C-4

POKREFKE

SECTION 1.1.1 WITH INCLUDED REMARKS

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1.1.1. Basic Methodology of WES Movable Bed Models

The large movable--bed models employed by the Corps of Engineers at the Waterways Experiment Station (WES) in Vicksburg, Mississippi, as stated previously, were classified as loose-bed models that used an empirical modeling approach. The models utilized relatively large horizontal scales (typically 1:120 to 1:600) and relatively low vertical distortion (typically ~~4 to 10~~1.5 to 4). By taking an empirical approach, the~~The~~ models -did not utilize established, Froude similitude criteria during the design or operation of a model. Warnock (1949) stated that the primary step in the development of a movable--bed model involved the selection of suitable scales and bed material which would result in two phase flow **(do not know what is trying to be stated here, if you are talking about water and sediment, fine)** similar to the prototype. To accomplish this, a thorough knowledge of the characteristics of the prototype based upon hydraulic and hydrographic survey data was required. In addition, experience in the field of river mechanics and movable--bed hydraulic models was needed for proper model ~~calibration~~verification. Figure 2-1 is a typical movable--bed model used at WES.

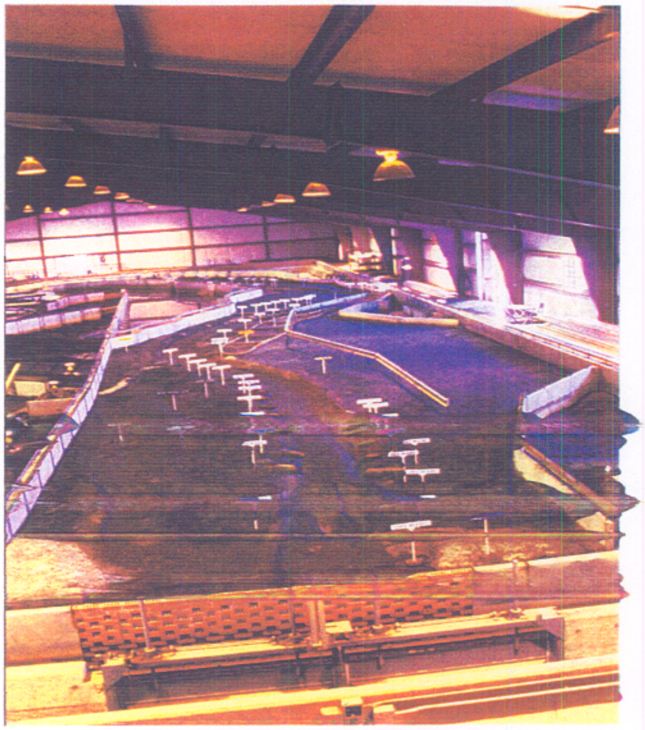

Figure 2-111: Large Movable Bed Model at WES, Middle Mississippi River at Dogtooth Bend, Miles 39.2 to 20.2, Scales 1:400 Horizontal & 1:100 Vertical

The distortion or exaggeration of the vertical to horizontal scale ratio in the WES models was necessary to generate satisfactory bed movement in the models. Franco (1963) recommended that distortion should be as small as practical primarily because it tends to affect the relationship of velocity, width-depth ratio of the channel and curvature, and, consequently, the distribution of energy within the channel. Franco goes on to state that the effect of distortion on the performance of some structures such as sills or stilling basins can usually be eliminated by using the vertical scale to reproduce certain horizontal dimensions, particularly the dimensions in the direction of flow.

These models were used in both indoor and outdoor facilities. A rectangular channel flume composed of concrete or a combination of concrete and mortared brick was designed and constructed according to a chosen planform or bankline alignment of the prototype. The movable-bed portion of the model within the flume was then molded or formed from a chosen prototype survey. The molding process usually involved establishing comparative range lines or cross sections on the model at intervals consistent with hydrographic surveys (typically 4 feet~~1000 feet~~ apart on the model~~Mississippi River~~). The model bed was then interpolated and contoured between these sections by skilled technicians and model makers. Figure 2-2 is a photo illustrating the molding process and the contouring of the model bed.

