HYDRAULIC METHODS AND MODELING

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Keywords: Hydraulic Methods, Contextual Framework, Hydraulic Phenomena, Philosophy of Modeling

Contents

Summary

The means available to the practicing engineer and theoretical scientist to understand and analyze flow behavior are basically two-fold, namely analytical study and/or simulation by modeling. The second method implies creating an analog or model of the problem and measuring or observing its behavior. This is then interpreted according to scientific theory and/or empirical relationships that are known to be representative of the behavior being observed. This article gives an outline of the concepts used by the researcher and designer to develop a framework within which to model complex, three-dimensional hydraulic phenomena. It only serves as an introduction to the subject, aimed to point the reader in the right direction to allow in-depth analysis, as provide the ability to design and operate efficient hydraulic models.

1. Introduction

Water is the key to the survival of mankind. Water resources are increasingly becoming under more pressure as civilization expands. In addition, the greenhouse effect is influencing climate and the associated regional hydrology. It is incumbent upon civil and hydraulic engineers and hydraulic scientists to understand hydraulic process and flow behavior and to use it in the design of hydraulic structures. Thus, they can in a small way contribute to the judicious use of water resources.

The understanding of the laws of physics in general, and of hydraulics specifically, has expanded dramatically since the first recording of hydraulic observations was made more than five hundred years ago.

For simple hydraulic systems, where basically only the continuity principle is involved, understanding of hydraulic processes is exact, and the design engineer can use exact theoretical solutions to predict the behavior of such systems. In complex hydraulic systems, where the boundaries of the system itself could be mobile, such as in a river, where both the banks and the riverbed can erode or accrete, an exact understanding is not possible. Although the processes themselves are well understood, prediction of the effect of human intervention on such a system is more complex. The design engineer may have to resort to hydraulic modeling to allow a prediction of how the intervention will influence the hydraulic system (see *Applied Hydraulics, Flow Measurement and Control*).

This article describes the considerations used to model hydraulic phenomena. The scope of the article includes hydraulic phenomena at hydraulic structures, in rivers, estuaries, the coastal region and oceans, and overland and groundwater flows. It serves as an introduction to the topic, but does not discuss the detail of each area of modeling covered.

In essence, hydraulic modeling is a matter of trade-offs. On the one hand, answers are sought which are as accurate as possible, but on the other hand, there is the very real issue of the cost at which this accuracy is to be achieved. The true success criterion is the ability of the designer to strike just the right balance between these two aspects.

The literature abounds with articles and publications that relate to hydraulic modeling. Good reference journals, which deal both with hydraulics and with modeling, are the IAHR *Journal of Hydraulics, La Houille Blanche*, the ASCE *Hydraulic Engineering Journal*, the *Journal of Hydrology* and Elsevier's *Coastal Engineering Journal* (see *Hydraulic Structures for Coastal Protection*).

2. Brief History of Hydraulic Methods and Modeling

There are many examples of hydraulic systems and structures in history, which predate the Renaissance by thousands of years.

Frequent examples, which date back to 3000 BC and earlier, are quoted in the literature. In Mesopotamia, there exists a network of canals, which predates the "deluge." Vaulted irrigation canals dating back to 5200 BC. were found in Nippur. The first dams were built in Egypt, under the reign of King Menes, the first of the pharaohs, around 3000 BC.

The Persians developed networks of underground canals which carried water from water-bearing geological basins over tens of kilometers to areas where water was required. The sophistication of these canals is superior to anything else reported in ancient times. The Greeks later copied many of the hydraulic achievements of its "colonies," such as Egypt and Persia. When the Greek civilization faded, the Roman empire started expanding. The Romans can truly be said to be the fathers of modern water supply engineering. About a hundred significant water supply systems are known. At its peak, Rome had seventeen separate water supply systems, which in total delivered 1.5 megaliters of water per day (see *Potable Water*).

