WATER CONVEYANCE SYSTEMS AND FLOOD CONTROL WORKS

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Contents

Summary

In this article dealing with applied hydraulics and design of water control structures, two aspects are described. Firstly, the orderly control and conduction of water through conveyances such as canals and pipelines from source to user area. Secondly, the mitigation of the effects of extreme flooding events by judicious provision and operation of flood control structures.

1. Introduction

Applied hydraulics involves the design of water conveyance systems and flood control works. In the first case, water conveyance, the objective is to provide the desired through-put from the source to the user area in an orderly, controlled manner. In the latter case, flood control, the aim is to develop and optimum strategy of control against an unpredictable adversary. The impacts of floods which are uncontrolled are awesome, as happened not long ago, during the 1960's, when the river Arno flooded a large part of the city of Florence, Italy, due to the sudden opening of control gates to release an oncoming flood.

In 1981 the town of Laingsburg in the arid Little Karoo of South Africa was devastated by a flash flood originating over three sub-catchments and concentrating the effects at the junction of three rivers, exactly where the town is situated. No control was possible, but the devastated area was eventually converted into a landscaped park to avoid the recurrence of loss of life and damage.

In the case of the city of Los Angeles, frequently visited in the past by flash floods from the Santa Ana Mountains, a well-engineered flood detention and containment system was developed, to reduce the impact of such floods.

Water consumption points are usually situated at great distances from water supply sources. To cover these distances water conveyance systems are utilized. These may consist of free surface or enclosed pressure conduits, e.g. open canals, tunnels, gravity pipelines, pumping mains and penstocks.

Typical examples are: a dam forming a raw water storage reservoir, supplying a canal to an irrigation project, or a bored water well-field feeding a clean water reservoir, connected by pipeline to a domestic water distribution system. In free-surface flow channels and canals, as well as closed conduits, the minimization of friction losses is very important, especially where the distances of conveyance become very large (tens to hundreds of kilometers).

Special hydraulic structures are also involved, e.g. inverted siphons, hydraulic tunnels, inlet and outlet works, junctions and fittings in conduits. In the hydraulic design of these flow structures, reliance is made on hydraulic principles and economics. The lower the hydraulic resistance is to be made, the larger the structure's cross-section becomes, and the more expensive the capital investment, but lower the energy cost, to operate it. To derive an optimum balance between usefulness and operating cost is the aim of the design engineer.

Considering briefly some aspects of economic design of canals, pipelines and related hydraulic structures, such as tunnels, inverted siphons, intake and outlet works, flow dividers and distribution networks, is the aim of this article. The layout of drainage/sewerage systems, such as municipal storm water and waste disposal engineering is a further field of application of open and closed conduit flow.

The basic theory of control of free-surface and closed conduit flow is contained in textbooks and postgraduate courses, with its applications dealt with in hydraulic design practice manuals and speciality courses, as well as in another article in this theme (see *Elements of Control Systems*).

In the following sections a number of guiding principles are presented relating to the design and management of canals and closed conduits, as well as flood control works.

2. Water Conveyance Systems: Canal Design

Before dealing with the design of canals for water conveyance a few fundamental principles are reviewed. Much of this information is available in standard hydraulic textbooks, and therefore only a brief review of the main criteria is presented here.

2.2. Discharge Capacity

Discharge capacity is determined by means of a head-loss gradient/discharge equation, such as Manning, Chezy or Hazen-Williams. Canals mostly comprise the conveyances of greater water supply projects and must be visualized and designed in the total context of the project. Canals are mainly utilized for transporting raw (untreated) water, such as agricultural water, as well as bulk water supply for industrial and domestic use (see *Measurement of Open Channel Flow*).

For smaller scale treated water supply, especially for networks such as used in sprinkler irrigation, residential household and urban office block supplies, pipelines are used because they have a lower loss of quantity, higher supply pressure and elimination of contamination and require smaller servitude areas. At times a direct pipeline, tunnel or inverted siphon may be several times shorter, and therefore more economical, than a canal having to follow contours and grade lines over a much longer distance. It therefore depends on the terrain's relief, degree of existing building, road and street development, which optimum route to choose and whether canals or pipelines will be used and in what combination.

2.2. Gradients and Head Losses

Canal gradients may be as low as 1 in 10 000 for very large discharges (around 100 m^3/s) to 1 in 4000 for the usual main supply canals; to 1 in 1000 or steeper, for drainage canals coping with variable flows down to very small values (less than one cubic meter per second).

Additional head losses are implicit because of:

- uneconomical (narrower) cross sections in steep cross-slope terrain;
- tunnels, inverted siphons, flumes;
- transverse and side-spilling weirs;
- bends and section changes; and
- take-off points.

These head losses are calculated in terms of loss coefficients times velocity head. Aging can also reduce the canal's capacity due to increased losses on account of:

- roughening of lining (reinforced concrete);
- alignment changes of panels of lining; and
- sediment deposition and chemical, biological fouling.