Figure 2-2~~2~~: Technicians molding or forming WES large-scale model

Franco (1978) presented guidelines for design, adjustment, and operation of physical sediment models at WES. Franco listed eight factors to be considered during model design. These factors were:

1. Discharge scale
2. Time Scale
3. Sediment type, rate, and method of sediment input
4. Supplementary slope
5. Entrance and exit conditions
6. Bank alignment and overbank roughness
7. Erosion resistant boundary(ies)
8. Regulating Structure elevation and condition.

In addition to the factors listed above, a ninth, very important factor integral to the model design was the adjustment of rails to provide a supplemental slope on the model to aid in the movement of the model bed material.~~for the changing of the survey datum reference throughout the model.~~ Each of these nine factors are discussed in detail.

1. **Discharge Scale.** Discharge in the models were controlled through the use of a pump, weir or venturi meter, and associated values~~sluice gate~~. The ability to vary the discharge was required because the models used hydrographs. An important observation by Franco (1978) relates to the type of hydrograph used in model operation. Franco notes that many hydraulic laboratories operated physical models based on the dominant discharge concept where a single flow rate is used for all model simulations. He advocates use of a variable hydrograph because "most problems in alluvial streams result from changes in river stages and discharges…" (Franco, 1978).

   In selection of a discharge scale relation, care was taken to ensure that the model was operated very near the critical tractive force (or critical velocity) required to start movement, realizing that the prototype operated considerably above that range. Therefore, the model discharge scale had to be variable to provide the same relation of model sediment movement to that of the prototype for the range of flows and stages reproduced. ~~Due to the distortion of the model, the use of a single scale for the full range of discharges would result in an exponential increase in forces in the model which would be well above that of the prototype at the higher discharges.~~ To compensate for this exaggeration of energy and to prevent the bed from becoming abnormally mobile as compared to the prototype, the rate of increase in discharge was exponentially reduced in the model as compared to the prototype, such that as the maximum prototype discharge was approached, the discharge scale relation approached the Froude discharge scale factor for the model scales. ~~The model discharge did not follow a direct linear scale relationship to the prototype. As the model hydrograph increased, a greater scale factor was applied to the model discharge to represent the prototype discharge.~~ Depending upon the particular model, the application of these applied discharge factors was different.

   An example of this exponential, non-linear model discharge scale relationship to the prototype was presented by Franco (1978) on a coal bed model with distortion of 1.5 (Figure 2-3). The graph shows that as the

