and sediment transport, beach profiles and inlet hydrography were periodically measured and compared to historic hydrographic charts, and sediment samples were collected and analyzed.

Calculated values of Manning's n show a similar range of values as those found at the Corpus Christi Water Exchange Pass. Also, occasional less well defined progressive increases in Manning's n were observed during the flood and ebb phases of the tidal cycle. The average peak ebb/flood velocity ratio in the inlet gorge was 1.22, the ebb dominance being attributed to the greater effeciency of water exchange at high tide because of a significantly larger bay surface area.

This and other field studies of tidal inlets have investigated sediment transport modes and patterns, and resulting erosion and deposition environments in the inlet and vicinity. Additional field work is needed to thoroughly define natural inlet sediment bypassing mechanisms as a function of inlet geometry, tidal range, and incident wave climate. The results must then be used to develop artifical inlet bypassing schemes that will maintain a navigable channel with a minimum of dredging and construction of permanent structures. Most typical bypassing schemes consist of fixed structures that establish a sediment trap and control the navigation channels. Such schemes are too costly to construct at many inlets. The ideal bypassing system would employ a dredging program that is flexible and reacts to the natural channel and sediment bypassing conditions.

Inlet channels stabilized by jetties may maintain an adequate channel between the jetties but it is usually necessary to conduct maintenance dredging across the outer bar (seaward of the jetties). Additional field and possibly laboratory and analytical studies are needed to define the rates and patterns of shoaling to be expected in this portion of the channel. Better understanding of the shoaling patterns will allow a more effective program of overdredging in anticipation of the subsequent shoaling that will occur.

Analysis of Historic Field Data

Using data primarily for the Pacific coast inlets, O'Brien (1931, 1969) established a power function relationship between the mean cross-section area of the inlet throat and the diurnal or spring range tidal prism. Combining O'Brien's data, data from a few other sources (92 data points total) and an analysis of additional Atlantic and Gulf coast inlets (70 data points), Jarrett (GITI 3) developed tidal prism-inlet area relationships for a total of 108 inlets (162 data points). His tidal prism data development used both the "cubature method" which employs measured tide ranges throughout the bay at the instant when slack water occurs at the inlet, and the "NOS current data method" based on current measurements at the inlet throat.

The prism-area data were presented for combinations of three physical categories (all inlets, unjettied and single jetty inlets, and dual jetty inlets) and four geographical categories (inlets on all coasts, Atlantic inlets, Pacific inlets, Gulf inlets). Power function regression curves were fit and 95% confidence limits were established. Figure 2 is a typical result. The prism-area relationships for unjettied and single jetty inlets did vary somewhat for the three coasts, probably because of the differences in tidal and wave characteristics. In no cases was there significant variation from the original O'Brien relationship.

It is reasonable to expect that other relationships besides that relating tidal prism and inlet throat area could be formed between pairs of inlet geometric parameters. An investigation of hydrographic charts and air photographs for 67 natural inlets in the U.S. was conducted: "to isolate a set of parameters than can be used to quantify inlet geometry, to analyze relationships between the basic parameters selected, and to analyze the relationships between inlets based upon the parameters selected" (GITI 20). Over 50 parameters were evaluated and 13 were selected for detailed investigation. They are the inlet channel length and minimum width; the average and maximum depth of the inlet channel at the minimum width; the depth at the crest of the outer bar; the area of the ebb tidal delta; and eigenvectors of the minumum width channel cross section (three), the channel thalweg profile (two), and the ebb tidal delta shape (two).

