Hydraulics

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Preface

TO FIFTH EDITION

THE purpose of this revision is (1) to improve the clarity and arrangement of the text and problems in the light of continued experience in the use of the book with classes in elementary hydraulics, (2) to add new problems illustrating applications of basic theory to certain engineering problems not previously covered, and (3) to expand the text material somewhat to include new developments in theory and practice which have been accepted in the past few years as an integral part of hydraulic engineering.

Changes to improve the wording and clarify the meaning have been made in many places throughout the book. Nearly all the problems of the fourth edition have been retained, although with some rearrangement to provide a more logical order. A number of new examples and problems have been added.

New text material is introduced on the variation of hydrostatic pressure with altitude in a compressible fluid, on the flow through gates and over dams, on the general consideration of the flow of liquids in pipes, on the analysis of flow in pipe networks, and on the resistance offered to motion of objects through a fluid. To give students an elementary knowledge in the field of hydraulic model testing, in which they are finding employment in increasing numbers, a chapter on hydraulic similitude and dimensional analysis has been added.

Although a quarter century has elapsed since this book was first prepared, the authors have no fault to find with the statements made in the preface to the first edition. The book is still intended to present to the engineering student or to the practicing engineer the fundamental principles relating to fluids at rest or in motion as they apply to engineering practice and to illustrate those principles with practical problems.

Thanks are due to many friends and associates whose suggestions and advice have greatly helped with the revision, in par-

ticular: A. T. Lenz, G. A. Rohlich, J. A. Borchardt, J. R. Villemonte, and A. C. Ingersoll of the University of Wisconsin; E. R. Dodge of Montana State College; E. F. Brater of the University of Michigan; R. D. Goodrich of the University of Wyoming; and F. W. Greve and W. E. Howland of Purdue University. Professor Howland read the manuscript and offered many valuable suggestions.

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Preface

TO FIRST EDITION

THIS book deals with the fundamental principles of hydraulics and their application in engineering practice. Though many formulas applicable to different types of problems are given, it has been the aim of the authors to bring out clearly and logically the underlying principles which form the basis of such formulas rather than to emphasize the importance of the formulas themselves.

Our present knowledge of fluid friction has been derived largely through experimental investigation, and this has resulted in the development of a large number of empirical formulas. Many of these formulas have necessarily been included, but, in so far as possible, the base formulas to which empirical coefficients have been applied have been derived analytically from fundamental consideration of basic principles.

The book is designed as a text for beginning courses in hydraulics and as a reference book for engineers who may be interested in the fundamental principles of the subject. Tables of coefficients are given which are sufficiently complete for classroom work, but the engineer in practice will need to supplement them with the results of his own experience and with data obtained from other published sources. Acknowledgment for material taken from many publications is made at the proper place in the text.

H. W. K.
C. O. W.

University of Michigan
April 1922

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GENERAL NOTATION

A	area, total cross-sectional
A_m	area, mean in reach
B	width of canal bed
b	breadth of weir
C	coefficient of discharge; also Chezy coefficient
C_c	coefficient of contraction
C_v	coefficient of velocity
C_1	Hazen-Williams coefficient
D	diameter
d	depth
d_c	depth, critical
d_m	depth, mean in reach
E	energy
F	force
f	pipe friction coefficient (Darcy-Weisbach)
G	work, or power
g	acceleration, gravitational
H	head, total
H_0	head, above stream bed
h_f	head lost by friction
h_v	head, velocity
K	coefficient of loss
k	roughness, of pipe wall
L	length along stream bed; also crest length of weir
m	coefficient of roughness (Bazin)
N_F	Froude's number
N_R	Reynolds' number
N_W	Weber's number
n	coefficient of roughness (Kutter and Manning)
P	wetted perimeter; also height of weir
P_m	wetted perimeter, mean in a reach
p	pressure, intensity of
p_a	pressure, atmospheric
p_v	pressure, vapor
Q	discharge, total
q	discharge, per unit width
R	hydraulic radius, A/P
R_m	hydraulic radius, mean in a reach
S	slope of energy gradient
S_0	slope of channel bed
S_w	slope of stream surface
s	side slope (s horizontal to 1 vertical)
V	velocity, mean, Q/A
V_c	velocity, critical
V_m	velocity, mean in a reach
V_w	velocity of wave
W	weight
w	weight per unit volume
Z	elevation above datum
α	coefficient, unequal velocities in cross section
μ	viscosity, dynamic (absolute)
ν	viscosity, kinematic, μ/ρ
ρ	density, mass per unit volume, w/g
σ	surface tension