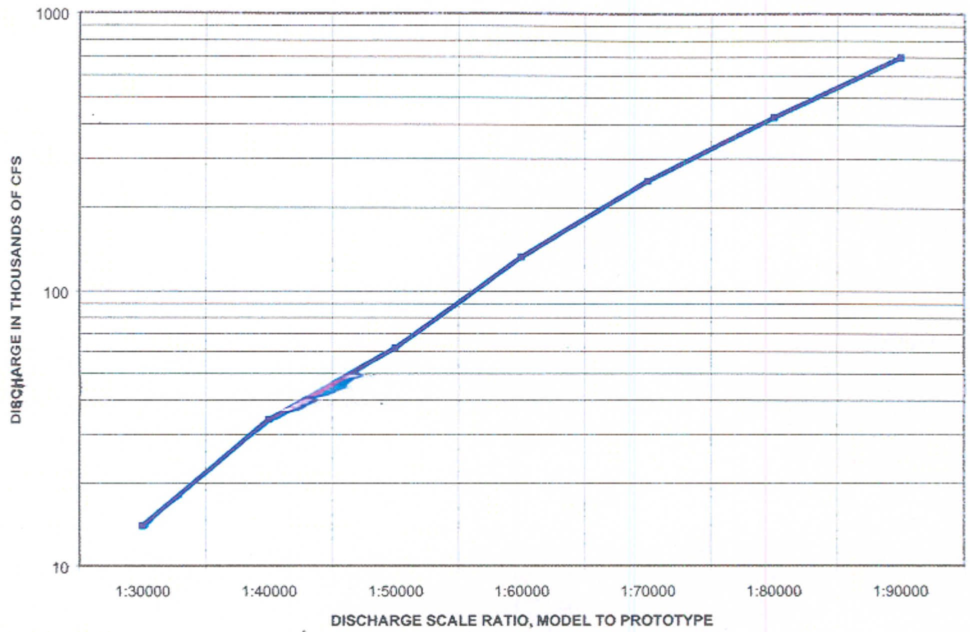

Figure 2-333: Discharge Relation Curve, WES Coal Bed Model, Scale 1:120 - 1:80

discharge of the model increased, the scale discharge ratios applied to represent the prototype increased exponentially. It should be noted that this plot is on semilog graph paper resulting in an exponential (or power) relationship.~~According to Franco, the discharge scale relation must be such that movement of model bed material is similar to prototype bed movement for the range of flows in the simulated hydrograph.~~ Models are generally too small to develop the forces required to move typical model bed materials, especially at lower flows. The additional forces needed to move the sediment must be provided through discharge scale relations that are greater than the Froude theoretical scale derived from the model horizontal and vertical scales. However, over the range of model discharges, there was always more distortion (increase) of low flow than high flows relative to the Froude criteria.

Besides reproducing prototype discharge hydrographs, using distorted model discharges, the corresponding stage hydrographs were also maintained in the model. This was accomplished by installation of a movable tailgate in the model exit area. For all intensive purposes this tailgate was used to reproduce the portion of the river downstream of the modeled reach to create backwater and maintain selected stages in the model based on the stage hydrograph. ~~Due to this exponential discharge scale, the water stages in the model would not correspond to the appropriate stages in the prototype. As a result, the smaller discharges in the model would result in reduced stages. To~~

~~compensate for these discrepancies, the model stages were manipulated via a movable tailbay weir at the end of the model.~~ This tailgate~~bay~~, in combination with the changing scale discharge releases at the upper end of the model, was moved upward~~s~~ or downward~~s~~ to maintain a desired model water surface elevation at a preselected location in the model~~create a distorted water surface profile~~. ~~By artificially raising the stage, this operational procedure compensated for the fact that a exponential discharge scale relationship was being utilized.~~ Figure 2-4 from Franco (1978) shows the discharge scale ratio versus stage from a sand bed model with a distortion of 7. The graph shows that as stages increased, the discharge scale ratio conversion to the prototype increased exponentially.

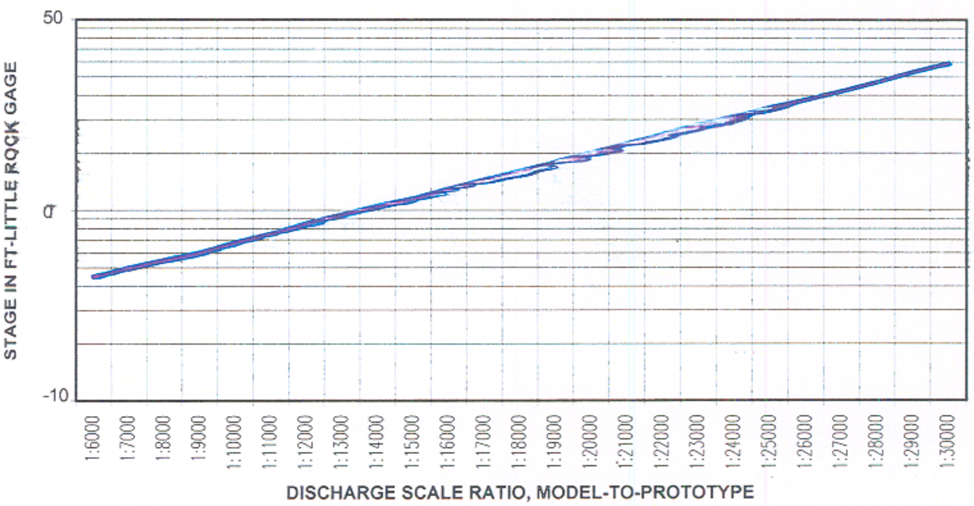

Figure 2-444: Discharge Relation Curve, WES Sand Bed Model, scale 1:250 - 1:36

2. **Time Scale.** Franco (1978) noted that time scales in the WES models should be adjusted in order to reproduce sequences and durations of stage and discharge in the prototype. The time scale should indicate a relation between the time required for bed development in the model and in the prototype. The WES models utilized time scales between 5 and 10 minutes to equal one day in the prototype, depending on the bed material used. The vast majority of the models operated at WES used a time scale of 6 minutes equal to one prototype day. ~~This translated into a hydraulic time ratio (t_r) of between 144 and 288.~~ These times were based primarily on prior model work.

