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The First Half Century Of Hydraulic Research At The University Of Iowa

Edited by
Enzo O. Macagno
David D. Moran
David W. McDougall

Iowa Institute
Of Hydraulic
Research

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UNIVERSITY OF IOWA
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Edited by
ENZO O. MACAGNO
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Research Engineers
Iowa Institute of Hydraulic Research

Bulletin 44
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THE IOWA INSTITUTE OF HYDRAULIC RESEARCH

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PREFACE

In order to make available the results of all research conducted at the Iowa Institute of Hydraulic Research, a series of bulletins containing abstracts of graduate theses, reviews of Institute research and lists of staff publications has been published at irregular intervals. Previous titles in this series, a part of the Iowa Studies in Engineering, have been Bulletin 19, *Two Decades of Hydraulics at the University of Iowa* (1939); Bulletin 26, *Investigations of the Iowa Institute of Hydraulic Research,* 1939-1940; Bulletin 30, *The Iowa Institute of Hydraulic Research,* 1946; Bulletin 33, *Third Decade of Hydraulics at the State University of Iowa* (1949) with Supplement (1952); and Bulletin 40, *Fourth Decade of Hydraulics at the State University of Iowa* (1960) with Supplement (1965). The present publication has as its twofold purpose to bring this series up to date with a discussion of the Institute's fifth decade of hydraulic research and to summarize at the half-century landmark the entire research picture as collected in all of the graduate theses and staff publications.

The contributions of the Institute staff to this Bulletin are gratefully acknowledged. Dean Hunter Rouse and his Office, the Department of Mechanics and Hydraulics, and the Admissions and Registrar's Office were also extremely cooperative in the preparation of this publication. Ms. Cathy LeBlanc and Ms. Beth Buffum's help in typing and correcting the manuscript is deeply appreciated.

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THE IOWA INSTITUTE OF HYDRAULIC RESEARCH

Historical Résumé

The heritage of the Iowa Institute of Hydraulic Research might be said to have begun in 1844 with the construction of a grist mill and low dam on the Iowa River above Iowa City, just three years before the founding of the University. Although active and prosperous throughout the remainder of the nineteenth century, declining revenues and a series of disastrous floods so discouraged the mill owner that in 1903 he deeded the water rights to the College of Applied Science at the University.

In 1904 the Iowa General Assembly appropriated $10,000 for the construction of a dam and power generating plant for the University. Within two years construction was completed on a 300-foot-long, 10-foot-high dam about a mile below the old mill site. The possibility of hydraulic experimentation was foreseen, and a 10-foot opening was left at the west end of the dam to provide an entrance to an experimental channel. Stop planks closed the opening.

Construction of a concrete arch bridge across the river at Burlington Street, immediately upstream from the new dam, began in 1914. In the wake of this development, the Department of Mechanics and Hydraulics acted to influence the location and design of a retaining wall south of the west abutment, in order to favor the construction of a hydraulics laboratory. Preliminary plans for the retaining wall, as well as for a 10-foot channel and a small laboratory building, were prepared

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by Professors J. H. Dunlap and R. E. Hutchins. Professor S. H. Sims completed the plans and prepared a report which led to an appropriation from the Iowa General Assembly in 1917.

With Professor Sims in charge throughout most of the construction period, the original laboratory came into being. The construction was essentially complete by 1919, with students of the Engineering College comprising a large share of the work force.

The original laboratory, shown in Figure 1, consisted of a 130-foot open channel (10 feet wide), a small pump for unwatering the channel at moderate to high river stages and a building at the downstream end, 22 feet square, serving primarily as a shop. The total cost of the laboratory, when equipped to begin experimental work, was $26,000.

Figure 1. Hydraulics laboratory in 1919.

In 1920, a recent Ph.D. from the University of Michigan, Professor F. A. Nagler, assumed charge of the laboratory. It is recognized that Professor Nagler's rare combination of energy, enthusiasm and technical ability provided the tremendous impetus which soon resulted in Iowa's renown for hydraulic research.

Professor Nagler considered the new laboratory unique in its capability to handle large-scale experimental work requiring large volumes of water under moderate head. His original expectation was that the laboratory would undertake an extensive program of turbine testing,

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since the only existing facilities for such tests were in Massachusetts. Although this priority guided the addition of new equipment, the publicity given the new undertaking attracted the interest and support of the Department of Agriculture, an organization which came to play an important part in the early growth of the laboratory.

Not all hydraulic activity in the early years was confined to the river-channel laboratory. In 1924 the Department of Mechanics and Hydraulics established laboratory space for hydraulic and materials testing in a mill-type building just south of Engineering Hall. This complementary facility provided an elevated constant-level tank and two weighing tanks of 18,000-pound capacity, and was devoted to student instruction as well as student and staff research.

By 1927 the press for additional space and a desire to consolidate the hydraulic research activity under one roof prompted the announcement of plans for a four-story structure to be built over a 60-foot extension of the river channel. The new laboratory would be approximately 30 feet by 60 feet in plan. A year later construction was complete and the large scales and other equipment were moved from their quarters to the new building. Figure 2 shows the hydraulics laboratory at that time and this represents what is the north wing of the present structure.

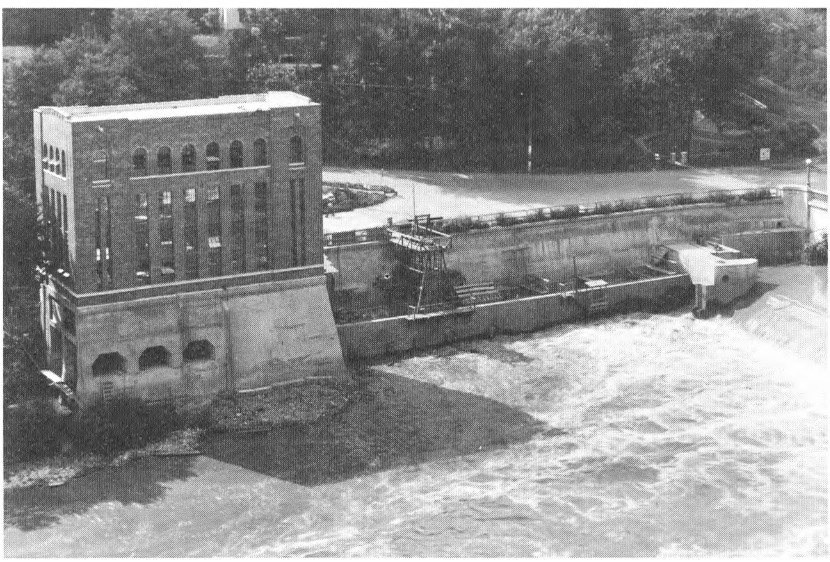

Figure 2. Hydraulics laboratory in 1929.

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A large constant-head tank in the top story and a circulating water system permitted experimentation on all floors. In addition to the continued large-scale experiments in the river channel, this new facility ushered in an era of small-scale model testing and, accompanying this, a new level to the national attention given to the work being done at the University.

In 1929 the U.S. Army Corps of Engineers rented quarters at the laboratory, in order to begin an extensive program of model studies on dams, spillways, locks and navigation problems.

The broadening scope and complexity of problems being undertaken by the laboratory personnel prompted the formal organization of the Iowa Institute of Hydraulic Research in 1931. It afforded an agency for the coordination of talent, facilities and resources available throughout the University to be brought to bear on problems in hydrology and hydraulic engineering. The Institute as an organization consisted of a research staff, a board of consultants drawn from other departments of the University and an advisory committee of prominent practicing hydraulic engineers. Although an integral part of the Engineering College, the Institute at the same time functioned as a separate entity in the negotiation of agreements and contracts with persons, organizations or governmental agencies. The staff was headed by Professor Nagler as Director, and D. L. Yarnell and M. E. Nelson as Associate Directors. University Consultants were Professors S. M. Woodward, hydraulics; B. J. Lambert, structures; A. C. Trowbridge, sedimentology; G. W. Stewart, physics; H. L. Rietz, mathematics; and Edward Bartow, chemistry. The original Advisory Committee consisted of the following well-known engineers: Dean Clement C. Williams (Chairman), Nathan C. Grover, LeRoy E. Harza, Robert E. Horton, Ivan E. Houk, Samuel H. McCrory, Arthur E. Morgan and George R. Spalding.

The new facilities were soon overtaxed by the new work that was at once attracted. Accordingly, tentative plans for a still larger building were soon begun. The need for revised and improved plans was frequently stimulated, as the demand for space saw experimental setups encroaching on places never intended for such use.

In 1930 and shortly thereafter it was found possible to construct part of the foundation for such a new laboratory. A boost to river-channel research occurred with the installation of a second 16-foot-wide channel supplied by a 48-inch steel pipe extended southward from the dam, and other improvements, including a motor-driven headgate.

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1932 saw the realization of a $50,000 laboratory addition — a six-story central tower section and another four-story wing to the south. As shown in Figure 3, the Hydraulics Laboratory appeared then much as it does today. The 10-foot river channel was extended to 311 feet and the 16-foot channel to 120 feet. Maximum river-channel capacity was 1000 cfs, pumped supply was 25 cfs under 50 feet of head, and the total laboratory floor area was now 36,230 square feet. A vestige of our heritage, a pair of century-old, well-preserved mill stones rescued by the director were chosen to grace the foyer of the new addition to the Institute.

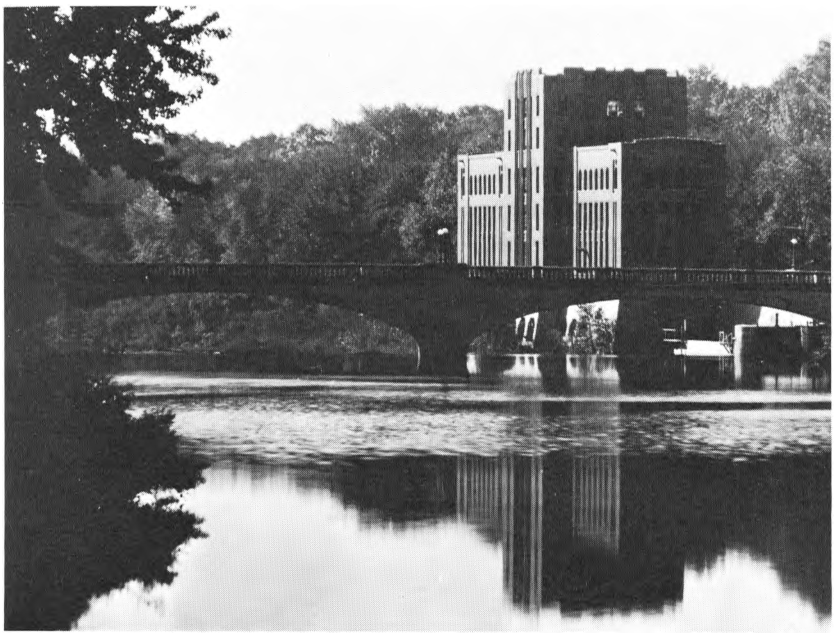

Figure 3. Hydraulics laboratory in 1933.

Near the peak of his career in 1933, Professor Nagler succumbed to a sudden illness. In a 20-year period he had become a nationally recognized authority on river and drainage problems and was clearly responsible for the initial vigorous growth of the Iowa Institute of Hydraulic Research.

Following the untimely death of Professor Nagler, Dean Williams assumed the directorship of the Institute and made Professor F. T.

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Mavis Associate Director in charge of the laboratory. Under Professor Mavis there was a great increase in graduate work, and the problem of sediment transportation began to receive attention. Dean F. M. Dawson replaced Dean Williams as Dean of the Engineering College and Director of the Institute in 1936, and the following year Professor E. W. Lane became Associate Director in charge, Professor Mavis having decided to devote all his time to the Mechanics and Hydraulics Department. Under Professor Lane's guidance an intensification of sediment studies occurred, culminating in a project carried on cooperatively with six government agencies.

Late in the decade Professor Mavis conceived the idea of hosting a professional meeting devoted to the specific needs of hydraulic engineers. The resulting event took place in 1939 and brought together nearly 250 engineers in a four-day meeting. Twenty-one papers summarizing current knowledge on various aspects of hydraulics were presented by recognized authorities in the field, and were later published as the *Proceedings of Hydraulics Conference,* Bulletin 20, Iowa Studies in Engineering. The desirability of continuing the effort was recognized by all, and over the next 20 years six more such conferences under Institute sponsorship were to appear.

With the onset of war in 1941, the Army and Navy turned to many of the University laboratories for technical assistance. Institute contributions included research on the drag of stationary ships in flowing water; air-tunnel studies of fog dispersal for military airfields, the diffusion of smoke and gas in urban districts, and wind structure over mountainous terrain; water-tunnel investigations of cavitation around undersea bodies; and the development of fire monitors for naval vessels. After the cessation of hostilities, several of the government agencies, realizing the value of fundamental research, continued their support of Institute research.

Professor Lane was granted a two-year leave of absence in 1942, and Professors Hunter Rouse and A. A. Kalinske were appointed associate directors, the former being placed in charge of Institute activities. When in 1944 Dean Dawson resigned as Director of the Institute, Professor Rouse was appointed to that position.

Professor Rouse had come to the Institute in 1939, having previously spent three-year periods engaged in teaching and research at Columbia University and at the California Institute of Technology. At the Institute he ushered in an era in which new emphasis was added in research

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contributions to the understanding of fluid motion.

At the time of his appointment the original plan of organization of the Institute was modified to consist of the active staff, drawn from the College of Engineering, and a single board of consultants, chosen primarily from organizations outside the University.

Three more hydraulics conferences were held in the 1940s in which Professor Rouse began the practice of proposing a theme to encourage an in-depth discussion. The second meeting, held in 1942 under wartime conditions, suffered somewhat in attendance but by no means in excellence. Twenty-four papers, devoted to the applications of fluid mechanics in many interrelated fields, were presented and published as the *Proceedings of the Second Hydraulics Conference,* Bulletin 27, Iowa Studies in Engineering. Attendance in 1946 rose to 325 as 24 papers were presented with the general theme of post-war applications of war research. These papers were published in the *Proceedings of the Third Hydraulics Conference,* Bulletin 31, Iowa Studies in Engineering. The fourth conference, held in 1949 with 425 in attendance, was devoted to a discussion of a major textbook in hydraulic engineering. Under the editorship of Professor Rouse, 13 authors contributed chapters in their particular areas of expertise, and a year later, the 1,000-page volume, *Engineering Hydraulics,* was published by John Wiley & Sons.

The last major laboratory expansion began in 1947 with the announcement for the planned construction of a hydraulics laboratory annex, the major anticipated role of which would be an expansion and continuation of sediment transport studies. Furthermore, a large air tunnel for the investigation of boundary-layer phenomena was to be included. The one-story concrete block structure, approximately 70 feet by 120 feet in plan, was completed a year later at a cost of $92,000. The expansion, together with the office space vacated by the closing of the Iowa City suboffice of The Corps of Engineers, almost doubled the amount of laboratory space available.

Declining activity in the use of the river channels allowed the 10-foot channel to be covered and converted into a towing tank 300 feet long, 10 feet wide, and nine feet deep. Construction, begun in 1954, was completed in 1957, and, together with the variable-speed drive, towing carriage and other appurtenances, represented a cost of $127,000.

Shortly thereafter, demand for research space took precedence over the occasional need for the second river channel. The channel area has since been taken over by a variety of apparatus.

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The Fifth, Sixth and Seventh Hydraulics Conferences, averaging in attendance in excess of 200 engineers, were held in 1952, 1955 and the last in 1958. With the themes sediment transportation, flow measurement, and agreement between prototype and model behavior, these collected papers have been published respectively in Bulletins 34, 36 and 39, Iowa Studies in Engineering. It was the consensus of the Institute research staff that the need that these conferences were once intended to meet was now being served by many national organizations, and thus they were discontinued.

Professor Rouse organized exchange visits between five Russian and five U.S. directors of hydraulic engineering laboratories in 1961-62. In 1965 he began a similar exchange with hydraulic engineers in Japan on the subject of instrumentation.

The summer of 1965 brought about 100 participants for the three-day Iowa Hydraulics Colloquium, a meeting part professional and part reunion. A series of round-table presentations were made by alumni of the college and former associates of the Institute and followed by discussions at large. The discussion topics were educational trends, current research, instruments and facilities, and computer potentialities.

In 1965 Professor Rouse accepted the invitation of Iowa's College of Engineering to become its Dean. In over 20 years as Director of the Institute, Professor Rouse acquired international renown as an educator and researcher. He contributed to and edited a number of textbooks which guided several generations of engineers in their mastery of fluid mechanics. Dr. Rouse stressed the dual role of research and education in the post-graduate education of hydraulic engineers and personally supervised 35 doctoral students in their dissertations.

Professor J. F. Kennedy succeeded Professor Rouse as Director of the Institute in 1966. With advanced degrees from California Institute of Technology, he had most recently been associated with the Hydrodynamics Laboratory at the Massachusetts Institute of Technology. Operating in a period when research funds are tight, Professor Kennedy has managed to maintain a judicious balance of basic and applied research.

Organized jointly by Professor Kennedy and Dean Tokio Uematsu of Osaka University, the U.S.-Japan Seminar of Similitude in Fluid Mechanics took place in 1967. The program consisted of visits to four U.S. universities by 12 Japanese delegates, where they were joined by representatives of a U.S. delegation for laboratory tours, presentation of short papers and informal discussions.

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In 1967 an IBM 1801 Data Acquisition System was installed at the Institute. Since a more complete description of the new computer is included elsewhere in this bulletin, suffice it to say here that it has had an impact on virtually every phase of the Institute's research program.

A low-temperature flow facility, also detailed elsewhere in this bulletin, was added in 1970. Consisting of a 40-foot-long refrigerated flume, housed in a temperature-controlled room, it became the first such laboratory-controlled research facility of its kind in the Western Hemisphere.

The present organization of the Institute consists of a senior professional staff of 12 research engineers drawn from the Department of Mechanics and Hydraulics, 25 research associates and assistants who are concurrently pursuing advanced degrees, and a staff of 11 support personnel consisting of secretaries, shop supervisor, machinists, carpenters, welders, and electronics technicians.

The Institute is headed by the Director, who is ultimately responsible for all Institute endeavors, including staff activities, laboratory facilities, research procedure, reports and finances, and who also pursues his own research and teaching program. Research engineers directly supervise the various Institute projects and graduate student investigations, and usually share a joint teaching appointment with the College of Engineering. Research associates and assistants conduct the actual tests and evaluate the results of experiments and frequently choose to prepare their theses on the same subjects to which they have become allied through their research appointment.

Current Research Activities

The most important change in hydraulic research at the Institute during the last decade has been the introduction of automatic collection and reduction of data with the IBM 1801 Computer owned by the laboratory. The effect of the computer on all research projects has been so dramatic that special attention must be focused on this facility.

Many data points representing pressures, elevations, or velocities may be read in a fraction of a second. Thousands of such data points may be stored immediately in the memory of the computer, and half a million more may be stored on a rapid-access magnetic disk. The result of this is the ability to obtain discretized records of rapidly varying processes, such that further numerical reduction and manipulation of the information proceeds quickly and smoothly.

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Using the computer, the wave system generated by a moving ship model is obtained from readings of the wave elevation every hundredth of a foot or less. The information, punched on cards, may be used to determine the wave resistance of the model, and the frequency spectrum of the wave system. In past years, reading wave elevations from a strip chart would take days or weeks, where now it is done in seconds. The result is obvious: the number of experiments performed is increased by 10 to 50 times. Many more variations on a specific experiment may be performed and verification of experimental results is no longer a task as difficult as the original experiment.

Complete surveys of a sand bed may now be taken, where previously only one or two profiles were possible. Using an echo sounder, the sand bed elevations often may be obtained without stopping the channel flow. This allows the experiment to continue uninterrupted and without the physical changes which accompany starting and stopping the flow in a movable-bed model.

By using a magnetic-tape recorder, similar bed profiles may be obtained in the field. The computer's unique ability to sample the recorded profile at a later time, but in sychronization with the recorder, results in extremely accurate data.

In the field of sediment transportation, the 1801 system has made it possible to determine the periodic nature of sediment motion under a breaking wave. The technique is called signal averaging, and involves synchronizing the computer to the wave cycle. Several thousand readings are taken in each wave cycle and each reading is averaged over hundreds of cycles. The final result is a clear picture of the time history of the phenomenon. Using the electro-optical sediment analyzer described in this report, this technique has been used to study the temporal behavior of suspended-sediment particles under the breaking wave.

The computer has been used in the study of diffusion and dispersion of tracer materials in many different experiments, in the rapid scanning of several pressure tubes in the wake of a moving body, and in simultaneous readings of temperatures from as many as 14 thermistors in two laboratory studies of thermal pollution.

Two additional examples which illustrate the flexibility of the computer require special note. The first is the ability to compute correlation coefficients of fluctuating signals in real time. The pressures near a rapidly vibrating structure, or the instantaneous velocities in a turbulent region, may be used as they are sensed to compute both spatial and tem-

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poral correlations. Several different correlation coefficients may be computed from several simultaneous readings.

The last example has only recently shown its future possibilities. The computer is capable of generating signals as well as recording them. This allows the experimenter to program the computer to respond in different ways to various experimental situations, and to modify the experiment while in progress. This technique is being used to control the actions of a model of the human intestine, and allows the experimenter to quickly adjust the model to the desired response.

The computer facility has certainly changed both the texture and thrust of the experimental process at the Institute during the last decade, but other changes in experimental philosophy have also taken place. This decade has witnessed an enormous interest in the problems of our environment. Fluid mechanics is at the heart of many environmental issues, such as thermal pollution of rivers subjected to the thermal load of nuclear power plants. The laboratory has responded to the concern for ecology by pursuing several projects in this area. The hydraulic characteristics of cooling towers have been studied in detail. Models of these towers have been tested both in water and in air.

Through these and other studies of environmental problems, the Institute will continue to play an important role in the meaningful application of engineering technology to our nation. Basic research and engineering practice continue to be independent, and the Institute continues to stress the desire to make all hydraulic research pertinent to the needs of society.

Institute Personnel

During the past half century 53 senior staff members have participated in the guidance of the hydraulic research at the The University of Iowa. In order to show the names of those who have been active in this role, a chronology of the senior staff members, past and present, is presented in Figure 4, with a solid black bar spanning each person's years of service. For those cases in which a person was also associated with the Institute as a graduate student, an open bar is used to denote that period. The lengths of stay of the various government agencies which have been located at the Institute are included, along with an indication of some of the more important historical highlights during the development of the Institute.

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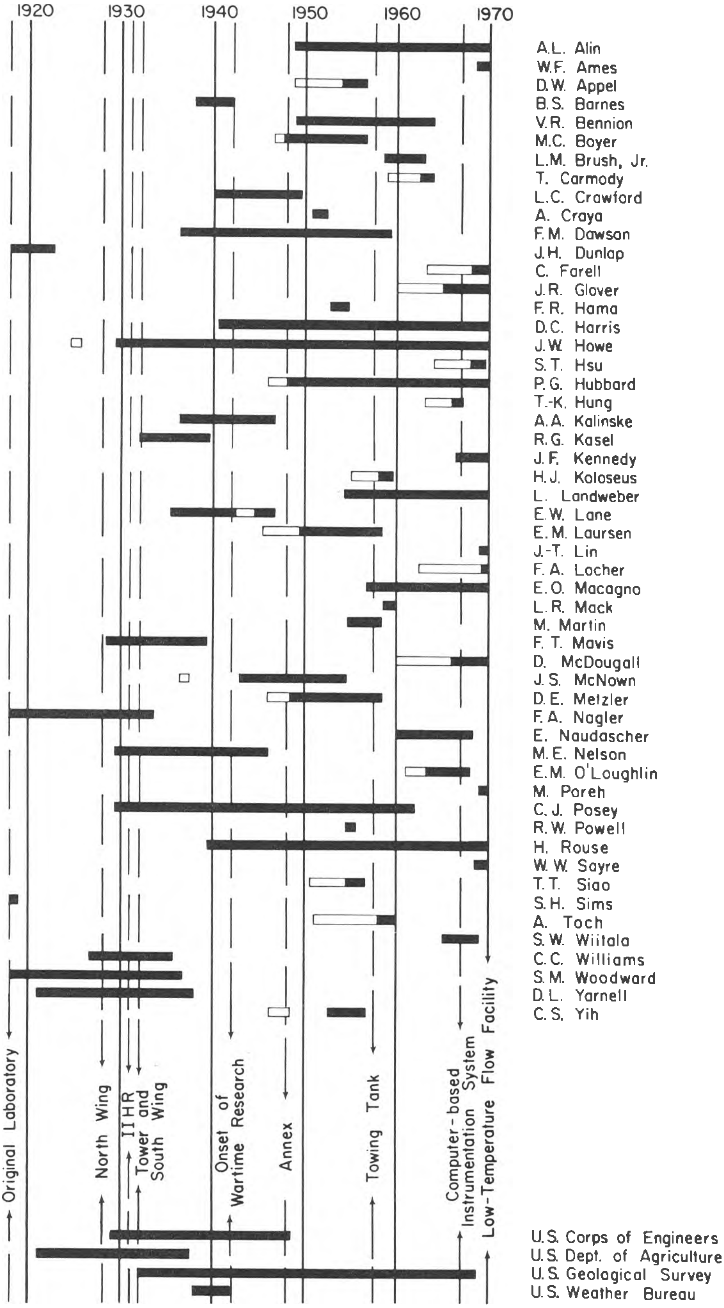

Figure 4. Bar graph of Institute personnel.

Board of Consultants

During the period that Professor Rouse was Director of the Institute, he sought the advice of a nine-member Board of Consultants, who were selected from organizations usually outside of the University. The Board was composed of prominent engineers and scientists from various parts of the country who were chosen because of their interest in or direct association with the research activities of the Institute. Their three-year terms of service were so arranged that one-third of the membership would change each year. The function of the Board was always purely advisory, directed primarily toward the strengthening of the research program and the development of outstanding conference sessions. All of those who have served as members of the Board are listed below, both as a matter of historical interest, and to show the diversity of the organizations with which the Institute has been in contact.

1946

W. F. Durand, Stanford University
L. A. Jones, Soil Conservation Service
C. G. Rossby, University of Chicago

1946-47

B. A. Bakhmeteff, Columbia University
W. G. Hoyt, U.S. Weather Bureau
H. U. Sverdrup, Scripps Institution of Oceanography

1946-48

H. O. Croft, State University of Iowa
G. A. Hathaway, Corps of Engineers
H. E. Saunders, David Taylor Model Basin

1947-49

H. L. Dryden, National Advisory Committee for Aeronautics
M. E. Nelson, Corps of Engineers
K. E. Schoenherr, University of Notre Dame

1948-50

M. L. Nichols, Soil Conservation Service
C. G. Paulsen, U.S. Geological Survey
G. B. Schubauer, National Bureau of Standards

1949-51

B. A. Bakhmeteff, Columbia University
Carl F. Izzard, Public Roads Administration
W. H. Leahy, Office of Naval Research

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1950-52

V. R. BENNION, U.S. Geological Survey
MARK MORRIS, Iowa State Highway Commission
J. B. TIFFANY, Waterways Experiment Station

1951-53

PIERRE DANEL, Etablissements NEYRPIC
MINA REES, Office of Naval Research
F. H. TODD, David Taylor Model Basin

1952-54

ADOLPH J. ACKERMAN, Consulting Engineer
PAUL C. BENEDICT, U.S. Geological Survey
RICHARD R. TIPTON, Bureau of Public Roads

1953-55

CARROLL H. DUNN, Waterways Experiment Station
W. E. JONES, Iowa State Highway Commission
G. B. SCHUBAUER, National Bureau of Standards

1954-56

V. R. BENNION, U.S. Geological Survey
PHILLIP EISENBERG, Office of Naval Research
C. J. MCLEAN, Commonwealth Edison Co. of Chicago

1955-57

W. H. LEAHY, Office of Naval Research
MARK MORRIS, Iowa State Highway Commission
GLEN G. POWERS, Iowa State Conservation Commission

1956-58

CARL F. IZZARD, Bureau of Public Roads
C. A. LEE, Kimberly-Clark Corporation
J. B. TIFFANY, Waterways Experiment Station

1957-59

ROLLAND W. CARTER, U.S. Geological Survey
JOHN B. PARKINSON, National Advisory Committee for Aeronautics
E. A. WRIGHT, David Taylor Model Basin

1958-60

V. R. BENNION, U.S. Geological Survey
D. C. BONDURANT, Corps of Engineers
H. M. MARTIN, Bureau of Reclamation

1959-61

PHILLIP EISENBERG, Hydronautics, Inc.
MARK MORRIS, Iowa State Highway Commission
E. S. TURNER, National Research Council of Canada

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1960-62

R. D. Cooper, Office of Naval Research
J. B. Tiffany, Waterways Experiment Station
Melvin R. Williams, U.S. Geological Survey

1961-63

S. G. Holt, Consolidated Water Power & Paper Co.
Donald F. Peterson, Rock Island Arsenal
Raymond Seeger, National Science Foundation

1962-64

V. R. Bennion, U.S. Geological Survey
D. C. Bondurant, Corps of Engineers
James J. Murray, Army Research Office

1963-65

Frank B. Campbell, Waterways Experiment Station
Rex A. Elder, Tennessee Valley Authority
Stephen E. Roberts, Iowa Highway Research Board

1964-66

Patrick Leehey, M.I.T., Dept. of Naval Architecture and Marine Engineering
Ralph D. Cooper, Dept. of the Navy, Fluid Dynamics Branch
C. M. Stanley, Stanley Engineering Company

1965-67

Jacob Douma, U.S. Corps of Engineers
H. Garland Hershey, Iowa Geological Survey
Ralph D. Cooper, Office of Naval Research

1966-68

William E. Cummins, Naval Ship Research and Development Center
Jacob E. Fromm, International Business Machines Corporation
S. W. Wiitala, U.S. Geological Survey

1967-69

Francois M. Abboud, University of Iowa Hospitals
Roy E. Oltman, U.S. Geological Survey
Gerald T. Orlob, Water Resources Engineers, Inc.

1968-70

James Christensen, University of Iowa Hospitals
Donald A. Parsons, USDA Sedimentation Laboratory
Thorndike Saville, Jr., U.S. Corps of Engineers

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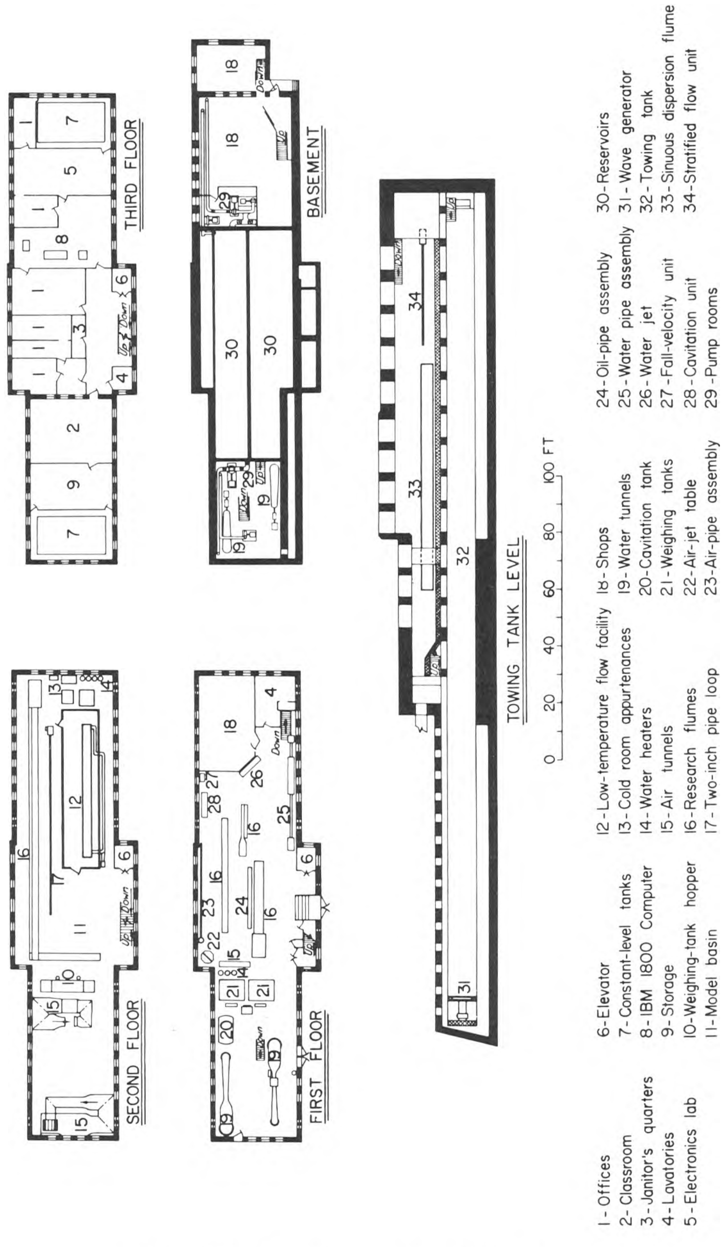

Figure 5. Plan view of main laboratory.