Archaeological remains exist of ports built by the Phoenicians, Carthaginians, Greeks and Romans, in the ten centuries BC in the Iberian Peninsula. Similarly, remnants of Greek and Roman ports from the same time period can be found throughout the Mediterranean Sea. No clear picture exists of what approaches were used to design and improve the hydraulic structures referred to above. However, it is reasonable to assume that some form of "hydraulic design practice" existed, which more than likely included some form of hydraulic simulation, or modeling.

The first recorded hydraulic experiments are found in the translations by Reti (ca. 1974) of the Leonardo da Vinci 1452 to 1519 papers. Da Vinci obviously had a keen grasp of what is involved in understanding flow behavior. On the one hand he summarizes the philosophy of designing human interventions in a natural environment: "O investigator do not flatter yourself that you know the things nature performs for herself but rejoice in knowing the purpose of those things designed by your own mind." On the other hand, he also understood the difference between theory and practice, as signified by the two quotes from his writings, given in Figure 1.

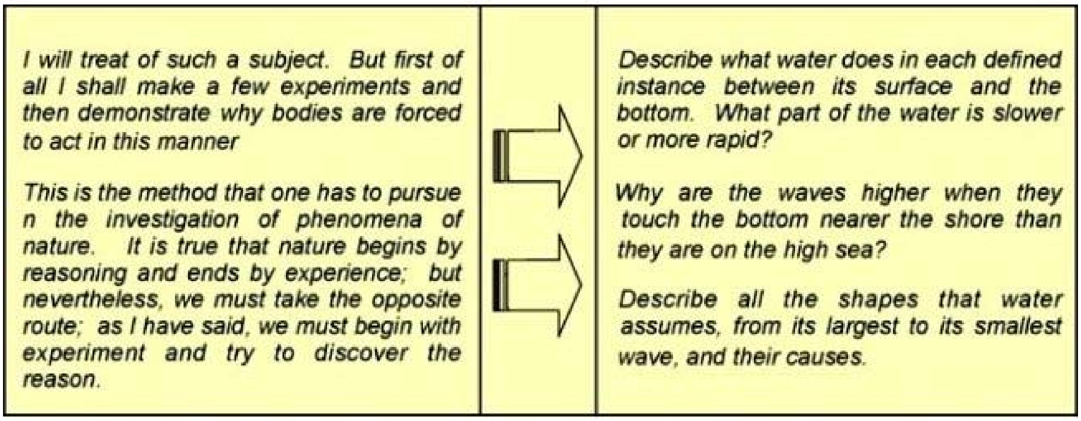

Figure 1. Da Vinci's views on theory and practice

It can, therefore, be said that Leonardo da Vinci turned hydraulics into a science. He wrote a treatise on hydraulics, consisting of nine individual volumes. The text is amply supported by sketches, which seem to imply that da Vinci had the use of some sort of elementary flume, in which observations were made. Apart from being a keen observationalist and experimentalist, da Vinci also designed and supervised the construction of major hydraulic structures in Italy and France. He is thus the first recorded individual to have researched hydraulics and used the experience gained in this manner for design purposes.

Unfortunately, because of his fear of retribution by the Church for his various endeavors in research, amongst others in the human anatomy, da Vinci recorded all of his work in a self-styled mirror-language. His work was first published ca. 1650. Only in the twentieth century, ca. 1920, was a reedited version published. As a result, much of what da Vinci had found during his studies was lost to later generations and had to be redeveloped.

Galileo Galilei (1564–1642) showed great interest in the motion of water. One of his pupils, Castelli (1577–1644) is considered to be the founder of the Italian School of Hydraulics. He developed the continuity principle, and in his writings he frequently refers to hydraulic experiments.
Many references to hydraulic studies undertaken in the seventeenth century are available, and it can safely be said that this is the time when researchers had mastered the principles that were originally developed by da Vinci, but sadly not shared by him. Hydraulic modeling and design was already becoming accepted practice by the seventeenth century.

