CHAPTER 17

CONTRIBUTION OF HYDRAULIC MODELS TO COASTAL SEDIMENTATION STUDIES

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INTRODUCTION

The use of hydraulic models in coastal sedimentation studies dates back more than 60 years. To the best of the writer's knowledge, the first such model was of the tidal portion of the Mersey River in England, and was constructed and operated by Professor Osborne Reynolds in the year 1887. Data obtained from the model tests by Professor Reynolds were used in the location and design of navigation channels from the sea to the port of Liverpool.

Since the time of Professor Reynolds, numerous models have been used in this and other countries for studies of coastal sedimentation problems. The first such study made by the Waterways Experiment Station was of Winyah Bay, South Carolina in 1933, and was followed by studies of Ballona Creek outlet near Venice, California; Galveston Harbor, Texas; Absecon Inlet at Atlantic City, New Jersey; the Umpqua River entrance in Oregon; Lynnhaven Inlet near Norfolk, Virginia; and many others. This paper covers in a general way the types of coastal sedimentation problems subject to model analysis, the types of models used, model instruments and appurtenances, field data requirements, adjustment and verification of models, testing of proposed improvement plans, the analysis of test results, and the limitations of models.

GENERAL PROBLEMS SUBJECT TO MODEL ANALYSIS

Coastal sedimentation problems of primary importance to the Corps of Engineers are those pertaining to maintenance of navigation channels and to erosion or accretion of ocean beaches. Materials transported along the coasts by the combined action of waves, littoral currents, and tidal currents, and materials discharged into the oceans by rivers and estuaries shoal the entrances and access channels to the harbors of our nation. Such shoaling is very detrimental to navigation because of decreased channel depths; also, large amounts of public and private funds are expended each year for maintenance dredging of these channels. Model studies have contributed to the design of channels and appurtenant jetties, dikes, etc., for the reduction of shoaling in numerous cases. Beach erosion problems may be caused directly or made more serious by the construction of works designed to reduce shoaling of navigation channels. Such works are usually designed to halt or diminish the movement of material to a given area; therefore, shore areas downbeach from the improvement works may be eroded due to interruption or elimination of their normal supply of material. It is therefore necessary that studies be made of all proposed jetties, breakwaters, and other control works designed to reduce channel shoaling in an effort to determine their probable effects on beach erosion and accretion. Models for testing such improvement works usually reproduce a considerable length of the shore line on each side of the problem area so that the effects of the works on adjacent areas can be noted.

TYPES OF MODELS USED

Coastal sedimentation problems are usually studied by means of a movable-bed model, in which the bed of the model in the problem area is molded of sand, crushed coal, haydite, or other erodible materials. Fig. 1, which shows the layout of the Absecon Inlet model, will illustrate the general features of the movable-bed model. It will be noted that the inlet proper and the adjacent beaches for distances of four miles to the north and south of the inlet, and offshore to about the 30-ft. contour of depth in the Atlantic Ocean, were molded of sand. The remainder of the wetted portion of the model was molded of concrete to a common elevation. This area provided space for the pipe system used to repro-

