Waterways Experiment Station,
Hydraulic Laboratory
Halls Ferry Road, two miles south of I-20
Vicksburg
Warren County
Mississippi

HAER No. MS-2

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PHOTOGRAPHS
WRITTEN HISTORICAL AND DESCRIPTIVE DATA

Historic American Engineering Record
National Park Service
Department of the Interior
Washington, DC 20013-7127

HAER
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HISTORIC AMERICAN ENGINEERING RECORD

WATERWAYS EXPERIMENT STATION,
HYDRAULICS LABORATORY

HAER No. MS-2

Location:	On a 685-acre tract along the eastern side of Halls Ferry Road, two miles south of I-20 in Vicksburg, Warren County, Mississippi.
Date of Construction	Established 1928, construction underway by 1930.
Owner:	U.S. Army Corps of Engineers
Use:	Hydraulics laboratory
Significance:	Established in response to a campaign to create a national hydraulics laboratory during the 1920s, the Waterways Experiment Station's activities include the resolution of hydraulic problems in waterways and harbors as well as the design and testing of hydraulic structures through the use of physical and numerical (computer generated) models. The Station has become the world's largest and best-equipped laboratory facility for practical application of experimental hydraulics. It has been designated an Engineering Landmark by the American Society of Civil Engineers.
Historian:	Billy Joe Peyton, 1986.

EXECUTIVE SUMMARY

The Waterways Experiment Station (WES) is a U.S. Army Corps of Engineers installation situated on a 685-acre tract at Vicksburg, Mississippi. In addition to this main facility, WES maintains a sub-office at Clinton, Mississippi (35 miles east of Vicksburg) where the physical model of the lower Mississippi River Basin is located. WES laboratories conduct basic and applied research, develop methods and techniques, test materials and equipment, and provide consulting expertise in such broad fields as hydraulics, rock and soil mechanics, concrete, earthquake engineering, coastal engineering, weapons effects, vehicle mobility, pavements, protective structures, water quality, engineering geology, and dredged materials. The six laboratories which comprise WES are the Hydraulics Laboratory, Geotechnical Laboratory, Structures Laboratory, Environmental Laboratory, Coastal Engineering Research Center, and the newly formed Information Technology Laboratory.

The origins of WES date to 1924, when a campaign was launched to construct a national hydraulics laboratory. However, it was not until after the tragic 1927 Mississippi River flood that a national hydraulics laboratory -- the Waterways Experiment Station -- finally became a reality with passage of the Flood Control Act of 1928. Building construction was underway in 1930 on a 245-acre tract of land, 4.5 miles south of Vicksburg. From its beginning as a hydraulics laboratory, WES has burgeoned into a multi-laboratory research facility.

During its long history of operation, the Hydraulics Laboratory at WES has become the world's largest and best-equipped laboratory facility for practical application of experimental hydraulics. Its general function is the resolution of hydraulic problems in waterways and harbors and the design and testing of hydraulic structures through the use of physical and numerical (computer-generated) models. Each model study involves problems and phenomena that require special techniques.

The Hydraulics Laboratory has continued to this day to grow in size and scope of operations, and in so doing has subdivided according to specific problem or study areas. Fifteen gigantic shelters spanning a total of 28 acres have been built over the years to house a portion of the thousands of physical models studied at WES since the 1930s. Model test facilities, equipped with such appurtenances as reservoirs, pumping plants, and water-supply systems now occupy an area of nearly 100 acres.

Overall Hydraulics Laboratory organization has evolved over the years as WES has grown; it presently consists of four divisions, each headed by a division chief, and each made up of three branches. Current Hydraulics Laboratory organization is as follows: Estuaries Division, Hydraulic Analysis Division,

Hydraulic Structures Division, and Waterways Division. In addition, the Mississippi Basin Model (MBM) at Clinton is included under the jurisdiction of the Waterways Division, River Regulation Branch.

With the subsequent founding of five additional laboratories, WES has expanded its scope of operations from strictly hydraulics study to a wide variety of research areas. WES annually handles over 1,500 projects for 120 different sponsors, and accomplishes a work program in excess of 100 million dollars. The Hydraulics Laboratory has been on the cutting edge of hydraulic engineering research for over fifty years, and in that time has produced a number of originally designed instruments for use on physical hydraulic models. These instruments, along with certain commercially manufactured ones, have been an integral part of the Hydraulics laboratory's long and distinguished history.

The Waterways Experiment Station was recently designated a Landmark by the American Society of Civil Engineers. In recognition of this significance, WES asked the Historic American Engineering Record (HAER) to conduct a study of hydraulic engineering instrumentation used in the Hydraulics Laboratory. The HAER field team sent to WES in the summer of 1986 was responsible for the completion of two primary tasks: an inventory and historical evaluation of Hydraulic Laboratory instrumentation; and an historical and technological overview of the development of hydraulic instrumentation technology at WES.

The inventory resulted in the categorization and evaluation of 150 different instrument types. A five-criterion ranking system was formulated to assess the significance of each inventoried instrument. After this evaluation each instrument was placed in one of three categories of historical significance -- those in Category A possessing the highest level of significance, those in Category C possessing little or no significance. Of the instruments inventoried and evaluated, 8 were assessed to be in Category A, 20 in Category B, and 122 in Category C. A master list of these instruments was prepared which groups each instrument by function (i.e., current/velocity instruments) and cross-references photo number. For 75 of these instruments HABS/HAER inventory cards were prepared, which feature descriptive, historical and significance statements, plus a 35mm contact print of the instrument.

The historical and technological overview was based primarily on research undertaken at the WES technical library. The focus of the overview was on WES-designed, obsolete, or otherwise unique and important pieces of instrumentation within the Hydraulics Laboratory. The objectives were to develop a better understanding of the history of instrumentation at WES and to establish the criteria for the evaluation of instrumentation. Included in the report are general preservation guidelines for instrumentation in each level of significance. Finally, the report includes several recommendations, such as: the need for more specific preservation guidelines for Category A instrumentation to be developed by a qualified curator; and that additional research be undertaken to locate historic photographs and drawings, as well as conducting additional interviews with long-time employees and retirees.

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PREFACE

This report presents the results of a pilot inventory project of instrumentation used in the Waterways Experiment Station (WES) Hydraulics Laboratory undertaken by the Historic American Engineering Record (HAER). For WES, this report will contribute to a better understanding and appreciation of this resource by assisting station personnel identify and plan preservation measures for significant instrumentation. For HAER, it contributes a unique opportunity to augment its understanding of the considerations which go into the design of 20th Century hydraulic structures (such as dams, canals, and bridges), which represent a substantial portion of sites documented by HAER.

Section One of the report describes the project scope, methodology, and recommendations for preservation; Section Two presents an historical and technological overview of WES Hydraulics Laboratory instrumentation; and Section Three contains preservation recommendations for instruments and suggestions for future documentation projects at WES. A bibliography and glossary of hydraulic terms supplement the text.

This report is submitted in partial fulfillment of the requirements set forth in a memorandum of agreement between the Historic American Engineering Record of the National Park Service and the U.S. Army Corps of Engineers, Waterways Experiment Station. As a pilot inventory project, this study focused on WES Hydraulics Laboratory instrumentation. Dr. Michael C Robinson, historian for the Corps of Engineers Lower Mississippi Valley Division and WES, directed the program for the Corps, and Robie S. Lange, HAER historian, was overall HAER project leader for the project. Technical assistance was provided by Romano S. Caturegli, Chief of the Office of Administrative Services at WES. The inventory team wishes to thank the personnel of the Waterways Experiment Station for their gracious assistance during the course of this project. They especially acknowledge the support of COL Dwayne G. Lee, Commander and Director of WES; COL Allen F. Grum, former Director of WES; LTC Frederick D. Reynolds, former Acting Commander of WES; Frank A. Hermann, Jr., Chief of the Hydraulics Laboratory; Richard A. Sager, Assistant Chief of the Hydraulics Laboratory; and Roger T. Saucier, Director of the Environmental Information Analysis Center and head of the Waterways Experiment Station Historical Committee.

The Waterways Experiment Station possesses the complete HABS/HAER documentation for this program. Archival copies of this same information is included in the HABS/HAER collection in the Prints and Photographs Division of the Library of Congress, under the designation HAER No. MS-2.

SECTION ONE

Scope of Work

This report is based on an historic inventory of instrumentation found in the WES Hydraulics Laboratory and at the Mississippi Basin Model at Clinton. The survey was conducted during the summer of 1986 and included the following tasks:

a) completion of documentary research on the evolution of hydraulic instrumentation technology.
b) completion of an inventory of Hydraulics Laboratory instrumentation.
c) preparation of an historical and technological overview of instrumentation technology.
d) establishment of criteria for evaluation of hydraulic instrumentation.
e) development of recommendations for preservation of significant instrumentation.

Also completed as part of this historic inventory project are HABS/HAER inventory cards for approximately 75 separate pieces of instrumentation. These cards include written descriptive and historical data, an assessment of significance, and 35mm black and white photography. In addition, large format photographic documentation was undertaken for select features at WES and the Mississippi Basin Model (MBM).

The inventory cards, 35mm contact prints, and copies of the large format photographic prints are in the possession of WES. Archival copies of the cards, 35mm negatives and contact prints, and large format photography are available in the HABS/HAER collection of the Prints and Photographs Division at the Library of Congress, under the designation: HAER No. MS-2.

Methodology

Documentary Research

The Waterways Experiment Station currently consists of five research laboratories and an information technology laboratory. In order to understand and appreciate the significance of WES contributions in these areas, an overall awareness of its history and development is crucial. Excellent documentation of past activities is available in the WES Technical Information Center Library. Nearly all sources utilized in this study originated from the library, which serves as the Corps of Engineers central reference source for the engineering and scientific fields in which WES is involved. Its extensive holdings number in excess of 300,000 items: books, technical reports, periodicals, reprints, and microforms. The inventory team spent the first days of the project familiarizing itself with the library and learning the overall history and development of the Station. At the conclusion of prefatory research, Beth Redmond (inventory historian) commenced field work

and Billy Joe Peyton (field supervisor/historian) shifted his research emphasis toward the principles of hydraulic engineering and measurement.

The library contains a sizable number of survey texts on the subjects of hydraulic engineering principles and instrumentation technology. WES-generated technical reports, technical memoranda, and miscellaneous papers contained useful data on the required topics. In addition, ASCE Proceedings, Separates, and Transactions furnished supplemental information, as did other miscellaneous periodicals. At the termination of this phase of general research, focus shifted to the study of specific instrumentation.

An effort was made to locate sources dealing with the history and development of WES Hydraulics Laboratory instrumentation. Naturally, the bulk of research time and effort was spent in this phase. A multitude of special WES reports were located which detail specific instrumentation development and capabilities. In most cases, these in-house reports addressed WES-designed instruments, but on occasion details of commercially manufactured examples were found. By far the most beneficial information sources in the library were the continuing series of Hydraulics Laboratory reports, memoranda, and papers produced since the Station's creation. Numbering in the hundreds, these model study reports and special papers specified construction details, model appurtenances, test procedures, instrument developments, and final model test results; a similar series of MBM reports generated since 1942 detail the development of automatic instrumentation, history and description of the model, and meetings of the Mississippi Basin Model Board. A wealth of information was drawn from this data, although the research involved a tedious scanning of nearly all extant Hydraulics Laboratory reports dating from 1930. Various user's manuals, trade catalogs, and specification sheets were also utilized in several cases of specific instrument research.

In addition to the library, the WES Records Holding Area was perused for useful data. Several files yielded information helpful to the project, but the majority of records retained there consist of field notes or other forms of raw data. Fortunately, most of the project's needed documentary research materials were readily on hand in the library stacks or on microfilm. Only a few desired reports were not located (probable reason being the 1960 fire that destroyed the library). A listing of documentary material used during the course of the project may be found in the bibliography.

Field Inventory

A field survey of hydraulic instrumentation was conducted at the Waterways Experiment Station during the summer of 1986. Field survey procedures were based on HABS/HAER Inventory Guidelines.[1] A master inventory list was compiled and 35mm black and white photographs were taken of all located model and prototype instrumentation. Field inventory forms were completed for representative samples of each type of instrument. When several similar instruments were found, one field inventory form was prepared to represent all instruments of that type with mention made of minor variations. Information

collected on the field forms was later edited and transferred to HABS/HAER inventory cards. In addition to the 35mm contact print attached to the back of the cards, a supplemental sketch or diagram of the instrument was attached to some of the cards.

The inventory field work was initiated by a pilot inventory of instrumentation in the Estuaries Division's Estuarine Processes Branch. This group, working exclusively in field experimentation and measurement, was an ideal choice to test field procedure because its entire stock of instruments were conveniently located within a small enclosed compound. After successful testing of inventory methodology, field work for the most part progressed systematically on a division by division basis. The search for instrumentation required a thorough investigation of potential hiding places; model shelter closets, back rooms, dark corners, warehouses and office trailers were searched for "lost" instruments. Patient assistance offered by WES personnel greatly aided in the completion of the inventory field work.

A principle challenge faced by the inventory team stemmed from the portability of the items being inventoried. In most cultural resource inventories the units under study are fixed and immovable, thus insuring that the unit inventoried will not reappear somewhere else; or on the day an area is scheduled to be inventoried a given unit will not have been temporarily relocated. In instances when the items to be inventoried are portable, it is essential that each item be assigned an identification number. However, in the inventory of instrumentation at WES, neither of these requirements were present. In the event that this situation has caused the inventory team to "miss" a particular instrument the "discovered" unit should be evaluated under the criteria outlined in this report.

Another challenge faced by the inventory team centered around the question: "When is an object not an instrument?" The decision was made that attention would be give to instrumentation used in the conduct of hydraulic testing and measuring. This excluded from study such things as batteries and other multi-purpose, commercially available objects which do not specifically pertain to the unique activities associated with a hydraulics testing lab.

Historical Overview of Instrumentation Technology

A combined historical and technological overview was prepared from the documentary research and field inventory. It was written in three parts: 1) a brief introductory description of hydraulic model and instrument types; 2) a history of model and prototype instrumentation by type of measure, including a history of MBM appurtenances, and 3) recommendations for preservation of significant instrumentation and suggestions for future work at WES.

The focus of the overview was on WES-designed, obsolete, or otherwise unique and important pieces of instrumentation within the Hydraulics Laboratory. The objectives were to develop a better understanding of the history of instrumentation at WES; to establish the criteria for evaluation of

instrumentation; to identify important instrumentation and assist station personnel plan for the most appropriate maintenance and preservation of significant instrumentation; and to provide information which may be used in subsequent and more in-depth documentation projects.

Instrumentation Evaluation and Preservation Recommendations

A five-criterion ranking system was formulated by the HAER inventory team to assess all inventoried instrumentation based on a review of historical and technological significance. Individual pieces were awarded either zero (0) or one (1) point for each of five criterion; totals were added for each instrument to arrive at a score of zero to five. All instruments were assigned a designation of historical significance (i.e.. A, B, or C) according to their total scores. The highest rating "A" was given for instruments scoring 4 or 5 points, "B" was given for those scoring 2 or 3 points, and "C" was given to those scoring 0 or 1 point. Finally, a set of general preservation recommendations were developed for each category of significance (see Section Three). This system offers station personnel a fast and efficient method of selecting appropriate preservation and maintenance treatments for historically important instrumentation at WES.

Criteria of Historical Evaluation of Instrumentation

1) WES Instrumentation Scarcity--
This category addresses the rarity of a particular instrument type at WES, based on results of HAER's Hydraulics Laboratory instrument inventory. Relative scarcity is defined as three or fewer of a particular instrument located during the course of the inventory (1 point awarded if instrument is scarce at WES).

2) Overall Instrumentation Scarcity--
This category addresses the current availability (scarcity) of a particular instrument in relation to the field of hydraulic engineering in general. Scarcity is defined as either a) not a "commercially available" stock item, or b) not easily or routinely constructed on demand (1 point awarded if instrument is scarce outside of WES).

3) Design or Major Modification of Instrumentation Attributed to WES--
This category addresses instruments originally designed by WES personnel, whether constructed by WES personnel or manufactured from WES-prepared specifications; also includes major and significant modifications made by WES personnel of instrumentation not originally designed at WES (1 point awarded if designed or modified by WES).