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PHYSICAL PLANT AND EQUIPMENT ADDITIONS

No major construction effort took place during the past decade, but the internal layout of the laboratory space has undergone considerable change in order to accommodate many new research endeavors. A plan view of the main laboratory structure is shown in Figure 5, displaying how the laboratory space is currently being utilized. Most of a former model basin on the second floor has now been taken over by a new pipe loop assembly and a new low-temperature flow facility with accompanying refrigeration equipment; the old 16-foot channel now accommodates studies on dispersion and stratified flow; a wave generator has been added to the towing tank; and the new IBM 1801 Data Acquisition System occupies a spot on the third floor. Figure 6 reflects similar changes in the laboratory annex. Scour-channel facilities have been reduced in favor of a large meander flume, and a wave tank and a small air tunnel have been added.

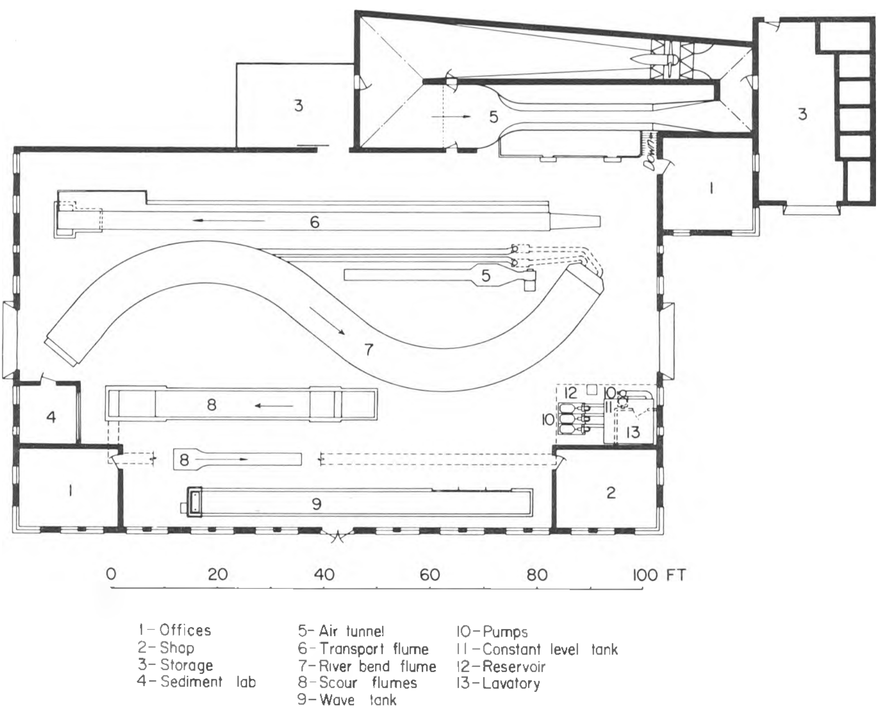

Figure 6. Plan view of laboratory annex.

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Low-Temperature Flow Facility

The low-temperature flow facility is depicted schematically in Figure 7, which shows the flume, pumping systems and related piping, refrigeration and heating systems, and cold room. The working section of the facility consists of a rectangular-cross-section flume, 40 feet long, two feet wide and one foot deep. The flume is mounted on a tilting truss supported on a pivot near the downstream end and on a motorized jack near the upstream end; the slope can be varied from zero to 2.2 percent. Flow enters the flume through a vaned inlet section and moves along the working section and into a stationary outlet sump, which is attached to the tilting flume by means of a rubber connection. From the sump the flow passes to the intake of an axial-flow pump, which is driven by a variable-speed motor, and then through the eight-inch-diameter return line, calibrated Venturi meter, flexible hose connecting the return line to the inlet section, and thence through the inlet and back into the flume. The maximum discharge attainable is 3.1 cfs. The discharge can be reduced to any desired value by means of the variable-speed motor and removable baffles in the sump outlet. The speed of the pump motor is remotely controlled from either inside or outside the cold room.

The flume walls and floor were constructed from specially fabricated steel heat-transfer plates. Each 10-foot-long wall and floor panel is connected separately to the coolant inlet and outlet manifolds. The six coolant passages in each wall cross section consist of a pair of parallel passages which make three traverses of the panel length. Each wall panel is connected to its intake and outlet manifolds by two inlet and two outlet hoses; these are valved such that either the upper, middle, or lower pair of passages, or any combination of these, may be turned off. The twelve coolant passages in each ten-foot-long floor panel are connected in parallel. These are connected to the same manifolds that supply coolant to the wall panels.

The outside of the plates is insulated with two inches of polyurethane insulation board, which is covered with three-quarter-inch-thick plywood. One-inch-diameter rails mounted on the flume walls support the motorized instrument carriage. Both the flume and the rails are supported on leveling bolts, so that the vertical alignment of each can be adjusted.

The coolant circulated through the flume boundaries is a 50 percent solution of ethylene-glycol base, rust-inhibiting anti-freeze. The coolant is distributed to the flume panels by means of three inlet manifolds, one

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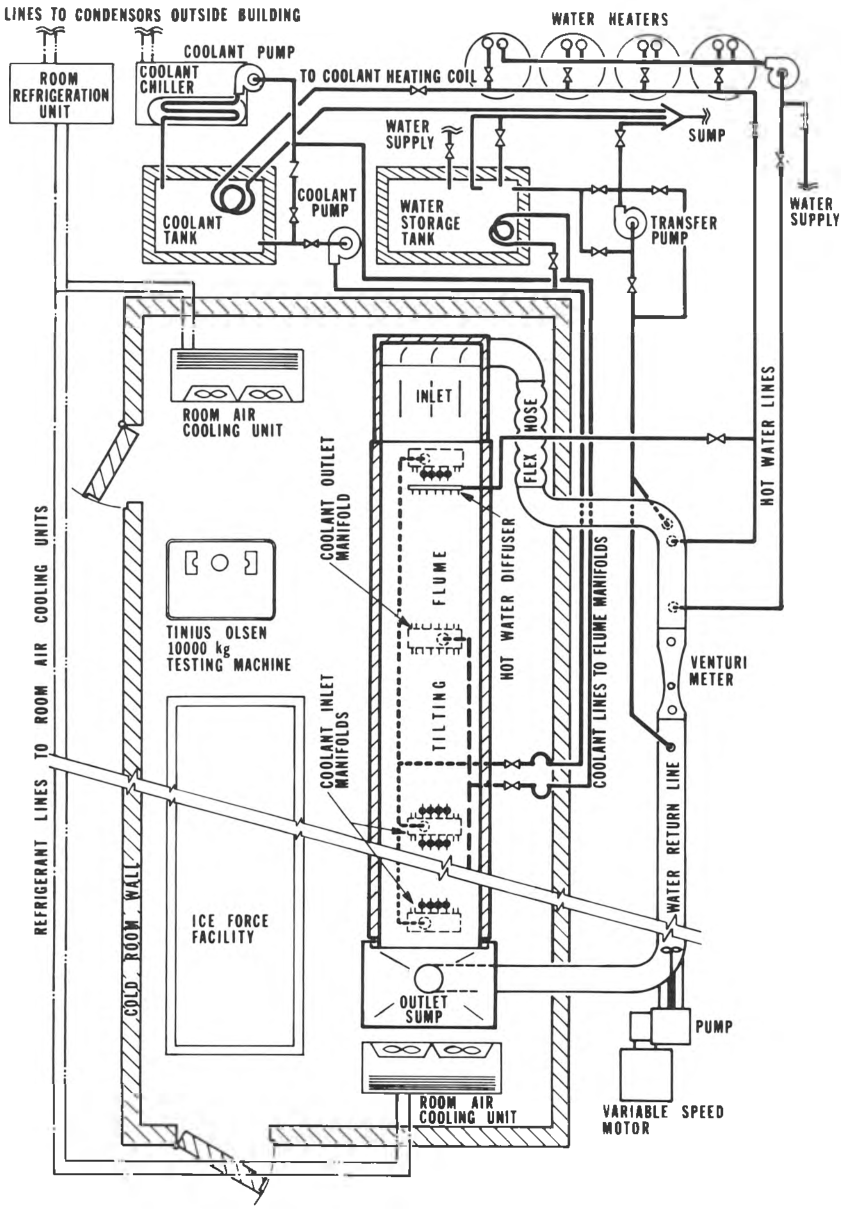

Figure 7. Plan view of low-temperature flow facility.

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near the center and one near each end of the flume. After passing through the panels the coolant is collected through the two outlet manifolds, one located at 10 feet from each end of the flume.

The coolant chiller is a 10-horsepower packaged liquid cooling unit. The outlet temperature is thermostatically controlled and can be maintained to within about 0.5°F at any desired level from 10°F to 30°F; the corresponding heat-transfer capacities of the cooler are 52,000 BTU/hr to 96,000 BTU/hr, respectively. The liquid cooling unit is equipped with a centrifugal pump which circulates the coolant through the chiller and the 500-gallon coolant storage tank. A second centrifugal pump circulates the coolant through the flume heat-transfer panels. The pumps may be operated independently. The design discharge for coolant was 60 gpm, with either both pumps running and coolant circulating through the plates, chiller and tank, or with just the chiller-unit pump circulating coolant through the chiller and tank.

The four gas-fired water heaters shown in Figure 7 have a combined heat-transfer capacity of 300,000 BTU/hr. Their function is to heat either the flume water or the coolant, to accelerate the melting or ablation during experiments concerned with these aspects of ice behavior.

An insulated tank located outside the cold room (see Figure 7) provides storage for chilled water. This tank makes it possible to drain the flume, in order to measure ice accumulation or configuration, or, when the flow is stopped overnight, to later refill it with water whose temperature is only slightly above the freezing point.

The insulated room in which the flume is installed is 54 feet long, 12 feet wide, and eight and one-half feet high. The walls and roof of the room are insulated with eight inches of polystyrene insulation board, and the floor with four inches of polyurethane board covered with a two-inch concrete wearing surface. The refrigeration system for the room consists of a 7.5 horsepower compressor, two 12,500 BTU/hr (at a temperature differential of 10°F) dual fan evaporators and a condenser. Room temperature is thermostatically controlled; temperature variations do not exceed ±0.5°F from the thermostat setting. The two-stage thermostat activates either one or both evaporator units, depending on the difference between the room temperature and thermostat setting. The fans of one evaporator unit operate continuously (except during defrost) to maintain uniform temperature throughout the room. The design minimum temperature for the room was -20°F, and during a test run with no water present in the flume a temperature of -22°F was attained.

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The minimum temperature obtained for a given heat-transfer rate is, of course, heavily influenced by the amount of water present in the flume, its temperature and state of freezing, and the rate of evaporation from the flume water and consequent frosting of the evaporator coils. Room temperatures down to about -10°F can be obtained under all operating conditions. Because of the high humidity in the room, the evaporator coils rapidly become ice-covered. A defrost period (during which the coils are electrically heated) of at least 20 minutes every six hours is required to keep the coils acceptably ice free.

The water-return line, coolant lines, refrigerant lines, drain-fill lines, etc., are all insulated as required to prevent condensation and frosting.

Recirculating Pipe Loop

The Institute's recirculating pipe loop was constructed in 1968. Figure 8 presents a schematic diagram of the facility as equipped for experiments on sediment transport in pipes. The loop was fabricated from stainless-steel pipe with an inside diameter of 2.125 inches. It consists of the working section, return section and two vertical sections, one of which passes through a reservoir tank, as shown in Figure 8. A section of pipe just above the bottom of the tank is fitted with a sliding sleeve, which fits sufficiently tightly that sediment cannot escape from the pipe but water can flow freely between the tank and the pipe loop; hence, the reservoir tank "floats" on the system. A butterfly valve located in the sleeve maintains positive pressure in the working section. A funnel connected through a gate valve to the downstream of the working section is used to introduce sediment into the circuit for solid-liquid flow experiments.

The fluid is circulated through the loop by means of a centrifugal pump driven by a 1.5 horsepower motor through a stepped-cone pulley. The discharge can be adjusted in discrete steps by changing the pump speed by means of the pulleys, and further regulation is achieved with the butterfly valve and gate valve installed in the return section. Discharge is measured with the calibrated Venturi meter located near the downstream end of the return section of the loop. Four piezometer rings are provided at intervals approximately 20 feet along the working section; each ring consists of four interconnected piezometer taps at 90-degree intervals around the pipe. For dispersion experiments saline tracer can be injected into the flow from an air-pressurized reservoir through the piezometer rings. Ports are provided at each piezometer-

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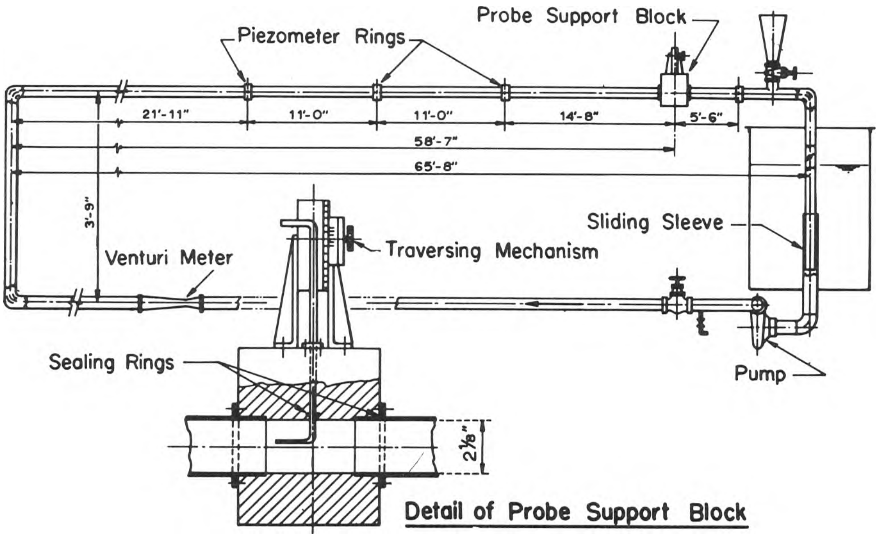

Figure 8. Diagram of recirculating pipe loop.

ring section for insertion of a salinity probe, Prandtl tube, sediment sampling tube or other sensor.

Large Meander Flume

The large, curved, recirculating flume located in the Hydraulics Laboratory Annex (Figure 9) was constructed in 1962 with funds provided by the National Science Foundation. The channel cross section is a two-foot-deep rectangular section. The width of the flume is 10 feet. In plan form the channel consists of two 90-degree bends with a center-line radius of 28 feet connected by a 14-foot-long straight section. A seven-foot-long straight section is provided at each end of the flume. The overall length of the channel is 116 feet. The channel was fabricated from nine reinforced concrete slabs which are supported on 1.5-inch screw jacks embedded in concrete pedestals. Flume slope is adjusted by means of the screw jacks.

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Figure 9. Large meander flume.

Circulation is accomplished by means of two variable-speed pumps which return the water from the tail tank through two 10-inch-diameter pipes to the upstream diffuser. Discharge measurements are made by means of a streamlined contraction consisting of a curved plate welded into a four-inch recess cut into the side of each pipeline. The maximum discharge achievable is 12 cfs.

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Small Meander Flume

The small meander flume, located in the basement of the main Hydraulics Laboratory, has been used principally for investigations of dispersion processes in sinuous channels. This flume, shown in Figure 10, has

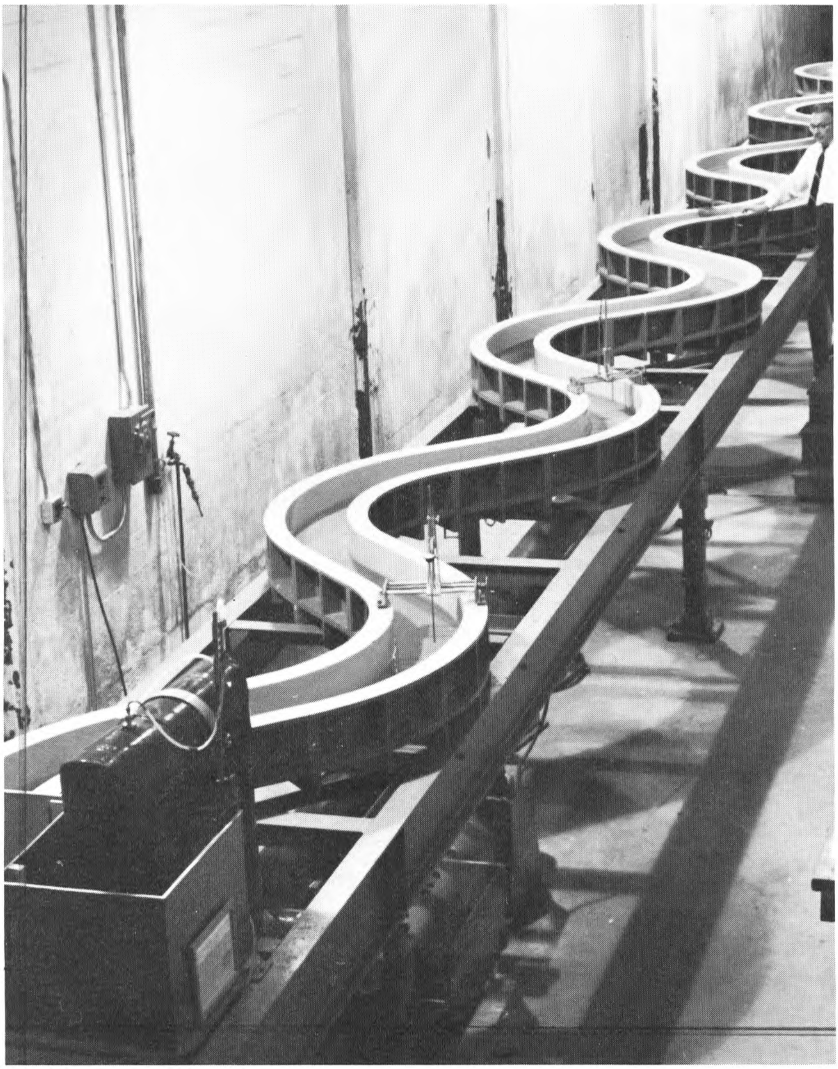

Figure 10. Small meander flume.

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a rectangular cross section that is 10 inches wide and eight inches deep, and a length, measured along the centerline, of 85 feet. In alignment, the flume has thirteen 90° three-foot-radius bends in alternating directions, that are linked by 18.75-inch-long straight reaches. The flume is mounted on a frame that is supported by manually-operated hydraulic jacks, so that the slope can be varied. The circulation system, which is closed, includes a headbox, a tailbox, an eight-inch-diameter return pipe, a centrifugal pump powered by a 0.5 h.p. variable-speed motor, a two-inch pipe orifice meter and a valve.

Drag-Reduction Facility

In order to study the phenomenon of drag reduction due to the addition of minute amounts of certain polymers, a closed-circuit one-inch inside-diameter pipe-flow facility has been constructed and equipped with a venturimeter, pressure taps for measuring the longitudinal pressure gradient and a pitot probe for measuring the velocity profile.

Wave Tank

The Institute wave tank is 65 feet long, four feet wide, and three feet deep. The walls are constructed of concrete blocks, except for a window section which extends over the full tank depth and 15 feet along one long wall near the end away from the wavemaker. The wavemaker consists of a triangular wedge with a slope of 1:2, which is oscillated vertically by a scotch yoke driven through a vee-belt drive by a five-horsepower variable-speed electric motor (U.S. Motors Vari-Drive). Wave amplitude is adjusted by altering the throw of the scotch yoke, while wave period is adjusted by means of the variable-speed motor. The wave tank is equipped with a motorized carriage, which rides on one-inch-diameter adjustable alignment rails affixed to the tops of the long walls.

Towing Tank

The towing tank, built in the 1950s, has acquired a five-horsepower plunger-type wavemaker driven through a scotch-yoke mechanism and situated at the north end of the tank. The plunger used is a two-foot by one-foot wedge with a vertical back face adjacent to a vertical bulkhead to assure that the waves are transmitted only in one direction. When the wavemaker is in use, it is necessary to lower the water level to avoid interference from the disturbance-damping 12-inch-wide boards along the walls, described in Bulletin 40. At the south end of the tank, a shallow beach, consisting of several layers of slotted wooden slats, is

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used to absorb the incoming waves and to prevent wave reflection.

A new drag dynamometer has been built employing a diaphragm with a strain gage as the force-sensitive element.

A trailer which can be attached to the carriage has been built to be used in wake-survey work. In viscous-drag tests the trailer is used to support a pitot rake, a Scanivalve and a pressure transducer. Electrical signals from the equipment on the carriage or trailer are transmitted through a cable, which rides in a succession of loops along an overhead trolley, either to recorders alongside the tank or to the IBM 1801 computer.

Ship-Model Construction

This refers to a capability rather than a facility. The fine craftsmanship required to build a wooden ship model from a given set of lines to a high degree of accuracy, and to coat it with a smooth waterproof finish, was found to be available in the Institute's shop staff. Several tanker models and a set of Series-60 models have been built by the staff.

Electronic and Mechanical Shops

The Institute's shop staffs construct practically all of the experimental apparatus, facilities, mechanical and electrical instrumentation, and models at the Institute, and take care of the maintenance of laboratory equipment. Special skills have been carefully developed through the years, and the shop personnel have acquired a remarkable capability to assist research engineers in their planning of new experimental units and facilities. The Institute also designs and constructs experimental equipment and instrumentation for other laboratories and schools in this country and abroad. The electronics shop is playing an ever-increasing role due to the application of modern procedures in the sensing of signals and the recording of data. This shop is also very useful to the instrumentation section of the Institute; the most important new instruments developed there are described under Instrumentation in the following chapter.

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REVIEW OF RESEARCH AT THE INSTITUTE

Accelerated Flows

Motivated by problems encountered in shock absorbers, a research effort which lasted almost 10 years was concentrated on the hydrodynamics of rapidly accelerated liquids. At the time the investigation was started, only calculations based on incompressible fluid flows had been developed. Based on the trends shown by experimental records, a first analytical method was set up which would take into full account the compressibility of the hydraulic fluids used in the shock absorbers. This method proved to be very accurate, but also extremely complicated, except for simplified situations (Reprint 175). A simulation of the accelerated flow of the compressible liquid was therefore based on the hypothesis that except for extremely rapid phenomena, the wave propagation would be unimportant. The compressibility was not eliminated, however, but was incorporated only in the continuity equations (IIHR Misc. Paper by Macagno and Ho, 1962; Report 113). The results for realistic impulse-time diagrams were in satisfactory agreement with the more exact theory and with the experimental records.

For a shock absorber in which a steel spring was included, a hydraulic analogy was used to develop a model for the spring, which was known to be subject to severe loading conditions for which the coils would coalesce into a solid mass. The model was confirmed by laboratory experiments. The results of these last studies have been described in detail only in laboratory reports (IIHR Reports 112, 113).

Biomechanics

Among the Institute endeavours in the area of Biomechanics, the hydrodynamics of flow in the lower urinary tract is presently the subject of a joint research effort with the Department of Urology of the College of Medicine (Report 122). In a different field, a study of swimming, jointly with the Department of Physical Education, is now getting under way.

For the past two years an investigation of the fluid mechanics of the human small intestine has been conducted by personnel from both the Institute and the College of Medicine. This project had its origins in a

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general interest in biologically related fluid-mechanics problems and preliminary studies at the Institute of possible pumping mechanisms similar to those found in biological systems. The scope of this research has been narrowed and it is now supported by grants from the National Institutes of Health.

There are currently two main facets to this project. The first is an investigation of the movement of the wall of the small bowel. This involves studies of the size and shape of contractions as well as their distributions in time and space. The second, and more important to the Institute, is a description of the relationships between these contraction patterns and the resulting flow of the intestinal contents. This is being studied both analytically and experimentally. A computer-operated model of the small bowel has been constructed. The model can be controlled to simulate various contraction distributions, while the resulting transport and dispersion are studied.

Results to date include an estimate of the minimum length of contractions. The frequency distribution of contractions, as well as the joint frequency distribution of groups of contractions with rest periods, also have been obtained, by Christensen, Glover, Macagno, Singerman and Weisbrodt. Preliminary model studies have been conducted using single contraction and pseudo-random and simulated peristaltic contraction patterns, with the resulting fluid motion being observed. Future studies will involve the statistical spatial distributions of contractions. A detailed model study will also be undertaken, accompanied by a matching analytic model.

Boundary-Layer Studies

Studies of flat-plate boundary layers in the previous decade culminated in a reanalysis of flat-plate boundary-layer data by Landweber (Reprint 182), and an attempt to resolve a controversy concerning the calibration of Preston tubes. Following this work, and that on the effect of transverse curvature by Yu (Reprint 161), some three-dimensional boundary-layer measurements were undertaken. These consisted of shear stress and velocity-distribution measurements on an ellipsoid of three unequal axes, by Pavamani (see M.S. thesis).

For most of the remainder of the decade boundary-layer studies were displaced by investigations of wakes and jets in the wind-tunnel facility. In 1969, however, the facility once again became available for boundary-layer research, and a study of the thick boundary layer at the tail of a body of revolution was undertaken by Landweber and Satija (see 1971

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Ph.D. dissertation). Several procedures for computing three-dimensional boundary layers have been proposed, some of which have been applied to calculate ship boundary layers. Some of the assumptions of these procedures were reviewed by Landweber in the paper "Characteristics of Ship Boundary Layers", presented at the Eighth Symposium on Naval Hydrodynamics (IIHR Misc. Paper, 1970), and were found to be inconsistent with Pavamani's data mentioned above, as well as the available data on ship forms. The frequently employed small-cross-flow assumption is inconsistent with the generation of secondary flow and the occurrence of separation along the hull at the free surface discovered by Chow (see Ph.D. dissertation) and verified by Tzou (see M.S. thesis), and with the generation of the so-called bilge vortices near the bow, investigated by Tatinclaux (Reports 102, 107, 117, Reprint 270).

Cavitation

Studies of cavitation have proceeded along the lines of a number of earlier investigations. Bulletin 32, a postwar report on cavitation around various torpedo head forms at zero yaw, was supplemented by Bulletin 42, describing tests on many of the same head forms at various angles of yaw. The relation between cavitation and pressure fluctuation was determined for flow around bodies by Newsham (see M.S. thesis) and through conduit expansions (Reprint No. 204).

Classical Papers in Fluid Mechanics

By special arrangement with the French journal, *La Houille Blanche,* a series of selected works of classical authors is being published. The series is directed by Professor E. Macagno, who represents the Institute. Mr. Valembois (Chatou National Laboratory of France) is the French counterpart in the selection of authors to be included. Landmarks in dimensional analysis due to Fourier and Vaschy have already been published, matched by those of Galileo and Newton in similitude theory. Theoretical works have been represented so far by excerpts from Euler, Navier and Stokes, while experimental contributions of permanent classical value comprise publications due to Pitot and Smeaton.

The titles of the classical papers published in *La Houille Blanche* are listed in this Bulletin (p. 173).

Computational Modeling of Viscous Flows

Because sudden expansion presents the most striking situation of internal flow separation, both two-dimensional and axisymmetric flows through

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expansions have been investigated numerically. Complete forms of the Navier-Stokes equations were treated by numerical techniques based on the discretization of the equations. The captive annular eddy, resulting in the case of flow through an axisymmetric expansion, was studied in great detail, and the results of the calculation were compared with flow visualizations; the agreement between the analysis and the experimental result was very striking.

A second effort in this area referred to accelerated flows of viscous fluids through expansions; a third concerned the flows generated by moving a wall in a rectangular domain, or rotating a base in a region of fluid confined within a circular cylinder. An application was made to a case in which the fluid possessed a continuous density stratification.

DENSITY-STRATIFIED FLOW

The first studies of flow of fluids with density stratification were undertaken at the Institute during World War II. In the past decade the emphasis was mainly on flows with mass transfer which resulted in irreversible mixing. An investigation on the interfacial instability and on the subsequent mixing of two fluid layers of different density was carried out by Macagno and Rouse (Reprint 173). The thickness of the mixing zone and the rate of mass transfer across the interface were investigated as the Froude and Reynolds numbers of the flow were varied.

The stability of an enclosed stratified flow in the region of flow establishment was also found to depend on the Froude and Reynolds numbers of the flow. Macagno and Hinwood studied experimentally the interfacial instability and the subsequent mixing of the two fluids, which flowed from a large reservoir into a rectangular duct (Reprint 192). Hinwood developed a numerical simulation of this phenomenon, based on complete forms of the Navier-Stokes equations (Ph.D. dissertation, Reprint 241).

The behavior of a stratified fluid system, otherwise at rest, when a transverse flow cutting across the isopycnic lines is induced in the field, has been the subject of two investigations: Alonso (see M.S. thesis) studied experimentally the free-surface rotationally symmetric flow developed in a continuously stratified fluid contained in a cylinder with a rotating bottom; Aguirre-Pe (see M.S. thesis) extended this investigation to the case of a two-layered system. (See also paper by Aguirre and Macagno, 1969).

The flow in a rectangular cavity with a fluid with uniform density

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gradient was studied by means of numerical models, which would reproduce only the initial phases of the flow, as was confirmed by experiments. A study which referred to the mixing induced by the secondary flow in a 90° curve in an open channel was also completed during this decade.

In many estuarine harbours, under certain flow conditions, the ocean salt water flows upstream for an appreciable distance and forms a wedge of salt water underlying the river water. This salt-water wedge may greatly affect the pattern of sediment deposition in an estuary. This process was the object of an experimental study carried out by Hinwood, while working at the University of New South Wales (Reprint 196).

ENVIRONMENTAL FLUID MECHANICS

New areas of research at the Institute have developed in response to the growing national concern over the deterioration of the natural environment. The Federal Water Quality Administration has sponsored experimental studies on longitudinal dispersion and lateral mixing in meandering channels (see 1971 Ph.D. dissertations by Fukuoka and Chang). Various aspects of stratified flows have been investigated by Macagno, Rajagopal, and Alonso; they studied internal hydraulic jumps and stratified flow in a channel bend.

In the area of thermal pollution, the Marley Company has for several years sponsored an investigation on the performance of induced draft cooling towers, with particular emphasis on eliminating recirculation and optimization of the geometrical arrangement of clusters of cooling towers. The National Science Foundation and the Iowa State Water Resources Research Institute are supporting a basic investigation of the mixing of heated effluents in open-channel flow. More recently a thermal model study of the proposed condenser-cooling-water outfall system for the Quad Cities Nuclear Power Plant has been undertaken. Related to this is a field study on the effect of thermal discharge from the Quad Cities Plant on the distribution of temperatures and ice thicknesses in the Mississippi River.