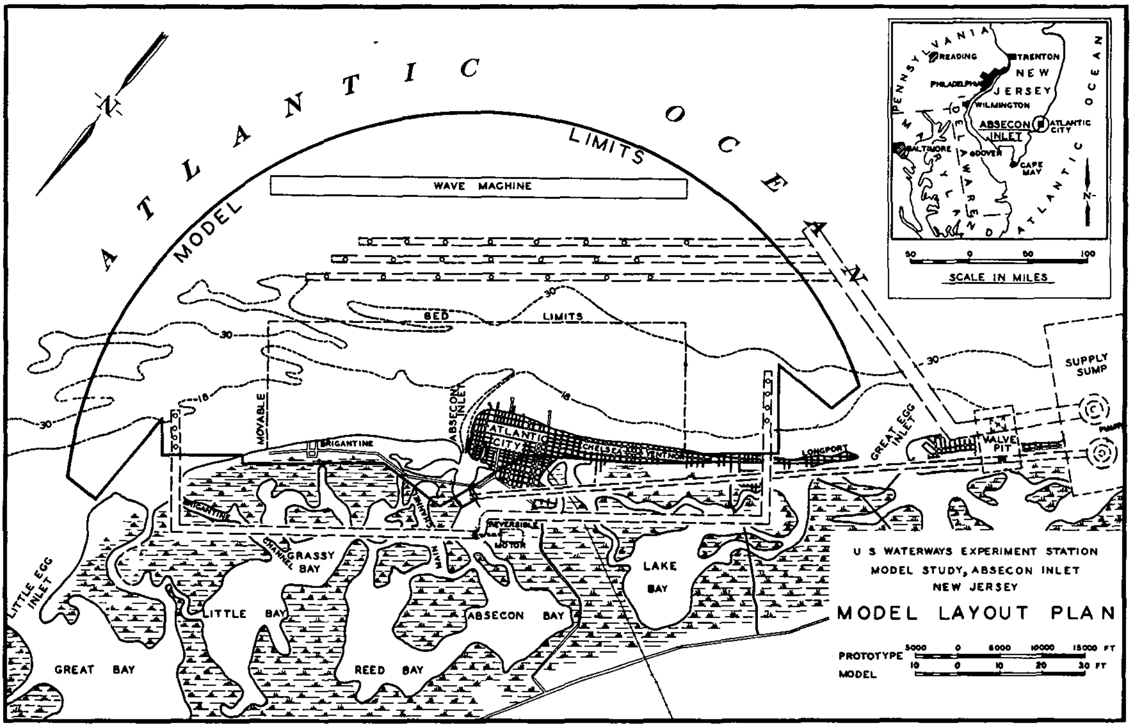
ATLANTIC OCEAN
MODEL LIMITS
WAVE MACHINE
BED LIMITS
MOVABLE
ABSECON INLET
ATLANTIC CITY
BRIGANTINE
CHELSEA
VENTNOR
LONGPORT
GREAT EGG INLET
VALVE PIT
SUPPLY SUMP
PUMPS
REVERSIBLE MOTOR
GRASSY BAY
CHANNEL
MAIN
LITTLE EGG INLET
LITTLE BAY
ABSECON BAY
LAKE BAY
GREAT BAY
REED BAY
PENNSYLVANIA
READING
TRENTON
NEW JERSEY
PHILADELPHIA
WILMINGTON
ABSECON INLET
ATLANTIC CITY
BALTIMORE
DOVER
CAPE MAY
MARYLAND
DELAWARE
ATLANTIC OCEAN
SCALE IN MILES
U S WATERWAYS EXPERIMENT STATION
MODEL STUDY, ABSECON INLET
NEW JERSEY
MODEL LAYOUT PLAN
PROTOTYPE
MODEL