Linear regression and R^2 analyses of all combinations of pairs of the 13 parameters were performed. Several strong relationships were found. For example $AED = 3.92 \times 10^{-7} L^{1.71}$ ($R^2 = 83.4$ percent) where AED is the area of the ebb tidal delta (square miles) and L is length of the channel from the point of minimum channel width to the

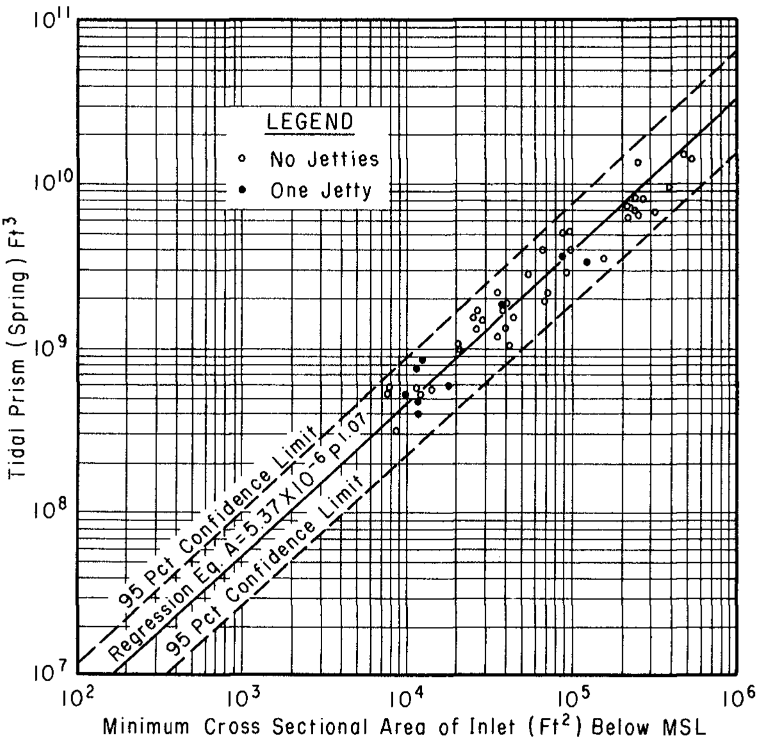

Figure 2 Prism vs area for Atlantic coast inlets with one or no jetties. (GITI 3)

crest of the outer bar(feet).

The parameters defining the gross scale dimensions and shape of the ebb tidal delta and the channel showed a strong relationship to the minimum width channel cross-sectional area (represented by the product of the average depth and width). However, there was no strong correlation with either the channel width or average depth separately. Apparently, the channel width and depth at the minimum width are free to adjust to the wave climate while the cross sectional area is controlled by the tide (tidal prism).

The multivariate statistical method of cluster analysis was used to evaluate tendencies for the various geometric parameters to define groups or clusters of inlets. Then, discriminant analysis was used to test the strength of these clusters

The 67 inlets can be grouped into six well defined clusters plus five inlets that do not form a cluster or fit into any of the basic six clusters. The various clusters do exhibit some stratification based on size and some based on geographic location but these factors are not strong enough to solely explain the resultant clustering. As an example, Figure 3, shows the channel width and length groupings for the six clusters.

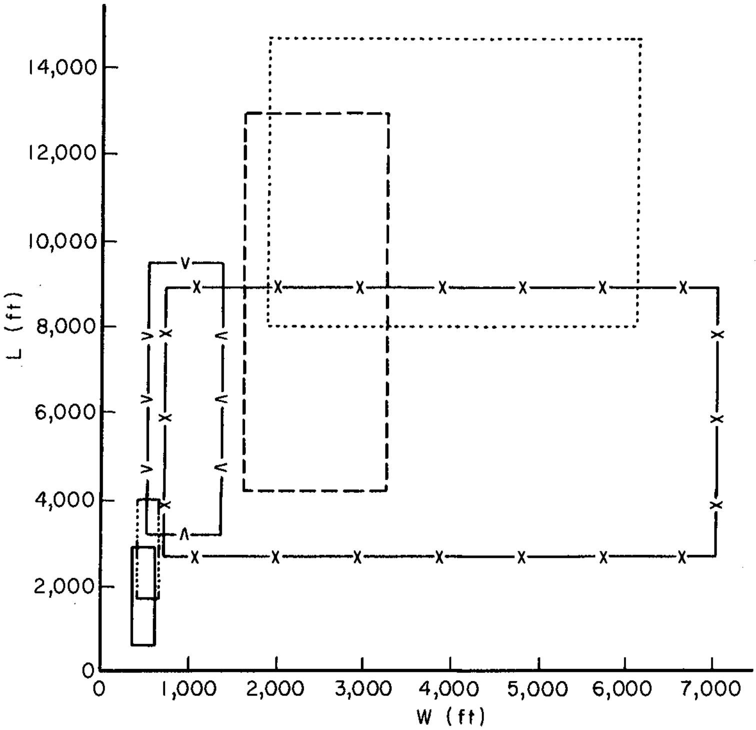

Figure 3 Channel width-length relationships for six inlet clusters. (GITI 20)