An extensive thermal model study for the Commonwealth Edison Company of the cooling-water discharge system for the Quad Cities Nuclear Power Plant is currently underway. The originally proposed scheme, which involved the use of a wing dam as a training wall, was tested in a model of a reach of the Mississippi River and found to be unsatisfactory. This led to the design and testing of a diffuser pipe system, which involves two 16-foot-diameter pipes, with multiple ports,

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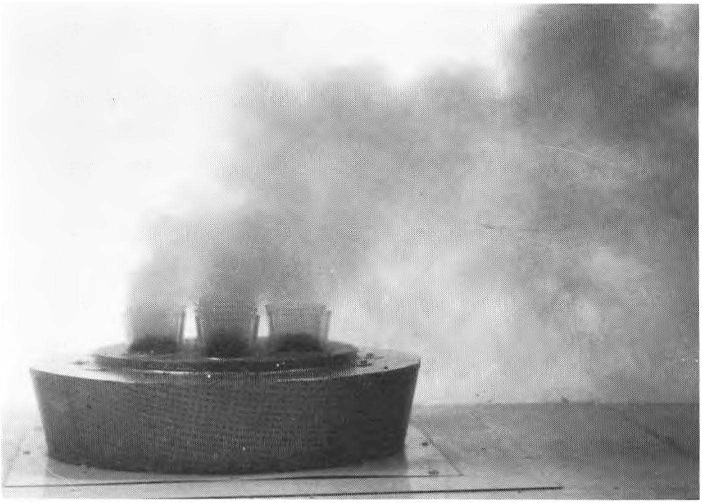

Figure 11. Effluent of cooling-tower model tested in water.

that extend nearly across the Mississippi River. Dr. Jain, Professors Kennedy, Sayre and McDougall, and Dr. Akyeampong have all been heavily involved in this project.

Related to the Quad Cities Nuclear Power Plant study is a field study of temperature and ice conditions in the reach of the Mississippi River to be affected by the thermal discharges from the plant. This investigation is under the joint direction of Professors Sayre and Kennedy.

The processes by which heated effluents are mixed with an ambient open-channel flow are being investigated in basic research studies sponsored by the National Science Foundation and the Iowa State Water Resources Research Institute. The main study objective is the region, downstream from the initial mixing zone, where ambient turbulence and velocity distribution play a key role in the mixing process. Professor Sayre is in charge of this investigation.

EDUCATIONAL FILMS ON THE MECHANICS OF FLUIDS

Near the beginning of the decade, with the aid of a grant from the National Science Foundation, the Institute undertook the preparation of a series of six motion pictures for use in teaching fluid mechanics to undergraduate engineers. The project was conceived and supervised by Hunter Rouse; he was assisted by members of the Institute staff and

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that of the Audiovisual Center of the University. Particular mention is due Lucien Brush, who collaborated on the first three films, and Emmett O'Loughlin, who did most of the camera work on the last three.

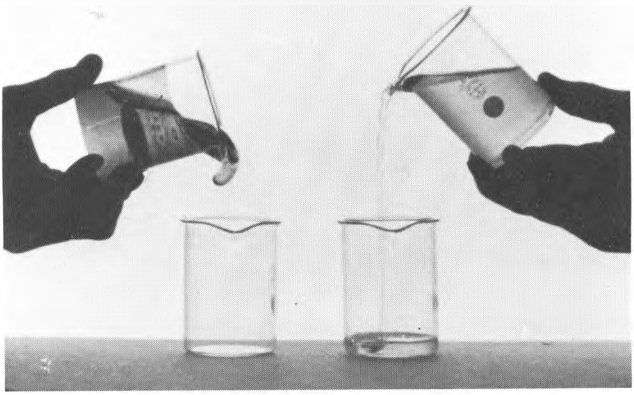

Figure 12. Frame from educational film comparing the rheological behavior of fluids.

The six films are as follows: *Introduction to the Study of Fluid Motion,* which stresses the great breadth of the subject, the necessarily close tie between theory and experiment, the role of the scale model in engineering analysis and design, and methods of flow measurement in laboratory and field; *Fundamental Principles of Flow,* including continuity, momentum and energy, and their application to typical problems in many professional fields; *Fluid Motion in a Gravitational Field,* which deals with jets, nappes, channel transitions, waves, surges and effects of density stratification; *Characteristics of Laminar and Turbulent Flow,* showing effects of viscosity, examples of laminar flow, characteristics of fluid turbulence and problems of surface resistance; *Form Drag, Lift, and Propulsion,* stressing phenomena of separation, their influence upon profile lift and drag, and application of the latter to principles of fluid machinery; *Effects of Fluid Compressibility,* such as water hammer, gravity-wave and sound-wave analogies, and supersonic drag.

All films are 16-millimeter, in full color, and carry an optical sound track. Their average length is some 20 minutes. An illustrated copy of the script accompanies each print; these films may be rented from The

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University of Iowa Audiovisual Center or purchased singly or together. To date 321 prints of one or another of the six films have been purchased by 114 institutions in 29 different countries. In several countries foreign-language sound tracks have been added magnetically to the films for alternative use.

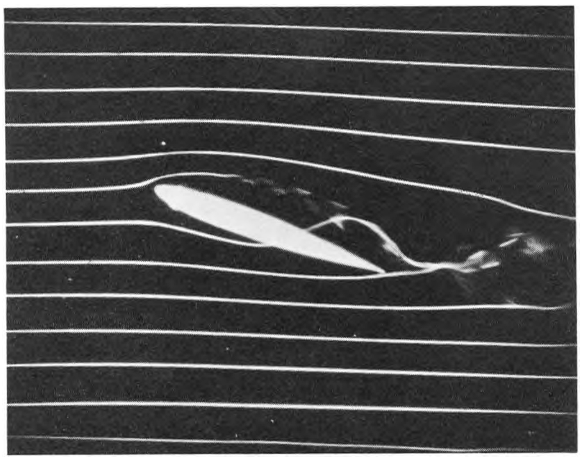

Figure 13. Frame from educational film showing streamlines at an airfoil tip.

HYDROLOGY

The recession characteristics of Iowa streams were studied by J. W. Howe late in the decade (Bulletin 43). The investigation was undertaken to help the State Water Commissioner predict the low-water flow of streams subject to minimum-flow regulations. Low-water periods from May to September were studied on all rivers having flow records with a recession period of 10 days or more in length. Recession constants were calculated at all stations and plotted on state maps for the different months. The variation in coefficients in large regions was small. A study was also made on the flow at the beginning of such recession periods, multiple correlations being made with area, preceding precipitation, mean air temperature and soil characteristics. Correlation coefficients varying from 0.95 to 0.97 were obtained with standard errors of estimate ranging from 0.25 to 0.59. Antecedent rainfall was found to have an extremely small effect; it could be eliminated from the regression equations with but slight modification of the exponents of

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the other parameters. The project was financed by the Iowa State Water Resources Research Institute.

The Ralston Creek hydrologic data-gathering project has been in continuous operation since June 1924. In the past decade, however, the south branch was put under observation by the U.S.G.S., who installed a control and recording gage at Muscatine Avenue in east Iowa City. The area above this gage was three square miles, the same as the area above the gage on the north branch. Thereafter, the Agricultural Research Service, noting the rapid spread of urbanization on the south branch, asked that rainfall observations on the south branch be collected, as has been done on the north branch. Accordingly, three recording rain gages were placed at points in the south branch drainage, so that a good coverage of rainfall on both branches could be secured. It happened that two of the rain gages on the north branch were on the divide between the two branches. These gages, thus, adequately covered both basins. This made it possible to put the new gages south of the stream itself, giving rather uniform Thiesen polygons for the entire area. The new gages went into operation in June 1967. In January 1971 the Weather Bureau agreed to publish the records of the three new rain gages, along with those on the north branch, so that, in the latter years of the decade, the flow and rain gage records are published by the U.S. Geological Survey and by the U.S. Weather Service in its monthly bulletins. The Institute's annual report includes the full spectrum of data beginning with 1967.

With the new coverage, a policy of securing annual photographs from a number of vantage points was initiated, and each May pictures are taken from identical locations looking across the valley. This gives a pictorial record of the increasing urbanization of the area. Pictures were also started on the north branch, in those areas where urbanization seemed likely. The annual reports contain 36 such pictures.

Ice Research

The Institute's ice research program began in 1968, when a grant was received from the National Science Foundation for construction of a recirculating flume housed in a temperature controlled environment (see Research Facilities). Design and construction of the facility, both carried out by Institute staff, required approximately 18 months. Research utilizing the facility began in early 1970.

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Figure 14. Recirculating flume in low-temperature facility.

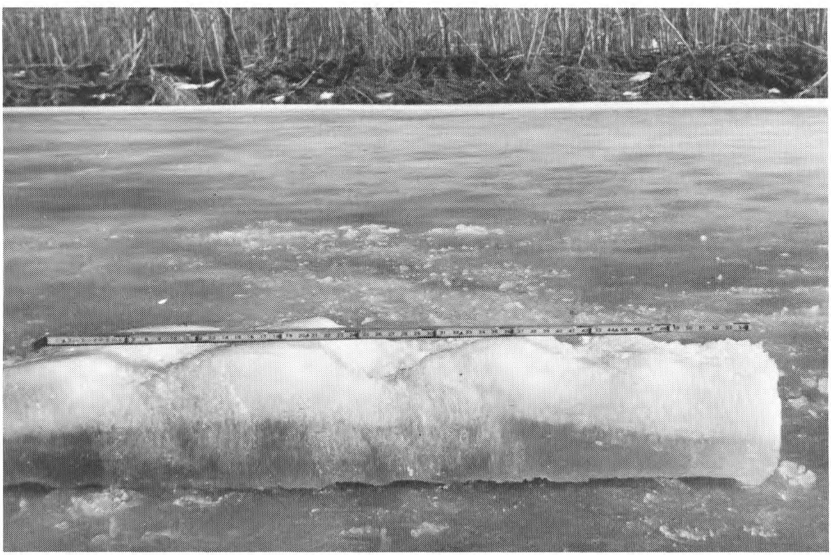

Figure 15. Inverted ice slab showing ice ripples

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During the winter of 1969-70 a program of field research was conducted on Cedar River and Iowa River. Vertical and lateral temperature and velocity distributions, and ice thickness and configuration, were

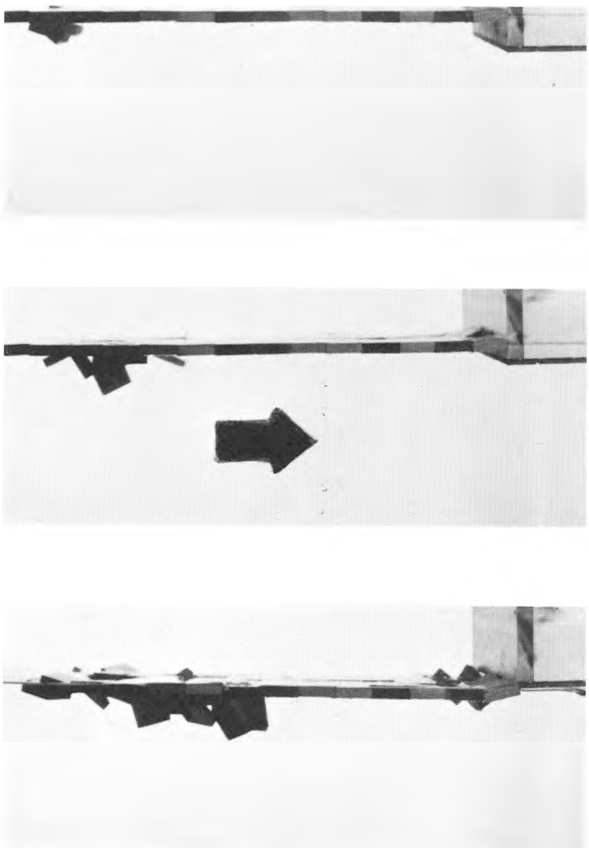

Figure 16. Model of ice jam development using square wooden blocks.

measured at frequent intervals during the ice season. The vertical variation of temperature was found to be extremely small, while lateral variations across the river channel frequently amounted to as much as 0.1°C. These lateral variations apparently resulted from geothermal input in the form of ground-water flow. The under surface of the ice

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was observed to remain plane as the ice thickened and to become wavy as the ice melted. Just prior to breakup the ice cover was observed to become very porous over its lower reaches. Ice melting was found to proceed more rapidly from below than above.

Two other investigations of ice were also initiated in 1969. The first was directed toward the mechanics of ice jams, while the second involved a theoretical investigation of the stability of the interface between an ice boundary and a turbulent flow.

Figure 17. Ice breaker and navigation channel on Mississippi River.

INSTRUMENTATION

Electronic instrumentation during the past decade made the transition to a computer-based system. Transducer, signal-conditioning elements and specialized instruments, such as the hot-wire anemometer, are still as important as ever in supporting experimental research at the Institute. Now, however, they operate in conjunction with a digital computer, in order to permit more sophisticated analyses and faster reduction of experimental data. This latter capability permits the study of problems heretofore not possible, simply because of the effort needed to process the data.

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The computer system is an IBM 1801 Data Acquisition System which operates in a time-sharing environment under control of IBM's TSX system. Process and control programs reside on disk and are queued for execution by an interrupt process. Signals from any of the instruments in the laboratory are connected to the computer through either a 32-point solid-state multiplexer or a 48-point relay multiplexer. Various multiplexer points are assigned to different locations in the laboratory, thereby providing access to the machine for many users.

Examples which illustrate the flexibility and advantage of the system include experimental studies which range from the processing of data representing contractions in the small intestine to the measurement of temperature in studies of thermal pollutants in rivers. A study in conjunction with the small intestine research is the computer operation of a model simulating flow conditions in the small bowel. The model is controlled by processed data obtained from volunteers who have swallowed specially designed transducers for recording contractions of the wall of the intestine.

The study of thermal-pollution effects in rivers is related to a problem of local concern. A nuclear power plant is being built at Cordova, Illinois, by Commonwealth Edison Company of Chicago and Iowa-Illinois Gas and Electric Company of Rock Island. When the unit is completed it will discharge as much as 2,270 cfs of heated water 23°F above ambient into the Mississippi River. Several models have been constructed at the Institute to study various aspects of thermal problems. Thermistors are used to measure the temperature at many different points in the models, and calibration and processing programs which compute temperatures and ratios of temperatures directly are executed on command.

Two new instruments which have been developed and which are extensively used with the computer are a multi-channel conductometer for measuring salinity concentrations in laboratory flumes and an electro-optical system for measuring mean and statistical properties of sediment suspensions. Conductivity rather than resistivity is measured to eliminate non-linear concentration-voltage relationships and special circuits were designed to reduce channel-to-channel influence and sensitivity to extraneous grounds. The electro-optical sediment instrument was developed for *in situ* measurement of suspended-sediment concentrations in alluvial channel flows. The transducer for the system consists of a P-N gallium arsenide diode as light source and an N-P-N planer silicon

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phototransistor as light sensor. The source light detected by the light sensor is modulated by the suspended sediment in the gap between the source and sensor. The amplifier for the sensor output has been combined on one chassis with signal-analyzing circuits, which include an analog-to-frequency converter and multiplier. The resulting system is capable of measuring suspended-sediment concentrations down to 100 ppm, and can compute the mean concentration, the mean square of the concentration fluctuations, and the correlation between sediment con-

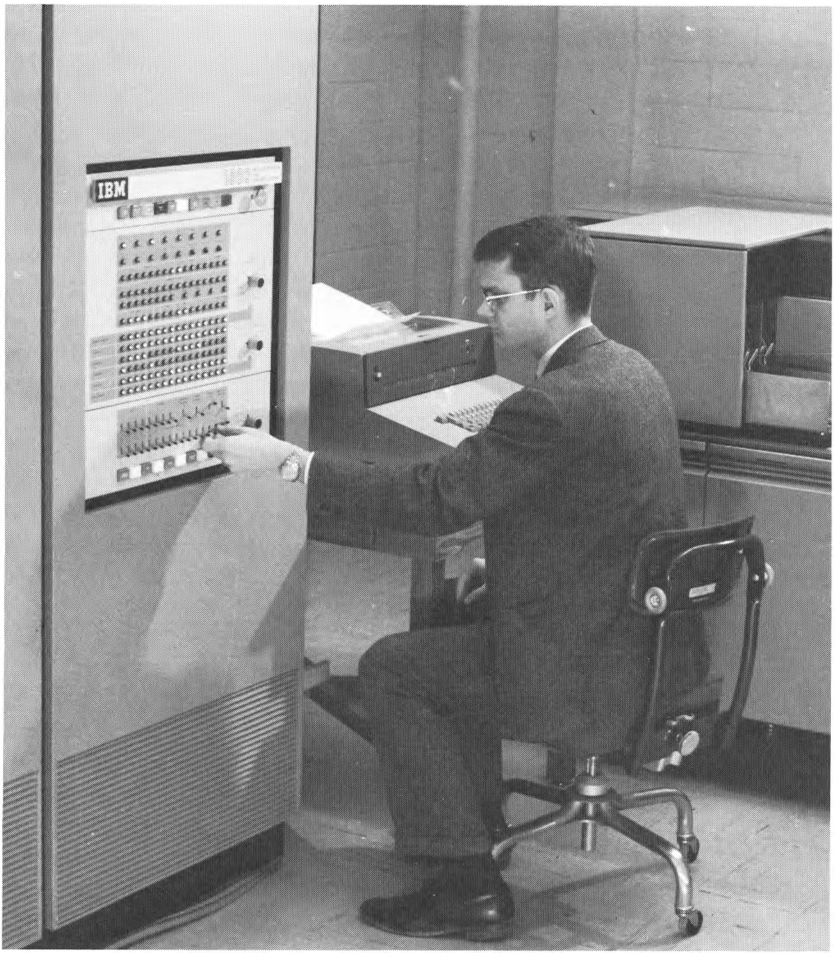

Figure 18. Control panel of the Institute's IBM 1801 computer.

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centration and another signal supplied to the system.

Techniques for detecting turbulence and converting the resulting signals to a form suitable for analysis were an important phase of the Institute's operation for most of the first half century. Early work included turbulence measurements in the Mississippi River by A. A. Kalinske, using a midget current meter which could respond quickly to the secondary fluctuations. Recordings from this meter were reduced by hand to obtain values of the mean and fluctuating velocities at various elevations in the river. Several promising techniques were studied, including measurement of the forces upon submerged obstacles, such as very small spheres, and the diffusion of various substances (heat, dye, suspended particles) as a function of space downstream from the point of introduction.

One of the methods studied in the late 1940s was the Hot-Wire Anemometer. Its small size, very fast response and desirable directional characteristics were unmatched by any other technique. For gases, it was equally effective for measuring mean velocities or fluctuations and was readily linearized through electronic circuitry to yield signals which were directly proportional to the components of the velocity. In liquids, however, solid impurities tended to collect on the wire, so that its usefulness for mean velocities was substantially reduced. It worked reasonably well in clean water or other liquids, and special insulating coatings also improved the performance. This improvement, however, was at the expense of the extremely rapid response which marked the performance in air or other gases.

Techniques and equipment for analyzing the signals were developed simultaneously with the instruments for detecting the velocity components. Early instruments used heavily damped ammeters for recording mean velocities and thermal meters for determining the root-mean-square values of the fluctuations. At an intermediate stage of development, analog-to-frequency converters were used in conjunction with electronic counters to obtain mean values, and semi-conductor devices were used to obtain instantaneous products of the various components of the fluctuations. The most recent instruments rely upon multiple-channel sample-and-hold amplifiers as interface components to the analog-to-digital converters. From this point the analysis could be accomplished by special-purpose digital computers.

Turbulent fluctuations in pressure were also the subject of intensive research, and several instruments were produced in which strain-gage

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or crystal detectors were placed inside of a flat surface or a streamlined headform connected through small piezometric openings to the flow. As might be expected, these instruments could not be reduced to the very small size of hot-wire anemometers and, as a consequence, were useful only in larger systems. Signals from these transducers were analyzed using the instruments which had been developed for hot-wire anemometers.

IRROTATIONAL FLOW

The methods of potential theory have been found useful in a variety of practical problems. These include the vibration of bodies in a liquid, the conformal mapping of ship sections and the determination of the flow about bodies moving through a fluid.

A method for mapping a ship section accurately into a circle is needed both for calculating the added mass of a vibrating ship and in a procedure for obtaining a parametric pair of equations of a ship form. A method, taking advantage of the maximum area property of the circle, developed by Landweber and Macagno (Reprint 227), was compared with other methods by Macagno (Reprint 247). When it was found that the area method failed for certain sections, another procedure, based on the Gershgorin integral equation, was developed by Landweber ("Mapping of Ship Sections," Seventh Symposium on Naval Hydrodynamics, Rome, 1968).

In calculating the natural frequencies of a vibrating ship, a strip method which uses the two-dimensional added-mass coefficients at each transverse ship section with three-dimensional overall corrections, is usually employed. The aforementioned development of methods of mapping ship sections, from which the added-mass coefficients can be directly obtained, was motivated by this problem. Three-dimensional correction coefficients, derived from studies of the irrotational flow about spheroids, were reported by Macagno and Macagno (Reprint 171) and by Matilde Macagno (IIHR Misc. Paper, 1963). It was then suggested by Landweber (IIHR Misc. Paper, 1963) that the vibration frequencies could be obtained by combining the kinetic energies of the vibrating body and the fluid as a single quadratic form and calculating the eigenvalues of the potential energy matrix of the elastic body with respect to the kinetic energy matrix. This essentially replaced a diagonal matrix composed of the sectional added masses with a nondiagonal matrix. Trials of this method were reported by Warnock (Ph.D. thesis), Pita (Ph.D. thesis) and Landweber (Reprint 231). An application to a

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vibrating body of revolution, given by Landweber (Report 111), will be published in modified form in the *Journal of Ship Research,* 1971.

The irrotational flow about a body can be expressed in terms of a vorticity distribution on its surface. For bodies of revolution in arbitrary states of translational and rotational motion, three basic Fredholm integral equations of the first kind were formulated and applied to obtain the pressure and velocity distributions of the DTMB Series 58 family of bodies of revolution (NSRDC Report 2505, 1967). A procedure for determining the vorticity distribution for arbitrary three-dimensional forms was included in the paper, "Characteristics of Ship Boundary Layers," by Landweber at the Eighth Symposium on Naval Hydrodynamics (IIHR Misc. Paper, 1970).

An alternative means of representing the irrotational flow about a form assumes a distribution of sources on the surface. The Fredholm integral equation of the second kind for determining such a distribution was treated by Landweber and Macagno (Report 123) for the case of a ship form, taking into account the presence of a free surface.

When a free surface is present, one usually treats the problem by linearizing not only the free-surface boundary condition, but also that on the surface of the body. An investigation by Farell of the flow about a spheroid near a free surface, in which the boundary condition on the surface of the spheroid is satisfied exactly, showed that the errors due to linearization of the boundary condition could be large (Ph.D. dissertation). Measurement of the total and viscous resistance of a spheroid (employing the wake-survey technique for the latter measurements) by Güven (M.S. thesis) have partly confirmed the analytical results. The analysis has also yielded values of the added mass of a spheroid moving near the free surface (to be published in the *Journal of Ship Research*).

An application of the Lagally theorem and the method of source images, by Landweber and Macagno (Reprint 194) yielded expressions for the image system within a spheroid and the hydrodynamic force acting upon it in an arbitrary axisymmetric potential flow. In a sense these results extended the *sphere theorem* for irrotational flow. For non-axisymmetric flows the image system was found to include series of multipoles. Consideration of these led to a generalization of the Lagally theorem for multipoles by Landweber (Reprint 225).

Three significant doctoral dissertations have involved the solution of potential-flow problems through refined combination of analytical and numerical (digital-computer) methods. That by Strelkoff yielded the

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pattern of flow over a vertical sharp-crested weir ranging from zero to infinite head-height ratio. That by Cassidy dealt with the pattern of flow over a spillway of arbitrary profile curvature. Finally, that by Hunt superseded the earlier relaxation study by Abul-Fetouh of the axisymmetric jet from an orifice in the wall of a large tank.

Jets and Wakes

In connection with the then-new field of ground-effect machinery, a series of basic studies were undertaken with the support of the ONR.

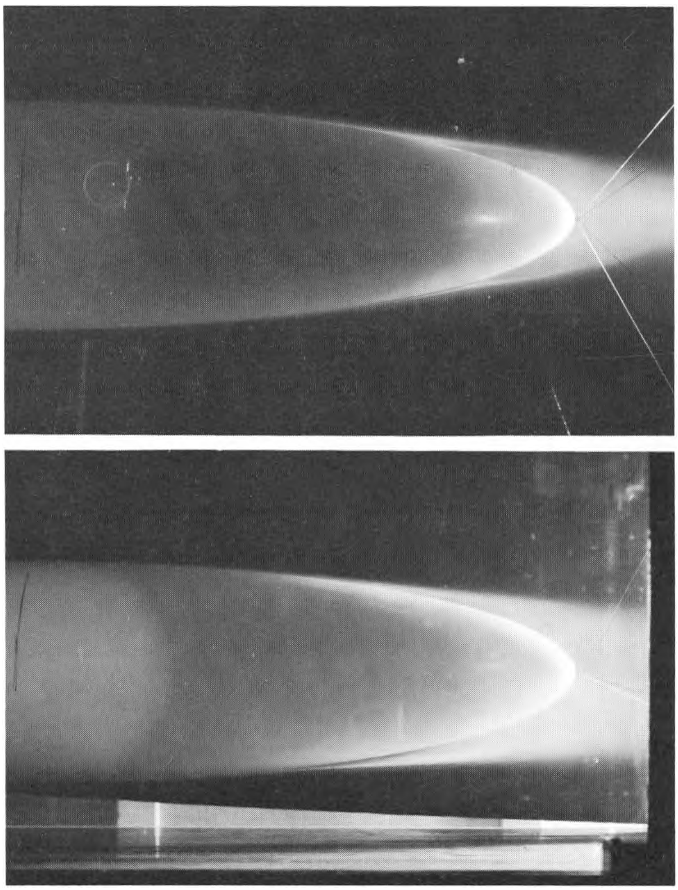

Figure 19. Smoke study of the wake of a spheroid showing alteration of the wake due to the proximity of a boundary (lower photograph)

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These included: (1) a stationary annular jet impinging against a rigid ground plate; (2) an annular jet impinging against a rigid ground plate in the presence of an ambient flow; (3) a stationary annular jet directed against a water surface; and (4) an annular jet traveling over water. (See Malsy M.S. thesis, Mack-Malsy 1960 report to ONR, Yen 1962 report to ONR.)

In connection with the use of expansion chambers for energy dissipation, tests were made in a series of pipe expansions of varying diameter ratio, including the jet in a semi-infinite fluid as the limiting case. The tests included both cavitation prediction and vibration evaluation. (Reprint 210.) In 1966 Rouse was invited to give a Freeman Lecture before the Boston Society of Civil Engineers; this reviewed the many Institute investigations of submerged jets. (Reprint 216.)

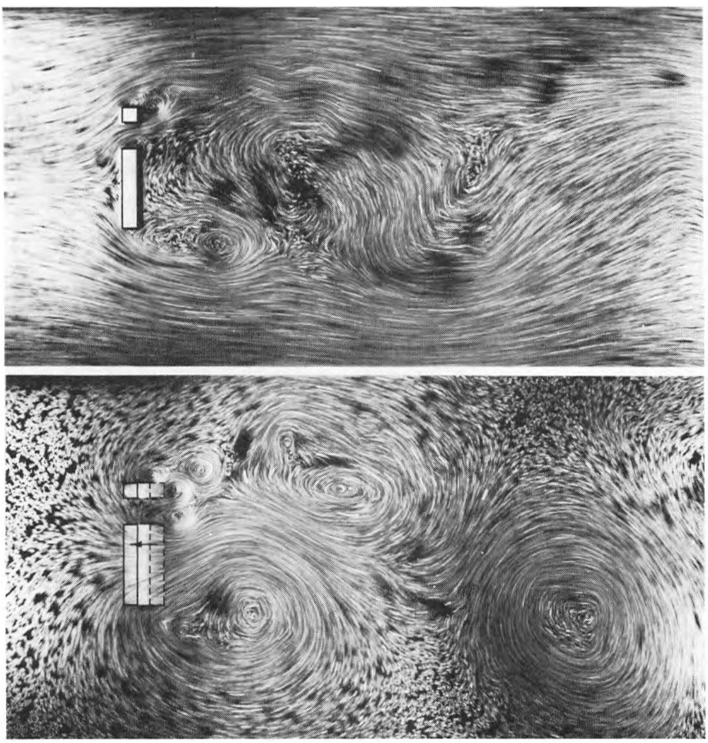

Figure 20. Pattern of flow past a stationary pair of bars of different heights (upper) and the pattern of eddies produced by a moving pair of bars (lower).

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Wake studies have emphasized the analogy between flow around bodies and flow through conduits of comparable geometry, with particular emphasis upon the eddy patterns in zones of separation. (Reprints 170, 181.) Doctoral dissertations in this field included those by Carmody, on flow past a disk; by Chaturvedi, on flow in expansions; and by Narasimhan, on flow at conical afterbodies. (See also Reprints 197, 187.)

In a 1962 paper (Reprint 179) Rouse extended the Bernoulli theorem to conditions of turbulent flow, especially in zones of separation. Four cases were evaluated by Chevray (see M.S. thesis) and covered further in Reprints 198, 205 and 265. Chevray also measured turbulence characteristics in the wake of a body of revolution (see Ph.D. dissertation) as had Chen and Gear several years earlier (see M.S. theses). These were related to studies on wakes with zero momentum flux (see M.S. thesis of Caruso, and Ph.D. dissertations by Ridjanovic and Wang).

A numerical study of wake deformation has determined the collapse shape and internal velocity field of an initially circular homogeneous fluid mass surrounded by a linearly stratified fluid. During the initial stage of collapse the fluid is assumed to be inviscid and the motion irrotational. For the later stages, when viscous effects assume a significant rate, the complete Navier-Stokes equations are solved. The final stage of collapse is analyzed by means of a viscous, long-wave theory. The pressure acting on the boundary of the mixed region is assumed to be hydrostatic throughout the collapse process. A new numerical method is described for obtaining solutions for the complete Navier-Stokes equations in problems involving moving boundaries (see Ph.D. dissertation by H. Padmanabhan and Reprint 268). The technique involves an extension of an approach due to Chorin.

Experimental information on various elementary types of free-turbulence shear flows, mainly on jets and wakes, has become almost as comprehensive in recent years as that on homogeneous turbulence. The flow in the wake of an axisymmetric body with hydrodynamic self-propulsion, a type of free-turbulence flow with widespread practical application, had received little attention in the past, however, and was therefore extensively investigated under the sponsorship of the Office of Naval Research. (Reprint 203, Caruso M.S. thesis, and doctoral dissertations by Ridjanovic and Wang.) Self-preservation hypotheses for plane-symmetric and axisymmetric free-turbulence shear flows were discussed in particular by Naudascher in the light of these data, data by

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Ortega (see M.S. thesis) on the turbulent round jet in a coaxial stream, and other published data. (Reprint 203, Reports 106 and 110.) A by-product of these investigations was an analysis of turbulent flow past a grid, as the plane-source counterpart of flows past point and line sources of turbulence (Reprint 269). The effect that a linear density stratification has on the flow past a grid has also been investigated under ONR sponsorship (see 1971 Ph.D. dissertation by Tao).

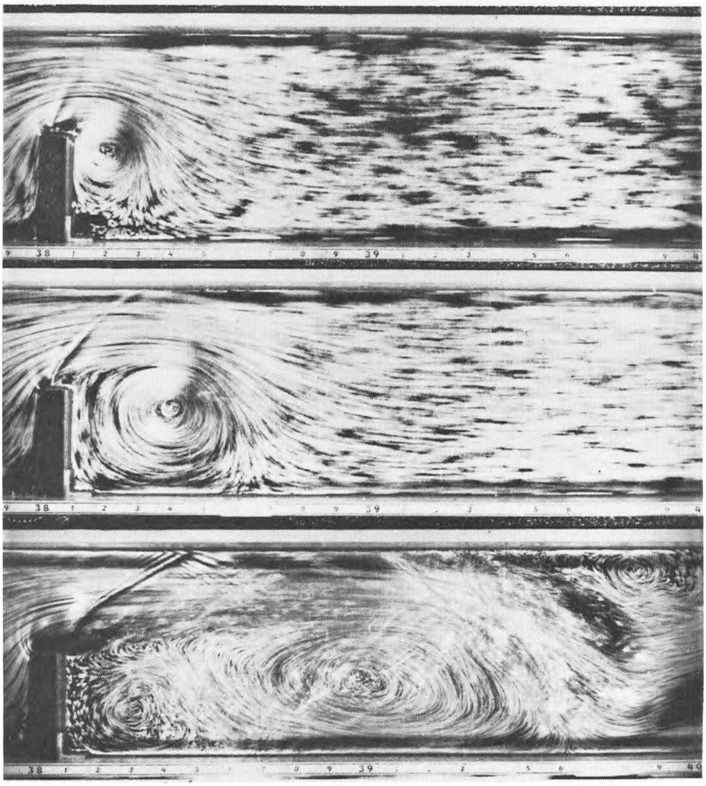

Figure 21. Development of the eddy pattern behind a sill with increasing velocity.