4) Longevity of Use--
This category addresses instrumentation manufactured, or the original design for which was developed, prior to 1950 and is still in use with only minor modifications (1 point awarded if instrument was manufactured or designed prior to 1950 and is still in use).

5) Major Technological Advancements Adapted to Hydraulic Testing at WES--
This category addresses instrumentation developed since the establishment of WES which was considered to be a major advance in the efficiency, reliability, or accuracy of hydraulic model/prototype testing (1 point awarded if instrument, developed since WES's existence, is a major advance in hydraulic testing).

Notes

1. Historic American Buildings Survey/Historic American Engineering Record, National Park Service, HABS/HAER Inventory Guidelines, (unpublished draft), June, 1986.

SECTION TWO

Background

The Waterways Experiment Station (WES) is a U.S. Army Corps of Engineers installation situated on a 685-acre tract at Vicksburg, Mississippi. In addition to this main facility, WES maintains a sub-office at Clinton, Mississippi (35 miles east of Vicksburg) where the model of the lower Mississippi River basin is located. As the principal research, testing, and development facility of the U.S. Army Corps of Engineers, WES employs over 1,500 persons. This includes a staff of 600 professionals, over 100 of which have earned Ph.D's. WES functions on a reimbursable basis with sponsors paying all project costs. Major sponsors include the Corps of Engineers, all branches of the U.S. Armed Forces, Tennessee Valley Authority, Federal Emergency Management Agency, Environmental Protection Agency, Department of Transportation, Federal Aviation Administration, local, state, and foreign governments and private industry.

WES laboratories conduct basic and applied research, develop methods and techniques, test materials and equipment, and provide consulting expertise in such broad fields as hydraulics, rock and soil mechanics, concrete, earthquake engineering, coastal engineering, weapons effects, vehicle mobility, pavements, protective structures, water quality, engineering geology, and dredged materials. The six laboratories which comprise WES are the Hydraulics Laboratory, Geotechnical Laboratory, Structures Laboratory, Environmental Laboratory, Coastal Engineering Research Center, and the newly formed Information Technology Laboratory.

The origins of WES date to 1924, when a campaign was launched in Washington, D.C. to construct a national hydraulics laboratory. However, it was not until after the tragic 1927 Mississippi River flood that a national hydraulics laboratory -- the Waterways Experiment Station -- finally became a reality with passage of the Flood Control Act of 1928. Original plans called for the lab to be in Washington, D.C., under the jurisdiction of the Bureau of Standards, and later plans called for it to be built at Memphis, Tennessee. However, Vicksburg was ultimately chosen as its home in 1929, after the Mississippi River Commission moved its headquarters there from St. Louis. Building construction was underway in 1930 on a 245-acre tract of land, 4.5 miles south of Vicksburg.

The first physical hydraulic model built at WES in the late summer of 1930 was carved out of the Vicksburg loess soil. It was a small-scale model of the Illinois River, used to determine the limits of backwater on the river. WES was still under construction at the time and all attention was focused on this fledgling model effort. Although skeptics doubted that it could be done, the successful test christened WES's entry into the field of hydraulic research.

Model construction techniques and instrumentation technology have undergone tremendous changes since the early 1930s. Small-scale models are now of fixed-bed construction (non-erodable bed and side materials), movable-bed construction (bed or side materials, or both, are erodable and transported in a manner similar to the full-scale original), or semimovable-bed construction (combination of both). Models may be built to study a given phenomenon or problem such as cavitation* or wave agitation, or for examining forces or effects of forces at or near hydraulic structures. In addition to physical modeling, the Hydraulics Laboratory at WES also engages in numerical (computer generated) modeling. Numerical modeling is an ever-increasing tool for hydraulic research. While numerical modeling has replaced physical modeling in some areas of study, the two techniques are used concurrently in others.

During its long history of operation, the WES Hydraulics Laboratory has become one of the world's largest and best-equipped laboratory facility for practical application of experimental hydraulics. Its general function is the resolution of hydraulic problems in waterways and harbors and the design and testing of hydraulic structures through the use of physical and numerical (computer-generated) models. Each model study involves problems and phenomena that require special techniques. The WES Hydraulics Laboratory is recognized as a leading expert in the technical areas of river, tidal, and structural hydraulics modeling. The lab's activities include basic and applied research, engineering design analysis, laboratory and field testing, and field measurement.

The Hydraulics Laboratory has continued to this day to grow in size and scope of operations, and in so doing has subdivided according to specific problem or study areas. Fifteen gigantic shelters spanning a total of 28 acres have been built over the years to house a portion of the thousands of physical models studied at WES since the 1930s. Model test facilities which now occupy an area of nearly 100 acres, are equipped with such appurtenances as reservoirs, pumping plants, and water-supply systems.

Overall Hydraulics Laboratory organization has evolved over the years as WES has grown; it presently consists of four divisions, each headed by a division chief, and each made up of three branches. Current Hydraulics Laboratory organization is as follows: Estuaries Division, Hydraulic Analysis Division, Hydraulic Structures Division, and Waterways Division. The Estuaries Division, specializing in estuarine environment problems, consists of the Estuarine Simulation Branch that deals almost exclusively in numerical modeling; the Estuarine Processes Branch, responsible for performing field measurements and full-scale testing to set model parameters; and the Estuarine Engineering Branch, solving problems of dredging equipment operation and logistics, and numerical modeling of typical estuarine problems. The Hydraulic Analysis Division is made up of the Prototype Evaluation Branch

* Words underlined in the text are defined in the glossary.

that measures, monitors, and evaluates Corps of Engineers hydraulic structures; the Design Criteria Branch, responsible for hydraulic technology transfer; and the Math Modeling Group, specializing in theoretical aspects of numerical modeling. The Hydraulic Structures Division concentrates on design and evaluation through modeling of all types of hydraulic structures. Within this division are the Spillways and Channels Branch, Locks and Conduits Branch, and Reservoir Water Quality Branch. The fourth Hydraulics Laboratory sub-group is the Waterways Division, which addresses inland hydraulic problems of geographic concern. Included in this division is the Potamology Branch, studying the science of rivers; the Navigation Branch; and the River Regulation Branch. The entire Hydraulics Laboratory is collectively managed by the Chief and Assistant Chief of the Laboratory. In addition, the Mississippi Basin Model (MBM) at Clinton is included under the jurisdiction of the Waterways Division, River Regulation Branch. The Mississippi Basin Model Board was originally charged with determining policies and programs for development and operation of the model.

Evolution of the MBM from its conception in 1942 to the present is a truly unique chapter in the history of hydraulic modeling. The presently active portion of the model reproduces the Mississippi River drainage basin from Hannibal, Missouri to Baton Rouge, Louisiana, the Atchafalaya Basin to the Gulf of Mexico, and portions of the Arkansas, Missouri and the Ohio Rivers. Inactive portions of the model include the remainder of the Mississippi River drainage basin and its tributaries. Ground was broken on the MBM by German Prisoners of War in 1943 under the auspices of the Mississippi Basin Model Board. An internment camp adjacent to the site lodged as many as 1,800 German soldiers of Field Marshall Erwin Rommel's famed Afrika Korps at its peak of operation. Ex-POWs occasionally return to the Clinton site to view the world's largest small-scale working hydraulic model on which they labored to build. After the prisoners departed in 1946, WES civilian personnel were employed on its construction until the model's completion in 1966.

Testing of local problems for various Corps of Engineers Division and District Offices within the Mississippi basin was begun in 1949. Full-scale model testing was undertaken from 1959 through 1971, and again after 1973, when the model was reactivated. During the Missouri River flood of 1952, the MBM proved its worth by accurately predicting time and occurrence of flood crests. Emergency crews concentrated on bracing areas targeted by the model to flood, and thus prevented an additional sixty-five million dollars worth of damage in the Sioux City, Iowa/St. Joseph, Missouri area. On a strictly cost-benefit basis, the MBM has proven an overwhelming success. The millions saved in the Missouri River flood alone was more than triple the $17,724,617 total model expenditure through 1972. [1]

The Mississippi Basin Model has been, and continues to be, an effective tool for the engineer in attempts to control flooding in the Mississippi River Basin, to aid in determining design heights of comprehensive levee systems, to check reservoir operation procedures, and in the establishment of parameters used in developing more reliable numerical models. Still equipped with a

majority of its theoretically obsolete original stock and custom manufactured instrumentation, the MBM continues to operate reliably. This fact is but one of the many reasons why it is such a unique and intriguing example of physical hydraulic modeling. The operating system is currently being updated in order to maintain this reliability and improve response time.

WES has expanded its scope of operations from strictly hydraulics study in 1930 to a wide variety of research areas encompassing five separate disciplines. WES annually handles over 1,500 projects for 120 different sponsors, and accomplishes a work program in excess of 100 million dollars.[2] The Hydraulics Laboratory has been on the cutting edge of hydraulic engineering research for over fifty years, and in that time has produced a number of originally designed instruments for use on physical hydraulic models. These instruments, along with certain commercially manufactured ones, have been an integral part of the Hydraulics laboratory's long and distinguished history.

Notes

1. McGee, H. C., Automatic Instrumentation of the Mississippi Basin Model, Mississippi Basin Model Report 1-5, U.S. Army Corps of Engineers, Waterways Experiment Station, Nov. 1955, Table V.

2. U.S. Army Corps of Engineers, Waterways Experiment Station, 1985 Summary of Capabilities, U.S. Army Engineer Waterways Experiment Station, U. S. Corps of Army Engineers, Waterways Experiment Station, p. 3.

Historical Overview of Instrumentation Technology

A physical hydraulic model uses the physical properties and behavior of modeling material to reproduce full-scale phenomena of an existing or proposed prototype system or structure. The object of every hydraulic model is to obtain a carefully planned series of measurements. Sir Isaac Newton first conceived the idea of utilizing models as a means of determining full-scale performance in 1686. In his treatise, the "Principia," he stated in one paragraph the Principle of Similitude. This principle is the foundation of successful modeling techniques. Basically, in order to accurately reproduce flow conditions in a hydraulic model it is necessary for similarity to exist between the two systems. That is, at corresponding times any two identical forces in the full-scale and model must be in a constant ratio to one another. The model may not necessarily look like the original, but it must be capable of acting the same in order to accurately predict given phenomena. The procedure of adjusting the model to reproduce events that have occurred in nature so it is capable of accurately predicting what will occur in the future is called model verification. This is accomplished by repeatedly adjusting the model and recording instrument readings and making necessary adjustments until proper conditions are replicated. Only then can the model faithfully represent performance of the prototype.

In order for a model to be effective it must be an accurate reproduction of the prototype; it must be equipped with instruments capable of reliably measuring and/or recording data; it must be able to reproduce the quantities under investigation; it must be made of readily available materials; and, it must be equipped with adequate appurtenances to assure proper flow. The instruments necessary to perform tests and accurately make measurements are a vital feature of any hydraulic laboratory's equipment. Many models -- chiefly those of hydraulic structures -- must be built on an undistorted scale to truly reproduce desired physical quantities. It is often necessary to design models with a larger vertical to horizontal ratio, or on a distorted scale, as is the case of flood-control models and those having a movable bed. The largest number of physical models constructed at WES are of this type.

Many different kinds of instruments are necessary in order to achieve desired measurements. With even a single instrument, procedures and capabilities vary and must be adapted to the particular conditions under which the measurement is taken. Although there are only a limited number of measurements which may be taken on a physical model or its full-scale equivalent, dozens of methods exist for obtaining and/or recording these measurements.

Generally, hydraulic instrumentation measures discharge, water surface elevation, velocity, pressure, salinity, temperature, and sedimentation levels. Direct measurements and calculations of force, stress, or vibration may also be made on hydraulic structures. WES has engaged hundreds of instruments with design variations on this small number of measurement possibilities.

Laboratory studies basically involve measurements of static or dynamic quantities. Static or slowly changing hydraulic measurements are made by relatively simple instruments such as pitot tubes and point gages, while electronic equipment is necessary to take satisfactory dynamic measurements. A wide array of both types of instrumentation is found at WES.

The Hydraulics Laboratory has employed several methods through the years to acquire its model and prototype instrumentation. First, and foremost, is by purchase from commercial manufacturers. Scores of American and foreign instrument companies have sold pieces to WES over the years. In exceptional cases, WES designs and installs original instrumentation where nothing suitable is commercially available. In-house instrumentation is normally designed and produced by the Instrumentation Services Division (ISD), a technical support organization (ISD has existed under several different names since the 1940s). In the unique case of the Mississippi Basin Model, WES supplied specifications to commercial manufacturers who then produced custom instruments. These methods of acquisition have combined to create an expansive legacy of evolving instrumentation technology at WES, covering all periods of development and including all types of hydraulic measurement.

Water Level and Model Bed Elevation Measurement

The Waterways Experiment Station's first model, built in 1930 to determine limits of backwater influence on the Illinois River, was carved out of the Vicksburg loess soil and molded with sheet metal templates.[1] Some of the most basic of all hydraulic instruments were installed on this model to measure water level. Small staff gages were placed along banks and levees to monitor water level in the main channels. These staff gages were simply vertical rods with a marked graduated scale from which depth measurement was read visually. In extreme reaches of this model, pegs and nails driven flush to the water surface allowed technicians to determine at a glance the height of the water.

On WES's 1931 study to determine the erosive effects of floodwaters on railroad embankments, needle point gages were first used to measure water levels.[2] A point gage consists simply of a sharp point attached to an arrangement which slides on a graduated staff. When the point is lowered until it just touches the water surface, an elevation to the desired datum is visually taken from the staff. These commercially manufactured gages are graduated to 0.001 feet and are often placed at locations on the model corresponding to prototype gaging stations. Point gages are popular because they offer a simple and reliable method of measurement. There are scores of point gages at WES which are still widely used in many capacities today. Their major function, though, remains as an appliance to measure water level or tidal elevation on physical models. In 1933, WES began to use portable point gages mounted on sliding rails affixed to the sides of models in order to obtain levels from more points on the models. Point gages were the first commercially manufactured water level indicators in use at WES, and they are considered to be among the most reliable today.

By 1934, a method was devised to read water levels from a multitude of points with one device.[3] Still in use today, this apparatus consists of pipes or tubes (piezometers) set flush with the surface of the model and connected by pipes to a central gage pit. From there, a number of buckets are arranged under a sliding rod so that the depth of water flowing into each bucket can be measured by the same sliding hook gage. The hook gage is a variation of the point gage that has an upwardly hooking end attached to a sliding vernier on a graduated staff. The hook is lowered into the water and raised until the point just cuts the water surface, and from there an elevation measurement is taken. The hook gage is an extremely accurate means of water level measure, but is not practical for direct use on most hydraulic models because water depth is not sufficient to submerge the gage. Depth in piezometer (or gage) buckets is such that hook gages are practical. These buckets save time and equipment since many points of measure are read from one station. WES presently uses this identical procedure on many models. A plan has recently been formulated to replace the point gages in a piezometer bucket system with a more sophisticated sonar-type computer compatible water-level indicator. Point gages are found in all divisions of the Hydraulics Laboratory, while piezometer buckets, on the other hand, are used exclusively by the Waterways Division in river geography studies of movable-bed models.

Another instrument used in this type of testing is known as a sounding rod. The sounding rod measures bed elevation in movable-bed models. It consists of a long graduated staff with a metal shoe on the bottom to keep the rod from penetrating the bed of the model. First used at WES in the 1940s, the rod is mounted on a horizontal movable sounding carriage on rails suspended by graded templates. One side of the carriage is graduated so distances may be quickly determined. The rod, read to the nearest scale 10th of a foot, slides across the carriage the entire width of the model to allow a profile of bed elevation. A variation of this sounding system was described in the 1974 report on navigational channel improvements for Barnegat Inlet, New Jersey.[4] In this case, a light cart was constructed to roll above the model along rails located twelve feet apart and supported by one inch diameter steel rods positioned in the model to minimize flow disturbance. The cart was propelled by a hand crank, sprocket, and chain system on one of the wheels. The sounding rail was bolted to the model cart and a manually operated aluminum sounding rod with slide and pointer-type dial was used on the rail to record bottom elevations. This type of sounding system is often used in Waterways Division studies on movable-bed models to determine changing bed elevations.

