FLUID MECHANICS SERVING HYDRAULIC ENGINEERING IN CHINA

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Many problems of fluid mechanics have arisen from hydraulic construction in China. In this article problems in connection with high-dam developments and river training are reported. Even in this limited scope, time and space will allow only partial review.

HIGH-DAM DEVELOPMENTS

In China, dams up to 157m high have been built and dams exceeding 240m in height are being designed. Discharge from the outlet works of these dams may exceed 30,000 m^3/sec at velocities as high as 50m/sec. Severe damages are known to have been caused by such a flow either by the enormous amount of kinetic energy it carries or by the cavitation its high velocity often induces. The problem is further complicated by the hydrological conditions in China which are such that frequent operation of the outlet works is anticipated in many localities. Thus great risks are to be taken. It is because of this situation that much attention has been given to the study of high-velocity flow, especially air entrainment and cavitation.

1. Aerated flow

A program of air entrainment research was initiated and directed by the writer at IWHR in 1957. A key step in this program is to set up the necessary apparatus. A movable flume was constructed to generate aerated flow at speeds up to 17 m/sec in the laboratory. It is 15 m long and may be set at any inclination between 0 and 57 degrees. Instrumentation for aerated flow proves to be a rather difficult problem, if velocities

of the mixture are to be measured over a full range of air concentration up to 98%. Finally a special procedure of sampling was developed to achieve full calibration of a Pitot tube and an electric concentration gage[1]. The instruments were then used to determine the discharges of water and air through the flume just mentioned and a closed conduit by the area integration method. The discharges so found were checked against the known rates fed upstream. The discrepancy found so far does not exceed 5% for water discharges and 9% for air discharge[2]. Our experiments indicate that air and water concentrations could not be simultaneously represented by samples drawn at a single rate of pumping. Therefore some of the published data of air and water concentrations in the literature obtained by separating the same sample seem to be questionable. Instruments for field measurements have been constructed and calibrated likewise. It may be of interest to mention here that, on a suggestion by the writer, the idea of equivalent velocity originally proposed by Prof. C.S. Yih[2] for nonturbulent stratified flow was tried on turbulent aerated flow, by setting

$$U_1 = \sqrt{\beta + C\frac{\rho_a}{\rho_w}}\,U \cong \sqrt{2g\Delta h_w}, \qquad (1)$$

It is surprising to find that the experimental distributions of U_1 for the highly turbulent aerated flow in a flume conform to those for single-phase turbulent wall jets. Here β and C are water and air concentrations, ρ_a and ρ_w the densities of air and water, U the velocity measured in an aerated flow and Δh_w the differential head registered by the manometer connected to the Pitot tube.

Air entrainment is mainly a beneficial element in the defence against the dangerous high-velocity flow. It is well known that air concentration of a few per cent in the neighborhood of a solid boundary is sufficient to prevent pitting due to cavitation. Air entrainment will also result in better dispersion and will enhance energy dissipation when the high-velocity flow is discharged to the river channel downstream of a dam. Laboratory and field studies of air slots as a means to mitigate pitting have been carried out[3-5]. In one case the prototype tested had a velocity of about 29 m/sec in its spillway, whereas in another case it exceeded 43 m/sec with air slots installed no damage occurred even behind artificial roughnesses up to 3 cm in height intentionally built into the invert of the tunnel. Without aeration these roughnesses are expected to cause severe erosion or pitting of the concrete downstream. Laboratory studies performed on the high-velocity flume mentioned above predicted the appropriate geometry for the slot as well as the range of protection provided by each slot. In order to bring about greater dispersion of high-velocity jets through aeration, many devices have been suggested. An effective device is to make use of the stationary shock formed on the free surface of a supercritical flow in a converging channel. Stream lines passing through the shock will have inclinations varying over a large range, so that on leaving the converging walls, the jet will expand rapidly in a vertical plane and, with the attendant intensive air entrainment, the kinetic energy per unit volume of the flow is much decreased. Consequently the erosion in the river bed downstream caused by such jets is dramatically reduced. An innovative device based on this principle is that of flaring gate piers proposed by Mr. Gong Zhenying in 1974[6–8]. Another device used is that of the slit-type bucket[9] as first employed by the Portuguese[10].

An undesirable consequence of air entrainment is the "bulking" of flow, It turns out, however, that this seldom poses a real threat to high-dam developments because the structures of concern are usually too short for the inception of aeration to occur within the structures at design discharges. Nevertheless considerable research has been devoted to this problem just to be sure. General inception of aeration in high-velocity flow is taken to be the result of surfacing of the floor boundary layer on a structure, with instability of the surface at the point of emergence taken for granted. As the length Reynolds number can easily reach 10^9 in a high-dam development, empirical methods for the calculation of boundary layer development at smaller Reynolds numbers are of doubtful value in dealing with high dams. It happens, however, that in a spillway the velocity in the region outside of the boundary layer varies exponentially with distance. High Reynolds number and exponential variation of velocity in the irrotational portion allow the application of Townsend's approximate theory of self-preservation[11] to the calculation of boundary layer in a spillway. Critical points of aeration inception computed by Lin et al with this theory come quite close to the data of observation[12]. Detailed measurements with laser Doppler velocimeter indicated no appreciable effects of the presence of a free surface on the velocity distributions in a boundary layer[13] along a spillway.