   Although a physical time sequence was used while model testing of alternatives, the model time was never used as a representation of the actual elapsed time one could expect sediment response changes to occur from a particular design alternative or plan. The primary reason for this was that so little was known about the actual sediment transport response time in the prototype. In addition, multiple, successive average model hydrographs were sometimes run for a particular design alternative to ensure that the full, ultimate model bed response to stability was achieved. The resultant bed configuration at the end of the hydrographs was always meant to represent the general trends of that particular design and was never meant to give the river engineer an estimate on the actual time it would take for the design response to fully develop in the prototype. This approach was taken based on making comparison of model results for alternative plans tested, and the realization that any plan constructed in the prototype would be subjected to stage and discharge hydrographs different those used in the model testing.

3. **Sediment Type, Rate, and Method of Sediment Input.** Model sediment was not sized according to the model scales because of physical limitations. Reducing particle sizes to smaller sizes would have required even larger model scales and would change the behavior of the model bed material from non-cohesive to cohesive. Foster (1975) described model sediments predominantly used in the WES models to be a 0.2 mm diameter for sand bed models (specific gravity of 2.65) and 4 mm diameter for crushed coal bed models (Specific gravity of 1.3). The sizes of these sediments equated to approximately 1.5 inches to 9 inches in prototype diameter, depending upon the particular model that was in use. The Mississippi River is comprised mainly of sand and silts. Franco (1978) states "in natural streams, the size of bed material does not vary in direct proportion to the size of the river and tends to be larger in smaller streams".

   The method of sediment input used in the WES models involved a ~~trial and error~~ procedure whereby bed material was manually introduced at the upper end of the model. The rate of transport of this material through the model was ultimately a function of the energy supplied by the model and was developed during the verification process. The immediate goal was to ensure that sufficient model bed material was available to enter the model if energy conditions were such to have that occur. While the ultimate goal was to establish equality in the amount of sediment introduced into the model as compared to the amount of sediment leaving the model, during verification the amount of material input to the model was independent of the amount of sediment extruded from the model. An agreement in model sediment budget, particularly during plan testing, would ensure that the channel bed would not degrade nor aggrade. This was one portion of the term~~termed as the~~ "stability" of the model. The other portion of the "stability" term addressed the channel bed configuration. When the channel configuration was not changing significantly and the sediment input and output amounts were in agreement over consecutive hydrographs, the model was considered "stable."~~Often times, stability varied, whereas sediment equilibrium changed because of the dynamic nature of the physical model.~~ Adjustments to sediment~~in~~ input were~~had to be~~ made only during model verification based~~accordingly and was solely dependent~~ upon the watchful eye of the modeler. At the end of the verification phase, a model sediment-discharge curve was developed and provided input parameters for base and plan testing.

4. **Supplemental Slope.** Supplemental slope (also referred to as tilt) is the slope needed in addition to that resulting from the linear scales to produce adequate bed movement. Franco expressed supplemental slope as:

$$S_{su} = S_m - \left[S_p \frac{y_r}{x_r} \right]$$

where
S_{su} = supplemental slope,
S_m = total model slope required to mobilize the model bed sediment,
S_p = slope at full scale (prototype)
x_r = the horizontal scale ratio, and
y_r = the vertical scale ratio.

For model studies conducted at the WES values for total slope were reported as:

S_m = 0.00065 to 0.0010 for 0.2 mm sand
0.00030 to 0.00050 for 4 mm crushed coal

Typically a model operates very near the critical tractive force while the prototype operates considerably above the critical level. Vertical distortion is an adaptation to increase tractive force in a model. The distortion of the discharge scale also aids in increasing the tractive velocity to accomplish the model bed sediment movement. However, in most loose bed models supplementary slope is also required to develop the total necessary force~~s~~ for bed movement.