Other important instruments used at the Station to measure water level include automated water level detectors designed and installed in 1957 expressly for the New York Harbor model. Devices of this type, still presently used at WES, have a non-contacting water surface sensor which is raised or lowered by an electrical servo system to maintain a constant air pocket between it and the water. The sensor must be kept dry to work properly. By riding just above the water, floating debris does not disturb its measurement, and the instrument does not disrupt flow in the model. Automated water level detectors are historically significant at WES because they were part of the

first automated system for acquisition of model data and model controls, included on the New York Harbor model when it was first constructed in the late 1950s. This WES Automated Data Acquisition and Control System (ADACS) has traditionally had two major functions: 1) to automatically acquire water level data in a computer compatible magnetic tape or disc format, and 2) to automatically control sensor calibrations.[5]

Another interesting and significant instrument to measure water level which has survived at WES since the 1940s is the Stevens stage recorder unit. Originally designed exclusively for the MBM (see the MBM section of this report), these devices have been used on various model studies at WES, and are among the longest continuously operating instruments in the Hydraulics Laboratory.

Notes

1. Experiment to Determine the Limit of Backwater Influence in the Illinois River, Paper "Y", U.S. Army Corps of Engineers, Waterways Experiment Station, Feb. 1931.

2. Experiments to Determine the Erosive Effects of Floodwaters on Railroad Embankments, Paper "R", U.S. Army Corps of Engineers, Waterways Experiment Station, May 1931, p. 2.

3. Experiments to Determine the Backwater Effects of Submerged Sills in the St. Clair River, Paper 16, U.S. Army Corps of Engineers, Waterways Experiment Station, Apr. 1934, p. 8.

4. Navigational Channel Improvements Barnegat Inlet, New Jersey, U.S. Army Corps of Engineers, Waterways Experiment Station, TR H-74-1, Mar. 1974.

5. Recent Automation Changes in Model Velocity Analyses and Data Acquisition by Miniature Price Meters, U.S. Army Corps of Engineers, Waterways Experiment Station, MP HL-79-6, May 1979, p. 4.

Velocity and Flow Measurement

The first use of velocity measuring instrumentation at the Station was in 1931 on a study of erosive effects of floodwaters on railroad embankments.[1] In this test, a Pitot tube connected to an inclined manometer was mounted on a sliding frame above the model railroad track. The Pitot tube is a device for measuring pressure from which the velocity of flowing water is determined. In its very simplest form, it consists of an open tube or pipe bent at a right angle near its base (see HAER photo # MS-2-31). When placed in water with the horizontal leg pointing upstream, water flows into the tube. By attaching a pressure measuring device to the tube called a manometer, velocity is determined from the measured pressure.

Henri de Pitot introduced the first Pitot tube in 1732. Originally, the device was made of two slender straight glass tubes mounted side by side onto one of three flat surfaces of a triangular wooden rod. One tube was bent ninety degrees on one end pointing upstream; the other tube was straight, with its lower end the same level as the bent end of the other tube. When submerged, water entering the bent tube would cause the water to rise in the tube as a pressure head. Since no rise would take place in the straight tube, the differences in the two elevations became a function of the stream's velocity. Pitot's method of measurement was not nearly as accurate as that performed today, but his invention was the foundation for present-day tubing applications. A change that was made in the Pitot tube in the 19th century ultimately had a direct effect on the Station's early history. Around 1858, Henri P.G. Darcy bent the straight tube ninety degrees in the downstream direction, causing a draw-down effect in the elevation of its water; this doubled the reading on the scale and reduced probable measurement errors. This Darcy tube was eventually modified at WES to become the Bentzel tube.

Pitot tubes are now made of metal instead of glass; they consist of only one ninety degree open-ended tube facing upstream, with several additional openings located in the sides of the tube. It is impossible to read the height of the water column directly, since the tubes are metal; other flexible tubes are connected with these tubes to a nearby manometer. A manometer is a general term for a hydraulic measuring device that operates by calculating pressure differences. Manometer openings are connected individually to two points on the Pitot tube (the end and side openings) creating a differential water pressure in the manometer tube. Simply, a U-shaped manometer is a graduated tube that measures pressure differences in water by means of a liquid that does not mix with water. For example, mercury is used for high velocity flows and oil for low velocities. In addition to the U-type manometer, WES also uses the well, inclined tube, and digital type manometers, The digital manometer is gaining popularity as a highly accurate and compact device. There are no cumbersome appurtenances or conversions which must be made with the digital model, as it offers a continuous readout of pressure.

The Pitot tubes discussed thus far are used to measure pressures in open conduits. WES has used Pitot tubes in closed conduits, as well. These are basically tubes with two openings in the ends (upstream and downstream) placed horizontally in a closed pipe. Like the open conduit tubes, they are connected to manometers. Pitot tubes are popular instruments for laboratory work for several reasons: no timing is required in connection with an observation, the flow of the water is disturbed much less than with other devices, and they collect data from a smaller point in the cross-section of the stream. Pitot tube-manometers give extremely accurate measurements and have been reliably used at WES since 1931 with few major changes.

The principle of Pitot/Darcy tube operation was incorporated by Carl E. Bentzel when he developed the Bentzel velocity tube while he was a Research Assistant at WES in 1932. Bentzel, a graduate of the Chalmers Institute of Teknologi in Gothenburg, Sweden, subsequently left WES before 1936 to work as a hydraulics engineer for the Tennessee Valley Authority. While at WES, he developed the tube for the study of river bed movement in laboratory models where, for a time, it superseded the use of the Pitot tube and other current measuring devices.

Operation of the Bentzel tube was based on a theory which Carl E. Bentzel formulated in 1928 while designing a flow meter for the gasoline supply line in an automobile. This early investigation was never completed, but Bentzel confirmed that small flows could be measured by floats or weights operating in a tapered tube.[2] In essence, the Bentzel tube was a two legged Darcy-type tube. As originally designed, both legs were tubes bent ninety degrees, one facing upstream and one downstream. Water flowing into the upstream leg of the tube caused a positive pressure to be created; pressure on the downstream side, on the other hand, was negative. This pressure difference caused the circulation through the tube of a small stream of water, the amount dependent upon the velocity of water flowing through the model. In the downstream vertical leg of the tube a small float was enclosed within a graduated transparent tube. When there was no flow through the tube, the float rose until it rested against a wire stop in the top of the tube. When water flowed through the tube, it caused the float to move down the tapered tube. The force of the water and buoyancy of the float caused it to position along the graduated scale. The Bentzel tube could be calibrated very closely by towing it through still water. For every velocity within the instrument's range there was a corresponding position of the float. This did not vary by more than one to two per cent in all trials. By using floats of different specific gravities and tubes of varying dimensions, almost any low flow velocity could be measured.

The major strength of the Bentzel tube was its accurate and rapid measurement of very low velocities. Pitot tubes and Venturi tubes (see below) were most accurate at a higher velocity, and shallow model depths almost entirely ruled out the use of standard current meters. In the 1930s, the Bentzel tube was a revolutionary instrument due to its range of measurement capability from 0.2 to 3 feet per second, and accuracy to within one or two per cent.[3] It filled

a need in hydraulic engineering for a low flow measuring device that indicated instantaneous velocities. Bentzel tubes served to lower the limits of accurate velocity measurements in hydraulic models in an age when adequate instrumentation was just beginning to appear.

Two major shortcomings were encountered with the Bentzel tube. One was the fact that a slight variation in water temperature had a definite effect on the Bentzel tube's accuracy by causing air bubbles to form in the tube when water temperature was lower than surrounding air temperature. The second drawback was that turbid water caused the float to move erratically, making accurate measurements extremely difficult. These factors could be controlled to a degree in a laboratory setting, and therefore they were not considered an unsurmountable problem for model testing purposes.

Variations of the Bentzel tube for prototype measurement were tested at WES in the 1930s. The first such device was a standard design tube approximately eleven feet long. Obvious difficulties were encountered due to its size and weight. From all indications, the Bentzel tube was never used to take actual velocity measurements in the field, partially due to its radical reaction to temperature differences and turbid water under prototype conditions.

Bentzel suggested the principle of his instrument to Leupold Volpel and Company of Portland, Oregon (now Leupold and Stevens, Inc. of Beaverton, Oregon), and they manufactured several variations of the Bentzel tube in the 1940s with a range of measurement from 0.15 to 4 feet per second.[4] Two major innovations by Leupold Volpel and Co. were the use of a non-breakable sinker in the tube instead of a float, and the addition of a vacuum pump. Its appearance also changed from the original with the addition of a hand grip and bottom stand (see HAER photo # MS-2-33 to MS-2-35). They produced three different models of the tube: Model A was used for ordinary lab practice, Model B was a short tube for low velocities, and Model C was for taking measurements in small streams and ditches.

Bentzel tubes were frequently used on WES hydraulic models through the 1940s, before small impeller and cup-type current meters were used. Although it was in use only a short time, the Bentzel tube was a revolutionary instrument in 1932. Few devices on the market at this time were designed specifically for laboratory velocity measurement; the Bentzel tube was one of the first. Bentzel considered his invention so important that he secured a limited patent for the tube, with rights of manufacture and use retained by the Government. The last recorded use of a Bentzel tube at the Station was in 1950, by which time the WES Midget current meter (see below) was in frequent service.

Current meters have long been an integral part of Hydraulics Laboratory equipment at WES. The first use of a current meter at WES was in 1932 when a deflection-type meter was employed on a model study of dike locations on the Mississippi and Ohio Rivers. As water deflected off a submerged appendage, velocity forced it to bend downstream, the amount of bending calibrated to approximate current velocity. No deflection meters remain at WES today.

In 1944, WES developed its own cup-type current meter, which has since become one of the most well-known instruments ever used in the Hydraulics Laboratory. The WES Midget Velocity meter was developed in response to a need for a small, reliable device to quickly measure extremely low velocities. Shortly after the Midget's introduction, the Bentzel tube was left in the wake of advancing instrumentation technology. The basis for design of the WES Midget goes back to Daniel Farrand Henry and his vertical axis cup-type current meter for field measurements, which he invented in 1868. Subsequently, William Gunn Price, whose name is synonymous today with cup-type current meters, patented four vertical axis cup-type meters between 1885 and 1926. These immediate forerunners of the WES Midget meter have been among the most commonly used velocity meters in the U.S. for field measurement in the last fifty years. The W. and L. E. Gurley instrument company of Troy, New York, which first contracted with Price in 1885 to produce his current meters, remains the predominant manufacturer of the items to this day (see HAER photos MS-2-24 to MS-2-28).

The Midget Velocity current meter (called the WES Miniature current meter after 1953) is constructed on the same principle as the Pygmy Small Price current meter, the tiniest commercially available cup-type meter. The Midget originally consisted of a bucket wheel made up of six cups 0.02 inches in diameter, mounted on a vertical phonograph-needle shaft set in jeweled bearings. The impeller on the Miniature meter was 1-3/16 inches in diameter -- just over half the diameter of the Pygmy meter. Unlike most prototype meters of this type, the Miniature has no tailpiece; it is submerged into the model by a suspension rod, at which time the bucket wheel begins to revolve in flowing water. It can be placed anywhere in the model (having sufficient depth) to gain a thorough cross-sectional measurement. It has performed accurately to a minimum velocity of 0.03 feet per second (0.3 feet per second prototype at the common model scale of 1:100) on dozens of WES models since 1944.[6] In spite of the meter's actual minute size, on a model scale of 1:100 the wheel would measure about ten feet in diameter in the prototype (in reality, a Gurley 665 current meter used by WES in field measurements is approximately five inches in diameter). Obviously, the meter could never be made to reproduce exact scale, but it comes as close as all available impeller-type current meters except for one recently developed horizontal-axis type (discussed later in this section).

The basic design of the Miniature meter has not been altered, but recording of its bucket wheel revolutions has evolved since its introduction. Originally, one cup on the wheel was painted white while all others were black. Each revolution was counted over a given period, then converted to a prototype feet per second velocity using a WES-calculated calibration curve. Readings from the Miniature meter were taken visually by the model operator until around 1974, when a photoelectric recording apparatus was introduced on the Masonboro Inlet model to study the effects of temperature in model results (TR H-75-10).

The process of photoelectric recording of the meter's impulses was as follows: the miniature meter emitted electrical impulses as the bucket wheel cups

passed an attached fiber optics element; the fiber optics system was designed to detect painted white spots on the dark cups as the meter rotated in the current (specifically, a light was directed through a fiber optic element toward the white dots on the cups) the reflected light formed a pulse train where the number of impulses per second was representative of velocity; this pulse train was directed through a return fiber optic to a photo cell which converted light energy to electrical energy. An electric counter was used to measure current in a digital format which could be readily recorded on a computer compatible magnetic tape, and the sensors were attached directly to an Automatic Data Acquisition Control System (ADACS).[8] A variation on this pioneer photoelectric method of recording is presently used whereby the light impulse is relayed directly to a digital counter, which automatically converts the impulse to a measurement of velocity.

The Midget/Miniature Velocity meter was originally constructed at WES, but now P & S Enterprises of Ridgeland, Mississippi manufactures them on an exclusive contractual basis. A few minor construction changes have occurred on the meter over the years. For example, the once metal cups are now economically constructed of plastic. The meter comes with a choice of 1/2 inch, 7/16 inch, and 5/16 inch diameter cups for a wider range of flow measurement. Regardless of whether a visual, acoustic, or photoelectric system of velocity recording is preferred (all are currently used), the Miniature Price-type current meter continues to serve WES well as it has since 1944. Ease of calibration has made it the most commonly used current meter in the Hydraulics Laboratory; all indications are that this will continue to be the case for years to come.

The Corps of Engineers sponsored the design of the first and largest Price current meter, patented by William Gunn Price in 1885 while he was employed by the Mississippi River Commission. It is ironic that the WES Miniature Velocity meter, the latest and smallest cup-type current meter produced, is also Corps sponsored.

Price-type current meters are used for taking field velocity measurements by Hydraulics Laboratory personnel. One particular design frequently used is a slight modification of the Model 622, which was first introduced in 1926 by the W. and L. E. Gurley company. After several improvements on its design, the 622-AA emerged in 1937 and is still sold today. The 622-AA consists of a bucket wheel mounted on a vertical axis with an attached tailpiece. The bucket wheel revolves when suspended in flowing water. A wire contacts the rotating shaft and intermittently closes an electrical circuit; a small dry cell supplies power. This system consists of a contact device mounted on the impeller which relays an impulse (for each revolution, or fifth revolution) to an operator via a telephone head set. The number of sounded clicks is recorded for a time varying from forty to seventy seconds. From a rating table, velocity in feet per second is read over a range of 0.1 to 11 feet per second. The 622-AA can be held in water by a suspension cable and lead weights or by a wading rod.

A modified version of the Model 622-AA is now in use at WES; it is the Gurley 665 direct reading salt water current meter. Introduced in 1966, this meter offers WES a portable field measuring device to indicate and/or record water velocities directly in deep salt water, eliminating the need for rating tables. Chance for error in counting revolutions, time, and conversion is minimized. The 665 has two main units: the sensing unit and the indicating unit. The frame, bucket wheel, pivot and bearing, tailpiece, and rotor assembly make up the sensing unit. The indicator is a one piece fiberglass and aluminum unit containing modern, low power, semi-conductor circuits and a self-contained mercury battery. A built-in meter displays velocities in feet per second and meters per second. The 665 Direct Reading current meter is used extensively in field measurement by the Estuarine Processes Branch of the Estuaries Division as part of their so-called "Over the Side Unit."

