OPEN-CHANNEL HYDRAULICS

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PREFACE

In recent years water-resources projects and hydraulic engineering works have been developing rapidly throughout the world. The knowledge of open-channel hydraulics, which is essential to the design of many hydraulic structures, has thus advanced by leaps and bounds. To the students and engineers in the field of hydraulic engineering, such valuable new knowledge should be made available in suitable book form. It is therefore not surprising that some new books have already appeared. However, most of them are presented in limited scope and all are written in foreign languages.[1] In the English language, the two well-known books, respectively by Bakhmeteff and by Woodward and Posey, were published nearly two decades ago.[2]

This book gives broad coverage of recent developments; it should meet the present need. It is designed as a textbook for both undergraduate and graduate students and also as a compendium for practicing engineers. Emphasis is given to the qualities of "teachability" and "practicability," and attempts were made in presenting the material to bridge the gap which is generally recognized to exist between the theory and the practice. In order to achieve these objectives, the use of advanced mathematics is deliberately avoided as much as possible, and the explanation of hydraulic

[1] Such as: Étienne Crausse, "Hydraulique des canaux découverts en régime permanent" ("Hydraulics of Open Channels with Steady Flow"), Éditions Eyrolles, Paris, 1951; R. Silber, "Étude et tracé des écoulements permanents en canaux et rivières" ("Study and Sketch of Steady Flows in Canals and Rivers"), Dunod, Paris, 1954; Martin Schmidt, "Gerinnehydraulik" ("Open-channel Hydraulics"), VEB Verlag Technik-Bauverlag GMBH, Berlin and Wiesbaden, 1957; N. N. Pavlovskiĭ, "Otkrytye rusla i sopriazhenie biefov sooruzheniĭ" (Open channels and adjustment of water levels), in the "Sobranie sochineniĭ" ("Collected Works"), vol. 1, pp. 309–543, Academy of Sciences of U.S.S.R., Moscow and Leningrad, 1955; and the new edition of M. D. Chertousov, "Gidravlika" ("Hydraulics"), Gosenergoizdat, Moscow and Leningrad, 1957.

[2] Boris A. Bakhmeteff, "Hydraulics of Open Channels," McGraw-Hill Book Company, Inc., New York, 1932; and Sherman M. Woodward and Chesley J. Posey, "Hydraulics of Steady Flow in Open Channels," John Wiley and Sons, Inc., New York, 1941.

theories is greatly simplified as far as practicable. Illustrative examples are given to show the application of the theories, and practical problems are provided for exercises. Furthermore, short historical accounts are given in footnotes in order to stimulate the reader's interest, and ample references are supplied for his independent studies. Some references, however, may not be readily available to the reader, but they are listed for academic and historical interest.

In essence, the book is the outgrowth of the author's 20 years' experience as a student, teacher, engineer, researcher, and consultant in the field of hydraulic engineering. The manuscript of the book was drafted for the first time in the academic year of 1951–1952 for use in teaching the students of civil, agricultural, and mechanical engineering and of theoretical and applied mechanics at the University of Illinois. Since then several revisions have been made. In the beginning, the material was prepared solely for graduate students. Owing to the general demand for a book on the design of hydraulic structures for undergraduate studies, the manuscript was expanded to include more fundamental principles and design procedures. At the same time, most of the advanced mathematics and theories were either omitted or replaced by more practical approaches using mathematical operations of a level not higher than calculus.

From 1951 to 1955, the author made several special visits to many major engineering agencies and firms in the United States to discuss problems with their engineers. As a result, a vast fund of information on hydraulic design practices was collected and incorporated into the manuscript. Thereafter, the author also visited many hydraulic institutions and laboratories in other countries and exchanged knowledge with their staff members. In 1956 he visited England, France, Belgium, the Netherlands, Germany, Italy, and Switzerland. In 1958 he visited Austria, Turkey, India, and Japan, and again England, France, and Belgium. The information obtained from these countries and from other countries through publications and correspondence was eventually added to the final draft of the manuscript as supplements to the American practice.

The text is organized into five parts—namely, Basic Principles, Uniform Flow, Gradually Varied Flow, Rapidly Varied Flow, and Unsteady Flow. The first three parts cover the material which would ordinarily be treated in a one-semester course on open-channel hydraulics. For a one-semester course on the design of hydraulic structures, Chaps. 7 and 11 and Part IV should supply most of the material for the teaching purpose. Part V on unsteady flow may be used either for advanced studies or as supplemental material to the one-semester course, depending largely on the discretion of the instructor with reference to the time available and the interest shown by the students.