5. **Entrance and Exit Conditions.** The entrance condition was constructed and modified so as to dissipate excessive energy and bed scour resulting from the discharge introduction point at the upstream portion of the model. In addition, modifications were made to ensure the proper direction of flow into the model. Baffles or guide vanes constructed of~~,~~ concrete, screen, and other materials were used to accomplish this. The exit condition was constructed far enough downstream from the area of interest in the model study to ensure minimal negative model influence, and contained an adequately sized pit to collect the bed material extruded from the model.

6. **Bank Alignment and Overbank Roughness.** The accurate alignment of the banks in the model, or channel planform, was critical to the proper development of the resultant bed configuration. For this reason, it was necessary to acquire accurate maps, drawings, or photos of the prototype for accurate horizontal boundary conditions in the model. In addition, often some representation of overbank roughness, usually in the form of folded~~concrete and~~ screen~~, and other materials were~~ was incorporated in the models to simulate overbank prototype roughness associated with vegetation, etc. The purpose of this folded screen was not to exactly model the prototype vegetation and roughness, but to provide some degree of increased flow resistance, as compared to the channel, on the overbank areas. In most WES models, a small, parallel portion of the floodplain or overbank was usually included in the model; however, some WES movable-bed models reproduced significantly large overbank areas.

7. **Erosion Resistant Boundaries.** There are many erosion resistant materials that occur in the prototype in the form of gravel and cobble bars, clay plugs, rock strata, sunken vessels, debris, etc. The WES models utilized several different materials in the model to simulate resistance to erosion including haydite, screen, gravel, and concrete. Figures 2-5 and 2-6 are photos illustrating some of the different materials used. In Figure 2-5, concrete was used to simulate both a rock feature and dikes in the model. In Figure 2-6, haydite was used to simulate an erosion resistant bar (Boston Bar). The determination of erosion resistant boundaries in the model was usually made during model verification based upon either information obtained from the prototype or upon judgment made by the modeler.

   In addition, pile dikes and rock structures of the prototype were represented in the model. Pile dikes were constructed using appropriately sized, based on the horizontal scale, cylindrical rods. Rock structures were typically constructed using small limestone or pea gravel with some type of cement binder to take into account the physical, scale distortion in the model. ~~by a variety of materials, including pervious thin-walled metal screen and impervious material in the form of thin-walled sheet metal, concrete, and pea gravel.~~ Figures 2-7 and 2-8 illustrate impervious structures used in the WES models.

8. **Regulating Structure Elevation and Condition.** Critical to the performance of the WES models was the amount of available information describing the condition of existing channel regulating structures in the prototype. This included basic information on dike elevation and dike length, dike type, pile or rock. During verification~~In addition~~, as much information about the general condition of the dikes was necessary for successful completion of this effort~~model calibration~~.

Figure 2-555: Tower Rock Bar Model Showing Concrete Formed Geologic Rock Feature (Tower Rock) and Concrete Formed Dikes.

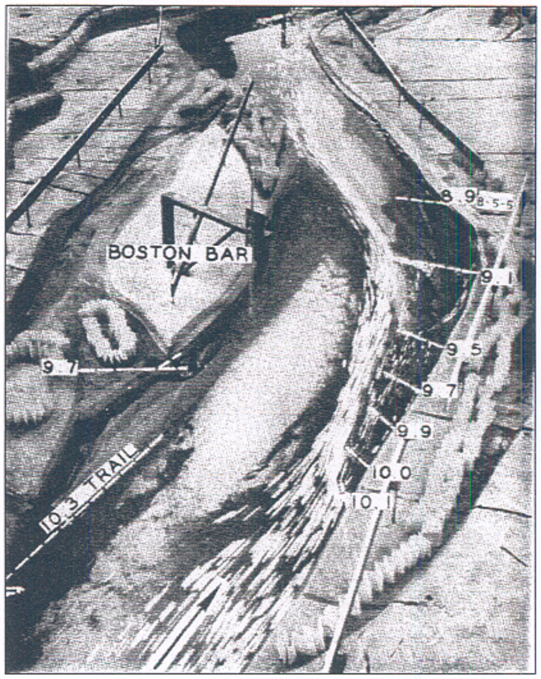

Figure 2-666: Mississippi River Boston Bar Model Study, Scale 1:600 H and 1:100 V. Boston Bar is at Left Center and was Constructed out of Erosion-Resistant Haydite.