In the eighteenth and nineteenth centuries, rapid advances were made in Europe in the understanding of hydraulics and the physical laws that govern it. This period also saw the advent of numerous empirical approaches to hydraulic phenomena, that is, numerical and/or approximate approaches based on observation of water-flow behavior. Much of what was recorded was based on trial-and-error, but gradually the subject field was becoming more scientific, and the foundations for modern-day hydraulic modeling and design were being formed.

3. Contextual Framework for Hydraulic Processes and Phenomena

In order to understand the principles behind hydraulic modeling, it is first necessary to develop a simple reference framework. The discussion below should be read in conjunction with the theme articles on hydraulics and fluid mechanics.

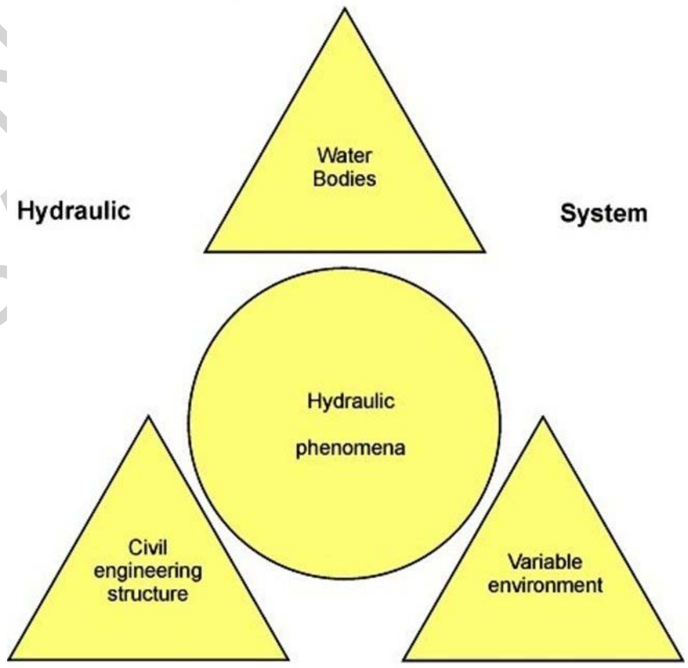

Figure 2. The hydraulic balance

For the purpose of this discussion, consider a hydraulic system which can contain any number of complex elements. Figure 2 schematically shows the elements, which would be in some sort of dynamic balance in a system of this nature. The discussion below is done from a modeling perspective.

The water body: Hydraulics and fluid mechanics deal with the behavior of fluids at rest and/or in motion. Typically, this article considers the modeling of fluids in motion. Density and viscosity are the two key fluid properties which help determine fluid motion. Fluid density simply represents the fluid mass per unit volume. Fluid viscosity determines the amount of resistance to a shearing force (see *Fluids at Rest and in Motion*).

When the fluid body also contains suspended particulate matter, specific gravity is also important. It denotes the ratio between the mass of the particulate substance and that of a similar volume of water (see *Sedimentation Data Acquisition*).

When fluid motion is through porous substances, such as in groundwater flow, the capillary forces become important. They reflect the relative magnitude of the cohesion of the fluid and the adhesion of the capillary-pore walls, formed by the narrow spaces between closely packed particles (see *Ground Water Hydraulics*).

When modeling the behavior of hydraulic water bodies, the interrelated scaling of these properties in nature, in relation to their similarly interrelated scaled counterparts in the model, is of crucial importance. The principle of similitude between prototype and model must be maintained, pertaining to geometric, kinematic and dynamic scaling, as will be discussed in Section 4 below.