In Part I on basic principles, the type of flow in open channels is classified according to the variation in the parameters of flow with respect to space and time. For simplicity, the depth of flow is used as the flow parameter in the classification. The state of flow is classified according to the range of the invariants of flow with respect to viscosity and gravity. The flow invariants used are the Reynolds number and the Froude number. Since the effect of surface tension of water is insignificant in most engineering problems, the Weber number as a flow invariant is not introduced. In fact, the state of flow can be further classified for its stability in accordance with the Vedernikov number or other suitable criteria. However, such a criterion has not been well established in engineering practice, and therefore it is taken up only briefly later in Chap. 8.

Four coefficients for velocity and pressure distributions are introduced. In particular, the energy coefficient is presented throughout the book. This coefficient is usually ignored in most books on hydraulics. In practical applications, the effect of the energy coefficient on computations and hence on designs is quite significant and therefore should not be overlooked, even though the value of the coefficient may not always be determined accurately.

The energy and momentum principles constitute the basis of interpretation for most hydraulic phenomena. A thorough treatment of the two principles is given in Chap. 3. Since the book is intended for the use of practicing engineers, the treatment of a problem is in most cases based on a one- or two-dimensional flow.

In Part II on uniform flow, several uniform-flow formulas are introduced. Despite many new proposals for a formula having a theoretical background, the Manning formula still holds its indisputable top position in the field of practical applications. This formula is therefore used extensively in the book. In certain specific problems, however, the Chézy formula is used occasionally.

The design for uniform flow covers nonerodible, erodible, and grassed channels. The erodible channels in general may be classified under three types: channels which scour but do not silt, channels which silt but do not scour, and channels which scour and silt simultaneously. In channels of the second and third types, it is necessary for the water to carry sediments. As will be stated later, the sediment transportation is considered as a subject in the domain of river hydraulics. Therefore, only the channels of the first type, which carry relatively clear water in stable condition, are treated in this book.

In Part III on gradually varied flow, several methods for the computation of flow profiles are discussed. A new method of direct integration is introduced which requires the use of a varied-flow function table fir developed by Professor Boris A. Bakhmeteff in 1912.[1] The table given in Appendix D of this book is an extension of the table to nearly three times its original size. This extended table and a table for negative slopes were prepared during 1952 to 1954 by the author for teaching purposes at the University of Illinois.[2] For the computation of flow profiles in circular conduits, a varied-flow function table is also provided in Appendix E.

The method of singular point is a powerful tool for the analysis of flow profiles. Since this method requires the use of advanced mathematics, it is described only briefly in Chap. 9 for the purpose of stimulating further interest in the theoretical study of flow problems.

In Part IV on rapidly varied flow, the treatment of the problems is largely supported by experimental data, because this type of flow is so complicated that a mere theoretical analysis in most cases will not yield sufficient information for the purpose of practical design. The use of the flow-net method and the method of characteristics is mentioned but no details are given, because the former is so popular that it can be found in most hydraulics books, while the latter requires the knowledge of advanced mathematics beyond the scope of this work.

In Part V on unsteady flow, the treatment is general but practical. It should be recognized that this type of flow is a highly specialized subject.[3] The knowledge of advanced mathematics would be required if a comprehensive treatment were given.

It should be noted that the subject matter of this book dwells mainly on the flow of water in channels where water contains little foreign material. Consequently, problems related to sediment transportation and air entrainment are not fully discussed. In recent years, sediment transportation in channels has become a broad subject that is generally covered in the study of river hydraulics, which is often treated independently.[4]

[1] Boris A. Bakhmeteff, "O Neravnomernom Dvizhenii Zhidkosti v Otkrytom Rusle" ("Varied Flow in Open Channels"), St. Petersburg, Russia, 1912.

[2] Ven Te Chow, Integrating the equation of gradually varied flow, paper no. 838, *Proceedings, American Society of Civil Engineers*, vol. 81, pp. 1–32, November, 1955. Closing discussion by the author in *Journal of Hydraulics Division*, vol. 83, no. HY1, paper no. 1177, pp. 9–22, February, 1957.

[3] Special references are: J. J. Stoker, "Water Waves," vol. IV of "Pure and Applied Mathematics," Interscience Publishers, New York, 1957; V. A. Arkhangelskiĭ, "Raschety Neustanovivshegosia Dvizheniia v Otkrytykh Vodotokakh" ("Calculation of Unsteady Flow in Open Channels"), Academy of Sciences, U.S.S.R., 1947; and S. A. Khristianovich, "Neustanovivsheiesia dvizhenie v kanalakh i rekakh" ("Unsteady Motion in Channels and Rivers"), in "Nekotoryie Voprosy Mekhaniki Sploshnoĭ Sredy" ("Several Questions on the Mechanics of Continuous Media"), Academy of Sciences, U.S.S.R., 1938, pp. 13–154.