An analysis of the dynamic nature of inlet geometry was conducted by determining the temporal variation of selected inlet geometric parameters (GITI 21). This effort employed from four to twenty-one air photographs at each of 51 inlets. Geometric parameters used included the minimum entrance width, the channel length, and the thalweg position and orientation. These parameters were quantified from the air photographs and non-dimensionalized to remove size effects; then the temporal rates of change of the dimensional and non-dimensional parameters were evaluated. Somewhat arbitrary limits were set on each parameter to delineate stable and unstable inlets and to allow grouping or classification based on this delineation.

Both the geometric pattern and stability analyses provide much insight into the geometric characteristics of natural inlets but the information has not been related to causative factors e.g. wave climate, tide characteristics, net and gross longshore sediment transport. The important next step will be to conduct these analyses. Another, potentially fruitful area of research will be to evaluate the specific changes in the various geometric parameters as inlet structures are constructed (realizing that some of the parameters would be strongly controlled by structures such as dual jetties).

In 1957 an eight-mile channel was dredged across Padre Island and Laguna Madre to the Intracoastal Waterway at Port Mansfield, Texas. Gulf and laguna tide elevations, channel current velocities, and channel hydrographic data were collected periodically from 1957 to 1975. Longshore transport rates were estimated from wave hindcast data for the Gulf.

These data were analyzed to evaluate the channel's hydraulic response, shoaling patterns, and resulting stability (GITI 12). Strong channel instability, indicated by channel shoaling patterns and a required dredging rate of 350,000 cubic yards/year is in agreement with the stability criteria proposed by O'Brien (1931), Escoffier (1940), and Bruun and Gerritsen (1960). The length of the channel across the barrier island (3 miles) and the small Gulf tidal range are such that no channel crosssectional area would develop sufficient scouring velocities to eliminate the need for maintenance dredging.

Another effort was a study of thirteen tidal inlets each having a single updrift or downdrift jetty in order to evaluate the response of the entrance channel to jetty construction (GITI 19). This effort used information from periodic hydrographic charts, some of which date back to the 1890's.

In all cases, the channel thalweg was driven toward the jetty by wave action and the resulting longshore sediment transport, regardless of the inlet-bay orientation and resulting tidal flow patterns, the direction of net longshore sediment transport, or the orientation of the jetty. Channel cross section areas decreased up to 40 percent with the construction of a single jetty. In some cases the tendency of a channel to migrate toward a fetty was so strong that undermining of the jetty occured. In cases where two jetties were eventually constructed and one had deteriorated so sand could move over or through the jetty, channel movement toward the underiorated jetty was observed.

Numerical Models of Inlet Hydraulics

Available mathemetical models for inlet hydraulic calculations vary greatly in complexity and commensurate cost (time, money, expertise) of application. They range from the simple one-dimensional model (e.g. Keulegan, 1967; King, 1974) which makes very restrictive assumptions about channel and bay geometry, sea water level time-histories, bay surface level variations, etc. to the complex two-dimensional finite difference numerical models that compare with physical hydraulic models in capability. The former are useful for simple quick preliminary calculations while the latter, operated by specialists, will provide the detailed flow pattern and water level information necessary for final design of major inlet developements. There was a need for an intermediate level model that would yield information on the velocity pattern at an inlet for relatively complex inlet-bay hydrography and nonsinusoidal sea water levels but that could be operated by Corps field offices without the need for special expertise and substantial investment of time and money. To satisfy this need a spatially integrated quasi two-dimensional numerical model was developed (GITI 14).