Non-Newtonian Flows

Work on the analysis of viscous fluids with nonlinear constitutive equations was begun as an Institute project in 1965. The first publication, dealing with unsteady flow of non-Newtonian fluids, appeared in 1966.

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Research in this general area was then extended to rotationally symmetric flow, to flow through an expansion, and to stability of plane and axisymmetric Poiseuille flows subject to finite disturbances. The work on flow expansion was based on a power law which would represent shear-thinning and shear-thickening fluids, but for the other investigations a polynomial model was introduced by E. Macagno based on a formulation for the rheological behavior in terms of the invariants of the strain-rate tensor (Reprints 214, 222, 250).

Open-Channel Resistance

Resistance studies for free-surface flow have incorporated those for surface and cross-sectional-shape effects of closed conduits and proceeded therefrom to effects involving various aspects of gravitational action. Surface roughness was the basis of the Roberson and O'Loughlin dissertations (Reprint 199, and IIHR Misc. Papers). Effects of cross-sectional shape were treated by E. Macagno in Reprint 208. Effects of channel non-uniformity were typified by bridge piers (see Hsieh thesis). Apparent resistance changes due to the onset of rollwaves were evaluated for both smooth and rough channels (see Koloseus dissertation and Reprint 185). All of the foregoing aspects of the problem, plus that of channel curvature, were reviewed in a summary paper by Rouse (Reprint 202).

Sediment Studies

Sediment studies continued, as in earlier years, to be directed toward clarification of the mechanics of transport, with the goal of developing more rational predictors for engineering applications. The types of studies conducted may be divided into four principal categories. The first has been concerned with the effects of sediment properties on transport characteristics. Diamandis (see M.S. thesis) found that the range of particle sizes present in the bed material limits the depth of scour, but has no effect upon the non-dimensional profiles. This work was continued by Hannan (see M.S. thesis) who conducted his experiments using two different sediments with the same mean diameter and same standard deviation, but with different skewness of size distribution. Again, the non-dimensional scour profile was found to be independent of both time and skewness. The effect of particle size distribution on the characteristics of the suspended load was considered by Lee (see M.S. thesis), who made systematic experiments using two different

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sands of the same mean size and skewness but different standard deviations. The standard deviation of the bed material was found to have a significant effect upon both the mean concentration and size distribution of the suspended load.

The second main type of study has focused upon fluid-particle interaction. The effects of turbulence-induced random velocities on the settling velocities of particles was investigated by Ho (see Ph.D. thesis). His experiments with spheres settling in an oscillating fluid showed that the fluid oscillation reduces particle fall velocity significantly below the quiescent-fluid value. A numerical solution of the equation of motion yielded an estimate of the effect of fluid oscillation on the fall velocity. The relationship between the diffusivities for momentum and sediment has a significant effect on the available theoretical models for sediment suspension. Singamsetti (see Ph.D. thesis) investigated diffusion of sediment particles in a vertical, axisymmetric, sediment-laden submerged jet directed downward into stationary water. The diffusivity for sediment was found to be as much as 20 percent greater than that of momentum. The results were explained on the basis of heuristic arguments concerning the inertial and gravitational effects on the sediment-particle motion.

Practically oriented investigations of scour constituted the third area of research. The study of Chu (see M.S. thesis) was concerned with effectiveness of *rock sausages* placed over filter layers to protect them from erosive attack. The various types of scour failure possible were observed, and the flow regimes over which each can occur were considered. Scale effects in model tests of rock-protected structures were explored in the M.S. theses of Mehrotra and Chang, in which scour-pocket experiments were made using glass spheres. In each set of experiments the Froude number was maintained constant and the Reynolds number was varied over a considerable range. The minimum value of Reynolds number above which the non-dimensional scour rate is insensitive to Reynolds number was then determined. The rate of scour was found to be extremely sensitive to upstream flow conditions. Chang sought to clarify the role of Reynolds number by measuring the spectra of the velocity fluctuations over a range of Reynolds numbers in a flow over a rigid geometry modeled after a scour pocket. The spectra showed no systematic effects of Reynolds number. The scour investigations were extended to wave-induced erosion by Hulman (see M.S. thesis), who undertook an experimental investigation of raveling of riprap embankments by obliquely breaking waves.

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Flow in alluvial channels was the subject of the fourth category of study. In their Ph.D. theses Squarer and Annambhotla considered the relationship between friction factor and the geometrical characteristics of ripples and dunes on the beds of alluvial channels. Squarer's investigation was conducted in the Institute's larger, sinuous channel, while Annambhotla used data obtained in a field investigation conducted

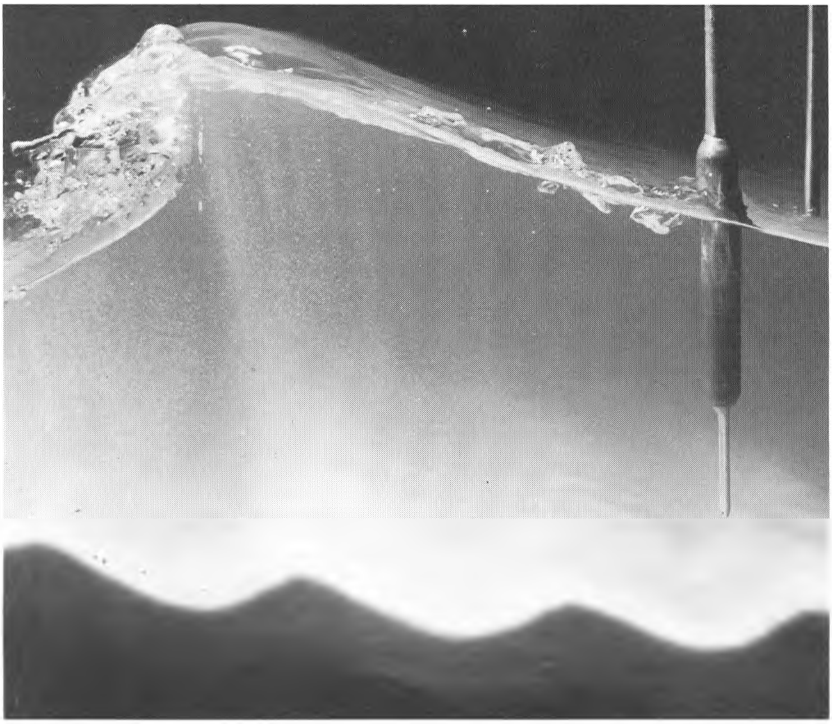

Figure 22. Wave breaking over a sand bed, showing sediment-concentration analyzer.

on the Missouri River near Omaha. Both sought to characterize the bed geometry by means of parameters based on the spectra of the boundary profiles, and both found a strong relationship between bed roughness and a measure of the bed-wave steepness (such as square root of variance of bed-undulation displacement divided by a characteristic wave length determined from the normalized spectrum).

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Ship Resistance

In the past decade a notable development in the field of ship hydrodynamics is the appearance of methods for the separate determinations of the viscous and wave resistance of ship models. By applying the Betz-Tulin theory, viscous resistance can be calculated from measurements of the total-head and pressure distributions in the wake of a ship model. An experimental arrangement and procedure for obtaining and analyzing these measurements were reported by Wu (see M.S. thesis); refinements in the theory of the method were given by Landweber and Wu (Reprint 186) and by Landweber (*Proc. Eleventh ITTC*, Tokyo, 1966). The basic assumptions of the Betz-Tulin theory were examined by Wu (see Ph.D. dissertation) and Tzou (see Ph.D. dissertation). Application of the method to a Series-60 ship model showed that, contrary to the usual assumption, the viscous drag of a ship model varied in a sinuous way with Froude number (see Landweber and Wu, IIHR Misc. Paper, 1963). One of the basic assumptions, that the wave resistance is unaltered when the rotational wake is replaced by the analytical continuation of the external irrotational flow, was investigated by Tzou (see Ph.D. dissertation) and Landweber (*Proc. Twelfth ITTC*, Rome, 1969). With the Institute's acquisition of an IBM 1801 computer and *Scanivalve*, a motorized device with many pressure nipples for measuring a sequence of pressures in controlled and rapid succession, it became possible to automate the wake-survey measurements and their analysis, as is described by Glover, Tzou and Landweber (IIHR Misc. Paper).

Several methods have been proposed for determining the wavemaking resistance of a ship model from surface-profile measurements. A basic assumption of the theory on which the data analysis is based is that, beyond about a model length downstream, the surface disturbance may be represented adequately by the far-field part of its theoretical mathematical representation. This assumption was examined for a source in a channel by Landweber (IIHR Misc. Paper, 1963) and by Landweber and Tzou (Reprint 243) for a particular source distribution when "transverse-cut" data are analyzed. Application of the method to a modified ogive in a channel by Kobus (see Ph.D. dissertation) showed large discrepancies between the theoretical and measured wave resistances. An explanation of this discrepancy in terms of wavemaking of the vorticity in the wake and a way of correcting the analysis of trans-

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verse-cut data for the effect of the wake were given by Tatinclaux (Reprint 264).

On some ship bows there are streamlines which pass downwards and around the bilges to the underside of the hull. Because of the small radii of curvature at the turn of the bilge, a large cross flow may develop in the boundary layer which could give rise to a secondary flow and vortex generation. Such vortices, called bilge vortices, contribute appreciably to the total resistance. Measurements of their strength under various conditions, and estimates of their contribution to resistance were given by Tatinclaux in a series of papers (IIHR Misc. Paper, 1966; Reports 102, 107, 117; Reprint 270).

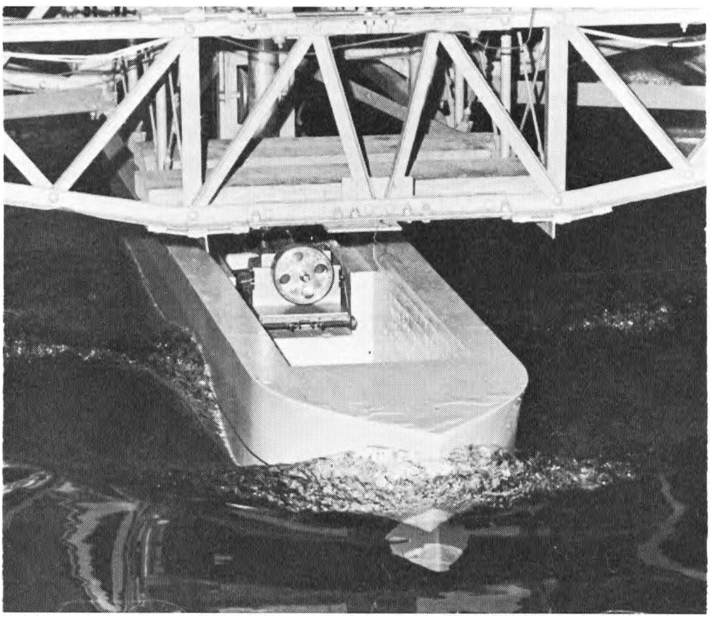

Figure 23. Ship model underway in the towing tank.

An old ship-model-testing problem is that of correcting ship-model data for the influence of the tank walls, the so-called *blockage effect.* It has been found that velocity corrections based on irrotational flow and the method of images are inadequate. A study of the pressure on the back face of a hemisphere in a wind tunnel with movable walls by Lin (see M.S. thesis) confirmed that the walls have a large effect on the base pressure. An analytical study by Landweber ("A Note on Blockage

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Effect," *Jubilee Memorial,* W.P.A. van Lammeren, 1970) indicated that the body-wall geometry determines the length of the separation bubble which, in turn, mainly determines the pressure at the separation point, and hence on the back face; a practical application of this mechanism was suggested.

Ship Rolling

Two investigations on ship rolling were completed during the decade. One, on the wavemaking of rolling ship forms by McLeod and Hsieh, verified a theory due to Ursell that a certain form was least desirable from the point of view of roll damping. The other, a study of the mechanism of roll damping due to bilge keels, extended the work by Martin (see Ph.D. dissertation). Ridjanovic (Reprint 174) studied the effect of the aspect ratio of flat plates oscillating normally to their planes; and Tseng (see M.S. thesis) included the effects of a superimposed stream, as well as examining the errors due to linearization in the analysis. It is common practice to employ turbulence stimulation in ship-model resistance tests, but not in ship-rolling studies; although, as shown by Martin, McLeod and Landweber (Reprint 167), turbulence stimulation is necessary in rolling tests, especially for forms without bilge keels.

Similarity Representations

An extensive study of similarity representations in fluid mechanics and related areas based on finite and infinitesimal groups has been carried out by H. J. Woodard and W. F. Ames. These authors presented the paper "Application of Lie Algebra to Similarity Theory," at the Summer 1970 Meeting of the Society for Industrial and Applied Mathematics. A second paper, "Infinitesimal Transformation and Similarity Variables in Fluid Mechanics," and report, "Similarity Solutions for Partial Differential Equations Generated by Finite and Infinitesimal Groups," describe the procedure in some detail for three examples in fluid mechanics.

Ever since the pioneering researches of Boltzmann and Blasius the similarity variable has played an important role in fluid mechanics. Improvement and implementation of a deductive method for determining similarity variables has been underway for three years with the support of the Office of Naval Research. The procedures, based on the theory of finite and infinitesimal groups, have been applied to general boundary-layer problems, nonlinear diffusion and Burgers' model of turbulence. Present studies are being carried out on the Reynolds equa-

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tions for turbulent flow. These researches are under the direction of Professor Ames.

Structural Vibrations

A series of investigations started at the beginning of the decade contributed to a better understanding of the concepts and mechanisms responsible for flow-induced structural vibrations. (See Reprints 189 and 228.) Among the specific problems studied were the hydrodynamic forces on high-head gates. (See M.S. theses by H. Kobus, R.P.R. Rao, N. Gillisen and C. Farell; and Reprint 193.) The results of these investigations, primarily concerned with hydraulic downpull forces, have become useful in engineering practice for the design of prototype structures.

In addition to the mean force characteristics, the fluctuating components of the induced hydrodynamic loading received considerable attention as well. In particular, studies of vibration during simultaneous overflow and underflow of leaf gates (Reprint 172) and flow-induced vibration of high-head gates (see Ph.D. dissertation by F. A. Locher) should be mentioned, together with a number of investigations of pressure fluctuations as influenced by the geometry of the gate lip. (See M.S. theses by F. A. Locher, J. C. Tatinclaux, Y. Chu; and Reprint 234.) In conjunction with these studies, an investigation of the pressure fluctuations on low ogee-spillway crests was also conducted. (Report 130.)

A by-product of these investigations of flow-induced forces was a study of the effects of confining walls on the periodic wakes of cylinders and plates. (See M.S. theses by C. Farell, A. Toskas and Y. Chen.)

Unsteady Hydraulic Phenomena

Due to the special interest in Latin America on pressure waves in conduits and effects in surge-tank installations, the course Hydraulics of Unsteady Phenomena was open to special work in this area by students from that continent. This resulted in a number of papers by those students and their professor presented at the regional congresses of the IAHR in Latin America; and in the publication of a monograph on control of pressure waves in systems of conduits; plus a volume of notes on pressure waves, which were published by Federal University of Paraná (Brazil) and the Central University of Venezuela.

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Waves Breakdown

Research on the breakdown in solutions of nonlinear wave equations has been completed and published by W. F. Ames (Reprint 257). The method is applied to a variety of problems, including the transonic flow of a gas, gas dynamics, shallow-water waves and transmission lines. When applicable, the procedure is simple to use, as compared with the unfolding method of Riemann invariants.

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GRADUATE DEGREES

Following the granting of the first master's degree in 1922, over five hundred advanced degrees have been awarded for studies in hydrology and hydraulics, and in many areas of theoretical and applied fluid mechanics. Such areas range from accelerated flows to water waves and from aerodynamics of buildings to transport of sediments. In this educational endeavor, the Institute has worked in close cooperation with the Department of Mechanics and Hydraulics, and during certain periods also with the Department of Civil Engineering. Of the total of 503 advanced degrees, 89 were at the doctoral level, and were earned by students from Australia, Canada, China, Egypt, France, Germany, India, Iraq, Israel, Mexico, Turkey, United States, Uruguay, and Yugoslavia. Inclusion of the master's degrees adds thirty more countries to the list. A detailed breakdown according to degree and the country of origin is presented in the accompanying table. It is certainly noteworthy that over half of the students have held appointments as Research Associates or Research Assistants at the Institute. Some of them also held appointments as Teaching Assistants in the Department of Mechanics and Hydraulics; these were usually students who already had teaching experience or were planning academic careers.

The name of each degree recipient, together with degree date and degree awarded is listed in alphabetical order in the Author Index of Theses and Dissertations, or in the Appendix if he earned a master's degree without thesis. Accompanying the names in the Author Index are page numbers referring the reader to the dissertation or thesis title, date, and adviser. If the degree was awarded within the decade 1961-70, an abstract of the dissertation or thesis is also included. The abstracts for those works presented in earlier years are to be found in other decade bulletins of this series cited in the Preface. Copies of all the dissertations and theses are kept at The University of Iowa Engineering Library. Requests concerning such documents should be addressed to the Research Library of the Institute, which can either loan a copy, prepare retention copies for sale, or refer to available publications containing the essential results of the thesis.

Graduate Degrees and Countries Represented, 1922 to 1970

Country	*M.S.*	*Ph.D.*
Argentina	3	
Australia	3	2
Austria	1	

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Graduate Degrees and Countries Represented, 1922 to 1970

Country	*M.S.*	*Ph.D.*
Brazil	5	
Burma	1	
Canada	12	2
Ceylon	2	
China	88	27
Colombia	10	
Czechoslovakia	1	
Denmark	1	
Ecuador	2	
Egypt	4	2
England	4	
France	3	3
Germany	6	2
Greece	5	
Guyana	1	
Hungary	1	
India	34	9
Iran	1	
Iraq	1	1
Ireland	1	
Israel	1	1
Japan	2	
Korea	2	
Luxembourg	1	
Mexico	3	1
Netherlands	1	
Nicaragua	1	
Norway	1	
Pakistan	5	
Panama	1	
Peru	2	
Philippines	6	
Poland	1	
Spain	1	
Sweden	1	
Thailand	1	
Turkey	9	4
United States	171	33
Uruguay	2	1
Venezuela	10	
Yugoslavia	2	1
Total	414	89

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ABSTRACTS AND TITLES
OF GRADUATE THESES

Boundary Layers

Free-Surface Effects on Boundary-Layer Separation on Vertical Struts. SHIN-KIEN CHOW. Ph.D. Dissertation, June 1967; Professor Landweber, adviser. This dissertation represents an investigation of free-surface effect on boundary-layer separation on vertical struts piercing a free surface. The investigation consists of two phases. In the theoretical phase, the theory of infinitesimal waves was used to derive the velocity potential for the flow about the strut, generated by a distribution of semi-infinite vertical line sources below the free surface of an otherwise-undisturbed semi-infinite fluid. This line-source distribution was determined by solving an integral equation of the first kind for the two-dimensional (infinite strut) problem, and then assuming that the same distribution could be used when a free surface is present. Piezometric-head distributions (surface elevation) along the strut at the free surface were calculated for 12 Froude numbers and the separation points were calculated by the modified Stratford method.

In the experimental phase, observations were made in a horizontal flume. Two stationary, vertical struts were used. Both the theoretical and analytical results showed that the nondimensional piezometric-head distribution at the free surface was quite different from that at great depth. The calculated and observed separation point at the free surface on one of the struts occurred farthest forward at a Froude number of 0.25. At smaller or greater Froude numbers, separation occurred farther downstream, or, at the highest Froude numbers, not at all. Observation on another strut showed that below the free surface, but in proximity to it, there existed another separation zone which, it is believed, was caused by secondary flow within the boundary layer induced by the surface waves.

Boundary-Layer Development at Curved Entrances of Conduits. PALEPU V. RAO. Ph.D. Dissertation, August 1964; Professor Rouse, adviser. With the aim of studying how the energy reduction occurs in a conduit inlet shaped according to potential theory, boundary-layer

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measurements were made in a nonrecirculating air duct with circular, square and rectangular types of inlet. The compound elliptical shape of the U.S. Corps of Engineers was adopted in all three cases. The effect of conduit Reynolds number on the growth of the laminar and turbulent boundary layers in the inlet portion of the conduit was studied for all three types of inlet. The potential velocity distribution for the axisymmetric inlet was obtained by solving the difference equation for the Stokes stream function. The laminar-boundary-layer growth was calculated by the finite-difference method of Görtler and Witting. Proper turbulent-boundary-layer growth in the inlet was obtained by artificial roughness. Comparison of the coefficients of energy reduction for the circular, square, and rectangular inlets shows that the reduction of energy flux is least for a circular inlet and highest for a rectangular inlet at the same Reynolds number. Graphs are given showing coefficients of energy reduction as functions of relative distance into the inlet and Reynolds number.

Three-Dimensional Turbulent Boundary Layer. F. S. A. PAVAMANI. M.S. Thesis, August 1960; Professor Landweber, adviser. Measurements were made in an air tunnel on an ellipsoid of principal axes five feet, one foot and 0.25 foot at a wind speed of 60 fps. Velocity profiles in the boundary layer, the direction of flow and the total pressure at the surface were measured. The data were analyzed to determine the pattern of velocity variation within the boundary layer, the variation of wall shear and boundary-layer thickness, the applicability of the inner law and the angle of flow at various points, and to detect cross flows and separation. It was found that the boundary-layer thickness decreases and the shear stress at the wall increases with increasing curvature in the transverse direction. The inner law of the boundary layer seemed to be valid at least where the curvature was small.

The Development of the Turbulent Boundary Layer on Steep Slopes. WILLIAM JOHN BAUER. Ph.D. Dissertation, August 1951; Professor Rouse, adviser.

An Experimental Investigation of the Boundary-Layer Development Along a Rough Surface. WALTER L. MOORE. Ph.D. Dissertation, August 1951; Professor Rouse, adviser.

An Exploratory Investigation of Boundary-Layer Development on Smooth and Rough Surfaces. WILLIAM DOUGLAS BAINES. Ph.D. Dissertation, August 1950; Professor Rouse, adviser.

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Building Aerodynamics

Boundary Layer Effects on the Pressure Distribution of a Hangar-Type Building. I-MING CHENG. M.S. Thesis, February 1968; Professor Kennedy, adviser. The objective of the research reported herein was to obtain the pressure distribution on a hangar-type model ($L/D = 1$) with different boundary-layer thickness. The model was first mounted on a large ground board, to give a further information on the pressure distribution on the model using the classical test set-up. A six-inch semi-cylinder ($L/D = 1$) was positioned on the floor of a wind tunnel at different distances from the entrance to the test section, in order to examine the relationship between the pressure distribution and the degree of boundary-layer immersion of the hangar-type building. Four different angles of attack were investigated, and seven different boundary-layer thicknesses were considered.

Results proved conclusively that the boundary-layer effect has a pronounced influence on the pressure distribution. In general, the pressure coefficients on the roof increase strongly with decreasing the values of δ/R. A similar behavior is exhibited by the pressure coefficients for the windward gable of the model. As for the leeward gable, the pressure distribution tends toward uniformity with increasing values of δ/R.

Effects of Eaves on Pressure Distribution Around Model Buildings. J. V. NAGARAJA. M.S. Thesis, June 1959; Professor Howe, adviser.

The Effect of Relative Height of Model Buildings Upon Wind Pressure Distribution. WILLIAM S. HARTLEY. M.S. Thesis, August 1958; Professor Howe, adviser.

Modification of Pressure Distribution Around Buildings Due to Parapets. PHILIP S. NACY. M.S. Thesis, June 1951; Professor Howe, adviser.

Pressure Distribution on Models of Three-Dimensional Buildings Exposed to Moving Air. NING CHIEN, YIN FENG, HUNG-JU WANG. M.S. Thesis, June 1948; Professor Howe, adviser.

A Study of Pressure Distribution on a Series of Two-Dimensional Roof Forms. GEORGE A. AUSTIN, JR. M.S. Thesis, June 1947; Professor Howe, adviser.

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CAVITATION

Pressure Fluctuations in a Cavitating Flow Past a Wall. YEN-HSI CHU. M.S. Thesis, February 1967; Professor Naudascher, adviser. Pressure fluctuations were measured at several points in the vicinity of a normal wall, in order to ascertain the effects of cavitation on the vortex formation, and thus on the intensity and spectral density of the pressure fluctuations induced by the flow. The principal conclusions of this study are: (1) although the incipient and intermediate stages of cavitation increase the intensity of the pressure fluctuations, this increased intensity is primarily at very high frequencies; (2) with transition to supercavitation, the RMS value of the pressure fluctuations increases 2.4 and four times the value for non-cavitating flow for ratios of wall width to wall height of one and 3.5 respectively; and (3) cavitation within the large-scale eddies stabilizes them with respect to random breakdown, and can bring about more intense and more nearly periodic pressure fluctuations in comparison with non-cavitating flows with similar geometry.

Cavitation and Pressure Fluctuation Behind a Bluff Body With and Without a Trailing Splitter Plate. ARTHUR D. NEWSHAM. M.S. Thesis, February 1963; Professor Rouse, adviser. The lateral oscillation of the flow behind a bluff body can be prevented by introducing a splitter plate in the wake of a normal plate. The disappearance of the oscillating flow pattern changes the pressure distribution and, therefore, also affects the conditions in which cavitation first appears. The mean pressure distribution was determined along the line of symmetry, and the spectral density of the pressure fluctuation was recorded at three points in the wake. When the splitter plate was introduced, the dominant frequency associated with the flow around a bluff body was no longer evident and the pressure fluctuation was more random.

The Effect of Cavitation on a Rotating Cylinder. DINSHAW N. CONTRACTOR. M.S. Thesis, February 1960; Professor Landweber, adviser.

The Drag of Cavitating Cylinders Arranged in a Straight Grid. JEAN JACQUES GEIST. M.S. Thesis, February 1959; Professors Rouse and Landweber, advisers.

Water-Tunnel Tests of a Cavitating Hydrofoil. TSUYOSHI MATSUOKA. M.S. Thesis, August 1957; Professor Landweber, adviser.

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Theoretical and Experimental Investigation of Forces on Cavitating Hydrofoils. MICHEL HUG. Ph.D. Dissertation, February 1956; Professor Landweber, adviser.

An Investigation into the Point of Incipient Cavitation of Submerged Jets. JOHN P. WHITEHOUSE. M.S. Thesis, February 1952; Professor Rouse, adviser.

Cavitation and Pressure Distribution at Gate Slots. ARISTOKLI SPENGO. M.S. Thesis, June 1949; Professor McNown, adviser.

The Effect of Angles of Yaw on Pressure Distribution Around Various Head Forms. CHARLES A. LAMB. M.S. Thesis, August 1948; Professor McNown, adviser.

Cavitation at Sluice-Gate Slots. ABDEL-HADI ABUL-FETOUH. M.S. Thesis, August 1947; Professor Rouse, adviser.

CONDUITS

Effect of High-Polymer Additives in Water on Characteristics of Turbulent Flow in Pipes and Along a Flat Plate. TING-CHENG HUNG. M.S. Thesis, June 1968; Professor Landweber, adviser. Velocity distributions and pressure gradients were measured for turbulent flow of water solutions of Guar Gum in a pipe of one-inch diameter. Concentrations by weight varying from 10 to 50 ppm (parts per million) were investigated. Similarity laws derived from the measurements were applied to predict the viscous drag-reduction for flows of Guar-Gum solutions in a flat-plate boundary layer.

Effect of Solutions of Guar-Gum in Water on Shear Stress and Velocity Distributions in Flow Through a Pipe. JURGEN RICHTER. M.S. Thesis; February 1967; Professor Landweber, adviser. Velocity distributions and pressure gradients were measured for turbulent flow of water solutions of Guar Gum in a pipe of one-inch diameter. Results were obtained for concentrations by weight from 50 ppm (parts per million) to 800 ppm. Some drag-reduction data were also obtained at lower concentrations. The results were in good agreement with published data.

Laminar Flow in Conduit Expansions. TIN-KAN HUNG. Ph.D. Dissertation, August 1966; Professor Macagno, adviser. This investigation is based on a computational simulation of viscous flow in two-

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dimensional and axisymmetric conduit expansions of ratio 2:1. The complete Navier-Stokes equations were solved numerically with finite-difference methods in two different manners. In the first, named steady approach, a solution was obtained through calculations based on the vorticity-transport equation without the local acceleration terms. In the second, or unsteady approach, the stationary flow was obtained asymptotically through computations with the equations including the local terms. The steady approach is simpler and consumes less computer time than the unsteady technique for flow with low Reynolds numbers, while the unsteady approach is numerically more stable for larger Reynolds numbers. As a verification of the reliability of the methods, the steady approach was applied for a computation of Poiseuille flow; the numerical results converged to the exact solution. The steady nonuniform flows obtained from these two approaches are almost identical, and experimental and computational flow patterns for the axisymmetric case are in good agreement.

Both the kinematic and dynamic characteristics of the steady eddies for the two-dimensional flow were found to be similar to its axisymmetric counterpart. The generation of corner eddies appeared even for creeping flow, and the length of the laminar eddy increased continuously with the Reynolds number, while the eddy intensity approached constant values asymptotically for Reynolds numbers larger than 200. Photographic records indicate that laminar eddies are still possible for Reynolds numbers as high as 4,500. Pressure, normal and tangential viscous stresses, and the balance of the impulse-momentum relationships are also presented. The peaks of vorticity and shearing stress are not on the line of separation, but move to the mainflow side, and then come back to the wall well downstream from the reattachment point. Within the eddy the variation of the Bernoulli sum along the streamlines was found to increase in the direction of the mainflow, then decrease during the counterflow. The integrated form of the work-energy equation can be simplified to only three of its terms in spite of the fact that the local value of each term is relatively significant in the zone of separation. From the kinematic and dynamic characteristics explored with the computational model, it can be concluded that the role of laminar eddies is principally that of helping to shape the mainflow without much exchange of energy. The two-dimensional eddy under computational acceleration due to a sudden variation of viscosity may exhibit the splitting of the eddy in two, while the annular eddy under similar conditions

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appears to be more stable in the sense of remaining as one during its subsequent growth.

Discharge Characteristics of Skewed Orifice. PAI-CHUAN LIN. M.S. Thesis, August 1965; Professor Howe, adviser. Discharge characteristics of skewed orifices have been investigated in a smooth pipe. Three different d/D ratio namely 0.34, 0.52 and 0.70, and four skew angles, 90°, 75°, 60° and 45°, were used in this experiment. The experimental results indicated that when the gross area of the orifice opening is used in the computation of the rate of efflux the discharge coefficient of the 90° orifice of identical d/D ratio can be used regardless of the skew angle, so long as the Reynolds number is sufficiently high and d/D does not approach unity. It was also found that the jet comes out of the orifice perpendicularly to the plate, regardless of its skew angle and the relative diameter of the orifice and pipe.

Distribution of Head at a Rectangular Conduit Outlet. SATYA PRAKASH GARG. Ph.D. Dissertation, June 1965; Professor Rouse, adviser. The analytical solution of the problem involved the determination of the geometry of the free streamlines of the jet. A new method for solution of such problems has been developed in this paper. By the use of this method an improved approximation to the free-streamline geometry is obtained, proceeding from an assumed configuration, and better accuracy is achieved with each subsequent iteration. Solutions for flow through a two-dimensional conduit at Froude numbers of 1, 2, 3 and 4 have been obtained by employing this method and programming it on an IBM 7070 computer. A relation between the location of the piezometric-head line at the outlet of the conduit and the Froude number has thus been determined. The effects of the geometry and the roughness of the conduit on the flow were evaluated by means of a series of experiments in which conduits of various width-depth ratios and with coatings of different sand sizes were used. The relation obtained from the relaxation solution has been extended to incorporate the effects of the resistance of the boundaries and the geometry of the conduit on the location of the piezometric-head line.