[4] Special references on the subject of river hydraulics are: Serge Leliavsky, "An Introduction to Fluvial Hydraulics," Constable and Co., Ltd., London, 1955; and T. Blench, "Regime Behaviour of Canals and Rivers," Butterworth & Co. (Publishers) Ltd., London, 1957.

Similarly, the transient flow in channels subject to the influence of the tides is a special topic in the rapidly developed fields of tidal hydraulics and coastal engineering and is therefore beyond the scope of this book.

In a science which has reached so advanced a state of development, a large portion of the work is necessarily one of coordination of existing contributions. Throughout the text, the author has attempted to make specific acknowledgment regarding the source of material employed, and any failure to do so is an unintentional oversight.

In the preparation of this book, engineers and administrators in many engineering agencies have enthusiastically furnished information and extended cooperation. The author is especially indebted to those in the U.S. Bureau of Reclamation, U.S. Geological Survey, U.S. Soil Conservation Service, U.S. Agricultural Research Service, U.S. Army Engineer Waterways Experiment Station, Offices of the Chief Engineer and District Engineers of the U.S. Army Corps of Engineers, U.S. Weather Bureau, U.S. Bureau of Public Roads, and the Tennessee Valley Authority. Also, many friends and colleagues have kindly supplied information and generously offered suggestions. In particular, the author wishes to thank Dr. Hunter Rouse, Professor of Fluid Mechanics and Director of Iowa Institute of Hydraulic Research, State University of Iowa; Dr. Arthur T. Ippen, Professor of Hydraulics and Director of Hydrodynamics Laboratory, Massachusetts Institute of Technology; Dr. Giulio De Marchi, Professor of Hydraulics and Director of Hydraulic Laboratory, Institute of Hydraulics and Hydraulic Construction, Polytechnic Institute of Milan, Italy; Dr. Roman R. Chugaev, Professor and Head of Hydraulic Construction, Scientific Research Institute of Hydraulic Engineering, Polytechnic Institute of Leningrad, U.S.S.R.; Monsieur Pierre Danel, President of SOGRÉAH (Société Grenobloise d'Études et d'Applications Hydrauliques), France, and President of the International Association of Hydraulic Research; Dr. Charles Jaeger, Special Lecturer at the Imperial College of Science and Technology, University of London, and Consulting Engineer of The English Electric Company, Ltd., England; Professor L. J. Tison, Director of Hydraulic Institute, University of Ghent, Belgium; Dr. Tojiro Ishihara, Professor of Hydraulics and Dean of Faculty of Engineering, Kyoto University, Japan; and Dr. Otto Kirschmer, Professor of Hydraulics and Hydraulic Structures, Technical Institute of Darmstadt, Germany.

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PART I

BASIC PRINCIPLES

CHAPTER 1

OPEN-CHANNEL FLOW AND ITS CLASSIFICATIONS

1-1. Description. The flow of water in a conduit may be either *open-channel flow* or *pipe flow.* The two kinds of flow are similar in many ways but differ in one important respect. Open-channel flow must have a *free surface,* whereas pipe flow has none, since the water must fill the whole conduit. A free surface is subject to atmospheric pressure. Pipe flow, being confined in a closed conduit, exerts no direct atmospheric pressure but hydraulic pressure only.

The two kinds of flow are compared in Fig. 1-1. Shown on the left side is pipe flow. Two piezometer tubes are installed on the pipe at sections 1 and 2. The water levels in the tubes are maintained by the pressure in the pipe at elevations represented by the so-called *hydraulic grade line.* The pressure exerted by the water in each section of the pipe is indicated in the corresponding tube by the height y of the water column above the center line of the pipe. The total energy in the flow of the section with reference to a datum line is the sum of the elevation z of the pipe-center line, the piezometric height y, and the velocity head $V^2/2g$, where V is the mean velocity of flow.[1] The energy is represented in the figure by what is called the *energy grade line* or simply the *energy line.* The loss of energy that results when water flows from section 1 to section 2 is represented by h_f. A similar diagram for open-channel flow is shown on the right side of Fig. 1-1. For simplicity, it is assumed that the flow is parallel and has a uniform velocity distribution and that the slope of the channel is small. In this case, the water surface is the hydraulic grade line, and the depth of the water corresponds to the piezometric height.[2]

Despite the similarity between the two kinds of flow, it is much more difficult to solve problems of flow in open channels than in pressure pipes. Flow conditions in open channels are complicated by the fact that the

[1] It is here assumed that the velocity is uniformly distributed across the conduit section; otherwise a correction would have to be made, such as is described in Art. 2-7 for open channels.

[2] If the flow were curvilinear or if the slope of the channel were large, the piezometric height would be appreciably different from the depth of flow (Arts. 2-9 and 2-10). As a result, the hydraulic grade line would not coincide exactly with the water surface.