To apply the model, a somewhat subjective net of subchannels and cross sections is drawn at the inlet (see Figure 4). GITI 14 provides guidance for drawing the net. The one-dimensional equation of motion, with the friction term at each time step being evaluated by spatially integrating over the net, is solved simultaneously with the continuity equation for the inlet-bay in a time-marching fashion. This yields the inlet discharge and bay water level at each time step. Given the instantaneous inlet discharge, the velocity at each grid section can be calculated. Important capabilities of the model include: any sea level variation as a function of time (tsunami, storm surge, complex tide) may be specified; more than one inlet can connect the sea and bay; river inflow and surface runoff can be considered; and the bay surface area can vary with the surface elevation. Limitations include: wind stress and Coriolis effects are neglected, and the bay water surface is assumed to remain horizontal.

As part of an effort to evaluate the effectiveness of mathematical and physial models of tidal inlet hydraulics, an RFP was issued and studies were funded to calibrate and apply three mathematical models for predicting water-surface time histories and current velocities at Masonboro Inlet, N.C. (GITI 6, Appendices 2, 3 and 4).

One was a simple lumped parameter model that extended the method developed by Keulegan (1967) by allowing for variable bay surface area, a nonprismatic inlet channel, a nonsinusoidal ocean tide, inclusion of inertial effects, and surface inflow to the bay. The other two were two-dimensional (vertically integrated)finite difference model using explict solution schemes and having their genesis in the hurricane

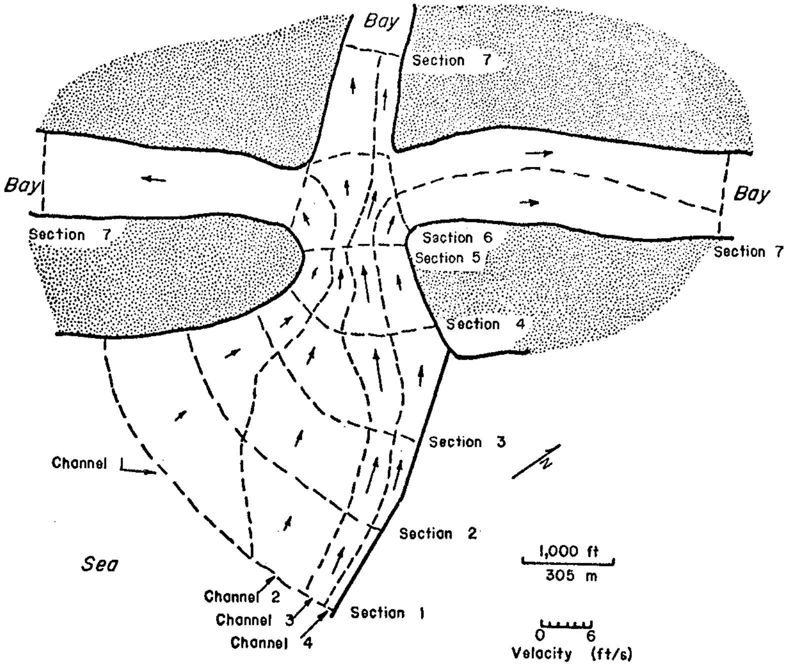

Figure 4 - Net and flood flow velocity distribution, Masonboro Inlet, N.C. (GITI 14)

surge model of Reid and Bodine (1968). GITI 6 is a summary discussion of inlet hydraulic models and a comparison of the effectiveness of the three mathematical models applied to Masonboro Inlet. Figure 5 shows a typical calculated flood flow pattern at the entrance to Masonboro Inlet using one of the two-dimensional models.

Implicit and explicit finite difference models of inlet hydraulics have been steadily improved since the applications discussed above were completed in the early 1970's. They now provide an extremely effective tool for detailed inlet investigations. The next development should be to include sediment transport in inlet numerical models. Perhaps this should be done in two steps. The first step would be to develop a model in which regions of erosion and deposition are determined without quantifying transport rates and the resulting changes in hydrography. The second step would be to develop a complete interactive hydraulic/sediment transport model that quantifies sediment transport rates, resulting bed elevation changes, and resulting tidal flow modifications.