Chapter I

FUNDAMENTAL PROPERTIES OF FLUIDS

1. The Science of Hydraulics. Hydraulics is defined as that branch of science which treats of water or other fluid in motion. A prerequisite to the understanding of the motion of fluids, however, is a knowledge of the pressure exerted by fluids at rest. This study, called hydrostatics, is usually included in hydraulics. The field of hydraulics also includes hydrodynamics, which relates to the forces exerted by or upon fluids in motion.

2. Fluids. Fluids are substances capable of flowing, having particles which easily move and change their relative position without a separation of the mass. Fluids offer practically no resistance to change of form. They readily conform to the shape of the solid body with which they come in contact.

Fluids may be divided into liquids and gases. The principal differences between them are:

1. A liquid has a free surface, and a given mass of a liquid occupies only a given volume in a container, whereas a gas does not have a free surface, and a given mass occupies all portions of any container regardless of its size.

2. Liquids are practically incompressible and usually may be so considered without introducing appreciable error. On the other hand, gases are compressible and usually must be so treated.

The theory and the problems of this text deal mainly with fluids which may be considered incompressible. A few examples and problems require the use of the simple gas laws which give the relationship of pressure, volume, and temperature.

The distinctions between a solid and a fluid should be noted here:

1. A solid is deformed by a shearing stress, the *amount* of unit deformation up to a certain point being proportional to the unit stress; a fluid is also deformed by a shearing stress but at a *time rate* of deformation which is proportional to the stress.

2. If the elastic limit is not exceeded, the application of a given unit shearing stress to a solid produces a certain unit deformation

which is independent of the time of application of the force, and when the stress is removed the solid returns to its original form. On the other hand, if a given shearing stress is applied to a fluid, deformation continues to take place at a uniform rate with time, and when the stress is removed the fluid does not, through forces contained within itself, return to its original form.

The application of sufficient heat will change many solids into a fluid state. The hardest steel can be melted so that it will flow easily. A block of cold tar shows properties of a solid but if heated becomes fluid and can be poured into small cracks in concrete. The change from solid rock to molten lava is a well-known occurrence in nature. Relatively high temperatures are required for these changes. The change from solid ice to fluid water, however, occurs at 32° F.

The mechanics of the borderline condition in which a substance may be either a plastic solid or a very viscous fluid has not been as thoroughly studied in engineering as have the strictly solid and the strictly fluid states.

3. Units Used in Hydraulics. Engineering practice in the United States is generally based on the *foot-pound-second* system of units. In practically all hydraulic formulas these units are used, and if not otherwise stated they are understood. Frequently the diameters of pipes or orifices are expressed in inches, pressures are usually stated in pounds per square inch, and volumes may be expressed in gallons. Before applying such data to problems, conversion to the foot-pound-second system of units should be made. Care in the conversion of units is essential. Errors in hydraulic computations result more frequently from wrong use of units than from any other cause.

Since it is frequently necessary to interchange metric and foot-pound-second units, the relations of these systems of units are briefly reviewed here.

The fundamental equation relating force F, mass M, and acceleration a is

$$F = kMa$$

where k is a proportionality factor. The value of k is made equal to 1 by two different systems of defining units.

1. *Gravitational system,* in which k is made equal to 1 by defining the unit of mass. If a body of unit weight falls freely, unit force

is acting and the acceleration is g. Thus for unit force to produce unit acceleration the unit of mass must consist of g units of weight.