Fig. 1

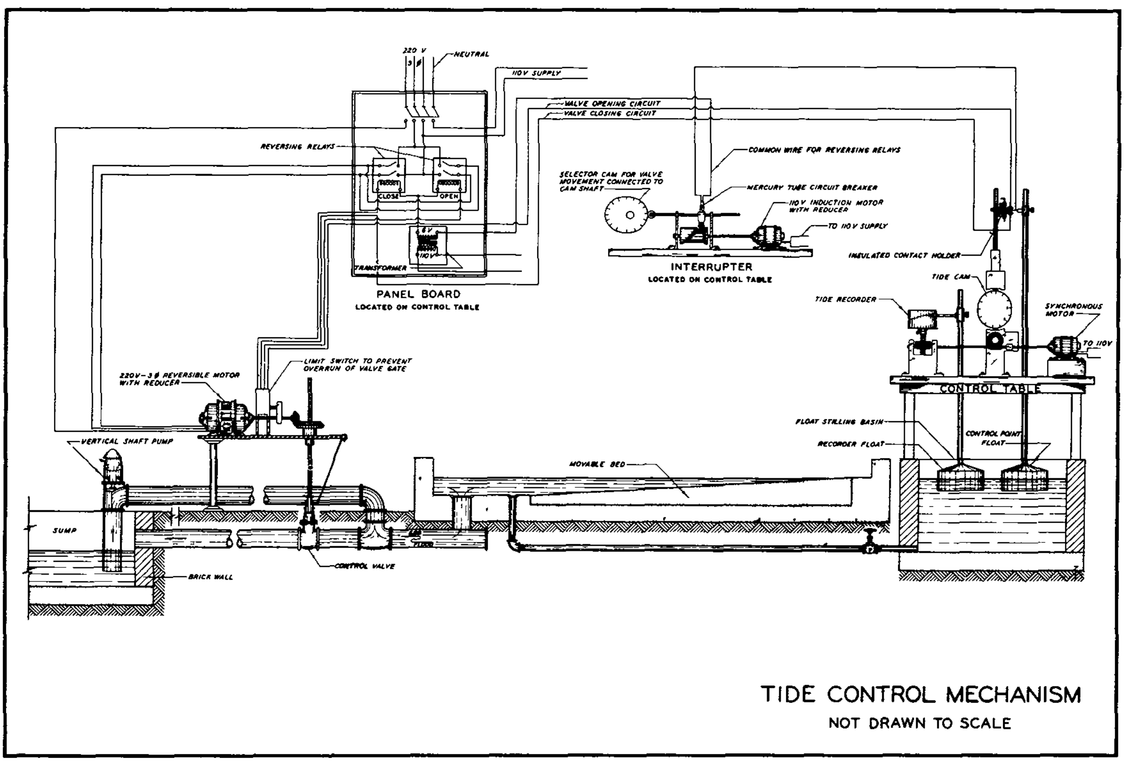
220 V
NEUTRAL
110 V SUPPLY
VALVE OPENING CIRCUIT
VALVE CLOSING CIRCUIT
REVERSING RELAYS
CLOSE
OPEN
TRANSFORMER
PANEL BOARD
LOCATED ON CONTROL TABLE
COMMON WIRE FOR REVERSING RELAYS
SELECTOR CAM FOR VALVE MOVEMENT CONNECTED TO CAM SHAFT
MERCURY TUBE CIRCUIT BREAKER
110 V INDUCTION MOTOR WITH REDUCER
TO 110 V SUPPLY
INTERRUPTER
LOCATED ON CONTROL TABLE
INSULATED CONTACT HOLDER
TIDE CAM
TIDE RECORDER
SYNCHRONOUS MOTOR
TO 110V
CONTROL TABLE
LIMIT SWITCH TO PREVENT OVERRUN OF VALVE GATE
220V-3 ϕ REVERSIBLE MOTOR WITH REDUCER
VERTICAL SHAFT PUMP
SUMP
BRICK WALL
CONTROL VALVE
MOVABLE BED
FLOAT STILLING BASIN
RECORDER FLOAT
CONTROL POINT FLOAT
TIDE CONTROL MECHANISM
NOT DRAWN TO SCALE

Fig. 2

duce the ocean tide, and served as a floor for the wave machine which was operated from a number of positions from south to east. The movable-bed portion of the model was molded by means of male templets suspended from permanent sounding rails, the templets being spaced not more than two feet apart so that accurate molding could be obtained.

INSTRUMENTS AND APPURTENANCES

Appurtenances usually required on movable-bed, coastal sedimentation models are tide-control mechanisms, wave machines, littoral-current reproducers, bed-load feeders, and an assortment of gages, current meters, sounding rods, and other minor equipment. One of the tide-control mechanisms in present use at the Waterways Experiment Station is illustrated schematically in Fig. 2. This mechanism consists of the following component parts: (a) a large header sloping from the model to a nearby water-supply sump; (b) a pump supplying through a separate line a constant flow from the sump into the header at a point near the model; (c) a motorized, rising-stem valve installed in the header a few feet toward the sump from the entrance of the pumpline into the header; and (d) an automatic control apparatus located within the model for regulating the operation of the valve by means of a system of floats and electric contacts. It is obvious that the complete closing of the valve will divert the full pump output into the model and produce a rapidly "flooding" tide; with the valve wide open, the full pump output plus gravity flow from the model will return to the sump and produce a rapidly "ebbing" tide. Thus, by means of intermediate valve openings, any desired rate of ebb or flood can be reproduced in the model. The automatic control apparatus for regulating the valve operations is equipped with a cam, cut to a polar plot of the tide to be reproduced, rotated by a synchronous motor at a speed determined by the computed model time scale. Riding vertically on this cam is a rod carrying a pair of electric contacts, one above the other, which rise and fall in accordance with the plotted tide curve. A third contact, placed between this pair of contacts with very slight clearances above and below, is attached to a rod supported by a float on the model water surface. Thus whenever the model water surface rises above or falls below its proper elevation at any time during the tidal cycle, the float forces the middle contact to close the circuit through the upper or lower contact, respectively. Closing of the upper circuit actuates the valve in an opening direction, which directs more of the pump output back to the sump and causes the model water surface to fall to its proper elevation; closing of the lower circuit reverses this operation, causing the model water surface to rise to its proper elevation. The tide thus reproduced can be controlled to an accuracy of approximately 0.001 ft. in the model. The control apparatus is equipped with a recording device which inks on a roll of paper a continuous record of the model tide curve, superimposed upon the prototype curve being reproduced. The prototype curve is inked by a pen riding on the plotted tide cam, while the model curve is superimposed by a pen riding on a float on the model water surface. This feature is of utmost importance during adjustment of the apparatus, and permits a visual check on the accuracy of the model tide reproduction at all times.