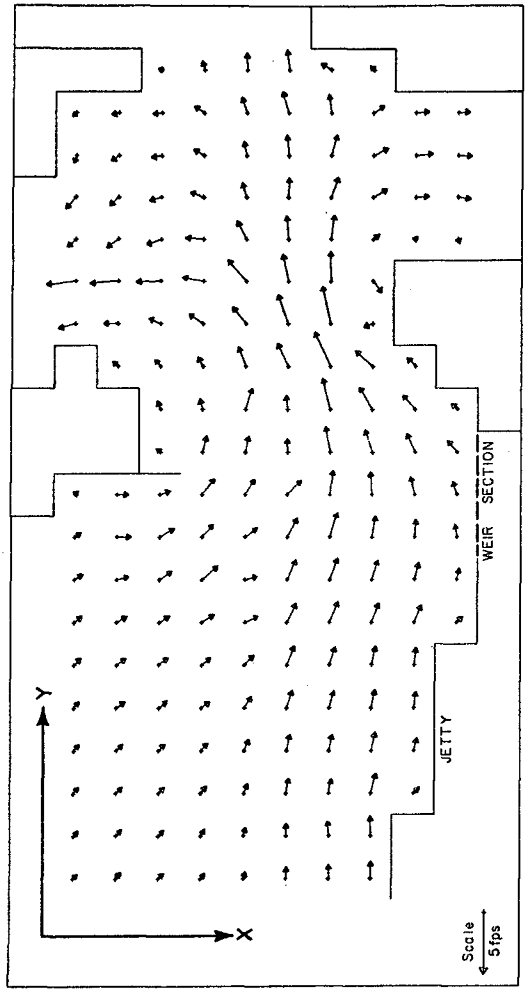

Figure 5 - Flood flow pattern at Masonboro Inlet entrance calculated using two-dimensional finite difference model (GITI 6 App. 2).

Movable and Fixed Bed Physical Models

A concrete distorted-scale hydraulic model of Masonboro Inlet was included in the evaluation of the effectiveness of mathematical and physical tidal inlet hydraulic models (GITI 6, Appendix 1; GITI 15). The model, constructed (at WES) to a 1:60 vertical scale and 1:300 horizontal scale, was run with and without waves to evaluate the effect of waves on tidal flow patterns. The general result of the comparison (GITI 6) is that the physical model and the two-dimensional finite difference numerical models are about equally effective in predicting resulting flow velocities and water level time-histories in the inlet and bay. The physical model can include the effects of waves which can improve simulation of flow patterns on the ocean bar and inlet throat as well as resulting bay water levels. It also simulates finer scale turbulence. Numerical models, which are less expensive to operate and easier to store for future use, can simulate wind stress, Coriolis acceleration, and atmospheric pressure gradients.

To further evaluate numerical and physical inlet hydraulic models, additional tide, current, wave and hydrographic data were collected at Masonboro Inlet at a later date (July 1974). The models were operated for the new ocean tide and inlet channel hydrographic conditions to predict channel velocities and bay levels for comparison with measured data. For details of the comparison see GITI 22. Generally, the conclusions of GITI 6 were confirmed.

Before the Masonboro Inlet physical model was destroyed a variety of supplementary tests was conducted (GITI 18). These included an evaluation of : 1) the effects of various level weirs in a proposed south jetty as well as in the existing north jetty (see Figure 4), 2) the effects on inlet flow patterns of closure of any of the three interior channels (see Figure 4), and 3) the efficacy of various sediment tracer materials (sand, expanded shale, ground pumice and plastic) in qualitatively predicting observed shoal and scour trends.

A movable bed (0.34 mm sand) model investigation of basic tidal inlet behavior was conducted at the University of California Hydraulic Engineering Laboratory (GITI 11). Jettied and unjettied prismitic channels of various cross sectional areas were cut across a barrier island to connect an ocean and bay. Experiments were run with a sinusoidal ocean tide and, in some runs, ocean waves or steady bay inflow. Data collection included bay and ocean tide levels, wave characteristics, channel velocities, channel cross sections and centerline profiles, and overhead photographs to define bed forms.