The "Over the Side Unit," technically referred to as a Velocity-Direction Indicator, was first developed by WES's Instrumentation Services Division in 1957.[7] It is used for determining prototype current directions while simultaneously measuring velocities. Components are a remote reading Marine-type Magnesyn Compass System (transmitter, indicator, and inverter), Gurley Model 665 Direct Reading current meter and streamlined weight, a drum-type winch, and a DC power source. The direction-indicator is a remote reading compass designed by WES so that it indicates the magnetic north azimuth of the direction from which the current flows (see HAER photo # MS-2-23). Precision of the readout device is plus or minus two degrees, but it is dependent on correct balance of the weight and current velocity. For currents greater than 0.5 feet per second, accuracy is plus or minus ten degrees, and for lower velocities it is plus or minus twenty five degrees in rough waters and when tidal currents slacken and turn. The transmitter assembly is constructed of rolled brass stock with a connector on the bottom to fasten the housing to the current meter hanger bar. This enables the housing, current meter, and weight to rotate as a unit on a vertical axis. A shackle, ball bearing swivel joint, and a cable grip are attached to the top of the housing. A shielded cable electrically connects the transmitter to the indicator. The current meter and housing terminals are connected by means of a single wire. Remaining components of the indicating system are contained in an 8" x 8" x 8" sloping panel cabinet; these include the direction indicator, inverter, power switch, and cable receptacles. Because the "Over the Side Unit" is extremely unwieldly, it is lowered into the water via a support frame equipped with pulleys and a drum-type winch. The winch operates an indicator that shows the depth of the unit below the water surface (as indicated by the length of cable played out), measures water depth, and positions the current meter for each reading. Each unit, less the winch, is housed in its own storage container and kept at WES when not being used.

Few changes have been made in the Velocity-Direction Indicator as first developed by WES personnel in the late 1950s. It has proven to be a valuable tool for gathering accurate field data necessary to recreate prototype conditions in the lab. ISD has manufactured Velocity Direction Indicator systems for every Corps district which does work in estuarine environments.

These units are still used by the Hydraulics Laboratory, and the Model 665 current meters and accoutrements are still purchased from W. and L. E. Gurley.

In the past, WES has used the Model 625 Pygmy-type current meter, designed by the Gurley company in 1939, to measure flows of 0.05 to 3 feet per second in shallow streams, flumes, and canals where a larger meter would not give sufficient results.[8] The meter has no tailpiece and no provision for cable-suspended measurements. A metal bracket supports the meter and wading rod; its bucket wheel is two inches in diameter.

Another type of current meter used at WES in the 1940s for laboratory work was the Leupold Volpel and Company (now Leupold and Stevens, Inc.) Midget current meter. This all metal meter was mounted horizontally on a graduated rod. It came complete with two interchangeable paddle-type impellers capable of measuring velocity ranges from 0.15 to 5 feet per second, accurate to minimum depths of 0.1 feet.[9] An electrical contact was mounted to count each revolution by way of a telephone headset and dry cell. These are no longer in service at the Station.

The Nixon current meter is the newest and smallest impeller-type current meter in use at WES. It was first put into service in the 1970s. Smaller than the WES Miniature meter, its plastic paddle wheel is mounted on a horizontal axis and measures approximately 1/2 inch in diameter; the entire meter is about the size of a dime. In essence, the Nixon meter is a miniature version of the 1940s-era Leupold Volpel and Company Midget current meter, except it comes equipped with a component digital readout monitor. An appealing feature resulting from its size is the ability to obtain velocity measurements very near the bottom of models and close to hydraulic structures. Because the Nixon meter has only been on the market a short time, it remains to be seen whether this device will gain widespread use at WES.

The most advanced form of current meter in the Hydraulics Laboratory's inventory is a commercially produced electromagnetic-type. Fast becoming widely accepted in laboratory use, this device consists of a probe (either 7/16 inch spherical or cylindrical) with four sensing projectiles which detect disturbances in magnetic fields in upstream, downstream, and lateral velocities when submerged. This type of meter operates on electromagnetic induction by generating a magnetic field in the water and utilizing the water as the electrical conductor. A suspension rod with an enclosed cable from eight inches to approximately fourteen inches in length is hand-held to give an instant digital readout, or computer readout if so desired (those at WES are not computer connected). It detects water conductivity with two electrodes excited by AC voltage. The impulse is converted and read out as velocity measurement. The advantage of this type of current meter is that it offers an instant four-pole velocity measurement, eliminating the chance for human calculation error. A disadvantage lies in the fact it is so sensitive that any piece of nearby metal on the model will give an erroneous reading and any foreign objects in the water will do the same. This presents a potential problem as most models are equipped with metal appurtenances.

Electromagnetic current meters were used as secondary means of gathering velocity data on WES hydraulic models in the middle 1970s. They were used as such "because of development imperfections but showed promise for future studies."[10] Surprisingly, the first electromagnetic current meter was developed in 1902 but it was not widely recognized. The present generation of electromagnetic meters, still in their infant stages of development, embody state of the art technology. This may well be the current meter of the future.

Another form of velocity measuring instrument utilized in the Hydraulics Laboratory is the Venturi tube/meter. This device for measuring velocity in closed conduits has been in service at WES since before 1940. The Venturi tube was originally patented circa 1887 by Clemens Herschel and named for J.B. Venturi, an 18th century Italian professor of natural history who devised the general concept of the device. Basically, it is a pipe which consists of a converging entrance cone, followed by a constriction of throat, and then an expansion to normal diameter. The reduced pressure at the throat is measured, as is the pressure upstream where the diameter of the pipe is normal. Small pipes at these points lead to manometers measuring the pressure difference, which is then converted to velocity of flow. A major benefit of the Venturi tube is that it does not interrupt water flow within the conduit. Venturi tubes vary in size at WES from approximately two to twelve inches in diameter, although they can be up to several feet in diameter. The size of the closed conduit dictates the tube size. Since they work only in a closed conduit, their use is limited to inflow/outflow systems.

Venturi tubes are expensive devices and use at the Station is supplemented by such instruments as turbine flowmeters, impeller-type current meters, and modern ultrasonic meters. A turbine flowmeter consists of an impeller housed in a short length of pipe which can be spliced into a line of the same diameter, an impeller-type current meter is simply inserted into openings in the conduit and it operates much like the Price-type current meter, and an ultrasonic meter attaches to the exterior of a pipe and "reads" velocities by timing ultrasonic signals in the flow. Any combination of these three instruments may be used on the same system to check data accuracy.

Velocity measurement in prototype structures has evolved considerably since WES first began structural modeling in 1939. From 1946 to 1949 ISD worked to develop its own velocity meter for prototype relief wells.[11] Pressure relief wells are often installed at the top of earth dams and behind levees to intercept seepage and provide relief for excess hydrostatic pressure beneath the structures. Wells were once wooden or metal pipe, and are now PVC pipe several inches in diameter, extending vertically to a proper depth into the earth. The pipes have openings to allow seepage water to enter; the water rises in the wells under the effects of hydrostatic pressure and disperses itself on the ground or in collector pipes. The flow meter is essential to check design values, well performance and efficiency, and seepage levels.

The velocity meter as developed consisted of a frame supporting a light weight aluminum impeller with eight blades on a forty five degree pitch. The

impeller was mounted on a pivoted vertical axis on which a mounted lobe made contact with a spring wire on each revolution of the shaft. Accompanying the meter was an adapter for centering the yoke in the pipe, a cable for lowering the assembly to desired depths, and an electrical system for counting impeller revolutions.

These meters were originally assembled for exclusive use in six inch diameter pressure relief wells; and now ISD manufactures them in various sizes. Ruggedness, reliability, and accuracy are key features of the meters. Simplicity of construction and ease of maintenance are of primary concern in their design. Maximum use of commercially available parts is an added feature; the impeller shaft, bearings, and contact chamber are interchangeable with a Gurley Model 622 current meter.

In operation, the meter is lowered to the desired depth in the well and the time required for the impeller to make a given number of revolutions is measured by a stop watch. From this figure revolutions per minute is calculated and flow is determined from a calibration curve. Impeller revolutions now may be detected electrically by a contact activated by a lobe on the impeller shaft. The contact assembly produces impulses either every revolution or every tenth revolution. The suspension rod is specially constructed to contain a copper cable used to transmit impeller revolution impulses to a counting device at the water's surface. An acoustic counting system, featuring a battery and earphones, is used to detect clicks.

The body of the meter (yoke, suspension rod, and adapter) was originally stainless steel and later brass. Attached to the suspension rod is an adjustable spring-leaf adapter designed to center the meter in the well and enable it to pass uneven sections of the well wall. The meter's range of measure is approximately ten to 10,000 gallons per minute with a plus or minus 3 per cent reliability factor.[12] Calibration of the meter is done by the Prototype Evaluation Branch of the Hydraulic Analysis Division.

In addition to the utilization of digital output indicators, design developments in the relief well flow meter have wrought minor changes in the yoke configuration and material. Once pear-shaped, it is now a circular section of standard galvanized pipe. The impeller assembly has remained essentially the same since its initial 1946 design. The WES-built relief well flow meter is currently in use in a number of Corps of Engineers hydraulic structures nationwide.

Waterways Experiment Station personnel, aided by NASA and David Taylor Model Basin (U.S. Navy) advisors, developed an interesting device in 1949 to investigate the flow characteristics of a large full-flowing circular water tunnel. This wing-like Pitot strut was installed in Fort Randall Dam in South Dakota.[13] In order to take velocity distributions and turbulence measurements, the instrumented Pitot strut spanned the inside of the tunnel horizontally. Pitot struts had been used before 1949, but this was the first attempt to use one in a tunnel this large (22 feet in diameter and 861 feet

long).[14] This particular tunnel offered the Corps of Engineers a unique prototype testing opportunity to study flow in a large conduit, because a model could not reproduce flow and pressure conditions of such a magnitude. The strut was elliptical in body with a streamlined tail. A specially mounted scaffold on a truck bed was employed to mount the strut. After the dam's stilling basin was emptied of water, the truck was lowered to the basin floor by a crane and driven to the strut location inside the tunnel. The strut was then secured to the tunnel wall and several instruments installed to measure pressure and velocity. Three hot-film anemometers were developed especially for these tests by the Hubbard-Ling Company in the late 1950s. They are similar in principal to the hot-wire anemometer developed in the 1930s. Measuring 5 inches long by 1/2 inch wide, a hot-film anemometer contains a tiny strip of platinum (one millimeter long) at its tip. It determines longitudinal instantaneous velocity in a hydraulic structure by monitoring the flowing water's cooling of the platinum strip, which is being simultaneously heated electrically. Velocity is determined from a time-temperature correlation between the heating and cooling of the platinum. WES still employs them in both model and prototype testing.

Tests were again performed at Fort Randall Dam in 1960 and 1962 to investigate flow characteristics of its spillway chute under various flow conditions.[15] During hydraulic design of the dam by the Corps of Engineers in the late 1940s, it was realized that there existed a lack of design information for high velocity flow on spillways. Pressure measurements obtained from models with low velocity are not directly applicable to full-scale high velocity spillways, and so provisions were made to install Pitot piers in the spillway chute to measure velocities parallel to the spillway at different vertical elevations. Tests were made to determine characteristics of supercritical flow and to provide data for future design application. WES and the Corps' Omaha District collaborated on design and WES constructed the Pitot piers. This research once again actively involved WES in a pioneer hydraulics study, for at the time of the tests the only known attempt to obtain Pitot pier measurements under such high velocity forces had been by the engineers of Electricite de France in the Chastung Dam spillway.[16]

The piers installed in Fort Randall Dam were made from 5/16 inch steel side plates welded to three 1/4 inch plate diaphragm stiffeners. The chute was dewatered and eight total-head Pitot tubes were installed vertically in each pier. The tubes were connected to pressure-measuring mercury manometers. From results of these tunnel and spillway tests at Fort Randall Dam, WES was able to ascertain valuable information on flow characteristics in prototype structures and collect useful data for future design recommendations.

In 1973, the Waterways Experiment Station undertook an investigation of turbulent flow characteristics (average flow 27 feet per second) in a four foot by six foot rectangular concrete conduit at Rend Lake Dam in Illinois. Two cantilevered velocity probes were mounted through six four inch diameter capped pipes which connected the two parallel conduits to measure horizontal velocity profiles.[17] A mercury manometer recorded the differential between

dynamic and static pressure in the conduit.

In 1974, tests were conducted on the low-overflow spillway of the Ozark Dam in Arkansas to study vibrations and pressure fluctuations in relation to flow through the spillway. Three velocity probes were designed and manufactured at the Waterways Experiment Station for installation in the spillway to measure velocities at ten points from 1/2 inch to 11-1/4 inches above the spillway face. The probes consisted of ten Pitot-type tubes mounted vertically into a cylindrical housing assembly. Eight short tubes on each probe measured stagnation pressures, and two longer tubes measured both stagnation and static pressure. The plastic tubes ran from the probes to the recording device, a differential pressure transducer manufactured by Consolidated Electrodynamics Corporation.

A variation of the Pitot-tube strut was constructed at the Station and used in 1982 for prototype evaluation of the sluiceway aeration system at Libby Dam in Montana.[18] Here, the strut housed Pitot tubes for measuring air velocities in air vents. The airplane wing struts were in two halves bolted together with interiors hollowed to house the Pitot tubes, pressure transducers, electrical cables, and plastic tubing.

WES has designed and constructed many different Pitot-tube struts since the 1940s. These struts have provided a means for measuring internal velocities and pressures in hydraulic structures, and for collecting critical hydraulic data which could not otherwise be ascertained. The valuable research performed at WES in this area of study is but another example of its ever-growing list of contributions to the field of hydraulic engineering.

Generally speaking, accurate velocity and flow measurements are the cornerstone for a large portion of WES model and prototype studies. Often, the success of a given study depends upon the Hydraulics Laboratory's ability to faithfully reproduce past or present prototype flow patterns in the lab in order to predict future ones. Flow measurements also have a tremendous impact on the behavior of hydraulic structures. Such instrumentation must necessarily be reliable and durable in order to perform accurately. A large number of flow measuring devices have been utilized since 1931 that have more than adequately filled these requirements; many WES-designed devices are currently in service alongside commercially produced ones.

Notes

1. Experiments to Determine the Erosive Effects of Floodwaters on Railroad Embankments, Paper "R", U.S. Army Corps of Engineers, Waterways Experiment Station, May 1931, p. 2.

2. Falkner, Francis H., The Bentzel Velocity Tube, U.S. Army Corps of Engineers, Waterways Experiment Station, p. 1-2.

3. Ibid., p. 1-4.

4. Leupold & Stevens, Bulletin 18, p. 6-7.

5. Galveston Bay Hurricane Study, TR H-69-12 Report 1, U.S. Army Corps of Engineers, Waterways Experiment Station, Sept. 1969, p. 11.

6. Recent Automation Changes in Model Velocity Analyses and Data Acquisition by Miniature Price Meters, MP HL-79-6, U.S. Army Corps of Engineers, Waterways Experiment Station, p. 7.

7. Duke, Leiland M., Status of Velocity-Indicator Development, U.S. Army Corps of Engineers, Waterways Experiment Station, Feb. 1958, p. 2-3.

8. W. & L. E. Gurley Hydrological Instruments, Bulletin 700, p. 2.

9. L & S Bulletin 18, p. 7-8.

10. Improvements for Murrell's Inlet, South Carolina, TR H-78-4, U.S. Army Corps of Engineers, Waterways Experiment Station, Apr. 1978, p. 22.

11. WES Relief Well Flow Meter, MP 5-83, Apr. 1954.

12. Ibid., p. 5.

13. Flow Characteristics in Flood-Control Tunnel 10 Fort Randall Dam, Missouri River, South Dakota, TR 2-626, U.S. Army Corps of Engineers, Waterways Experiment Station, June 1963.

14. Ibid., p. ix.

15. Flow in Chute Spillway at Fort Randall Dam, TR 2-716, U.S. Army Corps of Engineers, Waterways Experiment Station, Apr. 1966.

16. Ibid., p. 4.

17. Turbulent Flow in Rectangular Outlet Conduit, Rend Lake Dam, Big Muddy River, Illinois, H-75-2, U.S. Army Corps of Engineers, Waterways Experiment Station, January 1975, p. 8-9.

18. Prototype Evaluation of Sluiceway Aeration System, Libby Dam, Kootenai River, Montana, TR HL-84-2, U.S. Army Corps of Engineers, Waterways Experiment Station, Mar. 1984.