Various modifications of the above described apparatus are made in special cases. For example, if computations show that the discharge through the outflow valve would be so great as to require a very large valve, then separate automatic controls are installed on the inflow and outflow valves and operated in such manner that, during an ebbing tide in the model, the control on the inflow line progressively decreases the pumped supply as the control on the outflow line progressively increases the gravity flow to the supply sump. This procedure is reversed during the flooding tide, so that the two controls operate in balance at all times. The control of the inflow valve is usually fixed; that is, the valve operates through a predetermined cycle of movement at all times, while operation of the outflow valve is controlled by the contact point and float system previously described. Therefore, the outflow valve compensates for small variations in pump efficiency and other factors which are sure to occur over a period of months or even years of model operation.

Wave machines of the eccentric roller type, flap type, and plunger type have been used in coastal sedimentation models at the Waterways Experiment Station.

Since it is usually necessary to reproduce waves from several directions during the course of such a study, the plunger type machine has been found most suitable. Fig. 3 is a schematic diagram of one of the plunger type machines in present use.

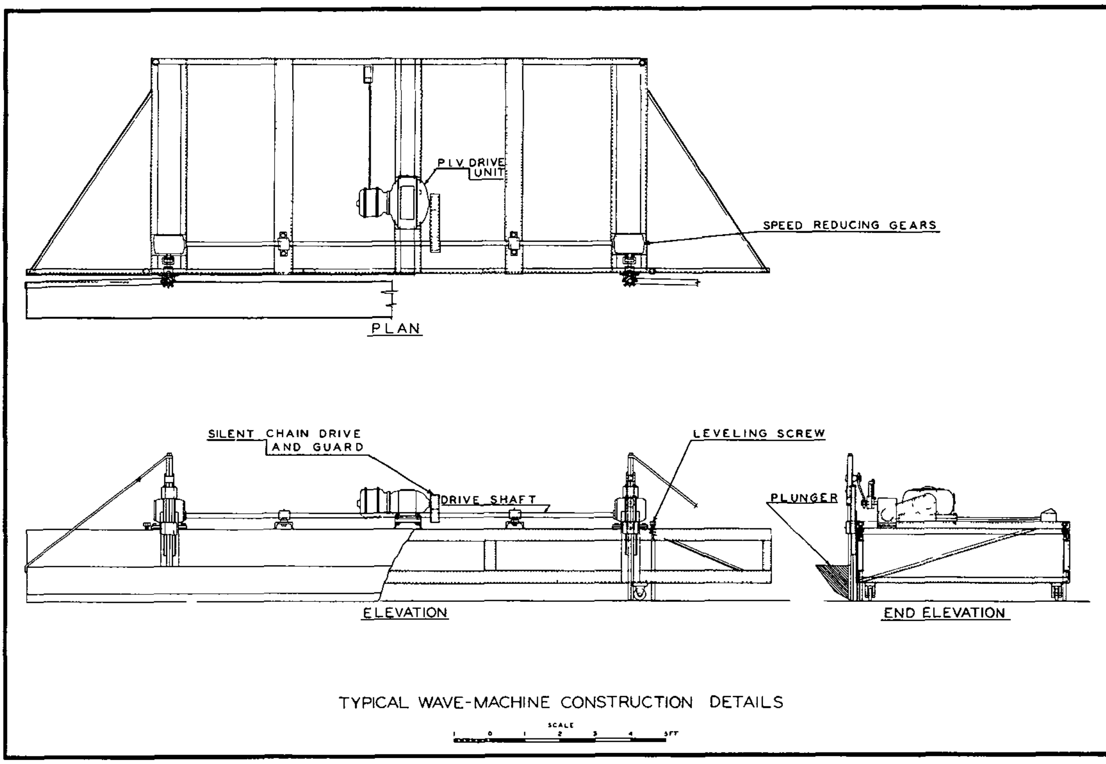

Fig. 3

This machine consists of a heavy angle-iron frame mounted on castors so that it can be moved readily. If the machine is more than about 50 ft. long, a small motor-driven winch is usually mounted on the frame and the machine is moved from place to place by means of a cable wound on a drum. An electric motor and link belt P.I.V. gear arrangement drives a number of special speed reducers, the number depending on the length of the machine, to which are connected slotted cams which are bolted to the risers from the plunger. The connection between the cams and plunger risers are adjustable so that the submergence of the plunger can be set as desired. With the above arrangement, the speed, length of stroke, and submergence of the plunger can be easily adjusted so that the plunger will reproduce the characteristics of the desired waves.