Calculations using simple mathematical models (Keulegan 1967; GITI 6, Appendix 4) satisfactorily predicted the maximum channel velocity and the bay tide range, high and low water time lag, and superelevation.

Comparison with tidal prism versus channel area relationships for prototype inlets (GITI 3) showed that for a given tidal prism the area was an order of magnitude larger than the area predicted by an extrapolation of the prototype curve. Wave action reduced these areas up to 40 percent.

One tool for evaluating the effects of proposed structures and other modifications on tidal inlets is the movable bed hydraulic model. They are the most difficult of all movable bed models because the entrance to a tidal inlet is a region of strong current and wave effects combined. The only known U.S. movable bed tidal inlet models were the seven conducted by WES from 1939 to 1969. GITI 17 presents an evaluation of the effectiveness of six of these models as well as a review of the state-of-the-art of movable bed model similitude requirements and suggested similitude conditions that should be observed in future movable bed inlet model studies.

Movable bed model calibration is achieved by operating the model to produce changes observed in the field between successive hydrographic surveys. If additional field surveys are available the model is operated to verify that it predicts these changes. Five of the WES models were evaluated by quantitatively investigating the accuracy of calibration as no field data were available for subsequent model vertification. A sixth model (Galveston Harbor Entrance) had post channel modification data available for evaluation of model verification.

In general, the report concludes that calibration of the five models was unsatisfactory in terms of their reproduction of prototype hydrographic changes between field surveys. Entrance channel shoaling rates and patterns predicted by the Galveston model were not in agreement with subsequent prototype observations.

Deficiencies observed are believed to be caused by: scale and lab effects caused by nonsimilarity between model and prototype processes and conditions; insufficient historical and contemporary data to allow adequate model calibration and operation; and oversimplification of prototype conditions in the model.

In an appendix to the report WES provides background information on the purposes for conducting the model studies, practical limitations encountered, and results of positive practical value achieved by the model studies.

Miscellaneous

Information compiled on over 6000 inlet photographs during the search for imagery for the inlet geometry and stability classification studies is listed in GITI 2. Included are: inlet name and geographic coordinates, photograph date and scale, georef grid square, agency holding photograph, and NOS chart covering the inlet.

An indepth annotated bibliography of over 1000 books, journal papers, and published and unpublished reports on the geologic, hydraulic and engineering aspects of tidal inlets has been compiled in GITI 4. It covers material dated up to 1973.

GITI 5 is a collection of memoranda by M.P. O'Brien giving miscellaneous thoughts on the hydraulic behavior and stability of tidal inlets. It also recommends a series of field and laboratory studies.

In GITI 13 Escoffier reviews most of the important basic developments concerning analysis of the hydraulics and stability of tidal inlets. He also summarizes functional design requirements for the development of inlets and briefly presents four case studies. The most valuable contribution of this report is the extension of his original inlet stability concept (Escoffier 1940).

In 1940 Escoffier presented a diagram in which the mean channel velocity (ordinate) was plotted against the channel cross-sectional area (abscissa) for a range of areas starting from zero. He assumed that a constant channel velocity (horizontal line) defines equilibrium conditions for the inlet,and its intersection point with the first curve defines the stable inlet area. In GITI 13 Escoffier uses O'Briens prism-area relationship to show that the equilibrium velocity is not contant but increases with channel area. He presents the new version of his diagram (Figure 6) as a plot of dimensionless mean velocity, ν, versus Keulegan's repletion coefficient, K to yield the inlet stability point B.

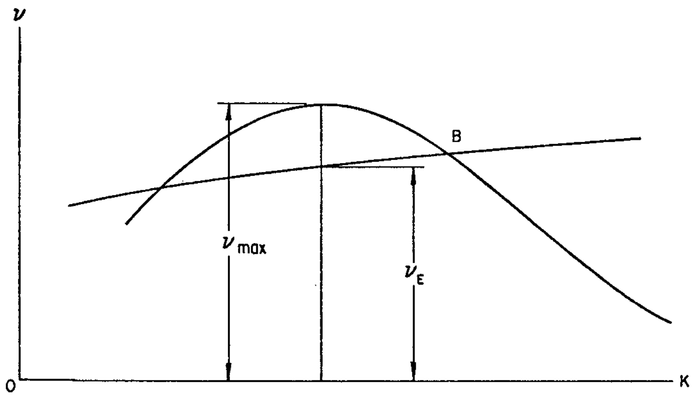

Figure 6 - Escoffier inlet stability diagram (GITI 13).