Energy Loss in Pipe Expansions. THOMAS TSUNG-TSE HUANG. M.S. Thesis, February 1964; Professor Rouse, adviser. An experimental study was made to determine the effects of the variation of expansion angle, entrance condition and Reynolds number on the over-all energy loss in pipe expansions. This investigation was an extension of the

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1962 doctoral study by M. C. Chaturvedi. The half angles of expansions used in this experiment were 3½°, 7½°, 15°, 25°, 30°, 35°, 45° and 90°. A bellmouth entry, an 11½-foot-diameter smooth brass pipe, and a six-foot artificially roughened pipe preceding the expansions were chosen to provide three different entrance conditions for the flow. The Reynolds number at the entrance section was varied over a range of 3×10^4 to 1.5×10^5. The value of the expansion ratio, D_2/D_1, was taken as 2, the same as that used in Chaturvedi's work.

Establishment of Flow at an Abrupt Inlet. IRVATHUR V. NAYAK. M.S. Thesis, August 1960; Professor Rouse, adviser. The important characteristics of the zone of flow establishment at an abrupt inlet were studied over the critical range of Reynolds number R (400 to 5,400). The loss coefficient was found to vary with R in a similar fashion to the drag coefficient of an immersed body or discharge coefficient of an orifice or Venturi meter. The resistance coefficient f was found to differ consistently from the theoretical values given by the Poiseuille and Blasius equations.

Distribution of Velocity and Pressure at a Submerged Outlet. YA-TAI LIN. M.S. Thesis, August 1960; Professor Rouse, adviser. An experimental study was undertaken for the purpose of tracing the relationship between the pressure distribution around a submerged pipe outlet and the velocity distribution across the outlet for air-flow of high Reynolds number. As the velocity variation across the outlet was increased, the pressure loss along the pipe was found to decrease because of a partial compensation by a longitudinal decrease in momentum flux, and the pressure at center of the outlet, which was invariably lower than the wall pressure, was found to change from positive to negative values. Studies were also made of the deflection of streamlines, and a functional relationship was derived between the inward velocity along the wing wall and the mean velocity.

Inlet Loss in Laminar and Turbulent Flows. I YU. M.S. Thesis, February 1959; Professors Rouse and Landweber, advisers.

Velocity Distribution Along a Short, Smooth, Square Culvert. NARAIN R. RIJHWANI. M.S. Thesis, August 1956; Professor Metzler, adviser.

Pressure Distribution in Two-Dimensional Flow at a Conduit Outlet. YUN-SHENG YU. M.S. Thesis, February 1956; Professor Rouse, adviser.

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Variations of the Kinetic Energy Coefficient at the Outlet of Square Culverts. PETER M. SMITH. M.S. Thesis, February 1956; Professor Metzler, adviser.

Measurement of Fluid Resistance in Oscillatory Unsteady Flow in a Smooth Pipe. DON B. JONES. M.S. Thesis, August 1954; Professor McNown, adviser.

Improved Culvert Inlet Design. JOHN E. FLACK. M.S. Thesis, August 1954; Professor McNown, adviser.

Pressure Conditions at the Outlet of a Pipe. DANIEL RUEDA-BRICENO. M.S. Thesis, February 1954; Professor Howe, adviser.

Effect of Inlet Design on Square Culvert Flow. HENRY MAKSOUD. M.S. Thesis, February 1954; Professor Metzler, adviser.

Studies of Multiple Laterals in Manifold Flow. ADOLFO YANES. M.S. Thesis, February 1951; Professor McNown, adviser.

Studies of Manifold Flow. JULIO ESCOBAR. M.S. Thesis, August 1948; Professor McNown, adviser.

A Study of Converging Flow in Pipe Lines. SADIQ M. NIAZ. M.S. Thesis, June 1947; Professor McNown, adviser.

A Study of Diverging Flow in Pipe Lines. JAMES R. BARTON. M.S. Thesis, August 1946; Professor McNown, adviser.

The Removal of Air from Pipe Lines by Flowing Water. PERCY H. BLISS. M.S. Thesis, May 1942; Professor Kalinske, adviser.

Hydraulics of Vertical Drain and Overflow Pipes. WILLIAM M. WACHTER. M.S. Thesis, August 1941; Professor Kalinske, adviser.

Entrainment of Air in Pipes by Flowing Water. JAMES M. ROBERTSON. Ph.D. Dissertation, August 1941; Professor Kalinske, adviser.

Correlation of Experimental Data and Rational Equations on Boundary Roughness and Resistance. FREDERICK L. HOTES. M.S. Thesis, August 1941; Professor Rouse, adviser.

Pressure and Velocity Conditions at a Conduit Outlet. NOLAN PAGE. M.S. Thesis, June 1931.

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Measurement of Pressure in the Interior of Pipes. HERBERT E. HOWE. M.S. Thesis, August 1930.

A Study of the Hydraulic Phenomena at Sudden Enlargements Within a Pipe. LLOYD L. HESKETT. M.S. Thesis, July 1929.

Investigation of the Pressure and Velocity in Conduit Outlets. RAYMOND N. WELDY. M.S. Thesis, June 1929.

Investigation of Pressure and Velocity Distribution in a Conduit. J. C. DUCOMMUN. M.S. Thesis, June 1928.

Study of Spiral Motion of Flow of Water Around Bends. GOGULAPATI GANGADHARAN. M.S. Thesis, June 1927.

A Study of Pressure and Velocity Changes at the Outlet of a Conduit. FRED B. SMITH. M.S. Thesis, June 1927.

Pressure and Velocity Distribution at Conduit Outlets. HARRY DALE BROCKMAN. M.S. Thesis, June 1926.

A Study of Flow Conditions at the Outlet of a Circular Pipe. WALDO E. SMITH. M.S. Thesis, June 1924.

The Flow of Water in Vitrified Clay Pipe. VERNER RAYMOND MUTH. M.S. Thesis, 1923.

DAMS, SPILLWAYS, AND STILLING BASINS

Spillway Discharge at Other Than Design Head. JOHN J. CASSIDY. Ph.D. Dissertation, June 1964; Professor Rouse, adviser. A method was developed for the numerical solution of steady, irrotational, free-surface flow over a known continuous lower boundary in a gravity field. In particular, the method involves the solution of finite-difference approximations — in the complex-potential plane — of the Laplace equation in terms of the inclination of the velocity vector. All geometric variables were specified in the physical plane, but, for subcritical approaching flow, the total head was unknown at the outset. However, it was possible, by comparison of successive iterations for the coordinates of the free-surface profile, to formulate an algorithm for correction of an assumed total head. Free-surface profiles, pressure distributions and discharge coefficients were obtained for flow over three spillway shapes at five ratios of head to design head. The results compared favorably

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with experimental measurements. Boundary-layer characteristics were obtained experimentally for flow over a spillway model of standard shape. As a result it can be concluded that separation will not occur on a standard spillway unless heads greater than three times the designed are allowed; if the spillway is large, cavitation may occur at a much lower head than that for which separation occurs. Spillways which will not cavitate through the entire range of expected heads can be designed from the pressure-characteristic curves resulting from this study.

Discharge Characteristics of a Tainter Gate on a Spillway. ZYNOWIJ M. GLOWIAK. M.S. Thesis, February 1955; Professor Metzler, adviser.

Effect of the Reduction of Stilling Basin Sidewalls on Tailwater Elevations in the Basin. JOHN R. SHEPPARD. M.S. Thesis, June 1953; Professors Alin and Howe, advisers.

A Study of Flow Over Lateral Spillways. HECTOR MORENO-GOMEZ. M.S. Thesis, August 1948; Professor McNown, adviser.

Tests on Morning-Glory Type of Siphon-Spillway. HARI SINGH CHOWDHARY. M.S. Thesis, June 1948; Professor Posey, adviser.

Roller-Type Stilling Action. HAROLD W. FELDT. M.S. Thesis, August 1945; Professor Posey, adviser.

Experimental Study of the Free Overfall as a Function of the Froude Number. JAIME M. MONTAÑA. M.S. Thesis, April 1945; Professor Posey, adviser.

Design of a Dam on the Seyhan River, Turkey. ORHAN AKYUREK. M.S. Thesis, June 1940; Professor Lane, adviser.

The Functional Design of Flood-Control Reservoirs. FU-TE I. Ph.D. Dissertation, June 1938.

A Study of Piping Action Below Masonry Dams on Earth Foundations by Electric Analogy. K. W. LIU. M.S. Thesis, August 1937.

Stilling Pools for Spillways. CHARLES WESLEY KINNEY. M.S. Thesis, June 1935.

A Laboratory Investigation of Overflow Sections with Sand Core. HERROL JAMES SKIDMORE. M.S. Thesis, May 1935.

History of the Art of Building Earth Dams. ORVAL J. BALDWIN. M.S. Thesis, June 1934.

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Lateral Dispersion of Spillway Discharge. FREDERICK S. WITZIGMAN. M.S. Thesis, June 1933.

The Causes of Failure of Gravity Masonry Dams. TEVFIK FIKRET. M.S. Thesis, June 1932.

Tests on Sand Dikes Protected Against Erosion by Overflowing Water. KARL JETTER. M.S. Thesis, August 1931.

Study of Stilling Basin Design. C. MAXWELL STANLEY. M.S. Thesis, February 1930.

The Determination of the Coefficients of Discharge Over an Ogee Dam, With and Without Pier Contractions. E. E. ERICKSON and P. L. MERCER. M.S. Thesis, June 1922.

DRAFT TUBES AND DIFFUSERS

Comparison of Efficiencies of Axial Flow Draft Tubes. SHIEH-WEN MAO. M.S. Thesis, February 1957; Professor Howe, adviser.

Relative Efficiency of Draft Tube Forms. BENOYENDRA CHANDA. M.S. Thesis, August 1955; Professor Howe, adviser.

Tests of Model Flaring Draft Tube with Conical Inserts. HSI-HOU CHANG. M.S. Thesis, June 1937.

Flow Characteristics in Elbow Draft Tubes. CHARLES A. MOCKMORE. Ph.D. Dissertation, August 1935.

A Study of the Hydrodynamics of Spreading Draft Tubes. ANDREAS LUKSCH. Ph.D. Dissertation, June 1935.

An Experimental Study of the Most Favorable Distance of a Water Turbine Draft Tube from the Tail Race Floor. ANDREAS LUKSCH. M.S. Thesis, July 1933.

Flow in Bends of Quarter-Turn Draft Tubes. CHARLES A. MOCKMORE. M.S. Thesis, June 1932.

ELECTRICAL ANALOGIES

Analogue Computer for Multiplication. JOHN J. STAFFORD. M.S. Thesis, August 1952; Professor Lonsdale, adviser.

Deflection of a Liquid Jet by a Perpendicular Boundary. ANDRE LeCLERC. M.S. Thesis, August 1948; Professor Rouse, adviser.

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Use of the Three-Dimensional Electrical Analogy in the Design of Conduit Transitions. MOHAMED M. HASSAN. Ph.D. Dissertation, August 1948; Professor Rouse, adviser.

The Solution of Certain Two-Dimensional Flow Problems by Means of an Electrical Analogy. HORACE FENNELL SYKES, JR. M.S. Thesis, June 1935.

A Study of Certain Analogies in the Fields of Dynamics and Elasticity. ROBERT K. VIERCK. M.S. Thesis, August 1933.

FLOW MEASUREMENT

Evaluation of Polyurethane Coated Wires for Hot-Wire Anemometry. SATYESH KUMAR NANDA. M.S. Thesis, August 1968; Professor Glover, adviser. An experimental and theoretical investigation of the frequency response of coated wires for operation with constant-temperature hot-wire anemometers is presented. The wire studied is a commercially available wire coated with polyurethane varnish. Results obtained show that stable operation of hot-wire anemometers is possible with coated wires and that the frequency response is adequate for low-frequency studies.

Effect of Turbulence Characteristics Upon the Registration of a Price Current Meter. MIN-HSIUNG YANG. M.S. Thesis, August 1967; Professor Howe, adviser. The effects of turbulence characteristics on the response of a Price current meter have been investigated. The current meter was observed to over-register when placed in a turbulent stream, and the causes of the over-registration have been considered. The influence of turbulence intensity, turbulence scale and diffusion coefficient was studied, and the significance of these characteristics was evaluated.

Optimum Traversing Speeds for Measurements in Zones of Turbulence. CHENG YENG HUNG. M.S. Thesis, June 1966; Professor Hubbard, adviser. The purpose of this study was to determine the optimum traversing speed of the probe when performing a continuous measurement of the turbulent variables. The relationship between the measured error and the traversing speed was derived as

$$E_{lag} = \frac{1}{q_d(t)} \frac{dq_d(t)}{dS} RCv$$

where $q_d(t)$ is a turbulence variable, S is a reference distance, RC is a time constant, and v is a velocity.

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When the amplitude of a measured quantity is low enough and the frequency of the fluctuation of a measured quantity is high enough, this method can be used with confidence.

Factors Affecting the Stability of Hot-Wire Velocity Sensors in Liquids. SHENG-TIEN HSU. M.S. Thesis, February 1966; Professor Hubbard, adviser. Measurements were made to verify the heat transfer parameter in Kramers' formula and to investigate the viscous and aging effects on the stability of energy dissipation of the wire. Typical two-mm-long 0.0007″ Hytemco wires were used in doing this experiment. Significant results showed that King's relationship between energy dissipation and velocity was valid and that the energy dissipation of the wire tended to be much more stable after it was aged.

Use of Pressure Probes for the Measurement of Fluid Turbulence. VLADIMIR JEZDINSKY. M.S. Thesis, August 1965; Professor Hubbard, adviser. The purpose of this investigation was to find some simple method for measuring turbulence, which would permit operating under field conditions where no electronic equipment can be used. The paper demonstrates a feasibility of computing the turbulent characteristics u′, v′, u′v′ from the mean pressures at the openings of a probe consisting of two modified total-head tubes with tip openings sloped at 55°. Calibration of the probe by rotating it in non-turbulent flow gives the mean-pressure difference and sum as a linear and parabolic function of the angle of attack, respectively. Rotating the probe in the turbulent flow gives the same functional relationship, but the coefficients contain quantities u′, v′, u′v′ which can be computed therefrom.

The method was evaluated by taking measurements with the suggested probe in a submerged air jet, and comparing the results with those from the hot-wire anemometer.

Techniques for Detecting and Analyzing Unsteady-Flow Variables. JOHN RICHARD GLOVER. Ph.D. Dissertation, June 1965; Professor Hubbard, adviser. The first three parts of this dissertation deal with the design and improvement of electronic instruments that are used for the detection and analysis of unsteady-flow variables. The last part is an analysis of the error, introduced by the averaging of the signal before squaring, in the measurement of power spectral density of unsteady-flow variables when the filter used in selecting the frequencies has a very narrow bandpass. The first of two instruments that have had their performance improved is the constant-temperature hot-wire anemometer.

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An increased signal-to-noise ratio has been achieved by reducing the regenerative or positive feedback in the control amplifier. Also, a linearizing circuit has been developed which is completely transistorized (no function generator) and temperature stable. The second instrument which has been improved is the one that measures the intermittency factor of a completely random signal, such as generated by a turbulence-detecting instrument. The improvement results because the smoothing filter normally required for pseudo-satisfactory operation, has been eliminated by including the slope of the signal in the control of the frequency-gating signal. The third instrument included as a part of this dissertation is an Unlimited-Time Integrator. The instrument is capable of integrating a signal for a period of time that is limited only by the unsteadiness of the system which is external to the integrator.

Heat Transfer from Fine Wires in Flowing Liquids. ALBERT Y. KUO. M.S. Thesis, January 1965; Professor Hubbard, adviser. Because of the instability of a hot-wire anemometer in water, the factors influencing heat transfer from an electrically heated wire in flowing liquids were investigated. Kramers' formula was shown to agree with experimental results for filtered fresh water and unfiltered mineral oil. In salt water the rate of heat transfer decreased with increasing electrical conductivity. Deposition was found on the wire after being used in highly concentrated salt water. The deposition of the impurities in unfiltered water invariably reduced the rate of heat transfer.

Transistorized Hot-Wire Anemometer and Linearizing Circuit. JOHN R. GLOVER. M.S. Thesis, August 1961; Professor Hubbard, adviser. Transistorized control circuits were employed to keep the temperature of a wire for use in air essentially constant, thus eliminating the need for consideration of the thermal lag of the wire. Also, by using constant-temperature operation of the wire the frequency response of the instrument was greatly increased. The nonlinear signal voltage developed by the wire was linearized by a new method that increased the dynamic range of the instrument, which also increased its accuracy and reliability.

Application of a Magnetic Tape Recorder to the Analysis of Continuous Random Signals. JACK L. MORTLEY. M.S. Thesis, August 1959; Professor Ware, adviser.

Measurement of Flow Characteristics by the Hot-Film Technique.

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SUNG-CHING LING. Ph.D. Dissertation, June 1955; Professor Yih, adviser.

Constant-Temperature Hot-Wire Anemometry with Application to Measurements in Water. PHILIP G. HUBBARD. Ph.D. Dissertation, June 1954; Professor Rouse, adviser.

The Study of the Price Current Meter in Low Velocity Flow. WILLIAM G. HALL. M.S. Thesis, February 1953; Professor Boyer, adviser.

An AC-Bridge Hot-Wire Anemometer with Constant Temperature Operation. PETER L. BERNTSEN. M.S. Thesis, August 1950; Professor Lonsdale, adviser.

A Direct Optical Method for Measuring Fluid Velocities in Laminar Flow. ELLIS BERTRAM PICKET. M.S. Thesis, August 1950; Professor Posey, adviser.

The Development of a Turbulence Pitot for Use in Water. DAVID W. APPEL. M.S. Thesis, June 1949; Professor Rouse, adviser.

A Constant-Temperature Hot-Wire Anemometer for the Measurement of Turbulence in Air. PHILIP G. HUBBARD. M.S. Thesis, February 1949; Professor Rouse, adviser.

The Measurement of Velocity of Flowing Water by Electrical Methods. MARION C. BOYER. M.S. Thesis, August 1947; Professor Rouse, adviser.

Determination of Shape of Nappe and Coefficient of Discharge of a Vertical Sharp-Crested Weir, Circular in Plan, with Radially Inward Flow. CECIL S. CAMP. M.S. Thesis, June 1937.

Investigation of Side-Contraction Meter. HENRY P. EVANS. M.S. Thesis, August 1933.

An Investigation of the Characteristics of a Jet Pitot Tube. FRANK A. KULAS. M.S. Thesis, July 1933.

An Investigation of the Side-Contraction Meter. R. F. POSTON. M.S. Thesis, June 1932.

An Investigation of the Causes for Variation in the Discharge Coefficients of Triangular Weirs. MONTOK TOM. M.S. Thesis, June 1931

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Abstracts Of Graduate Theses

A Comparison of Discharge Measurements by Weir, Pitot Tube and Current Meter. DAVID LEROY YARNELL. M.S. Thesis, June 1926.

The Flow of Water Over a Rectangular Weir as Affected by Various Degrees of Roughening of its Upstream Face. GLEN N. COX. M.S. Thesis, 1926.

The Effect of Roughness of Weir Face on Discharge Over a Rectangular, Suppressed, Sharp-Crested Weir. J. W. HOWE. M.S. Thesis, June 1925.

A Study of Variations in Water Pressure as Measured by Piezometer Tubes. GEORGE E. SHAFER. M.S. Thesis, June 1924.

Calibration of a Large Head Gate. HASHU AJWANI. M.S. Thesis, 1923.

Ground Water

Mechanics of Bank Seepage During Flood Flows. ERNEST C. POGGE. Ph.D. Dissertation, August 1966; Professor Howe, adviser. The mechanics of bank seepage during flood flows was studied both analytically and by the collection and analysis of field data. Six standard methods were used in the analysis of the field data to determine the hydraulic characteristics of the alluvial aquifer. An analytic model was developed to predict ground-water levels, bank seepage and bank storage during the passage of a flood wave. The results of the model were verified by field data.

Evaluation of Unconfined Flow to Multiple Wells by the Membrane Analogy. VAUGHN E. HANSEN. Ph.D. Dissertation, June 1949; Professor Rouse, adviser.

Ground-Water Flow in Rapid Creek Watershed. MAURICE L. ALBERTSON. M.S. Thesis, July 1942; Professor Howe, adviser.

An Investigation of Ground Water Movements. TSUNG-PEI TSUI. Ph.D. Dissertation, June 1937, Professor Mavis, adviser.

Experimental and Analytical Study of the Permeability of Sand. EDWARD FRANKLIN WILSEY. Ph.D. Dissertation, June 1935.

A Laboratory Study of the Flow of Water Through Granular Material. CHIH-CHAO WANG. M.S. Thesis, June 1935.

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A Laboratory Study of Ground Water Profiles. TSUNG-PEI TSUI. M.S. Thesis, June 1935.

Capillary Flow Through Sand Dams. RICHARD LEE JEWETT. M.S. Thesis, July 1934.

HYDRAULIC JUMP

The Mechanism of Energy Dissipation in the Hydraulic Jump. S. NAGARATNAM. M.S. Thesis, June 1957; Professor Rouse, adviser.

Characteristics of Turbulence in an Air-Flow Model of the Hydraulic Jump. TIEN-TO SIAO. Ph.D. Dissertation, June 1954; Professor Rouse, adviser.

Effect of the Submergence of the Stilling Basin Sidewalls on the Hydraulic Jump. STAVROS NICOLAOU. M.S. Thesis, August 1951; Professors Howe and Alin, advisers.

Control of the Hydraulic Jump by Sills. JOHN W. FORSTER and RAYMOND R. SKRINDE. M.S. Thesis, February 1947; Professor Rouse, adviser.

A Length Criterion for the Hydraulic Jump. BHUBANESHWAR BEHERA and ASRAR AHMAD QURESHY. M.S. Thesis, February 1947; Professor Posey, adviser.

The Effect of Certain Fluid Properties Upon the Profile of the Hydraulic Jump. MORGAN D. DUBROW and JOHN C. GOODRUM. M.S. Thesis, February 1941; Professor Posey, adviser.

The Hydraulic Jump in Trapezoidal Channels. PEI-SU HSING. Ph.D. Dissertation, August 1937.

Hydraulic Jump in Enclosed Conduits. CARL E. KINDSVATER. M.S. Thesis, February 1937.

The Moving Hydraulic Jump. GILBERT H. DUNSTAN. M.S. Thesis, August 1929.

HYDRAULIC STRUCTURES

Some Aspects of Flow-Induced Vibrations of Hydraulic Control Gates. FREDERICK A. LOCHER. Ph.D. Dissertation, February

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1969; Professors Kennedy and Naudascher, advisers. Vibration of control gates such as those used in dams and appurtenant outlet works have been noted by several of the agencies responsible for their design and construction. The objective of this research program was to investigate how basic flow instabilities present in the flow past an idealized gate geometry could lead to flow-induced structural vibrations.

The gate geometry chosen for study represented a two-dimensional, flat-bottomed gate just protruding into the flow. Two ratios of protrusion distance b to gate thickness d ($d/b = 1$ and $d/b = 3$) were investigated. The RMS values and spectral density functions of the fluctuating force on a significant portion of the gate bottom were measured.

The study was divided into two phases: (1) the gate model was held stationary; and (2) the gate model was forced to vibrate at a series of known amplitudes and frequencies. During phase 1, measurements of the RMS values and spectral densities were obtained with cavitating and noncavitating flows. The role of cavitation was found to be strongly dependent upon the gate geometry.

For $d/b = 1$, no tendency toward periodicity in the flow-induced forces was detected with the gate model stationary, whereas for $d/b = 3$, a definite tendency toward periodicity was indicated by the spectral density function. The periodicity results from the unstable reattachment of the free-shear layer formed at the leading edge of the gate to the downstream edge of the model. This flow instability produces fluctuations of sufficient intensity to initiate vibrations.

Forced oscillation of the gate model for $d/b = 1$ showed conclusively that the free-shear layer is highly sensitive to disturbances at its origin, as might be expected. For $d/b = 3$, not only does a flow instability exist which may excite vibrations, but the mechanism of this instability does not break down once the structure begins to vibrate. The dominant frequency component remains present on the fluctuating force induced on the gate bottom to maintain or further augment the vibration.

Effect of Lifting-Beam Geometry on the Vibration of Multiple-Leaf Gates. CESAR FARELL. M.S. Thesis, June 1965; Professor Naudascher, adviser. The vibration-inducing hydrodynamic forces acting on a simulation of a multiple-leaf gate during closure of the bottom leaf were studied experimentally. From the various excitation mechanisms that were found to exist, particular attention was given to the effect of the interacting periodic wakes behind gate leaf and lifting beam as a function of gate position, beam height and spacing between gate and beam.

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The essential role played by hydroelastic effects in flow-induced structural vibrations is emphasized.

Effect of Gate Slots Upon the Hydrodynamic Forces Acting on High-Head Gates. NORBERT M. GILLISSEN. M.S. Thesis, January 1965; Professor Naudascher, adviser. This investigation is a continuation of the studies done by Kobus and Rao. The downpull was obtained by graphical integration of the pressure distribution on the gate bottom. Oil-flow pictures of the flow pattern over the gate lip are presented for various gate openings and configurations of the slot.

Effect of Gate and Conduit Geometry Upon the Hydrodynamic Forces Acting on High-Head Gates. RAGAM PANDU RANGANADHU RAO. M.S. Thesis, August 1963; Professor Naudascher, adviser. In an extension of Kobus' study (M.S. thesis, 1963) of the effect of lip shape on hydraulic downpull, the effect of the relative upstream radius of the gate lip and of the relative conduit height upon the dimensionless downpull coefficients was made. The determination of the susceptibility of a given gate and conduit geometry to development of subatmospheric pressures along the gate bottom and to unstable flow conditions was also made. Results showed that the downpull decreases with an increase in the upstream relative radius of the gate lip and increases with an increase in the relative conduit height.

Effect of Lip Shape Upon Hydraulic Forces on High-Head Gates. HELMUT E. KOBUS. M.S. Thesis, February 1963; Professor Naudascher, adviser. The relative pressure distribution along the bottom and top surface of a vertical leaf gate at partial openings has been obtained from air-tunnel experiments. The effects of the angle of inclination of the bottom surface and of an extension of the downstream skinplate have been investigated. It was found that lip shapes with large angles of inclination of the bottom surface or large extensions of the downstream skinplate yield the most favorable conditions with respect to the mean downpull. Violent pressure fluctuations were observed near the transition to complete separation of flow from the gate lip. The conditions for the development of subatmospheric pressure along the gate lip were examined and analyzed.

An Experimental Study of Energy Dissipators for Culvert Outlets. LEONCIO RODA. M.S. Thesis, August 1953; Professor Metzler, adviser.

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The Effect of Lip Angle Upon Flow Under a Tainter Gate. ARTHUR TOCH. M.S. Thesis, February 1952; Professor Metzler, adviser.

A Study of Flow From a Submerged Sluice Gate. HAROLD ROBERT HENRY. M.S. Thesis, February 1950; Professor Rouse, adviser.

Diffusion of Flow From a Submerged Sluice Gate. HSIN-KUAN LIU. M.S. Thesis, February 1949; Professor Rouse, adviser.

Design of Outlet Works of the Han River Flood Control Reservoir. HSUAN KUO. M.S. Thesis, August 1939; Professor Lane, adviser.

Hydraulics of Culverts. ARTHUR R. LUECKER. M.S. Thesis, February 1939; Professor Mavis, adviser.

Discharge Coefficients for Non-Submergible Tainter Gates. EDWARD S. PRETIOUS. M.S. Thesis, January 1939.

The Hydraulics of Tainter Gates. ROSS NYMAN BRUDENELL. M.S. Thesis, August 1938.

Determination of the Coefficient of Discharge of a Tainter Gate Over a Horizontal Sill. JUNG-KO PENG. M.S. Thesis, June 1937.

The Effect of Symmetrical and Unsymmetrical Roller Gate Operation on Discharge Coefficients. CLARENCE N. MORANG. M.S. Thesis, February 1937.

Coefficients of Discharge of Tainter Gates. HOY D. DAVIS. M.S. Thesis, June 1936.

The Stability of Embankments in Water. FRANCIS R. HOEHL. M.S. Thesis, June 1935.

Stress Analysis in a Roller Gate Dam, No. 15, Mississippi River. PHILIP F. KROMER, JR. M.S. Thesis, 1933.

Discharge Coefficients of Tainter Gates. SUDHENDU KIRAN GUHA. M.S. Thesis, June 1932.

Hydrology

Comparison of Peak Discharge from Rainfall and from Combined Rainfall and Snow Melt. TOMMY A. CAMARILLO. M.S. Thesis, August 1967; Professor Howe, adviser. The comparison of peak dis-

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charge with runoff volume from rainfall and from combined rainfall and snow melt revealed greater runoff volume under the latter conditions for the streams of Northern Iowa. The correlation coefficient between peak discharge and runoff volume showed that drainage and stream density characteristics were the important parameters for surface runoff from rainfall, whereas drainage density, stream density and basin shape characteristics were the more prominent parameters under snow covered ground conditions.

The Use of Probability and Statistics in Prediction of Runoff Frequency Based on Precipitation and Infiltration Frequencies. CHUN-YO SHEN. M.S. Thesis, February 1967; Professor Howe, adviser. The purpose of this investigation was to determine the runoff frequency from precipitation and infiltration frequencies. In this study the analysis was made with the available data for the two watersheds, the Roanoke River and the Hudson River.

A method for serving this purpose was developed by the writer, which was introduced briefly as follows: If the precipitation and infiltration data are arranged in descending order of magnitude designated by I- and J-values, respectively, it can be seen that each amount of the observed runoff is constituted by an ordered pair of precipitation and infiltration values. Analyzing these various ordered pairs, there appeared two obvious characteristics. (1) The precipitation of a given order may combine with a certain range of orders of infiltration. For example, in the Roanoke River, the precipitation of order 10 may combine with the infiltration from order 3 through 27, and the precipation of order 15 with the infiltration from 8 to 32. (2) The different value I-J, obtained from each ordered pair, has different probability of occurrence. Also, a storm can cause one and only one flood.

Based on these facts, order of precipitation and order of infiltration were introduced in formulating the model of probability density function. Since runoff was obtained from the I-th order precipitation minus the J-th order infiltration, the probable occurrence of runoff could be determined by substituting the statistical parameters I, J in that probability density function. From different combinations of the precipitation and infiltration, the same value of runoff could be obtained. The probable occurrence of this runoff should be the sum of probable occurrences from such different combinations.

Then the number m of times of runoff of a particular amount or greater was determined by cumulating the probable occurrences in ac-

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cordance with the runoff arranged in descending order of magnitude. Consequently, the estimated recurrence interval of a given runoff, in years, could be computed by

$$Fr = \frac{t + 1}{m}$$

in which t is the number of years of record.

Prediction of Runoff Frequency Based on Precipitation and Infiltration Frequencies. SRINIVASAN MUKUNDAN. M.S. Thesis, February 1963; Professor Howe, adviser. A study based on the assumption, Runoff frequency = Precipitation frequency × Infiltration frequency, was made on two watersheds: of 388- and 792-square-mile areas with 56 and 45 years of record, respectively. The observed surface runoff was compared with the estimated runoff based on combinations of precipitation and infiltration frequencies and did not show any agreement. The frequency of estimated runoff was found to be far greater than the observed frequency.

The Effect of Flood Magnitude on Unit Hydrograph Characteristics. JAMES LAWRENCE LONG. M.S. Thesis, February 1962; Professor Howe, adviser. This thesis is an analysis of the factors affecting the unit hydrograph with special emphasis on the effect of flood magnitude on the peak of the distribution graph and on the time of occurrence of the peak with respect to the center of precipitation excess. Included is also the study of 24 hydrographs from two different drainage basins, involving runoff volumes varying from 0.6 to 5.75 inches and peak flows from 2,800 to 36,000 cubic feet per second.

Flood Insurance. GERALD R. HARTMAN. M.S. Thesis, June 1960; Professor Posey, adviser. The insurance and technical problems involved in a flood insurance program are discussed, using basic insurance principles and information relative to floods as guides. The Federal Flood Insurance Act of 1956 and its results are also discussed. Other approaches to the flood problem are summarized and suggestions to make flood insurance a reality are offered.