Coastal sedimentation problems are usually affected to some extent by littoral or alongshore currents. Regardless of the origin or cause of such currents, it is always necessary to reproduce them in coastal sedimentation models since they have a direct effect on the transportation of materials. Since such currents usually change direction in nature, it is necessary to provide for flow in either direction in the model. Fig. 1 illustrates the usual method for reproducing littoral currents in a coastal sedimentation model. Bays are constructed at both ends of the model, beyond the limits of the movable-bed section, and are connected by a pipe in which is installed a reversible pump. With the pump operating in one direction, water is removed from one end of the model and introduced into the opposite end, thus setting up a current from one end of the model to the other. A valve is installed in the pipeline at a convenient location so that the pump discharge, and therefore the velocity of the littoral current, can be controlled. Vanes are usually installed at the two bays so that the direction of the current can be set properly as it leaves the bays. In some coastal sedimentation problems the alongshore currents are tidal and therefore of a regular pattern, reversing in direction about every six hours and passing through a regular cycle from slack to maximum and back to slack. In such instances it is necessary to install an automatic control on the valve which will vary the discharge in such manner that the cycle of current velocities will be reproduced accurately. A pair of cam-actuated electrical switches appurtenant to the automatic control reverses the direction of the pump at the proper times.

Inasmuch as the movable-bed section of a coastal sedimentation model represents only a relatively short section of a shore, it is obvious that material must be fed artificially at the end of the movable bed from which the drift of material is moving. The amount of material to be introduced per unit of time is determined by oversvations and estimates of the amount passing the comparable point in the prototype. The material is usually added to the model by an endless belt driven by an electric motor; the material is spread evenly on the belt and is dropped into the model by rotation of the belt in accordance with a predetermined rate of introduction. Material moving out of the movable-bed section at the opposite end is carefully picked up and measured so that a constant check is kept on the rate of littoral drift of material through the model.

FIELD DATA REQUIREMENTS

The degree of accuracy attained in a model study of coastal sedimentation problems depends to a large extent on the availability of accurate and adequate field data for its design, construction, and operation. It goes without saying that a movable-bed model, adjusted on the basis of inaccurate field data, will unquestionably furnish inaccurate results during subsequent tests of proposed improvement works. It is also imperative that adequate field data be available for a proper analysis of the problem before the selection of model scales and design of the model and appurtenances are undertaken.

As will be explained more fully later in this discussion, the proper adjustment of bed movement is of principal importance in the coastal sedimentation model. It is necessary, therefore, that a sufficient number of periodic hydrographic surveys of the prototype be available to determine progressive changes in hydrography over a considerable period of time. Otherwise, the adjustment of bed movement in the model may be based on a period during which the trend of hydrographic changes is not in accordance with the long-time trend.

Once the trends and magnitudes of hydrographic changes have been established from studies of periodic surveys, it is necessary to determine what hydraulic forces are responsible for such changes and the relative importance of each of the forces involved. This information can usually be obtained from a comprehensive study of the tides, tidal currents, littoral currents, and waves in the problem area. Such studies should cover a considerable period of record so that inaccurate conclusions will not be reached because of inadequate records. It is believed that such investigations should cover at least one year of record.

One very important factor, and probably the most difficult to obtain, is the determination of the volume of material moving through the area under investigation as littoral drift. It is entirely possible that a certain section of the coast will remain stable for a period of years while hundreds of cubic yards of material per day are moving through the area from an unstable reach on one side to an unstable reach on the other. Periodic hydrograph surveys of the area would indicate that no changes were taking place; however, if an entrance channel were dredged through such an area it would shoal very rapidly. While it is practically impossible to determine the rate of littoral drift accurately except in isolated cases, some indications can be obtained from examinations of erosion or accretion characteristics of the shore line and offshore bars for considerable distances in each direction, dredging records of nearby channels, and erosion and accretion adjacent to jetties, groins, and other structures in the vicinity.