Pressure

The Waterways Experiment Station made its first investigation into design and performance of hydraulic structures in 1931, when model studies were performed on planned spillways for the St. Lucie Canal in Florida.[1] These initial experiments were to determine the adequacy of preliminary spillway designs, and this research signalled the advent of a new area of study at the Station. Uplift pressure, force, vibration, and displacement measurements are now made as needed for tunnels, penstocks, siphons, spillways, stilling basins, gates, and valves where testing is needed on selected Corps of Engineers projects. In the St. Lucie study, uplift pressure was measured by perforated 1/2 inch iron pipes covered with wire gauze placed beneath the spillways. One end of each pipe was connected to a vertical pipe serving as a well or standpipe; the other led to a glass manometer tube where pressure was directly read to corresponding elevations in nature.

By 1940, WES was using piezometers to measure pressures on spillways and conduits. The piezometer is basically an appliance for measuring pressure head that consists of a small pipe tapped into the wall or base of a conveyance system (spillway, conduit, vent, etc.) and connected by tubes to a manometer.

WES Instrumentation Services Division began research and development in 1947 on its own pressure-measuring device for use in Soils Division testing (now part of the Geotechnical Laboratory) to measure unit pressures in soil masses over extended periods.[2] With modifications, the instrument was found to be valuable to hydraulic research for the measurement of earth pressure against concrete stilling basin walls and conduits in dam outlets, and determining effects of soil consolidation in dams and levees. The need for a reliable device for determining effective pressures within earth masses or on rigid structures was great at this time, because previously installed earth pressure transducers had been failing miserably due to moisture invading the gage chamber.[3] This failure is evidenced by WES observations of hydrostatic pressure measuring devices installed at Wappapello Dam in Missouri. Out of sixty-nine transducers installed in the dam during construction circa 1940, twenty failed soon after insertion. Only nine were still operational in 1956. In essence, a change in design was necessary to guarantee an hermetically sealed cable assembly. By 1954, WES pressure transducers were modified. That is, they were being installed with airtight seals and with the cable enclosed in copper tubing soldered to the transducer and crimped into the rubber covered cable.

The typical Waterways Experiment Station earth pressure transducer resembled a doctor's stethoscope. It was stainless steel or brass with a 2 inch diameter body, a 3 inch diameter flange, and a 1-3/4 inch diameter diaphragm. One side of the diaphragm received water pressure. On the opposite side was cemented four SR-4 commercial strain gages. These were mounted on the underside of the diaphragm to measure strain due to bending of the diaphram caused by water

pressure and were connected to a bridge circuit. The strain in the diaphragm resulting from the water pressure caused a resistance change in the SR-4 strain gages. Change in resistance caused a change in the current flow in the bridge circuit on which the gages were connected. This change of current was very small, and amplifiers were needed to magnify the change so it could be recorded by an oscillograph (a device invented in 1893 to record electrical oscillation). The record was printed on chart paper in the form of an oscillogram. The WES-designed pressure transducer was installed in both model and prototype structures. Similar commercial transducers as small as 3/8 inch diameter have been successfully installed by Station personnel. Today, commercial pressure transducers of even smaller diameter (predominantly Consolidated Electrodynamics Corporation) are used in the Hydraulics Laboratory's work, and ISD still adds a custom waterproof housing to the transducers.

The dynamic pressure measuring system used in a 1943 field study of the Fort Peck Powerhouse penstock consisted of five WES hydrostatic pressure transducers with a range of 0-150 p.s.i.[4] The transducers were assembled in pipe caps and installed in four inch pipe nipples welded into the wall of the penstock. They were connected to a suitable amplifier and oscillograph for recording purposes. A four-channel WES-built amplifier was capable of taking pressures from four transducers simultaneously (a six-channel oscillograph began to be used at the Station in the 1950s). Output from the transducers was connected to one of the galvanometer elements of a Westinghouse oscillograph, which then recorded pressure fluctuations on photographic paper. This process offered a time history of pressure in the penstock. Pressure measuring devices have been in use at the Waterways Experiment Station to measure water levels and structural pressures since initial hydraulic structures testing began in 1931. The most widely used device has been and continues to be the pressure transducer. The basic design concept has not been seriously altered since the 1950s. Through the years, WES personnel have installed dozens of the Station's own pressure transducers or similar commercially produced ones in both Corps of Engineers' prototype structures and hydraulic models.

Since the 1950s, pressure transducers have been used to record water surface levels in lock chambers and pressures in culverts downstream from the filling valve in both the model and the prototype. By 1960, Consolidated Electrodynamics Corporation commercial pressure transducers (50-150 p.s.i.) and amplifiers had appeared, and their signals were being recorded on eighteen-channel oscillographs. The transducers themselves were of standard design, but the new eighteen-channel oscillograph enabled up to eighteen pressure transducers to be monitored simultaneously.

The 1970s was a period of rapid modernization of pressure recording techniques. For example, on a typical pressure measuring system signals were amplified and recorded simultaneously on analog FM magnetic tape and an oscillograph strip chart. The power source was a 110 volt generator. This particular type of recording apparatus was housed in a van for mobile

prototype testing. By 1977, a WES-fabricated amplifier was employed to condition the output signals to a thirty two-channel magnetic tape recorder, making rapid and permanent recording of pressure data possible. Current data recording devices are WES bridge amplifiers, commercial thirty-two track magnetic tape recorders, and twelve inch chart oscillographs capable of reproducing up to thirty six channels of data.

Notes

1. Spillways for St. Lucie Canal, Paper 14, U.S. Army Corps of Engineers, Waterways Experiment Station, Sept. 1933.

2. Summary of Earth Pressure Cell Development to 1954, MP 5-21, U.S. Army Corps of Engineers, Waterways Experiment Station, Oct. 1954.

3. Review of Observations from Hydrostatic Pressure Measuring Devices Wappapello Dam, Wappapello, Missouri, TR 3-460, U.S. Army Corps of Engineers, Waterways Experiment Station, June 1957.

4. Field Pressure Measurements, Fort Peck Powerhouse Penstock, TM 206-1, U.S. Army Engineer Waterways Station, May 1944.

Force Measurement

When a boat ties up in a lock to wait through the filling or emptying process, a great deal of longitudinal and/or transverse stress may be exerted upon the craft tie-off cables. The uneven distribution of water entering the lock chamber through the lock filling system causes this stress, referred to as a Hawser force. Measurement of the Hawser force is taken to help design filling and emptying systems which will cause minimum forces on moored vessel cables. This would ultimately reduce the risk of damage to vessels in the lock and the lock itself. Force measuring appliances called strain gages have been used in WES hydraulic studies of this type since the early 1940s. Electric strain gages operate in conjunction with suitable sensing and actuating mechanisms to produce a displacement action, and they can be used for both static and dynamic measurement.

In a 1944 and 1945 study of water requirements and salt water intrusion in the New York Bay-Delaware River section of the Intercoastal Waterway, electrical strain gages were employed to measure longitudinal forces acting on simulated boat hawsers during filling, emptying, and flushing of the locks, with an oscillograph recording the data. The model boat was restrained longitudinally by a somewhat stiff steel member 7/8 inch wide by 1/10 inch thick by six inches long, mounted so it would rise and fall with the boat's vertical action. Strain exerted on the steel cantilever beam was proportional to longitudinal force on the boat hawser. To insure that all forces exerted on the boat were longitudinal, guides were placed on the boat to arrest any transverse movement. By determining resultant changes in a resistance-wire strain gage mounted on the cantilever, strain was measured. Variations in resistance were detected and amplified by use of electronic equipment and applied to an oscillograph. Calibration of the strain gage was accomplished by placing known loads on the cantilever and monitoring deflections on the oscillograph.

Many other types of gages have been employed through the years in an effort to accurately measure crucial forces. For example, a coiled-spring gage was employed in a 1946 model study to measure forces on barge tows passing through the lock at Demopolis Lock and Dam in Alabama.[2] The gage was mounted on the model's edge and connected to the boat. Deflections on the gage indicator were determined by the amount of force exerted against the coiled spring. Various other basic force measuring devices saw service at the Station in the 1950s: pulleys and weights measured force required to pull barge tows away from guard walls, and the impact of a tow against guard walls was determined by a strain gage or precision springs. A typical circa 1950s force gage to measure direct impact of a tow on a guard wall was mounted at the head of the craft. A Statham commercial force gage was commonly used with a Brush Recording System made up of Universal amplifiers and direct marking recorders. Flexible wires led from the force gage to amplifiers and recorders. Measurements of this type were often erratic due to pulsating water currents and changes in tow approach. Consistent averages were obtained

by taking ten to fifteen measurements and eliminating readings that were obviously out of line. It is obvious that this empirical process would not be the fastest or most efficient means of determining force.

Precision springs have been used for direct force measurement at WES. A drawback with the spring is that it absorbs energy while reaching maximum deflection, and this necessitates correcting the measurement. To measure force with springs, a differential transformer or comparable device would be used with the spring to obtain correct deflection. A more reliable method was to use a spring-loaded potentiometer with springs having desired constants, but many factors could still adversely affect the accuracy of a measurement.

Many methods were tried to measure force needed to pull a tow away from a lock guard wall in a 1952 to 1956 model study of navigation conditions at Greenup, Kentucky, Lock and Dam on the Ohio River.[3] One attempt was made with a light string attached to a mechanical scale. The scale was pulled manually with a slow steady movement to the maximum force, which was then recorded. This technique was repeated using a Statham force gage and Brush Recording System. These methods were erratic because a uniform slow pull was difficult to maintain. A pulley and weight system was also employed whereby weights were added to the model tow in one gram increments until it pulled away from the guard wall. When the weight required to pull the tow away was ascertained, the weight required to overcome friction in the pulley was determined and subtracted from the weight needed to move the tow. This method was slow and results were not totally reliable.

After World War II, an ambitious amount of lock and dam construction was undertaken by the Corps of Engineers, and WES subsequently began a growing number of structural studies to secure answers to theretofore unsolved hydraulics questions. By the middle of the 1950s a reliable device to accurately and efficiently measure longitudinal and transverse stress was badly needed by the Corps. Such a device to measure these stresses, or Hawser forces, was designed and constructed by WES Instrumentation Services Division and is in service today.

This Hawser-pull device consists of standard SR-4 strain gages cemented to the inner and outer edges of semicircular aluminum force links (see HAER photos MS-2-29 and MS-2-30). One end of the link is pin-connected to a model ship in a lock and the free end is affixed to a vertical rod through a roller bearing. The link can move up and down the rod on roller bearings as lock water surface rises and falls. Any motion of the barge causes the links to deform and vary a signal to a recorder. Calibration of the links is achieved by inducing deflection on them with known weights. On most model ships three separate devices are used: one for longitudinal stress and two for transverse stress on the bow and stern, respectively. Mechanical to electrical sensing elements are cable-connected to amplifiers where outputs are stepped up to required levels.[4]

The most pronounced change in the Hawser-pull apparatus has been in the technological advancement of mechanical to electrical conversion devices and recorders. Data was recorded in the 1950's by a commercial six-channel direct writing recorder, and eighteen to thirty six-channel recorders are currently used. The Hawser-pull force links instrument has faithfully measured longitudinal and transverse stress on model ships in locks since the 1950s without undergoing major functional changes, although some very basic design modifications have been made.

Notes

1. Model Studies of Water Requirements and Salt-Water Intrusion, Intercoastal Waterway, New York Bay-Delaware River Section, TM 221-1, U.S. Army Corps of Engineers, Waterways Experiment Station, June 1946.

2. Spillway and Lock Approach Currents, Demopolis Lock and Dam, Tombigbee River, Alabama, TM 2-252, U.S. Army Corps of Engineers, Waterways Experiment Station, Apr. 1948, p. 11.

3. Navigation Conditions at Greenup Locks and Dam Ohio River, TR 2-469, U.S. Army Corps of Engineers, Waterways Experiment Station, Jan. 1958.

4. Filling and Emptying Characteristics of Calumet River Lock Project, Illinois, TR 2-497, U.S. Army Corps of Engineers, Waterways Experiment Station, Apr. 1959, p. 7-8.

Salinity

A fresh water hydraulic model can faithfully reproduce needed phenomena with relative ease if requirements of similitude are met. In contrast, a model of a system where a river meets a tidal current is extremely complicated and much more difficult to recreate. It is so difficult that very few, if any, hydraulics laboratories other than WES conduct estuarine model studies which reproduce all measurable prototype phenomena. Accuracy of an estuarine model at WES may be dependent upon a combination of many factors. Tidal cycle, currents, wave action, and salinity concentration are but a few of the variables which must be reproduced and measured.

Salinity levels and flow patterns are very important factors in hydraulic engineering. Salt water has a higher density than fresh water, and thus tends to stay at the bottom when the two meet in an estuarine system. This can create difficult problems for the hydraulics engineer. Intrusions of salt may affect the tidal currents to cause shoaling, or existing salinity patterns may affect proposed channels or harbors. These type of problems can best be addressed by the physical hydraulic model when salinity is introduced and appropriate tests are performed.

Basically, two sumps are used to introduce salinity into a model; one sump for fresh water control and one for salt water control. By properly mixing the inflow from both sumps and running the model through several tidal cycles, a salt water condition is established. A skimming weir is utilized on estuarine models to prevent excessive dilution of salt water and to maintain correct fresh water elevation (a weir is a general term for a group of flow retarding, increasing, or measuring instruments commonly used in hydraulics). Excess fresh water skims over the weir and is either returned to the sump or wasted. It is generally set just below water level on the downstream end of the model.

Generally, the two methods incorporated to measure salinity levels are electrical conductivity and chemical titration testing. Both have been used by the Hydraulics Laboratory since the 1940s when salinity studies were first undertaken.

Instrumentation used at WES in the conductivity method of determining salinity has nearly all been commercially manufactured since the 1940s. High conductivity, a property of salt water, is one of several factors that increases water's specific gravity. By comparing known specific gravity of a liquid with the unknown specific gravity of a sample and applying the difference to a conductivity curve, salinity may be determined. The electrical conductivity method of determining salinity through specific gravity of a salt water sample was performed by using a conductivity bridge and dip cell on the 1940 to 1946 study of plans for improvement of navigation conditions and elimination of shoaling in Savannah Harbor.[1] When a sample was taken from a given location, the conductivity bridge measured resistance

to an electric current passing between two metal plates on the dip cell that was immersed in a water sample. A calibration curve was plotted by measuring the resistance of a set of samples of known specific gravities. From this data, specific gravity of model samples could then be easily determined by applying their measured resistances to the calibration curve.

A second relatively simple procedure for determining salinity, by chemical titration, has remained unchanged since its initial usage at WES. A known concentration of a substance (silver nitrate) is added to a known volume of sample water to which an end point indicator has been added; the amount of silver nitrate required to precipitate all salt in the sample is converted to a parts per thousand measure of salt content. Parts per thousand is then converted into a measurement of specific gravity using a table prepared by the U.S. Coast and Geodetic Survey. Equipment consists of a graduated 10 cc burette for measurement of silver nitrate, pipettes for salinity samples, sample jars in which to perform the titration, and potassium chromate used as an end point indicator in the process. The chemical titration method is desired over the salinity meter when great accuracy is required, albeit a much slower process. These methods are employed in tandem on most models, with titration being a calibration check for the salinity meter.

The majority of salinity samples taken in the 1960 model study of hurricane surge control structures and effects of the Mississippi River-Gulf Outlet Channel on Lake Pontchartrain, Louisiana were from one depth (the bottom), so a single pipette was all that was necessary.[2] A short piece of plastic tubing was attached to to the pipette to allow the sample to be drawn by suction through the tube. A multidepth sampler was devised whereby several small copper tubes were taped together, each fitted with a two hole stopper to which a sampling bottle was attached. Each tube was cut at a different length to draw samples from varying depths, with the longest submerged to the bottom. As negative suction was applied by a pump to a single plastic tube connected to all the others by separate plastic tubes, each bottle filled with sample water. This set-up was improved in the late 1960s when the multidepth sampler was mounted on a modified point gage and tripod, and sample bottles were arranged on a manifold also attached to the point gage and carriage. This innovation affords the sampling unit a high degree of portability.