Prediction of Runoff Frequency from Precipitation and Infiltration Frequencies. MANZUR AHMED CHOWDHURY. M.S. Thesis, August 1958; Professor Howe, adviser.

Relation of Soil Moisture Content and Rainfall Intensity to Infil-

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tration Rates on Rapid Creek. JYUH-SHENG CHANG. M.S. Thesis, June 1958; Professor Howe, adviser.

Investigation of Storage Effects of Reservoirs Subjected to Superfloods. YUAN-PO KOU. M.S. Thesis, February 1958; Professor Posey, adviser.

A Study of the Factors Which Affect Infiltration Rates on the Ralston Creek Watershed. MERWIN D. DOUGAL. M.S. Thesis, February 1958; Professor Howe, adviser.

Hydrologic Safety Standards for Spillway Capacity. OLAF M. ERICKSON. M.S. Thesis, August 1957; Professor Posey, adviser.

Investigation of Storage Effects of Reservoirs Subjected to Superfloods. STEVEN DOLA. M.S. Thesis, February 1957; Professor Posey, adviser.

A Method for the Synthesis of Unit Hydrographs for Small Watersheds. ALBERTO M. VILLARES. M.S. Thesis, June 1956; Professor Howe, adviser.

Synthetic Unit Hydrographs Based on Triangular Inflow. JAMES C. I. DOOGE. M.S. Thesis, June 1956; Professor Howe, adviser.

Frequency of Infiltration Intensities on Rapid Creek Watershed. CHIEH-SHYANG SONG. M.S. Thesis, February 1956; Professor Howe, adviser.

Evaluation of the Storage Factor for Flood Routing in Natural Channels. ALBERTO VAL. M.S. Thesis, June 1954; Professor Boyer, adviser.

A Policy for Flood Control. IBRAHIM MAHMOUD MOSTAFA. Ph.D. Dissertation, June 1954; Professor Posey, adviser.

A Study of the Relationship Between Watershed Characteristics and Distribution Graph Properties. RICHARD G. WARNOCK. M.S. Thesis, February 1952; Professor Howe, adviser.

Minimum Expected Yield from Small Watersheds Using Synthetic Meteorological Years. CHARLES E. LEWALD. M.S. Thesis, June 1950; Professor Howe, adviser.

Influence of the Location of Storm Runoff on Shape of the Unit

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Hydrograph. YU-CHEH SOONG. M.S. Thesis, February 1950; Professor Howe, adviser.

A Study of Concentration Time on Ralston Creek Watershed. ROBERT L. SMITH. M.S. Thesis, August 1948; Professor Howe, adviser.

Analysis of Evaporation as a Boundary-Layer Phenomenon. MAURICE L. ALBERTSON. Ph.D. Dissertation, January 1948; Professor Rouse, adviser.

A Study of Infiltration on Rapid Creek Watershed. ROBERT W. MOORMAN. M.S. Thesis, August 1947; Professor Howe, adviser.

A Comparison of Maximum Runoff Formulas with Actual Measurements on Certain Watersheds in Iowa. FU-HUAN FANG. M.S. Thesis, June 1947; Professor Doty, adviser.

Synthesis of the Runoff Hydrograph on Ralston Creek. MARION R. CARSTENS. M.S. Thesis, June 1947; Professor Howe, adviser.

A Study of Possible Extensions of the Huai River Flood-Control Plan. PAO-FU CHU. M.S. Thesis, July 1942; Professor Lane, adviser.

Analysis of Discharge-Recession Curves for Three Iowa Streams. JULIAN R. FLEMING. M.S. Thesis, August 1941; Mr. B. S. Barnes, adviser.

The Effect of Freeboard on Evaporation from a Class "A" Evaporation Pan. RUSSELL W. REVELL. M.S. Thesis, February 1941; Professor Howe, adviser.

Studies on Runoff from River Bottom Lands. MARVIN O. KRUSE. M.S. Thesis, June 1940; Professors Lane and Howe, advisers.

A Digest of the English Literature of Flood Waves. HUNG-CHI LAY. M.S. Thesis, June 1938.

Water Requirements for Rice Irrigation. TSZE-TING CHENG and CHUNG-LING PIEN. M.S. Thesis, June 1938.

Infiltration of Water in Some Iowa Soils. HAROLD E. COX. M.S. Thesis, August 1929.

Runoff Characteristics of Certain Iowa Streams. CHARLES L. BARKER. M.S. Thesis, July 1928.

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Runoff Characteristics of Certain Iowa Streams. CHARLES R. HUBER. M.S. Thesis, June 1927.

A Study in Flood Waves. ELMER E. MOOTS. Ph.D. Dissertation, February 1927.

A Study of Iowa River Floods at Iowa City. G. H. HICKOX. M.S. Thesis, 1926.

Prediction of Floods. PING-YI LIN. M.S. Thesis, January 1926.

A Hydrographic Survey of the North Branch of Ralston Creek. T. L. HERRICK. M.S. Thesis, June 1924.

IRROTATIONAL FLOW

A Free-Streamline Model of a Two-Dimensional Wake. AN-CHING LIN. Ph.D. Dissertation, January 1970; Professor Landweber, adviser. Flow of a uniform stream past a two-dimensional wedge (or flat plate) with finite separation pocket is simulated by a pair of symmetric closed free streamlines placed behind a wedge (or a flat plate). Explicit solutions of the problem are obtained by conformal mapping. The physical plane has been treated as triply connected and mapped to a canonical annular region and then to a parametric rectangular region. Analytic continuations are possible, by the Schwarz reflection principle, to permit the construction of mapping functions in terms of the Weierstrass elliptic and associated functions. The corresponding flows with symmetric wall restrictions have also been solved. Some cases of flow past a flat plate with and without walls have been computed.

Potential Flow about a Prolate Spheroid in Axial Horizontal Motion Beneath a Free Surface. CESAR FARELL. Ph.D. Dissertation, August 1968; Professor Landweber, adviser. The potential flow about a prolate spheroid in axial horizontal motion beneath a free surface is treated analytically. While the free-surface boundary condition is linearized, the boundary condition on the surface of the body is satisfied exactly. Thus, an "exact" solution, within the theory of infinitesimal waves, is obtained. The solution is sought in the form of a distribution of sources on the surface of the spheroid, of unknown density; the analysis yields an infinite set of equations for determining the coefficients of the expansion of the density function in spherical harmonics (and, therefore, for determining the coefficients of the expansion of the potential in spheroidal harmonics). An expression is derived for the wave re-

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sistance of the spheroid in terms of these coefficients through application of the Lagally theorem. The expression for the wave resistance given by Havelock in 1931 is obtained as the first approximation in the present analysis.

Numerical evaluations were performed, using an IBM 360/65 computer, for a Froude number (defined with respect to the distance between foci) of 0.4, a focal distance equal to twice the depth of submergence and several values of the eccentricity. The numerical solution of the infinite set of equations was obtained, keeping an increasing number of equations (and, therefore, calculating an increasing number of coefficients of the series expansions), up to a maximum of 20. The wave resistance and the density of the source distribution were evaluated at each stage, the latter along meridian planes of the spheroid. For a prolate spheroid with a slenderness ratio slightly larger than five, the wave resistance is larger than Havelock's by about 34 percent. For slenderness ratios of 3.64 and 2.40 the corrections are as much as 90 percent and 368 percent, respectively, of Havelock's approximation (the spheroid corresponding to the latter slenderness ratio is very close to piercing the free surface).

An infinite set of equations, essentially equivalent to that obtained in this work for determining a source distribution on the surface of the spheroid, which satisfies exactly the boundary condition on its surface, was obtained by Bessho, using an entirely independent derivation. The coefficients of Bessho's system of equations, however, appear to be incorrect, possibly because of typographical errors, and his numerical evaluations are rather inaccurate. The value of the wave resistance obtained by Bessho, for a Froude number of 0.395, a focal distance equal to twice the depth of submergence, and a slenderness ratio of 4.17, exceeds Havelock's approximation by 146 percent; according to the numerical evaluations reported here, the correction should instead be in the neighborhood of 60 to 65 percent of Havelock's value.

Numerical Solution of an Integral Equation for Flow from a Circular Orifice. BRUCE W. HUNT. Ph.D. Dissertation, August 1967; Professor Rouse, adviser. Three internationally separate investigations since the year 1916 have treated specific cases of free-surface potential flow through an axially symmetric orifice. In the year 1956, however, the American mathematician, Garabedian, questioned the accuracy of these previous solutions. Hence, this study was initiated as an attempt to either confirm or disprove the results of previous research on the

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problem. An integral equation resulting from a vorticity distribution over the boundary is used to solve numerically for the flow through an orifice. Free-surface profiles, contraction coefficients and boundary pressure distributions are determined for four different ratios of orifice area to pipe area, and a comparison is made between the numerical and experimental results of both this study and previous studies. The final results of this study agree closely with the results of Garabedian's investigation.

Vibration Frequencies of a Free-Free Cylindrical Beam of Finite Length Immersed in an Inviscid Fluid. ANTONIO PITA-SZCZESNIEWSKI. Ph.D. Dissertation, August 1967; Professor Landweber, adviser. Free vibrations of an elastic bar of circular cross-section and finite length, which is immersed in an inviscid fluid contained in an infinite cylindrical duct, are studied. The vibration is assumed to be of small amplitude, and the end conditions of the bar are taken to be free. The fluid region is divided into three parts; velocity-potential expressions, in terms of Bessel functions, are derived for each part. The velocity potentials and their normal derivatives are required to be continuous at the interfaces between the various fluid regions. The motion of the fluid is then incorporated into the system through its kinetic energy, and the technique of Rayleigh-Ritz is employed to evaluate the natural frequencies of vibration. Final results are then compared with those obtained by other methods.

Experimental Investigation of the Added Mass of Cylinders Oscillating Horizontally in a Free Surface. CHOU-CHEN WU. M.S. Thesis, August 1959; Professor Landweber, adviser.

The Added Masses of Prolate Spheroids Accelerating Under a Free Surface. M. R. BOTTACCINI. Ph.D. Dissertation, June 1958; Professor Landweber, adviser.

Path of a Spherical Particle in the Flow Field about a Sphere. WOOK DONG KIM. M.S. Thesis, February 1956; Professor Landweber, adviser.

An Exploratory Study of Vortex Rings. ARTHUR K. JOHNSTON. M.S. Thesis, June 1953; Professor McNown, adviser.

Approximate Analyses Interrelating Pressure Distribution and Axisymmetric Body Form. EN-YUN HSU. Ph.D. Dissertation, February 1950; Professor McNown, adviser.

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Characteristics of Irrotational Flow from Axially Symmetric Orifices. ABDEL-HADI ABUL-FETOUH. Ph.D. Dissertation, August 1949; Professor Rouse, adviser.

JETS AND WAKES

Effect of Confining Walls on the Periodic Wake of Ninety Degree Wedges. YI-SHUNG CHEN. M.S. Thesis, February 1967; Professor Naudascher, adviser. The purpose of this investigation was to examine the effect of parallel confining walls on the periodicity of the wake behind a 90° wedge. The chief objective was to find whether or not the "universal" Strouhal number is constant, as Poshko's investigations in an unlimited flow suggest.

Effect of Confining Walls on the Periodic Wake of Cylinders and Plates. ALEXIOS TOZKAS. M.S. Thesis, August 1965; Professor Naudascher, adviser. The dominant frequency of velocity fluctuations in the wake of circular cylinders and sharp-edged plates, placed normally at different distances from the centerplane of a two-dimensional conduit, was determined from hot-wire measurements. The Strouhal number corresponding to that frequency was found to first increase and then to slightly decrease as the width of the cylinder or the plate is increased with respect to the conduit width. At the same time, the velocity fluctuations were found to become progressively more irregular. A displacement of cylinder or plate from the center of the conduit led to an increase in both Strouhal number and irregularity. So far as could be concluded from the limited number of Reynolds numbers tested, the effect of viscosity on the Strouhal number is more pronounced than for unconfined flow.

A Submerged Vertical Jet Beneath a Free Surface. BRUCE W. HUNT. M.S. Thesis, January 1965; Professor Rouse, adviser. Profiles of the free surface above a three-dimensional, vertical, submerged jet were measured and plotted as a function of the momentum flux and nozzle submergence depth. The surface profiles were found to be almost geometrically similar for submergences greater than or equal to 16 nozzle diameters, and the relative centerline surface displacement was found to be nearly independent of the relative submergence depth for submergences greater than or equal to 25 nozzle diameters. In addition, an approximate analytical method for determining the centerline displacement of the free surface is given.

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Preliminary Studies of the Wake of a Body With Zero Difference of Momentum Flux. HORACIO ALBERTO CARUSO. M.S. Thesis, February 1963; Professor Rouse, adviser. The wake of a disk in a uniform air stream with a jet emerging from its center was explored by stagnation-tube traverses for the condition of a zero change of momentum flux. The mean-velocity profiles were found to assume a self-preserving form within a relative short distance from the disk. Based on the assumption of a straight-line velocity distribution, the interrelationship between various mean-flow characteristics, including a volume-flux parameter, was investigated by an algebraic procedure.

Experimental Investigation of an Annular Jet Traveling Over Water. JOACHIM K. MALSY. M.S. Thesis, August 1960; Professor Mack, adviser. In connection with the development of an air-cushion vehicle, an experimental study was conducted of the flow phenomena occurring when a 7-inch-diameter annular nozzle, with a 1/8-inch air gap, was towed over water. The height above the water surface, the speed of tow, and the rate of air discharge were varied, pressures on the base plate of the annular nozzle were measured, and the resulting lift was computed. It was observed that the jet approached the water surface at a steeper angle than analysis of the effect had indicated, and that the surface disturbances were larger than predicted. A vortex ring, observed in the water near the free surface in the region of deflection of the air jet, is believed to account for these phenomena.

The Effect of a Free Surface Upon the Velocity Distribution of a Submerged Jet. JAMES JOSEPH MROSS. M.S. Thesis, February 1960; Professor Hubbard, adviser.

An Annular Jet Directed Against a Nearby Water Surface. BEN-CHIE YEN. M.S. Thesis, August 1959; Professor Mack, adviser.

Studies of an Annular Jet in Proximity to the Ground with Ambient Velocity. SATYA PRAKASH GARG. M.S. Thesis, August 1959; Professor Mack, adviser.

Investigation of the Penetration of a Jet into a Counterflow. T. R. KRISHNA RAO. M.S. Thesis, February 1958; Professor Rouse, adviser.

Pressure and Velocity Fluctuations in a Submerged Jet. S. REX CARR. M.S. Thesis, February 1958; Professor Rouse, adviser.

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Entrainment of Air by Liquid Jets. ROBERT W. SHIRLEY. M.S. Thesis, August 1950; Professor Rouse, adviser.

The Spreading of a Water Jet on a Flat Floor. ENVER MURAT-ZADE. M.S. Thesis, January 1940; Professor Lane, adviser.

MISCELLANEOUS

Laminar Flow Through Orifices Onto Filaments. JULIAN C. S. SHYR. M.S. Thesis, May, 1970; Professor Kennedy, adviser. Discharge coefficients for laminar flow through circular orifices onto concentric vertical filaments were determined experimentally, and the stability of flow along the filament was examined. The discharge coefficients are expressed graphically as a function of Reynolds number, diameter ratio, and the ratio of Weber number to the square of the Froude number. Eccentricity of the filament was found to have a significant effect on C_D only at lower Reynolds numbers. Beyond a certain distance below the orifice the flow formed surface waves which, at larger distances, coalesce into individual beads. The distance, measured in filament diameters, to the point of onset of discernible surface waviness decreases with increasing Reynolds number. However, this distance is very sensitive to outside disturbances.

Secondary Flow Near a Simulated Free Surface. TONG-SHYAN TZOU. M.S. Thesis, June 1966; Professor Landweber, adviser. This study was undertaken to establish the existence of secondary flows generated near the crest of a surface wave and separation due to these secondary flows. Such a flow along an ogive strut was simulated in a wind tunnel with a wavy ceiling. By means of light silk streamers the presence of secondary flows and the occurrence of separation were made visible. A set of three-dimensional laminar boundary-layer equations was solved approximately in a simple case to illustrate the generation of secondary flows by applying a combination of a finite-difference technique together with Blasius' solution for a flat plate.

Transfer and Dissipation of Energy in Laminar Flow. CARLOS E. QUEVEDO. M.S. Thesis, February 1966; Professor Macagno, adviser. The equation of balance of energy in laminar flow of a Newtonian fluid has been analyzed with emphasis on the role played by the vector rate of transport of energy and its terms, the Bernoulli and the Navier vectors. The mathematical as well as the physical features of these concepts

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were studied for the various classical cases of laminar flow. The corresponding transfer and dissipation functions were computed and their features explained with reference to the vectors mentioned before.

The Application of the Bernoulli Theorem in Zones of Separation. RENE CHEVRAY. M.S. Thesis, February 1964; Professor Rouse, adviser. A general discussion of the conversion of energy in flow with separation is presented through use of the Bernoulli equation for turbulent flow. The pertinent terms of the Bernoulli theorem are evaluated, line by line, for flow past a normal wall, for flow in pipes with 90° and 15° expansions and for flow around a circular disk. The results, presented in graphical form for different sections along a streamline, show the role played by the eddy in a region of separation; production of turbulence in the transition zone; transfer of energy from one streamline to another; and, finally, loss of energy in the region of the eddy. More than elucidating the role of the eddy and checking on overall analysis, this thesis offers a method of predicting the values of the turbulent shear stresses.

Aspirative Efficiency of Chimney Shapes. MAHESH C. CHATURVEDI. M.S. Thesis, August 1960; Professor Posey, adviser. The factors controlling the flow of air through a perforated pipe under flow of wind past it were analyzed. Experimental study of three chimney shapes and the effect of variation of size and number of holes was carried out. It was found that an aspirative velocity equal to 0.35 external velocity was obtained for a cylindrical chimney, and that it could be increased linearly by increasing the number of holes.

A History of Hydraulics to the End of the Eighteenth Century. SIMON S. INCE. Ph.D. Dissertation, August 1952; Professor Rouse, adviser.

An Investigation of the Aerodynamic Stability of Bridge Sections. ELMO G. PETERSON. M.S. Thesis, August 1948; Professor Rouse, adviser.

Practical Hydraulics in Highway Engineering. CARL F. IZZARD. M.S. Thesis, June 1940; Professor Dawson, adviser.

Reinforcement of Concrete Flume Corners. ORVILLE KOFOID. M.S. Thesis, June 1940; Professor Posey, adviser.

An Analysis of the South Side of the Edmonton Waterworks Dis-

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tribution System. CHARLES KENNETH HURST. M.S. Thesis, June 1940; Professor Howe, adviser.

Chinese River Control During the 16th Century. FA-YAO WONG. M.S. Thesis, June 1939; Professor Mavis, adviser.

A Comparison of the European and American Methods of Towing Barge Fleets. WILLIAM F. CASSIDY. M.S. Thesis, August 1934.

Ocean Bar Improvement for Purposes of Navigation. WALKER W. MILNER. M.S. Thesis, July 1934.

A Study of the Use of Bernoulli's Theorem. EDWARD SOUCEK. M.S. Thesis, June 1934.

A Study of the Characteristics of Sewage Flow of West Iowa City. CHARLES D. MULLINEX. M.S. Thesis, June 1932.

The Improvement of the Taihu Lake Basin in Connection with the Lower Yangtse Estuary in China. DZIEN-ZOEN SHEN. M.S. Thesis, January 1925.

MODEL STUDIES

Scale Effects in Model Tests of Rock-Protected Structures. SUBHASH C. MEHROTRA. M.S. Thesis, June 1967; Professor O'Loughlin, adviser. The effect of scale on the scouring of glass beads in a pocket immediately downstream from a horizontal submerged jet of water was studied.

Model scales corresponding to bead sizes, which ranged from 3 millimeters to 15 millimeters, were used. The Froude number for all model scales comprising a set of experiments was kept constant. Two sets of experiments employing two different values of Froude number were carried out.

The effect of Reynolds number, which varied from experiment to experiment, was studied on a plot of non-dimensional weight of the scoured material versus non-dimensional time.

The significance of the Froude number in scaling phenomena of this type was verified. It was found that the scale effects became significant when the Reynolds number based on the efflux velocity of the jet and the diameter of the beads was less than a critical number (2.5×10^3). Scale effects resulted in a diminishing of the relative depth of scour.

Some suggestions as the possible lines of extension of the present study are also made.

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Effect of Screens on Damping of Currents and Resistance of a Model In a Towing Tank. YONG-KWUN CHUNG. M.S. Thesis, June 1965; Professor Landweber, adviser. Since towing tanks were first introduced for studies with ship models, scientists involved in this field have had to wait patiently for the next run until the disturbances created by the ship model die out. These disturbances of the fluid due to the passage of the ship model consist of three principal kinds; one is the linear motion of the fluid particles, the second is the oscillatory motion of the waves, and the third is due to vorticity and vortices in the wake behind the ship model.

It was found that screens are effective for damping disturbance currents. But their effect on the variation of drag of the ship model is so large that the screens are not adequate as a damping device in a towing tank. It may be suggested that the size of the screens may be adjusted so that a compromise between the effects may give a lesser reduction of drag of the ship model.

The agreement with the experimental results of the trends given by a simple theory for the drag reduction indicates that such reduction is principally due to the modification of the potential flow about the model due to the presence of the screens. It is not implied, however, that the actual effect of the screens on the drag can be calculated by such a simple theory.

A Model Study of Tainter-Gate Operation. DONALD E. METZLER. M.S. Thesis, August 1948; Professor Rouse, adviser.

Comparison of Model and Prototype Performance of Two Miami Conservancy District Retarding Basin Stilling Pools. JOHN D. LEE. M.S. Thesis, May 1942; Professor Lane, adviser.

Hydraulic Characteristics of a Navigation Lock with Floor Culverts. MILES M. DAWSON. M.S. Thesis, June 1939; Professor Mavis, adviser.

Laboratory Tests on Hydraulic Models of Lock and Dam No. 20, Mississippi River, Canton, Mo. FREDERICK S. WITZIGMAN. C.E. Thesis, June 1938.

Hydraulic Studies of a Model of the University Dam at Iowa City. CLIFFORD L. MORGAN. M.S. Thesis, June 1938.

Observed Effects of Geometric Distortion in Hydraulic Models. KENNETH D. NICHOLS. Ph.D. Dissertation, August 1937.

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A Model Study of the Ralston Creek Control. JOHN S. McNOWN. M.S. Thesis, August 1937.

A Slope Ratio Study of a Movable Bed River Model. JAMES D. LANG. M.S. Thesis, June 1937.

The Effect of Scale Ratio on Scour in Model Stilling Pools. PHILIP CHARLES STEIN. M.S. Thesis, June 1937.

Scour Below a Model Dam With Shallow Backwater. ARTHUR HOUSTON FRYE, JR. M.S. Thesis, June 1937.

Flood Control of Mill Creek, Milan, Illinois. JAMES E. REEVES. M.S. Thesis, August 1930.

Model Study of Sediment Removal at Gays Mills Hydro-Electric Plant, Wisconsin. FRANK W. EDWARDS. M.S. Thesis, June 1930.

OPEN-CHANNEL FLOW

Statistical Properties of Bed Forms in Alluvial Channels in Relation to Flow Resistance. V. S. SHASTRI ANNAMBHOTLA. Ph.D. Dissertation, August 1969; Professor Sayre, adviser. The objective of this study was to investigate the statistical properties of dune bed forms in alluvial channels and relate them to the hydraulic friction factor. Emphasis was placed on doing this for large rivers because very little is known about the relationship between resistance to flow and bed configuration in rivers.

Bed profile records were acquired from a straight three-foot wide laboratory flume and from the Missouri river at Omaha, Nebraska. The bed material in both cases was fine sand. Discrete digital data of the sand bed profiles were obtained from continuous records. Statistical computations were performed on a digital computer.

The river data were seen to be nonstationary, both in the mean and in the mean square. A suitable filter, designed to attenuate the low frequency trends in the data, was selected, on the basis of some exploratory studies, to render the data stationary in the mean. Pilot studies, made by analyzing selected river data by spectral analysis and zero-crossing distances and amplitudes analysis, suggested that the latter of the two methods is preferable, mainly because spectral analysis of data that is nonstationary in the mean square is more apt to give misleading results.

Statistical properties of the wave lengths, amplitudes and heights were evaluated by the zero-crossing distances and amplitudes analysis for selected flume data and all river data. A study of the frequency

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distributions of the bed form characteristics showed that the bed elevations were approximately normally distributed and that the wave lengths, amplitudes and heights were approximately exponentially distributed.

The bed form friction factor was plotted against a modified relative roughness parameter defined in terms of the bed form dimensions and the hydraulic mean radius of the flow. This showed reasonably promising results. A more definite resistance relationship could not be formulated, however, because of the limited number of observations and also because of the suspected effects of the variations in the shape and arrangement of dune forms, concerning which adequate information is lacking.

Effects of water temperature on bed-form roughness were observed to be significant. The tendency in the Missouri River was that the bed forms became rougher with increasing temperatures and vice versa. However, there seem to be some other undetermined factors also influencing the bed forms. Variation in sediment size, with respect to time, is suggested as one possible factor.

The study indicates that reasonably good measures of bed form characteristics can be obtained by statistical analyses.

Friction Factors for Flat-Bed Flows in Alluvial Channels. FEDERICO LOVERA. M.S. Thesis, June 1968; Professor Kennedy, adviser. Data from field and laboratory streams, which were known or could reasonably be assumed to have been flowing in the flat bed regime, were analyzed, with the goal of deriving an improved predictor for Darcy-Weisbach friction factors of flows with an active state of sediment transport over flat sand beds. Dimensional analysis and imposition of some only moderately restrictive limitations (bed sediment characterized by median diameter; analysis limited to water and sand; no free-surface-wave effects, and hence gravity disregarded) led to a functional relationship between the flat-bed friction factor, f_f; Reynolds number, $\mathbb{R} = UR/\nu$ (where $U =$ mean velocity, $R =$ hydraulic radius, and $\nu =$ kinematic viscosity); and ratio of hydraulic radius, R, to median sand size, D_{50}. The functional relation was given quantitative expression, using the selected laboratory and field data presented in the format of the well-known stanton pipe friction diagram. The variation of f_f with $\mathbb{R}$ for constant R/D_{50} was found to be much different for mobile-bed and fixed-bed channels.

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Bed Configuration and Characteristics of Subcritical Flow in a Meandering Channel. CHIN-LIEN YEN. Ph.D. Dissertation, February 1967; Professor Naudascher, adviser. The flow of water and configuration of channel bed in a stream with movable boundaries are complicated, firstly, by the nonlinear alignment of the channel; secondly, by the presence of movable boundaries. The flow and the bed configuration are interdependent, because the flow which erodes the channel depends on the shape of the channel and vice versa. The bed configurations in a meandering channel with fixed walls have been studied for cases of different width-depth ratios and Froude numbers. An approximate analytical solution for bed configuration in the case of fully developed flow in a bend with fixed walls indicates that the transverse bed slope at a given point is directly proportional to the maximum radial velocity above that point; this solution is in good agreement with the actual measurements. The flow characteristics — mean flow velocity, flow direction, bed shear, water-surface elevation and turbulence intensity — were measured in a fixed-bed model, of which the bed topography conformed to a representative alluvial-channel configuration determined from experiments with a movable-bed meandering channel. It has been found that the bed shear is highest in the area where deposition occurs, and that the point bar creates a resistance which may be in excess of that of a meander with uniform cross section.

Effect of Shape on the Mean-Flow Characteristics of Turbulent Flow Through Smooth Rectangular Open Channels. KOTHA KOTESWARA RAO. Ph.D. Dissertation, February 1967; Professor Rouse, adviser. A range of width-depth ratios was made possible by introducing a glass splitter wall at various positions between the walls of a 30-inch glass-walled tilting flume. Measurements were made of the distributions of velocity and boundary shear in uniform flow over a centrally located 20-foot section of the available 85-foot length at various slopes and Reynolds numbers for width-depth ratios varying from 1 to 30. The effect of the cross-sectional proportions was seen in both the distribution of shear and the secondary flow; at small B/b ratios the former was dominant, and f was smaller than its asymptotic limit for very large aspect ratio; at intermediate B/b ratios the second factor dominated, and f was larger than its limiting value. The lower the Reynolds number, the more widespread was the range of width-depth ratio over which the effects were noted. For B/b values between 1 and 6, the velocity profiles showed a maximum below the water surface over the entire

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width; for values exceeding 6, the maximum was at the free surface in the central zone, this zone increasing in relative extent with aspect ratio. The ratio of maximum to mean boundary shear was roughly similar in trend to that computed for laminar flow, attaining a peak value of 1.27 at the midpoint of the bed for $B/d = 4$.

Some Considerations on the Three-Dimensional Aspects of Fully Developed Turbulent Flow in an Open Channel of Circular-Segment Cross Section. BRASIL P. MACHADO. M.S. Thesis, February 1967; Professor Rouse, adviser. In a combined analytical and experimental study, comparisons were made between the distributions of velocity and wall shear in a pipe flowing full, half full and one-third full. It was concluded that the free surface cannot be regarded as equivalent to the plane of symmetry for full-pipe flow, in that the flow is definitely three-dimensional; that the generation of vorticity at the free-surface corners is like that at the solid corners, but yields different patterns because of differences in diffusion; and that the secondary flow results from the variation in dissipation rate across an asymmetric section — i.e., secondary currents are the factor that allows the necessary adjustment of the mean-flow energy balance.

Characteristics of Subcritical Flow in a Meandering Channel. BEN-CHIE YEN. Ph.D. Dissertation, June 1965; Professor Naudascher, adviser. The flow in a meandering channel is complicated by its curvilinear characteristics. Consequently, spiral motion and superelevation develop, and the velocity and boundary-shear distributions are modified. Through an approximate theoretical solution and experiments in a fixed-bed model of constant radius, central angle and uniform cross section, the influences of the Froude number and the width-depth ratio of subcritical flow with sufficiently high Reynolds number in a relatively wide meandering channel were determined. The velocity and boundary-shear distributions, the superelevation and the growth and the decay of the spiral motion were studied in detail, through analysis of the experimental results. The turbulence intensity of the flow was also measured. Experimental results are presented in generalized form.

Effect of Radius of Curvature Upon Loss in Trapezoidal Equiradial 90° Open-Channel Bend at Constant Slope. SIE-LING CHANG. M.S. Thesis, January 1965; Professor Howe, adviser. The investigation of the effect of radius of curvature upon the loss in trapezoidal equiradial 90° open-channel bends leads to the conclusion that the larger the

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radius, the smaller the loss of head. Considering the curved channel only, the total head loss through the bend (H_l) and the loss of head due to the bend itself (h_b) are compared. The loss coefficients are also evaluated.

The Variation of Loss Coefficient With Froude Number in an Open-Channel Bend. SIKANDAR HAYAT. M.S. Thesis, January 1965; Professor Rouse, adviser. The purpose of this investigation was to study the variation of loss coefficient with Froude number in an open-channel bend at different depth-width ratios. Since it was difficult to get the loss of head in a single bend with precision, six successive similar 90° bends were used in the experiment. The loss of head due to a bend was obtained after subtracting the loss of head in an equivalent straight channel from the total loss in a bend. The loss coefficient per bend was determined as a function of the Froude number from the ratio of loss of head to the velocity head at depth-width ratios of 1:4, 1:8 and 1:16.

Air-Tunnel Study of a Meander Model. HENRY WILLIAM TIELEMAN. M.S. Thesis, February 1964; Professor Naudascher, adviser. The purpose of this study was to obtain the longitudinal and transverse velocity distribution in a closed conduit, with a central angle of bend of 90 degrees. The results were compared with the corresponding data obtained from the open-channel model. Reasons are given for the discrepancies between the results of the two models.

Optimum Shape of a 90° Bend in a Trapezoidal Channel. ANNAMALAI SHANMUGAM. M.S. Thesis, August 1963; Professor Howe, adviser. Model studies conducted to evolve the optimum shape of a 90° bend in a trapezoidal channel for minimum head loss under conditions of subcritical flow showed that the loss of head is a minimum when the inner and outer curves are equiradial. In an equiradial bend with a ratio of radius of curvature to normal bed width of 5.5, the energy loss was found to be only half that encountered in a conventional constant-width bend. With decreasing ratio of center-line radius to normal bed width below 5, the loss of head increased.

