DESIGN OF SUSTAINABLE HYDRAULIC STRUCTURES

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Contents

Summary

Design principles are outlined first, with listings of typically varied applications to hydraulic engineering practice. More detailed discussion is devoted to dams, spillways, flow control works, and storage reservoir structures. The importance of turbulence phenomena as related to hydraulic design is noted, and this is followed by a discussion of hydraulic computations for various purposes. Criteria are discussed for assuring the reliability and sustainability of hydraulic structures through adhering to proper design principles.

1. Introduction

Hydraulic design involves the application of flow theory to the design of various water containment and control structures. The designer should ensure that the structure and the systems will function effectively and economically under all foreseeable service conditions. Hydraulic structures must be capable of withstanding flow conditions and forces caused by both static and flowing water loading. They must be so designed as to last over their design life span and be resistant to deterioration, aging, and extemporaneous forces due to weather extremes and earthquakes.

In designing a hydraulic structure, the designer chooses from many options available, and from past experience, that particular design believed to be the most cost-effective, functional, and safe.

Examples of waterworks and systems comprising many detailed hydraulic structural components are the following: raw water storage reservoirs, dams, hydroelectric power plants, pumping stations, intake structures and diversion weirs, tunnels, canals and pipelines, water treatment and sewerage disposal works, flocculation tanks, clarifiers, control and measuring structures, storm-water draining and confining structures, clear water (municipal) reservoirs, water towers, surge tanks, spiral casings, draft tubes, manifolds, energy dissipating devices, spillways, and stilling basins.

Clear water reservoirs, as an example, are dealt with in more detail, while *dams* and associated *water control structures* are dealt with in reasonable detail. Turbulence and its associated effects on hydraulic design, and hydraulic design computations are also dealt with in this article. Another article provides a broad overview of fluid behavior (see *Fluids at Rest and in Motion*).

In addition to the above listing of structures, which are concerned mainly with water supply and distribution, there are also the following categories of water-related structures and water-control operations not further discussed in this article. These are also dealt with by hydraulic design engineers, with the aid of hydraulic theory and its application, hydraulic engineering:

- harbors, docks, piers, seawalls, breakwaters, coastal and beach protection, locks and canals
- ocean pipelines for effluents, gas or petroleum products, moorings, and anchorages
- deep ocean construction, floating, guyed, or free-standing platforms such as used for oil rigs
- undersea tunnels, manmade islands in oceans and estuaries, coastal engineering, lighthouses
- bridges and piers for road and rail, river training works, offshore airport runways, caissons
- hydraulic-fill dams, slurry and tailings dams, hydraulic dumping, hydraulic mining (monitoring)
- underwater excavation, dredging, deep-drilling, hydrofracturing, tremie-concrete foundations

2. Design

The design of the hydraulic structure or system must be done according to classic and applied hydraulics theory dealing with the motion or containment of water. (*Hydraulics* here excludes what is known as *hydraulic control systems* using oil as the fluid.)

The criteria to be satisfied in hydraulic design involve several considerations:

- Structural behavior must be acceptable during all possible *normal* and *abnormal*, *working* and *nonworking* circumstances, and each has to be investigated, including for obsolescence. For example, in the case of a canal, pipeline, dam, or reservoir: empty, first filling, normal operation, overload conditions, failure, and restoration are all design conditions. Here *dam* denotes the impounding structure of a storage reservoir; but *reservoir* may also denote the enclosing structure itself, as in a *service reservoir*.

- The hydraulic structure, as part of a system, must be *functional* and should achieve its purpose under all circumstances and ideally must be able to survive all natural and manmade events to fulfill its function.
- The structure or system must be *safe* and not embody any danger to or negatively influence any other structure or system, endanger human life or property, or be an environmental hazard.

The following elements of sound hydraulic design are considered to be the most important:

2.1. Preliminary Design

- *Planning* investigations, to arrive at alternative solutions for a water supply, hydropower, or wastewater disposal system, go hand in hand with state-of-the-art design.
- *Design choice* procedure, e.g., for the types of spillway in a dam, consists of a preliminary design (flow rates, yield determination, storage capacity) and advanced design (application of free-surface flow and closed-conduit flow theory, along with hydraulics and fluid mechanics principles).
- *Optimization* and testing of tentative design and costing. Water pressure and hydrostatic and hydrodynamic forces are determined (moments, stresses, shear, overturning, uplift, flotation) on elements of the design of the structure or system (inverted siphon, bell-mouth spillway, anchor blocks). The effects of erosion, cavitation, and seepage have to be evaluated and pressure-relief systems incorporated (earth dams, concrete dams, tunnels, hydropower, and pump station structures).

2.2. Revision of Design

Revision of design involves control calculations, alterations, and further optimization.

2.3. Final Detailed Design

Together with specifications and cost estimates, final detailed design includes the production of working drawings for construction purposes.