Figure 2-777: Pea Gravel-Concrete Conglomerate Representing Bendway Weirs in the Dogtooth Bend Model

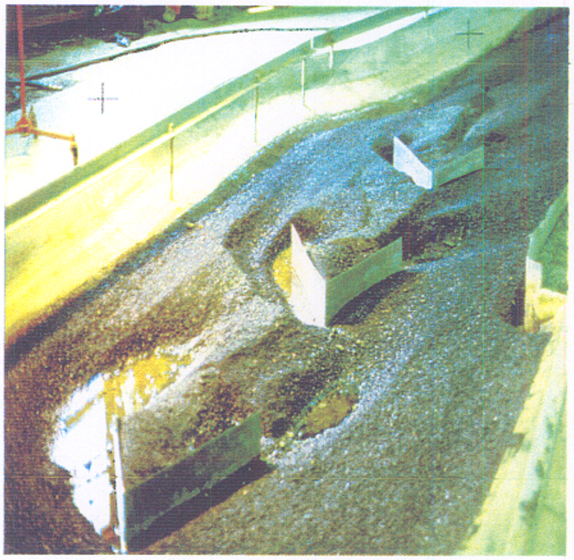

Figure 2-888: Thin-Walled Metal Representing Chevrons in the St. Louis Harbor Model

9. **Adjustments of Rails.** ~~Localized adjustments in the reference datum along the models were employed in the WES Models.~~ A series of adjustable rails were placed on either side of the model banks, and used to install the desired supplemental slope in the model. These rails were also used to hold the templates used to mold the initial model bed configuration and to survey the model at the end of tests. Elevations used to establish the supplemental slope were based on a fixed benchmark established and maintained for the specific

model. That benchmark was related to prototype elevations and was the basis for all vertical measurements on the model.~~. By raising or lowering the rails, the datum of selected areas of the model bed were shifted (either decreased or increased in elevation), depending upon the requirements of the particular model. In this manner, localized areas of the model where bed movement was either too great or too low were adjusted by either raising or lowering the molding template in that area. Conversely, the elevations of the model bed would then increase or decrease.~~ The rail adjustments to obtain the desired supplemental slope were made during the verification process and were then held constant throughout the duration of the model study. WES was able to use this approach because specific stages were maintained in the model, and areas of excessive or limited bed material movement could be identified during verification. Subsequently, the supplemental slope in the rails was increased or decreased as needed to obtain acceptable bed material movement. Figure 2-9 is a photo showing the location of rails for datum elevation adjustments.