(a) Foot-pound-second system: 1 lb force = 1 slug mass × 1 ft per sec per sec, in which 1 slug mass = g pounds weight divided by g feet per second per second. An average, commonly used value of g is 32.2 ft per sec per sec.

(b) Metric system: 1 gram force = 1 unit of mass × 1 cm per sec per sec, in which a unit of mass = g grams weight divided by g centimeters per second per second. An average, commonly used value of g is 981 cm per sec per sec.

2. *Absolute system*, in which k is made equal to 1 by defining the unit of force.

(a) Foot-poundal-second system: Unit force is that force which, acting on a body of 1 lb mass, gives it an acceleration of 1 ft per sec per sec, and is called a poundal. Therefore, 1 poundal force = 1 lb mass × 1 ft per sec per sec. By 1 lb mass is meant an amount of matter equivalent to that in a block of metal, known as the standard pound, which is kept in Washington, D. C.

(b) Metric system: Unit force is that force which, acting on a body of 1 gram mass, gives it an acceleration of 1 cm per sec per sec, and is called a dyne. Therefore, 1 dyne force = 1 gram mass × 1 cm per sec per sec. The unit of mass is the gram, which is defined as 1/1000 of the mass of a block of platinum kept in Sèvres and known as the kilogram prototype.

The metric and foot-pound-second systems are related by the following units of length and weight:

$$1 \text{ meter} = 3.2808 \text{ ft}$$

$$1 \text{ kilogram} = 2.2046 \text{ lb}$$

EXAMPLE. How many dynes force are equivalent to 1 lb force?

Solution. 1 slug mass weighs g lb or 453.6 g grams. Also 1 ft per sec per sec = 30.48 cm per sec per sec. Therefore 1 lb force = 453.6 g × 30.48 = 444,800 dynes.

4. General Properties of Fluids. The properties of fluids which are of fundamental importance in the study of hydraulics are defined here.

Unit Weight w: The weight of a unit volume of a fluid. In foot-pound-second units, the unit weight is expressed in pounds per cubic foot.

which is independent of the time of application of the force, and when the stress is removed the solid returns to its original form. On the other hand, if a given shearing stress is applied to a fluid, deformation continues to take place at a uniform rate with time, and when the stress is removed the fluid does not, through forces contained within itself, return to its original form.

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But by assumption 3, the unit shearing stress

$$\tau \text{ (tau)} = \mu \frac{dv}{dx} \tag{2}$$

where μ is a proportionality factor called the coefficient of viscosity. Thence

$$\frac{V}{x} = \frac{\tau}{\mu} \tag{3}$$

and

$$\mu = \frac{\tau x}{V} \tag{4}$$

If the plates are unit distance apart and moving with unit relative velocity

$$\mu = \tau \tag{5}$$

In this case μ is known as the dynamic, or absolute, viscosity and is thus defined as the force required to move a flat surface of unit area at unit relative velocity parallel to another surface at unit distance away, the space between the surfaces being filled with the fluid.

The foot-pound-second units in which dynamic viscosity is expressed can be evaluated from equation 4. Unit shear τ is in pounds per square foot, distance x is in feet, and velocity v is in feet per second. Hence, the units of μ are

$$\frac{\text{lb/ft}^2 \times \text{ft}}{\text{ft/sec}} = \frac{\text{lb sec}}{\text{ft}^2} = \frac{\text{slug}}{\text{ft sec}}$$

In the metric system, the unit of viscosity is called the poise, 1 poise being 1 dyne sec per cm^2. A centipoise is 0.01 poise. It has been found experimentally that the dynamic viscosity of water at 68° F (20° C) is 1 centipoise. The ratio of the dynamic viscosity of any fluid to the dynamic viscosity of water at 68° F is termed the relative viscosity. Therefore, when expressed in centipoises, the dynamic viscosity and relative viscosity of any fluid are numerically equal.