VERIFICATION OF MODELS

It is obvious that the worth of any coastal sedimentation model study is wholly dependent upon the ability of the model to produce with a reasonable degree of accuracy the results which can be expected to occur in the prototype under given conditions. It is essential, therefore, before any model tests are undertaken of proposed plans of improvement with a view to predetermining their effects in the prototype, that the required similitude first be established between the model and prototype and that all scale relationships between the two be determined.

In the case of fixed-bed model studies involving the investigation of purely hydraulic problems, the existence of hydraulic similitude with the prototype can be shown and all scale relationships determined by mathematical means. However, in the case of a problem requiring the use of a movable-bed model to study the movement of bed material under the influence of hydraulic forces, what is commonly known as hydraulic similitude with the prototype sometimes is not compatible with the all-important similitude with respect to the phenomenon of bed movement. This is brought about by the fact that the bed material used in the model fails to conform to the linear scale ratios which govern all other model dimensions. It therefore becomes necessary in such a model to depart somewhat from hydraulic similitude by adjusting the various hydraulic forces so that their effects upon the model bed material will be similar to the effects of the corresponding prototype forces upon the prototype bed material.

It is evident, therefore, that the attainment of complete hydraulic similitude between a movable-bed model and its prototype, although desirable, is not necessary. Instead, a proper analysis of such a problem requires that scale relationships be carefully adjusted to provide a high order of similitude with respect to the effects of the various hydraulic forces upon the scour, travel, and deposition of bed and beach material, which is the essence of such a study. However, the obtaining of this required similitude and the establishing of the model-to-prototype scale relationships involved are altogether impossible by mathematical means, and can be accomplished only through the empirical process of verification.

The verification of a movable-bed model is an intricate cut-and-try process of progressively adjusting the various hydraulic forces and the model operating technique until the model will accurately reproduce hydrographic changes which are known to have occurred in the prototype between certain dates. In this manner the accuracy of the functioning of the model is established and certain of the scale relationships with the prototype are determined. The verification process usually consists of the following steps: (a) two prototype surveys of past dates are selected -- the time between these dates being known as the "verification period" -- and the movable bed of the model is molded to conform to the earlier survey; (b) the hydraulic phenomena which occurred in the prototype during the verification period are simulated in the model to the proper time scale, all regulative measures undertaken in nature during that period being reproduced in the model at their proper times; and (c) the movable bed of the model is surveyed at the end of this period, and the model is considered to be satisfactorily verified only when this survey is an accurate reproduction of the later prototype survey.

However, in operating a model subject to such a variety of forces as confronts the experimenter in coastal sedimentation studies, it is absolutely necessary to abide by the principle that departure from scale simulations of the several forces should not be regarded lightly. The over-all effect of the forces acting is a resultant of the various component forces. And, as previously stated, the verification of the model is dependent upon its similitude with respect to the effects of the various hydraulic forces. It can be readily understood that the results of the introduction of some improvement plan, such as a jetty, which would alter the hydraulic regimen of an area, may be erroneous if the component forces acting in the model are definitely dissimilar to those acting in nature. Therefore, every effort should be made during the verification process to keep the model forces as undistorted as possible.

It was mentioned previously that the verification process of a movable-bed model established one of the model-to-prototype scale relationships, and this is the all-important scale relationship with respect to bed movement. Tides, currents, and waves are reproduced in the model in accordance with the time scale computed from the linear scale relationship; however, this time scale bears no relationship whatsoever to the time required for the model to reproduce a change in bed configuration which occurred in a known period of time in the prototype. Let us assume that the verification period selected for adjustment of a movable-bed model covers a three-year period in the prototype, and that the model is adjusted so that all changes in bed configurations known to have occurred during the period are reproduced accurately in the model in an actual operating time of 36 hours. It is therefore evident that the time scale for bed movement, model to prototype, is 12 hours to one year or one hour to one month.

TESTING OF IMPROVEMENT PLANS

After the verification procedure of the coastal sedimentation model has demonstrated the ability of the model to reproduce with a reasonable degree of accuracy the bed configurations which are known to have occurred in the prototype under corresponding conditions, the model is ready for tests of existing conditions and proposed improvement plans. One fixed testing procedure -- that developed during the verification phase of the study -- is followed during all such tests; the only variations between the subsequent tests being in the lengths of the tests and in the features of the proposed plans of improvement.