Between 1957 and 1959, when the Hydraulics Laboratory undertook model studies for plans to reduce shoaling in the Southwest Pass of the Mississippi River, WES used a commercial salinity measuring system consisting of a conductivity recorder, a three-electrode conductivity cell, and a proportioning cell.[3] It measured salinity from 250 to 50,000 parts per million. The recorder had two parts: a delicate galvanometer and a recording pen. The conductivity cell was situated inside a small box, with the intake side of the cell attached to a point gage to allow a steady flow of sample water to be drawn at any desired elevation. To reach all points on the model, the cell was connected to a pump by a plastic tube and a 150 foot long wire. The wire ran through a resistor to the recorder, where data was converted into a readable measurement.

By the middle 1960s, a more up-to-date conductivity measuring device appeared in the Hydraulics Laboratory that is still in use today. It determines salinity concentration in the same general way as the previously described versions -- that is, from conductivity of the water. This unit, more portable than previous designs, consists of a commercial cell switch box, a conductivity indicator unit with a meter reading specific conductance, a digital indicator, and three conductivity cells for measuring various ranges of salinity. All pieces of the unit are manufactured by Beckman except the digital reading indicator, which is a Weston Model 4440. The cells have an accuracy to within plus or minus two per cent of full range (plus or minus 0.2 to plus or minus 0.5 ppt). The unit is compact and extremely reliable. In addition to its model testing application, field salinity samples taken by Estuarine Processes Branch personnel are brought to the lab for analysis.

Since the 1960s, WES has employed many different makes of conductivity meters for both prototype and model measurement. Although technology has improved the design and efficiency of salinity meters to allow more rapid and reliable results, the basic principle of obtaining conductivity (salinity) by determining the resistance of a column of water to a given AC current has remained virtually the same to the present. Chemical titration, which is commonly used along with the conductivity method, also remains virtually the same as when it was first performed at the Station.

Notes

1. Plans for Improvement of Navigation Conditions and Elimination of Shoaling in Savannah Harbor, Georgia, and Connecting Waterways, TR 2-268, U.S. Army Corps of Engineers, Waterways Experiment Station, Mar. 1949.

2. Effects on Lake Pontchartrain, Louisiana, of Hurricane Surge Control Structures and Mississippi River-Gulf Outlet Channel, TR 2-636, U.S. Army Corps of Engineers, Waterways Experiment Station, Nov. 1963.

3. Plans for Reducing Shoaling Southwest Pass, Mississippi River, TR 2-690, U.S. Army Corps of Engineers, Waterways Experiment Station, Aug. 1965.

Tide and Wave Height Measure

The Waterways Experiment Station conducts hydraulic model studies of problems peculiar to regions where a river current meets a tidal system. In fact, one division within the Hydraulics Laboratory deals strictly with estuarine environments. Few hydraulics laboratories have the capability to reproduce the range of coastal phenomena such as tide, wave height, salinity, shoaling, and littoral transport which are an integral part of WES's model testing drift = sand program. Two of the most obvious facets of an estuary which must be reproduced in order to reliably recreate prototype conditions are tide and wave height. WES has been active in investigations of this nature since 1935 when a model study was undertaken of maintenance works at Ballona Creek outlet in Venice, California.[1] The plan called for methods to maintain the outlet channel against shoaling caused by littoral transport of beach sand.

The movable-bed model was constructed within a wooden frame structure to protect the model from rain and eliminate wind interference with tidal reproduction (early models were generally constructed outdoors). A device was developed especially for the study to reproduce any desired prototype tidal cycle on the model. The tidal reproduction apparatus consisted of a control drum, an indicator float, an electrically operated tide-gate and several recording drums. Fins were affixed to the outside circumference of the drum for each type of tide to be reproduced; the drum was driven at a preset speed so that one revolution of it corresponded to one lunar tidal day of 24.84 hours. The fin's vertical range corresponded exactly to the tidal fluctuations as required in the model. The indicator float was situated in a stilling well, and a manometer tube ran from the well to the tide-gate area so that float elevation was determined by the water level at that point. Two electrical contacts were affixed to the indicator float and the control-drum fin. A small space existed between the two points and the fin, and when the water surface in the model did not correspond to desired levels either the upper or lower contact touched the fin. This completed an electrical circuit triggering one of two electrical motors on the tide-gate, which in turn moved to correct the discrepancy between actual water level and desired water level. When all testing was completed, the Waterways Experiment Station concluded its first estuarine model study and this started a new era of Hydraulics Laboratory research.

Just prior to World War II (1940 and 1941), WES was involved in studying plans to eliminate shoaling in the Delaware River.[2] In order to faithfully model prototype conditions on the model, it was necessary to reproduce estuarine phenomena including tide elevations and ebb and flood tide currents. Three identical automatic tide control devices were employed to do this. Each apparatus consisted of four parts: a) a movable motorized waste weir installed across a pit at the end of the model, b) a centrifugal pump for supplying water to this pit on the model, c) a waste line to connect the waste weir to the sump, and d) the automatic tide control apparatus in the model, used to regulate the waste weir to maintain correct tidal reproduction at the end of

the model. Installed on this tide generator and all subsequent ones was a large tidal clock (see HAER photo # MS-2-22), divided into prototype hours and geared to make one revolution per lunar tide cycle (about 1/2 day in the Delaware River).

Each of the automatic tidal control devices was equipped with a cam cut to an appropriate plot to simulate prototype tide. The cam was turned by a synchronous motor at a speed corresponding to a model time scale. Mounted vertically over this cam was a rod with two electrical contacts, one over the other, that moved in an up and down motion with the tide plotted on the cam. Between the two contacts was a third one with slight clearance above and below. The third contact was attached to a float-supported rod in the control pit. Pipes connected the control pit to the model. Whenever water surface in the model rose or fell slightly off the desired tidal cycle elevation, the float forced the middle contact to close the electrical circuit by touching either the upper or lower contact (a distance of 0.001 foot). Closing the upper circuit activated the waste weir in a downward direction, causing water level to drop; closing the lower circuit did the opposite and water level rose. An interrupter consisting of a cam, a mercury-tube circuit breaker, and a motor, powered the waste weir in its variety of movements. Tidal simulation by this device was very accurate to prototype mean tide. This same theory of operation is employed on modern tidal apparatus presently in service at WES.

Early automatic tide control devices (tide generators) were outfitted with an automatic recording apparatus which used an inked pen on a roll of paper to log a continuous record of the model tide curve superimposed over the prototype curve being reproduced. The prototype tide curve was marked by a pen riding on the plotted cam and the model tide was inked by a pen fixed to a staff riding on a float in the control pit. This offered a visual accuracy check at any time during testing.

Improvements on the tide control mechanism were made during the 1940s. The major difference in this design and the one preceeding it was predominantly in the automatic tide reproducer apparatus; the waste weir was replaced with a header and a rising-stem valve system. The main components of the newer version were: a main header (pipeline) from model to water supply sump; a pump supplying a constant flow from the sump to the main header through a separate line; a motorized, commercially made rising-stem valve installed in the main header and; the automatic tide control device for regulating the valve by a system of floats and electrical contacts, which was the same as had previously been in use. Closure of the valve would divert the output of the pump into the model to create a flooding tide; opening the valve would create an ebbing tide. Any desired rate of ebb and flood tide could be reproduced by varying the valve's opening or closing. After this design emerged, tide control and recording devices remained much the same through the 1940s.

In a 1950 to 1952 study to plan the improvement of Gray's Harbor and Point Chehalis, Washington, the Hydraulics Laboratory installed an automatic tide reproducer on the model which used two motorized commercial rising-stem valve

systems.[3] One was implanted in a line from a pump to the model, designated as the inflow valve; the second was located in a return line from the model to a supply sump, and designated the outflow valve. This valve was equipped with limit switches to fix the points of maximum opening and closing which represented maximum ebb and flood, respectively. The position of the outflow valve was also synchronized by the limit switches with respect to time twice each tidal cycle. This allowed the tidal control mechanism to operate fully automatically. Continuous tide recorders were included on the tide generator to visually check accuracy of model tide. This design was used through the 1960s.

In subsequent studies beginning in the 1960s, some models required the use of two primary tide generators or one primary and one secondary generator, in order to reproduce differing tidal cycles. In these cases, the generators were synchronized to correct time-phases. A secondary tide generator was part of the appurtenances on a model to study enlargement of the Chesapeake and Delaware Canal from 1970 to 1972.[3] This example of a secondary tide generator, synchronized with the primary generator, consisted of two inflow control devices (one for fresh water and one for salt water) and an automated overflow weir. Salt and fresh water were introduced at rates proportionate to prototype salinity levels. An adjustable cam controlled the overflow weir and also positioned it to cause the inflow to enter the model from an eastward direction, or to cause an outflow from the model during periods when flow in the canal was westward.

Most estuary models require one or perhaps two tide generator systems, but occasionally three are installed, as on the mid-1960s New York Harbor model study to determine effects of hurricane surge barriers on the hydraulic environment of Jamaica Bay, New York.[4] The reason for three generators here was the need to reproduce tidal patterns in three distinct areas: the ocean, the connection to Long Island Sound, and the upstream limit of the Hudson River.

An improved version of the 1960s tide control system first appeared on early 1970s models. As in earlier designs, a pump supplied a constant flow of water to the model from a nearby sump. Gravity discharge from the model to the sump was controlled by an automatic rolling-gate valve. Mechanical signals generated by a radially eccentric cam were converted to an electrical signal by an amplifier and transmitted to a bubble tube positioner. The positioner moved an air bubble tube in the direction that the water surface must go in order to produce the desired water level. Air pressure sensed by the bubble tube acted as input to a hydraulic controller, and any fluctuation between the bubble tube pressure and a preset controller pressure signalled an error in water surface elevation. Input was amplified 50,000 times by the hydraulic controller and triggered movement of the automatic roller-gate valve to correct errant water level. The tidal clock contained a timer to indicate accumulated total tidal cycle and to provide a reference for periodic measurement of tides, currents, salinity, or any other desired sampling event. This feature made a correlation of measurements possible from

different tidal cycles and from test to test. The predominant tide generator in the Hydraulics Laboratory today is this WES-designed and constructed version.

Developed in the early 1970s, this system incorporates five major components: a) a program cam; b) a differential amplifier and power supply; c) a bubble tube positioner; d) a hydraulic-pneumatic amplifier; and e) a hydraulic cylinder and control gate assembly. When the differential amplifier detects a water level discrepancy between the bubble tube positioner and desired water level as indicated by the cam, a signal is sent to the hydraulic cylinder to alter the control gate. This system offers a reliable method for the Hydraulics Laboratory to accurately reproduce prototype tidal cycles in estuary models.

When the Waterways Experiment Station conducted model studies on the Ballona Creek outlet model in 1935, it was the Station's first attempt to reproduce estuarine phenomena.[5] To successfully accomplish the task, a tidal reproduction apparatus was built and incorporated on the model. Since this initial effort, dozens of estuarine models have been duly equipped with reliable tide generating systems. Evolution of these devices was slow from the World War II-era until the 1970s, when major design changes were incorporated. A wave generator and wave height measuring devise was also included on the Ballona Creek model. Since then, dozens of models have incorporated wave generators in conjunction with tidal reproduction devices, and both have undergone a similar metamorphosis.

Height, length, period and angle of approach are four factors that define a wave. To effectively recreate these variables in WES's first estuarine model, a sixty foot triangular plunger was oscillated vertically by a system of shafts and cranks driven by two 1-horsepower motors. The amount of oscillation governing wave height was controlled by the throw of the crank arms, and wave period was determined by the size of pulleys on the driving motors. The apparatus sat in a wave generator pit, and by placing casters underneath the generator it could be moved in a twenty degree horizontal arc (the range of wave angularity was ten degrees either way from parallel to the beach line).

The Ballona Creek study included a Waterways Experiment Station-designed instrument to measure wave height consisting of a vertical resistance staff installed in a DC circuit. The resistors of the electrical circuits varied directly with the staff's submergence in water. Several of the gages were able to detect vertical fluctuations of the water surface to within 0.002 foot in the model, or 0.03 foot in the prototype. To record the rapid fluctuations of wave heights as detected by the resistance staff circuitry, the electrical leads were connected to a modified galvanometer of a recording oscillograph. Seven moving coil galvanometer units were connected to the oscillograph. Deflections from the coils due to current changes in the gage-staff circuit were transmitted as beams of light to a strip of moving, sensitized photographic recording paper. Improvements on the wave generator were made

soon after the initial 1935 trial.

In 1942, a study was undertaken of wave action in Agate Bay Harbor on Lake Superior, in Minnesota.[6] A twenty one foot trapezoidal plunger-type wave generator was in use for this study. It was a more compact generator than was on the first model. It was driven by a three-horsepower induction motor powering a variable gear reducer, crank shaft, and system of levers. As in the first generator, displacement of water by the plunger's vertical motion created model waves; speed, stroke, and submergence of the plunger formed waves of varying characteristics. The speed of stroke could be changed with a handwheel during operation. Changing the plunger stroke took thirty minutes with the generator turned off. The idea of placing the generator on casters to generate waves from various directions continued with this design and is still an integral feature on wave generators today.

Casters mounted on wave generators allow for some degree of portability for these cumbersome devices. They are manufactured in twenty foot sections which may be bolted together to fit any model requirement; WES has assembled generators as large as 120 feet in length, as was the case in 1980 on the Cleveland Harbor model (TR HL-83-6). Time required to move a sixty foot wave generator was discussed in the results of a late 1960s study of navigational channel improvements for Barnegat Inlet, New Jersey. In order to move a wave generator, leveling screws must be raised until the wheels touch the ground. At least two persons are required to roll a sixty foot generator to its new position, and then three must work to level it -- an instrument person, a rod person, and one person to adjust the leveling screws. Approximate moving time is one hour.[7]

Engineers at Terminal Island Naval Operating Base in San Pedro, California, used a pressure cell as a wave height measuring device in the early 1940s and WES engineers expressed an interest in its adaptation for use at the Station.[8] Tests were conducted at the Station, but it was determined that the pressure cells were not reliable. After this series of testing, WES engineers focused their energies on the development of what was eventually to become a successful design.

Wave generators have not changed in principle for a number of years, although appearance varies according to generator length (naturally, larger ones are heavier and better braced). The plunger-type generator has proven to be a reliable method of wave reproduction. Different length generators are produced depending on the needs of a given study. It has been found that by using several short generators (twenty to forty foot lengths), with parallel plungers in synchronized movement, much time is saved in model construction because a smaller wave pit area is required.

One of the smallest plunger-type wave generators ever in service at the Station was installed in 1953 in a model study of design for a rubble-mound breakwater for Crescent City Harbor, in California. A five foot generator was fit into a five foot wide concrete wave flume to reproduce model waves. A

parallel-rod type wave gage measured wave heights in this case.[9] The parallel-rod differed in design from the vertical staff gage in use in the 1940s and 1950s. WES-built parallel-rod wave height gages were made of two parallel wires, two millimeters in diameter, that formed the legs of a circuit. The instrument used a printed circuit type staff gage of chrome-plated micarta that measured water surface elevations with respect to time dependent on the gage's submergence. The complete apparatus contained the parallel-rod gage, a balancing circuit, Brush Universal Analyzer, and a magnetic pen and motor oscillograph. The staff-type wave gage consisted of a single resistance staff installed in a DC current in which the circuit resistors were designed so that the current through them varied with the staff's submergence in water.

A plate-type wave generator reproduced model waves in 1954 and 1955 inside a plate glass/aluminum flume built to study wave effects on levee sections at Lake Okeechobee, Florida.[10] This four foot generator created model waves through a horizontal sweeping motion of the plate. Wave heights were measured by a parallel-rod with gage, a balancing circuit, a commercial Brush Universal Amplifier, and a Brush magnetic oscillograph. This study also incorporated a five foot plunger-type wave generator within a concrete flume.