He further reasons that an indication of the stability of an inlet is given by $\lambda = \frac{\nu max}{\nu E}$. When $\lambda < 1$ no channel area could be stable for the given channel length, bay area and ocean tide. When $\lambda > 1$ a stable channel is possible, the degree of stability being indicated by the magnitude of λ. An evaluation of this concept using data for a series of inlets of known historic stability is needed.

Summary

The General Investigation of Tidal Inlets was a varied and effective program of inlet studies that has made significant contributions to supporting the Corps' Civil Works effort. However, continued inlet research is needed and should receive high priority as part of the Corps' coastal engineering research program.

Acknowledgement

The analyses and results presented in this paper, unless otherwise noted, were based on research conducted under the Coastal Engineering Research Program of the U.S. Army Corps of Engineers. The findings of this paper are not to be construed as official Department of the Army position unless so designated by other authorized documents. Permission to publish this information is appreciated.

Appendix - GITI Reports

1. "Reanalysis of BEB TM 94" E.C. McNair (in press).
2. "Catalog of Tidal Inlet Aerial Photography" J.H. Barwis, June 1975.
3. "Tidal Prism-Inlet Area Relationships" J.T. Jarret, February 1976.
4. "Annotated Bibliography on the Geologic, Hydraulic and Engineering Aspects of Tidal Inlets" J.H. Barwis, January 1976.
5. "Notes on Tidal Inlets on Sandy Shores" M.P. O'Brien, February 1976.
6. "Comparison of Numerical and Physical Hydraulic Models, Masonboro Inlet, North Carolina" D.L. Harris and B.R. Bodine, June 1977 (plus four separate appendices on individual models by various authors).
7. "Model Materials Evaluation" E.C. McNair, June 1976.
8. "Hydraulics and Dynamics of New Corpus Christi Pass, Texas: A Case History, 1972-73" E.W. Behrens, R.L. Watson, and C. Mason, January 1977.

9. "Hydraulics and Dynamics of New Corpus Christi Pass, Texas: A Case History, 1973-75" R.L. Watson and E.W. Behrens, September 1976.

10. "Hydraulics and Dynamics of North Inlet, South Carolina, 1974-75" R.J. Finley, September 1976.

11. "Laboratory Investigation of Tidal Inlets on Sandy Coasts" R.E. Mayor-Mora, April 1977.

12. "A Case History of Port Mansfield Channel, Texas" J.M. Kieslich, May 1977.

13. "Hydraulics and Stability of Tidal Inlets" F.F. Escoffier, August 1977.

14. "A Spatially Integrated Numerical Model of Inlet Hydraulics" W.N. Seelig, D.L. Harris and E.E. Herchenroder, November 1977.

15. "Physical Model Simulation of the Hydraulics of Masonboro Inlet, North Carolina" R.A. Sager and W.C. Seabergh, November 1977.

16. "Hydraulics and Dynamics of North Inlet, South Carolina, 1975-76" D. Nummedal and S.M. Humphries, September 1978.

17. "Evaluation of Movable Bed Tidal Inlet Models" S. Jain and J.F. Kennedy, February 1979.

18. "Physical Model Simulation of the Hydraulics of Masonboro Inlet, North Carolina - Supplementary Tests" W.C. Seabergh and R. Sager, June 1980.

19. "Tidal Inlet Response to Jetty Construction" J.M. Kieslich (in press).

20. "Geometry of Selected Tidal Inlets" C.L. Vincent and W.D. Corson, May 1980.

21. "Stability of Selected Tidal Inlets" C.L. Vincent and W.D. Corson, (in press).

22. "Evaluation of Physical and Numerical Models - Masonboro Inlet, North Carolina" J. McTamany (in press).

23. "General Investigation of Tidal Inlets - A Summary" R.M. Sorensen (in preparation).

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