Test situations are also investigated so that the final product will be able to cope with the most critical conditions in addition to standard conditions. Hypothetical events during construction, commissioning, and the service life of the structure or system also have to be considered (such as earthquake, flood, war, civil unrest, and so on).

2.4. Hydraulic Calculations

These calculations involve assessments of roughness, resistance, turbulence, eddy currents, smoothening, and rounding-off effects. Also considered are the following aspects:

- control systems: automatic and manual backup

- observation, performance monitoring, and warning systems
- maintenance and in-service operation

2.5. Approval of Plans

The approval of plans follows final design, and includes the invitation of bids and the award of contracts, the supervision of construction, and finally the commissioning of the completed work.

2.6. Postcommissioning Activities

Postcommissioning activities include the following:

- case studies and investigations into failures and reasons
- dam safety regulations, guidelines, statistics, registers
- learning through experience
- reporting on case studies
- advance of the state of the art (e.g., in dam design: earth, rock-fill, mass concrete, gravity, arch, buttress, reinforced concrete, roller-compacted concrete)
- documenting the sequence developed in perfecting the state of the art of specialized hydraulic structures (e.g., morning-glory spillways, failure and improvements of flood-control structures)

As an example of the variety of designs prevalent in hydraulic structures, one category among the subjects listed above that is of great practical significance is examined next in more detail, namely, *clear water reservoirs.* This is merely an introduction to the subject and not even a guideline; the subject is more comprehensively dealt with in another article (see *Ground Level Reservoirs and Elevated Storage Tanks*).

3. Clear Water Reservoirs

The hydraulic and structural design of these reservoirs, as used in urban water supply and distribution systems, affords an excellent example of the complex process an engineer faces when designing a dependable water-containing structure. There are two types of reservoirs in use: *ground-level reservoirs* and *elevated storage tanks*, the first for the purpose of short-term balancing storage and the second for providing system pressure.

3.1. Types of Ground-Level Reservoirs

Ground-level reservoirs are of the following types:

- rectangular, circular, polygonal, or irregular in form
- sloping or self-supporting sides of earth (lined) or reinforced concrete, with ring-tension beams and domed roofs, or beam- and column-supported flat-slab roof
- floating or inflatable cover, or even without a roof

- floors of concrete (lined) or earth (compacted) with plastic liner
- Structural elements to be designed are the following:
- floors, walls or sides, ring beams, roof slabs, columns
- linings, membrane or concrete, or compacted soil
- roof, membrane cover, floating, pneumatically supported, dome, cone, flat slab, and columns
- excavation, substructures, construction and expansion joints, lining, backfill, trimming, and finishing
- performance and service equipment: inlet and outlet works, control valves, flow meters, and operating gear

3.2. Elevated Water Towers (considered as examples of structural water-containing units):

Types of structures

- *free-standing:* funnel, cylinder, cupola, spherical, ellipsoid, toroid, cone, rectangular
- *supported:* steel or concrete tanks on columns, self-supporting shafts, columns, footings

Design aspects (influencing the choice of structure):

- materials: concrete, steel, lined earth
- construction techniques: excavation, compacting, trimming, lining, placing, erection

This overview merely indicates some of the considerations governing the successful design of water-retaining structures. Other articles deal with their planning and operation, and with water uses and impacts (see *Guidelines for Potable Water Purification*).

4. Hydraulic Design of Dams and Control Works

Hydraulic design of a complex structure such as a dam (with its control works) is an involved process, fully dealt with in separate articles. The main considerations are dealt with by subject in another article (see *Project Design: Dams and Reservoirs*).

4.1. Spillways

Spillways are required auxiliary structures to a dam and its water storage reservoir for safely passing excess water (floods). Spillway types are crest overspill, side channel, saddle, or lateral (off-axis).

Crest overspilling spillways are centrally located for arch dams, having a width approximately equal to that of the riverbed at the bottom. They can have at their crests energy dissipaters or a stilling basin with an end wall to create sufficient depth, or with

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Biographical Sketch

J.M. Jordaan is a retired professor of civil engineering and professional engineer in civil engineering hydraulics. He graduated from the University of Witwatersrand (B.Sc. Eng.) and obtained the degrees M.S. (U. Wisconsin), Civil Engineering (MIT), and Sc.D. (MIT). He has lectured at the Universities of Hawaii, Delaware, and Pretoria.

His professional career included hydraulic and coastal engineering research with the Council for Scientific and Industrial Research in Pretoria, South Africa, and the US Naval Civil Engineering Laboratory, Port Hueneme California, US.

He specialized in hydraulic engineering practice for 28 years with the Department of Water Affairs in South Africa and Namibia, and he was active as technical assessor for the proposed Misicuni Multiple-Purpose Hydroelectric and Water Project, Cochabamba, Bolivia, South America.

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