A 110-foot vertical bulkhead-type wave generator was installed in 1957 to study the proposed relocation of the north entrance channel to Buffalo Harbor in New York.[11] The difference in this generator and the plunger-type was in the action of the wave producing device. The bulkhead generator created waves with a horizontal paddle-like movement, as opposed to a vertical plunger motion. This particular study required a wave generator capable of generating waves of the period and heights found on Lake Erie, and the bulkhead-type wave generator accurately simulated this phenomenon with its infinitely variable speed and placement. Parallel-rod wave gages measured wave height on this model. Vertical bulkhead wave generators were occasionally used in model studies requiring reproduction of specific wave curvatures due to refraction. They are no longer used by the WES Hydraulics Laboratory, but are still in service in the Coastal Engineering Research Laboratory at WES.

A bulkhead-type hurricane surge generator was developed for model study in the 1960s. This form of wave generator recreated a hurricane surge, a sudden swell of water that heaves itself ashore during a hurricane. To accurately recreate this phenomenon, a special basin was constructed adjacent to the model to hold a volume of water greater than that of the largest surge to be studied. An independent system similar to a standard tide generator could have been used, except that the large amplitude of the surge would require a costly assemblage of pumps, pipes, and valves. The hurricane surge was generated by programming forward and backward motion of a motorized horizontal bulkhead within the basin so that forward motion displaced water from the basin toward the model. This simulated the rise of a specific surge selected for study; backward bulkhead motion permitted flow back to the basin, thereby reproducing the falling surge stage. A three-phase drive motor supplied necessary reversal of movement and a positive, variable speed control unit

permitted accurate variation of bulkhead speed. The device could be adjusted to reproduce any desired surges when needed, and the system performed satisfactorily throughout.

Because hurricane surges rise and fall very rapidly, special recording instruments were used with the just described generator on the Galveston Bay hurricane study, undertaken from 1965 to 1967, to monitor and record surge elevations.[12] The gages had a float-supported pen which marked a continuous record of water surface elevation on a roll of recording paper mounted over a revolving drum. It was driven at a constant speed by a small motor. The recording apparatus sat on flat plates mounted on tripods permanently set at designated surge measuring points on the model.

In the early 1970s, remote controlled wave rods appeared on hydraulic models as part of a ten-channel wave height measuring system. For each channel there was a corresponding wave rod to detect water levels, a remote controlled motor driven assembly to raise and lower the rod for calibration purposes, and circuitry to connect the rod to a power supply and light-beam oscillograph. Two 0.08 inch diameter parallel wires formed the legs of an electrical circuit that was closed when the wave rods were submerged. The rods were calibrated about twice daily in still water. The process involved moving the rods up and down in the water by the remote-controlled wave rod assembly. Light beam deflection off of the rods was recorded for calibration, and deflection was directly proportional to the wave rods submergency in the water. All wave appurtenance controls were housed in an instrument room bordering the model.

While no major design changes have been made on the plunger-type wave generator in recent years, a major advancement occurred in 1974 when wave heights began to be recorded on some models by an Automated Data Acquisition and Control System (ADACS) developed at WES. In essence, a minicomputer recorded onto magnetic tape the electrical output of resistance rod wave gages as they measured changes in water surface elevation. These sensors determined wave height variations with respect to time. Analysis of the magnetic tape revealed wave height data on the Station's Honeywell 635 computer.

In the 1974 and 1975 design study of Jubail Harbor, Saudi Arabia, the Hydraulics Laboratory used both a twenty-channel light beam oscillograph and later a newly developed ADACS to obtain wave height data. A comparison of the two systems shows that the ADACS was "more stable, less sensitive to temperature changes, utilized a faster and more accurate calibration procedure, and included more exact analysis programs....Relative comparisons of plans using data taken with the previous system are certainly valid. The main difference was in the absolute magnitude of some of the larger wave heights."[13] In essence, the ADACS offered a faster, more accurate means of wave-height recording of water elevation to within 0.001 foot model.

A special wave height recording device was developed, during 1974 testing on the Masonboro Inlet, North Carolina model, by utilizing a modified Stevens stage transmitter (the same type of device custom made in the 1940s for the

MBM).[14] In this case, the transmitter's standard three inch probe was replaced by one eighteen inches long, the tip of which moved upward or downward in water until it was stopped by successive wave troughs or crests. The probe's final position in the water marked the lowest wave trough-tide combination or the highest wave crest-tide combination, depending on the mode of operation of the instrument. From the output, it was possible to plot continuous curves of the highest and lowest water-surface elevation throughout a tidal cycle.

As WES entered the decade of the 1980s, the complexity of wave model studies and the solving of long-wave problems requiring large model areas was on the increase. A strong need existed for automation of operation, and for data acquisition and analysis; an ADACS consisting of wave generators and sensors, analog recorders and channel selection circuits, and digital data recording apparatus, were designed and built to fill that need. They have the ability to automatically calibrate wave gages and rapidly acquire data from them, to control wave generators, and to analyze test data. This data is recorded on disc or tape for either direct analysis by a minicomputer or by magnetic tape compatible with the WES central computer. Automatic calibration of wave gages (sensors) has made calibration possible in one-fourth of the time required before ADACS development. Many more tests may be run daily with the benefit of computer memory, and data can be analyzed by a minicomputer at each day's end. During data acquisition, wave data for a given condition can be collected (for up to fifty wave sensors), recorded on analog strip charts, digitized, and recorded on magnetic tape or disc.

Wave generator instruments were first put in use by WES in 1935, the first of which was a plunger-type device. With but a few minor improvements and modifications, the same basic design principle is predominant to this day. The greatest single advance since the device's introduction has been the development of the Automated Data and Acquisition Control System in the 1970s. This move propelled wave-height measuring technology at WES into the computer age.

Notes

1. A Model Study of Maintenance Works at Ballona Creek Outlet, Venice, California, Paper 18, U.S. Army Corps of Engineers, Waterways Experiment Station, June 1937, p. 8.

2. Enlargement of the Chesapeake and Delaware Canal, TR H-73-16, U.S. Army Corps of Engineers, Waterways Experiment Station, Oct. 1973.

3. Plans for the Improvement of Grays Harbor and Point Chehalis, Washington, TM 2-417, U.S. Army Corps of Engineers, Waterways Experiment Station, Nov. 1955, p. 5-10.

4. Effects of Hurricane Surge Barrier on Hydraulic Environment, Jamaica Bay, New York, TR H-76-14, U.S. Army Corps of Engineers, Waterways Experiment Station, Sept. 1976, p. 8-10.

5. A Model Study of Maintenance Works at Ballona Creek Outlet, Venice, California, Paper 18, p. 8, 10.

6. Wave Action in Agate Bay Harbor, Minnesota, TM 203-1, U.S. Army Corps of Engineers, Waterways Experiment Station, Dec. 1943.

7. Navigation Channel Improvements Barnegat Inlet, New Jersey, H-74-1, U.S. Army Corps of Engineers, Waterways Experiment Station, p. 13.

8. Memoranda on Wave-Measuring Device Development, MP 5-20, Report 1, U.S. Army Corps of Engineers, Waterways Experiment Station, Mar.-Apr. 1944, p. 1.

9. Design of Tetrapod Cover Layer for a Rubble-Mound Breakwater, Crescent City Harbor, Crescent City, California, TM 2-413, U.S. Army Corps of Engineers, Waterways Experiment Station, June 1955, p. 6, 7.

10. Wave Run-up and Overtopping Levee Sections, Lake Okeechobee, Florida, TR 2-449, U.S. Army Corps of Engineers, Waterways Experiment Station, Jan. 1957, p. 7, 8.

11. Proposed Relocation of North Entrance Channel, Buffalo Harbor, Buffalo, New York, TR 2-536, U.S. Army Corps of Engineers, Waterways Experiment Station, Feb. 1960.

12. Galveston Bay Hurricane Surge Study, TR H-69-12, Report 1, U.S. Army Corps of Engineers, Waterways Experiment Station, Sept. 1969.

13. Design of Jubail Harbor, Saudi Arabia, Royal Saudi Naval Expansion Program, TR H-76-2, U.S. Army Corps of Engineers, Waterways Experiment Station, Jan. 1976, p. 15.

14. Masonboro Inlet, North Carolina, Movable-Bed Model Study, MP H-75-10, U.S. Army Corps of Engineers, Waterways Experiment Station, Dec. 1975.

Mississippi Basin Model

The Mississippi Basin Model (MBM), in addition to being the world's largest physical model, is the only one operated completely by automatic stage recording instrumentation. Centrally located instrument control houses serve as nerve centers for the automatic devices. There are three primary types of appliances on the model-inflow, stage, and outflow appurtenances-synchronized by a single timing device (see HAER photos MS-2-36 to MS-2-48).

The inflow unit has a controller on the model and a programmer in the control house; the stage unit consists of a transmitter and records with a telemetering circuit; the outflow system has a programmer, hydraulic regulator and a V-notch weir. A master timer and calendar indicating month, day, and hour in model time make up the timing unit. These features on a circa 1980s hydraulics model may not be considered technologically significant; an astounding fact is that the model was designed, and its instrumentation installed, in the 1940s and 1950s.

Engineers and technicians from the Station's Instrumentation Services Division worked with participating instrument manufacturers to successfully outfit the MBM with a battery of measuring devices which represented a completely new type of hydraulic model instrumentation. It was built on a distorted scale of (1:100) vertical, (1:1000) horizontal, (1:267) time, and (1:1,500,000) discharge, and instruments needed great precision to reliably measure such miniscule quantities. Skeptics at first doubted that a model of this magnitude could be built and fitted with automatic appurtenances synchronized by a single timing device. The fact that the original pieces are still in operation is a fitting tribute to those that did successfully design and produce the instrumentation.

The years 1943 to 1947 were spent studying and developing the automatic instrumentation. Both commercial and special designed devices were tested and it was determined that automatic instruments were needed on the MBM because: 1) manually operated instruments could not accurately reproduce stages for the entire Mississippi Basin, 2) labor and cost required for manual instruments was unfeasible (a staff of 600 would be needed for manual instrumentation), and 3) a survey of the commercial instrument market revealed that no existing instruments had the required range of accuracy. Early in MBM development, the decision was made to specially design appropriate instrumentation.

By 1947, specifications were drawn up and manufacturers were invited to bid on the instruments and to submit alternate design proposals, some of which were in fact accepted and incorporated on the model. In July of 1948, contracts were awarded to Infilco, Inc. of Chicago, Illinois for 76 inflow devices and to Leupold and Stevens of Portland, Oregon (now in Beaverton, Oregon) for 160 stage instruments.

The inflow system on the MBM consists of a controller on the model and a

programmer in the control house. The controller, at the inflow point on the model, is a multiple orifice apparatus that measures predetermined flows. An orifice plate divides the tank into two sections: the top is connected to the model inflow point, and the lower section connects to the water supply. Thirteen, or in some cases sixteen, orifices are on each plate and they are opened and closed by a metal disc connected to the valve stem. Orifice area and pressure determine flow through the inflow controller. Orifice area is fixed; a differential pressure across the orifice plate of four p.s.i. is necessary to maintain required flows.

A transmitter measures, amplifies, and transmits differential pressure to the control unit in the form of measured variable pressure. The control unit in turn compares measured pressure to a set control pressure and changes the signal pressure proportionally, and opposite, to the pressure variation.

Some of the original controllers were replaced in 1966 by ones manufactured by Lawrence Systems. The original Infilco design operated pneumatically with a solenoid. The Lawrence controllers are also pneumatic devices, but without solenoids.

The inflow programmer has an automatic or manually operated electrical switch that powers the circuits to actuate the orifice valve in the inflow controller. Leaf switches in the switch box pneumatically open and close as a perforated program roll pressing over a tracker automatically controls operation; toggle switches are located on the control panel for manual operation. The automatic tracker bar roll works on the vacuum principle much like an old player piano.

The program roll is a perforated record of an inflow hydrograph for a given inflow point. Each set of perforations on the roll represents a certain grouping of orifice openings. A series of perforations exists for each orifice in the controller, the two intake valves, and three pneumatic gears (forward, reverse, and stop). Lights on the control panel indicate the leaf switches that are closed. When the perforator keys (resembling a typewriter) are depressed, they trigger electrical switches which complete circuits to the indicator panel. Program roll perforations can be checked against gallons per minute requirements for the given model hour.

The second type of automatic instrument on the MBM is the stage instrument system. This unit is comprised of a transmitter and a recorder. One selsyn motor in the transmitter and one in the recorder, connected by an electrical cable, make up the telemetering circuit. The transmitter on the model "feels" the water surface with an electronic sensing probe and relays the elevation to the recorder housed in the control room.

The transmitter features a reversible motor geared to a precision screw and the selsyns, and two electronic circuits that control the motor as a result of the water's effect on the sensing probe. Three probes are on the bottom part of the precision screw; one grounds the circuit and two regulate it. If the

needle probes are out of the water when the instrument begins operation, a current is passed to an electron tube (thyratron) that fires the motor to run the precision screw down. As originally operated, when the long needle probe touches the water, the voltage is cut to the control grid of the electron tube, thereby stopping the motor. When the short probe touches the water, the flow of current in the circuit that raises the precision screw triggers the thyratron to restart the motor in the opposite direction. This process has since been modified.

As the precision screw moves up and down and the needle probes sense the level of water, a pen on the recorder moves vertically with the screw. Movement of the pen is recorded in ink on a chart fastened to a drum powered by electrical clockworks. The stage hydrograph is drawn on the chart for a particular gaging station. Normally, the drum revolves six inches per hour. At this rate over six hours can be recorded on the chart, which converts to seventy prototype days (one hour prototype = 13.5 seconds model). The length of the chart is about thirty one inches.

Outflow instruments on the model measure discharge at selected points. Originally, control of the outflow was maintained manually by a tailgate weir. Head over the weir was initially read manually by a hook gage or automatically by a stage transmitter and recorder. In the 1950s an automatic control for programming either stage or discharge hydrographs was developed by Askania Regulator Company. Basically, this system employed a bubble tube principle whereby a two inch column of air was maintained between the water and bubble tube. By changing the tube's elevation, water level also was changed. Movement of the tube was actuated by a 100 p.s.i. oil jet discharge into two adjacent orifices. The hydraulic regulator is not currently used on the model, because testing is of a localized nature and a V-notch weir and Stevens water level transmitter all provide necessary outflow requirements.

In addition to the three types of devices just described on the MBM, a master timer and calendar control the correct model time. The timer maintains timing functions in accordance with model time scale and synchronizes all instruments. The electro-mechanical device consists of a series of cams, driven by a synchronous motor, with reduction gears producing speeds determined by the model time-scale.

The date-hour indicator calendar is designed so that model time is continuously observed in the control house on a wall-mounted display panel. A series of relay circuits operates lamps which light the correct model hour, day, and month on the panel. The calendar will emit audible hourly signals for a variety of pre-set periods.

All instruments are run from the control house. To conduct a specific test the timer, calendar, inflow programmers, and stage recorders are all set for the appropriate time (month, day, hour) and one switch then activates all instruments in the control house and on the model.

WES has built and tested small flood-control models similar to the MBM for over fifty years. The original ones were manually operated, and more recent ones contain both automatic and manual instrumentation. The reproduction of verification floods using manual instruments or a combination of manual and automatic devices has been achieved with roughly the same level of accuracy as with the automatic instrumentation of the MBM. The greatest benefits of automatic instrumentation on the Mississippi Basin Model have been from the high degree of accuracy when repeating identical tests, the elimination of the human factor, and the reduction of expenses by employing fewer staff.

Placed on inactive status in 1971, the model was closed and given to the City of Jackson, Mississippi College and the public school system. During the 1973 flood the model was leased and has been in operation since. WES is currently installing a computer controlled operating system. The presently active sections of the model (from Hannibal, Missouri to Baton Rouge, Louisiana; the Atchafalaya Basin to the Gulf of Mexico; and a portion of the Ohio River) continue to be a valuable tool of study for the Corps of Engineers.

As this report was being written, WES was just beginning to update MBM instrumentation to modern standards by replacing the original programmers with personal computers, each of which is capable of regulating up to nine controllers. Also being studied is a plan to replace the stage recorders with more modern equivalents, but thus far no suitable replacements have been found. An alternative to replacement is to upgrade existing recorders to computer standards, a major drawback of which is the prohibitive expense. Until further modernization is implemented, the Mississippi Basin Model will continue reliable operation with its existing instrumentation.