Boundary Shear in a Triangular Open Channel. JOSE JESUS MAIRENA. M.S. Thesis, August 1960; Professor Posey, adviser. The variation of the boundary shear along the wetted perimeter of a V-shaped open channel in which water was flowing at a uniform depth has been computed from special pitot gagings using two different meth-

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ods; that is, Preston's method and one which is based on the evaluation of the shear from observed velocity distributions. In the latter method the Kármán-Prandtl equation was used. There is no conclusive evidence in favor of either method, though the results differ in the pattern of the variation and in the accuracy of the integrated total.

Optimum Shape of a 90° Bend in a Rectangular Channel. CARL ERNEST DENZLER. M.S. Thesis, February 1960; Professor Howe, adviser.

Study of Backwater Curves in a Triangular Channel. KRISHAN PIARA SINGH. M.S. Thesis, August 1958; Professor Posey, adviser.

Lowering of Channel Entrance Grade Line to Increase Discharge. CHUAN-CHUNG CHANG. M.S. Thesis, February 1957; Professor Posey, adviser.

A Study of Meanders. CEZAR P. NUGUID. M.S. Thesis, August 1950; Professor Posey, adviser.

Unsteady Flow Problems from Massau's Line of Attack. PIN-NAM LIN. M.S. Thesis, June 1947; Professor Posey, adviser.

An Experimental Study of Backwater Curves. HSU-HUA HU. M.S. Thesis, February 1947; Professor Posey, adviser.

Characteristics of Supercritical Flow at a Gradual Open-Channel Enlargement. EN-YUN HSU. M.S. Thesis, February 1946; Professor Rouse, adviser.

A Study of Stream Meanders. DANIEL ESCOBAR-E. M.S. Thesis, April 1944; Professor Posey, adviser.

Characteristics of Supercritical Flow at an Abrupt Open-Channel Enlargement. BABOOBHAI V. BHOOTA. Ph.D. Dissertation, December 1942; Professor Rouse, adviser.

An Experimental Study of the Flow of Water Through Transitions in Rectangular Open Channels. GEORGE B. LYON. M.S. Thesis, February 1942; Professor Posey, adviser.

Determination of Best Proportions for Canal Bend. CHEN-HSING YEN. Ph.D. Dissertation, February 1941; Professor Howe, adviser.

The Flow of Water in Transition Sections of Rectangular Channels

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at Supercritical Velocities. WARREN E. WILSON. Ph.D. Dissertation, August 1940; Professor Lane, adviser.

A Comparison of Lacey's Stable Channel Relations with the Conditions in the St. Clair and Lower Mississippi Rivers. CHUNG-TEH LI. M.S. Thesis, June 1940; Professor Lane, adviser.

Investigation of Hydraulic Characteristics of Inflow and Outflow Conduits of Inland Waterway Locks. MARVIN J. WEBSTER. M.S. Thesis, June 1937.

The Hydraulics of the Curtis Bend of the Iowa River. WILLIAM DIXON SMITH and GEORGE WOOD BEELER. M.S. Thesis, June 1936.

Channel Straightening by Cut-offs With Special Reference to the Mississippi River. THOMAS A. ADCOCK. M.S. Thesis, July 1934.

An Investigation of the Flow Around a River Bend. FRANK L. BLUE, JR., JAMES K. HERBERT and ROBERT L. LANCEFIELD. M.S. Thesis, July 1933.

Loss of Energy in the Gradual Expansion of an Open Channel. DONALD D. CURTIS. M.S. Thesis, August 1931.

A Study of the Transverse Profile of the Mississippi River. NED L. ASHTON. M.S. Thesis, June 1926.

Investigation of Velocity Formulas for the Calculation of Flow of Water in Open Channels. SING-WU HSU. M.S. Thesis, January 1926.

A Study of the Backwater Caused by Diagonal Obstructions. JOHN W. HUMMER. M.S. Thesis, June 1925.

Determination of Kutter's n for Reaches of the Iowa River. ARNOLD NESHEIM. M.S. Thesis, June 1925.

Sediment Transport

An Analysis of Relationships Between Flow Conditions and Statistical Measures of Bed Configurations in Straight and Curved Alluvial Channels. DAVID SQUARER. Ph.D. Dissertation, June 1968; Professor O'Loughlin, adviser. The reliability of predictors for friction factors and rates of sediment transport in alluvial channels is open to question when they are applied to sinuous channels. Bed-form geometry in a curved channel and a straight flume, which are subject to the same

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nominal flow conditions, is investigated by statistical analysis of records of stream bed profiles. Autocorrelation, spectral density and probability density functions of a process defined by the bed elevation as a function of the distance along the channel, or as a function of elapsed time at a fixed point of the channel, are computed by digital computer. Comparison of the statistical descriptors obtained from the curved channel and from the straight flume permit a quantitative evaluation of the marked differences between bed geometry in curved and straight channels.

The total area of sediment transport in the curved channel is approximately 15 times as much as that of a straight flume which is subject to nominally identical flow conditions. This difference increases with increase in Froude number. At the same time the overall mean water surface slope in the curved channel is comparable to the water surface slope in the straight flume.

It is shown that bed-friction factors in alluvial beds can be determined either in terms of flow conditions or in terms of the size of the bed forms. The statistical approach described in the text permits practical and relatively simple methods to be used for obtaining characteristic heights and lengths of the bed forms in terms of the moments of the spectral density function. These characteristic bed form dimensions are used in turn to evaluate bed friction factors in a straight flume.

It was found that characteristic dimensions of the bed forms can be obtained from stationary as well as from nonstationary sample records.

Comparison between time and space spectra permitted evaluation of ripple celerity. The resulting relationship showed that small ripples move faster than large ones and that the celerity of ripples increases with increasing flow velocity. These results were confirmed by results obtained from time-lapse photography and are suggested for use in relating time and space domains.

It was shown that the theoretical second order linear Markov model used by other investigators, as well as other simple exponential, sine or cosine spectral density functions do not fit the observed phenomena.

Erosion of Riprapped Embankments by Oblique Waves. LEWIS G. HULMAN. M.S. Thesis, August 1967; Professor O'Loughlin, adviser. The design and maintenance of rock bank protection for confined waterways has become a problem due to the increasing size and speed of transiting vessels. The erosion of two rock-protected plane slopes by three different short period trochoidal-type waves originating with angles of incidence between 45 and 60 degrees was investigated. A dimensional

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analysis illustrates the complexity of relationships between variables, indicating only trends between factors may be surmised without very extensive experimentation. The conclusions indicate an underwater berm, or flatter slope, will significantly retard or eliminate erosion.

Diffusion of Sediment in a Submerged Jet. SURYA RAO SINGAMSETTI. Ph.D. Dissertation, January 1965; Professor Rouse, adviser. Diffusion of sediment particles in a vertical, axisymmetric, sediment-laden, submerged jet directed downward into stationary water was studied. From the measurements of mean velocity distribution and mean sediment-concentration distribution, the ratio β of the eddy diffusivity for momentum was obtained. It has been found that in the region of measurements the parameter β has a limiting value of about 1.2 within the Stokes range, and it increases with increase in the particle Reynolds number for the range covered in the experiments. These results have been explained by physical considerations regarding the inertial and gravitational effects on the motion of sediment particles in turbulent flow, in which the fluid motion in the eddies is circulatory rather than linearly oscillatory. Moreover, it is expected that β increases with increase in the particle Reynolds number only so long as the fall velocity of the sediment particles is less than the rms value of turbulence fluctuations in the direction of fall; beyond a certain value of the ratio of the fall velocity to the rms value of turbulence fluctuations, β decreases with increase in the particle Reynolds number.

Fall Velocity of a Sphere in a Field of Oscillating Fluid. HAU-WONG HO. Ph.D. Dissertation, June 1964; Professor Brush, adviser. In the application of the diffusion equation for sediments in a turbulent fluid, the fall velocity of the sediment particles is often assumed to be the same as the fall velocity in a stationary fluid. The validity of the assumption has been questioned. In order to demonstrate the effect of the motion of the fluid on the fall velocity of sediment particles, the fall velocity of particles settling in a field of oscillating fluid was determined experimentally. It was found that the fall velocity of particles in an oscillating field of fluid was much lower than that in a stationary fluid. The numerical solution of the equation of motion of a settling particle has been found to be useful in estimating the fall velocity of a particle in an oscillating fluid.

Sediment Transport in a Pipe With Secondary Circulation. ALAN LEE PRASUHN. M.S. Thesis, June 1963; Professor Brush, adviser.

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The use of short vanes placed at regular intervals along the top of a pipe at an angle of attack was investigated as means for increasing sediment transport with a minimum power increase. The vane angle, the sediment discharge and the fluid discharge were varied independently, and observations were made of the over-all head loss. It was found that the maximum head-loss reduction was achieved when the vanes were at an angle of 20° with the pipe axis. The head-loss reduction was greatest in the region where the head loss was a function of the sand concentration, but for the region where the head loss was independent of sand concentration, or nearly so, no head-loss reduction was possible.

The Effect of a Change in Skewness of Particle Size Distribution on the Depth of Scour. ABDUL HANNAN. M.S. Thesis, February 1962; Professor Brush, adviser. Five different mixtures of sand, having the same mean diameter and the same standard deviation but different skewnesses, were used to investigate the scour due to a submerged jet. The nondimensional scour profile was found to be independent of both time and skewness. Small secondary effects upon the scour phenomena were observed, and these were explained directly in terms of the distribution of particle sizes in the extreme size ranges.

Erosion Tests of a Protected Embankment Section. KI-SHUN CHU. M.S. Thesis, June 1961; Professor Posey, adviser. A model fill made of fine sand was protected from scour by rock sausages placed over filter layers. The maximum head over the crest of the model reached as high as 14.4 times the mean diameter of the rock sausages. Types of failure observed were the lifting of upstream ends of the sausages and the creeping of the sausages, when pulled by the rapid flow downstream. On the other hand, failure was rapid and occurred at a head of 2.4 times the mean particle diameter of the top layer, when rock sausages were omitted and only filter layers used. With sausages alone and no filter layers, failure was slow, but started as soon as the water reached the crest level.

Effect of Change in Standard Deviation of Particle-Size Distribution on the Depth of Scouring. LEONIDAS E. DIAMANDIS. M.S. Thesis, August 1960; Professor Brush, adviser. A continuation of previous studies performed by H. Rouse and E. M. Laursen with uniform sand. The effect of change in the standard deviation of particle-size distribution (in the range of $\sigma = 0.25$ to $\sigma = 0.70$) on the rate of scour-

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ing, similarity of profiles and limiting velocity was studied. Nonuniformity limits scour, but has no effect upon profiles.

Effect of Particle Size Distribution on Characteristics of the Suspended Load. TSE MIN LEE. M.S. Thesis, June 1960; Professor Brush, adviser. This study was to investigate the effect of the bed-material size distribution on: (1) the concentration of the suspended load; (2) the size of the material moving as suspended load; and (3) the height of dunes which form on the beds of alluvial channels for equal hydraulic conditions. Two sands, each with the same mean size and skewness, but with different standard deviations, were used as bed materials. Theoretical analysis of the suspended load was incorporated. The effect of bed configuration on the channel resistance was studied. The sampling techniques were also discussed. Use of the experimental results to predict the size distribution and concentration of suspended load in streams was discussed. Also, recommendations were made for future investigations.

Scour at Relief Bridges. ROBERT C. STIEFEL. M.S. Thesis, August 1959; Professor Brush, adviser.

Riprap Protection Against Scour Around Bridge Piers. NELSON LUIZ DE SOUSA PINTO. M.S. Thesis, August 1959; Professor Posey, adviser.

The Total Sediment Load of Streams. EMMETT M. LAURSEN. Ph.D. Dissertation, February 1958; Professor Rouse, adviser.

Motion of a Spherical Particle in the Accelerated Portion of Free Fall. ROBERT W. MOORMAN. Ph.D. Dissertation, February 1955; Professor McNown, adviser.

Exploratory Study of the Measurement of the Suspended Sediment Characteristics by Sonic Means. CAY G. WEINEL, JR. M.S. Thesis, August 1953; Professor McNown, adviser.

An Instrument for Rapid Size-Frequency Analysis of Sediment. DAVID W. APPEL. Ph.D. Dissertation, August 1953; Professor McNown, adviser.

Transportation of Sand in a Pipe. H. RUPERT VALLENTINE. M.S. Thesis, June 1953; Professor McNown, adviser.

Initial Bed-Load Movement Caused by a System of Periodic Stand-

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ing Waves. JOHN M. F. ROGERS. M.S. Thesis, February 1953; Professor McNown, adviser.

Efficiency of Short Sand Traps. RASIN Z. ETIMAN. M.S. Thesis, February 1953; Professor McNown, adviser.

Tests of Graded Riprap for Protection of Erosible Material. HENRY DE SILVA MANAMPERI. M.S. Thesis, June 1952; Professor Posey, adviser.

The Transportation of Uniform Sand in a Smooth Pipe. HARRY H. AMBROSE. Ph.D. Dissertation, June 1952; Professor Rouse, adviser.

A Study of the Transportation of Sand in Pipes. JOHN PINNA CRAVEN. Ph.D. Dissertation, August 1951; Professor Rouse, adviser.

The Effect of Sand-Trap Proportions on the Efficiency of Operation. ALY BALIGH. M.S. Thesis, August 1951; Professor Rouse, adviser.

Effect of Spacing and Size Distribution on the Fall Velocity of Sediment. PIN-NAM LIN. Ph.D. Dissertation, August 1951; Professor McNown, adviser.

Protection of Earth Embankments by Riprap of Uniform Size. JOSE O. DE ABREU LIMA and WILLIAM B. MORGAN. M.S. Thesis, August 1951; Professors Posey and Metzler, advisers.

An Investigation of the Effect of Bridge-Pier Shape on the Relative Depth of Scour. DOUGLAS E. SCHNEIBLE. M.S. Thesis, June 1951; Professor Rouse, adviser.

Mutual Influence of Two Freely Falling Spherical Particles and the Effects of a Plane Vertical Boundary on a Single Spherical Particle. JAGDISH RAJ BAMMI. M.S. Thesis, August 1950; Professor McNown, adviser.

Accelerated Motion of a Sphere. MARION ROBERT CARSTENS. Ph.D. Dissertation, June 1950; Professor McNown, adviser.

Effect of Shape of Particles on Their Settling Velocities — Triaxial Particles. HIMANSU RANJAN PRAMANIK. M.S. Thesis, February 1950; Professor McNown, adviser.

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MALAIKA. Ph.D. Dissertation, February 1949; Professor McNown, adviser.

Development of a Stratified-Suspension Technique for Size-Frequency Analysis. HERROL J. SKIDMORE. Ph.D. Dissertation, August 1948; Professor Rouse, adviser.

An Extension of the Study of Boundary Influence on the Fall Velocity of Spheres. SELAHATTIN M. ENGEZ. M.S. Thesis, January 1948; Professor McNown, adviser.

Boundary Influence on the Fall Velocity of Spheres at Reynolds Numbers Beyond the Stokes Range. MURRAY B. McPHERSON. M.S. Thesis, August 1947; Professor McNown, adviser.

A Modification of Stokes' Law to Account for Boundary Influence. HSIN-MIN LEE. M.S. Thesis, February 1947; Professor McNown, adviser.

A Study of a Method of Computing Sediment Deposits in Retarding Basins. KAI LEI. M.S. Thesis, February 1946; Professor Lane, adviser.

A Study of the Transportation of Fine Sediments by Flowing Water. CHEN-HUAN HSIA. Ph.D. Dissertation, July 1943; Professor Kalinske, adviser.

Investigation of Turbulence and Suspended Material Transportation in Open Channels. CHUNG-LING PIEN. Ph.D. Dissertation, June 1941; Professor Kalinske, adviser.

Sediment Behavior in Upward Flow. WARREN DeLAPP. M.S. Thesis, June 1940; Professor Rouse, adviser.

A Study of Bed Movement and Hydraulic Roughness Changes in the Lower Mississippi River. EDWIN W. EDEN, JR. M.S. Thesis, June 1938.

Traction of Pebbles by Flowing Water. JOHN BOGARDI and C. H. YEN. M.S. Thesis, June 1938.

The Control of Silt Deposits Near Condenser Intakes at a Steam Power Plant. EDWARD R. VAN DRIEST. M.S. Thesis, August 1937.

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A Study of Bottom Velocity and Capacity in the Transportation of Bed Load. TE-YUN LIU. Ph.D. Dissertation, February 1937.

Transportation of the Bottom Load in an Open Channel. TE-YUN LIU and ARCHIE N. CARTER. M.S. Thesis, June 1935.

Sediment Transporting Power in Open Channels. YUN-CHENG TU. Ph.D. Dissertation, June 1934.

Sedimentation in Southern Iowa Reservoirs. GEORGE A. MARSTON. M.S. Thesis, July 1933.

A Critical Analysis of Grove Karl Gilbert's "The Transportation of Debris by Running Water." ROLAND A. KAMPMEIER. M.S. Thesis, June 1933.

Determination of Bottom Velocity Necessary to Start Erosion in Sand. CHITTY HO. Ph.D. Dissertation, June 1933.

A Study of Sedimentation at the University Water Treatment Plant. QUENTIN B. GRAVES. M.S. Thesis, June 1932.

SHIP HYDRODYNAMICS

On the Measurement of the Total Resistance and the Viscous Resistance of a Submerged Spheroid. OKTAY GÜVEN. M.S. Thesis, May 1970; Professor Farell, adviser. Resistance components of a submerged prolate spheroid with a major-to-minor-axis ratio of five are investigated in this experimental study. Measurements of the total resistance for three different depths of submergence over a Froude-number range of 0.30 to 0.45 are reported. The viscous resistance obtained by means of wake surveys is found to be much larger with the model close to the free surface than the deep-submergence resistance, with a marked dependence on the Froude number. A strong influence of the presence of a free surface on the viscous resistance is indicated.

On the Determination of the Viscous Drag of a Ship Model. TONG-SHYAN TZOU. Ph.D. Dissertation, June 1969; Professor Landweber, adviser. Analysis of wake-survey measurements has indicated that the viscous drag of a ship model varies with the Froude number. Results similar to those of Jin Wu, showing a sinuous trend of the viscous drag in the neighborhood of $\mathbb{F} = 0.25$, but in better agreement at low Froude numbers with the 1957-ITTC correlation line, were obtained, employing automated equipment and a new method of analysis.

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Studies of flow characteristics for a Series-60 model suggest that the sinuous trend of the viscous-drag curve is attributable to the change in surface configuration near the stern and the shear-stress distribution on the ship hull, and cannot be attributed to the presence of a laminar boundary layer.

Another achievement in the experimental study of this topic was to develop a reliable, quick and convenient routine technique in which the IBM 1800 Computer with a scanivalve and pressure transducer were put on-line in the wake-survey experiment. By this system, all the data can be accumulated in the computer and analyzed immediately following the termination of the measurements to yield the values of the viscous drag.

Two contributions are presented in the theoretical study of this topic. First, a refinement of the Betz-Tulin formula for viscous drag is obtained by replacing Betz's approximate formula for the force on the wake sources by an exact one. Secondly, it has been found that for an assumed vorticity distribution the error in the wavemaking resistance due to the wavemaking assumption in the Betz-Tulin theory for an ogival strut is 6.8 percent at a Froude number of 0.249. Assuming the same percentage error for a Series-60 ship model, the effect of that error on the resultant viscous-drag curve would vary from -0.5 percent for $\mathbb{F} = 0.166$ to -4.2 percent for $\mathbb{F} = 0.332$, the negative sign denoting that the values of the viscous drag should be increased by the indicated percentages.

Effect of a Rotational Wave on the Wave-Making Resistance of an Ogive. JEAN-CLAUDE TATINCLAUX. Ph.D. Dissertation, June 1969; Professor Landweber, adviser. Among the various methods proposed in the last decade for the direct determination of the wave-making drag from wave profile measurements, Eggers' method appears to be the most promising. In deriving his formula Eggers assumed that the waves produced by a ship in steady translational motion are composed only of a system of free waves at some distance downstream from the ship, and that the effect of a viscous wake can be neglected. The validity of the first assumption, under certain conditions, has since then been verified. The purpose of the present work is to investigate the second assumption.

In the present study, the ship form, taken to be a two-dimensional ogive, is assumed to be stationary and subjected to a uniform stream of constant velocity. The fluid is considered to be inviscid, except within

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the boundary layer along the body, where vorticity is generated. Although there is actually a continuous generation of vorticity, which is carried downstream by the mean flow to form the rotational wake, the wake can be "frozen," and represented by a volume distribution of vorticity traveling with the body. This vorticity distribution modifies the source distribution on the center-plane of the ogive and creates a vector potential and a disturbance potential function due to the presence of the free surface, in addition to the potential function describing the irrotational motion. An expression for the wave elevation is then obtained from the modified boundary condition on the free surface.

The wave profiles computed at transverse sections one, two and four model lengths behind the stern of the ogive represent still only a qualitative approximation to those observed experimentally. The theoretical wave resistance, obtained from momentum considerations, is from 14 percent larger to 40 percent smaller than the values given by potential theory, which yields far greater values than measured experimentally by subtracting the estimated viscous resistance from the measured total resistance.

When the wave profile $\zeta(x, y)$ is expressed as the sum of its asymptotic form ζ_{as} and a function $Z(\bar{\omega}; x,y)$ representing the local effect of the vorticity, then the wave-resistance coefficient can be obtained in terms of the asymptotic wave elevations at two transverse cuts; in other words Eggers' formula is valid when applied to the quantity $[\zeta(x, y) - Z(\bar{\omega}; x,y)]$. It was not possible here to present a simple way of evaluating the function Z. However, since the function Z depends essentially upon the vorticity distribution due to viscous effects along the boundary of the body, it is suggested that future work be undertaken to try to determine some relationship between the viscous drag and the function Z.

Induced Drag Due to Bilge Vortices. GABRIEL ECHAVEZ. M.S. Thesis, February 1966; Professor Landweber, adviser. Three bodies, with different bilge curvature, were investigated. The study was done by visual means, by using dye when testing in water and smoke when testing in air. The vortex characteristics for a body with infinite bilge curvature were recorded and an analytical expression, which yields both the induced drag and the induced lift, was developed. The results obtained emphasize the importance in considering this effect and point out that the main factor in the vortex drag evaluation is the value of the strength of the vortices.

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Effect of Channel Walls on Base Pressure and Flow About a Blunt Body. AN-CHING LIN. M.S. Thesis, February 1966; Professor Landweber, adviser. The influence of wall restrictions upon base pressures of a hemisphere was investigated experimentally to study wall effect on the flow around a blunt body. A hemisphere with its flat face downstream was tested in an air duct with movable side walls, as well as in a larger wind tunnel with negligible wall effect, and pressures on the base of the hemisphere were measured. The method of images was applied to estimate the velocity increment of the flow past the hemisphere due to the walls, in order to correct for the wall effect. Such a correction was found to be highly inadequate. It was concluded that the wake formation of the flow around a blunt body is strongly affected by the existence of wall restrictions.

Analytical and Experimental Study of Eggers' Relationship Between Transverse Wave Profiles and Wave Resistance of a Modified Ogive in a Channel. HELMUT E. KOBUS. Ph.D. Dissertation, August 1965; Professor Landweber, adviser. A two-dimensional vertical strut with a cross section obtained by conformal mapping of an ogive in an unbounded plane into a channel has been investigated. For both the exact and the linearized zero-Froude-number source distribution, wave profiles have been calculated from linearized potential theory along the hull and at various transverse sections behind the model. The profile along the hull and transverse wave profiles over a range of one-half to four model lengths have also been obtained from towing-tank experiments on a six-foot model. Whereas fair agreement between analysis and experiment is obtained along the hull, the transverse profiles show a qualitative agreement only, which diminishes with increasing distance from the body. This is mainly due to flow separation near the stern of the body and the presence of a viscous wake.

The asymptotic form of the wave profile far downstream has been calculated for both the linearized and the "exact" source distribution and has been compared with the "exact" wave profiles, which include the near-field term. At one-half model length behind the body, the asymptotic profiles resemble the exact form already quite well, but a certain discrepancy between the two remains even as far as eight model lengths downstream. The calculations necessary to obtain the exact form are increased by a factor of 50, as compared to the asymptotic form, whereas the gain in accuracy of describing the actual wave pattern is minimal.

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Eggers' relationship between transverse wave profiles and wave resistance has been applied to both the analytical and the experimental profiles, and the results are compared with the theoretical wave resistance obtained from the known similarity distribution. The theoretical wave resistance has been evaluated for the modified ogive in a channel as well as in an infinite fluid, and the increase in resistance due to the channel walls was found to be one percent. The analytical profiles yielded Eggers' resistance values of about 80 percent of the theoretical resistance. This discrepancy results from the fact that the near-field term disappears only very gradually; therefore, the assumption of a free wave system is only approximately satisfied in the range from one-half to eight model lengths. Egger's resistance value from experimental profiles is about 57 percent of the theoretical wave resistance. About one half of the discrepancy is to be ascribed to the effects of viscosity, the other half to the presence of the near-field wave.

Verification of Method of Determining the Viscous Drag of a Ship Model. KENNETH KEY. M.S. Thesis, January 1965; Professor Landweber, adviser. Application of the Betz-Tulin method for measuring the viscous drag of a ship model in a previous work by Jin Wu resulted in an unexpectedly sinuous variation of the curve of viscous drag versus Froude number. Because of the importance of this curve in the usual procedure of predicting ship resistance from model tests, the experiment was repeated with refined equipment and improved calibration technique. The new results are somewhat less sinuous, but essentially confirm the variation previously found.

Measurement of Viscous Drag of Ship Forms. JIN WU. Ph.D. Dissertation, August 1964; Professor Landweber, adviser. An "exact" expression for the viscous drag was derived, on the basis of which it became possible to evaluate the accuracy not only of the Betz-Tulin's formula but also of two alternative, approximate versions suggested by the "exact" formula. The validity of these three approximate expressions was then checked experimentally by means of wake surveys. The theoretical study, experimental investigation and numerical evaluation of the turbulence effects on the viscous-drag formula and measurements are also presented in this work. Subsequently, with this method of measuring viscous drag, the actual variation of viscous drag with Froude number was investigated experimentally. Finally, a practical, routine technique for making viscous-drag measurements by using electronic sensing device and recording and computing equipment is suggested.

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Added Masses of Vibrating Elastic Bodies. RICHARD GLENN WARNOCK. Ph.D. Dissertation, February 1964; Professor Landweber, adviser. The effect of the surrounding fluid on the natural frequencies of a vibrating ship is presently computed by an approximate two-dimensional theory known as strip theory. A more exact three-dimensional theory, which employs the kinetic energy of the fluid in the Lagrangian equations of the vibration, is illustrated by application to a sphere, a vibrating string and a free-free cylindrical bar of finite length. Numerical calculations for an aluminum bar of length-diameter ratio 10 show close agreement with two-dimensional strip theory.

The Separation of Viscous Drag and Wave-Making Drag. JIN WU. M.S. Thesis, February 1961; Professor Landweber, adviser. Towing tests of ship models are generally conducted in water, and difficulty arises in satisfying the conditions for exact dynamical similarity. In order to overcome this difficulty, the ship is then tested by the Froude procedure. A theoretical possibility of separating the viscous and wave drag of ship forms was suggested by Tulin. This thesis is essentially the detailed description and the experimental proof of Tulin's method.

Experimental Investigation of Ursell's Theory of Wave Making by a Rolling Ship. W. CURTIS McLEOD. M.S. Thesis, June 1959; Professor Landweber, adviser.

Roll Damping Due to Bilge Keels. MILTON MARTIN. Ph.D. Dissertation, June 1959; Professor Landweber, adviser.

Measurements of Velocity Distribution Around a Stationary Ship Model in Flowing Water. WALLIS S. HAMILTON. Ph.D. Dissertation, December 1943; Professor Rouse, adviser.

STRATIFIED FLOW

Wake Deformation in Density-Stratified Fluids. HARIHARA IYER PADMANABHAN. Ph.D. Dissertation, February 1969; Professor Ames, adviser. The purpose of this investigation was to build an analytical model for the collapse of a cylindrical fluid mass in a density-stratified medium. In the early stages of collapse, accelerative forces are much more significant than the viscous forces, and a computational model which assumes the fluid to be inviscid and the flow irrotational yields results which show good agreement with available experimental

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data. Another computational model, which takes into account viscosity also, yields almost identical results in this range. The methodology used for the viscous case is very similar to the one recently developed by Chorin.

In the later stages of collapse, viscous forces are of importance while the accelerative forces are not. Using a long-wave approximation suitable for viscous flows, an asymptotic solution has been derived. Results agree fairly well with experimental data.

Confined Flows of Homogeneous and Stratified Fluids Induced by a Rotating Disk. JULIAN AGUIRRE-PE. M.S. Thesis, February 1969; Professor Macagno, adviser. Two liquid layers of different density, initially at rest in a cylindrical tank, were set into a Kármán confined motion by means of a rotating bottom disk. A spiral motion which tended to alter the density stratification by gradual mixing was thus generated, similar to the spiral motion in open-channel curves. In this manner, the intereffects of spiral motion and stratification were studied as temporally rather than spatially dependent. The analogy is incomplete, but basic features of density-stratified flow in bends were found in this study to be displayed in time instead of in space. The phenomena observed were found to depend on a Reynolds number, a densimetric Froude number, and a C-number based on the ratio of centripetal acceleration and gravitational acceleration. This investigation also included a study of the flow patterns induced in a fluid of uniform density by the same rotating disk. The features of this flow were quite similar to those of the lower layer in the initial phases of the stratified flow.

Effects of Curvilinearity on Stratified Flows. CARLOS V. ALONSO. M.S. Thesis, June 1967; Professor Macagno, adviser. The unsteady, free-surface motion induced in a linearly density-stratified liquid initially at rest, and contained in a still cylinder with a rotating bottom, was studied. The initial stratification strongly affects both the primary and secondary flows. In turn, the stratification is continuously modified and finally disappears. Before reaching this final state, the secondary motion breaks into three separate cells with the same direction of circulation. The instantaneous meridian density distribution depends on three geometric dimensionless ratios, a time parameter, a Reynolds number, a Froude number and an additional physical parameter designated as a C number. The influence of the Reynolds number is important only during the initial stage of the motion.

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The Stability of a Stratified Flow in the Region of Flow Establishment. JONATHAN BARRY HINWOOD. Ph.D. Dissertation, February 1966; Professor Macagno, adviser. It is shown that the confined flow of two fluid strata, moving in the same direction and with the same velocity, is less stable than the flow of a homogeneous fluid, despite the stabilizing action of gravitational forces. Flow visualization and direct measurements of interfacial waves indicate that the reason is that the stratified flow is subject to disturbances originating at the interface, in addition to those originating at the outer edge of the boundary layer. The latter affect both stratified and homogeneous flows. The wave length of the disturbances has been obtained, and density profiles have been directly drawn, using a newly developed conductivity probe to measure density *in situ.* From the measured density and velocity profiles, the amount of intermixing of the strata has been computed and has been used as a stability criterion. By utilizing this criterion, and checking by means of visual observations, the boundaries of the different flow regimes have been found as functions of the Froude and Reynolds numbers.

The existing analytical methods of studying hydrodynamic stability were unsuitable for use here, and so numerical simulation of the flow was undertaken, using a finite-difference representation of the complete Navier-Stokes equations, in a manner similar to that of Fromm and Harlow. As finally developed, the method is capable of simulating flows with any chosen inflow and outflow conditions and any desired density distribution. Special treatment of convective terms allows discontinuities to be treated with only relatively small diffusive errors being obtained. The results of the numerical simulation agree well with published solutions for steady two-dimensional flow establishment, and with the experimentally obtained stability limits. Experimentally observed types of disturbances were successfully simulated for moderately long periods of time, proving the reliability of the numerical method and at the same time yielding new information about these flows.