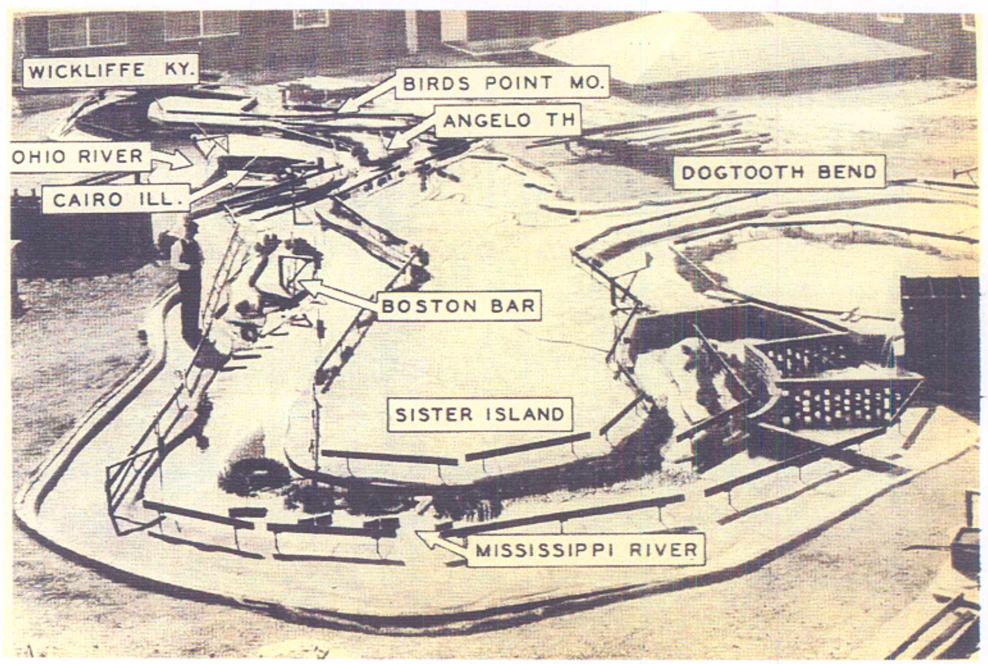

Figure 2-999: Mississippi River, Boston Bar Model. The Photo Illustrates the Use of an Adjustable Rail System for Localized Control of a Variable Datum.

Once the bed was molded, the model was ready for testing. The procedure at WES for the initial adjustment or calibration of the model bed behavior was termed "model verification" (Franco 1968). Each of the above 9 parameters were adjusted during the verification phase of the model study. Franco (1968) states that the normal verification is an intricate process of adjusting the various hydraulic forces and model operating technique until the model demonstrates its ability to reproduce with acceptable accuracy the changes in bed formations that are known to have occurred in the prototype during a given period. Franco (1978) adds that the "principal considerations in the design of movable-bed models should be that the hydraulic forces developed be sufficient to move the material forming the bed in simulation of prototype sediment movement and that the model is capable of defining the problem at hand." With this as the focal objective, sediment movement was guided by the following considerations:

1. Model bed movement should occur during all flows that produce prototype bed movement.
2. During low flows, m~~M~~ovement should be mostly in crossings with little or no movement in deep channels~~ during low flows~~.
3. During high flows, s~~S~~ediment movement should be fairly general throughout, but movement in bends and deeper channel areas will be greater than elsewhere~~ during high flows~~.
4. Resultant bed conditions are dependent on the point of time in the hydrograph cycle when a survey is made (surveys made at the end of a high-flow period indicate deeper channels in bends and shallower crossings while surveys made at the end of a low-flow period indicate shallower channels in bends and deeper crossings).

During the verification a representation of the discharge and stage hydrographs are introduced and maintained in the model ~~non-linear scaled historical hydrograph was run through the model ~~over a starting bed configuration that was molded to represent the actual prototype bathymetry that existed at the beginning of the hydrographs. The planform or bankline alignment of the model associated with this bed was constructed from available historical information as close to the era of time that the starting bed configuration was based upon. After the hydrograph was run, the model bed configuration was surveyed. The resultant bathymetry was visually compared in planform and elevation to a hydrographic prototype survey representative of prototype conditions occurring at the end of the historical hydrograph. The time duration of the historical hydrograph was kept relatively short, ~~which was~~ usually one prototype year. This was based on the premise that the model should be capable of reproducing prototype trends and tendencies that were documented between annual prototype surveys. ~~due to the fact that if the time period was too long, m~~Major changes in the bankline occurring in the prototype due to bankline recession could ~~would have to~~ be incorporated into the model based on timing within the hydrograph, but this was an unusual case. ~~in order for the proper bed response to occur.~~ Longer time durations were consider impractical from both a model operation and economic perspective (Derrick 2002).

After the stage and discharge hydrographs were ~~was~~ run through the model and the ending bed configuration was compared to the prototype survey, the model was re-molded to the starting bed configuration and adjustments were then made as discussed earlier. The hydrograph was then again simulated and the process repeated as necessary until the modeler felt that similarity was achieved with the ending prototype survey. Special attention was given to the input ~~and output~~ of sediment to ensure that the model had sufficient (neither too much nor too little) bed material available. ~~bed stability.~~

After the described~~previous~~ process was complete, the model was considered verified. At this point, an "average annual design hydrograph" was developed in coordination with the study sponsor and used for all subsequent model runs. These stage and discharge~~is~~ hydrographs were ~~was~~ based upon the particular problem at hand and were~~was~~ empirically determined usually by averaging a set of historical data. The average annual design hydrograph was then used to establish a base test condition in the model.