Sustaining the capacity of a canal therefore necessitates periodic maintenance and refurbishment.

2.3. Design of Canals for Water Conveyance

The most economical canal cross-section is a shape into which a semi-circle may be placed, either a rectangle, a trapezium or a parabola. Hydraulic theory requires that the hydraulic radius (area divided by wetted perimeter) be a maximum. The available terrain, width and cross slope are further factors influencing the optimal choice of cross section.

For example, a practical trapezoidal concrete-lined canal will have side slopes of 1:1 or 1:1.5 instead of the ideal, 60° with the horizontal. An earth canal will have side slopes even flatter: 1:2 or 1:2.5. In all cases freeboard must be added. Maneuvering room for excavating and lining machines, inspection roads and spoil banks on either side of the canal must be added to the top width, thus doubling or trebling the overall width. However, this implies large expropriation areas due to the extra width, as well as the longer grade-line length of canals.

Part of the terrain may be so special as to require different cross-sections, with transitions from and to the optimum cross-section of the main reaches. For example, for economical in-rock excavation, one or both sides might be vertical or sub-vertical. In weak rock, the canal side slope would be steeper than in compacted soft earth material, since it would be self-supporting. Spoil banks and roadways would be suitable means for raising the freeboard on either side.

Cross-drainage. Cross drainage is necessary to conduct storm runoff water safely across the canal and avoid such water, carrying rock and soil debris, from entering and contaminating clean water supplied by the canal. Such water should also not run in drainage channels next to and parallel to the canal sides, as undercutting of the lining would result, causing collapse.

In culvert type storm-drainage crossings under a canal, the transverse slope of 1:100 is customary, with an energy dissipating structure at the end, to deal with supercritical flow and conduct the runoff safely into a natural drainage feature, or into a constructed out-fall drain for multiple purpose use.

Hydraulic Considerations. Hydraulic calculations for flood cross-drainage units are made using standard storm drainage algorithms for small drainage areas. Depending on the terrain, cross-drainage structures consist of either super-passages or sub-passages (culverts) and should recognize the natural drainage pattern of the area that existed before the canal was built. They should be sized to cater for a 1 in 20 year storm runoff. Other structures needed such as vehicle and livestock crossings over the canal should be adequately supported to avoid reduction of the canal width.

When a canal has to cross a major tributary, creek, canyon or narrow valley, comparative cost estimates should be made to determine the optimum point and means of crossing, e.g. inverted siphon, aqueduct or flume, spanning the natural drainage feature. Similarly, at promontories, economic studies can determine if, when and where to tunnel through, rather than take the canal around the particular feature.

A general rule to observe is that a tunnel is more economical than a canal ten times longer in length and an inverted cut-and-cover siphon is more economical than a canal three times longer in length. A flume is only viable over a steep cross-flowing creek where it passes high over it, and the terrain slope is too steep to cut a lengthy canal to follow the grade-line around.

Drains and sewers have to take care of variable effluent flow and therefore must have steeper slopes (1:500 to 1:100) than near-constant flow water supply canals. Where solid material has to be moved by water, e.g. in sewers, a 1:100 slope is common for main sewers and 1:50 for household sewer lines. For feeder and trunk sewers, sections are mostly circular and flowing partly full, while *horseshoe* or *ovoid* (egg) *shaped* sections are used in main out-fall sewers.

Both free surface and pressure flow (closed conduit) may occur, which necessitates installation of vertical ventilation pipes at regular intervals, to allow air to escape or enter, as the case may be. These vent pipes must have turned-down ends where they emerge above ground to avoid contamination or being tampered with. Sewer design is rather complicated aspect of urban hydraulic engineering and is generally dealt with in sanitary engineering handbooks.

3. Water Conveyance Systems: Design of Pipelines and Other Closed Conduits

For the conveyance of purified water for industrial as well as municipal water supply purposes open canals cannot be used. The reason is that potable water must be preserved from contamination, and also not subjected to undue losses on the way to the consumer. Furthermore it is supplied under pressure, which requires that it be conveyed in a closed conduit and therefore pipelines are used for this purpose. Some basic principles of pipeline design are first reviewed below.

3.2 Theory of Pipe Flow

Closed conduit flow, such as occur in pipelines, pressure tunnels, penstocks, inverted siphons and distribution mains and networks, involve hydraulic losses, (as dealt with in the article Fluid Mechanics in Pipelines). Friction head-loss, and hence flow resistance, is determined by means of the Darcy-Weisbach relationship where f, the resistance coefficient, is a function of the Reynolds Number and the roughness of the pipe wall relative to its diameter (see *Flow Measurement in Closed Conduits*).