The first test made following a satisfactory verification of the model is a base test or test of existing conditions. The purpose of the base test is twofold: (a) to provide all possible data as to the accuracy and dependability of the functioning of the model over a relatively long period of time (the base test usually covers a period of time equivalent to five to ten years in the prototype, as dictated by the time scale for bed movement); and (b) to provide data which will serve as a basis for the comparison of results of subsequent tests in which proposed regulative works are simulated (a comparison of base test results with results of a test of regulative works makes it possible to isolate the effects of the regulative works in the model). Tests of proposed regulative works are made in exactly the same manner and for exactly the same length of time as the base test, the only difference being that the regulative measures of each plan are installed in the model at the beginning of the test of that particular plan of improvement. The movable-bed portion of the model is surveyed in detail at the end of each test of a proposed plan of improvement, and the survey is compared to that made at the end of the base test to determine the effects of the plan on the scour and deposition of bed material throughout the model. In addition, hydraulic measurements of tidal heights, current velocities, and current directions as affected by the plan, and volumetric measurements of the effects of the plan on movement of material as alongshore or littoral drift are made.

ANALYSIS OF TEST RESULTS

Direct comparisons are made between hydrographic surveys obtained at the end of each test of a proposed improvement plan and that made at the end of the base test, and comparative maps showing plus and minus changes in bed configurations as effected by each plan are made. These maps illustrate very clearly the effects of the various plans on the movable-bed section of the model, and they may be used for computations of scour and fill in critical areas if considered necessary. Comparisons of the volume of material moving out of the movable-bed portion of the model in the direction of the littoral drift during the base test with comparable volumes during tests of proposed improvement works will indicate the effects of each plan on the passage of material through the area under investigation. These data are significant in the case of tests of jetties or other coastal improvement works which might cause deterioration of downcoast beaches by decreasing their normal supply of material.

Measurements of tidal heights, current directions, and current velocities for each plan tested are compared directly to base test measurements. Such comparisons will indicate the effects of each plan on the hydraulic characteristics of the area under investigation, and are of particular significance if navigation is of importance to the problem under study. For example, a proposed jetty at a tidal inlet might indicate the desired effects on bed configurations but might also create such undesirable hydraulic conditions that it will be dropped from further consideration.

MODEL LIMITATIONS AND CONCLUSIONS

It has been emphasized during this discussion that the adjustment and verification of the coastal sedimentation model, and hence the accuracy of results to be obtained therefrom, are based upon data obtained from comprehensive prototype investigations. The completeness and accuracy of such prototype studies are most essential, since the model study would unquestionably produce erroneous results if its adjustment and verification were based upon inaccurate or incomplete field data.

In the above connection, model-prototype confirmation studies are of inestimable value to the engineer who works with coastal sedimentation models. Following the installation of an improvement plan in the prototype as a result of such a study, the question immediately arises as to how closely the functioning of the plan in nature corresponds to model predictions. Where inconsistencies are revealed through such a confirmation study, model operating techniques may be improved to the end of eliminating such inconsistencies in the future. Model-prototype confirmation studies are believed to be of such importance to the further development of coastal sedimentation model technique -- and thus to the solution of the problems involved -- that plans for a confirmation study should be included as a part of each comprehensive improvement plan that has involved study on a model.

It is apparent that the coastal sedimentation model has certain limitations, imposed largely by the characteristics of the available model bed material, the adequacy of prototype data, the distortions inherent in small-scale models used for such purposes, and the uncertainties that still exist as to the mechanics of sediment movements in both model and prototype systems. These limitations are considered to be far out-weighed, however, by the many advantages gained through the relatively inexpensive and positive expedient of model analysis as contrasted to the prohibitive and tremendous cost, effort and hazard that would otherwise be involved in achieving similar solutions by trial and error in the field.

It is to be understood that the hydraulic model is not proposed as a substitute for analytical design; nor can its use eliminate the need for extensive field investigations. The three are mutually supporting. The need for experimentation is basically fostered by the fact that present-day knowledge of coastal sedimentation phenomena has not advanced to the point where such problems can be resolved by theory alone. Until that point is reached the hydraulic model will continue to be a most useful expedient in providing information not obtainable by other means. Thus, in its usefulness to the engineer responsible for the solution of coastal sedimentation problems, the hydraulic model occupies a position of great importance lying somewhere between the provinces of abstract theory and rule-of-thumb field engineering.