Notes

1. McGee, H. C., Automatic Instrumentation of the Mississippi Basin Model, MBM Report 1-5, U.S. Army Corps of Engineers, Waterways Experiment Station, Nov. 1955.

2. Foster, J. E., History and Description of the Mississippi Basin Model, MBM Report 1-6, U.S. Army Corps of Engineers, Waterways Experiment Station, Aug. 1971.

SECTION THREE

Conclusion and Recommendations

Accurate hydraulic measurements are a cornerstone for successful model and prototype studies at the Waterways Experiment Station. Success of a given study depends upon the Hydraulics Laboratory's ability to repeatedly reproduce prototype flow patterns. Failure to do so may result in erroneous predictions of future occurrences or potential failure of hydraulic structures, both of which could result in grave consequences. WES relies on a wide range of instrumentation, from cheap and simple point gages, to costly and delicate computer adaptable electromagnetic current meters. As each model study is different, so are the attributes of the instrument selected to measure desired phenomena. WES has created several pieces of instrumentation unique in the field of hydraulic engineering, such as the Miniature Velocity meter, the Bentzel tube, and the Hawser stress device, but the vast majority of Hydraulics Laboratory instrumentation has been purchased through the years from commercial manufacturers. Whatever the origin, one fact has remained constant. In order for an instrument to survive months or years of test application, it must be rugged, reliable, and repairable. Some pieces of instrumentation, such as the devices on the MBM, have lasted nearly half a century because they exhibit all three characteristics. Others have come and gone because they were inadequate in one or more respects. HAER's task at WES for the summer of 1986 was to locate and document existing Hydraulics Laboratory instrumentation. This was done to give Station personnel a better understanding and appreciation of this resource and assist them in planning preservation measures for those instruments identified as significant.

General Preservation Recommendations for Instrumentation

Category A Instrumentation--

Instrument reflects the highest significance in terms of WES Hydraulics Laboratory history and hydraulic model/prototype testing in general. An instrument in this category is unique and worthy of preservation. Strong consideration should be given to removing it from use and retaining it under archival storage conditions. At a minimum, use and circulation of the instrument should be monitored by a responsible party familiar with archival preservation standards. If the piece is not removed from use it should be properly stored and a maintenance schedule should be developed. It is recommended that a non-obstructive numbered identification tag be affixed to each instrument in this category to insure accountability. More detailed preservation guidelines for each Category A instrument should be developed by a qualified curator.

Category B Instrumentation--

Instrument reflects significance in terms of Hydraulics Laboratory history and hydraulic model/prototype testing, and therefore should be maintained in good condition. Due to the rapid pace of change in 20th century

technology instrumentation in this category should be re-evaluated every five to ten years. As the instrument may become more significant in the future it may become appropriate for it to be treated under the conditions of the recommendations established for Category A instrumentation. Until that time, a non-obstructive identification tag should be affixed to the instrument and a responsible party should monitor its circulation. Continued use under proper conditions is encouraged to prolong the device's utility. A maintenance schedule and appropriate storage facilities should be arranged.

Category C Instrumentation--
Instrument has little or no historical significance at this time, however, periodic review for future elevation to a higher category should be made. Routine repair and maintenance procedures are advised. Negligent storage practices, mistreatment, or the giving away of instrumentation should be avoided. Continued use under proper conditions is encouraged to prolong the device's usefulness.

Additional Recommendations

The WES Historical Committee should review the findings of the HAER inventory and select an example of each Category A and select Category B instruments which should be relocated to the planned Vintage Room, or some other appropriate repository at WES.

Effort should be made to contact similar institutions or technological history-oriented museums, such as the scientific instrumentation division of the Smithsonian Institute, and make arrangements to exchange for exhibit, on a temporary basis, mutually pertinent instrumentation.

A serious need exists to inventory and obtain proper storage conditions for photographs and drawings of instrumentation and model construction details. This should be addressed as soon as possible due to their fragility and high risk of being destroyed. If WES has no in-house personnel for the inventory of photographs and drawings a contract could be let to a historical consultant or a graduate student acquainted with this type of historical document. A qualified archivist or curator from within the Corps of Engineers should be consulted to recommend appropriate storage conditions.

A problem encountered during the inventory was the inability to identify some antiquated instrumentation, and not successfully locating other devices which were rumored to exist. It is recommended that a more thorough oral history project be conducted of retirees and senior employees in an attempt to ascertain historical information on these "ghost" instruments. These individuals should be requested to loan or donate such instrumentation back to WES. A contract should be let to obtain the services of a historical consultant to review existing historical studies and undertake an oral history program under the direction and with the assistance of the WES Historical Committee.

Consideration should be given to conducting a similar inventory project at additional historically significant laboratories at WES. Furthermore, in recognition of WES's status as an ASCE Landmark, an additional documentation project of the construction, modification, and use of specific models operated by the Hydraulics Laboratory at WES should be undertaken.

GLOSSARY

Cavitation - a hydraulic phenomenon characteristic of turbines, pumps, propellers and irregular surfaces. Air dissolved in the water comes out of solution at low pressure and causes severe turbulence. When it occurs, cavities filled with liquid vapor will alternately develop in areas of low pressure and collapse in the high-pressure region, damaging hydraulic apparatus. The formed bubbles reduce the capacity of a conveyance system.

Distorted-scale Model - geometrically distorted hydraulic model in which the vertical and horizontal scales are different.

Galvanometer - instrument for measuring or detecting small electric current by means of the movements of a magnetic needle or of a coil in a magnetic field.

Hawser Force - stress exerted on a vessels securing lines which occurs when the vessel is secured within a lock during emptying or filling.

Littoral Current - ocean current that moves along and roughly parallel to shore.

Littoral Transport - amount of material moved by the littoral current.

Manometer - tube for measuring pressure differences in water. It contains a liquid that does not mix with water (kerosone, mercury, etc...) and its ends are connected to points where a difference in pressure is required.

Model Verification - process in which the behavior of an adjusted model is checked against a set of prototype conditions.

Piezometer - tube or appliance to measure pressure head; usually a small pipe tapped into the side of a closed or open conduit and connected to a gage .

Potentiometer - instrument for precise measurement of electromotive forces. A portion of the voltage to be measured is balanced against that of a known electrical force and thereby computed.

Prototype - in hydraulic modeling, denotes the full-scale, or actual, system or structure upon which the model is designed to replicate.

Selsyn - a system consisting of a generator and motor connected by a multiple wire circuit, transmitting currents that turn the motor simultaneously to the same position as the generator; this repeats instrument indications and valve settings remotely.

Skimming Weir - apparatus used on a hydraulic model to control water level. Generally used on estuarine models when a proper mix of fresh and salt water must be maintained.

Specific Gravity - the ratio of the density of a substance to the density of some substance taken as a standard. Both densities are obtained by weighing the substance in air.

Total Head - measure of the sum totals of kinetic energy, pressure energy and potential energy heads in a given column of water.

Undistorted-scale Model - hydraulic model in which the vertical and horizontal scales are the same.

Uplift Pressure - water pressure exerted on the base of a hydraulic structure. It varies from a maximum at the upstream edge to a minimum at the downstream edge.

BIBLIOGRAPHY

Frazier, Arthur H., William Gunn Price and the Price Current Meters. Washington, D.C.: U.S. Government Printing Office, 1967.

Historic American Buildings Survey/Historic American Engineering Record, National Park Service, HABS/HAER Inventory Guidelines, (unpublished draft), June 1986.

Kolupaila, Steponas, "Early History of Hydrometry in the United States," ASCE Proceedings, HY 1, No. 2335. Jan. 1960.

Leupold and Stevens, Bulletin 18.

Nelson, A. and K.D. Nelson, Dictionary of Water and Water Engineering. Cleveland, Ohio: The Chemical Rubber Co., 1973.

Rhodes, Thomas J. and Grady C. Carroll, Industrial Instruments for Measurement and Control. New York: McGraw-Hill Book Co., 1972.

Rouse, Hunter, Hydraulics in the United States, 1776-1976. Iowa City, Iowa: The Institute of Hydraulic Research of the University of Iowa, 1976.

Troskolanski, Adam T., Hydrometry. Oxford: Pergamon Press, 1960.

U.S. Army Corps of Engineers, Waterways Experiment Station, A History of the Waterways Experiment Station, 1929-1979, Cotton, Gordon. Vicksburg, MS: U.S. Army Corps of Engineers, 1979.

----------, A Model Study of Maintenance Work at Ballona Creek Outlet, Venice, California, Paper 18. Vicksburg, MS: U.S. Army Corps of Engineers, June 1937.

----------, Automatic Instrumentation of the Mississippi Basin Model, MBM Report 1-5, McGee, H.C. Vicksburg, MS: U.S. Army Corps of Engineers, Nov. 1955.

----------, Design of Jubail Harbor, Saudi Arabia, Royal Saudi Naval Expansion Program, TR H-76-2. Vicksburg, MS: U.S. Army Corps of Engineers, Jan. 1976.

----------, Design of Tetrapod Cover Layer for a Rubble-Mound Breakwater, Crescent City Harbor, Crescent City, California, TM 2-413. Vicksburg, MS: U.S. Army Corps of Engineers, June 1955.

----------, Effects of Hurricane Surge Barrier on Hydraulic Environment, Jamaica Bay, New York, TR H-76-14. Vicksburg, MS: U.S. Army Corps of Engineers, Sept. 1976.

----------, Effects on Lake Pontchartrain, Louisiana, of Hurricane Surge Control Structures and Mississippi River - Gulf Outlet Channel, TR 2-636. Vicksburg, MS: U.S. Army Corps of Engineers, Nov. 1963.

----------, Enlargement of the Chesapeake and Delaware Canal, TR H-73-16. Vicksburg, MS: U.S. Army Corps of Engineers, Oct. 1973.

----------, Experiment to Determine the Backwater Effects of Submerged Sills in the St. Clair River, Paper 16. Vicksburg, MS: U.S. Army Corps of Engineers, Apr. 1934.

----------, Experiment to Determine the Limit of Backwater Influence in the Illinois River, Paper Y. Vicksburg, MS: U.S. Army Corps of Engineers, Feb, 1931.

----------, Experiments to Determine the Erosive Effects of Floodwaters on Railroad Embankments, Paper R. Vicksburg, MS: U.S. Army Corps of Engineers, May, 1931.

----------, Field Pressure Measurements, Fort Peck Powerhouse Penstock, TM 206-1. Vicksburg, MS: U.S. Army Corps of Engineers, May 1944.

----------, Filling and Emptying Characteristics of Calumet River Lock, Calumet Project, Illinois, TR 2-497. Vicksburg, MS: U.S. Army Corps of Engineers, Apr. 1959.

----------, Flow Characteristics in Flood-Control Tunnel 10, Fort Randall Dam, Missouri River, South Dakota, TR 2-626. Vicksburg, MS: U.S. Army Corps of Engineers, June 1963.

----------, Flow in Chute Spillway at Fort Randall Dam, TR 2-716. Vicksburg, MS: U.S. Army Corps of Engineers, Apr. 1966.

----------, Galveston Bay Hurricane Surge Study, TR H-69-12, Report 1. Vicksburg, MS: U.S. Army Corps of Engineers, Sept. 1969.

----------, General Principles and Scope of Usefulness of Hydraulic Models, Patterson, C.B. Vicksburg, MS: U.S. Army Corps of Engineers, Nov. 1947.

----------, History and Description of the Mississippi Basin Model, Foster, J.E., MBM Report 1-6. Vicksburg, MS: U.S. Army Corps of Engineers, Aug. 1971.

----------, History of the Waterways Experiment Station, Tiffany, J.B., ed. Vicksburg, MS: U.S. Army Corps of Engineers, 1968.

----------, Improvements for Murrell's Inlet, South Carolina, TR H-78-4. Vicksburg, MS: U.S. Army Corps of Engineers, Apr. 1978.

----------, Instrumentation for Hydraulic Research, MP 2-156. Vicksburg, MS: U.S. Army Corps of Engineers, Sept. 1955.

----------, Masonboro Inlet, North Carolina, Movable-Bed Model Study, TR-75-10, U.S. Army Corps of Engineers, Dec. 1975.

----------, Memoranda on Wave-Measuring Device Development, MP 5-20, Report 1. Vicksburg, MS: U.S. Army Corps of Engineers, Mar.- Apr. 1944.

----------, Navigation Conditions at Greenup Locks and Dam, Ohio River, TR 2-469. Vicksburg, MS: U.S. Army Corps of Engineers, Jan. 1958.

----------, Navigational Channel Improvements, Barnegat Inlet, New Jersey, TR H-74-1. Vicksburg, MS: U.S. Army Corps of Engineers, Mar. 1974.

----------, Plans for Improvements of Navigation Conditions and Elimination of Shoaling in Savannah Harbor, Georgia, and Connecting Waterways, TR 2-268. Vicksburg, MS: U.S. Army Corps of Engineers, Mar. 1949.

----------, Plans for Reducing Shoaling, Southwest Pass, Mississippi River, TR 2-690. Vicksburg, MS: U.S. Army Corps of Engineers, Aug. 1965.

----------, Plans for the Improvements of Grays Harbor and Point Chehalis, Washington, TM 2-417. Vicksburg, MS: U.S. Army Corps of Engineers, Nov. 1955.

----------, Proposed Relocation of North Entrance Channel, Buffalo Harbor, Buffalo, New York, TR 2-536. Vicksburg, MS: U.S. Army Corps of Engineers, Feb. 1960.

----------, Prototype Evaluation of Sluiceway Aeration System, Libby Dam, Kootenai River, Montana, TR HL-84-2. Vicksburg, MS: U.S. Army Corps of Engineers, Mar. 1984.

----------, Recent Automation Changes in Model Velocity Analyses and Data Acquisition by Miniature Price Meters, MP HL-79-6. Vicksburg, MS: U.S. Army Corps of Engineers, May 1979.

----------, Spillway and Lock Approach Currents, Demopolis Lock and Dam, Tombigbee River, Alabama, TM 2-252. Vicksburg, MS: U.S. Army Corps of Engineers, Apr. 1948.

----------, Spillways for St. Lucie Canal, Paper 14. Vicksburg, MS: U.S. Army Corps of Engineers, Sept. 1933.

----------, Status of Velocity-Indicator Development, Duke, Leiland M. Vicksburg, MS: U.S. Army Corps of Engineers, Feb. 1958.

----------, Summary of Capabilities, Waterways Experiment Station. Vicksburg, MS: U.S. Army Corps of Engineers, 1985.

----------, Summary of Earth Pressure Cell Development to 1954, MP 5-21. Vicksburg, MS: U.S. Army Corps of Engineers, Oct. 1954.

----------, The Bentzel Velocity Tube, Falkner, Francis H. Vicksburg, MS: U.S. Army Corps of Engineers.

----------, Turbulent Flow in Rectangular Outlet Conduit, Rend Lake Dam, Big Muddy River, Illinois, H-75-2. Vicksburg, MS: U.S. Army Corps of Engineers, Jan. 1975.

----------, Wave Action in Agate Bay Harbor, Minnesota, TM 203-1. Vicksburg, MS: U.S. Army Corps of Engineers, Dec. 1943.

----------, Wave Run-up and Overtopping Levee Sections, Lake Okeechobee, Florida, TR 2-449, Vicksburg, MS: U.S. Army Corps of Engineers, Jan. 1957.

----------, WES Relief Well Flow Meter, MP 5-83. Vicksburg, MS: U.S. Army Corps of Engineers, Apr. 1954.

U.S. Department of the Interior, Hydraulic Laboratory Techniques. Denver: U.S. Government Printing Office, 1980.

Vogel, Herbert D., Practical Laboratory Hydraulics for the River and Harbor Engineer.

Vogel, Herbert D., "Practical River Laboratory Hydraulics," ASCE Transactions, Paper No. 1894.

W. & L. E. Gurley Hydrological Instruments, Bulletin 700.

ADDENDUM TO:
WATERWAYS EXPERIMENT STATION, HYDRAULICS LABORATORY
Halls Ferry Road, 2 miles south of I-20
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