2. Cavitation

Many cases of damage due to cavitation, i.e., pitting, have occurred in China. As a result, much effort has been devoted to the study of methods to mitigate pitting. In general four approaches are followed, namely to provide for aeration, to improve the boundary geometry, to remove the surface irregularities and to look for more resistant materials. Regarding boundary geometry, a curve of equal cavitation number was proposed by the writer et al[14,15], and was found to agree quite well with an existing spillway Known to have operated well under a flow velocity of more than 40 m/sec. In this case, by employing such a profile the effective head drop, as far as cavitation is concerned, may be reduced from 105 m to about 62 m. As Chinese rivers are usually carrying heavy load of sediment, in recent years attention has been directed to the study of possible effects of sediment on cavitation and pitting. It has been observed that at low concentrations (less than 3%) the incipient cavitation number is higher than that in a flow of clean water, when the concentration goes beyond this range, the trend is reversed[16]. Moreover, Huang Jitang et al. have carried a study of the effects of sediment in the flow on the pitting of concrete. Theoretical evaluation of incipient cavitation number by calculating the minimum pressure coefficient has been performed for a gate pier with circular head[17].

RIVER TRAINING

Over 80,000 dams have been built in the last thirty some years to train the rivers in China, yielding an aggregate storage of about 400 billion m^3. Considerable construction has also been executed in the estuaries for flood control as well as the reclamation of tidal flats. In dealing with these projects, many problems of fluid mechanics are encountered. Some are discussed below.

1. One-dimensional tidal flow

A characteristic oriented scheme was proposed by Zhang in 1966[18], and has been found to give good results in such a well-mixed estuary as the Qiantang. It is an explicit scheme. If $\lambda^{\pm}$ denote the characteristic directions corresponding to the St. Venant equations governing the flow, then when $\lambda^{\pm}<0$, forward difference quotients are used in this scheme to replace the space derivatives, whereas, for $\lambda^{\pm}>0$, backward difference quotients are employed. For temporal derivatives, however, a forward difference quotient is always taken[19]. This scheme has been extensively used with success on the Qiantang estuary where a strong tidal bore runs. The space step length is usually kept constant. A version of variable space step is, however, also available.

As field data often show the bed slope and the spatial variation of channel cross section $\partial A/\partial x$ to be discontinuous functions of distance, and as smoothing of data is a moot operation dictated by personal experience, a procedure was developed by Jin Danhua, Shi Linbao and Yu Dajin to avoid the computation of $\partial A/\partial x|_h$. For a simple channel without flood plains, the basic equations of motion in terms of cross section A and discharge Q may be written as

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{2}$$

and $$\frac{\partial Q}{\partial t} + 2u\frac{\partial Q}{\partial x} - u^2\frac{\partial A}{\partial x} + gA\frac{\partial z}{\partial x} = -gA\frac{u|u|}{\bar{C}^2 h} \tag{3}$$

where x denotes distance, t the time, u the mean velocity in a cross section, z the surface elevation, h the depth of flow, g the gravitational acceleration and $\bar{C}$ the Chezy coefficient. Since

$$\frac{\partial A}{\partial t} - B\frac{\partial z}{\partial t} = 0 \tag{4}$$

one can derive three characteristics

$$\lambda_1 = \underline{u} + \underline{c}, \quad \lambda_2 = \underline{u} - \underline{c} \text{ and } \quad \lambda_3 = 0 \tag{5}$$

in which $\underline{c} = \sqrt{gA/B}$, with B denoting the surface width. Corresponding to the three characteristics, there are three equations

$$-u^2\frac{dA}{dt} + (u\pm c)\frac{dQ}{dt} + gA\frac{dz}{dt} = -(u\pm c)gA\frac{u|u|}{\bar{C}^2 h} \tag{6}$$

and $$\frac{\partial A}{\partial t} - B\frac{\partial z}{\partial t} = 0 \tag{7}$$

with $$\frac{d}{dt} = \frac{\partial}{\partial t} + \lambda\frac{\partial}{\partial x} \tag{8}$$

It should be noted that in eqs. (6) and (7) the undesirable term $\frac{\partial A}{\partial x}|_h$ no longer appears. The advantage of using eqs. (6) and (7) in computation is obvious for it is now no longer necessary to feed $\frac{\partial A}{\partial x}|_h$ into the computer. It is also obvious that the additional characteristic $\lambda_3 = 0$ has no effect on the number of boundary and initial conditions necessary for the solution. Thus the characteristic λ_3 may be called a virtual or dummy characteristic. Its introduction does, however, improve the computations.

2. Two-dimensional tidal flow

For wide estuaries, depth integrated models have been employed in the numerical simulation of tidal flow without stratification, Methods used include those of characteristic theory[20], operator splitting[21], direct discretization of the basic equations such as reported by Robert and Rodine[22] and ADI[23]. The method of direct discretization when applied to the Bay of Hangzhou[23] seemed to require more computer time than the first two methods mentioned above. In all cases, both stage and current may be well simulated. The case of changing water boundary on a tidal flat as a result of changing tide has also been simulated on the computer by L.B. Shi and Z.Q. Han (publication of reports pending).

3. Dam-break waves

Safety considerations require, among other things, the study of dam-break waves. Important projects are often studied by model tests and sometimes by numerical computation on an electronic computer. As smaller dams are too numerous to be studied this way, theoretical analyses have also been carried out for idealized cases in order to supply dam-site hydrographs as upper boundary conditions for routing of floods through the channel downstream by the local engineers. In these analyses, instantaneous effecement of the dam and prismatic reservoir of a general parabolic cross section are assumed. Analytic solutions for the following cases have been obtained[24,25]:

(1) Horizonal reservoir of a finite length with negligible resistance
(2) Sloping reservoir with negligible resistance
(3) Sloping reservoir with resistance

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