The Stability of Stratified Flows on Nearly Vertical Slopes. WILLIAM M. SANGSTER. Ph.D. Dissertation, June 1964; Professor Macagno, adviser. The interfacial stability of the two-dimensional countercurrent flow of two incompressible fluid layers of differing density, viscosity and thickness confined between parallel solid boundaries was investigated for very steep slopes. An eigen-value problem resulted from the attempts at a power-series solution of the governing Orr-

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Sommerfeld equations and imposition of the appropriate boundary conditions. Expansion of the resulting determinant provided a relationship among the celerity and wave length of the applied disturbance and the Reynolds number of the primary flow. Graphical results of a computer solution for this relationship are presented. Limitations in the analysis required that the slopes be greater than 85° and the thickness of the lower stratum be always greater than that of the upper. A more stable flow results when: (a) the slope is reduced; (b) the density ratio is increased; (c) the viscosity ratio is brought closer to unity; (d) the thickness ratio is brought closer to unity; or (e) the interfacial tension is increased.

The Instability of Stratified Flow. GEORGE HENRY MITTENDORF. M.S. Thesis, February 1961; Professor Rouse, adviser. Two miscible fluids of different density were allowed to intrude into one another in a closed conduit at a given slope. Propagation of the two resulting fronts was observed by means of thermistors. Interfacial conditions were recorded photographically. Regardless of slope, the celerities of the two fronts became noticeably different for differences in density larger than one per cent. The onset of turbulence at the interface, as well as the thickness of the interlayer resulting from turbulence, were correlated with the Froude and Reynolds numbers of the flow.

Irrotational Motion of Two Fluid Strata Towards a Line Sink. DAVID GRANT HUBER. Ph.D. Dissertation, August 1958; Professor Rouse, adviser.

Flow Toward a Pipe in a Stratified Fluid. CHARLES O. MEYER. M.S. Thesis, February 1958; Professor Rouse, adviser.

An Investigation of Recirculation in Stratified Flows. GEZA L. BATA. M.S. Thesis, August 1956; Professor Yih, adviser.

Internal Hydraulic Jump in a Two-Layer Fluid System. CHITTA R. GUHA. M.S. Thesis, February 1954; Professor Yih, adviser.

Simultaneous Flows of Air and Water in a Closed Flume. TEMEL H. ORGA. Ph.D. Dissertation, June 1953; Professor McNown, adviser.

A Study of the Characteristics of Gravity Waves at a Liquid Interface. CHIA-SHUEN YIH. M.S. Thesis, February 1947; Professor Rouse, adviser.

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Surface and Form Resistance

Resistance to Flow over Boundaries with Small Roughness Concentrations. EMMETT M. O'LOUGHLIN. Ph.D. Dissertation, August 1965; Professor Rouse, adviser. Solution of the basic equations of fluid flow past boundaries of varying roughness concentration was shown to yield false predictions of boundary resistance, unless the equations include a velocity perturbation which characterizes the diffusion in a fluid region called the wake layer. The occurrence of the perturbation does not invalidate present concepts of pipe and channel resistance, but it does indicate some practical limitations which can be placed on the use of logarithmic velocity distributions close to a rough boundary. The importance of these limitations is apparent when an attempt is made to compute the fluid forces acting on roughness elements, which are small compared with the flow dimension. The inclusion of the perturbation may eliminate the discrepancy between observation and prediction, but little is gained by forcing such an analysis to its ultimate end, in view of the necessary inclusion of empirical coefficients which describe the perturbation.

Phenomenological models for the flow in the region near the boundary are proposed, and are based upon assumed distributions of the kinematic eddy viscosity. The models lead to the formulation of expressions for velocity distribution and resistance coefficient in terms of the diffusion in the wake layer. The phenomenon is observed experimentally for different boundary roughnesses in a uniform-flow situation. It is shown that the structure of the wake layer is more complex than that assumed, partially due to viscous effects which have been ignored in the models, but primarily because the wake-layer characteristics should embrace the features of both models simultaneously. However, if the boundary-resistance phenomenon is to be completely described, additional relationships defining the boundary conditions must be specified. Although reasonable assumptions are made in stating these relationships, the analytical solutions of this type remain sensitive to relatively small inaccuracies in the description of conditions at very small distances from the boundary.

The link which has been established between the resistance characteristics and the diffusion phenomenon near the boundary has applicability to any of several problems associated with diffusion, such as suspended-sediment transportation, heat transfer and evaporation.

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Drag of an Oscillating Plate in a Stream. MING-TE TSENG. M.S. Thesis, January 1965; Professor Landweber, adviser. The drag coefficients of three flat plates with different aspect ratios, oscillating in a stream, were determined. The drag equation was derived on the basis of linear damping and nonlinear restoring force. The results showed that the values of the drag coefficient depend strongly on the current velocity. An attempt was also made to examine the effect of including nonlinear and damping terms in the analysis of the oscillation data for determining the drag coefficients. The results showed that, when a plate was oscillating in a fluid at rest, the refinement of the analysis beyond the assumption of linear restoring force and simple harmonic motion was unnecessary.

The Resistance of Piers in High-Velocity Flow. TSU-YING HSIEH. M.S. Thesis, August 1962; Professor Rouse, adviser. An experimental investigation of the variation of the resistance coefficient of cylindrical piers in a rectangular channel was conducted. The resistance coefficient was determined as a function of the Froude number, of the relative depth of the oncoming flow and of the relative spacing of the piers.

Surface Resistance as a Function of the Concentration and Size of Roughness Elements. JOHN ARTHUR ROBERSON. Ph.D. Dissertation, August 1961; Professor Rouse, adviser. A method was developed which allows the surface resistance to be computed for flow in a conduit which is roughened with cubical roughness elements when basic data defining the roughness are given. The relative height of cube and cube concentration were the parameters which were used to define the roughness. The surface resistance is the sum of the viscous shear at the smooth wall and the drag on the roughness elements. Both of these resistance terms, however, are also functions of the mean boundary level and velocity distribution, and the latter, in turn, is a function of the over-all resistance. In order to achieve a solution, it was necessary to write an equation for each variable in terms of the appropriate remaining variables, and these equations were then solved for the desired resistance functions. The solutions were shown to be valid to the extent that they followed the trend of available experimental results. The experimental results were for various concentrations, the highest of which had 13 percent of the boundary covered with cubes.

Drag Coefficients of Flat Plates Oscillating Normally to Their Planes. MUHAMED RIDJANOVIC. M.S. Thesis, August 1960;

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Professor Landweber, adviser. A flat plate oscillating normally to its plane may experience much greater drag than one in steady flow. In the present work a previous two-dimensional study of this phenomenon is extended to the three-dimensional case, for plates of various aspect ratios. It was found that the mean drag coefficients for small amplitudes of oscillation may be five times as large as for steady flow. This result is explainable by the formation of vortices at each cycle of the oscillation and incomplete development of the wake. A consistent family of drag curves, which shows a trend toward the drag coefficient for a flat plate in steady flow at large oscillation amplitudes, was obtained.

The Effect of Free-Surface Instability on Channel Resistance. HERMAN J. KOLOSEUS. Ph.D. Dissertation, August 1958; Professor Rouse, adviser.

Flow Past a Normal Plate in Contact With a Boundary. MIKIO ARIE. M.S. Thesis, August 1955; Professor Rouse, adviser.

Drag Tests on Cylinders Arranged in a Straight Grid. CLARK G. DeHAVEN. M.S. Thesis, June 1953; Professor McNown, adviser.

Drag Coefficients of Multiple Plates as a Function of Solidity Ratio. TIEN-TO SIAO. M.S. Thesis, August 1950; Professor Rouse, adviser.

Effect of a Cylindrical Boundary on the Drag of Spheres. JOHN TERHUNE NEWLIN. M.S. Thesis, August 1950; Professor McNown, adviser.

TURBULENCE

Spectral Analysis of Pressure and Velocity Fluctuations in a Submerged-Jet Scour Model. YUNG-CHI CHANG. M.S. Thesis, February 1969; Professor Kennedy, adviser. Spectral analysis of pressure fluctuations at the bed of a well-developed scour pocket in a flume, and velocity fluctuations near the bed of two different sizes of well-developed scour pockets in air-tunnels, were performed, using IBM 1800 Data Acquisition and Control System. This study found that the normalized spectra of both pressure fluctuations and velocity fluctuations were independent of Reynolds number.

Characteristics of a Turbulent Round Jet in a Coaxial Stream. JOSE DE JESUS ORTEGA-LUEVANO. M.S. Thesis, February 1969; Professor Naudascher, adviser. Measurements of mean velocity, turbu-

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lence intensity and turbulent shear in a round jet in a coaxial stream were carried out in a wind tunnel for the purpose of obtaining a better understanding of the interdependence between the turbulence and the mean flow. The experimental data were analyzed with the aid of both the conventional and a new self-preservation assumption, and the mean-flow and turbulence characteristics were shown to have a strong tendency towards self-preserving profiles provided the new definition of self-preservation is used.

Turbulent Flow in Wavy Pipes. SHENG-TIEN HSU. Ph.D. Dissertation, August 1968; Professor Kennedy, adviser. Turbulent flow over sinusoidal pipes with amplitude-wavelength ratios of 1:45 and 1:90 was studied. The scope of the investigation included the following: (1) measurements of turbulent flow characteristics, total head and pressure head distributions, mean velocity profile, turbulence intensities distribution, Reynolds stress distribution and variation of boundary shear stress; (2) the analytical result of predicting the mean velocity profile; and (3) the approach of finding an empirical formula for the local friction factor.

Results of turbulence measurement indicated that there is a core of about 0.6 r_0 in which the turbulence characteristics are independent of the longitudinal position. This core was named as constant core. There is a very definite phase shift between the shear stress distribution and the inward boundary displacement. Phase shift of boundary pressure distribution was also found, although it cannot be determined as accurately as the one in the boundary shear stress. The mean velocity profile was found to follow both the power and logarithmic laws. The agreement between the measured and computed n — exponent in power law — was excellent. The empirical formula for the local friction factor agrees well with the measurement, but the applicability of this formula to other problems remains to be tested.

Turbulence in the Wake of a Body of Revolution. RENE CHEVRAY. Ph.D. Dissertation, June 1967; Professor Hubbard, adviser. The wake behind a 6:1 spheroid was studied for a Reynolds number equal to 2.75×10^6 at 12 sections downstream to 18 diameters of the stern of the body. The flow pattern was determined, and an analytical expression was derived to express the way in which the mean characteristics of the wake develop in the self-preserved region. Reynolds stresses were measured throughout the flow, and their magnitudes were checked

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through the momentum and mean-energy equation. Measurements were made of the micro- and macro-scales, intermittency of the turbulence together with the autocorrelation function and the spectral density function with particular consideration of the inertial subrange.

Velocity and Pressure Fields of a Diffusing Jet. SEDAT SAMI. Ph.D. Dissertation, August 1966; Professor Rouse, adviser. In the flow establishment region of an air jet issuing from a 1.0-foot-diameter nozzle into still air, mean and turbulent flow characteristics were measured. For the measurement of the pressure fluctuation, probes using piezoelectric ceramic tubes were developed. All terms of the differential and integral forms of the momentum, mean- and turbulence-energy equations were evaluated throughout the region. The pressure field associated with turbulence was closely similar in form to the velocity field. The axial scale of turbulence was found to be almost twice as large as the other two scales. The idealized model of isotropic turbulence did not satisfactorily represent the real flow field. Approximate values obtained for the correlation between the pressure fluctuations and the axial component of turbulent velocity were negative throughout the zone of flow establishment.

Pressure Fluctuations in the Vicinity of Normal Walls of Variable Thickness. JEAN-CLAUDE TATINCLAUX. M.S. Thesis, February 1966; Professor Naudascher, adviser. Pressure fluctation spectra were measured for different points upstream and downstream from the wall, with particular attention to the influence of the ratio of wall height to wall thickness, in an attempt to determine the range of frequency over which excitation of vibrations would occur. The spectra exhibited a dominant frequency when unstable reattachment of the separation pocket on the wall itself occurred.

Flow Behind a Point Source of Turbulence. HSIANG WANG. Ph.D. Dissertation, August 1965; Professor Naudascher, adviser. Results of an experimental air-tunnel study of the flow behind a point source of turbulence at Reynolds numbers of 6850 and 55000 are reported. The distributions of turbulence characteristics, including turbulence energy, triple velocity-fluctuation correlations, auto-correlation and energy spectrum, are presented. The rate of turbulence-energy decay, the form of its distribution, as well as the rate of wake spreading, are predicted by an approximation analysis and compared with the experi-

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mental results. Information on the finer structure of turbulence is provided. The effect of viscosity on certain flow characteristics is discussed.

Characteristics of Separation at Conical Afterbodies. SAMPATHIENGAR NARASIMHAN. Ph.D. Dissertation, June 1965; Professor Rouse, adviser. The mean-flow and turbulence characteristics of motion following separation from a conical afterbody were investigated for various combinations of initial boundary-layer thickness and angle of convergence of the boundary. For a given boundary geometry, the rate of turbulence production and the base drag increase with decrease in the value of the boundary-layer thickness, and the increasing importance of the role of the inertial effects of turbulence causes similarity profiles to be achieved earlier. For a given boundary-layer thickness, the flow characteristics remain almost unchanged for cone angles greater than 60 degrees. When the cone angle is reduced progressively to 50°, the rate of turbulence production increases and the size of the eddy pocket decreases. Upon reattachment of the separation profile to the boundary of the tailpiece, any further reduction in the cone angle causes the cumulative turbulence production to decrease continuously.

A Preliminary Investigation of the Pressure Fluctuations in the Vicinity of Normal Walls. FREDERICK A. LOCHER. M.S. Thesis, January 1965; Professor Naudascher, adviser. Spectral densities of the pressure fluctuations at three points in the vicinity of normal walls were examined to determine the range of frequencies over which enough energy was available to be considered as a possible source for the excitation of vibrations. Approximately the same dominant frequency was found at two points: (1) in front of the wall; and (2) at the end of the separation pocket behind the wall. The dominant frequency did not appear to be affected by the thickness of the walls which were investigated in this study. Development of the electrical network and analysis of the signal representing the fluctuating pressure are presented. The transient response of filters is qualitatively discussed, showing that the use of a squaring circuit in the spectral analysis of this particular type of signal yields erroneous results.

An Experimental Study of the Turbulence in the Wake of a Body of Revolution. P. J. L. GEAR. M.S. Thesis, January 1965; Professor Hubbard, adviser. The early results of a continuing study of the wake of a 6:1 ellipsoid are presented. Measurements were made at a Rey-

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nolds number based on model length of 4×10^6, and close to the stern, of the mean flow characteristics and of the three components of turbulence intensity. A value of 0.074 for total drag coefficient of the body was obtained through application of the momentum equation.

Turbulence Studies in the Wake Behind a Powered Surface Vessel. CHARNG-NING CHEN. M.S. Thesis, February 1964; Professor Hubbard, adviser. Turbulence characteristics in the wake behind a powered surface vessel, under the condition of zero rate of change of momentum, were studied by the aid of the IIHR constant-temperature hot-wire anemometer. The distributions of mean velocity and turbulence intensity were found to be unsymmetric. The maximum value of the longitudinal component of the turbulence intensity varies inversely as the distance to the 4/5 power. Depth of slipstream and turbulence dissipation were also investigated.

Wake With Zero Change of Momentum Flux. MUHAMED RIDJANOVIC. Ph.D. Dissertation, August 1963; Professor Rouse, adviser. This study was undertaken for the purpose of obtaining an insight into the flow characteristics and of tracing the energy changes in a wake simulating that of a self-propelled body. The experiments were carried out in an air tunnel with zero pressure gradient, a stationary disk emitting a jet into its wake in the direction of flow. The momentum flux of the jet was selected so as to reduce to zero the difference in momentum flux between sections well upstream and downstream from the disk. The detailed investigation was carried out in the region from $x/D = 4$ to $x/D = 130$ for a Reynolds number of approximately 6×10^4. The results for mean ambient and total-pressure distribution, mean velocity distribution, and turbulence-intensity and shear-stress distributions are presented graphically. Three zones of flow with basically different flow characteristics were found: (1) An eddy zone, with the most typical characteristics of high rate of mean-energy loss, where practically the entire energy input of the jet is converted into turbulence. (2) From $x/D = 4$ to $x/D = 50$, a zone associated with a high rate of change of all flow characteristics in the axial direction due to interaction of fluid between neighboring zones of positive and negative velocity defect. (3) A third zone displaying conditions of nearly uniform and isotropic flow beyond $x/D = 50$.

Establishment of the Wake Behind a Disk. THOMAS CARMODY. Ph.D. Dissertation, June 1963; Professor Rouse, adviser. An air-tunnel

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study of the establishment of the wake behind a disk at a Reynolds number of approximately 7 x 10^4 was undertaken. On the basis of the measured data, such a wake is fully established, that is, similarity profiles of the flow characteristics are formed, within 15 diameters of the disk, and approximately 95 per cent of the transfer of energy from the mean motion to the turbulence motion takes place within three diameters of the disk, in the region of the mean standing eddy. The measured mean ambient-pressure and mean total-pressure distributions, and the mean streamline pattern are presented in graphical form, as are the quantitative balances of the integrated momentum and mean-energy relationships. A stream function, consisting of a continuous distribution of doublets, is introduced to extend the radial limit of understanding of the flow characteristics to a very large, if not infinite, radius. Considerable attention is given to the problem of obtaining and interpreting turbulence-shear-stress data immediately downstream from the point of flow separation. The applicability of a local diffusion coefficient or virtual viscosity of the Boussinesq or Prandtl type for relating the turbulence shear stress to the radial gradient of mean axial velocity is discussed. The Bernoulli sum and the energy changes along individual streamlines investigated in an associated study are incorporated herein to obtain a quantitative estimate of the local errors involved in the turbulence-shear-stress measurements.

An Experimental Study of the Vorticity in the Wake of a Body of Revolution. LO-CHING HUA. M.S. Thesis, February 1963; Professor Landweber, adviser. The magnitude and direction of the velocity distribution in the wake of a prolate spheroid were determined from measurements with a three-hole pitot tube. A procedure for analyzing the measurements, taking into account the turbulence in the wake, was developed and applied. For this purpose it was also necessary to measure the distributions of various turbulence stresses in the wake. From the resulting velocity-vector distribution, it was then possible to compute the vorticity distribution as the curl of the velocity. These results may serve as a basis for a study of the mechanism of lift on a body of revolution.

Flow Characteristics at Abrupt Axisymmetric Expansions. MAHESH C. CHATURVEDI. Ph.D. Dissertation, August 1962; Professor Rouse, adviser. The flow at abrupt axisymmetric expansions represents a typical case of separation at an abrupt change of boundary and was

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studied in detail for four half angles of expansion — 15°, 30°, 45° and 90° — to determine the characteristics and the dynamics of flow. The characteristics of the mean flow and the secondary flow, such as the distribution of the mean velocity and pressure, the axial, radial and tangential turbulence intensities, and the turbulent shear, were evaluated. The basic hydrodynamic equations of impulse-momentum and work-energy for both mean and turbulent motion were formulated for the conditions of the study. These were evaluated section by section, to provide a check on the measurements and to determine the pattern of separation, the development of the force field and the dynamics of energy transfer from the mean motion through the turbulence toward its final form of heat. The experimental setup consisted of the abrupt expansion preceded by a bellmouth entry and followed by a uniform duct. The expansion was four and one-half inches and eight and one-half inches in diameter at the inlet and the outlet end, respectively, so that the expansion ratio was 1:2. The fluid used was air and the Reynolds number at the inlet was about 2×10^5. Additional independent measurements of head loss were also made on a water-pipe assembly.

Flow Characteristics in the Two-Dimensional Wake of a Flat Plate. RICHARD GEORGE HAJEC. M.S. Thesis, February 1961; Professor Rouse, adviser. The distribution of mean velocity, mean pressure, fluctuating longitudinal component of velocity, fluctuating pressure, and correlation of the fluctuating velocity and pressure in a two-dimensional wake of a flat plate are presented and discussed. Special experimental equipment and technique are included in detail. Closely related to the vortices shed from the edges of the plate, a zone of maximum turbulence was found to occur within the mean separation pocket. At a distance from the plate equal to its width, both the velocity and the pressure fluctuations reached maximum values, and the minimum mean pressure was recorded as -1.85 times the dynamic pressure in the undisturbed stream. The lateral location of the peaks in the distribution of velocity and pressure fluctuations were found to correspond closely with the centerlines of the trails of vortices as determined by von Kármán.

Decay of Turbulent Wakes Behind a Propeller. GERT ARON. M.S. Thesis, February 1960; Professor Hubbard, adviser.

Diffusion of Turbulence from Piers and Abutments of Spillways.

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LUIS FERNANDEZ-RENAU. M.S. Thesis, August 1954; Professor Rouse, adviser.

Gravitational Convection from Line Sources. HAROLD W. HUMPHREYS. M.S. Thesis, February 1950; Professor Rouse, adviser.

Characteristics of Mean Flow and Turbulence at an Abrupt Two-Dimensional Expansion. HSIEH-CHING HSU. Ph.D. Dissertation, February 1950; Professor Rouse, adviser.

Free Convection Due to a Point Source of Heat. CHIA-SHUEN YIH. Ph.D. Dissertation, August 1948; Professor Rouse, adviser.

Investigations in the Diffusion of Submerged Jets. W. DOUGLAS BAINES. M.S. Thesis, August 1948; Professor Rouse, adviser.

Distribution of Velocity in Turbulent Jets of Air. YAU-BEN DAI. M.S. Thesis, February 1947; Professor Rouse, adviser.

Diffusion Characteristics of Turbulence in an Open Channel. JAMES M. ROBERTSON. M.S. Thesis, January 1940; Professor Kalinske, adviser.

Falling of Bodies in a Stream and the Effect of Turbulence. GWOH-FAN DJANG. Ph.D. Dissertation, February 1935.

VORTEX FLOW

Vortex Over a Horizontal Orifice. KOTHA K. RAO. M.S. Thesis, August 1960; Professor Posey, adviser. As a continuation of H. C. Hsu's thesis, "Vortex Over Outlet" (1947), the variation of the discharge coefficient of a circular horizontal orifice with vorticity factor was investigated. The vortex was created and controlled by a simple arrangement of inclined water jets introduced over the free surface in a three-foot-diameter tank fitted with a three-inch circular orifice at the bottom. An interesting condition of instability leading to the formation of a whirling type of surge was observed to develop during some of the runs.

Vortex Over Outlet. HSIEH-CHING HSU. M.S. Thesis, June 1947; Professor Posey, adviser.

WATER POWER

Hydrological Phases of Water Development on the Upper Des Moines River. CHARLES KEITH WILLEY. M.S. Thesis, August 1937.

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A Study of Devices for Utilizing Flood Water to Increase the Power of Water Turbines. J. STUART MEYERS. M.S. Thesis, June 1928.

An Investigation of the Replogle Type of Head Increaser. EMIL P. SCHULEEN. M.S. Thesis, June 1927.

WAVES

A Nonlinear Numerical-Hydrodynamic Model of a Mechanical Water Wave Generator. R. H. MULTER. Ph.D. Dissertation, August 1970; Professor Landweber, adviser. A numerical method for solving nonlinear hydrodynamic problems of the initial-value type is developed and applied in the determination of the wave motion induced by a mechanical wave generator. The existence of a velocity potential, which satisfies the Laplace equation, is assumed. The corresponding kinetic and kinematic boundary conditions are not further simplified. In particular, a transformation of the free-surface conditions which facilitates a direct numerical integration of the nonlinear free-surface equations is utilized.

The transformation of the free-surface conditions reduces the computational problem to one of finding the velocity potential for a sequence of mixed boundary-value problems. A numerical superposition method for approximating the solution of the Laplace equation is developed. To integrate the nonlinear exact free-surface equations, the corresponding velocity distribution along the free surface must be determined. A technique developed by Lanczos is explained and then utilized for this.

A comparison of the numerical approximation of the nonlinear solution and the observed response of a vertical-bulkhead type generator which oscillates horizontally is made. The numerical results are found to be in good agreement with the observations. The corresponding linearized problem is also solved and compared to the nonlinear approximation and observed response. It is found that this solution does not predict many of the properties of the response which have been found to be significant to the utilization of mechanical wave generators for such things as model studies.

The transformation of the free-surface conditions is entirely general; and the resulting computational scheme could, therefore, be employed in the solution of any initial-value, free-surface flow problem reasonably treated as irrotational. The method developed for solving the mixed boundary-value problem is dependent on the geometry of the solid boundaries. Hence extension of this method of solution to other free-

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surface flow problems would require the development of techniques for solving the relevant boundary-value problem. Such techniques as conformal mapping may be utilized to do this.

Oscillatory Gravity Waves in Flowing Water. TURGUT SARPKAYA. Ph.D. Dissertation, June 1954; Professor Yih, adviser.

Experiments on Waves in Rectangular Channels. VICTOR A. KOELZER. M.S. Thesis, June 1939; Professor Mavis, adviser.

WEIRS

Overturning Moments on a Flashboard. HSING-HUA SHIH. M.S. Thesis, February 1964; Professor Howe, adviser. Changes of slope of a straight downstream apron of a spillway had been found by Bacci and Schultz to have certain effects upon the overturning moment of a flashboard. Lizarralde adopted the Corps of Engineers' Standard Spillway formula and tested one particular model. This investigation is concerned with another model, which is designed according to the same standard formula but based upon a small design head. The result is that, while the general geometry is similar to Lizarralde's model, the downstream apron inclination has been increased. Detailed comparison has been made between the present results and those of Lizarralde, the present data affording a means of rational flashboard design.

Irrotational Flow Over Weirs. THEODOR S. STRELKOFF. Ph.D. Dissertation, June 1962; Professors Rouse and Landweber, advisers. The problem of two-dimensional, irrotational flow over a vertical, sharp-crested weir is expressed, exactly, by an integral equation, derived with the aid of conformal mapping and singularity distributions. A numerical procedure for checking trial-and-error solutions of the equations is programmed in Fortran language for automatic calculation on a high-speed, electronic, digital computer — either the IBM 704 or IBM 709. The resulting approximate solutions are presented in the form of flow profiles and discharge coefficients for head-to-height ratios $h/w =$ 0.14, 1.15, 2.11, 4.36, 10.30. Available experimental data for comparable geometries are plotted on the same graphs to indicate the effects of viscosity and surface tension present in real flows. Inaccuracies, infeasible to reduce by trial and error, are shown to be present in the final results. The basis of an iterative procedure for solving the integral equation more accurately and less tediously is proposed and partially developed.

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Overturning Moments on a Flashboard Mounted on a Parabolic Spillway Crest. ALBERTO LIZARRALDE. M.S. Thesis, February 1962; Professor Howe, adviser. In this investigation the overturning moments on a flashboard mounted on a parabolic spillway crest are determined for various rates of flow and submergence ratios. Pressure measurements are made on the downstream and upstream faces of the flashboard. The results are given on a graph, which shows the dimensionless relationship between the overturning moments, the submergence and the rate of flow. A comparison is included of the moments obtained through the range of the experimentation with those computed assuming upstream hydrostatic distribution and downstream atmospheric pressure.

Moments on a Flashboard. ALAN H. SCHULTZ. M.S. Thesis, August 1959; Professor Howe, adviser.

Discharge Characteristics of Low Weirs and Sills. P. K. KANDASWAMY. M.S. Thesis, February 1957; Professor Rouse, adviser.

Pressure Distribution on Flashboards. ERNESTO D. BACCI. M.S. Thesis, February 1956; Professor Howe, adviser.

Aeration Demand of a Sharp-Crested Weir. GO CHEAN SHIEH and ARTURO OBADIA. M.S. Thesis, June 1954; Professor Howe, adviser.

Experimental Investigation of the Discharge Coefficient for a Rectangular Side Weir. CARLOS ACOSTA-SIERRA. M.S. Thesis, February 1951; Professor McNown, adviser.

Pressure Distribution on the Downstream Face of a Submerged Weir. MICHAEL BAR SHANY. M.S. Thesis, June 1950; Professor Alin, adviser.

Experimental Investigation of the Discharge Coefficient for a Rectangular Side Weir. RUSSELL JORDAN KENNEDY. M.S. Thesis, August 1949; Professor McNown, adviser.

Effect of Vacuum on a Free Nappe. LEROY A. THORSSEN. M.S. Thesis, June 1946; Professor Lane, adviser.

Effect of Aeration Rates Upon Discharge Over a Sharp-Crested Weir. CLAUDE C. LOMAX, JR. M.S. Thesis, February 1942; Professor Howe, adviser.

A Study of the Velocity and Pressure Distribution in the Nappe of a Sharp-Crested Weir. ERNEST T. SCHULEEN. M.S. Thesis, June 1927.

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APPENDIX

MASTER OF SCIENCE WITHOUT THESIS

Abascal, Francisco M.
(February 1958)
Albrecht, Theodore J., Jr.
(June 1956)
Balakrishna, Mattur R.
(August 1967)
Barr, James Robert
(February 1960)
Bottaccini, Manfred R.
(June 1957)
Briceland, Richard H.
(June 1955)
Burmeister, Ivan L.
(August 1965)
Champa, Swarng
(June 1960)
Cooper, James Fenimore
(June 1970)
Dougherty, Gale Barkman
(August 1949)
Ellsworth, William M.
(August 1948)
Fannon, William Walter
(August 1951)
Farooq, Arshad
(August 1959)
Goldstein, Moris
(February 1966)
Grinsteins, Valdis
(June 1962)
Haggag, Ragai Yousef
(June 1963)
Hakimian, Yusef
(August 1958)
Hateras, Stamatis C.
(August 1952)
Ho, Hau-Wong
(August 1958)
Hsieh, Lawrence W.
(February 1949)
Hsiung, Chuan Tze
(February 1953)
Huang, Jung-Han
(February 1949)
Ilio, Dominador Ibarra
(February 1952)
Ince, Simon Shunt
(August 1948)
Joering, Everard A.
(February 1967)
Johnson, Howard P.
(August 1954)
Kitchell, Robert P.
(June 1969)
Kumar, Pawan
(August 1968)
Kung, Ching-I
(June 1950)
Kwan, Chen-Hwa
(June 1959)
Lee, Chin
(August 1951)
Li, Kung-Shou
(August 1949)
Ling, Sung-Ching
(June 1950)
Liu, Shan Chien
(June 1949)
Lung, Yu-Chien
(August 1948)
Lwin, Maung Thein
(August 1952)
MacDonald, Edward G.
(June 1964)
Macoun, Kenneth G.
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Mann, Owen Robert
(August 1950)
Martin, Milton
(February 1958)
Mayer, Henry
(June 1961)
Mejía, F. Oscar
(August 1953)

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Méndez, Manuel V.
(February 1966)
Mercado, Gilberto G.
(February 1950)
Miller, Irene Elizabeth
(June 1953)
Moore, Edgar T.
(August 1958)
Mostafa, Ibrahim M.
(June 1953)
Mulay, Namdeo Laxman
(February 1950)
Muniz, Celso da Silva
(August 1959)
Murthy, Ivantury Gopal
(February 1954)
Nava, Roger Eugenio
(June 1954)
Orozco-Ochoa, Francisco J.
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Overgaard, Edmund K.
(August 1953)
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Pandit, Thakorbhai Bhikhabhai
(August 1967)
Parks, John Edwin
(February 1968)
Pendharkar, Ramkrishna S.
(August 1950)
Petersen, Margaret Sara
(June 1953)
Pickering, Charles William
(June 1952)
Post, Robert Francis
(August 1967)
Pujol, Alfonso
(August 1961)
Rahman, Mohammed M.
(February 1951)
Rao, Kannase Rahesh
(August 1947)
Relunia, Leopoldo Rontas
(February 1949)
Richardson, Ford, Jr.
(August 1950)
Rockwell, Glen Ellis
(June 1959)
Rodríguez-Díaz, Alberto José
(August 1954)
Sami, Sedat
(August 1957)
Sanchez, Salvador J.
(August 1962)
Sangster, William McCoy
(August 1948)
Schmidt, John J.
(August 1949)
Schuenemann, David A.
(August 1962)
Sierra, Francisco de Paula
(February 1958)
Singerman, Robert
(June 1969)
Sohan, Charles Haripal
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Strelkoff, Theodor S.
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Tao, Kwang-Yuen
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Thompson, Charles B.
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Thorn, Michael F. C.
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Villa, Salvador T.
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Villegas, Fabio
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Wang, Wen-Shao
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Warren, Moultri Alfred
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