The friction factor can be determined through a trial-an-error procedure from the Moody Diagram and/or the Colebrook-White equation or directly by means of monograms or logarithmic graphic diagrams (as explained in the article cited below, wherein an example is given). If the available discharge or the required delivery is known, and a designed distance and fall in hydraulic gradient is given, then only one solution is possible of the diameter and flow velocity for each pipe roughness value (see *Fluid Mechanics in Pipelines*).
The Wallingford charts are far easier to use than the Moody diagram, but the content is the same. For large diameters, as in tunnels or sewers, charts may not be available and the Moody diagram method is the only one available, especially where wall roughness due to aging or refurbishment may gradually or suddenly change.

3.5. Pipeline Conveyances

Pipelines and other closed conduit conveyances transfer water "from point A to point B" over a shorter distance than a canal does, because they do not have to closely follow the contours or grade lines and can be placed underground alongside roads or streets in straight line sections, or gently curving arcs.

Pressure pipelines do not need a downward gradient as gravity pipelines or canals do, and can therefore have more direct, straight-line connections between nodes, which allows them to follow both the positive or negative ground-surface gradients of roads and streets.

It then becomes necessary to install scour valves and air valves, at local low and high points of the profile, respectively, while the pipeline wall thickness must be designed to resist more severe maximum internal static pressure heads, as well as dynamic pressures (friction head losses, water hammer and surges). External loads of overburden and traffic have to be resisted by pipelines.

A great deal of infrastructure has to be created in the routing of pipelines through built-up urban areas, pumping stations are needed for housing the hydraulic machinery and other mechanical and electrical equipment, with their associated civil engineering structures (see *Hydraulic Structures for Pumping Equipment*).

3.6. Hydraulic Theory

Although the hydraulic theory for closed conduit flow as found in single-line pipe systems (gravity main and rising main) is more straightforward than the hydraulic theory for free-surface flow canal systems (of variable cross-sectional area), there are more design considerations associated with pipe flow on account of external loads, corrosion protection and aging effects. These aspects - including pump station design, hydroelectric power generation, valves, fittings and types of pipes and pipe materials - are thoroughly dealt with in hydraulic textbooks and corresponding postgraduate courses. These also deal with pumps and turbines, flow metering, water hammer, surge suppression and flow network analysis, as contained in companion articles in this Theme (see *Fluid Mechanics*).

3.7. Economical Considerations

The choice of economical pipeline diameters, materials, types and techniques of construction, comprises a specialized field which has developed very far into practical engineering, but consistently abides by sound hydraulic principles (e.g. calculating equivalent pipeline diameter and resistance coefficients in a complex flow network analysis), which is basic to the study of flow behavior in a closed conduit conveyance system. Time-dependent (variable) flow, or unsteady flow, particularly, is carefully analyzed in pumping- and hydroelectric power-projects to ensure that sudden flow variations, which might generate excessive hydrodynamic forces, are avoided or at least are capable of being tolerated by the system without damage.

Proper anchoring and support of pipelines and fittings are necessary from a structural engineering point of view and require careful design for all loading conditions. Both *iso-static* (statically determinate) and *hyper-static* (statically indeterminate) structural designs are made for above ground pressure pipeline installations, such as hydropower penstocks. More commonly, pipelines are laid underground in back-filled trenches.

4. Flow Measurements

Flow measurement, in closed-conduit flow circuits, is important for operation and the earning of revenue from the sale of purified water. It is a study area on its own and mainly uses direct velocity measuring equipment such as mechanical (positive displacement) and electrical (electromagnetic, acoustic, Doppler) flow measurement apparatus or *flow meters*.

Besides these, older types of meters that are based on pressure differentials are still used for measuring and recording flow. Derived velocity and integrated discharge may be used to give the delivered throughput directly by means of mechanical or solid-state electrical devices, which includes digital telemetry. Meters, such as the well-known Venturi, Dall Tube and orifice-plate meters are mainly used, with Pitot and Prandtl tubes employed for calibration purposes (see *Flow Measurement in Closed Conduits* and *Flow Measuring Techniques*).

5. Concluding Remarks Concerning Water Conveyances

The science of the subject constantly advances on practical lines and the state of the art progresses duly as new and better materials, hardware, specialist devices and controls are perfected. Theory and experience go hand-in-hand, and necessity is also the mother of invention, in hydraulic conveyance structures, especially related to small community projects. The above should be regarded as a brief introduction to the subject of Water Conveyance Systems, rather than an overview of the contents of another specialist article which follows (see *Guidelines for Sustainable Community Water Supply and Sanitation Projects*).

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Biographical Sketch

Jan Jordaan is a retired professor of civil engineering and professional engineer in civil engineering hydraulics. He graduated with the degree of B.Sc. Eng. from the University of the Witwatersrand, Johannesburg, South Africa, and then obtained the degrees M.S. (Wisconsin), Civil Engineer (MIT) and Sc.D. (MIT).

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 CA, USA. He also lectured at the Universities of Hawaii and Delaware in the USA and at the University of Pretoria in South Africa.

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