The variable environment (natural interfaces): The water body under consideration is set in a variable environment. In the extreme case, where the hydraulic system is simply a reservoir with an open inflow and a restricted pipe outflow, the environment consists only of the inflow and outflow and the reservoir with its particular geometry. In such a simple system, an analytical solution is available. However, if the water body is an estuary, consider the following complex situation:

- the estuary mouth is open to the sea;
- the possibility of overland runoff into the estuary exists;
- various little streams enter the estuary proper;
- a road and a train bridge cut across the estuarine flood plain, partially obstructing the flow through their columns; and
- upstream of the estuary, a dam has been built, which totally altered the flood hydrograph in its downstream reaches.

In order to be able to understand fully hydraulic behavior in such a system, the complex interactions between these various environmental elements and the water body need to be understood (see *Hydroinformatics*, *Environmental Assessment of Hydraulic Engineering Works*).

Civil engineering structures (man-made interfaces): When evaluating civil engineering or other man-made structures, both action and reaction need to be considered. One the one hand, these structures impede the fluid flow, whilst on the other hand, the fluids exert forces on the structures. Engineering design is all about the optimization of these two factors. Phenomena playing a role in the vicinity of structures and/or other obstructions, are motion-induced fluid forces, as well as scour and deposition processes (see *Loads on Earth- and Rock-fill Dams Arising from Water and Wind*).

Hydraulic phenomena: Fluid motion can be either steady or unsteady. This way of looking at flow uses time as the yardstick. If the flow does not change over a given time period, the flow is steady. Uniform flow occurs when the cross-section of the flow remains constant at every section along the flow path. Varied flow occurs when the opposite is true.

Fluid motion is inherently controlled by two basic laws of nature, namely, the continuity principle, and the equations of motion. These two laws specify the conservation of mass, momentum and energy (see *Fluid Mechanics*).

The continuity equation can be written as follows:

$$\frac{D\rho}{Dt} + \rho\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) = 0 \qquad (1)$$

where D/Dt = total derivative, or total rate of increase

$$= \underbrace{\left[\frac{\partial}{\partial t}\right]}_{\text{local term}} + \underbrace{\left[\frac{u\partial}{\partial x} + \frac{v\partial}{\partial y} + \frac{w\partial}{\partial z}\right]}_{\text{convective term}} \qquad (2)$$

x,y,z = 3 directions of potential motion, with x as principal direction
u,v,w =velocity components in the x, y and z directions
ρ = mass density of fluid

The equation of motion can, in a general form, be written as:

Surface forces + body forces = (mass).(acceleration)

This can be rewritten to read:

$$X - 1/\rho \cdot \left(\frac{\partial p}{\partial x}\right) = \frac{Du}{Dt} \qquad (3)$$

Similar equations apply in the y- and z-directions.

In the above:
X = body forces per unit mass, in the x-direction.

p = pressure force per unit area.

Depending on the exact nature of the fluid phenomena under consideration, these equations can be combined to develop governing equations for such phenomena (see *Fluid Mechanics*).

Examples will be given in the next sections, which deal with the modeling of hydraulic phenomena.

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Biographical Sketch

Harry Swart worked at CSIR, the South African Council for Scientific and Industrial Research, for twenty-one years, first in Stellenbosch, South Africa, from 1975 to 1989 as project manager for coastal engineering research, then for seven years until 1996 as Director of the Environmental Division, which included all marine research, geophysical research and applications and atmospheric work and estuarine research. He has a wide experience in coastal and estuarine engineering, design and research, environmental impacts and developmental pressures, and has worked in this field on projects in Africa, Europe, the Middle East and South America. He has published widely in these fields. As part of his research into oceanographic matters he became deeply involved in researching and understanding the extent of the implications of climate change on sea level, as input to developing sustainable options for future development. He obtained a D.Sc. in Ocean Physics from the Delft Technical University in the Netherlands in 1974 with a thesis on “Offshore Sediment Transport and Equilibrium Beach Profiles.” He entered the consulting field in 1996 and is now a Principal Researcher with Bentley West Management Consultants in Sandton, South Africa.