Kinematic Viscosity ν *(nu):* The ratio of the dynamic viscosity of a fluid to its mass density. Thus

$$\nu = \frac{\mu}{\rho}$$

Mass Density ρ *(rho):* The mass per unit of volume. Thus, in engineers' gravitational units,

$$\rho = \frac{w}{g} \quad \text{or} \quad w = \rho g$$

where g equals the acceleration due to gravity. In foot-pound-second units, mass density is thus slugs per cubic foot, or also

$$\frac{\text{lb/ft}^3}{\text{ft/sec}^2} = \frac{\text{lb sec}^2}{\text{ft}^4}$$

In the metric system density is measured in grams per cubic centimeter and is therefore numerically equal to specific gravity.

Specific Gravity s*:* The ratio of the unit weight of a fluid to the unit weight of water at 4° C (39.2° F).

Viscosity μ *(mu):* Viscosity is that property of a fluid which determines the amount of its resistance to a shearing stress. A perfect fluid would have no viscosity. There is no perfect fluid, but gases show less variation in viscosity than liquids. Water is one of the least viscous of all liquids, whereas glycerine, heavy oil, and molasses are liquids having comparatively high viscosities.

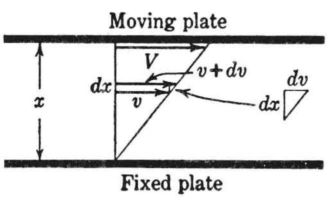

FIG. 1

The viscosity of liquids decreases with increasing temperature, whereas the viscosity of gases increases with increasing temperature.

The mathematical basis of viscosity may be derived from Fig. 1. Consider two parallel plates of indefinite extent at distance x apart, the space between them being filled with a fluid. Consider further that one of these plates moves at velocity V parallel to the other plate. Three assumptions are made:

1. That the fluid particles in contact with a moving surface have the velocity of that surface.
2. That the rate of change of velocity is uniform in the direction perpendicular to the direction of motion.
3. That the shearing stress in the fluid is proportional to the rate of change of velocity.

By assumption 2, from similar triangles

$$\frac{V}{x} = \frac{dv}{dx} \tag{1}$$

in the tube higher than the level outside, the meniscus being concave upward. The tube B is immersed in mercury or some other liquid which does not wet the tube. In this case the meniscus is convex upward and the level of the liquid in the tube is depressed. The effect of capillarity decreases as the size of tube increases. The liquid in a tube $\frac{1}{2}$ inch in diameter is approximately at the same level as the outside liquid, but it is appreciably different in smaller tubes. Water-proofing liquids have been developed which, when applied to the inside of small glass tubes, greatly reduce the capillary rise of water in the tubes.

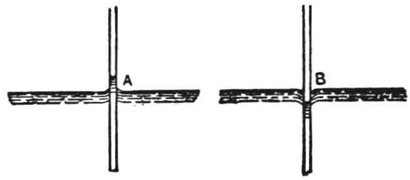

FIG. 2. Capillary action.

The dimensions of surface tension are pounds per foot, the surface film being considered of zero thickness. The surface tension of liquids decreases as their temperature rises.

5. Properties of Water. Various properties of water which are used in hydraulics are shown in the table on page 8. Certain properties are discussed briefly in this article.

Unit Weight. Water has its maximum unit weight at a temperature of 4° C (39.2° F). At this temperature pure water serves as a standard of specific gravity for all substances. Under atmospheric pressure at sea level, water freezes at 32° and boils at 212° F. The weight of pure water at its temperature of maximum density is 62.427 lb per cu ft.

As water occurs in nature, it invariably contains salts and mineral matter in solution. Silt or other impurities may also be carried in suspension. These substances, being heavier than water, increase its weight. The impurities contained in rivers, inland lakes, and ordinary ground waters do not usually add more than 0.1 lb to the weight per cubic foot. Ocean water weighs about 64 lb per cu ft. After long-continued droughts the waters of Great Salt Lake and of the Dead Sea have been found to weigh as much as 75 lb per cu ft.

Since the weight of inland water is not greatly affected by ordinary impurities or changes of temperature, an average weight of water may be used which will give results sufficiently accurate for ordinary purposes. In this book the weight of a cubic foot of water is ordinarily taken as 62.4 lb. In precise work, when the