The model bed configuration at the end of verification or a particular prototype survey served as the starting bed configuration for the base test. Usually, multiple average annual hydrographs would be run through the model ~~bed~~ until bed stability was achieved (sediment equilibrium and relative channel configuration consistency). Once this occurred, the resultant model bed configuration formed the base test template bed. This base test bed configuration was the bed normally used for the starting bed configuration of all design alternative tests. When a particular design was installed in the model, two to three hydrographs were usually simulated, depending upon the channelsediment response observed in the model. At the end of each hydrograph, the model was usually surveyed and then compared to the starting base test bed configuration. Sometimes additional hydrographs were simulated in a particular design alternative until model stability was achieved. Additional hydrographs were also simulated on plans of river training structures that involved progressive phases or stages of construction where the channel bed was allowed to react to a plan before another phase was installed and testing continued. When a new design was to be incorporated into the model, the bed was usually re-molded back to the starting base test bed configuration and the procedure repeated.

It was in the above manner that general conclusions were made on the effectiveness of particular design alternatives. Designs were always compared to the base test and not directly to the prototype; however, the desired improvements were also considered in this analysis. The river engineer then took these bed response indications from the model to assist in design and construction decisions for the prototype.

Flow visualization was also used in many movable--bed model studies at WES. Using time exposure or time lapse photography, confetti streaks or lighted drones were captured under certain flow conditions in the model usually during the base test and comparative design alternative tests. In the model study results, the flow visualization was used for a general indication of the relative effects of the main concentration of flow for a particular design as compared to the base test. Due to the fact that the model velocities were distorted above the theoretical values, this flow visualization provided general information and was not used in the design of testing plans. It was merely another indication of the plan effects and was not relatable to any type of navigation condition evaluation. Figures 2-10 thru 2-13 illustrate flow visualization used in some of the WES models.

Figure 2-101010: Flow Visualization of the Greenville Bridge Model, Lower Mississippi River, Vertical Scale Distortion of 3.6

Figure 2-111111: Flow Visualization of the St. Louis Harbor Model to Assess Flow Patterns through Multiple Bridge Crossings, Vertical Scale Distortion of 2.5

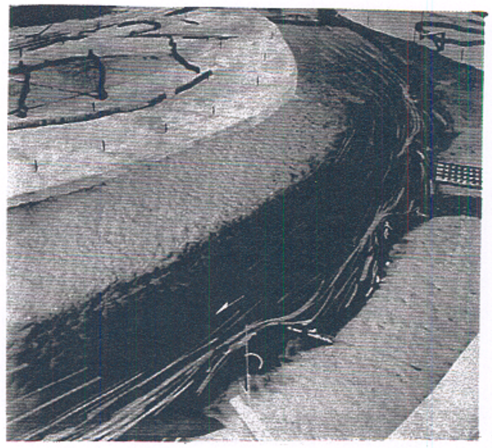

Figure 2-12~~1212~~: Flow Visualization of the Arkansas River Model, Vertical Scale Distortion of 4

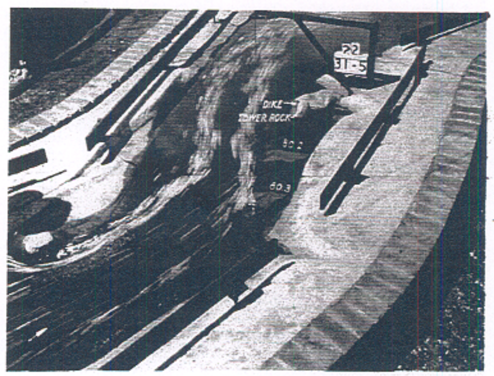

Figure 2-13~~1313~~: Flow Visualization of the Grand Tower Model, Middle Mississippi River, Vertical Scale Distortion of 4

1.2 Micromodel Methodology Compared With WES Model Methodology.

The development of the micromodel was based upon observation and experience with many of the same operational considerations established in the WES models. Both models have historically been used for studying similar river dynamics and for designing solutions to similar types of problems. Similarities and differences in methodology are as follows.

1. **Size.** Typically, the horizontal scales of micromodels are approximately one to two orders of magnitude smaller than most WES models. Horizontal scales in the micromodel have normally ranged between 1:3600 to 1:12000. Horizontal scales in the WES models normally ranged between 1:100 to